An analysis of misconceptions about thorium-based fuel cycles as a technical fix to the nuclear proliferation problem.

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Thorium cycles and proliferation

This paper analyzes several prevalent misconceptions about nuclear fuel cycles that breed fissile uranium-233 from thorium. Its main conclusions are:

- Uranium-233, despite the gamma radioactivity of associated isotopes, is a rather attractive material for making fission bombs, and is a credible material for subnational as well as national groups to use for this purpose.
- "Pure" thorium cycles, which in effect merely substitute uranium-233 for plutonium, would take many decades and much uranium to establish, and offer no significant safeguards advantage over plutonium cycles.
- "Denatured" thorium-uranium cycles, which dilute the uranium-233 with inert uranium-238 to a level not directly usable in bombs, are not an effective safeguard even against subnational bomb-making. This is because three factors—higher initial fissile content, larger mass difference between isotopes, and smaller amount of material needed for a bomb—make such "denatured" uranium-233/238 fuel one or two hundred times easier to enrich to bomb-usable levels than natural uranium. Such enrichment can be done at a modest scale with readily available centrifuges.
- Several other features of mixed thorium-uranium cycles are rather unattractive from a safeguards point of view.
- Thus thorium cycles of any kind are not a technical fix for proliferation (national or subnational) and, though probably more safeguardable than plutonium cycles, are less so than once-through uranium cycles that entail no reprocessing.
- While thorium cycles have some potential technical advantages, including flexibility, they cannot provide major savings in nuclear fuel resources compared to simpler ways of saving neutrons and uranium.
- Thus while advocates of nuclear power may find thorium cycles worth exploring, such cycles do not differ fundamentally from uranium cycles in any of the respects—including safeguards and fuel resources—that are relevant to the broader nuclear debate, and should not be euphorically embraced as if they did.—A.B.L.

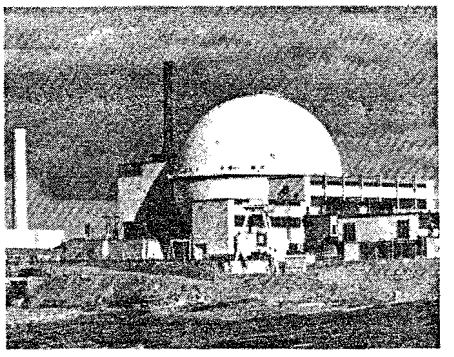
If nuclear fission is to be used as an energy source, whether it should use fuel cycles that require plutonium to be extracted and re-used turns on two independent questions [1]. The first is whether plutonium is bearable and the second is whether a lot of uranium is available (geologically and politically) at relatively low prices. Few if any analysts answer yes to both questions; and for any who do, policy choices are unconstrained. Those who believe plutonium is bearable and uranium scarce build fast breeder reactors. Those who believe plutonium is nasty and uranium plentiful write Ford-MITRE reports. Those who believe plutonium is nasty and uranium may be scarce call attention to fuel-efficient, non-plutonium fuel cycles. It is this last, perhaps most interesting, group that has recently recalled attention to thorium-based fuel cycles which appear to many nuclear advocates to merit study on several grounds, potentially greater resistance to the proliferation of nuclear weapons being high among them.

It is this cluster of proposals, and some prevalent misinterpretations of them (especially common in Britain and Canada), that this article briefly discusses. The arguments of critics of the plutonium economy are taken as read. Nothing in this article should be construed to imply that:

- the proliferation risks of plutonium fuel cycles can be made tolerable, or
- any commitment (even an exploratory one) to a plutonium economy need be made for many decades, perhaps even a century or two,
- any improvement in existing safeguards (such as those sought by the Carter administration) is not worth making only because it does not solve the whole problem, or
- any form of nuclear power is necessary or desirable.

All these fallacies are addressed elsewhere [2]. While some of my arguments have been previously advanced by advocates of plutonium fuel cycles, presumably seeking to suggest that their option is acceptable because the thorium alternative to it is nearly as bad, I shall suggest that *neither* is acceptable. Thus any out-of-context quotation of this paper in support of plutonium cycles would be perverse and misleading.

Since proposals were widely published in 1976-1977, notably by Taylor and Feiveson [3], for a "denatured" [4] thorium cycle which might be less proliferative (especially to subnational groups) than a plutonium-uranium fuel cycle [5], some people [6] have jumped to the conclusion that thorium cycles in general and denatured thorium cycles in particular offer a technical fix to the proliferation problem. This is incorrect. It is also certainly not what such authors as Taylor, Feiveson, Cochran, and von Hippel had in mind: they proposed denatured thorium only as proof of the existence of fuel cycles which might, on closer study, prove to be inherently less proliferative than uranium/plutonium cycles. Since at least one



The concern over weapons proliferation problems has lately led to serious international consideration of alternative nuclear fuel cycles. Among these, cycles involving the breeding of the uranium-233 isotope from thorium, especially with provisions for its "denaturing" with ordinary uranium, are generally believed to show great promise for a nuclear energy future without weapons proliferation. In this article the author dashes cold water on the most optimistic of such expectations.—Ed.

such fuel cycle could be envisaged, they argued, it is important not to rush ahead with a plutonium economy before potentially less proliferative options are carefully examined.

The early stages of that closer examination have made it clear that thorium fuel cycles, including denatured ones, do not *qualitatively* alter the proliferation problem (either national or subnational) and in some respects offer more avenues for proliferation than once-through uranium cycles. The reactor-physics and safeguards considerations supporting this conclusion are somewhat elementary, but the scarcity of systematic analyses of them has lately generated much misplaced enthusiasm [6]: hence this summary.

Thorium and Uranium-233. There are two basic kinds of thorium cycles, both of which may breed fissile uranium-233 from fertile thorium-232, mainly via the intermediate product protactinium-233, which has a 27-day half-life. The first kind is the "pure" thorium cycle, a self-sustaining one relying on previously bred uranium-233 for fission neutrons to breed more uranium-233 in fuel consisting of uranium-233 mixed with thorium-232. Burnup of this fuel produces various isotopes, up to and including small amounts of plutonium formed by successive neutron captures.

From a weapons physics point of view, uranium-233 is similar and in some respects perhaps superior to plutonium-239, the classical material. They are roughly equal in reactivity, as shown by the nearly identical bare-sphere critical masses [7] of uranium-233 (16 kilograms at a density around 18.8 grams per cubic centimeter) and the delta phase of plutonium-239 (17 kilograms at about 15.8 grams per cubic centimeter). (Corresponding figures for the alpha phase of plutonium, at around 19.8 grams per cubic centimeter, are 11 kilograms for nearly pure plutonium-239 and 13 kilograms for "reactor-grade" plutonium produced at a burnup around 30 thermal gigawatt days per metric ton of uranium. Of course all these quantities can be reduced greatly—more than fivefold—by reflection and implosion in a nuclear explosive.) Broadly speaking [7], for fast neutrons the relative neutron yield is

$$^{239}\mathrm{Pu} \gg {}^{233}\mathrm{U} \gtrsim {}^{235}\mathrm{U}$$

and the fission cross-section

$$^{239}\mathrm{Pu} \gtrsim {}^{233}\mathrm{U} \gg {}^{235}\mathrm{U}.$$

These conclusions are relatively insensitive to contamination of the uranium-233 with traces of other uranium isotopes.

Because uranium-233 is about three times as reactive as uranium-235 (whose bare-sphere critical mass at 93.5 percent enrichment is about 50 kilograms), one might expect that a third as much of it would be required for a bomb. In fact the reciprocal of this ratio, the "substitution factor," is not 3 but typically 5 to 10 because a physically smaller core can be compressed more in a convergent implosion. (An incompressible solid spherical shell, if imploded, provides a pressure varying as the inverse fourth power of its radius [8].)

Ordinarily uranium-233 has a substantial neutron background because of (α,n) reactions with light-element impurities. With a significant chemical effort, which is not normal practice, these impurities can be greatly reduced so that the neutron background becomes lower than in weapons-grade plutonium, permitting use of a gun-type rather than an implosive assembly—a further option which may be easier than an implosive design. Both chemically and metallurgically uranium-233 is considerably more tractable than plutonium: it is not very pyrophoric and has one solid phase, not six. Its inhalation toxicity is considered to be about 70 times lower than that of plutonium-239, several hundred times lower than that of reactor-grade plutonium.

The only significant disadvantage of uranium-233 is that after production, various daughters of uranium-232 build up in it (peaking about 10 years after extraction), notably thallium-208. Some uranium-232 daughters emit intense and penetrating gamma rays, of which thallium-208 typically contributes more than half the total with its 2.6- and 0.6-megavolt emissions. Commercial handling of uranium-233, especially if it were more than a few days old (whereas aging for about a year is desirable for full decay of the protactinium-233 parent of the uranium-233), would require heavy shielding—of order twice as much as the gamma- and neutron-emitting recycle plutonium requires—to protect workers from overexposure. But if relatively small amounts of uranium-233 were being dealt with for relatively short periods outside the restrictions of prudent health-physics practice, shielding could be greatly reduced or even dispensed with.

A kilogram of uranium-233 produced at 46 thermal gigawatt days per metric ton of heavy metal burnup and 32 thermal megawatts per metric ton of heavy metal specific power, for example (corresponding to about 140 milligrams of uranium-232 per kilogram of uranium), then aged 90 days, would contain [9] about 82 mil-

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licuries of thallium-208. Total unshielded gamma dose from that kilogram at a distance of 1 meter would be of order one-quarter roentgen per hour. An American Physical Society working group [10] cites a uranium-232 content of order 200 to 1,000 milligrams per kilogram [11], implying maximum dose rates (after roughly hundred-day aging) of order 1 roentgen per hour from 1 kilogram at 1 meter. Such dose rates, though substantial, are hardly a matter of major concern to people likely to put the material to illicit use in the first place. It is also possible that supervisors of such use might neglect to tell workers of the hazard.

Because uranium-233 is an attractive weapons material and because chemical processing by methods thoroughly described in open literature can readily separate uranium-233 from thorium-232, the safeguards implications of a pure thorium cycle differ only in detail from those of a plutonium-239 cycle. The former offers no significant safeguards advantage over the latter—not even the ease of detecting uranium-233 by remote sensors such as door monitors, since modern techniques can also (we are assured) sensitively detect the high-burnup plutonium present in plutonium-based fuel cycles.

Making enough uranium-233 to set up a self-sustaining pure thorium cycle also requires that a mixed thorium/uranium-235 cycle first be operated for a very long time—typically several decades at least. Such mixed cycles breed surplus uranium-233 as a by-product. The neutrons needed to do this and to sustain fission in the mixed cycle must be derived from either highly enriched uranium-235 or fissile plutonium—both weapons materials. Thus the persistent initial phase of any sort of thorium cycle inevitably entails the presence, in some form, of weapons materials, incurring in some degree the safeguards problems that the thorium cycle was alleged to prevent. The denatured thorium cycle is one attempt, on paper, to reduce those problems to a more tractable level.

Denatured Thorium Cycles. The denatured thorium cycle—actually a mixed thorium-uranium or thorium-uranium-plutonium cycle—relies on the possibility of denaturing uranium-233, that is, making it into a form not directly usable for weapons, by mixing it with at least seven times as much non-fissile uranium-238 from which it cannot be chemically separated as plutonium could. This denatured fuel flows between two different kinds of reactors in different places.

First, "national" reactors—most or all of the total reactor population—are built in relatively dispersed sites which could be internationally administered but are more likely to be under national control (often of non-nuclear-weapons states). These reactors are breeders or advanced converters with good neutron economy, such as heavy-water, spectral-shift, or high-temperature gas-cooled reactors. They are fueled with a mixture of uranium-233, uranium-238, thorium-232, and perhaps uranium-235. (Liquid-metal fast breeder reactors appear unsuitable for this role: with normal designs their fuel would have to be too enriched in fissile isotopes for denaturing to work, and if the core were redesigned to permit denaturing, it would make too much plutonium-239 and not enough uranium-233 for the cycle to work properly.)

Regardless of the type of national reactor used, the thorium-232 would be largely in a blanket (according to most analyses) and the denatured uranium-233/uranium-238 (/uranium-235) fuel mainly in a central core. The thorium-232 and uranium-238 respectively produce uranium-233 and plutonium-239 of which part is burned in the reactor and part discharged in irradiated fuel. The *minimum* net production of plutonium-239—constrained by the need to have at least seven atoms of uranium-238 in fresh fuel per atom of uranium-233—is nearly 40 kilograms per electric gigawatt-year sent out: 5 to 7 times [12] less than with a light-water reactor, not zero.

Second, "secured" facilities are to be centrally sited in at most a few places under international control. Irradiated fuel from national reactors is then shipped to these centers and reprocessed. All fissile materials, including both plutonium and uranium-233, are recoverable, and in many analyses are assumed to be recovered, then used in various ways to breed more uranium-233 for denaturing and shipment back to the national reactors as fresh, isotopically denatured fuel. This breeding might be done in a thorium-232-blanketed breeder (for example, a liquid-metal fast breeder reactor) that burns plutonium-239 and some uranium-233 in its core. (The good neutron yield of the resulting uranium-233 in thermal converters might make the asymptotic ratio of national converters to secured breeders as large as 3 to 4.) The principle, however, is that no plutonium-239 goes off-site; the only fissile material leaving the "secured" facilities is denatured fuel.

In some other proposals, any excess plutonium-239 is burned on the secured sites in special burner reactors that lack fertile inventories. This yields energy from the plutonium but wastes neutrons; the system is not a net fissile producer. In a further variation due to von Hippel, the plutonium is never even extracted, but is discarded (under international controls) still mixed with the fission products. This makes immediate safeguards easier (the plutonium-bearing waste must still be protected from eventual recovery) and is not such a great economic loss because the high plutonium-236 and -238 content offers a disincentive to plutonium extraction and reuse [13]. In a plutonium-throwaway cycle—which can still be 5 to 6 times as uranium-

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efficient as a once-through pressurized-water reactor—reactivity in fresh fuel going to national reactors is supplemented as needed, at least in the early stages, by makeup uranium-235. (This might be added as a feedstock at about 60 percent enrichment—whose critical mass is somewhat over twice that of fully enriched uranium-235—and then diluted with uranium-238 to a denatured level. Thus the total number of uranium-238 atoms in denatured fuel would be at least 7 times the number of uranium-233 atoms plus 4 times the number of uranium-235 atoms.) The secured facilities would then contain no reactors at all, but only reprocessing, enrichment, and fuel fabrication plants.

Regardless of the disposition of the plutonium within the "secured" sites, the important feature of these uranium-thorium cycles is that the denatured fuel that leaves those sites and forms an item of commerce is not directly usable for weapons nor, it is alleged, readily convertible to weapons material as mixed uranium-plutonium oxides, carbides, or nitrides would be. This allegation rests on the assumption that isotopic enrichment is not available to amateurs as chemical separation of fresh fuels presumably is. This assumption seems shaky, because "the technology to carry out such enrichment on non-economical, non-commercial scale is available in the open literature. This requires further evaluation" [14]. The relevant physical principles merit discussion here.

Wolf Häfele has stated [15] that "the construction of a set of crude centrifuges does not require unusual skills as long as efficiency and commercial competition are not the point." He added [16] that, to show this, a European centrifuge-builder once made in an American university machine shop (in about three weeks and with one technician) a crude centrifuge capable of respectably enriching natural uranium. (In practice, making a bomb from natural uranium with such centrifuges would require patience and tens or preferably hundreds of units because each has a relatively small mass flow.) But in interpreting this incident it must be recalled that:

- denatured thorium-cycle fresh fuel is not 0.7 percent enriched in the fissile isotope as natural uranium is, but rather about 12 percent—so that 85 percent of the separative work needed to attain high enrichment has already been done. (For example, at constant 0.25 percent tails assay, it can be calculated that 6.8 times less separative work is needed to enrich to a kilogram of, say, 93.5 percent product starting with 12-percent-enriched feed than with 0.71-percent-enriched feed.)
- the mass difference between uranium-233 and uranium-238 is two-thirds larger than the mass difference between uranium-235 and uranium-238. In gas-diffusion enrichment of hexafluorides this means the theoretical separation factor per stage would be 1.0072 (that is, enrichment from 0.12 to 0.935 in 286 ideal stages) rather than 1.0043 (in 478 stages), since diffusion velocities vary as the square root of molecular weight. With centrifugal enrichment, however, maximum separation factor varies exponentially with, and the separative power of a particular centrifuge varies as the square of, differences in molecular weight. Häfele confirms [17] that uranium-233 is three times (about $5^2/3^2$) easier to enrich than uranium-235—and separation factors for uranium-235 can be of order 1.2 to 1.5 or more per stage.
- as noted earlier, about 5 to 10 times less uranium-233 product is required than uranium-235.

These three considerations suggest that denatured thorium-cycle fuel is 100 to 200 times (= 7 x 3 x 5-10) easier to enrich to bomb usable levels than natural uranium—two orders of magnitude more than the difference between low-enriched and natural uranium. This factor implies that significant enrichment of denatured thorium-cycle fuel can be achieved not only with homemade centrifuges designed for this purpose by persons moderately skilled in the art but also with modified versions of commercially available medical ultracentrifuges. (These may have large volumes, speeds over 75,000 revolutions per minute, and accelerations over half a million gravities.) With patience, strategic quantities of uranium-233 could be accumulated with a few centrifuges (though a government would presumably use hundreds and make more uranium-233). Since the holdup in each centrifuge would be typically of order grams, the hard-gamma dose even for brief contact maintenance would probably be acceptable to those concerned (or at least to their supervisors)—though in the long run the concomitant enrichment in uranium-232 may increase the dose.

It could be argued fairly persuasively that conversion to uranium hexafluoride, centrifugal enrichment, and reconversion would be somewhat more difficult than extracting plutonium from fresh mixed-oxide fuel. But though different kinds of sophistication are required and the tasks are not strictly comparable, they do not seem to differ qualitatively in difficulty, especially for high-burnup recycle plutonium. Nor do the times required to perform both tasks necessarily differ by as much as an order of magnitude.

Denatured fuel, then, is not irrevocably denatured even for amateurs—let alone for governments. But the rest of the denatured thorium cycle also lends itself rather well to misuse. The national reactors have, of necessity, an excellent neutron economy. CANDU or similar reactors are likely in this role and, with their on-load refueling and slight excess of refueling-machine capacity, are well suited to clandestine introduction and brief irradiation of adequate amounts of fertile materials (thorium-232 or uranium-238) in a few channels for later clandestine reprocessing, perhaps in hot

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cells. In fairness, one must add that it may be easier to safeguard a reactor than a reprocessing plant; but the possibility of abuse remains, so that fully effective international inspection is still essential [18].

The spent fuel itself, rich in both plutonium-239 and uranium-233, and especially any blanket fuel, must be safeguarded against diversion and clandestine reprocessing—just what one is worried about with ordinary thermal reactors, with or without plutonium recycle or breeding. (Most nuclear power countries can today do laboratory-scale reprocessing, suitable for one or a few bombs, and could build a bomb-per-day crude reprocessing plant in a year or two for a cost one or two orders of magnitude less than the cost of a single power reactor.) Prompt reprocessing of irradiated thorium-cycle fuel—though it must cope with the high initial radioactivity—can also readily extract pure protactinium-233, which would then decay to isotopically pure uranium-233 with negligible gamma background [19]. And as with non-denatured fuel cycles, governments can disguise their own diversions as terrorist thefts, and can in dozens of effective but legal ways deceive international inspectors or make it impossible for them to do their job properly.

Further, the "secured" sites would indeed have to be secured—not only on paper—from both embezzlement and seizure of their extremely large fissile inventories. Though both embezzlement and seizure can be made more difficult by technical means, it appears to be impossible in principle to deny them altogether to a determined adversary. The formidable political problems of finding acceptable sites for multinational centers and protecting them from instability and expropriation would have to be overcome: most analysts who have carefully studied this problem consider it insoluble. Multinational reprocessing plants would legitimize reprocessing and disseminate its technology, somewhat like a hospital spreading disease, for thorium cycles, unlike uranium cycles, *require* reprocessing.

(If all these problems of the multinational centers were solved, one could also envisage a heavily spiked plutonium fuel cycle which would then have broadly similar problems. From a safeguards point of view the two cycles would appear similar—at least as regards small-scale bomb production; the plutonium cycle would probably offer more opportunities for rapid large-scale bomb production.)

It might be thought that centralization of reprocessing and of the use of pure fissile materials might make them easier to guard and assay; but it can equally be argued that this centralization makes the "secured" site a more valuable prize and a more vulnerable site to both accident and malice. It certainly makes the farflung net of dependent national reactors more vulnerable to all sorts of surprises.

Thorium and Nuclear Fuel Resources. Recent calculations—preliminary but probably fairly accurate—suggest [20] that no combination of national and multinational reactors that includes advanced converters can have a total conversion ratio greater than 1.0 (that is, be a net producer of fissile material)—except that a system using a one-to-one converter like a molten-salt reactor might in principle have a low breeding gain. The General Atomic Company also maintains that a carefully optimized system using high-temperature gas-cooled reactors can have a significant breeding gain [20]. Even breeder-breeder combinations would have a small fissile gain, typically of order two to three percent per year, and so would take many decades to come to equilibrium. They thus appear incapable of yielding the rapid gains in fissile inventory hoped for from advanced (and undemonstrated) plutonium-239 cycles.

If one assumes that the world will depend essentially forever on nuclear fission power on an enormous scale, this may be important—especially if one considers proneness to proliferation less important. If, however, one assumes more modest rates of growth in nuclear capacity or electrical demand, or views nuclear power as a parenthesis—even one of a century or two—then breeding gain is unnecessary, since efficient converters can stretch known uranium reserves far enough to suffice [5]. In particular, over the next 75 to 100 years, advanced converters can save as much uranium as plutonium-239 breeders. The advanced converters' relative insensitivity to the price of uranium expands reserves, and anxieties over security of supply can be cheaply relieved by stockpiling [21].

The mixed thorium/uranium-235 cycle has high initial requirements for uranium-235 and enrichment or for plutonium-239. These large first-core requirements can produce a dynamic materials-flow problem if one tries to set up such a fuel cycle quickly. This is analogous to the problem of rapid construction of fast breeders; a plutonium shortage for initial cores [22] is liable to arise unless many thermal reactors are also built and run in tandem with the breeders for many decades to produce their plutonium. The combined population of fast and thermal reactors is then likely to run short of uranium-235 (assuming this to be in short supply to start with). Starting with breeder cores of low specific plutonium inventory also means low breeding gain, thus uranium shortage, and substituting highly enriched uranium for scarce plutonium still does not take the pressure off of uranium supplies.

The reason this problem cannot be evaded points up an important feature of thorium fuel cycles—a feature so simple it often goes unrecognized. Using thorium does not

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magically expand the supply of nuclear fuel, only of *fertile* material, of which we already have a great deal in the form of uranium-238. No fertile material, whether it be uranium-238 or thorium-232, can be bred into a fissile material save by neutrons. These, the coin of the nuclear realm, must be derived ultimately from uranium-235 (either directly or via bred fissile materials such as plutonium-239) [23]. It is therefore the supply of uranium-235 in the ground that poses nuclear fuel constraints. The only sense in which using thorium helps with the nuclear fuel problem is that thorium-232 can be bred with thermal neutrons (and can then fuel efficient thermal converters), whereas uranium-238 can be most efficiently bred with fast neutrons. The former process may be more convenient, though the latter has higher neutronic efficiency—a property not wholly unlinked to its relevance to bombs. And the fast-breeding ability of uranium-238 is irrelevant if, as appears to be the case, the available uranium-235 is ample [5] when used in thermal converters.

People who wish to ascribe magical properties to thorium cycles should also remember that the above description of a denatured thorium cycle is theoretical. No such cycle has operated anywhere, though there has been minor use and reprocessing of thorium fuel at pilot scale. Dissolution and extraction are somewhat harder than for low-burnup uranium dioxide fuel [24]. It is possible that actual behavior of a thorium cycle might depart significantly from the above results of preliminary calculations, or that unexpected technical problems might arise as they have done persistently with moderate-burnup plutonium cycles. It does seem rather late in the day to start with a whole new set of fuel physics and chemistry. Of course, just the same could be said of high-burnup plutonium cycles—which, unlike their low-burnup predecessors that have rested on generous military subventions throughout their establishment, are now having to pay their own way, and are finding the burden of fuel-cycle investments unsustainable. Thorium cycles would have the same problem from the start: the visibility of full fuel-cycle costs could be a most ineluctable deterrent.

Among the criteria that Cochran and others proposed [5] as a minimal and partial basis for acceptability of commercial fuel cycles is that their

> "development and commercial utilization of the technology by a non-nuclear weapons state leaves that state no closer to a nuclear weapons capability than would be the case if all its nuclear power were derived from low-enriched uranium fueled reactors operating in a once-through fuel cycle . . . and with verified spent fuel storage in secured international facilities" [25].

It appears very doubtful that denatured thorium cycles could meet this criterion. Certainly they cannot greatly improve the present safeguards situation; and for reasons similar to those set out above, Theodore Taylor has recently described the notion that they can as "a snare and a delusion" [26]. A more mature assessment by the technical community of the grounds for his skepticism will probably lead many to share it. And he and I would both emphasize that the safeguards/proliferation problem has *no technical fix*. It is partly, even predominantly, a *political* problem. Facile assumptions [6] about technical fixes or near-fixes will not solve the political problem and might well make it worse by giving a false sense of security.

Thorium cycles have had the misfortune to be attacked both by plutonium advocates (for competing with their favorite technology) and by nuclear critics (for having the potential, in the hands of the uninformed, to give nuclear power an undeserved new lease on life) [1]. Neither basis for attack is a sound basis for public policy. Yet both contain an important lesson. Advocates of nuclear power should learn that there is no need to rush into the plutonium economy [27], and that a wide range of alternative fuel cycles [28] may offer attractive substitutes for it later. It is equally important that thorium cycles not be euphorically and falsely advertised as a solution to the proliferation problem—a problem that is the most compelling reason to reject all forms of nuclear power in favor of fission-free energy strategies [29].

1. This formulation is due to Lew Kowarski. I am indebted for discussions and correspondence to him, Tom Cochran, Floyd Culler, Warren Donnelly, Peter Fortescue, Sir Brian Flowers, David Hafemeister, Walt Patterson, Ted Taylor, and Frank von Hippel, many of whom suggested significant improvements in an earlier draft. I alone am responsible for the results.

2. See, for example, references 3 and 5; A. B. Lovins, *Soft Energy Paths: Toward a Durable Peace* (New York: Harper & Row, 1979), especially Chap. 11; International Technology Project, Institute of International Studies, University of California, Berkeley, *Non-Proliferation and Nuclear Waste Management*, Contract AC6AC725 (Washington, D.C.: U.S. Arms Control & Disarmament Agency, 1977); A. Wohlstetter et al., *Moving Toward Life in A Nuclear Armed Crowd?*, ACDA/PAB-263 (Los Angeles, Ca.: Pan Heuristics, 1977); Wohlstetter and T. B. Cochran, respective Proofs of Evidence for the summer 1977 Windscale inquiry (U.K.).

3. H. A. Feiveson and T. B. Taylor, "Security Implications of Alternative Fission Futures," *Bulletin* 32:10 (December 1976), 14-18, 46-8.

4. Of course, uranium cycles can be isotopically denatured too—as is the conventional once-through low-enriched uranium cycle.

5. T. B. Cochran, R. E. Train, F. von Hippel, and R. H. Williams, "Proliferation Resistant Nuclear Power Technologies: Preferred Alternatives to the Plutonium Breeder," including additional statements by T. B. Cochran and R. E. Train, part of the report of the LMFBR Review Steering Committee (R. Thorne, Chairman), report to the President, April 6, 1977.

6. See, for example, Sir Fred Hoyle, *Energy or Extinction?* (London: Heinemann Educational, 1977), pp. 50-1.

7. H. C. Paxton et al., "Critical Dimensions of Systems Containing U^{235}, Pu^{239}, and U^{233}," TID-7028 (Los Alamos Scientific Laboratory, June 1964); R. W. Selden, "Reactor Plutonium and Nuclear Explosives"

(Lawrence Livermore Laboratory, Nov. 1, 1976); *Reactor Physics Constants*, ANL-5800 (2d ed.), Argonne National Laboratory, 1963.

8. E. Teller, in S. A. Blumberg and G. Owens, *Energy and Conflict: The Life and Times of Edward Teller* (New York: Putnam, 1976), Appendix.

9. M. J. Bell and J. P. Nichols, "Penetrating Radiation Dose Rates and Shield Requirements in Fabrication of Fuels Containing ^{233}U and High Exposure Plutonium," in *Sol-Gel Processes and Reactor Fuel Cycles*, CONF-700502 (Oak Ridge National Laboratory, 1970), pp. 74-84. For dose vs. aging, see reference 10, p. S 154, figure 11.

The BNL paper cited in reference 17 states on page 23 that for uranium-233 dioxide with 1 gram of uranium-232 per kilogram, a 100-roentgen dose will be accumulated in 3 days, 5 hours, and 2 hours respectively, if an individual is 1 foot from 30 kilograms of uranium dioxide aged 0, 10, and 20 days since chemical separation.

10. American Physical Society, Study Group on *Nuclear Fuel Cycles and Waste Management, Reviews of Modern Physics* 50:1 (Jan. 1978), Part II, p. S 154.

11. See reference 10, p. S.171, citing T. Pigford and C. Yang, "Thorium Fuel Cycles," UCB-NE3227 (Berkeley: University of California, June 1977). The authors calcu- recycled uranium from a high-temperature gas-cooled reactor as about 500 milligrams per kilogram, but predict as high as 9 grams per kilogram for a uranium-thorium light water reactor fuel cycle.

12. APS Study Group (reference 10, p. S 155) says a factor of about seven in idealized fuel cycles, but notes that about three is possible in "more practical designs."

13. APS Study Group (reference 10, p. S 171). The plutonium-236 and-238 are formed largely from neptunium-237.

14. APS Study Group (reference 10, p. S 102, S 156).

15. W. Häfele, "Non-Proliferation of Nuclear Weapons" (Laxenburg, Austria: International Institute for Applied Systems Analysis, Dec. 1976), p. 10.

16. W. Häfele to Lovins, Feb. 16, 1977.

17. W. Häfele, in *Argumente in der Energiediskussion: 1. Schnelle Brüter: Pro und Contra* edited by H. Matthöfer (Necker-Verlag, Villingen, Oct. 1977), pp. 44-45.

For a discussion of separation factors for uranium-233 *vs* uranium-235, see Brookhaven National Laboratory, "Preliminary Safeguards Analysis of Denatured Thorium Cycles," file #5.8.13 (Upton, N.Y.: BNL Technical Support Organization, Nov. 10, 1976). An addendum (July 14, 1977) calculates that five kilograms per year of 90 percent uranium-233 can be separated (at 1 percent tails assay) from 49 kilograms of uranium per year that is 10% uranium-233 and 90 percent uranium-238 with an ideal cascade of 43 centrifuges, each having a capacity and a separation factor, respectively, of 3.0 kilograms of separative work per year and 1.10 for uranium-235 (8.3 kilograms of separative work per year and 1.17 for uranium-233). Gas centrifuges with better performance than this and costing around $10,000 or less are described in the open literature.

18. APS Study Group (reference 10, p. S 102) states: "It must be remembered that with *any* denatured fuel cycle, international inspection is still essential in guaranteeing that fresh fuel and/or natural uranium are not being diverted to small enrichment facilities, that reactors are not being misused to produce plutonium, and that small non-safeguarded separation facilities are not operated in addition to those at international centers. Such inspection goes beyond present IAEA agreements but must become part of any future political arrangements which institutionalize denatured fuel cycles."

The International Atomic Energy Agency report of June 8, 1977 to the IAEA Board of Governors, GOV/1842, calls attention in its Annex to the serious and, so far, unsurmounted difficulties of effectively safeguarding both reprocessing plants and on-load refueling reactors.

19. APS Study Group (reference 10, p. S 154) referred in its prepublication preprint (VIII. F 1) to "a relatively simple chemical separation." H. C. Ott states (*Power Engineering*, Nov. 1977, p. 28) that the minimum protactinium-233 assay—that characteristic of a pressurized water reactor—is 3.8 percent of the fissile uranium assay.

20. F. L. Culler, Jr., to Lovins, May 1977; the calculations, mainly by Argonne National Laboratory, are to be published in connection with supporting research for the International Fuel Cycle Evaluation. See also C. L. Rickard (General Atomic Co.), "The Thorium Fuel Cycle," AIF Fuel Cycle Conference, New York, March 5-8, 1978.

21. F. von Hippel and R. H. Williams have calculated that each ten years' worth of uranium stockpile bought at $40 per pound of U_3O_8 incurs a carrying charge (at 16 percent per annum) that raises the delivered price of nuclear electricity by an amount ranging from 0.9 percent (once-through PWR) to 0.2 percent (heavy water reactor with uranium-233 and-235 recycle and throwaway plutonium) (H. A. Feiveson, "Proliferation Resistant Fuel Cycles," *Annual Review of Energy* 3 (1978), 391, Table 8).

22. L. Grainger, *Energy Policy* 4 (Dec. 1976), 322-9; D. Merrick, *Nature* 264 (1976) 596-8.

23. Surplus neutrons might in principle be available from sources other than pure fission cycles—for example, spallation reactions in accelerators, or thermonuclear or near-thermonuclear reactors—but such sources are neglected here because of their uncertain or unfavorable feasibility, lead times, energy balance, and economics.

24. APS Study Group (reference 10, pp. S 36, S 153).

25. Verified fresh-fuel storage would also be required to prevent diversion to clandestine enrichment facilities or production reactors.

26. T. B. Taylor to Lovins, Sept. 30, 1977.

27. S. M. Keeney et al., *Nuclear Power: Issues and Choices* (Cambridge, Mass.: Ballinger, 1977); H.A. Feiveson et al., "The Plutonium Economy: Why We Should Wait and Why We Can Wait," *Bulletin* 32:10 (Dec. 1976), 10 ff, Feiveson, "Proliferation Resistant Fuel Cycles," *Annual Review of Energy* 3 (1978), 357-94. See also references 2 and 21.

28. See reference 27, Cochran [5], APS Study Group [10]. Unfortunately the discussion of alternative fuel cycles may be temporarily derailed by sophistical discussions of plutonium cycles based on breeder reactors that do not breed.

If the original goal of high breeding gain is to be abandoned (see, for example, W. Marshall, "Nuclear Power and the Proliferation Issue" (London: United Kingdom Atomic Energy Authority, Feb. 1978), fast reactors become unnecessary; and if it is felt desirable to incinerate stocks of plutonium (and perhaps other actinides), that are already separated, this can be done in low-power-density thermal reactors with a non-fertile matrix. Spent fuel not yet reprocessed can be disposed of irretrievably (one hopes) in the manner intended for vitrified high-level wastes. As for plutonium not yet generated in thermal reactors, the opportunity of generating it in order to be able to build non-breeding fast reactors in which to incinerate it can simply be foregone.

L. Kowarski has aptly remarked that the Marshall proposal reminds him of the entrepreneur whose herd of cows gave milk copiously while there was a glut of it and Europe was already sinking under a mountain of powdered milk. He said, "Don't worry; with high-pressure salesmanship I shall dispose of all my milk anyway." On being told, however, that the milk was full of cholesterol and might hence be dangerous to drink, he said, "That is more serious. But I have a solution: I shall simply feed the milk to the cows. They can be trained to drink vast quantities of it!"

29. See, for example, A. B. Lovins [2]; for a compendium of critiques and responses, see U.S. Senate, Select Committee on Small Business and Committee on Interior & Insular Affairs, *Alternative Long-Range Energy Strategies*, 2 vols. (Washington, D.C., U.S. Government Printing Office, 1977), condensed by H. Nash in *The Energy Controversy: Soft Path Questions and Answers* (San Francisco, Ca.: Friends of the Earth, 1979); Lovins, "Re-Examining the Nature of the ECE Energy Problem," ECE (XXXIII)/2/I.G. (Geneva: U.N. Economic Commission for Europe, Feb. 20, 1978); Lovins, "Soft Energy Technologies," *Annual Review of Energy* 3 (1978) 477-517.