What Are the Options for Disposition of Excess Weapons Plutonium?

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The following article is based on a talk for Symposium X presented by Wolfgang Stoll, Chief Scientific Advisor and Consultant in Siemens, Germany, at the 1996 MRS Fall Meeting.

Introduction

Since 1941 when Glenn Seaborg first isolated plutonium in milligram quantities, the total amount converted through neutron capture in U-238 has increased worldwide to about 1,200 tons [1,2] and continues to grow about 70 tons/year. What was fissioned *in situ* in operating nuclear power stations is roughly equivalent to 5 billion tons of black coal, while the fission energy contained in those 1,200 tons unloaded in spent fuel is equivalent to another 2 billion tons of coal. About[2] 260 of these 1,200 tons are ready to release their energy in about 4 kg-portions each in microseconds which is equivalent to 10,000 tons of coal. Most people believe this release of energy poses a major threat of the worldwide arsenal of weapons of mass destruction (WMD). The about 20-fold overkill stored in worldwide WMD is considered superfluous after the crumbling of the Soviet Union. Options are sought to dispose of this surplus in a safe, speedy, and controllable manner. While for highly enriched uranium (HEU) (the other nuclear weapons material) dilution into low-enriched uranium and utilization in current light water reactors (LWR) poses market adaptation problems only, and while the worldwide consensus on the elimination of chemical and biological WMD is still in an initial phase, the decision of both the United States (US) and the former Soviet Union (FSU) to remove most of the plutonium out of weapons looks as if it was a firm political decision.[3]

Present Amounts

Table I shows three best estimates based on the average of three inventories of W-Pu in the different northwest-states.[2] The FSU figures need presumably a correction of up to 20 tons more, but this has not been confirmed. Only the US and FSU have binding agreements on reducing the amount, going first to about half the amount stored in WMD.[3] So 2 × 50 tons W-Pu could be made available until 2002.

It would however be too simplistic (Table II) if the Pu stored in spent fuel—largely 900 tons together with the 150 tons, which have been separated in reprocessing plants and have partly been reintroduced into nuclear power stations—would be completely left out of the risk considerations.[4]

Isotopic Vectors and Chemical Forms

For economic purposes, nuclear power stations need relatively efficient burnup figures, which range from the Canadian CANDU of some 10,000 MWd/ton to the current LWR up to 50,000 MWd/ton and fast breeders up to 150,000 MWd/ton. Successive neutron capture transforms the Pu converted originally to Pu-239 from U-238 into higher isotopes, so that in an almost steady state, as is reached in high burnup-LWR, the sequence of higher isotopes falls off by about 1/3 per additional neutron captured; it starts with Pu-240 at about 30% contained, when the fuel is unloaded, and ends with Pu-242 at about 5%. Pu-238 reaches 3% in those mixtures. The sum of thermally fissionable isotopes Pu-239 + Pu-241 remains only slightly above half of the mixture (Figure 1).[5] In contrast, W-Pu is obtained as almost pure Pu-239 with less than 5% higher isotopes after burnups of only weeks, making simultaneous energy production economically unattractive provided there were on-load-refueling capabilities as are regularly available only in natural-U reactors.

Taking into account ongoing technological progress, the purity of 239-Pu for weapons has lost most of its importance for modern weapons. With refined ignition technology (not available to just any country) the presence of higher isotopes only marginally reduces the ignition probability and the explosion yield, leading to the perception that all Pu could be used for weapons.[6] Meanwhile Northwest nations have sided closely with the W-Pu specification in practice. Here is the point where future considerations on spent LWR-fuel and inventories of separated Pu from those elements must start.

The chemical form in weapons is determined by the highest density achievable and long-term geometric stability. Both are reached by using carefully machined parts of Pu-Ga alloy (0.5–2% Ga) coated with a corrosion-resistant layer, generally nickel. Storage of those pieces in dry air under ambient conditions has already been demonstrated for several decades and could go on for several decades more if needed.

Pu in spent fuel is in the form of an oxide, most often in a molecular mixture

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Table I: Estimates on Weapons Materials (tons)
(Average from three different sources)

	Source Material	In Weapons		In Outer Cycle	
	Natural Uranium	Highly Enriched Uranium	W-Pu	Highly Enriched Uranium	W-Pu
United States	65,000[a]	590[d]	80[e]	>50[f]	15
Former Soviet Union	50,000[b,c]	400–800	100	<10	25
France	5,000[c]	Small	6.3	?	<2
United Kingdom	5,000[c]	?	3.7	?	<2,(43[g]) (?)
China	10,000	?	2.5	?	?
India	Small	0	<0.4	0	<1 (?)

(a) 67,000, Reconst.? (c) Dual Use? (e) 56–85 (g) Ex Magnox!
(b) >160,000 ? (d)±10% (f) <150 ?

Table II. Plutonium Inventories per End 1996

In spent fuel		**860 tons (+ 70 tons/yr)**
United States	650	
Japan	90	
France	70	
Germany	50	
In operating reactors		**80 tons**
Separated (civil reprocessing)		**150 tons**
Military inventories		**250 tons**
Former Soviet Union	140 (+/- 15)	
United States	100	
France	6	
China	5	
Israel, India	1 (?)	
Rounded World Total		**1,300 tons**

with UO_2 and in the presence of three times as much fission products, which exhibit strong gamma radiation. Spent fuel can be handled safely only in hot-cells behind meters-thick concrete shielding, leading to the notion that this "spent fuel standard" prevents fast and efficient isolation of Pu. The validity of this barrier, however, can be questioned since shortcuts have been published[7] as far back as 1977 and new ones are occasionally discovered.[8] If LWR-Pu really would have an explosive quality comparable with weapons material, its removal, before the protection by fission radionuclides has decayed, would be another challenge. This topic, however, cannot be covered in the scope of this article.

If isolated via reprocessing, the Pu first is purified in solution and occurs as a Pu^{IV}-nitrate, practically free from fission products. This enables the material to be handled in glove boxes, and the material is stable against hydrolysis in an acidic environment. However, this process radiolytically decomposes water, creating an intermediate compound in most cases, and Pu^{IV} is precipitated as oxalate and calcined to oxide, which is a fine green-gray powder with a high specific surface area between 20 and 5 m^2/g. The transformation into mixed-oxide (MOX) fuel results in the form of sintered oxide pellets, geometrically similar to the well-known UO_2-fuel pellets for LWR.

In the course of refabrication of fuel some of the material unavoidably ends up in scrap and waste, be it rejected for reasons based on quality control, be it gloves, filters, or other debris, from which it is chemically tedious and expensive to recover the Pu. The same occurs naturally in weapons manufacturing (and refurbishing) in which waste and scrap bind

appreciable amounts of Pu as outlined as the outer military cycle in Table I.

Basic Risk Assumptions

Plutonium must be handled with caution because of radiotoxicity and nuclear criticality. Pu is often referred to as the most toxic substance known.[9] In reality more than 100,000 workers have handled plutonium in military and peaceful applications and only a handful of casualties have been traced to this element.[10]
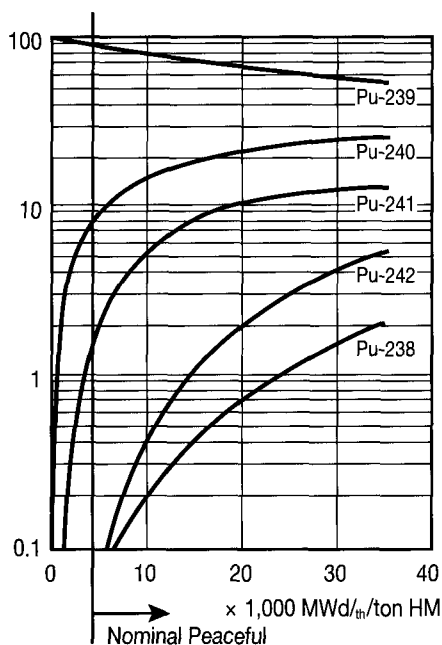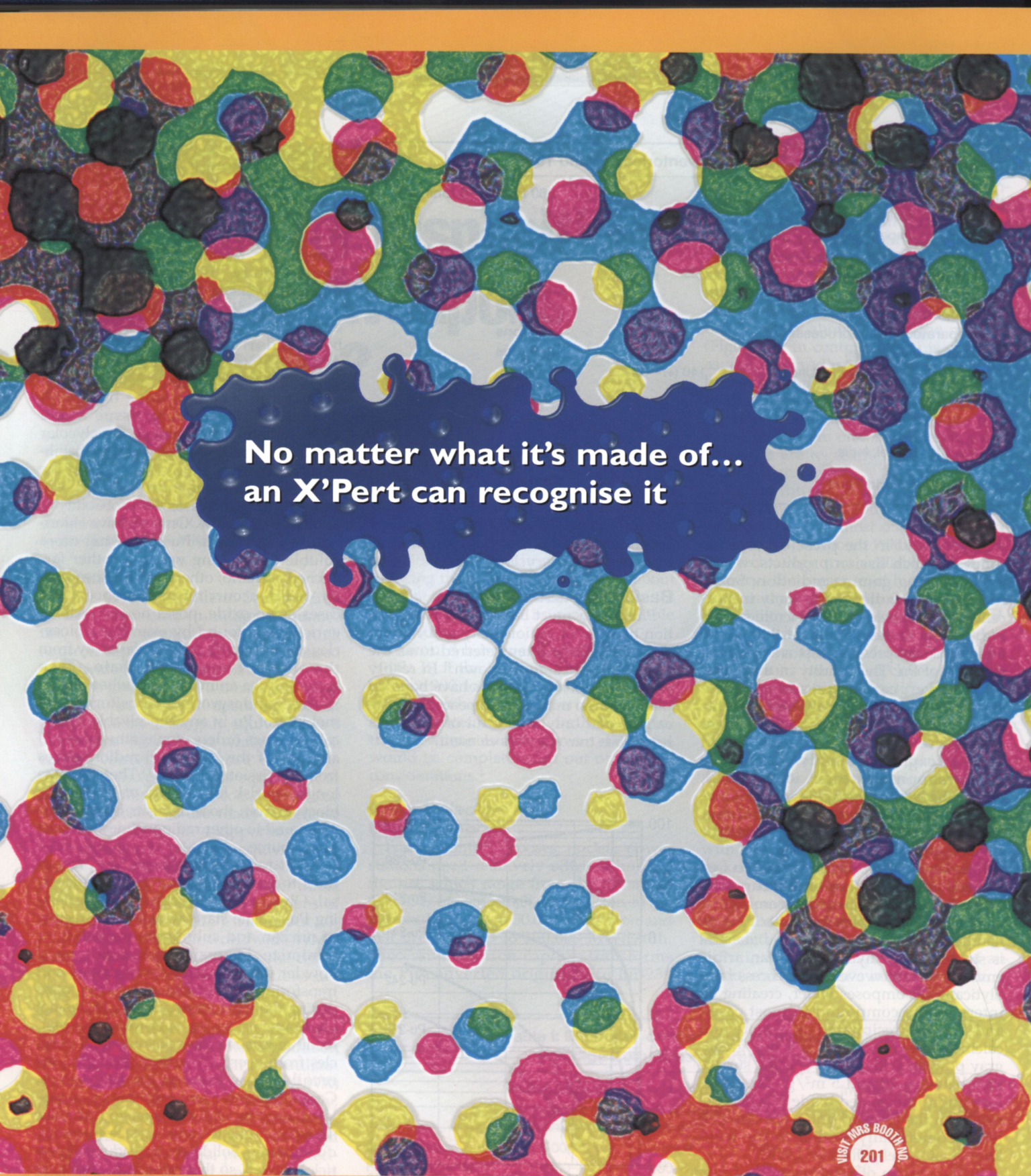

Figure 1. Change in isotopic composition with burnup in standard light water reactors (LWR).

To put radiotoxicity in perspective, Pu can be compared to radium. Both are alpha-emitters with a reach of some centimeters in air and some microns in human tissue. Unless exposed unshielded to kilogram-quantities, external exposure is negligible. What counts is Pu inside the human body. If the incorporation through wounds—a very rare occurrence for those handling Pu directly—is excluded, and the practical insolubility of Pu in body fluids is taken into account, the only dangerous incorporation pathway is inhalation of small particles (0.5–10-μm diameter as a conservative limit) and their deposition in lung tissue where alpha-radiation can damage the alveolar cells directly and with a certain probability can later cause lung cancer.[11] Here the toxicity is high—one microgram deposited in the lung increases the probability of cancer by about 1%. Only massive chlorination[12] can make Pu somewhat more soluble in drinking water, a rather far-fetched scenario; otherwise, the insolubility of Pu, occurring in all conceivable cases as an oxide, poses no risk. All re-enrichments found by examining biocycles shows that Pu remains far away from the normal human food chain—even including sea animals. Even when placed in deep underground repositories, the mobility of Pu in any conceivable chemical form lags orders of magnitude behind any one of the long-lived radionuclides from the fission products.[13] Therefore, the long-term risk for re-entry of Pu into the biocycle from those deposits is negligible compared to other radionuclides from the same source.

What remains, however, are precautions to be taken against powder dispersal. Obviously PuO_2 obtained by calcining Pu-oxalate starts with a large fraction of micron and submicron particles. To minimize dispersion risk, this type of powder must be carefully contained and transformed into stable and coarse solids during the fabrication process. This is not all, however, as the ever-present alpha-recoil mechanism knocks out small particles from every Pu surface, provided the recoil energy exceeds binding forces. Ceramic powder and particles up to pellets show this kind of dispersion. Metallic surfaces, prone to some surface corrosion, do the same. Solid salts spread recoil particles as well, so that most forms of Pu, as they are handled, exhibit this ornery behavior. Only when diluted by several orders of magnitude in alloys or ceramics, or kept together by surface tension, is this mechanism prevented. So droplets of solutions of Pu salts, PuO_2 in the amorphous glassy form, or other glasses con-

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taining Pu are essentially free from recoil dispersion. Also no dispersion or spread of contamination is found when a Pu-contaminated surface is kept wet.

Criticality means that a fission chain reaction will start if the number of neutrons produced in a given mass of fissionable material exceeds the number absorbed and are dissipated outward from the mass. As the halflife of a neutron generation is only 10^{-7} seconds, the process of fission must be prevented. The smallest conceivable critical mass of Pu-239 in aqueous solution, ball-shaped, and in 22 liters of water is only 509 g. In metallic form unreflected the value is close to 10 kgs.[14] Handling these constraints means that one has to resort to geometries with a large surface-to-volume ratio, to dilute the system, to use additional neutron absorbers in the system, and to avoid neutron moderators, or limit to extremely small quantities.

In regards to storage forms and geometries, absolutely no local re-enrichments can be allowed to reach a critical configuration. Dilution can also discourage anyone to reenrich the Pu for unauthorized explosives use. Unfortunately most Pu-isotopes are more or less fissionable by fast neutrons, as required for bomb quality. Those isotopes like Pu-238, whose large decay heat would make misuse difficult and unattractive, are not available in the necessary quantity for admixture. They could only be produced with an enormous additional effort—for example, by irradiating separated neptunium.[15] Every other diluent would be a chemically different element or substance, which could be separated again by any diverter by chemical processes with various degrees of effort.

Disposition Options

Here I mention only briefly the more far-fetched options for disposition, and then will turn to more likely alternatives. These less practical solutions include shooting the encapsulated Pu into outer space, fissioning it by controlled underground explosions,[16] diluting it in solution into all oceans—which would increase the alpha-emitters (uranium) and followers (mainly radium) only marginally—or utilizing the existing explosive charges for soil and rock movements like dams or canals. What remains is described already in the National Academy of Science (NAS)[4] study from 1992: storage in deep boreholes, storage in a mixture with fission products in vitrified form, or utilizing it as MOX in current or future nuclear reactors. The NAS study does not mention the (protected)
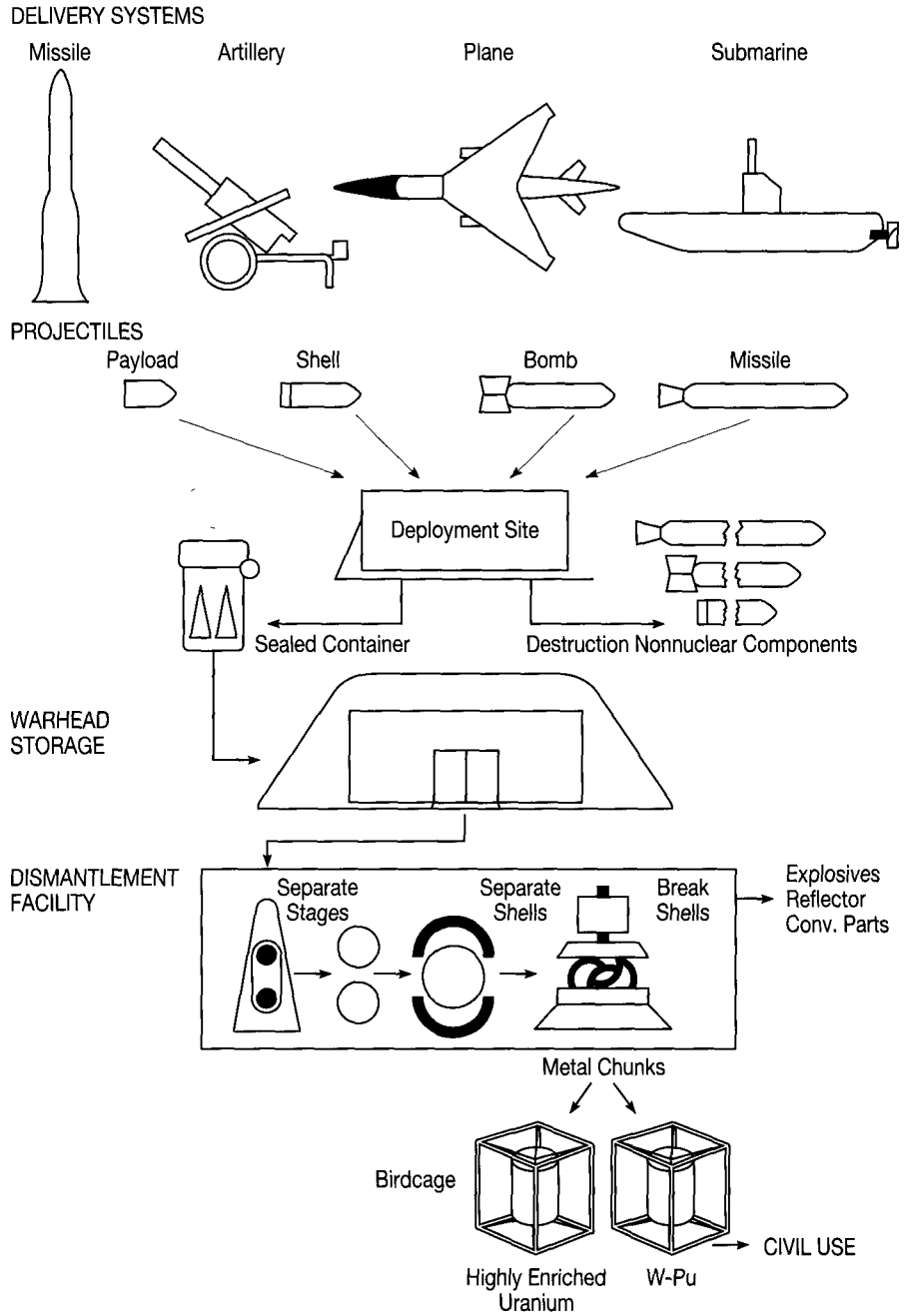

Figure 2. Disarmament steps on the military side.

storage of the unchanged nuclear explosive packages, named "Pit's," or the Pu-metal recovered from these processes (see disarmament steps in Figure 2).

Before the determination is made whether to directly store or first use the material, an intermediate form or composition should be considered that would complicate misuse of the material but still leave open both options of disposition. One alternative meeting these criteria is

$(Pu,Th)O_2$ with at least 50% thorium, which would allow incorporation in glass or zircon, or allow mixtures with uranium for MOX fuel, withstanding against chemical attack.[17]

Optimized Material Forms
For Storage

The concept of long-term storage of weapons material must be revisited. Current storage practice, like storing pits

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or Pu-metal, geometries plated with an anticorrosive layer, will tolerate storage for another decade or two, but it must be heavily safeguarded, eliminating it as a viable option in the long run. The concept of storage must be thought out for an unprecedented longevity. Let us consider that weapons material is almost pure fissionable material, even after 10 half-lives—the time used to mark the final decay of a radionuclide, here a quarter of a million years. The next following nuclide is U-235, which is equally fissionable and much more mobile and exhibits a halflife of 700 million years.

Whatever the final solution may be, there will be no way to prove that it will work under real conditions because all accelerating models for corrosion, chemical change, and dispersion can be questioned. Looking historically, Mother Nature has stored plutonium either long before there was modern life on this globe or only in relatively minute quantities and thin layers (Oklo-phenomenon[18]), so conclusions can only be drawn to a limited degree.

Now let us consider plutonium stored in underground repositories such as silicate inside of or together with fission product glass. Salt brine in a hot environment, expected in deep underground repositories, dissolves glass. Thus after, say, 10,000 years, when 70% of the plutonium is still present and 30% of it has decayed into the much more mobile U-235, the material will be released to diffuse freely into the surrounding geologic barrier. There diffusion and return into the biocycle will be largely determined by the chemical bonds, adsorption, and absorption qualities of the host rock more than by anything else. Comparing with current U-ore bodies, of which many are layered on diffusion barriers,[18] where they met, for example, reductants like coal, bone, or crude having fixed the mobile U^{VI} as immobile U^{VL}—one envisions a credible scenario for a new "Oklo"-reactor[19] underground somewhere in the vicinity—not a very reassuring outlook.

The only assumption, which brings us closer to reality, is the independence of lattice damage by an individual alpha spike over time. This is first a local question of the lattice and the matter irradiated, and afterward an assumption about the healing of this kind of damage. If the different lattice defects introduced via alpha spikes can be considered independent from each other and the temperature of the material is low enough that thermal healing is only of minor weight, the time interval between formation of those different defects plays no important role.

Because of lattice displacements, minerals show the metamict state. Most of those defects originate from alpha spikes. Because of varying interstitial lattice space and chemical bonds, minerals vary in the degree of lattice displacement they can tolerate without their properties being changed. Among minerals containing radioactive elements (e.g., monazite, a RE-phosphate; bastnäsite, a RE-carbonate-fluoride; pyrochlore and zircon, a zirconium silicate containing radioactive elements), zircon has the most promising long-term stability. Artificially made zircon with Pu-238 as a radiation source shows good stability and low leachability.[20]

For Utilization

More than 30 tons of fissile plutonium worldwide have been recycled so far as a $(U,Pu)O_2$-ceramic (MOX) in current LWR, containing between 2 and 7% Pu.[21] The amount utilized as MOX in fast-breeder fuel may be the same order of magnitude, but the number of operating plants is shrinking. Fast breeders, originally built to increase the mass of Pu inserted, seem to not consume very much material now, even if they run without blanket. The insertion of Pu in HTR is envisioned in some concepts,[22] and theoretically a very large fraction of the Pu inserted could be fissioned. Reactor sizes envisaged so far consume however only 10 kg Pu/year, so the process would require a large number of machines for a very long time. Other than one prototype planned by the FSU and a private U.S. firm, nothing has happened in reality as yet. Neither ship-reactors, nor research reactors, nor the appraised CANDU have consumed more than the Pu fissioned in situ as yet. So the mainstream for any fast solution would have to go into MOX-fabrication for elements inserted into operating LWR.

The weapons Pu alloy would have to be purified, oxidized, and formed into the right particle size distribution and to the right specific surface in order to fit into the current ceramic fabrication process as it is used for reprocessed LWR-Pu. To bridge this technological gap, several shortcuts and dry processes have been thought out and partly tested. The most obvious solution however is a straightforward dissolution and extraction process, similar to the tail-end of a reprocessing plant, resulting in PuO_2 precipitated from oxalate. If for polit-

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ical reasons this established way is considered to come too close to the banned "Pu-economy," dry processes such as hydriding the Pu and oxidizing the hydride over some technological complications may be the alternate solution. In any case the feed for MOX fabrication must enable the fabricator to achieve a very high fraction of homogenous mixed crystals in the fuel. If the PuO_2 is too coarse or too inactive, extensive comilling procedures with UO_2 resulting in a master-mix can repair the properties. Ideally the homogenous coprecipitation from a mixed U, Pu-nitrate solution would be best. This has been attempted through the COPRECAL-process, developed by GE at Savannah River, the coprecipitation of Pu^{IV} and U^{VI} as carbonates in the FSU; and the only "real" coprecipitation from a Pu^{VL}-U^{VI} mixed nitrate solution as complex ammonium-carbonates, as done in Germany.[23] As however the reprocessors stick to their oxalate-route, fabricators have to live with this complicating peculiarity. Historically this process was necessary to obtain an oxide with high specific surface for easy fluoridation into PuF_3 as intermediate to metal. The current MOX technology is open to many variations in ceramic compositions. If, for example, it was paramount to bring a larger amount of Pu faster into the "spent fuel standard," it would not be difficult to insert fresh MOX fuel only for one cycle into the reactor and let it sit in the cooling pond for full burnup later. This could even be combined with a neutral fuel matrix, that does not convert U into new Pu, such as aluminum oxide, zirconium oxide, magnesium oxide,[24] or similar diluents. However, since the reactivity drop during burnup of these fuels would be steep, a higher initial loading together with burnable neutron absorbers might be necessary. Diluents can complicate the in-pile behavior, like aluminum oxide, where the formation of lower melting perovskite is to be considered. The same problem may limit the mixture with three-valent RE materials as absorber. The most serious obstacle however is the burden of proof and/or guarantee for the in-pile behavior since defects could seriously limit the availability of a whole nuclear power station.

Value Factors

Nuclear weapons are—or at least are perceived to be—well guarded. In the military domain, an operative organization and strict rules together with tight controls and well-defined responsibilities are established to keep weapons—including WMD—under control. Most nuclear WMD need two additional safety systems: one containing a permissive action
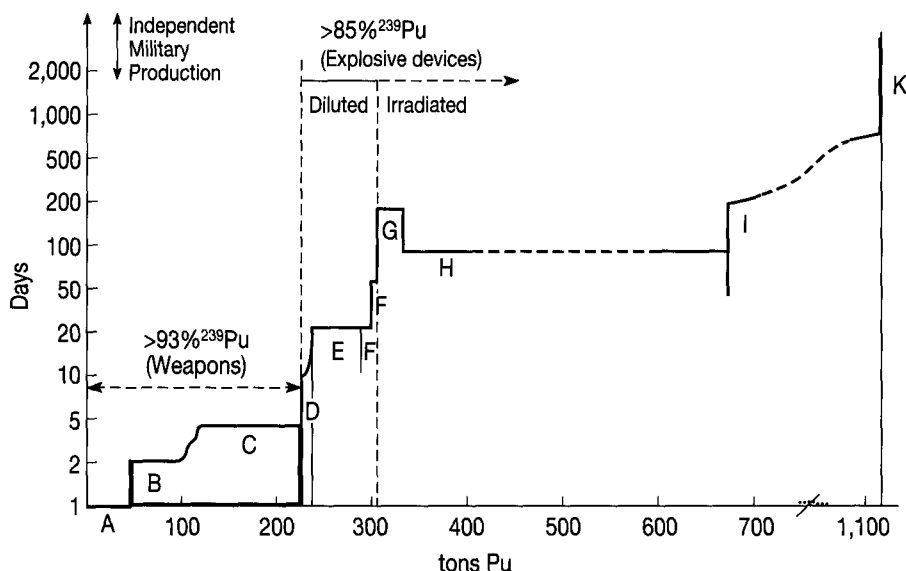
Figure 3. Present protection level/amount (world tons of Pu). "Days" mean minimum time for return into military use. A: US & FSU laboratories, reserves, scrap, waste (>0.1% Pu) still in production and national store in France, China, Israel, India...; B: principally accountable in weapons; C: counted and registered in weapons; D: separated, unaccounted for: Majak, in process, MUF; E: separated + safeguarded (Magnox); F: fabricated and stored as (U,Pu)O₂; G: MOX, in reactors (LWR + FBR); H: LWR-fuel, >20 years cooling; I: LWR-fuel, >150 days cooling; K: LWR-fuel in closed final repository.

link before the weapons can be triggered and one that introduces self-destruction or at least permanent disabling of the weapon if it was opened or manipulated by unauthorized personnel. As soon as the weapons are dismantled, as visualized in Figure 2, those safety devices no longer work. Therefore it is paramount to guard the fissionable materials by other means, such as safing and sealing them in storage buildings. But this is not enough. Diverters who attempt to utilize this material again for weapons purpose or for an explosive charge would have to reconvert what they steal from such a store back into a concentrated and dense fissile matter.

To prepare for the possibility that diverters utilize the material for an explosive charge, we must take into account the minimum time required to reconvert the material, disregarding other variables such as cost limitations. The device is limited at 8 kg W-Pu. A complete pit can be used faster than a button of Pu metal, the latter can be used faster than PuO₂, this faster than an unirradiated MOX-fuel element, and this again faster than an irradiated one. The respective data are given in Figure 3. The "inherent" protection can be defined as the material form based on the fraction of the Pu (metal) released from military protection (in kg fissile material

in several transition forms) times the time for reconversion back to a "device" needed for the relevant fractions of this material stock. This is limited by the consideration that disarmament is a process in its own limitations, defined on one side by the symmetry of agreements among the superpowers and on the other side by the technical capabilities given for the dismantling facilities and their crews (of about 1,500 pits/year/side, Figure 4). So it is obvious that on both sides a buffer store for material released from weapons must exist, as this material is not yet released from the military domain, so
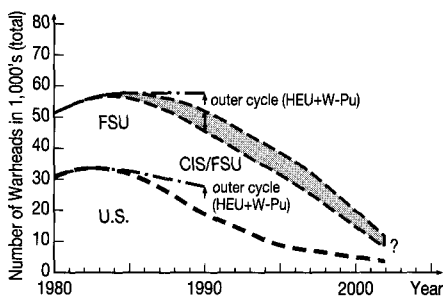

Figure 4. Projected speed of disarmament for the United States (US) and the former Soviet Union (FSU).

long as there is no final decision to convert it for either burial or utilization. The rule to be derived for optimum safeguarding is simple: The quantity of material in transition between pits and the final destination (fuel or storage-form) should be minimized. This would require effective and fast conversion technology with minimized material holdups in the different steps and an immediate insertion of the Pu in either form (MOX or storage) (see Figure 5).

How to Get to This Point?

Presently the major development effort is concentrated on the military side of conversion. The pits must be deformed in such a way that their geometry cannot be reconstructed. The mainstream is oriented toward a metal-hydride-metal conversion and the other route (FSU) is toward acid dissolution of the pits. Only then can the material be released into international safeguarding (IAEA) to be introduced either into a storage regime or into MOX fabrication.[25]

Despite some recent decisions not to support the vitrification concept as the only solution, the political field generally lacks patience for incorporating any of the more advanced routes into technical reality, be it anything better than borosilicate-glass for vitrification or MOX for LWR. Other solutions (breeder, CANDU, high-temperature reactors [HTR]) need special fabrication lines and/or special reactors, which even under favorable licensing conditions may take a decade or more before they could be operable and another several decades before they could consume appreciable amounts of plutonium.

As far as the optimized forms are conceivable, no single storage facility yet exists which can take spent fuel elements as a final repository. Even if such a facility would be already licensed, it is highly doubtful whether a license could be overstretched in public for incorporating isolated W-Pu in any form, concentrated or diluted.

Since high active waste-glass (HAW) is produced by reprocessing plants, it will likely be transferred together with spent fuel elements from temporary to final repositories in due time. Both activities may however take still another 50–100 years since there is no pressing need to initiate this highly controversial action. A delay also saves space in a repository. If HAW-Pu mixtures at this time can be introduced under the same safety category, they may also be candidates for such a store. If however any of the previously mentioned optimized storage forms for Pu become a potential technical reality,

the critical public will require this "better" storage method also be applied for all radioactive waste. This could get very expensive and time-consuming. So any improvement, as good as it may look,[20] could turn out to be the worst enemy of those already halfway-established solutions in this very sensitive field.

Political Preferences

Presently, the FSU economy is inelastic and relatively poor. Pu is regarded as an energy reserve not to be wasted.[26] The optimum use in fast breeders is still in the planning, however far the next generation of those reactors may be, due to shortage of funds.[27] The present metal-cooled submarine-reactor could be redesigned into a small and simple fast breeder by 2015, so any delay to keep the Pu in its current form is welcomed to keep all future options such as these open. Modernized military cannot be excluded from among these options. MOX utilization is accepted in small scale because it is hoped to modernize the fuel technology by such a model facility.[28]

The U.S. position could hardly be more controversial. Since the Carter administration plutonium has been a dirty word, along with "plutonium economy," coined by Margaret Mead and underscored by protestant churches in 1975. Two lines of thought reinforce each other. The one indicates that if the US as the leading power in the nuclear field would forgo the recycle option, other nations would follow. The second thought was reinforced after Vietnam, whereafter the US as a "world police" has to limit the death toll among its police force to the absolute minimum, but still be able to exert maximum credible threat in confrontations. This would only work if the exclusivity in the possession of WMD is not jeopardized by any small nation. So the importance of peaceful nuclear energy with the closed fuel cycle in a country with plenty of uranium and also plenty of energy sources ranges far behind defense considerations. This also limits the thinking and action of U.S. allies. The promotion of the closed fuel cycle therefore is suspected as being half the way to a nuclear weapons capability. This understandable preference has brought all disposal options, deep borehole storage as well as vitrification, into the foreground of discussion. While technical solutions for storage options may be derived from current technology, the public still distrusts that it is safe. A high degree of predictability for very long-term diffusion barriers may be the key to public acceptance.[24] It is in this context that the more expensive solutions with optimum-tailored materials, such as the inclusion ceramics outlined previously, may suffice.

Costs and Means to Cover Them

Safety and security of the Western world is priceless, which induces the wrong conclusion that governments provide an unlimited amount of money to preserve them. The balance with other needs is attained through the U.S. defense share in the budget; however, billions of dollars are being cut out of the U.S. budget since the threat of the Cold War has disappeared. It is deplorable that money formerly poured out for more and more powerful nuclear WMD now results only in a trickle of money to convert the weapons material. Since such a conversion helps secure world peace, it should be paid from money saved otherwise in the defense budget. But the logic of an integrated peace dividend has no chance so long as budgets are fought between the Department of Defense, the Department of Energy, and other institutions at play. So when looking to see who might be prepared to pay for conversion, the outlook is not all that bright. The minimum consensus in those cases remains most of the time the cheapest.

What are the Frame Conditions?

Most likely the military will be responsible for converting "pits" into some material form since the Pu has no market value as yet. At the end of the line for both options is deep underground burial, be it for fission-product, spiked and vitrified W-Pu, or spent MOX-fuel elements, having also roughly about the same volume and weight. The only difference is that for every MOX-fuel element buried another U-fuel element need not be fabricated and buried afterward so that the burial costs are canceled out. So the question remains if the 1/3 core load principle is followed for MOX and the UO_2-fuel elements and MOX-elements are being fashioned interchangeable in a power station with respect to burnup and in-core lifetime, what is the fabrication cost difference? The basis for such a comparison is simple. What is saved when a MOX-fuel element is fabricated is the natural uranium, about six times the weight going into the power station and the enrichment charge for this. At present uranium prices and enrichment charges together are somewhat between $1,000 and $1,400/kg fuel. Whether one needs all this money saved to cover the more complicated and therefore more costly MOX fabrication depends largely on the size of the operation. Normally MOX plants have only a fraction of the throughput of UO_2 fuel plants. Due to the very substantial effort in health physics, safety and safeguards, the fixed costs for such a MOX plant are up to 80% of the total fabrication costs. While 30 tons of MOX/year may not meet the UO_2 target,
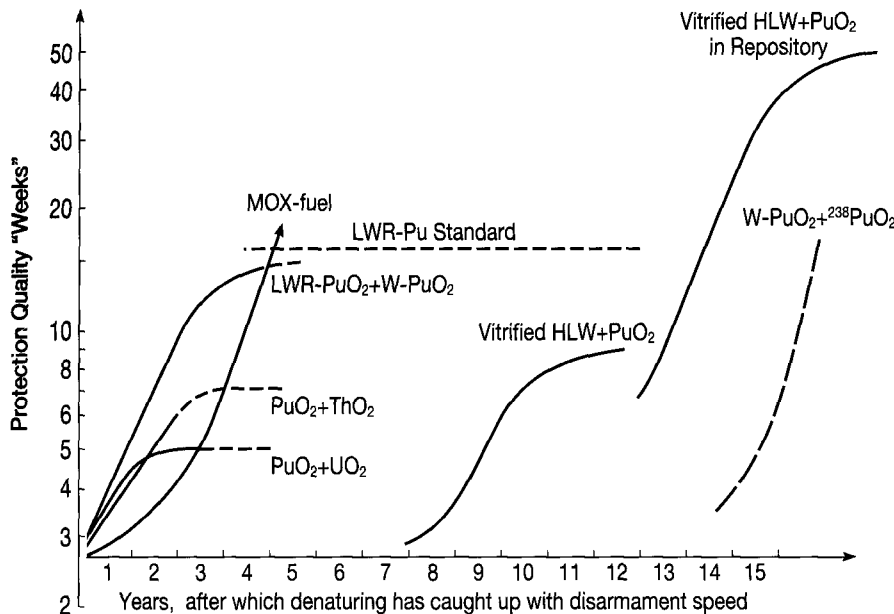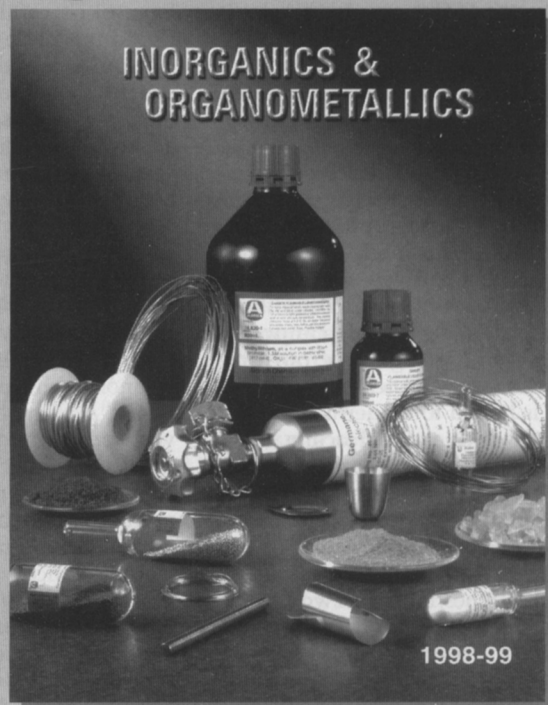

Figure 5. Protection gap after dismantling.

120 tons/year in any one plant certainly do. So both statements: MOX does cost more or MOX does cost less than the UO_2 fuel can be right, depending on the frame conditions chosen. As in several countries, however, utilities have bought MOX-fuel elements[30] and this—even on the basis of reprocessing, which is said to be so enormously more expensive than final repositories—plutonium supplied at zero cost must be a good bargain. It must however also be made clear that if no additional uranium and no enrichment costs are on the other side of the balance, the whole MOX-fabrication penalty shows as additional fuel cost, as one would expect in natural uranium reactors like the CANDU-type. So while exorbitant extra cost for LWR-MOX fuel are a cradled prejudice in nuclear communities where such fuel could never have been fabricated in an industrial scale, others (like France) silently sell and gain from MOX fuel business.

If one assumes as a very rough estimate, that 50 tons W-Pu result in 1,000–1,200 tons MOX fuel, with a kg-price of between $1,000 and $1,500, the whole business volume could be somewhere between $1 and 1.8 billion for every superpower. Spread over 20 years, this would still be $500–900 million/year,

whereas a MOX-fuel plant of a very sophisticated and supersafe design with 120 tons/year MOX capacity, such as the new Hanau plant, has investment costs of less than $700 million and operating costs of $100–150 million/year. So the quoted $400/kg gain over standard UO_2-fuel, when Pu is free, seems credible.

While the spent MOX fuel ends up with the real "spent fuel standard" almost undistinguishable from spent UO_2-fuel, which it replaces, the vitrification solution not only requires a special vitrification plant as an addition to any high active waste facility, it is also to be expected that the final repository because of the Pu addition will require special precautions, storage containers, or additional procedures, which all cost money. The arbitrary figure quoted from the promoters of this concept lies between $0.5 and $2 billion for those 50 tons mentioned previously.[31]

If the burial concept however should really take into account the specific long-term risk of isolated W-Pu storage (in whatever mixture), as just outlined, a dedicated (e.g., zircon) ceramics fabrication line would have to be built and operated, which is simpler than a fuel manufacturing plant, but still may run into cost of additional $0.5 billion to store those 50
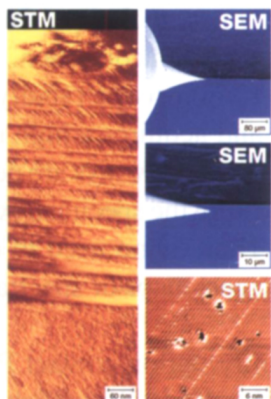
tons underground. It would be speculative now to put down more than those rounded figures for comparison of the various action plans, but the basic difference between burial and utilization cannot be questioned.

Outlook

Disarmament in the field of WMD will remain a lasting challenge for several decades. In the field of W-Pu several solutions are possible. A multiplicity of isotopic vectors and chemical compounds are to be treated. Stability criteria, retrievability considerations, criticality and toxicity limits are well-known, but can be met to various degrees by the different solutions envisioned. Because of the very long halflife and the risks W-Pu carries, still major research effort in the field of materials development is justified. The final selection among all the options and how to proceed will most likely be dictated by sensitive political defense considerations, existing resentments and taboos hard to overthrow in public and among politicians, and cost considerations. But if any final decision is delayed long enough, a future generation may take a fresh look on plutonium as an energy source and start a new generation of fast-breeder reactors, which would solve the problem elegantly.
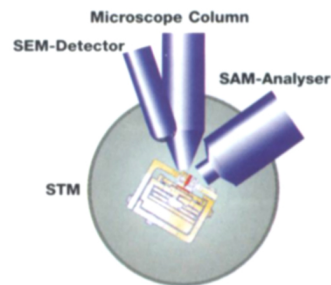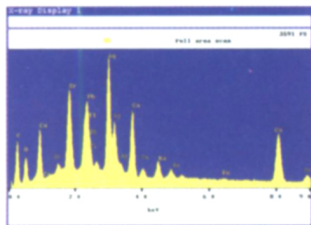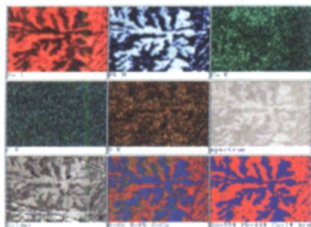
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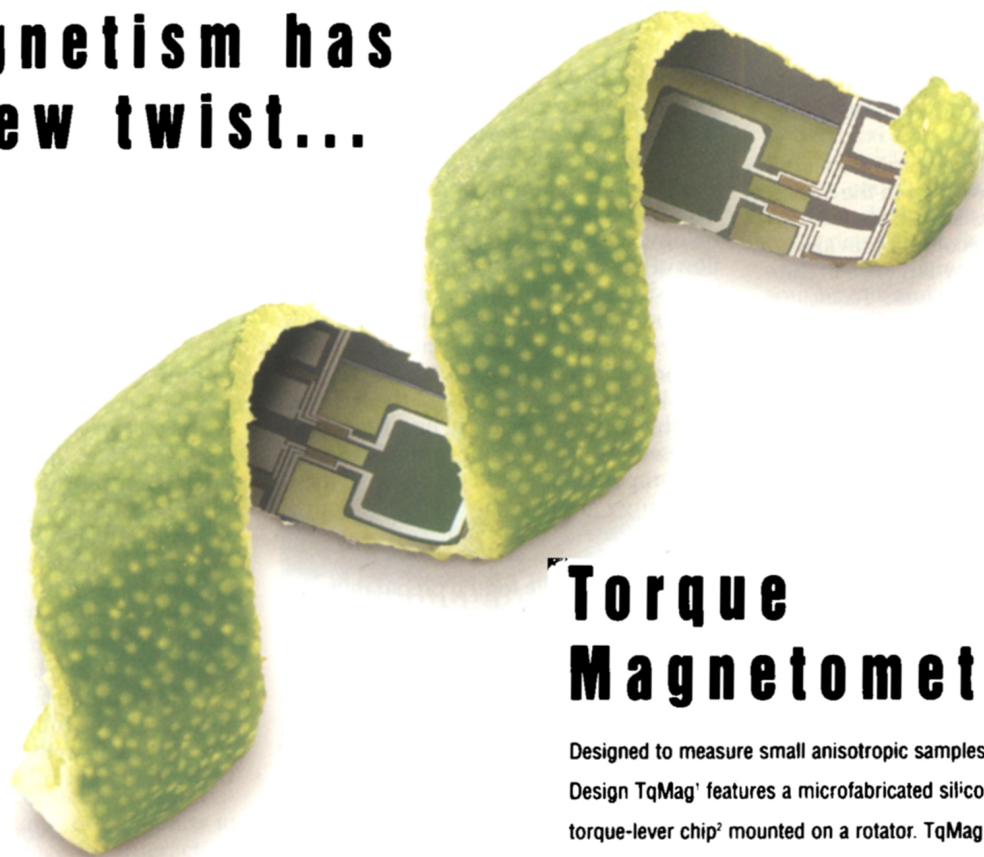
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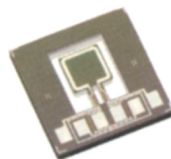
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[1] Developed in collaboration with IBM Research Division, Zürich Research Laboraory, and the Physik-Institut der Universität Zürich, Switzerland.

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