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Proposed contribution:

## Nuclear terrorism: the risk of Highly Enriched Uranium (HEU)

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See the Pugwash Issue Brief authored by Jeff Boutwell, Francesco Calogero and Jack Harrison the website of the Pugwash Conferences on Science and World Affairs [www.pugwash.org](http://www.pugwash.org)

[Note however that the following presentation is much closer to the presentation given by F. Calogero at the 2002 Amaldi Conference than to the text of the Pugwash Issue Brief referred to above]

1. Given a sufficient quantity of Highly Enriched Uranium (HEU), it is quite easy to manufacture a nuclear explosive device.
2. HEU is the only material that allows the easy manufacture of a nuclear explosive device.
3. A primitive nuclear explosive device based on HEU would not be transportable, and its explosive yield would be unpredictable, but it is quite likely that it would exceed that of all previous terrorist explosions, and there is a significant probability that it would be analogous to that of the Hiroshima bomb.
4. The most likely scenario of a terrorist act involving a nuclear explosive device is that a sufficient quantity of HEU be smuggled into a rented apartment or garage downtown in one or more cities and that the device(s) be manufactured clandestinely there and then set off by remote control or via a timer allowing ample time for getaway.
5. The effects of such a nuclear explosion are likely to exceed by far any previous terrorist action.
6. There are individuals and groups who would perpetrate such a terrorist act if they could.
7. The main -- in fact, perhaps the only effective -- defense against this danger is to prevent the would-be perpetrators from acquiring a sufficient quantity of HEU.

8. Adequate resources should be allocated to strengthen the physical security, especially against theft or clandestine diversion, of HEU. But there is no guarantee that this line of defense will be adequate.

9. The only fully reliable route to eliminate this danger is to eliminate altogether HEU. This is possible in the long run, compatibly with the maintenance of civilian nuclear energy.

10. In the immediate future -- which is our main concern -- every effort should be made to eliminate as quickly as possible as much HEU as possible, in particular the HEU the physical security of which is a matter of more justified concern. There are no technological barriers preventing major quick progress in this direction, which is instead mainly impeded by commercial considerations.

11. Procedures which would by-pass these commercial difficulties have been suggested, but their implementation has been so far stifled by lack of interest and by the unwillingness of (affluent) States to allocate the financial resources needed in the short run, altogether not exceeding B\$ 10 (ten billion dollars).

12. If the points made above are correct, and we do not manage to convey them with adequate impact to the uninformed public, and especially to -- also uninformed -- decision-makers, we carry a responsibility for which we shall be held accountable in the aftermath of a catastrophe which might happen soon.

1. Given a sufficient quantity of Highly Enriched Uranium (HEU), it is quite easy to manufacture a nuclear explosive device.

HEU is Uranium in which the concentration of the isotope U-235 has been brought to, say, 90% or more. By contrast, the concentration of U-235 is 0.7% in Natural Uranium (NU), and it is 3-4% in the Low Enriched Uranium (LEU) used as fuel in most nuclear reactors for the production of electricity.

For the purposes of this analysis it can be assumed that "a sufficient quantity" consists of 100 Kg (one hundred kilograms) of HEU, although less would actually suffice.

By "quite easy" we mean that this could be achieved clandestinely by a small commando. Inclusion of someone with previous expertise in the nuclear field would be useful, but is not essential: indeed my hunch is that even a single intelligent individual skilled as a mechanical bricoleur and without any previous knowledge of nuclear physics could acquire easily, in a matter of weeks, all the needed information and capabilities from easily available open sources, as well as all other needed materials besides HEU, to manufacture a nuclear explosive device having the characteristic outlined below.

2. HEU is the only material that allows the easy manufacture of a nuclear explosive device.

"Most people seem unaware that if separated U-235 is at hand it's a trivial job to set off a nuclear explosion, whereas if only plutonium is available, making it explode is the most difficult technical job I know". Luis W. Alvarez, key physicist in the Manhattan project, and subsequently Nobel laureate in physics, in his memoirs written in 1987, one year

before his death (Adventures of a physicist, Basic Books, New York, p. 125).

A nuclear explosive device based on Plutonium requires, to be set off, fast assembly of a supercritical mass by implosion. This is a much more demanding task than can be realized by a terrorist commando in a garage or apartment (see below), although it is not beyond the means of most States -- but it requires then a lot of previous experimentation, although not necessarily involving nuclear explosions, and even after such experimentation it remains quite difficult to realize (it also requires very sophisticated conventional explosives and electronics).

The radiation hazards associated with the handling of Plutonium are moreover much larger than those associated with the handling of HEU. And there is now much more HEU around than Plutonium (roughly ten times more). But while these are two additional arguments to identify HEU rather than Plutonium as the material of choice for a nuclear explosive device manufactured by terrorists, the main argument to focus primarily on HEU as the source of risk is the one given above, that casts much doubt on the possibility that terrorists beat all able to manufacture a nuclear explosive device based on Plutonium, while it emphasizes on the contrary the ease to manufacture such a device based on HEU.

There do not exist at present any other materials besides HEU and Plutonium suitable to manufacture nuclear explosives.

3. A primitive nuclearexplosive device based on HEU would not be transportable, and its explosiveyield would be unpredictable, but it is quite likely that it would exceedthat of all previous terrorist explosions, and there is a significant probabilitythat it would be analogous to that of the Hiroshima bomb.

The manufactureof a transportable reliable weapon is a much more demanding task than theconstruction of a bulky non transportable device. The explosive yield ofsuch a device would be difficult to predict in advance with any precision,but it is unlikely that it would be less than the equivalent of severaltons of high conventional explosive (say, TNT -- in the largest terroristact so far, the Oklahoma explosion, no more than three tons of explosivewere employed), and it is quite possible that it would be thousands oftimes larger (the yield of the Hiroshima bomb -- the first HEU-bomb, explodedon August 6, 1945 without having ever been tested -- was equivalent toover ten thousand tons of conventional explosive (say, TNT), this energyrelease being produced by the nuclear fission of about one kilogram U-235).

4. The most likelyscenario of a terrorist act involving a nuclear explosive device is thata sufficient quantity of HEU be smuggled into a rented apartment or garagedowntown in one or more cities and that the device(s) be manufactured clandestinelythere and then set off by remote control or via a timer allowing ampletime for getaway.

SmugglingHEU is no more difficult than smuggling, say, any forbidden drug like cocaineor the material to produce it. HEU can be hand-carried without any radiationrisk, and 100 Kg of HEU could be parceled in, say, five one-liter cartonssimilar to those used for milk. Manufacturing a non transportable deviceis much easier than making a transportable bomb.

5. The effects of such a nuclear explosion are likely to exceed by far any previous terrorist action.

A Hiroshima-type explosion downtown in a large densely-populated city is likely to cause several hundred thousand, possibly millions, of casualties, and property damages that, to the extent they could be estimated (many inestimable masterpieces would also be lost), would amount to trillions of dollars.

6. There are individuals and groups who would perpetrate such a terrorist act if they could.

After September 11 this is hardly in doubt.

The widespread view of nuclear weapons as the ultimate "absolute weapon" is moreover likely to prove particularly attractive to individuals and groups bent on perpetrating terrorism, inducing them to make major efforts to acquire the capability to set off one or more nuclear explosions.

And it is also clear that such individuals and groups exist who muster quite substantial financial resources.

7. The main -- in fact, perhaps the only effective -- defense against this danger is to prevent the would-be perpetrators from acquiring a sufficient quantity of HEU.

The transformation of Natural Uranium, or even of LEU, into HEU is certainly beyond the means of any terrorist group, or for that matter of most States. (Saddam Hussein's Iraq spent billions of dollars in a clandestine program which only managed to produce gram quantities of HEU; however Pakistan has certainly managed to produce a few hundred kilograms HEU, which is the main raw material for their nuclear arsenal). Hence the only way for a terrorist group to overcome the technological barrier that prevents them from achieving a nuclear explosion is to acquire (a sufficient quantity of) HEU. This can only be done illegally, since HEU is not available for sale, and it is only possessed legally by (few) States.

8. Adequate resources should be allocated to strengthen the physical security, especially against theft or clandestine diversion, of HEU. But there is no guarantee that this line of defense will be adequate.

In the former Soviet Union -- mainly in Russia -- there are now more than one thousand tons -- one million kilograms -- of HEU, namely enough to manufacture easily over ten thousand nuclear explosive devices. It is known that not all this material is adequately guarded. Over the last few years substantial funds (almost half a billion dollars per year) have been allocated by the USA to help Russia to upgrade the accounting and the physical security of this and other (Plutonium) fissile materials, as well as to prevent the leakage of nuclear-weapon expertise out of Russia, and, although more than half these funds were initially funneled to the USA nuclear-weapon labs rather than to Russia, these initiatives have certainly resulted in a significant improvement of the situation. Other affluent countries (Europe, Japan) have also contributed, but only to a marginal extent. It is however widely recognized that much more remains to be done, and also that the efficacy of any protective system, however technologically advanced, rests ultimately on the competence, dedication and reliability (including resilience against corruption) of the staff who must make it work, including those at the very end of

the hierarchical ladder. Unfortunately concerns in this respect are well justified in a social environment where salaries at the end of the relevant hierarchical ladder are very low (say, of the order of one hundred dollars per month) and sometimes were not paid at all.

The other country that possesses substantial stocks of redundant HEU is the USA (several hundred tons). The physical security of this material is presumably better guaranteed, although concerns remain about theft/diversion by an insider, who might be motivated by greed or be a supporter of terrorism (it is clear after Oklahoma and after the so-called unabomber that such individuals do exist in the USA and may behave quite cleverly even if they are crazy).

These enormous stocks of HEU are by-products of the spiraling out of the nuclear arms race during the Cold War, that yielded inflated nuclear-weapon establishments-- oversized by any reasonable measure (at least in hindsight -- although some pointed this out at the proper time, but were not listened to).

The quantities of HEU that exist in other countries (France, China, United Kingdom, Israel, Pakistan, India, South Africa,...) are smaller or much smaller, and presumably they are much better guarded because, especially in the case of countries that possess little quantities of military HEU, this material has such a high strategic value to mandate a high degree of protection.

Stealing HEU is particularly easy when it is stored in the oxide form, in which case its physical state as a powder makes it less susceptible to precise accounting.

Of course resources should also be allocated to intelligence networks and operations aimed at preventing stolen HEU from getting into the hands of would-be terrorists, or, if this happens, at allowing a preventive intervention before the terrorists use that HEU to manufacture a nuclear explosive device-- but no such initiative can guarantee with any certainty the prevention of a catastrophic outcome.

9. The only reliable route to eliminate this danger is to eliminate altogether HEU. This is possible in the long run, compatibly with the maintenance of civil nuclear energy.

It is unlikely that our civilization can avoid catastrophic disasters for the indefinite future, if large quantities of HEU continue to be available. The only long-range solution to this problem is the total elimination of HEU. It is important to realize that this is compatible with a continued reliance on civil nuclear energy, which could be entirely based on Natural Uranium and LEU (and possibly Plutonium) as nuclear fuels. Already now the only uses of HEU other than as nuclear-weapon material is as fuel for a few small research reactors (which are in the process of being phased out worldwide, with few exceptions) and for (most of) the nuclear reactors used for naval propulsion, especially for submarines (and, at least in some countries, the process to phase out also this use is already in progress, for instance in France it is planned that the new naval reactors shall be fueled by LEU rather than HEU). And almost everywhere, including in all the main nuclear countries (USA, Russia, UK, France, China), the production of HEU has now stopped-- although there is no international Treaty sanctioning these unilateral decisions (it would of course be wise to pursue such a Treaty).

It is remarkable that much more attention has been devoted to the issue of reconciling the survival of our civilization with the threat entailed by Plutonium, than to the similar problem with respect to HEU. The main reason is because the first problem (Plutonium) is much more complicated to deal with than the second (HEU: see above and below).

This seems an example of a well-known societal paradox: sometimes the fact that a problem is relatively easy to address results in its neglect rather than in its solution getting priority.

10. In the immediate future -- which is our main concern -- every effort should be made to eliminate as quickly as possible as much HEU as possible, in particular the HEU the physical security of which is a matter of more justified concern. There are no technological barriers preventing major quick progress in this direction, which is instead mainly impeded by commercial considerations.

The elimination of HEU is technologically easy and quite straightforward: de-enrich the HEU by mixing it with Natural Uranium (or possibly even with Depleted Uranium (DU) -- namely Uranium which contains less U-235 than NU -- a material of which there exist large stocks left over as tails from the enrichment process that produced the large existing stocks of HEU and LEU). This could be done very quickly and inexpensively in a number of ways: in the gaseous state using uranium hexafluoride, in the metallic state by melting, in the oxide state by mixing powders. The entire stocks of HEU could be eliminated in this manner quickly (within very few years), and the actual costs involved in this process (not including any compensation for the costs originally involved in the production of HEU) would be marginal (less than, say, one hundred million dollars for all the HEU now in existence). In all cases the end product is guaranteed not to be usable for manufacturing nuclear explosive devices as soon as it is de-enriched to, say, less than 20% U-235 content; and it can as well be guaranteed that re-enrichment of the resulting material to HEU would be exceedingly difficult, certainly beyond the means of any terrorist group and indeed of most States.

There is another motivation to proceed in this direction -- in addition to that of eliminating a material, HEU, the availability of which puts at risk the very survival of our civilization. The process of de-enrichment may be conducted so as to yield as its end product LEU, which is a commercially valuable material inasmuch as it can be used as fuel in most of the nuclear reactors used by utilities worldwide to produce electricity. Hence the LEU obtained in this manner easily and at low cost from the large stocks of available HEU could be sold to the utilities that produce nuclear electricity, and the resulting income would allow to compensate not only for the cost of de-enriching the HEU to LEU, but as well -- at least in part -- for the expenses originally incurred to produce the HEU (enriching Uranium is of course a much more expensive job than de-enriching it, partly because of the enormous energy consumption required, due to the fact of working against the second principle of thermodynamics: it is estimated that at some point the energy consumption of the Uranium enrichment plants at Oak Ridge in Tennessee exceeded that of France!).

But unfortunately this fact -- the possibility to get an income from selling to electrical utilities the LEU obtained by de-enriching HEU -- which should have fostered the process of elimination of HEU -- turned instead out to block quick progress in this direction, because it brought into the picture commercial considerations which entailed enormous complications and became the dominant element in determining the scope and the pace of this process, with the profit element, and the associated concern to avoid a decrease of the world market price of LEU, taking first seat with respect to the security motivations to eliminate as much HEU as possible as quickly as feasible.

It so happened that the implementation of the important agreement reached among the USA and Russia at the beginning of the 90' to de-enrich to LEU five hundred tons (half million kilograms) of Russian HEU was staggered over twenty years (what a sense of urgency!). To make matters worse the agreement was sold by the US Administration to a reluctant US Congress with the promise that it would be effected "at no cost to the American tax-payer", and its implementation was assigned to an American institution, the United States Enrichment Corporation (USEC), that had no interest to begin with to import Russian LEU (the natural competitor to its own activity) and which was moreover, at the same time, transformed, from being fully owned by the Federal USA government, into a private company, that obviously was not willing to lose money in the interest of U. S. and world security. The idea of this "HEU deal" was that Russia (that is, Minatom, the institution in Russia that is in charge of all nuclear matters) would de-enrich HEU to LEU (with the properties of this material specified to fit commercial standards of enrichment and purity), sell it to USEC, who would then re-sell the LEU to electrical utilities and thereby recoup the money paid to Minatom (and also make some profit). The order of magnitude of the funds to be transferred to Minatom for the entire HEU deal was 12 B\$ (twelve billion dollars). USEC assigned to this operation the public-relation name "megaton to megawatts" and made much publicity about the fact that it entailed the transformation of something very dangerous (the basic material to manufacture nuclear bombs) into something useful (electricity), but in fact -- in the context of a world decline of investments in nuclear energy and therefore of a world glut of Uranium hence a decrease of the market price of LEU -- USEC has been far from enthusiastic about implementing the HEU deal, which more than once was on the verge of foundering because of disagreements about its financial details so that it had to be rescued by interventions of the U. S. Administration, and in any case was realized even more slowly than originally envisaged (so far, after almost a decade, less than 150 tons of Russian HEU have been eliminated). At the moment the deal has been rescued once more and is proceeding at the rate of 30 tons of HEU eliminated per year. And USEC -- in contrast to Minatom -- does not seem interested in extending the deal to include additional quantities of Russian HEU.

11. Procedures which would by-pass these commercial difficulties have been suggested, but their implementation has been so far stifled by lack of interest and by the unwillingness of (affluent) States to allocate the financial resources needed in the short run, altogether not exceeding B\$ 10 (ten billion dollars).

In the aftermath of September 11, and in the light of the above considerations, it is natural to suggest not only that the implementation of the USA-Russia HEU deal described above be guaranteed and accelerated (by-passing altogether USEC if need be), but also that serious consideration be given to supplementary initiatives aimed at bringing about the elimination of as much HEU as possible as quickly as possible. It is quite obvious what to recommend in this respect.

From a technological point of view the immediate goal should be to de-enrich to less than 20% U-235 content as much HEU as possible as quickly as possible, so as to make it unfit as material for nuclear explosions. Such a de-enrichment could be realized much more quickly and rather more cheaply than that aimed at producing commercially viable LEU. Additional de-enrichment which fits the precise specification on U-235 content and

overall purity required to make it commercially viable as LEU could be postponed to the moment-- possibly decades later -- when this material shall find a buyer -- who will then specify the precise characteristics of the required LEU.

Affluent countries like the USA, the UK, France, should proceed in this direction forthwith, eliminating to begin with, as quickly as possible, all the HEU that is recognized as now redundant. This entails of course forsaking some-- albeit, for reasons we will not go into here, only a quite minor fraction-- of the separative work, hence of the expenses, originally made to produce this HEU.

Countries that are now facing economic difficulties, like Russia, should also proceed in the same direction, but are unlikely to do so unless they get some immediate financial inducement, in the guise of compensation for the separative work that is thereby forsaken. A reasonable form of such financial inducement would be in the guise of a loan without interest, to be paid back if and when the material produced from the de-enrichment of the HEU gets eventually sold as LEU. The financial inducement should be sufficiently substantial to motivate Russia to take very good care and retrieve all its HEU and to de-enrich as much of it as possible as quickly as possible. The amount of such a financial inducement shall of course be subject to negotiation and mutual agreement; an indicative figure could be \$ 10 (ten dollars) for every gram of HEU eliminated, entailing a total cost of \$B 10 (ten billion dollars) for the elimination of 1,000 (one thousands) tons of HEU, taking thereby care of essentially all the Russian HEU that constitutes a potential risk. There is little doubt that Minatom and Russia would be quite willing to enter such an agreement and to implement it speedily, even if it would entail -- as it certainly should -- some accompanying measures of transparency, to guarantee that no additional HEU is being produced in the meantime, to measure the amount of HEU that is being eliminated, and to safeguard (possibly via the International Atomic Energy Agency) the material produced so that, if and when it is eventually transformed into LEU and sold, the loan be paid back. It is conceivable that Russia might eventually earn twice as much money from the sale of LEU than the \$ 10 (ten dollars) for every gram of HEU eliminated, indicated above as a possible no-interest loan for de-enriching HEU, though such estimates are quite conjectural given the uncertainty about future market prices of LEU. Analogous terms should be offered to other States -- in particular, to all the New Independent States resulted from the disintegration of the Soviet Union -- where there also are (minor) quantities of HEU. The funds needed to finance this operation should come from all the affluent countries of the world who have a stake in the prevention of nuclear terrorism -- presumably primarily from the United States, but as well from Europe, Japan, Canada, the OPEC countries, possibly even from some private donors... - - although the urgency to start this process should take precedence over attempts to forge immediately a large coalition in order to share the costs. Of course the overriding motivation for undertaking this project and allocating to its speedy realization the required financial resources -- which are substantial but not outlandish -- should be the security of each country, and of the world as a whole, in the face of the tremendous threat of nuclear terrorism (not the prospect of making money by eventually selling LEU to electrical utilities).

It is also conceivable that, in the context of the negotiation of such a deal, some conditions might be agreed on the way the funds will be utilized by the countries receiving them: for instance it would be desirable that those received by Russia be used,

at least in part, to fund agreed measures of nuclear disarmament and/or the elimination of the enormous stocks of chemical weapons which Russia agreed to dispose of under the Chemical Weapon Convention, a commitment it seems however difficult for Russia to meet because of its cost. However all such conditions should take the back seat with respect to the main goal, to eliminate as much HEU as quickly as possible; indeed, even if (parts of) the funds transferred under such an agreement to some country were to end up in private bank accounts in exotic places, the main purpose of this operation would have been successfully achieved: indeed those situations where something like this is more likely to happen are precisely those more in need of an intervention the end result of which is the elimination of any temptation to make money by selling HEU clandestinely. In this respect the funds allocated to the elimination of HEU are more effective in definitely solving a problem than those allocated to upgrading its physical security, that require a continued additional commitment to make sure the protective barriers raised do continue to operate through time.

An interesting variation of the financial scheme outlined above has also been variously suggested (in Italy, by the Landau Network - Centro Volta, under the alluring title "Swap of debt for security"), in which some affluent countries, rather than providing cash, put on the table their credits, offering to transform them from interest-paying debts to non-interest-paying loans. For instance Russia -- out of a total debt of over \$B 71 (seventy-one billion US dollars) inherited from the past -- owes Germany over \$B 26 (twenty-six billion US dollars) and Italy over \$B 6 (six billion US dollars), and pays yearly substantial sums as interests (although the capacity hence willingness to do so is dwindling).

But unfortunately so far neither sufficient interest in, nor indeed any awareness of, this problematique seemed to emerge among the leadership of the main States who should be at the forefront of the attempts to eliminate the tremendous risk of nuclear terrorism -- including in particular the United States and Europe. Some possible progress in the right direction might emerge from the very recent G8 decision (dubbed 10+10/10) to allocate 10+10B\$ (10 by the USA, 10 by all the other affluent countries) over the next 10 years to the general problematique of preventing the proliferation and terroristic uses of Weapons of Mass Destruction: but the implementation of this program does not seem to be very effectively pursued (although it might still be too early to pass judgement).

12. If the points made above are correct, and we do not manage to convey them with adequate impact to the uninformed public, and especially to -- also uninformed -- decision-makers, we carry a responsibility for which we shall be held accountable in the aftermath of a catastrophe which might happen soon.