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Highly Enriched Uranium, a Dangerous Substance that Should Be Eliminated

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Summary

Either highly enriched uranium (HEU) or plutonium is needed to construct a nuclear weapon. While plutonium is radioactive and hazardous in handling, HEU is far less dangerous. Furthermore, it is more difficult to detect by technical means. Therefore, in comparison to plutonium, HEU is much easier to divert, smuggle and hide. Moreover, a crude nuclear explosive made of HEU can be constructed in a much simpler way than one made using plutonium. For these reasons, HEU is the material most wanted by terrorists. A few tens of kilograms are sufficient for one explosive, but the quantities existing in the world add up to hundreds of tons.

Due to the disarmament at the end of the Cold War, the NPT nuclear weapon states possess large quantities of HEU in excess of their needs for nuclear weapons. Therefore, these countries have not produced HEU for many years. Several international projects are working towards reducing the proliferation risks posed by HEU. The projects include the reduction of existing HEU by converting it to civilian reactor fuel that cannot be easily used for nuclear weapons. Other projects work towards reducing the number of countries and sites where HEU is stored by transferring it back to the countries of origin. And there are yet other projects which seek to minimize uses which would require new production of HEU.

An international non-proliferation goal should be to eliminate all uses of HEU and thus to eliminate the need for any future production. Uses of HEU other than for nuclear weapons are as fuel in civilian research reactors, as base material for the production of special isotopes used in medical diagnostics, so-called medical targets and as fuel in military naval reactors. It is desirable to replace the HEU in all these applications with other materials and thus cease all HEU production forever.

Use as fuel in civilian reactors has been greatly reduced during the last few decades. Within an international campaign, the *Reduced Enrichment for Research and Test Reactor* (RERTR) program, new denser fuels for research reactors have successfully been developed. In many research reactors it was possible to replace the previous HEU fuel with a new fuel type without affecting performance. Only a few exceptions are left. The hope was, and is, that the remaining reactors will reach the end of their useful life so that in future no more HEU will be needed for this application. Indeed, there was a moratorium for two decades during which no new HEU-fuelled research reactor was constructed.

The first reactor that breached this moratorium was the FRM-II in Garching near Munich. It made use of the newly developed fuels but in a way that resorted to HEU again. The decision-making on the reactor design neglected the political disadvantages for a long time, but stressed some technical advantages which, however, are disputed. Critics claim that a somewhat different design would have enabled the same applications. Discussions took place on both a domestic and international level. The lesson that can be learned is that proliferation danger criteria and foreign policy issues need to be made a part of the decision-making process at an early stage.

A campaign has been initiated to convert medical targets in order to avoid the use of HEU. It is showing promising first results but will be successful only when an international consensus and commitment is reached.

Only a few countries use HEU as fuel for naval reactors. The question arises why such reactors cannot be converted to different fuels. The most prominent opponents of banning the future production of HEU for naval fuel purposes are the U.S. and the UK. Their existing naval reactors could consume the huge excess quantities of HEU that these states possess. It would be sufficient for many decades. During this time, new naval reactors could be designed that use the new modern fuels based on LEU instead of HEU. Several states, including nuclear weapon states, use naval fuel made using uranium enriched to a much lower level. The reasons why the U.S. and the UK do not engage in such plans are unclear. In contrast to civilian reactors, hardly any information on naval reactors is available. The secrecy surrounding them even surpasses that of nuclear weapons. Without more technical information, it will be difficult for outside experts to conduct conversion studies.

The international community and the Federal Republic of Germany would be well advised to press much harder for a ban on the production of naval fuel using highly enriched uranium.

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Contents

1. Highly Enriched Uranium: Harmless or Hazardous?[1]

Highly enriched uranium (HEU) is a substance with only low radioactivity in comparison to several other materials such as plutonium or spent nuclear fuel. It emits only alpha radiation, which can easily be shielded. Unlike plutonium, the radiological hazards of handling highly enriched uranium wrapped in paper are relatively low. But HEU has another property: It can be used as a nuclear explosive material, making it one of the most dangerous substances on earth.

The quantities of highly enriched uranium (HEU) that exist worldwide are enormous, almost 1,300 tons, while the quantity needed for one bomb is only a few tens of kilograms or even less. A state or a terrorist group that gets hold of just such a small amount of HEU will sooner or later be able to construct a nuclear explosive device. HEU is the material most wanted by terrorists because it is far less hazardous to handle than plutonium, which is the other material with which a nuclear bomb can be made. Furthermore, the technology for a crude nuclear explosive made using HEU is far simpler than for one made using plutonium. Paradoxically, the ease with which it can be handled makes HEU an even more worrisome material than plutonium, because the probability that it may be misused for the purpose of manufacturing nuclear explosives is far greater.

Non-proliferation efforts therefore must ensure that no HEU can be diverted, and that all is accounted for. The huge HEU reservoirs that exist can also be misused by their owners for the purpose of building weapons. The amount would be sufficient for tens of thousands of warheads. Non-proliferation and disarmament measures must strive to make the process of disarmament irreversible by applying political means such as international controls, transparency and disincentives for misuse as well as by applying technical means, namely creating technical thresholds for explosives uses which would be too difficult for terrorists to overcome. The technical means would be to dilute the HEU so that it is converted into low-enriched uranium (LEU) which cannot be used for a nuclear explosive, unless it is re-enriched. But enrichment is a sophisticated technical procedure that cannot be mastered by terrorists or beginner states. The acquisition of enrichment technology carries with it a high degree of risk of being detected, as is currently evident in Iran.

The best option would be to eliminate all existing HEU. Indeed, after the end of the Cold War, the superpowers started to reduce the number of their nuclear weapons, creating large surplus stocks of HEU. Part of this excess HEU is diluted to LEU and sold as reactor fuel in the civilian sector. The United States, Russia, the UK and France have declared moratoria on the production of HEU and plutonium for weapons use and China is believed to have ceased production, too, although it has not officially declared this at senior diplomatic levels. Since the early 1990s, there have been plans to codify the moratorium in the form of

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[1] I thank Melanie Coni-Zimmer, Matthias Englert, Giorgio Franceschini, Karin Hammer, Daniel Müller, Harald Müller und Hajo Schmidt for their helpful comments, and I am grateful to Matthew G. Harris for his excellent language editing and to Susanne Schmidt for the final editing. All views expressed are my personal views.

an international treaty, namely the Fissile Material (Cut-off) Treaty (FM(C)T).[2] The FM(C)T has not yet been negotiated but now, years later, the moratoria are still being observed. The international community hopes that India, Pakistan, Israel and North Korea will also commit to observing similar moratoria.

However, there are other uses for HEU besides nuclear explosives, and they pose the danger of HEU potentially being diverted for weapons use. These other uses are fuel for research reactors and naval reactors, and HEU targets that are irradiated by neutrons for the production of medical isotopes. Because of the danger of proliferation, replacing civilian HEU with other materials has been suggested. The campaign to convert research reactors from HEU to LEU fuel has been going on for several decades and been quite successful. The possibility of converting HEU targets for medical isotope production is being investigated, with some promising results. Although there are only a few states that use it, among them the U.S. and the UK, the topic of eliminating the use of HEU for military naval propulsion has not yet been broached. If it were possible to replace HEU with other materials for these uses, there would be the prospect of stopping all production of HEU, not only for nuclear explosives as envisaged by the FM(C)T. There would be no justification for the resumption of HEU production, and therefore a realistic possibility of eliminating this material altogether.

The goal of phasing out all HEU production is the point I am making in this report. The end of the production of HEU for nuclear weapons seems realistic, provided an FM(C)T will be negotiated. Similarly, the phase-out of HEU production for civilian research reactors seems realistic. In the past, significant technical and political progress has been made, with only a few setbacks. Discontinuing production of HEU targets for medical isotope production is still in its early stages, but does not seem unrealistic in principle. The topic of the phase-out of HEU for civilian applications is widely discussed among scholars and governments, as is the desire to negotiate an FM(C)T, but the topic of phasing out military naval fuel production still seems taboo.

The report will discuss the prospects and technical and political obstacles to replacing HEU with other materials. Are there technical disadvantages that could be accepted? And how likely are they to be accepted? How far have past efforts proceeded? Are there lessons that could be learned for further progress? Which international measures could be taken that promote conversion campaigns?

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[2] Schaper 2011: This treaty is heavily contested, to an extent that even its name is controversial, so that the acronym FM(C)T has become common.

2. Uranium: Technical Background and Definitions

2.1 Uranium isotopic mixtures and chain reactions

In this section, some basics of the physics of uranium are explained so that the reader can understand why there are different kinds and mixtures of uranium with very different properties. The different properties are relevant with regard to explosive and other uses, and accordingly, there are legal classifications that play a role in safeguards and export controls. This section may be skipped by more informed readers.

Uranium ore is found in large quantities all over the world, and uranium oxide or metal can be obtained from it by well established industrial processes. So-called *natural uranium* as it occurs in nature consists of a mixture of two isotopes, namely U-235 and U-238. The U-235 content in natural uranium is small, only 0.7 percent.

Although chemically identical, the two isotopes have different physical properties: When a U-235 nucleus is struck by a neutron, it undergoes *fission*, resulting in two fission fragments, 2-3 neutrons, and a large quantity of energy. The lower the neutron energy, the larger the probability of fission of a U-235.[3] As soon as nuclear fission was discovered, it was understood that in a sufficiently large assembly of fissile nuclei, a chain reaction would start because each fission would result in a larger number of neutrons that would cause more fission processes with continuously multiplying numbers of neutrons and ever increasing energy release. Only in small assemblies of U-235 would more neutrons escape without coming close enough to another nucleus to fission. In the case of a sphere of pure U-235 of normal density, a mass of about 50 kg would be just *critical*, which means that the loss of neutrons would be such that just one neutron is left for fission of the next nucleus. Larger assemblies would be *overcritical* which means that the number of neutrons would grow exponentially. A *reflector*, namely material surrounding the assembly and reflecting escaping neutron back into the assembly, would further reduce the critical mass.

This is different with U-238: When it is struck by a neutron, another process is much more probable, namely *capture* which results in the disappearance of the neutron and the formation of plutonium-239 (Pu-239). It is not surprising that in natural uranium, no chain reaction takes place, no matter how large the assembly. In naturally occurring uranium, most neutrons released by a U-235 fission process are captured by a U-238 nucleus, and the number left is not sufficient to sustain a chain reaction.

There are two ways to achieve a chain reaction in uranium. One is to *enrich* it in its U-235 content, the other is to *moderate* the neutrons and thereby enhance the probability of fission of U-235 in comparison to that of capture by U-238. The latter is based on the fact that the probability of fission is higher when the neutrons are slow. Slowing down is achieved by the use of a *moderator* which is placed close to the nuclear material. Several materials can serve as a moderator. In so-called *light water reactors* (LWRs) it is ordinary water, because water molecules contain two hydrogen atoms whose mass is about the same

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[3] In contrast to U-238 which is fissioned only by very fast neutrons.

as that of a neutron.[4] However, because the hydrogen captures some of the neutrons, ordinary water is not sufficient for the moderation of natural uranium fuel. Therefore, with ordinary water the uranium still has to be enriched, typically to about 3-5 percent. Uranium enriched below 20 percent is called *low-enriched uranium* (LEU), and uranium enriched above 20 percent *highly enriched uranium* (HEU). The official definitions of HEU and LEU are presented in the next section.

If the moderator is heavy water which contains the isotope deuterium instead of ordinary hydrogen, the fuel can be natural uranium because deuterium captures far fewer neutrons. This is the case in so-called *heavy water reactors* (HWRs). In established nuclear power reactors such as LWRs, HWRs and others, the assembly of the fuel, the moderator and more materials are balanced in a way that the assembly is just critical.

In a nuclear explosion, the situation is much simpler. The assembly is not just critical but *over-critical* by a wide margin. There is no moderator, the chain reaction proceeds much faster, and the number of neutrons grows exponentially until the energy density becomes so large that the assembly is blown apart. Using a percentage of U-235 as high as possible reduces the mass needed for criticality. The uranium must be enriched to a high degree, typically above 90 percent.

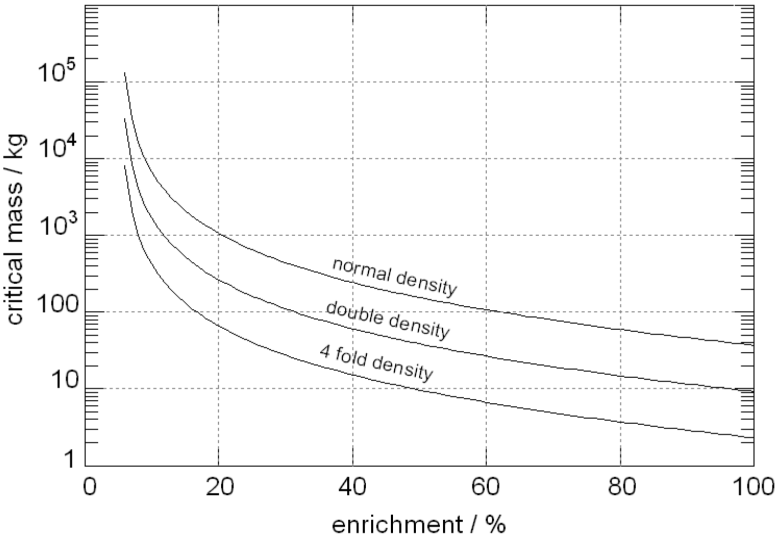

Figure 1: Critical mass of unreflected and unmoderated bare uranium spheres, depending on the enrichment, analytical approximation (for the calculation see the appendix).

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[4] The smaller the mass of their nuclei, the better the effect of slowing down neutrons. The moderated neutrons can be compared to billiard balls: Their velocity decreases when they hit another ball of the same mass, but does not when they hit the edge which has a much larger mass.

Figure 1 shows that a nuclear explosion is also possible with uranium enriched far below 90 percent; however, more mass is required to accomplish this. It also shows that the mass is reduced if the fuel is compressed to a higher density. It would be further reduced if surrounded by a reflector (not shown in Figure 1). Terrorists would not be able to construct a device that enhances the density of the HEU, but probably would be able to make use of a reflector.

The quantities in Figure 1 should not be confused with the true amount needed for one bomb, which varies depending on the sophistication of the design. But they provide a rough guideline estimate.

Enrichment is an endeavour that terrorists would not be able to master. But a state that possesses enrichment technology could principally use it for HEU production. The technology is the same for LEU and HEU, with a few modifications that are easy to accomplish. There are several options for enrichment which differ in their degrees of technical sophistication, efficiency, stage of development, ability to safeguard and economic viability. It is possible to detect clandestine enrichment by inspecting a suspicious site. In cases where the location of enrichment activity is unknown, there is nevertheless a certain detection probability, but it depends on the technology. The proliferation of enrichment technologies is a problem that is being dealt with using safeguards, export controls, diplomacy and politics. There is a vast body of literature on this subject. However the topic is not discussed further in this report.

2.2 Legal definitions of uranium categories

As illustrated in Figure 1, only uranium enriched to a certain level can be misused for nuclear explosive purposes, whereas, without further enrichment, this is not possible with natural uranium or low-enriched uranium. Accordingly, the International Atomic Energy Agency (IAEA) defines different categories of uranium to which it applies different safeguard regulations that differ in exhaustiveness and intrusiveness. Uranium enriched 20 percent and more is defined as HEU, and below 20 percent as LEU. This threshold is arbitrary. As Figure 1 shows, a self-sustaining and unmoderated chain reaction is theoretically possible in uranium enriched to less than 20 percent. On the other hand, Figure 1 also illustrates the large critical mass of such uranium. Any manageable weapon must contain HEU enriched well beyond only 20 percent. Otherwise, any ignition technology would be extremely difficult or technically impossible. At the time the 20-percent threshold was chosen, there were no technical applications that applied uranium enriched to near 20 percent, so that there were no interests that would have provoked opposition against this number, and consensus was easy to obtain.

The IAEA has defined several more categories which are codified in several legal documents. HEU is classified as *direct-use material*, a category whose definition includes the definition “nuclear material that can be used for the manufacture of nuclear explosives components without transmutation or further enrichment [...]”. Direct use material is subjected to the most stringent safeguard regulations.

LEU falls into a different material category, namely *indirect-use material*. It is defined as including "all nuclear material except direct-use material, e.g., natural uranium or LEU which must be further enriched to be converted into HEU [...]".[5]

Uranium that has not been enriched is called *natural uranium*. The enrichment process also yields the tails, namely uranium with a U-235 content below that of natural uranium, which is called *depleted uranium*. LEU and natural uranium can also be valuable for explosive purposes, however there is a technical threshold for their use, namely enrichment.

In order to set quantitative goals for safeguards, the IAEA defines the term *significant quantity* as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses [...]". For HEU, the significant quantity has been set as 25 kg of the U-235 component. For LEU, it is 75 kg.

It is likely that the mass needed for one warhead is much less than a significant quantity. That is why some analysts have called for the definition of smaller significant quantities (Cochran/Paine 1995). But it would be a mistake to take this term as a technical specification. Instead, it is a compromise between the competing goals of high verification confidence on the one hand and reasonable verification costs on the other. Therefore, the term "significant quantity" is only superficially related to the mass needed for one warhead, and the above wording should instead be understood as an illustration of its purpose. It is not a technical, but a legal, quantity. So the three terms "significant quantity," "mass needed for one warhead," and "critical mass" should be kept distinct and are not synonymous.

2.3 Worldwide quantities of HEU

Most of the HEU existing today is not subject to international controls or safeguards such as those of the IAEA or Euratom, and the level of transparency concerning inventories is still unsatisfactory. HEU does not change its explosive properties for many centuries due to its slow radioactive decay and slow accumulation of decay products. Plutonium, on the other hand, has explosive properties that change over a period of many decades that are at least disputed. The enormous existing stocks in the U.S. and Russia today could quickly be used for nuclear rearmament exceeding levels at the height of the Cold War.

The following table provides an overview of HEU quantities existing worldwide. It is broken down into several categories: HEU for explosives use can exist in weapons, in warhead components, in reservoirs, in production pipelines, or considered excess to explosive needs but not declared as such. After the end of the Cold War, the U.S. and Russia officially declared some EU in excess of nuclear weapon needs, but only very small quantities were placed under international safeguards. Most of the excess HEU is from dismantled nuclear weapons or from nuclear weapons fabrication pipelines. The U.S. and

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[5] Glaser assumes that 10-15 kg is sufficient for one explosive: Glaser 2005, p. 247.

the UK have published figures for their HEU stocks,[6] but similar publications by other countries in the list are still lacking. Their figures are estimates by nongovernmental organizations, often with large error margins.

The table shows clearly that by far the largest amount of HEU is still for nuclear explosive purposes, followed by unsafeguarded naval fuel. Large quantities of HEU have become excess to explosives needs, and much has already been eliminated by *down-blending*, which involves mixing the HEU with depleted uranium in order to produce civilian LEU fuel to be sold in the civilian sector. The reason why the U.S. does not subject more HEU to international safeguards is mainly that the HEU from dismantled nuclear weapons is considered a reserve for naval fuel (see further below section) (Maerli 2002).

Possessor	**For explosives use**	**Naval fuel**	**Declared excess**	**Technically disposed of (a)**	**HEU under IAEA safeguards**	**In civilian use**	**Total**
U.S. (b)	260	130	104 (c)	131 (c)	10 (d)	20	514
Russia (± 20%) (b)	616	30 (e)	104	413	0	20	770
UK (b, f)	21.64 (g)		4.72 (g)	0	0	1.404 (h)	27.76
France (± 20%) (b, f)	26	1 (i)	0	0	0	4.9 (j)	25
China (± 20%) (k)	16	??	0	0	0	1	16
India (b, l)		1.3 ± 0.5	0	0	0		1.3
Pakistan (b)	2.6 ± 1		0	0	0		2.6
Israel	??		0	0	0		
Non-nuclear weapon states (b)	0	0	0	0	7		7
Total	≈ 898	≈ 162	≈ 213	544	10	≈ 54	**≈ 1300**

Sources and remarks:

(a) The HEU has been down-blended to LEU by mixing it with depleted uranium.

(b) IPFM 2010, figures are as of mid-2010.

(c) Only parts of the excess HEU is enriched over 90 percent, much is enriched to less, between 20-90 percent (Maerli 2002).

(d) McGoldrick 1995.

(e) Composed of 20 t of fresh and 10 t of spent naval fuel.

(f) All civilian nuclear material of the UK and France is under Euratom safeguards.

(g) UK MoD HEU Report 2006. The UK report does not give figures for HEU enrichment. The UK does not specify the average enrichment of its HEU, nor does it specify how much HEU is devoted to naval fuel (IPFM 2010).

(h) INFCIRC/549/Add.8/13, 16 August 2010.

(i) Number from ISIS-Online: "The bulk of France's nuclear powered vessels used LEU fuel. However, one or two of its strategic submarines used HEU fuel." http://isis-online.org/uploads/isis-reports/documents/military_excess_heu.pdf, updated 2005.

(j) Composed of 3.3 t of fresh and 1.6 t of spent fuel.

(k) Zhang 2011.

(l) Enriched to about 30 percent.

Table 1: HEU quantities worldwide, figures in tons.

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[6] U.S. DoE HEU Report 2006; UK MoD HEU Report 2006. The UK report does not provide figures for HEU enrichment.

2.4 Projects aiming at reducing the proliferation risks of HEU

The vast existing reservoirs of HEU are sufficient for tens of thousands of nuclear weapons. Thus, not only must any incentive for new production be eliminated, but also the quantities of reservoirs reduced, and the proliferation dangers of stocks alleviated. The need to reduce the quantities that are in the possession of the nuclear weapon states is contested. This disagreement is a major reason why negotiations on an FM(C)T are not making headway.[7] Although the task of reducing the proliferation dangers posed by existing HEU is not the subject of this report, a short overview is given in this section as background information.

There are several national and international programs with a variety of activities aimed at reducing the threats through international collaboration (U.S. GAO 2010). They include the conversion of civilian research reactors from HEU to LEU use, which is dealt with in the next section of this report, the return of fresh and spent HEU fuel from various countries to supplier countries, both the U.S. and Russia,[8] reduction of the number of storage sites for civilian HEU within any single country, and improvements in the material protection, control, and accounting (MPC&A) of nuclear materials, the latter being a measure that also aims at the security of plutonium. Spent research reactor fuel still contains substantial fractions of HEU, typically half of its original U-235, and therefore also poses a proliferation threat. The history of U.S. efforts dates back to 1991, when shortly after the end of the Cold War the world realized that proliferation dangers might arise from the insufficient security of weapons-usable materials, and the so-called Cooperative Threat Reduction Program (CTR) was founded.

The return of HEU to the countries of origin aims at reducing the number of storage sites. Each storage site might be subject to theft and therefore needs substantial physical protection which cannot be afforded at several locations. In most cases, the various owners of the storage sites welcome the removal of the HEU, because otherwise they would have a disposition problem. The fuel returned to Russia is down-blended to enrichment below 20 percent.[9] Down-blending physically eliminates HEU by inserting *technical irreversibility*. In order to re-use it for nuclear weapons, the resulting material must first be re-enriched, which constitutes a substantial technical barrier.

In addition, there are efforts to reduce the number of storage locations of civilian HEU in Russia. After criticism of the slow pace of all activities, the U.S. launched the *Global Threat Reduction Initiative* (GTRI) that subsumes several initiatives seeking to "identify, secure, remove and/or facilitate the disposition of high-risk vulnerable nuclear and radiological materials around the world that pose a threat to the United States and the

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[7] For details see Schaper 2011.

[8] Some examples of successful shipments are listed by NTI: www.nti.org/e_research/cnwm/securing/ vulnerable.asp (20.3.2014).

[9] NTI: Past and Current Civilian HEU Reduction Efforts, updated April 2010, www.nti.org/db/heu/ pastpresent.html (20.3.2014).

international community".[10] GTRI benefits from substantial funding, and Russia, the IAEA and many other states have joined in these efforts.

There are also initiatives affecting not only civilian HEU but also military HEU in excess of explosives needs. After the end of the Cold War, the U.S. and Russia pursued substantial disarmament that included dismantling of thousands of warheads. As a consequence, they declared as excess certain quantities of nuclear weapon material including about 500 tons of Russian and 174 tons of U.S. HEU (see above Table 1). In order to prevent illegal diversion and reuse for potential future rearmament, and in order not to waste the separative work that had been previously invested, the U.S. and Russia wanted to transfer this HEU to the civilian nuclear energy market. In 1993, the *Russian-U.S. HEU Agreement*, also called *Megatons to Megawatts*, or *HEU deal* was entered into which specifies how Russia is to down-blend its HEU to LEU and sell it in the U.S. for civilian purposes. Both sides have mandated commercial companies for these tasks. The U.S. is also down-blending its declared excess HEU for civilian fuel fabrication.

Originally, the HEU deal had caused friction in the civilian market.[11] The prices that the two governments had negotiated in 1993 were felt to adversely affect the ability of the company tasked with selling the fuel to do so competitively. For this reason, both sides amended the agreement some years later in order to reflect the economic circumstances in the fuel market. The fuel originating from dismantled weapons covers about 15 percent of worldwide power reactor demand for LEU. The Megatons to Megawatts program came to an end in 2013. As seen in Table 1, the program has substantially reduced overall HEU quantities, although there is much more HEU originating from dismantled warheads than amounts officially declared. The companies that have implemented the program have set up a new 10-year follow-up contract including different business terms.[12] The HEU deal has been a disarmament success because it demonstrated that it is possible to reduce and eventually eliminate tremendous amounts of HEU.

Projects such as converting research reactors, improving MPC&A, or consolidating and down-blending HEU have beneficial non-proliferation effects but they also have shortcomings. One advantage of projects like these is that technical barriers against proliferation and rearmament are established which render nuclear disarmament *technically irreversible*. Another advantage is the ease of their comparatively rapid implementation. Often, projects are agreed upon bilaterally, and details worked out to satisfy the specific needs of the actors, often in a flexible way so that they can be amended according to experience gained. To a certain extent, their success simply depends on funding. Furthermore, these kinds of projects create the basis for follow-up projects that

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[10] National Nuclear Security Administration, Fact Sheet – GTRI: Reducing Nuclear Threats, 1 February 2011.

[11] Center for Defense Information, "Megatons to Megawatts": The U.S.-Russia Highly Enriched Uranium Agreement, 14 May 2004, www.cdi.org/friendlyversion/printversion.cfm?documentID=2210&from_page=/program/document.cfm (20.3.2014).

[12] Frank Lewis, New program to replace Megatons to Megawatts, Portsmouth Dailytimes, www.portsmouth-dailytimes.com/news/news/2580611/New-program-to-replace-Megatons-to-Megawatts (20.3.2014).

may go further, create a working climate between the actors and build confidence among parties, aspects which are vital preconditions for more ambitious endeavours.

The shortcoming of such projects is the only moderate impact they have on *political irreversibility*, because contracts between the actors, such as the HEU deal, can easily be phased out or terminated. In order to reinforce progress made so far, additional binding commitments should follow; in other words political irreversibility should be strengthened. This is achieved by nuclear arms control and multilateral regimes. An important arms control measure would be the (FM(C)T), which has been on the international arms control agenda for almost two decades (Schaper 2011). It would ban the production of fissile materials for nuclear weapons and thus codify the voluntary production moratoria and make reductions politically irreversible. The FM(C)T has not yet materialized; one of the reasons is disagreement on the question of whether it should not only ban future production but also implement measures – reductions, transparency or others – on the huge quantities of existing material (see Table 1).

3. Current Uses of HEU – Prospects for Phase-Out

The main focus of this report is to discuss all uses of HEU and to pose the question whether it is really needed or whether it might be possible to replace it with other materials. In the latter case, together with down-blending projects such as the HEU deal, it may be possible to eliminate all HEU from the face of the earth.

Apart from use as nuclear weapons fuel, there are essentially three other uses of HEU, namely as a research reactor fuel, as a target for the production of medical isotopes by neutron irradiations, and as fuel for naval reactors. In each application, HEU could theoretically be replaced by other materials, which is the topic of the following sections.

3.1 Research reactors

Research reactors are much smaller than power reactors.[13] They are used not for power but mainly for neutron generation. Neutron sources are used in a wide variety of applications. Neutrons can be used for breeding or fissioning nuclei in order to generate other nuclei, namely radioisotopes that can be used in medicine, industry or science. Other applications are material structure studies involving irradiation of the materials with slow neutrons and scattering analysis, neutron radiography, transmutation, neutron capture therapy, research on the behavior of nuclear fuel, and education and training of students and technical personnel. Often, research reactors are multi-purpose machines and serve several purposes at the same time.

The power of research reactors ranges up to about 100 MW(th), which is much less than the power of a typical power reactor. Energy is an unwanted by-product of research reactors and is not used. The design of research reactors is much more diverse than that of power

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[13] WNA on Research Reactors.

reactors. There are various kinds of fuels, moderators and coolants, and even prototype fast reactors without moderators.[14]

3.1.1 The proliferation risks posed by HEU use in research reactors

The goal of most research reactor designs is to have a high *neutron flux* that leaves the core, and at the same time a small reactor core and low power. The neutron flux is the number of neutrons per time and area. The higher the quantity and density of fissioning U-235 in the reactor core, the higher the neutron flux. This is the reason why, from the 1960s to the mid-1980s, many research reactors were constructed that used HEU fuel in which the U-235 concentration was higher and the parasitic neutron absorption by U-238 was lower, so that the reactor core could be made especially small. From a technical point of view, the use of HEU instead of LEU fuel is logical. But as a consequence of the increasing use, almost 60 countries received HEU fuel for research reactors. The United States supplied HEU enriched to 93 percent, while the Soviet Union supplied HEU enriched to mainly 36 percent. Figure 2 illustrates quantities of HEU exported by the United States to other countries from the 1950s to the 1990s.[15]

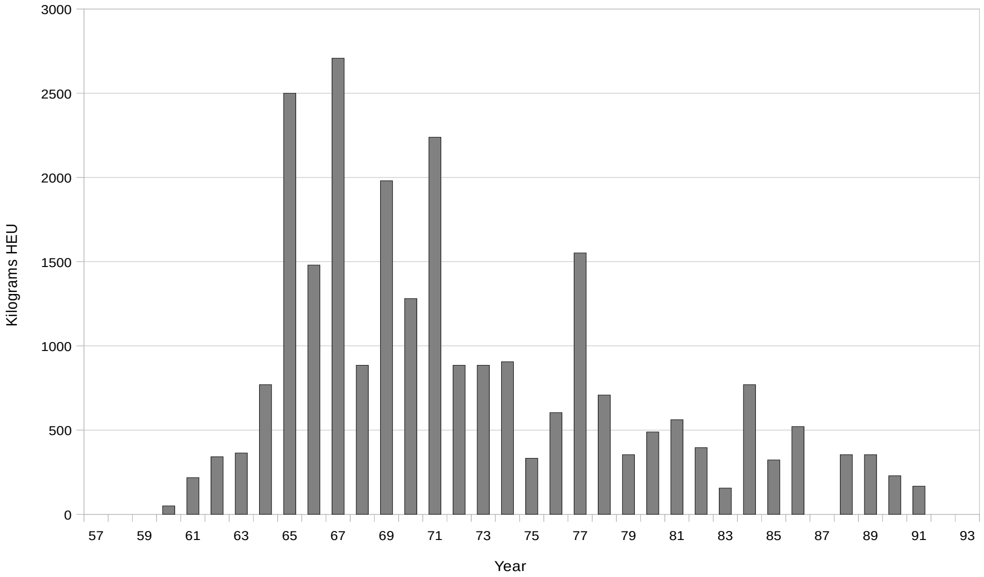

Figure 2: HEU exported by the United States. Source: U.S. HEU Report 2001

The above figure not only reveals the spread of substantial quantities of HEU, it also demonstrates that exports have diminished since the beginning of the 1980s thanks to efforts to curtail the civilian HEU trade (further described below). Some 30,000 kg of HEU have also been delivered for domestic U.S. research and a few energy-producing reactors. It is

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[14] For a detailed list of research reactors and background information, see Reistad/Hustveit 2008, Appendix II – Operational, Shut Down, and Converted HEU-fueled Research Reactors. A fast prototype reactor is the China Experimental Fast Reactor (CEFR). It is sodium-cooled. Sodium has only a minor moderating effect.

[15] U.S. DoE 2001, Figure 6-3, p. 98.

estimated that the former Soviet Union used 10,000 kilograms of HEU, mostly in its own research and fast breeder reactors, and exported almost 17,000 kg to Eastern Europe, Iraq, Libya, North Korea and Vietnam. Great Britain, France and China have exported smaller quantities.[16]

Research reactor fuel is the largest civilian use of HEU and the only reason for its international trade. Although a fuel element for a research reactor is a countable item whose control is as easy as the control of a fuel element for a power reactor, there is a difference: In the event an LEU fuel element were diverted, time would be needed not only to extract the LEU but also to convert and enrich it. This time raises the likelihood of detection before HEU production is complete. However, in the case of an HEU fuel element, only chemical and mechanical processing is required to obtain HEU. The threshold is lower and can be accomplished much faster with less technology and less risk of being detected. Although a spent HEU fuel element is radioactive, it still contains large fractions of unfissioned HEU. A terrorist group that did not care about long-term health risks would be able to extract the HEU using the same technical means as in the case of a fresh HEU fuel element.

The proliferation dangers of longer term international HEU trade can be illustrated using the example of Iraq's clandestine nuclear weapon program that would probably have continued, had the Gulf War not intervened. Iraq already possessed 12 kg of 93 percent HEU it had purchased for a subsequently destroyed research reactor in Osiraq. This HEU was slightly radioactive because it had already been exposed to neutrons in the reactor. Additionally, Iraq possessed 13 kg of nonirradiated 80 percent HEU sold by the former Soviet Union for another research reactor of Soviet design that was bombed during the Gulf War. The HEU in Iraqi possession would have been sufficient for one to two nuclear explosives.

The HEU was subject to IAEA safeguards, but inspections took place only every six months. Shortly before the Gulf War, the Iraqi leadership decided to divert the HEU in a nuclear weapon crash program. The plan was to further enrich the 80 percent HEU to a level of 93 percent within 6 months, and to separate the lightly irradiated HEU from the radioactive fission products. This scenario would probably have succeeded if the enrichment technology had already been operating and the activities had not been halted by bombing during the war. Experiments for an implosion design had already been conducted, but the compression achieved had not yet been sufficient (Albright 1997; Müller/Schaper 1992). These revelations have intensified the concern and the efforts to end civilian use and trade of HEU.

3.1.2 Converting research reactors: the INFCE and the RERTR study programme

After India conducted its first nuclear test in 1974, there was growing concern within the international community about the risks of proliferation of nuclear weapons from nuclear power fuel cycles, along with international disagreement on how to address these risks. In

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[16] China supplied approximately 200 kg of 20.05% HEU to Brazil in the 1980s (NTI, Civilian HEU: China, www.nti.org/analysis/articles/civilian-heu-china/). Great Britain and France supply HEU within the EU.

response to this an organizing conference was set up to carry out a technical and analytical study, the *International Nuclear Fuel Cycle Evaluation* (INFCE). This conference was held in Washington, D.C. on 19-21 October 1977, under the direction of the UN, and coordinated by the IAEA Skjoldebrand 1980). It published a report in 1980. Eight working groups held 61 meetings involving 519 experts from 46 countries and five international organizations. Not the result of political negotiations, the evaluation reports are an analytic and technical study which refrained from making policy recommendations. Nevertheless, it had a political impact since many countries adopted the recommendations and established new norms with regard to the civilian use of nuclear power. The report also addressed the problem of research reactor fuel, stating: The trade in and widespread use of highly enriched uranium and the production of fissile materials constitute proliferation risks with which INFCE is concerned. Proliferation resistance can be increased by: 1. Enrichment reduction preferably to 20% or less which is internationally recognized to be a fully adequate isotopic barrier to weapons usability of U-235; 2. Reduction of stockpiles of highly enriched uranium.[17] It also recommended intensifying research and development of new fuels for research reactors and stated “that neither any loss in reactor performance, e.g. flux-per-unit power, nor any increase in operating costs should be more than marginal.”

In 1978, the United States initiated a program with the goal of minimizing the civilian use of HEU with the long-term view of eliminating it altogether. The program was called *Reduced Enrichment for Research and Test Reactor* (RERTR) program, and is based at the U.S. Argonne National Laboratory (ANL). Other states joined the program, including in 1979 the Federal Republic of Germany with substantial funding and development projects. Germany spent over DM 50 million on the successful conversion of its research reactors, called the “AF Program” (Anreicherungsreduzierung in Forschungsreaktoren = reduction of enrichment in research reactors). In 1989 it was concluded that there would be no more HEU requirements for research reactors (Thamm 1991). The primary objective of RERTR is to develop different fuels that contain LEU instead of HEU and at the same time avoid significant adverse effects in experiment performance as well as economic and safety aspects of the reactors.[18]

At the same time, the former Soviet Union started a similar program and managed to reduce the enrichment of the research reactors supplied to other countries from 80 percent to 36 percent, with the plan of achieving further reduction of the enrichment. These efforts ceased, however, because of economic difficulties in the former Soviet Union.

The fuel used until then consisted of uranium dioxides mixed in an aluminium matrix (UAlx/U3O8), whose uranium density of about 1.5 g/cm3 is quite low. The decisive factor for the design of a research reactor is the neutron flux. In order to obtain a high neutron flux, the U-235 density must be high. At the same time, a small reactor core is desired. In

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[17] International Nuclear Fuel Cycle Evaluation, Working Group 8, Advanced Fuel Cycle and Reactor Concepts, International Atomic Energy Agency, 1980: 43, see also Chapter 4: Research Reactors: Subgroup 8C, pp. 137-180.

[18] RERTR publishes information and conference proceedings on its website: www.rertr.anl.gov/ www.rertr.anl.gov/PRGM/TRAVEL95.html (20.3.2014).

order to keep the reactor core small, HEU has been preferred for most of the earlier research reactors. But the neutron flux would still be the same with other fuel of a lower enrichment but higher density. Such fuel would maintain or even increase the U-235 quantity in the core. A certain increase is necessary in order to compensate for additional absorption by the higher U-238 content of less-enriched fuel.

Thanks to the international efforts triggered by RERTR, new fuels of higher densities have been developed, among them uranium silicide (U3Si2) with a uranium density of 4-8 g/cm3. In this way it has been possible to replace HEU with LEU enriched slightly below 20 percent. No reduction in reactor performance resulted from these substitutions, with performance sometimes even increasing. As noted earlier, this enrichment limit is somewhat arbitrary, but it has political significance because uranium enriched below 20 percent does not fall into the category of direct-use material. Respect for this definition is well established in the context of IAEA safeguards and it has become a robust norm. It makes sense that RERTR definitions are compatible and do not formulate other conflicting definitions. If that was the case, it would undermine the authority of the IAEA definitions.

Most reactors in the U.S. and Europe were converted to the replacement fuel, however, a conversion was not possible in the case of some modern high neutron flux reactors and reactors with unique Russian designs. Some U.S. universities also refrained from converting their reactors. So the RERTR efforts continued, and fuels of even higher uranium densities are under development. Promising ones are based on special U-Molybdenum (Mo) alloys which can be used in aluminium dispersions and achieve U-densities of 8-9 g/cm3. Even denser U-Mo fuel in a monolithic form which is essentially pure metal is being tested by many laboratories. Furthermore, there are programs that engage in U-Mo monolithic fuel with density as high as 16 g/cm3 (Lemoine/Wachs 2007). Up to the time of writing this report, no fuel was available for certification.

Should the development be successful, it will be possible to convert the remaining research reactors. The expectation is that all existing research reactors will either be converted or reach the end of their lifetime. New reactors are expected to be designed and constructed for LEU fuels. This means the civilian use, trade and international transfer of HEU could be entirely phased out.

3.1.3 The case of the research reactor FRM-II in Garching as an example of decision-making procedures regarding technical matters with a political impact

After INFCE, an informal moratorium for new research reactors that use HEU fuel prevailed for two decades. Seventeen new research reactors worldwide were built using LEU fuels.[19] Germany was also committed to the goal of phasing out HEU use and invested substantial sums and research effort in the above-mentioned AF Program. In 1984, the

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[19] NTI, Past and Current Efforts to Reduce Civilian HEU Use, Version of 15 November 2012, www.nti.org/db/heu/pastpresent.html (20.3.2014).

government stated in parliament that "new research and test reactors will be planned with low-enriched fuel from the outset."[20]

But at about the same time, design and planning for a new research reactor started that would become the only project worldwide, until today, which ever breached the moratorium. It was the 20 MW FRM-II in Garching near Munich (Forschungsreaktor München), the construction of which began in 1996 and which has been in operation since 2003. At the same time, RERTR had triggered intensive R&D on the new uranium silicide fuel. And the FRM-II uses only this new dense silicide fuel, but instead of the intended 20 percent LEU, it continued to use 93 percent HEU. This means the reactor achieves a neutron flux per power density higher than would have been possible either with the traditional dioxide fuel or with LEU silicide fuel. But, at the same time, the designers thwarted the intention of the RERTR research efforts, including progress made in Germany. The following figure by Alexander Glaser illustrates the U-235 and U-238 components of different research reactor fuels including the FRM-II fuel (Figure 3). Figure 3 shows that the only fuel viable for LEU conversion of the FRM-II with about the same U-235 density without loss of neutron flux would be the new metallic monolithic fuel still in development.[21] It would be necessary that U-Mo in aluminium fuel becomes available earlier and the operator plans to use it with 50 percent enrichment.

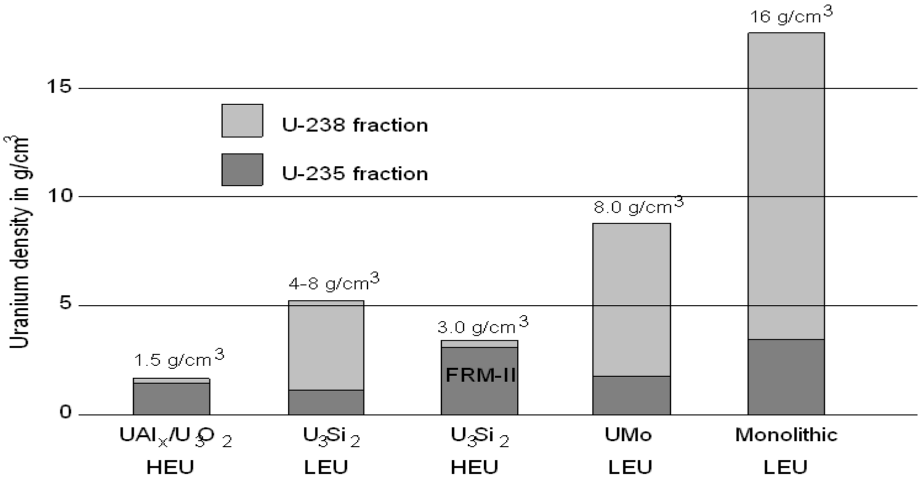

Figure 3: Comparison of research reactor fuels. The FRM-II is the only reactor that uses uranium silicide fuel with HEU. For its conversion, only the monolithic fuel still being developed could be used. Source: Glaser 2005.

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[20] "Bei neuen Forschungs- und Testreaktoren werden die niedriger angereicherten Brennstoffe von vornherein vorgesehen.": Antwort der Bundesregierung auf die Große Anfrage der SPD-Fraktion betreffend die Nichtverbreitung von Kernwaffen (BT Drs. 10/1269), 19 November 1984, answer to question No. 19.

[21] HEU with 50 percent enrichment is somewhat less unlikely to be used for a nuclear weapon without further enrichment, as can be seen from Figure 1. A few hundred kilograms would probably be needed for a simple device. Nevertheless such use cannot be ruled out. Furthermore, there is a consensus to adapt to the official IAEA definition of LEU and HEU.

The FRM-II poses a problem for the minimization of civilian HEU worldwide for several reasons: Firstly, it is the first newly constructed research reactor to use HEU after a moratorium of many years. Secondly, this reactor may serve as justification for future similar projects in other countries, perhaps among them some with less positive non-proliferation credentials than Germany. Thirdly, due to its use of HEU in higher density fuel, it is technically one of the most difficult reactors to convert to LEU. Fourthly, international trade with HEU has become more likely to rise again, entailing more risk of diversion. And finally, it has damaged Germany's credibility when calling upon other states to end civilian use of HEU.

A major justification for the policy decision at FRM-II was the claim that only with HEU would the neutron source be the "best," and "world leading". However, the neutron flux of the FRM-II is less than that of several other high-flux reactors. Instead, the "best" in this case means the highest neutron flux per power ratio. The benefit of this is a somewhat lower signal-to-noise ratio and thus reduced cooling in experiments with cold neutrons, one of the applications of the reactor. Even with 20 percent LEU, more cooling or longer measuring times would be necessary, an effect which many analysts deem tolerable in comparison with the political damage.

The use of HEU instead of LEU was heavily criticized by the international community and by national and international observers. Nevertheless, the decision was taken. Both technical and political arguments were put forward in the debate. Details of the discussion can be found in Appendix II.

The licenses for the reactor addressed nuclear activation, environmental dangers, accident risks, radiation protection and disposal on hundreds of pages. But the documents do not mention the international non-proliferation implications of the reactor. Had the concept of proliferation resistance been taken seriously, the implications would have played a much more prominent role from the early stages of decision making. Converting FRM-II to at least lower enriched HEU as soon as the new monolithic fuels are available is planned. The availability of the fuel is delayed due to material problems caused by high energy density during operation that still need to be solved. If all physicists and reactor designers knew they could rely on their peers elsewhere to comply with international norms, they would not need to fear unfair competition from others and will stop lobbying for an HEU concept. Meanwhile, the phase-out of civilian HEU use is a declared and uncontested interest of the German government. The norm against new HEU-fuelled research reactors still seems to be strong. Except if a project similar to the FRM-II were to materialize, the older reactors that still use HEU will reach the end of their useful life and use of HEU for this purpose can be discontinued.

The FRM-II decision-making process teaches several lessons: Firstly, there will never be a purely *technical* solution to the problem of the attractiveness of HEU. Only additional political measures will reduce the likelihood of this happening again, e.g. international treaties or contracts, consensus, and an "HEU non-proliferation regime" with compliant members. It is necessary for the norm against any use of HEU to be strengthened. Secondly, and on the other hand, political will does not have much of a chance without technical and scientific efforts, in this case the successes of RERTR. Thirdly, proliferation resistance should be a criterion in the decision making in any future project, as opposed to the case of FRM-II whose licenses completely disregard this aspect. Fourthly, the more transparent the political and licensing procedures are and the more accessible and honestly explained the information, the sooner an informed debate will be possible, and the less likely it will be that lobbyists and propaganda can mislead the public, politicians and decision makers. Fifthly, the debates – although largely uninformed – had the side effect of strengthening the norm against future HEU use in Germany. It has become highly unlikely that a similar case will happen again.

3.1.4 Critical assemblies and pulsed reactors

A variant of research reactors are so-called *critical assemblies* and *pulsed reactors* (von Hippel 2004/von Hippel 2005). They are very low-power research reactors with lifetime cores, some of which are fuelled with HEU. Only a small fraction of the HEU is fissioned during the lifetime of the reactors. Because of the low fission rate, the fuel is only moderately contaminated and has a low radiation barrier that would effectively discourage loss through theft. There are more than 50 HEU-fuelled critical assemblies worldwide, often with an inventory sufficient for a nuclear explosive. Their purpose is the simulation of other reactors, including naval reactors, some of them with an inventory of 100 kg or more. Conversion efforts have also been applied to them. Some are used to calibrate new neutronics codes, and a conversion seems to be difficult. Von Hippel suggests decommissioning most plants and consolidating all other critical assemblies. Some simulation tasks can be replaced by computers. Pulsed reactors are mainly used for military purposes to simulate a nuclear explosion in the vicinity of military equipment. There are already feasibility studies on conversion being carried out.[22]

3.2 Medical isotope production

Another common civilian application of HEU is as a target for the production of isotopes for medical diagnostics (IAEA 2010). This procedure involves a patient being injected with a radioactive isotope whose radiation produces an image of the body. Such an image, a so-called scintigraphic cancer test, can be very useful for the detection of certain forms of tumours. But any isotope used for this purpose must decay quickly in order to allow the radioactivity in the human body to disappear quickly after the diagnostic image has been taken. This means that the isotope cannot be stored for a long time and must be produced shortly before the injection. Furthermore, the decay product has to be essentially non-radioactive as otherwise the patient would carry around radioactivity for a long time. The most useful isotope that fulfils these conditions is technetium-99m (Tc-99m). It decays quickly with a half-life of six hours, leaving enough time for diagnostics. Its radiation (gammas of 140 keV) is ideal for imaging the human body and results in a virtually non-

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[22] A group at one of Russia's nuclear-weapon laboratories, the Institute of Experimental Physics in Sarov has proposed doing a feasibility study on the conversion of its BIGR pulsed reactor. The core of BIGR contains 833 kg of 90-percent-enriched uranium: von Hippel 2005.

radioactive product.[23] About 70 percent of all scintigraphic cancer tests are performed with technetium-99m (Tc-99m).

But how can a sample of Tc-99m be produced so rapidly and provided to a hospital very shortly before its use? The answer is to deliver its parent isotope, which decays at the hospital and let the hospital extract the freshly produced decay product. Tc-99m is a decay product of molybdenum-99 (Mo-99) which has a half-life of about 66 hours – enough time for the production and shipping of freshly produced Mo-99 to a hospital that has ordered it. The Mo-99 is delivered in a solution from which the hospital can extract Tc-99m on its own using a simple chemical method. For about a week, it can carry out a number of diagnostic procedures until the Tc-99m production in the solution is no longer high enough. Mo-99 cannot be stored and must always be freshly produced.

Mo-99 in turn is produced by fissioning U-235, more precisely by irradiating a target containing U-235 with neutrons. This usually takes place in a research reactor providing such neutrons and the target usually consists of HEU. Upon receiving an order from a hospital, a reactor operator irradiates an HEU target, extracts the Mo-99 and sends it to the customer.

The mass of such a target is in the range of only 100 g. Nevertheless, access to a sufficient number of targets might also pose a proliferation danger. An Mo-99 producer usually needs several kg of HEU annually.

Today, five research reactors cover most of the demand. In all of them, HEU targets are used and irradiated with a flux above 10^{14} $cm^{-2}s^{-1}$ for about a week, after which the Mo-99 is extracted. The remaining target still contains about 98 percent of its U-235. The worldwide annual consumption of HEU is about 40–50 kg. The demand for Mo-99–Tc-99m generators is high and increasing, with 70,000 diagnoses made each day worldwide.[24] Since the last quarter of 2007, the supply has been disrupted by shutdowns of the production reactors due to their age and other circumstances. A shortage is therefore being anticipated and new producers will enter the market. Several meetings have taken place and several working groups established involving the IAEA and several other international organizations, national governments and EU institutions to deal with the problem of a potential shortage in supply.[25] There is little market incentive to create additional production capacity.

The use of HEU targets has led to concern over proliferation similar to the use of HEU research reactor fuel. Currently, over 95 percent of the Mo-99 is produced with HEU

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[23] Tc-99m is an isomer, which is a nucleus containing more energy than the corresponding non-excited nucleus Tc-99. Tc-99m decays by emitting a gamma with a half-life of 6 hours: Tc-99m → Tc-99 (t1/2 = 6 h). The decay product has a half-life of 2.1 · 105 a (β-decay), which is practically non-radioactive.

[24] Klaus Konschak, Proliferationsrisiken in der Medizintechnik (proliferation risks in medical technology), presentation at the 5th Symposium on Nuclear and Radiological Weapons, Fraunhofer Institute INT, Euskirchen, 20-22 September 2011.

[25] Listed in IAEA 2010.

targets, but only 5 percent of its U-235 content is consumed. In 2008/2009, annual consumption was 50 kg HEU.[26]

Some states and producers are studying how to convert HEU targets for Mo-99 production to LEU targets, and how to create new capacities in order to avoid bottlenecks in supply. The U.S. National Academy of Sciences has concluded that, in principle, LEU targets for large scale production of Mo-99 could be used in reactors (NAS 2009). However, conversion of existing production equipment and processes requires substantial effort, is expensive and is time consuming. But the new production facilities which will be necessary in the future could be designed with different features. The report by the NAS is expected to have a significant effect on strategies for producing Mo-99 in the future (IAEA 2010). According to the NAS study, the cost increase would not exceed 10 percent. The recent shortage shows that higher prices are accepted. The U.S. is actively promoting projects that phase out the use of HEU targets.[27] The U.S. Sandia National Laboratory proposes a new production concept by an LEU-fuelled research reactor using LEU targets.[28] Several countries have announced studies to facilitate the development of high-density LEU target material to make conversion more economical (Loukianova 2012).

While the norm of avoiding HEU reactor cores has become comparatively strong, attempts to convert HEU targets for Mo-99 production are very new, and the concerns about how to secure new supplies at all are considered more urgent.[29] Targets without HEU in current use produce less Mo-99. New, denser LEU targets are under development, but it will be some years before they are available. New producers using HEU may enter the market which will place those engaging in conversion at a competitive disadvantage. The operators of the FRM-II are undertaking studies for future production of Mo- 66 generators by irradiating HEU targets.[30]

There is no consensus yet on the need for conversion, but calls for coordination and harmonization of efforts are intensifying. The need for new supply strategies also offers a chance to take into account proliferation concerns. It is likely that Mo-66 generators will become somewhat more expensive as a result of the use of LEU targets. The major obstacle to success would therefore be competition by suppliers who did not cooperate and thus undermined consensus. Much like the case of research reactors, international commitment is necessary in order to avoid unfair competition.

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[26] Presentation by Daniel Iracane at the International Symposium of HEU Minimization, Vienna, 23-25 January 2012.

[27] The White House, Fact Sheet: Encouraging Reliable Supplies of Molybdenum-99 Produced without Highly Enriched Uranium, 7 June 2012; On U.S. efforts see Loukianova 2012.

[28] Ed Parma, The Supply of the Medical Radioisotope Tc-99m/Mo-99, Presentation to the American Nuclear Society, 6 November 2009, SAND2009-6898P.

[29] The EU Council addresses concerns about shortages and insufficient market incentives, but does not mention the proliferation concern and possible conversion of HEU targets: Council of the European Union, Council Conclusions on "Towards the Secure Supply of Radioisotopes for Medical Use in the European Union", 3053rd Employment, Social Policy Health and Consumer Affairs Council meeting, Brussels, 6 December 2010.

[30] Technical University Munich, Cancer diagnosis isotopes from Garching, Press Release 27 June 2011.

3.3 Naval fuel and reactors

Many governments, analysts and observers favour the phase-out of civilian HEU use. The U.S. Government actively promotes this goal, as the following quotation illustrates[31]:

The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes.

This leaves just one use of HEU other than for nuclear weapons and civilian purposes, namely as fuel for military naval reactors. Today it is used in submarines, aircraft carriers and non-military icebreakers.[32] The reason for the use of nuclear reactors in military submarines is their silence, which is deemed necessary for reasons of strategy. Furthermore, a nuclear reactor does not need oxygen, so a submarine can stay underwater for a long time without surfacing, while continuing to produce energy.

The nuclear submarines of the U.S. and the UK are propelled by nuclear reactors fuelled with the best nuclear weapon-usable material, HEU enriched to 93-97 percent or more. Russian naval reactors are reported to use various degrees of enrichment ranging from 20 percent to over 90 percent, and the U-235 content is estimated to be between 47 and 190 t. With only few exceptions, most of them use 21-45 percent.[33] One exception to this is the civilian Russian icebreakers that use up to 90 percent enriched HEU (Sokova 2008; Reistad/Povl L. Ølgaard 2006). LEU fuel is planned for use in next generation icebreakers.[34] Britain purchases HEU for its naval reactors from the U.S., the total is estimated to be 5-7 t of weapon-grade HEU (Albright et al. 1997: 118). France's submarines use LEU fuel with an estimated average enrichment of 7 percent (Albright et al. 1997: 125). China is believed to use only 5 percent LEU fuel for its submarines (Gronlund et al. 1995; Zhang 2011). India has a nuclear-powered submarine whose reactor went critical in August 2013, and uses HEU with an enrichment of 40 percent.[35] It can be seen that the enrichment of naval reactor fuel varies, as was the case for the enrichment of civilian research reactor fuel.

The International Panel on Fissile Materials (IPFM) estimates that approximately 382.5 tons of HEU are destined for use by the world's nuclear naval vessels, of which 228 tons are fresh fuel, as illustrated in table 1.[36]

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[31] The White House, Fact Sheet: Encouraging Reliable Supplies of Molybdenum-99 Produced without Highly Enriched Uranium, 7 June 2012.

[32] For detailed lists of ships and submarines, their reactors, enrichments, and background information see WNA on Nuclear Powered Ships and Ma and von Hippel 2001, notably tables 1 and 2.

[33] Bukharin 1996, WNA on Nuclear Powered Ships.

[34] WNA on Nuclear Powered Ships.

[35] WNA on Nuclear Powered Ships.

[36] International Panel on Fissile Materials, Global Fissile Material Report 2009: 13, www.fissilematerials.org (20.3.2014).

3.3.1 The NPT loophole

Naval fuel poses a loophole in the NPT which permits non-nuclear weapon states to withdraw fissile material from IAEA safeguards for non-explosive military purposes such as naval propulsion.[37] This applies to both LEU and HEU. In INFCIRC/153 (§14b), it is foreseen that verification of fuel in a "non-proscribed military activity" is renounced as long as the nuclear material is used in such an activity.[38] The IAEA and the state are required to make an arrangement that identifies "to the extent possible, the period or circumstances during which safeguards will not be applied".

Up to now, there had never been such an arrangement in history, although several non-nuclear weapon states are seeking to or have attempted to introduce military naval reactors. During the late 1980s, Canada was interested in buying British submarines and making use of the NPT loophole to interrupt IAEA safeguards on its military fuel. This was severely criticized by analysts who warned that IAEA safeguards would be compromised and that Canada would set a negative precedent for imitators (Rauf/Desjadins 1988). The plan was abandoned because of high costs and declining public support due to the end of the Cold War. Up to today, voices occasionally call for Canadian military nuclear submarines.[39] There are also those in favour of leasing U.S. nuclear-powered submarines for Australia (Cowan 2012) They also recommend taking advantage of the NPT loophole and leaving a similar loophole in the FM(C)T. Brazil also plans to build a nuclear-powered submarine based on French technology.[40] Contracts with a French designer were signed in 2009. Although French-designed nuclear submarine propellants use LEU, the safeguard problem would remain, since military LEU should also be subject to IAEA safeguards because it could be used for further enrichment in breakout scenarios. In 2012, Iran announced it plans to build nuclear-powered submarines.[41] Although doubts may be raised whether Iran is able to master this advanced technology, the plan may be a pretext to enrich uranium up to 90 percent and use the absence of safeguards in order to misuse the fuel for nuclear weapons. In sum, the problem is twofold: Firstly, there is the loophole in the NPT that allows exemption from safeguards, which is a problem even in the case of LEU. Secondly, this is even more critical when HEU is used for submarines because the time span for achieving breakout is very small.

So far, there is no experience related to verifying naval HEU is not misused for building nuclear weapon. There is no clearly defined procedure concerning the conditions under which IAEA safeguards of the fuel can be interrupted. The interruption could be limited only to fuel in the reactor, or it could also be applied to other facilities. Facilities and

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[37] On the history of the loophole see Moltz 1998.

[38] INFCIRC/153 is the model for agreements between the IAEA and non-nuclear weapon states which regulates the safeguards.

[39] Philip Ewing, Nuclear submarines for Canada? DoD&Buzz Online Defense and Acquisition Journal, 28 October 2011, www.dodbuzz.com/2011/10/28/nuclear-submarines-for-canada/ (20.3.2014).

[40] NTI, Brazil Submarine Import and Export Behaviour, 18 July 2013, online-publication: www.nti.org/analysis/articles/brazil-submarine-import-and-export-behavior/ (20.3.2014).

[41] Iran plans nuclear-powered submarine: report, Reuters, 12 June 2012.

locations involved are the enrichment plants, fuel fabrication plants, transports, storage and the reactors themselves. Even if the interruption is limited only to fuel in the reactor, it could last for decades. It is clear that an interruption of safeguards would offer an opportunity to clandestinely misuse the HEU for nuclear weapons. It is also clear that the majority of states would not want such a scenario. In this respect, the situation is far worse regarding naval reactors than it is with research reactors, whose fuel is at least subject to IAEA safeguards in NNWS.

Similarly to the NPT, an FM(C)T would have a loophole if production for naval fuel were not banned.

As Table 1 shows, enormous amounts of HEU are reserved for use as naval fuel, and much of the HEU excess for defence needs is also reserved for the same purpose. These large amounts are sufficient for many reactors and for many decades to come. It is therefore astonishing that the U.S. wants to reserve the right to produce even more HEU for naval reactors, as has become evident in numerous discussions on the scope of a future FM(C)T, where the U.S. is categorically opposed to a ban on the production of naval fuel. The U.S. position is particularly incomprehensible in view of its many projects and policy initiatives in favour of the elimination of HEU. Britain falls in line with the U.S. position because its naval fuel is supplied by the U.S., and its naval reactors are of the same type. It is unknown what other states would also insist on HEU production in the future. Those that use HEU with an enrichment of only 40-50 percent could anticipating having fewer problems in the future by conversion to 20 percent. Like many other states, these states would, however, oppose a scenario in which non-nuclear weapon states exempt fuel from safeguards because of military needs other than nuclear weapons. Such a scenario is much more worrisome than civilian enrichment in countries of concern, although subject to safeguards. The FM(C)T would have the potential to close the NPT loophole by banning the unverified production of HEU. The NWS that need HEU for their nuclear reactors could use up the abundant HEU that already exists. During the time until this HEU is used up, in other words for decades, they could develop new naval reactors using advanced dense LEU fuel. Foregoing this unique chance in history is incomprehensible. Those NWS that plan to produce HEU in future for naval reactors are adopting a stance that worsens the discrimination inherent in the current NPT regime yet further, because they want to reserve rights for themselves that they would never grant to NNWS. The FM(C)T has the potential to grant the same rights and duties to all members, be they NWS or NNWS. Giving an extra right for only some members would again introduce a discrimination having a damaging effect on the non-proliferation regime. This poses the question why naval reactors are not converted to LEU fuel like the civilian research reactors. This will be discussed in the following sections.

3.3.2 Differences between military naval and civilian research reactors

The reason for the use of HEU is that it makes possible especially small and long-lasting reactor cores. The U.S. naval reactors are pressurized water reactors with a primary and a secondary circuit.[42] The core life is very long, so that refuelling is rare. Some reactors do not need any refuelling, and the core remains in the reactor for decades. Refuelling is a considerable and time-consuming undertaking, and reactor designers have striven to minimize its frequency.[43] The technical requirements for safety and reliability are extreme. Neutrons and radioactivity are unwanted side effects. Radiation levels outside the reactor must be extremely low because of the sailors living next to it. Quality control is expensive, and thus few companies engage in the production of naval reactors. The shielding is heavy and adds weight, which is another reason for minimizing the space taken up by the reactor core. Thermal power ranges up to about 500 MW, but many have only a tenth of this power or less.

Naval reactors differ from ordinary power reactors in several ways: Their rated power is far lower, the reactor core more compact, and refuelling takes place only rarely. Furthermore, the fuel must withstand mechanical stress and must contribute to structural strength. The reactor must also be able to modify its power output quickly in order to allow rapid manoeuvring. A rapid restart after a previous shutdown requires considerable reactivity. In an ordinary power reactor these requirements are far less stringent. Naval and power reactors have in common that their applications make use of the energy but not of the neutrons, in contrast to many research reactors that are tools for providing neutrons but whose energy is only a by-product.

Naval and research reactors both have cores that are kept small with resultant high power density, and comparable thermal power. They also share a need to have the U-235 density as high as possible. The difference between naval and research reactors is refuelling frequency. While refuelling of a research reactor is a routine matter which makes use of permanently installed equipment, it is a major interruption in the operation of a submarine. Therefore, submarine reactor fuel must tolerate a high burn-up and high radioactive inventory. While research reactors vary greatly in design because of many different applications and underlying scientific objectives, naval reactors are manufactured by only a few companies without much competition. Nevertheless, various designs have been explored in the past (U. S. Naval Office 1995; Eriksen 1990). In light water reactors such as U.S. and British naval reactors, changing the power level can be accomplished by inserting or removing control rods or by changing the water steam temperature. Water-steam temperature is modified by closing or opening throttles. Not many sources are available on technical details. An exception is a publication by Ward in which she cites an interview with a U.S. Naval Institute representative (Ward 2012: 184f): He claims that in light water reactors with LEU fuel, power changes without control rods would not be possible, while in those with HEU fuel it is, and that is what the U.S. Navy prefers because it allows more

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[42] Ragheb 2011; WNA on Nuclear-Powered Ships.

[43] A steady reactivity during the long core life time is achieved by adding the neutron posion gadolinium that initially reduces the reactivity and is progressively consumed during the life time of the reactor (WNA on Nuclear-Powered Ships).

rapid power changes and manoeuvring. The explanation is complex and will not be further elaborated here.[44]

The U.S. Navy prefers not to use control rods, in contrast to France that has successfully converted its naval reactors from HEU to LEU fuel (Ward 2012). The Russian, U.S. and British navies rely on steam turbine propulsion, and the French and Chinese submarines use a turbine to generate electricity for propulsion.[45] The question must be asked why it is acceptable for France to use control rods to generate power for propulsion, but not for the U.S. and Britain.

The requirements for naval reactors, namely a compact and long-lasting core, high power density, optimum reliability and safety and the possibility of rapid power changes, have not changed for a long time. In contrast to research reactors and civilian power reactors and their fuels, there is no international and large scientific community engaged in the subject of naval fuels and reactors.

Thus, there is one more difference between research and naval reactors: While many educated discussions take place in academic and diplomatic fora regarding the conversion of civilian research reactors, the transparency and security of civilian HEU and the disarmament of military HEU, there is far less discussion about naval reactors, and such discussion remains only superficial. The reason is the classified status owners give to technical aspects of their submarines and naval fuel (U.S. DoE 2006). The information known about the details of naval reactor fuel is much less specific than the information about civilian research reactors, whose conversion is studied and discussed in great detail by many scholars in and outside governments as described in the preceding section. As a result, discussion of the conversion of naval reactors must remain vague and speculative. It may be assumed that the small community of naval reactor designers overlaps with the much larger community of research reactor designers, and therefore, the fuel conversion efforts should be familiar to them. A study like Glaser's dissertation on the FRM-II reactor was possible because details of technical information were available (Glaser 2005). A similar study on naval reactors is overdue but the details required for such a study are secret.

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[44] A qualitative description of the background physics can be found in Ward 2012, pp. 184-186.

[45] WNA on Nuclear-Powered Ships.

The following table (table 2) summarizes the differences between research and naval reactors with regard to conversion:

Property	**Research Reactors**	**Naval reactors**
Power density	High, comparable	
Power	Comparable	
Size of reactor core	Small, comparable	
Product desired	Neutrons	Power
Refuelling frequency	High	Low
Burn-up	Less	Very high
Variety of designs	Many	Few
Scientific community engagement	Large	Small
Transparency	High	Non-existent
Cladding and stabilizing fuel elements	Being researched	Unknown
Chemical composition of uranium fuel	Several	U-zirconium or U-Al alloy[46]
Conversion studies with RERTR results	Yes	No

Table 2: Comparison of research and naval reactors.

3.3.3 *Prospects of conversion of naval reactors from HEU to LEU fuel*

As is true for research reactors, the conversion of naval reactors from HEU to LEU is desirable. There are several benefits: The only remaining application of HEU would be nuclear weapons, and the complete phase-out of *any* HEU production could become an international policy goal. It would facilitate the verification of an FM(C)T, close a loophole in NPT verification, and also reduce proliferation risks. In Russia, six known thefts of naval HEU fuel took place between 1993 and 1996 (Maerli 2002). The quantities of HEU reserved for naval use constitute a huge rearmament potential. The stocks that exist today are sufficient for many decades to come (see table 1).

The U.S. is in the process of replacing its current Ohio class submarines.[47] Apparently, several new technical features are planned, including greater silence by minimizing mechanical moving parts, and new reactors with lifetime cores that require no refuelling for 50 years. However, it is not known whether the new reactors will take advantage of advanced fuel developments. As always, representatives of the U.S. Navy or the U.S. government categorically reject calls to consider abolishing all HEU use.

In order to investigate the prospects of naval reactor conversion, the requirements described in the preceding section should be taken into account. In 1995 the U.S. Navy published a report on the question of whether U.S. naval reactors should be converted from HEU to LEU fuel.[48] In this report, the Navy rejected the idea. But all arguments it raises against conversion in its report may be reduced to the reasoning that an LEU reactor core

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[46] WNA on Nuclear-Powered Ships: It is unclear where the information comes from. Ragheb 2011 asserts that uranium nitride is used (p. 13), but experience on that is still very limited (IAEA 2003: 5).

[47] Sam Lagrone, Secret Nuclear Redesign Will Keep U.S. Subs Running Silently for 50 Years, 17 January 2013, www.wired.com/dangerroom/2013/01/secret-sub-design/ (20.3.2014).

[48] U. S. Naval Office, 1995. This report has been requested on the occasion of the idea of an FMCT that would ban the production of nuclear materials for nuclear explosives.

would either need much more volume or contain far less U-235, which would reduce useful life of the core. The report does not consider the idea that a higher U-235 content may be achieved by another chemical fuel composition. In other words, it completely ignores the RERTR efforts for higher density fuels that would make this reasoning obsolete. On the other hand, it is unclear whether the U.S. studied how to apply RERTR results to naval reactor core conversion since then, or how to design a new naval reactor with high density LEU fuel.[49]

It may be argued that naval fuel is different, so that the RERTR results do not apply. In order to discuss this, a distinction must be made between the fuel material and the so-called *cladding* in which the reactor fuel is embedded. It is corrosion-resistant material with low neutron absorption. Technical details of cladding and stabilizing materials in naval reactor cores are unknown. It is quite possible that they are different in comparison to research reactors, given the high mechanical stress resistance requirement. But what is decisive for reactor conversion is less the cladding and more the composition of the fuel "meat" itself. Some sources state that the fuel "meat" is made from metal alloys.[50] But the author of this report believes that the fuel consists of uranium oxide. There are two indicators for the latter assumption: Firstly, the cores in the more modern ships are designed using technology dating from the late 1970s (U. S. Navy 1995: 9). At that time, the new silicide fuels were not yet available, and all research reactors used uranium oxides, including high flux reactors. It is extremely unlikely that a new fuel composition had already been developed and qualified to meet the high reliability, safety and material stress requirements without any spin-off into the field of civilian research reactor fuel. A second clear indicator is the fact that the report does not consider any other chemical compound. If the reactors already use some new fuel, it would be very unlikely that the report would not address this topic.[51]

Thus, under the assumption that the core meat is uranium dioxide, which is not very dense, there seems to be potential for conversion because, in the interim, other higher density fuels have been developed within the RERTR program. Nevertheless, it would take many years to study the new LEU fuels together with the special naval fuel-stabilizing ingredients. However the lifetime of cores currently in use also extends many years into the future, and this time could be used to design new concepts for a future generation of naval reactors with converted cores.

Ma and von Hippel have challenged the Navy report with more arguments (Ma/von Hippel 2001): The report claims in one case that the addition of about two tons of U-238 to

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[49] In 2008, the Senate Armed Services Committee demanded: "The committee directs the Office of Naval Reactors to review carefully options for using low enriched uranium fuel in new or modified reactor plants for surface ships and submarines." Committee on Armed Services, United States Senate, National Defense Authorization Act for Fiscal Year 2009, p. 515, 12 May.

[50] An example is: WNA on Nuclear-Powered Ships. This and all sources citing uranium alloys as fuel "meat" can apparently be traced to a publication by Norwegian authors: Maerli et al. 1998. They, however, analyse Russian but not U.S. naval reactors and do not give any source regarding U.S. naval reactors.

[51] A third indicator for U oxide is noted in the report (p. 30): "Material is delivered from DoE as either UF6, oxide, or metal." Oxide does not occur as intermediate product in the production of U silicide.

dilute the U-235 would increase the weight of the submarine by 1,000 tons. Ma and von Hippel counter that this is mainly due to the geometry of the strong shielding of the reactor, and a different reactor design could result in a far smaller weight increase. They cite a French naval reactor design that is superior in this respect and also a nuclear engineering thesis that proposes 20 percent LEU fuel for naval reactors similar to a special French fuel satisfying the special naval reactor requirements (Ippolito 1990). The thesis concludes that by using this fuel, the core volume increase would be far less than claimed by the Navy report. The trick would be to change the arrangement and mix of uranium oxide and stabilizing materials. The 20 percent enriched core could be designed to have the same lifetime as a 97.3 percent enriched core. The thesis is from 1990, and in the meantime, many new results have been achieved in R&D of new research reactor fuels. In sum, the Navy study is not the last word on the conversion of naval reactors from HEU to LEU fuel.

Most of Russia's nuclear submarines are fuelled with HEU, but enriched to only about 45 percent. This is different with Russian civilian icebreaker reactors, most of which are fuelled with HEU of 90 percent enrichment and more.[52] An expert group has studied what is known about icebreaker reactor design information and concluded that the reactors could be fuelled with LEU without reducing core life (Diakov et al. 2006). The authors assume that military naval reactors have similar designs and it could be possible to transfer their conclusions. The question arises why Russian military submarines are not fuelled with HEU of 90 percent enrichment like the icebreakers. A speculative answer by Reistad and Ølgaard is “the inherent inertia in the Russian military-industrial complex and the absence of financial constraints in military spending until fairly recently” (Reistad/Ølgaard 2006). Should the elimination of HEU use in naval reactors become a global policy goal, Russia could use new modern LEU fuel for the modernization of its naval reactors. Indeed, Russia plans a new modern icebreaker (RHTYM-200) that will be powered by an LEU-fuelled nuclear reactor (Hinderstein et al. 2012).

This leaves mainly the U.S. and the UK as the only states that still seem to need future HEU production for naval fuel.

Naval reactors run for many decades without refuelling, but one day they will be decommissioned. Until then, and even beyond that date, abundant quantities of HEU from disarmament are available, namely from the category “excess but not declared so.” Therefore, any necessity to produce fresh HEU for naval reactors will arise only many decades into the future. It may be expected that until then, new naval reactors will be designed that make use of the new fuels, and in this way allow the use of LEU instead of HEU. Thus, a universal ban on HEU production becomes a more realistic prospect.

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[52] Information on Russian naval reactors is incomplete and partly contradicting. Diakov et al. (2006) note that in contrast to other sources, the Norwegian Bellona Foundation cites an enrichment of Russian icebreaker reactors of only 30-40%.

4. Decision Making, Secrecy, and Democracy

Only a small minority of states has an interest in future production of HEU for naval reactors, although if there were good will, solutions other than HEU could be found. But hardly any protests are visible. Many states, especially those in the Western Group, including the Federal Republic of Germany, do not dare to actively promote a position against the declared interest of the U.S. Some – in a spirit of anticipatory obedience – even seem to fatalistically adopt the position of excluding naval fuel production from the ban.

But a ban on the production of naval fuel is crucial to total abolition of HEU. Otherwise, further discrimination, in addition to the discrimination already inherent in the NP regime, would be implemented and impede the global goodwill to set up a taboo against any future HEU production. It would also affect the campaigns for converting civilian research reactors and targets for medical isotope production. The fatalism of not protesting against such discrimination would demotivate any effort and accept the various disadvantages that might entail.

It may be wondered to what extent the topic of making use of LEU fuel in new naval reactors has been discussed within the naval communities of the U.S., the UK and elsewhere, and whether it has been seriously considered at all. Hardly any information is known about discussion participants, arguments, interests or lobbyists, and even less about the details of technical reasoning – all of this apparently secret. In its early phases, discussion on the FRM-II also suffered from a lack of transparency, and thus decision making could be dominated by a small group, which was largely a coalition of the physicists with their lobby and Bavarian governmental decision makers who later managed to find supporters in the Federal government. This early "secrecy" may largely be explained by the failure of the public to become interested and to ask the right questions. Too little public education had taken place in the early phase. Later, when the case became better known, more and more journalists and domestic and international experts became involved. Although many discussions remained uninformed, a great deal of misleading propaganda occurred on various sides of the discussions, and many kinds of lobbying mechanisms were used, it was at least possible to lay the arguments on the table, even though the public discussions were too late. If the discussion had started earlier, better informed decision making would have been possible earlier. And if decision making had been more transparent, it may have evolved differently. But, as an example, it was possible for Glaser, a new expert coming from the outside, to study the technical details and to produce a Ph.D. thesis that analysed the technical arguments in detail (Glaser 2005). Today, it is possible to have a fairly clear picture of the technical arguments.

And today, it is quite clear that the main argument, that only with HEU would the FRM-II be "world champion", was greatly exaggerated. What proponents called "world championship" just meant a somewhat better signal-to-noise ratio in comparison to other research reactors. The advantage is more convenience in measurements. Decision making had to choose between two different benefits, the "championship" on the one hand, and the strengthening of a non-proliferation norm, namely the norm that civilian HEU use should be phased out, on the other. But it suffered from an information deficit. It perceived somewhat greater convenience in measuring as a grandiose championship, and believed it was worth spoiling the growing norm.

In political decision making on technical aspects, often "apples" must be compared with "pears," which is a subjective undertaking. Therefore, it must be clear what is apple and what pear. In a democracy, such comparison must be possible not only for decision makers but also for journalists and experts from the outside. They must be provided the necessary information at an earlier time in order to understand the nature of the problem and the upcoming decisions.

The case of the U.S. and UK naval fuel is much worse. The public has no chance to develop an educated opinion, because almost everything related to naval HEU and naval reactors is secret. The reason in the U.S. is mainly the desire to keep a competitive advantage (U.S. DoE 1995). The few arguments against conversion to LEU that are known were described in the preceding section. Some of them, namely those raised in the report by the U.S. Naval Office in 1995, are apparently outdated and can probably be rejected, as discussed in the section above (U. S. Naval Office 1995). But even the above reasoning is speculative, although plausible. For serious reasoning, more information about the fuel would be necessary.

There is an argument in favour of HEU for U.S. naval reactors that sounds more serious, namely the claim mentioned above that fast manoeuvring and rapid power changes are only possible without control rods, which in turn requires HEU fuel. This argument is an "apple" that must be compared with the "pear," which is the goal of phasing out all HEU use. First, the "apple" must be studied in detail: Is this advantage really as huge as its proponents claim? Are there really no alternatives? Does the use of control rods really make such a difference? But the details are secret. Even the reason why they are secret is secret. So decision making is left to a few insiders and lobbyists. It is even unclear who in this decision making is the advocate in favour of the "pear," i.e., HEU phase-out, and whether there is one at all. Those who make this case can easily be dismissed as being too ignorant to have a say.

The miserliness of many bureaucracies with regard to information release is often observed and cannot be explained with rational reasons of national security alone. Bureaucracies also use secrecy as a tool to avoid investigations from the outside and uncomfortable criticism, to limit the number of participants in decision making and thereby to strengthen their power and minimize interference from the public and other decision makers. This applies not only to matters of nuclear weapons and security but to all kinds of political subjects. A hundred years ago, the sociologist Max Weber wrote:[53]Any

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[53] Max Weber „Wirtschaft und Gesellschaft": Part 4, p. 38, Herrschaft, first published 1922. In German: "Diese Überlegenheit des berufsmäßig Wissenden sucht jede Bürokratie noch durch das Mittel der Geheimhaltung ihrer Kentnisse und Absichten zu steigern. Bürokratische Verwaltung ist ihrer Tendenz nach stets Verwaltung mit Ausschluß der Öffentlichkeit. Die Bürokratie verbirgt ihr Wissen und Tun vor der Kritik soweit sie irgend kann […] Allein weit über diese Gebiete rein sachlich motivierter Geheimhaltung wirkt das reine Machtinteresse der Bürokratie als solches. Der Begriff des „Amtsgeheimnisses" ist ihre spezifische Erfindung und nichts wird von ihr mit solchem Fanatismus verteidigt wie eben diese [...] Ein schlecht informiertes und daher machtloses Parlament ist der Bürokratie naturgemäß willkommener – soweit jene Unwissenheit irgendwie mit ihren eigenen Interessen verträglich ist."

bureaucracy seeks to increase its superiority by keeping its information and intentions secret. Bureaucratic administration always tends to be administration under the exclusion of the public. The bureaucracy hides its knowledge and actions from criticism as far as possible [...]. Its motivation for secrecy goes far beyond purely objective matters, foremost, it is the pure interest in power as such. The concept of the "official secret" is its specific inventtion, and it defends this concept with more fanaticism than anything else [...] A parliament that is poorly informed and thus powerless is naturally welcome to the bureaucracy – to the extent to which that ignorance is somehow compatible with its own interests.

This certainly applies much more to non-democratic states. But it is to be deplored that the U.S. and the UK fail in this case, although they are forerunners of democratic developments and have admirable merits in promoting transparency and democracy. The secrecy on naval reactors surpasses that on nuclear weapons by far, although the security risks are much higher in the latter case. This secrecy is also a nuisance in international fora, such as in an attempt to start negotiations on an FM(C)T. These states categorically reject the idea of banning production of HEU for naval reactors, but fail to explain the reasons and justify themselves. But without information on naval fuel, any verification is impossible. Instead the U.S. and the UK expect the other delegations simply to accept privileges for only a few and accept a huge loophole which is detrimental to the spirit of the NPT and the FM(C)T without asking questions. This silence is fatal for the goal of finding acceptable compromises.

The Federal Government of Germany and other states should first press for much more openness with regard to naval reactors and technical information that might be useful for studies on their conversion or redesign. For the sake of credibility, it should stress its commitment to promoting the conversion of the FRM-II reactor. Secondly, the international community should make clear that the phase-out of HEU production is a package for all uses and that no state may pick bits and pieces at its pleasure. Germany, as a major non-nuclear weapon state, has the responsibility to take the lead. It should look for like-minded states that probably think similarly but up to now have not dared to speak out. A context could be the Non-Proliferation and Disarmament Initiative (NPDI) that was founded in 2010 and jointly promotes practical steps towards non-proliferation. Currently, it is composed of Australia, Canada, Chile, Germany, Japan, Mexico, Netherlands, Nigeria, the Philippines, Poland, Turkey and the United Arab Emirates.

The focus of this report is the prospect of phasing out any HEU use. This would eliminate the need for any more HEU production. The huge surplus quantities of HEU that exist today may be consumed during an intermediate period until the new technologies are in place to enable the use of alternative material. The prospects that the use of HEU in research and other civilian reactors and medical isotope production may end seem promising, as long as the goodwill is maintained and strengthened. The only other use of HEU remaining is for military naval reactors, and it seems there are only two countries that refuse in principle to even consider alternatives. An educated discussion is impaired by exaggerated secrecy. Plausibility considerations, however, indicate that technical alternatives for naval reactors might also be possible.

The phase-out of HEU seems within reach, but this requires the goodwill of everybody.

Appendix I: Analytical assessment of critical masses of unreflected uranium spheres

It is assumed that uranium is a bare metal sphere without a reflector and without moderator. As an approximation, it is assumed that all neutrons have the same energy (one-group calculation). Then the effective multiplication factor k_{eff} of a critical assembly is (Glasstone/Sesonske 1994: 159).

$$k_{eff} = \frac{k_\infty}{1+L^2 \cdot B^2} = 1$$

k_∞ is the multiplication factor in a medium extended indefinitely, L is the neutron diffusion length, and B^2 is the buckling. The buckling is a factor that is influenced by the geometry of the assembly. For an unreflected sphere, it is

$$B^2 = \left(\frac{\pi}{R+0.71\lambda_{tr}}\right)$$

R is the radius of the sphere, λ_{tr} is the transport mean free path. The neutron diffusion length depends on the cross-sections for absorption σ_a and scattering σ_s, the mass number A and the density N:

$$L^2 = \frac{1}{3\,\sigma_a N^2(\sigma_a+\sigma_s(1-\mu_0))}$$

$$\mu_0 = \frac{2}{3A}$$

μ_0 is a correction term. For uranium, it is very small (μ_0 = 0.0028) and can be neglected in this assessment. For this reason, the transport mean free path is approximately the inverse of macroscopic total cross-section:

$$\lambda_{tr} = \frac{1}{N(\sigma_a+\sigma_s)}$$

The multiplication factor k_∞ in a medium extended indefinitely is

$$k_\infty = \frac{\nu\sigma_f}{\sigma_a}$$

ν is the average number of neutrons released in a nuclear fission, and σ_f is the cross-section for fission. Let p be the enrichment, then the fission cross section for enriched uranium can be calculated as

$$\sigma = p \cdot \sigma_{235} + (1-p)\sigma_{238}$$

With these formulas, the radius R of the sphere can be calculated depending on the enrichment of the uranium. The following values are assumed for the quantitative calculation:[54]

N = 4,85 · 10^{-28} m^{-3} (uranium with normal density)
ν = 2,52
σ_{f235} = 1,25 · 10^{-28} m^2 (fission cross-section of U-235)
σ_{s235} = 5,2 · 10^{-28} m^2 (sum of elastic and inelastic cross sections for U-235)
σ_{a235} = 1,37 · 10^{-28} m^2 (sum of cross sections for fission and absorption for U-235)
σ_{f238} = 0,02 · 10^{-28} m^2 (fission cross-section of U-238)
σ_{s238} = 7,1 · · 10^{-28} m^2 (sum of elastic and inelastic cross sections for U-238)
σ_{a238} = 0,15 · 10^{-28} m^2 (sum of cross sections for fission and absorption for U-238)

The results are shown in Figure 1.[55]

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[54] Software JEF-PC, NEA 1995, with neutron energy = 1 MeV. The average neutron number for fission has been taken from Ziegler 1983: 194f, group 0,8-1,4 MeV; von Hippel 2004b, pp. 137–164.

[55] The curves in this figure are compatible with the results calculated by Alexander Glaser who used a different method, see Figure 2.1 in Glaser 2005.

Appendix II: Domestic and international discussions on the FRM-II

General criticisms directed at the purpose of RERTR: The breach of the moratorium would set a precedent, imitators would follow, and so the efforts and successes of RERTR would be undermined, further conversion of reactors would be demotivated, international trade would resume and the phase-out of the civilian use of HEU would become impossible.

Proponents countered that any new fuel could either contain LEU or HEU, and sooner or later, a first project would use every new fuel with HEU instead of LEU anyway.[56] The project director Klaus Böning listed arguments generally against the need to phase out HEU, which can be summarized as a dismissal of the intention of INFCE, RERTR and the domestic efforts in converting research reactors.[57] Proponents also pointed at U.S. plans to build a new research reactor, the *Advanced Neutron Source* (ANS), which was also planned to use HEU. Frequently, the argument was raised that the fuel was not "bomb grade," because the HEU first had to be separated with chemical methods before it could be used in a bomb.[58] This claim neglects the official IAEA definition of what is direct use material. The reason for the IAEA definition is the fact that enriching uranium is much more difficult than chemical separation of un-irradiated uranium.

Fatally, within RERTR, the U.S. Department of Energy had been slow for many years to convert U.S. reactors (Krull 1998). At least until 1995, the domestic German discussions suffered from a perceived U.S. double standard. As an example, the Bavarian Minister President Edmund Stoiber was cited explaining that "he understood that the Americans wanted to prevent the operation of the FRM-II with HEU, in order to overtake the world-leading European neutron research. But this should not be allowed to happen."[59] The politician Wolf-Michael Catenhusen (SPD) who opposed the HEU use for years, said in a private communication in 1994 that he would probably not be able to maintain his opposition, should the U.S. proceed with HEU for the ANS.

Even after high costs – some $3 billion – led the DoE to cancel the ANS in 1995, German scientists and politicians continued to point out that this was not for proliferation but only for cost reasons.[60] They further tried to trigger resentment by pointing at attempts of the USA in the later 1970s to dissuade other countries from plutonium reprocessing, a policy that was still remembered and disliked in the nuclear establishment of that time.

In the design phase of the FRM-II, it would have been easy to have developed a different reactor concept based on LEU fuel without significantly increased costs. But there was no perceptible public debate about the reactor while the FRM-II project was initially being evaluated, neither nationally nor

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[56] This argument is not convincing: The denser the U-235, the higher the energy density in the fuel during operation. This will lead to damages of the crystalline structure, so that a limit to U-235 density is probable.

[57] Literally, in a hearing in the Bavarian Parliament on 29 April 1993, he commented "The proliferation risks […] are dramatized by interest groups in an irresponsible way. Many other reactors […] have been using HEU for decades up to today without a single case of proliferation. The complete fuel cycle of research reactors is subject to very strict safeguards and international control. As an example, the proliferation risk of HEU in politically insecure nuclear weapon states is incomparably higher." (Translated by the author).

[58] Answer of the Bavarian State Ministry for Education, Culture, Science and Art to an enquiry of the parliamentarian Peter Paul Gantzer (SPD) on 22 February 1995.

[59] Süddeutsche Zeitung of 28 July, 1994: "Offensive für Bayerns Zukunft" – Stoiber unterstützt das umstrittene TU-Konzept ("Offensive for Bavaria's future" – Stoiber supports the contested concept of the Technical University) Quotation translated.

[60] There was similar domestic criticism of the U.S. plans for the ANS: Daniel Charles, "DOE Undermines Own Non-proliferation Effort: The Department is Trying to Persuade Other Countries to Move away from Highly Enriched Uranium in Research Reactors but Is Planning a Reactor of Its Own that Will Use the Material, Science 238, p. 1224, 27 November 1987.

internationally. The German Foreign Office warned in vain that a HEU-based reactor would have negative foreign policy consequences and that the Federal Government would be in contradiction of earlier declarations.[61] In 1991, the Bavarian politician Hans Kolo (SPD) demanded conversion to LEU in order not to jeopardize efforts to phase out HEU use.[62] But his warnings were not covered by the press and did not create more opposition. Neither the Technical University Munich nor the Bavarian or other Federal Ministries were willing to discuss the possibility of LEU use, or even the use of slightly lower enrichment levels, including as high as 70 percent HEU (Krull/Jager 1996). The international political effects of a newly built research reactor using HEU were not taken seriously at the time. Before 1993, there were not enough advocates of stricter non-proliferation measures regarding HEU use in research reactors.

Promoters of the reactor believed that after some protests, the use of HEU would be accepted. Moreover, they expected the protest against the choice of fuel to be small in comparison to the protests of anti-nuclear environmental activists, a perception which was correct in the early phases of the debates. Both the Bavarian and the Federal Governments picked up the focus on the environment when they justified their support of the project and reasoned that because spent HEU fuel contains less plutonium than spent LEU fuel, it would pose fewer environmental risks:[63] The Federal Government has explained on numerous occasions that the use of HEU in the FRM-II project is highly recommended because of the specific scientific objectives involved, on grounds of cost, and in particular because of the comparatively limited effects on the environment and the smaller plutonium yield.

But in comparison to the quantity of plutonium and radioactive inventory in power reactor spent fuel, the difference is so marginal that this argument loses its value, which unfortunately was hardly noticed, although the comparison with power reactors had been made by the responsible scientists themselves in a "Neighbourhood Journal" that was distributed within a campaign in favour of the concept.[64] They stressed that the reactor power is only one-200th of that of a certain Bavarian power reactor (Isar II). As a result, the radioactive inventory is also only one-200th. But they fail to explain that the difference is equally marginal in the case of an LEU instead of an HEU concept, because the power would differ by only a factor of 1.5. The Bavarian Government even argued that spent HEU fuel poses a smaller proliferation risk because of its lower plutonium content, neglecting the fact that a large fraction of HEU remains in the irradiated fuel:[65] Conversion of research reactors from high to

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[61] Letter by Dr. von Wagner, representative of the Foreign Office to Federal Ministry of Environment, Dep. -RS13, and to the Federal Ministry of Research and Technology, Dep. Ref. 315, 3 February 1988.

[62] Press declaration of 26 March 1991.

[63] German Federal Parliament, "Antwort auf die Kleine Anfrage der Abgeordneten Probst, Altmann, Häfner, Hermenau, Kiper, Köster-Loßack, Schönberger und der Fraktion BÜNDNIS 90/Die GRÜNEN" (Reply to Parliamentary Question), Drucksa 13/600, reply to question 26, 1995. In 1993 the German parliament adopted a decision to avoid the use of HEU "as far as technologically possible": German Federal Parliament, Twelfth Election Period, "Beschlußempfehlung und Bericht des Auswärtigen Ausschusses (3. Ausschuss)-Nichtverbreitung von Kernwaffen" (Decision Recommendation and Report of the Foreign Affairs Committee (3rd Committee) – Non-proliferation of Nuclear Weapons), Document 12/5116, 15 June 1993 (Deutscher Bundestag, 12. Wahlperiode, Drucksache 12/5116, 6/15/1993).

[64] FRM_II mit Vollschutz (FRM-II with full protection), in: "Forschung rund ums Atom-Ei" 1/94 (Science around the Atomic Egg), Nachbarschaftszeitung der Projektgruppe FRM-II (Neighbourhood Journal of the project group Munich), Technical University Munich, responsible: Prof. Dr. Klaus Boening, March 1994.

[65] Bavarian State Parliament, "Anwort des Staatsministeriums für Unterricht und Kultus, für Wissenschaft und Kunst auf die Schrifliche Anfrage des Abgeordneten Kolo vom 23.4.1990" (Reply of the Bavarian State Ministry for Education and Culture to the Written Question of Parliamentarian Kolo of 23 April 1990), Document 11/17837, reply to question 4. Irradiated fuel from research reactors must first be reprocessed in order to obtain the HEU or the plutonium, it therefore qualifies as "indirect use material". Emphasis added.

low enrichment only shifts the risks. With low enrichment, *substantially* more plutonium will be bred during reactor operation than with high enrichment.

Instead of the wording “substantially more plutonium,” the term “a somewhat larger quantity of plutonium that however is irrelevant” would have been correct. The quantity of additional plutonium would be marginal in comparison to the quantity of un-burned HEU. Anyone who reprocessed the spent fuel in order to retrieve the plutonium would also retrieve the rest of the HEU. Less than one kilogram of plutonium per fuel element could be obtained in this way, and there are already thousands of tons of plutonium available in the world in the form of separated fuel elements. Even if a nuclear-aspirant state possessed recycling technology, spent HEU fuel elements would be much more attractive than spent LEU because they still contain 7 kilograms of unused HEU.[66] But a project member himself, a physics professor, wrongly declared in an interview that an alternative LEU concept would mean “casting out the demons with the ruler of the demons” because of additional radioactivity and plutonium.[67] Similar reasoning was used by the project director Klaus Böning: LEU use would result in “substantially more plutonium” which would be a “serious disadvantage.”[68]

Thus, in its campaign for the HEU reactor concept, the Technical University Munich attempted to exploit the anti-nuclear attitude of the majority of the population and used numbers not for clarification but for creating false impressions. From the opposite point of view, the reactor opponents, who until 1993 had based their arguments only on environmental, safety and cost considerations, became aware that the HEU debate seemed to offer arguments that convinced many more people than just those with an anti-nuclear attitude.[69] They drew attention to the danger of proliferation, hoping that this argument could be used as a tool to stop the FRM-II project altogether. The U.S.-based Nuclear Control Institute started a press and lobbying campaign in Germany against the reactor and promoted the non-proliferation arguments. But in addition to the non-proliferation rationale, it also asserted that the reactor as such was not necessary because there was already one in Grenoble that was shared among European researchers.[70] This proved counterproductive because it alienated several domestic opponents of the HEU concept in politics and academia who were in favour of an alternative LEU concept but nevertheless supported a neutron research tool for the Technical University Munich.[71]

Many proponents in turn happily denounced all HEU opponents of being just anti-nuclear, using the HEU argument as a pretext to kill the reactor altogether, accusing honest scientists of being

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[66] This number can easily be calculated from the design characteristics: 8 kg HEU are contained in a fresh fuel assembly (consisting of one element), the reactor power would be 20 MW, and the burning time 50 days.

[67] Wolfgang Gläser, quoted in: Süddeutsche Zeitung, Der Stoff, aus dem die Bombe ist (The substance from which bombs are made), Bayernteil, 11 January 1994.

[68] Klaus Böning, Uran hoher Anreicherung am FRM-II, in: FRM-II mit Völkerrecht im Einklang (FRM-II in accordance with international law), brochure published by the Technical University Munich, quotation p.18, 1996.

[69] At a Hearing in the Bavarian Parliament on 29 April 1993, the author was invited to elaborate on proliferation risks, see Schaper 1993.

[70] Paul Leventhal stated on 10 May 1994 that he deemed the planned reactor superfluous because the research capacities in Europe were surplus. See: Sachverständigenaussage als Einspruch gegen den geplanten Forschungsreaktor FRM_UU zur Vorlage am Bayerischen Staatsministerium für Landesentwicklung und Umweltfragen (Testimony for the Bavarian State Ministry for Regional Development and Environmental Affairs), 10 May 1994, p. 13, back translated from a translation into German by the author

[71] In fact, the research slots at the Grenoble reactor were scarce and in demand, and there had been disagreements on quota. As one of the applications of the FRM-II is to serve as a tool needed in dissertations, it is important that it is located near the University where the students reside.

potential thieves and dealers of HEU[72] and of misinterpreting the NPT banning the possession of HEU.

The U.S. exerted diplomatic pressure to abstain from an HEU concept and announced it would not sell HEU for the reactor.[73] Since all HEU in the EU was already designated for other reactors that were not converted, the European Supply Agency finally bought more HEU from Russia, although this ran counter to the goal to phase out international trade of HEU. For a while, the reactor operators tried to deny any negotiations with Russia, claiming that the HEU would be delivered by the Supply Agency from somewhere in the EU.[74] The Federal Ministry of Education, Science, Research and Technology still wrote in 27 March 1995, almost a year after first talks with Russian Suppliers:[75] "[...] The supply […] from stocks in the EU is sufficient for ten years. Nothing has been changed in this statement."

The Technical University Munich (TU Munich) established a public relations office for the FRM-II project group with an annual budget of DM 700,000.[76] This office kept distributing flyers and publishing press reports and brochures emphasizing the arguments cited above and also claimed that U.S. refusal to sell HEU for use in the reactor would violate article IV of the NPT,[77] that the reactor concept would not undermine INFCE and RERTR efforts but, in contrast, would confirm,[78] or that the critics were not qualified because they were not neutron physicists and used political arguments.[79]

The citations in preceding sections show how politics are sometimes carried out based on pseudo-technical reasoning. If the politicians had looked more closely at the underlying technical facts, and the physicists had more closely studied the political circumstances, a more educated and objective discussion would have taken place, and perhaps a different reactor concept would have been chosen.

The inconsistency in Germany's foreign policy stance became evident at the 1995 Review and Extension Conference of the NPT when Germany resisted the use of language that would have

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[72] Reader's letter to the Süddeutsche Zeitung, Absurde Gedanken (Absurd ideas), 19 November 1993.

[73] Gerd Rosenkranz, USA schicken "non-paper" ans Auswärtige Amt: Kein HEU aus Amerika für Garching (USA send "non-paper" to the Foreign Office: No HEU from America for Garching), Süddeutsche Zeitung, 11./12. Mai 1994; Süddeutsche Zeitung: pp. 1, 2; 13 April 1994.

[74] Officially, all nuclear material in the EU is always purchased by the Supply Agency. This is the only legal procedure in the EU for all nuclear material anyway. In the EU it is common to swap nuclear material as convenient without notification or publication. Reportedly, talks between the Russian Minatom and staff of the Technical University Munich (TU Munich) took place on 13-14 April 1994.

[75] Answer to the Kleine Anfrage der Abgeordneten Simone Probst, Elisabeth Altmann (Pommelsbrunn), Gerald Häfner, Antje Hermenau, Dr. Manuel Kiper, Dr. Angelika Köster-Loßack, Ursula Schönberger und der Fraktion BÜNDNIS 90/DIE GRÜNEN, HEU-Betriebener Forschungsreaktor (BT-Drs. 13/600); March 1995, answer to questions 6, 7 and 9.

[76] Letter by Ingrid Wundrak to the author, 28 July 1994.

[77] Süddeutsche Zeitung, Non-Paper läßt Reaktorplaner kalt (Non-paper of no interest to reactor planners), 6 July 1994; Dieter Blumenwitz, FRM-II und das Völkerrecht der Non-Proliferation (FRM-II and the international law on non-proliferation), presentation at the Forum im Pressehaus Bonn, 24. September 1996, reprinted in: FRM-II mit Völkerrecht im Einklang (FRM-II in accordance with international law), brochure published by the TU Munich.

[78] TU Munich, Project Group New Research Reactor, Public Relations FRM-II, Press Information, Bundesregierung unterstützt FRM-II-Reaktorkonzept – Verwendung von HEU verstößt nicht gegen INFCE und RERTR (Federal Government supports FRM-II reactor concept – Use of HEU does not violate INFCE and RERTR), 13 July 1994.

[79] TU Munich, Project Group New Research Reactor, Public Relations FRM-II, Press Information, Fragwürdige selbsternannte Neutronenexperten – Kapazitäten der Projektgruppe FRM-II lassen sich nicht für politische Scheingefechte mißbrauchen (Questionable self-titled neutron experts – Capacities of the project group FRM-II don't let themselves be misused for mock political battles), 10 June 1994.

banned civilian use of HEU.[80] The German delegation knew that the language, as formulated, conflicted with the plans for FRM-II.

In the early 1990s, scientists at Argonne National Laboratory outside Chicago became engaged in analysing the FRM-II design to determine what would have to be done in order to redesign it for LEU fuel. They first presented their findings at the RERTR 1994 International Meeting in Paris. The Argonne scientists proposed an alternative core design, concluding that use of LEU fuel could provide nearly the same neutron flux as the HEU design but would require a larger core and more fuel annually until higher density fuel (with a uranium density of 6–6.5 g/cm3) could be developed (Mo et al. 1994). However, a consensus between the scientific groups from Garching and Argonne was not possible, with Argonne complaining that the Garching scientists did not share design information and they in turn complaining that Argonne's calculations were incorrect.

In 1998, a new German Government was interested in converting the reactor from HEU to LEU use, even though construction was already well advanced, as was the legal licensing process. An expert commission was convened in early 1999 to explore the possibility of conversion. The commission heard experts including those from Argonne and Garching and presented a final report in June 1999.[81] Given the short time before the final report deadline, the committee was not able either to verify or discount the Argonne or Garching claims.[82] However, it was already clear that an alternative design with acceptable properties would require a slightly larger reactor core than the one planned. But construction progress, especially the concrete surrounding the reactor chamber with a limited space for the core, was already so advanced that it was too late for any change.

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[80] At the 1995 NPT Review Conference, eight European countries (Austria, Denmark, Finland, Hungary, Ireland, the Netherlands, Norway and Sweden) together with Australia, Canada and New Zealand drafted text to be included in the conference's final document, recommending "that no new civil reactors requiring highly-enriched uranium be constructed," see NPT/CONF.1995/MC.II/WP.8, 21 April 1995. See also Fischer/Müller 1995.

[81] Bericht der vom Bundesministerium für Bildung und Forschung eingesetzten Expertenkommission zur Prüfung der Umrüstbarkeit des Forschungsreraktors München II von HEU auf LEU" (Report of the expert commission initiated by the Federal Ministry of Education and Research on the evaluation of options for the conversion of the FRM-II from HEU to LEU), June 1999.

[82] Alexander Glaser later conducted computer calculations on the Garching and Argonne scenarios for his Ph.D. thesis. He concluded that it would have been possible to convert the reactor with only small (e.g., tolerable) performance disadvantages, confirming the Argonne data. However, this conversion would have required a slightly larger reactor core: Glaser 2005. See also Glaser 2002.

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Acronyms

ANL	Argonne National Laboratory
ANS	Advanced Neutron Source
DoE	Department of Energy (United States)
FM(C)T	Fissile Material (Cutoff) Treaty
FRM-II	Forschungsreaktor München II
GTRI	Global Threat Reduction Initiative
HEU	Highly Enriched Uranium
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
INFCE	International Nuclear Fuel Cycle Evaluation
IPFM	International Panel on Fissile Materials
LEU	Low-enriched Uranium
LWR	Light Water Reactor
MPC&A	Material Protection, Control, and Accounting
NNWS	Non-nuclear Weapon State
NPT	Non-proliferation Treaty
NWS	Nuclear Weapon State
R&D	Research and Development
RERTR	Reduced Enrichment for Research and Test Reactors