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MEASURING PROGRESS ON HEU MINIMIZATION - THE NEED FOR ACCELERATION AND ADDRESSING "OUT-OF-SCOPE" ACTIVITIES

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ABSTRACT

Currently, 294 reactors and isotope production facilities use HEU fuel or target material, out of which 154 are used for naval propulsion. These facilities are in annual need of more than 3 500 kg HEU for naval propulsion, more than 900 kg HEU in research reactors, and more than 80 kg HEU for isotope production in civilian facilities, in addition to 6 000 kg HEU in various other types of reactors. 48 civilian research reactors, representing a decrease in the HEU consumption on 278 kg – or 19% compared to the amount of HEU consumed in 1978 in similar facilities, have completed the conversion to LEU as a result over continued international assistance over three decades. The establishment of baseline measurements for assessing the results of the current HEU minimization effort calls for additional focus on the scope and methodology for HEU minimization. The justification for addressing only 54% of the remaining HEU-fueled research reactors as part of the GTRI program should be addressed together with increased focus on facility decommissioning as 120 HEU-fueled reactors with HEU consumption on 450 kg have been shutdown since 1978. There should be no need for converting all the remaining 133 HEU-fueled research reactors as decommissioning and dismantling should play a more prominent role in the future HEU minimization effort. As other sectors reduce the HEU fuel inventory, there is a need to evaluate the risk associated with the continued use of large quantities of weapons-grade HEU fuel for naval propulsion.

1. INTRODUCTION.

In 1980, the International Fuel Cycle Evaluation (INFCE) study led representatives from 59 states to realize that the widespread use of HEU in various types of applications posed significant proliferation risks, and a push was instigated to minimize the civilian use of HEU and reduce the number of sites with HEU. Efforts to minimize the use of HEU in civilian nuclear applications have been re-invigorated and revitalized recently. Yet, there is confusion with regards to the scope as well as the progress of on-going activities: Which materials and facilities are actually covered, at what pace are they converted and with what progress for HEU elimination as such? The aim of this report is to provide the technical basis for measuring progress in relation to the specific targeted area, and – as HEU in all contexts represents a similar risk – in relation to the entire HEU-fueled universe. This paper establishes baseline information on the number and different types of HEU-fueled facilities in 1978 and today, focusing on the following parameters: the number and size – in nominal power and core inventory – of HEU-fueled facilities, and the amount of HEU/ U-235 consumed annually. The HEU-fueled universe has been divided into two categories: (1) inside the scope of historical and present efforts to minimize the use of HEU, which currently means the Global Threat Reduction Initiative (GTRI), and (2) outside the scope of existing conversion efforts, including those not considered at all in the present context.

The risk associated with HEU has several components related to technical and societal factors. In this paper, selected parts of the technical dimension for the complete HEU-fueled universe will be addressed: the amount and type of material and the type and size of facilities. This universe consists of several distinct scientific or commercial areas, in this paper divided into research reactors, propulsion reactors and other types of reactors. For the two former, the relevant data given in this paper has been systemized as part of a database on the inventory and operation of HEU-fueled installations [1]. Regarding the latter, which dominates in material quantities though much smaller in number of facilities, other relevant sources are recognized where relevant.

2. ESTABLISHING BASELINE MEASUREMENTS.

Research reactors. The amount given by INFCE in its 1980 report for the amount of HEU consumed in civilian steady-state reactors in 1978 was ‘over 1200 kg U-235’. This number appears to be taken from the RERTR program, and the research facilities supplied with fuel from other countries of origin than the US were not included in this estimate. Calculations based on information from the IAEA Research Reactor Database on nominal power, average burn-up and availability show that the total amount for all identified civilian research reactors in 1978 was 1474 kg HEU. Soviet-designed facilities consumed an estimated 390 kg of this HEU (26%) [1]. As the baseline measurement used in the INFCE study was a) specified to be the amount of U-235, thus not including the fertile component U-238, and b) indicated the amount used for constructing the fuel and not the actual amount of fuel used in the various facilities at that time, the total amount we have calculated for 1978 can be compared to the amounts given in INFCE.

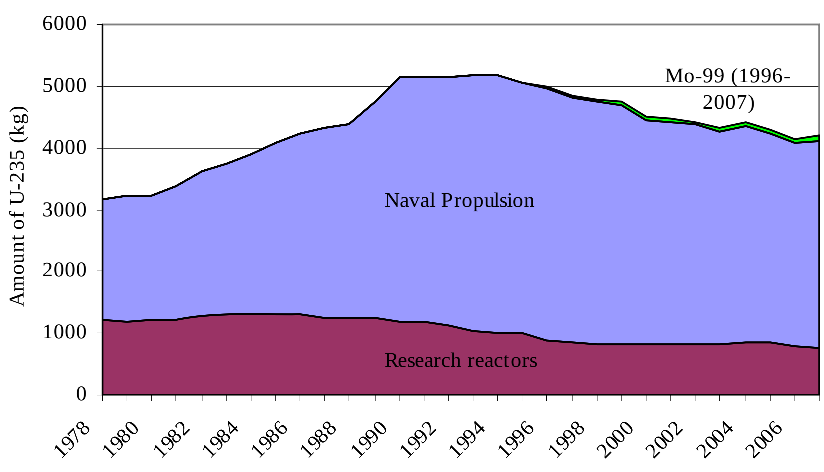

Figure 1: HEU consumption in research reactors, propulsion reactors (1978 – 2007) and isotope production (Mo-99)

Regarding the number of facilities and nominal power, INFCE referred to ‘more than 150 HEU-fuelled facilities of significant power’ with total nominal power of more than ‘1700 MW’. When re-establishing a baseline measurement taking into account all HEU-fueled facilities in all regions, the results show that there were at least 244 HEU-fueled research reactors in 1978 with a total nominal power of 1919 MW. As not all types of research facilities were included in the INFCE scope, in addition to the other elements mentioned above, comparing these data is less relevant. However, these data does indicate that the remaining HEU-fueled facilities represent a larger consumption of HEU than those converted so far.

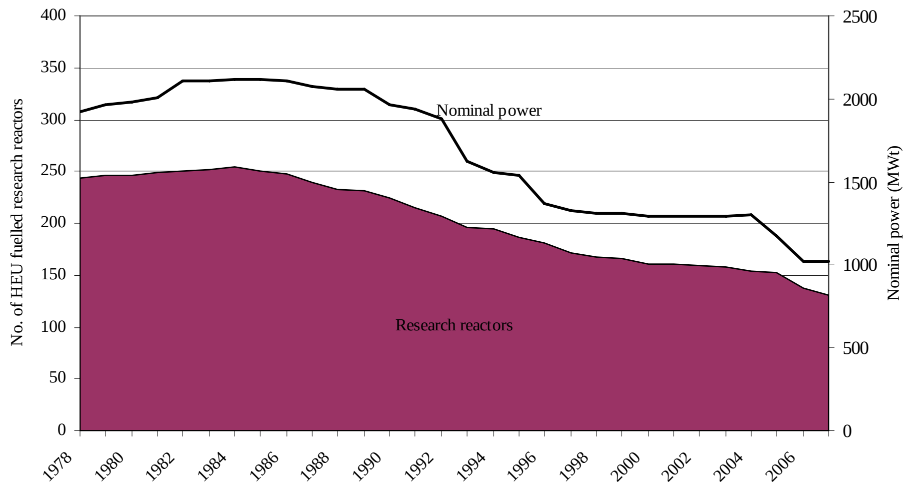

Figure 2: Number of HEU-fueled research reactors and nominal power 1978 – 2007

Figure 2 above includes only facilities where HEU has been used as reactor fuel, not targets. Regarding the latter, the world's four major producers of Mo-99 use HEU targets. As the main part of the production data for producing Mo-99 is proprietary, precise data on HEU use in this sector is not possible. Figure 1 has been based on data available on the Cintichem process [2], annual growth in the Mo-99 market of 10% [3] and a constant market share for the major isotope producers of 90%. For 2007, the use of U-235 in this sector has been estimated at 93.5 kg, then considering only the HEU consumption by the main producers.

Propulsion Reactors. Relevant areas are naval reactors, primarily military surface vessels and submarines, and space reactors. HEU-fueled naval propulsion installations in operation today include 154 reactors in four nuclear-weapon states. Annual consumption of U-235 for the world's civilian and military nuclear-propelled fleet from 1978 to 2007 is shown in Figure 1. The annual consumption of HEU has been calculated on the basis of the core inventory for each reactor type, number of cores consumed annually of each type, and the size and composition of each fleet. [1] As core inventory, fuel and reactor geometry, and operational characteristics are traditionally well-kept secrets, these properties have been estimated on the basis of reactor classes or generations. 40% of the US HEU consumption, for 2007 constituting 55% of the total U-235 consumption for propulsion reactors, takes place in aircraft carriers. The UK Navy has 15 naval reactors, consuming approximately 220 kg U-235 in 2007. Corresponding figures for the Russian submarine fleet for 2007 are estimated at 1100 kg U-235, part of which (the military component) is enriched to 20–45%. 350 kg of U-235 is being consumed in the civilian fleet, with a significant part enriched to 90%. While the Russian Navy spends little time at sea at the moment, other properties, such as corrosion, are probably the limiting factor for the lifespan of the core, thus the resulting HEU consumption still reaches significant levels.

Other reactors. Only one HEU-fueled fast breeder power reactor is currently in operation - the Russian BN-600. This facility alone consumes annually 4 metric tonnes of HEU enriched to 20-25%. [4]. The Russian BOR-60 is likely to use MOX-fuel in the future, as will the Chinese Experimental Fast Reactor (CEFR): although it will reportedly be fueled with HEU when commissioned in 2008, it will later be converted to MOX [5]. The fuel for the HEU-fueled breeder has different properties compared to the Pu-production facilities: while only part of the fuel for the Russian BN-600 is enriched to just above 20%, the Pu-production facilities use 90% enriched HEU and each facility uses about 200 kg HEU (90%) annually [6]. Russia has now agreed to close its Pu-production facilities in Seversk (2) and Zhelenogorsk (1) in 2008 and 2011, respectively. If still in operation, the two large military Russian light-water reactors *Ruslan* and *Lyudmila* are probably also using vast quantities of HEU. Believed to have a nominal power of 1000 MWt, they use HEU to spike up the flux in the isotope-producing regions. Their U-235 consumption has been assessed at 1500 kg HEU annually [6].

3. MEASURING PROGRESS IN HEU MINIMIZATION.

The HEU minimization programs that operated in the past and/or are currently active have to date primarily addressed civilian research reactors. Thus, this section chiefly assesses progress in this sector. For the other sectors, relevant efforts for promoting conversion or minimization are briefly assessed.

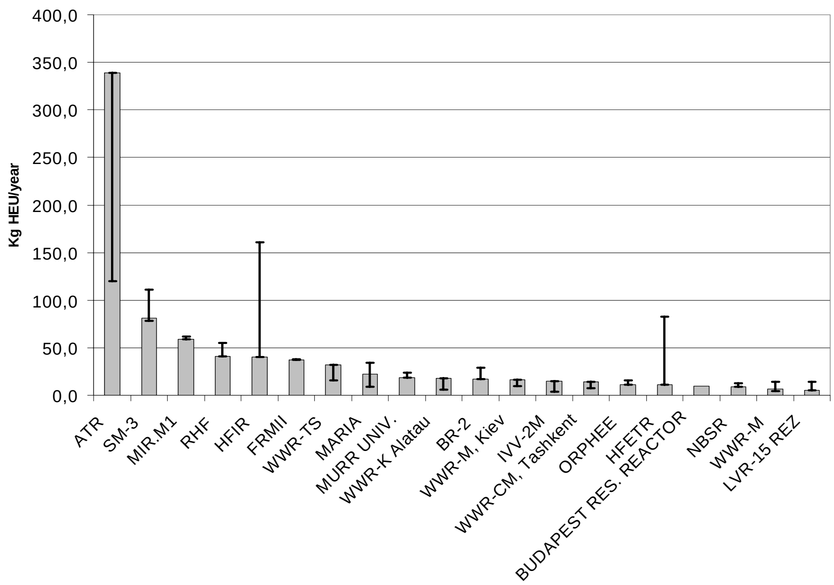

Figure 3: HEU consumption in civilian steady-state research reactors (Top 20) – 2006

Research reactors. The annual requirement for HEU in civilian research reactors has been reduced significantly: from 1474 kg in 1978 to 905 kg in 2007 as described in Figure 1. The 20 largest HEU consumers in the civilian steady-state reactor sector for 2006, described in Figure 3, uses a total of 831 kg HEU (89% of the total). The error bars indicate the span (min./max.) of consumption estimates for each reactor given in various sources. These 20 facilities consume approximately 2-10 cores each year, indicating that a considerable amount of fresh and spent fuel are stored at these facilities at any given time.

In total 52 HEU-fueled facilities have been converted since 1978, 48 as part of the RERTR program. If including the conversion projects completed as part of the Russian program to convert Soviet-designed reactors situated outside Soviet Union from 80% enriched fuel to 36% during the 1980s, the resulting figure is 63. The overall reduction in HEU consumption due to conversion from 1978 until 2007 is 278 kg. Virtually none of the pulsed reactors and critical assemblies has been converted, since until recently life-time cores have been outside the scope of the conversion programs. Regarding the production of Mo-99, no significant changes have occurred with respect to converting the main production facilities to using LEU targets. Due to the persistent increase, however, in the use of Tc-99 in medical diagnostics, the goal of having all new production based on non-HEU technologies has been pursued vigorously. If residual amounts of HEU in target waste are used in new targets the annual HEU consumption will not be affected, but the amounts of HEU in target waste will be reduced significantly. Burn-up for targets is typically 1-3% of the available fissionable material.

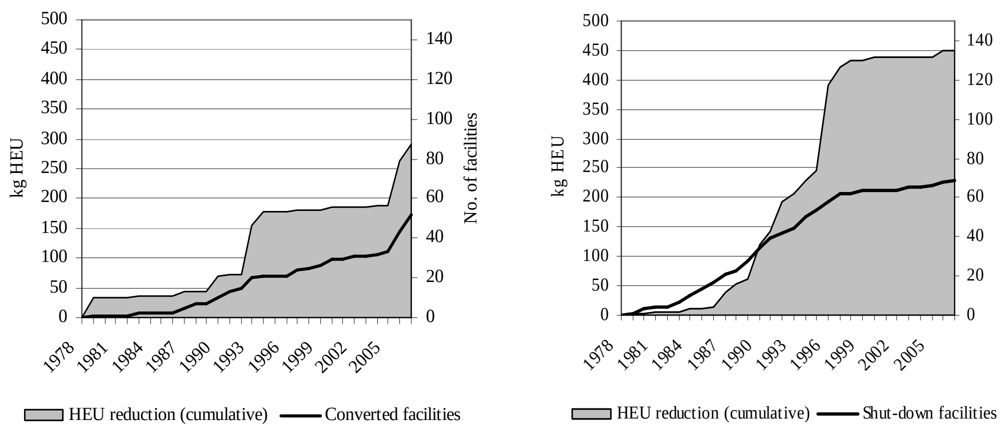

Figure 4: Converted vs. shutdown HEU-fueled research reactors and associated HEU consumption (cumulative) 1978 - 2007

Regarding facility decommissioning, 69 HEU-fueled steady-state research reactor facilities have been identified as shutdown, as seen in Figure 4, representing a reduction in HEU consumption from 1978 to 2007 of 450 kg. This does not include the 12 steady-state reactors converted in the same period and then shutdown. Out of these 12, 8 facilities were shutdown within 5 years after conversion. This indicates that too little emphasis has been put on considering reactor justification before conversion has been implemented. Only a few steady-state reactors that have been outside the scope of the international minimization programs are shutdown. The US decommissioned a large number of military critical assemblies and pulsed reactors (20) at the end of the 1980s and beginning of the 1990s, probably as a result of the fact that the development of new weapons and naval reactors slowed down and that computer simulations became an alternative. Other countries have also systematically decommissioned their critical assemblies, such as Germany (3), Spain, Belgium, and Poland. In addition, a few critical assemblies in Russia were also shutdown.

Naval propulsion. Early in their submarine program France made a decision to run its *Rubis* attack submarine on LEU fuel, and has probably abandoned HEU in its new strategic missile submarine class as well. The US, Russia, and the UK have shown no interest in similar initiatives for their navies (or, in the case of Russia, the icebreaker fleet). The US Navy was challenged in 1995 to assess the potential for conversion of the submarine cores to LEU. The main conclusion was that LEU-fueled reactors would, among other elements, cause greater occupational radiation exposure, generate more waste and have considerable economic consequences. To preserve the longevity of the core, core volume would have to be increased threefold. Subsequently the pressure vessel, the reactor compartment, and the size and cost of the vessel itself would have to increase correspondingly. According to the assessment, construction costs would rise *"about 28% for aircraft carriers and 26% for submarines – about $1.1 billion pr. year"* [7]. This assessment was made without any reference to the implications of continued operation on HEU related to proliferation risk or other security related issues to handling the fresh or spent fuel. An earlier academic study concluded that the dimensional increases associated with conversion are in fact small enough to be easily compensated for by an integral reactor design, as found in the French *Rubis* [8]. This design is a particular feature of the *Rubis* class, with the steam generator situated within the pressure vessel. The *Rubis* class is the smallest nuclear submarine ever built, with a displacement of 2,500 tons.

Regarding the Russian civilian icebreaker fleet, a study on conversion of icebreaker fuel to LEU concluded that it is technically feasible: a consideration of reactor neutronics and possible core configurations indicates that conversion is feasible. [9] In principle, as icebreaker technology probably has served as a model for submarine technology, this conclusion might be relevant for converting military propulsion facilities. The most promising area to expand conversion efforts today – due to its more transparent technical basis and greater openness as to operational requirements – is Russian icebreaker technology. A naval reactor using LEU has already been developed as a basis for the Russian floating power concept (a prototype is currently being constructed).

Other reactors. Limiting new reactor designs (including breeders) to LEU will place few if any limitations on developing future advanced power-reactor designs. None of the designs under development today, either through the IAEA's International Project on Innovative Nuclear Reactors and Fuel Programs (INPRO) or through the Generation IV International Forum (GIF) program, calls for the use of HEU, however, the R & D may, at least according to a French official, involve experiments where HEU presently constitute a vital role. [10] While the testing of fuel for future fast reactors does, at present, involve the use of HEU in critical assemblies, for example at France's Masurca facility at Cadarache, other potential roles of HEU in the development of new reactor concepts, if they exist at all, should be clarified as development continues. Today Cadarache does not have enough plutonium to undertake these experiments without HEU. It should be noted, however, that "enrichment higher than 30–35% does not seem to be needed to mock-up conceivable core design as proposed today" [11], and also that there is no new need for HEU fuels for future-generation fast reactors. The Russian program, like others worldwide, does not envisage the use of HEU in new generations of fast-breeder reactors [12]. As large amounts of weapons-enriched material may be stored at the other facilities, this should be an ongoing concern regarding adequate protection, removal, and, finally, conversion. In this case, the alternative to HEU is Pu – a change without any radical benefits with respect to the risk of proliferation.

When considering the risk of individual components of the various fuel cycles described here, it is clear that certain areas should be of primary concern – for example, areas where large amounts of HEU with high enrichment levels are split between many sites and used in a way that involves numerous transports of fresh and spent fuel. Steady-state research reactors are an obvious concern as are other types of facilities involving fuel with low burn-up that is easily accessible. Calculations show that converting target material to weapon-useable material would not require a great amount of shielding and could be performed anywhere with an insignificant dose to personnel [13]. A particular area that calls out for attention is naval propulsion. There have been diversions of HEU from Russian naval sites and the amounts of high enriched fuel are immense and weapon-enriched, even after use, though the number of sites for refueling are few – less than a dozen when combining the nuclear propulsion fleets of the US, Russia and the UK. The civilian icebreaker site inside the city limits of Murmansk has probably the largest inventory of weapon-enriched fuel in the world.

4. PRIORITIES AND PROJECTIONS TOWARDS 2020.

Research reactors. After enlarging the scope of the GTRI conversion program in 2004, 2005 and 2007, all civilian steady-state facilities, except for the Russian SM-3 (1) and RBT (2) reactors, are currently part of the GTRI conversion program. As described in Table 1, there are in total 133 HEU-fueled research reactors in operation today. Since the GTRI expanded the scope of its efforts in 2007, far fewer facilities are now outside the scope of the current minimization efforts than before the GTRI program was established. This group primarily consists of Russian critical assemblies and pulsed reactors. One military pulsed reactor – the UK's VIPER reactor – and several critical assemblies were included in the GTRI program in 2004.

	Russia	**China**	**Europe**	**United States**	**Other**	**TOTAL**	**In GTRI**	**Outside GTRI**
Steady state	13	3	12	11	23	**62**	58	4
< 0.25 MWt	1	3	5	1	12	22		
0.25-2.0 MWt	1	-	0	4	4	9		
2.1-10 MWt	6	-	2	3	6	17		
> 10 MWt	5	-	5	3	1	14		
Pulsed/Critical	48 + 3*	1	6	8**	5	**71**	15	56
TOTAL	**64**	**4**	**18**	**19**	**28**	**133**	**73**	**60**
Civilian	51	4	14	12	27	**108**	67	41
Military	13	-	4	7	1	**25**	6	19

Table 1. Operational HEU-fueled research reactors 2007 by power level in thermal megawatts (MWt) and type for selected countries and regions and part of the GTRI program and outside the scope of GTRI Approximately half are in Russia. *Includes 3 reactors of unknown mode of operation. **Includes 4 critical assemblies moved to the Device Assembly Facility, Nevada that are either operational or soon will be.

The US has committed to convert or decommission all of its civilian facilities by the end of 2014 as part of four steps to intensify efforts, though there is no detailed description of how this will be achieved. The status regarding conversion for some facilities is that they have only started to consider the technical premises for conversion. On the other hand, the US plans to re-commission HEU-fueled critical assemblies that have been shutdown for 3 years. This may raise concern in other countries about their potential need for similar capabilities. There is an obvious need for other regions or countries - Russia in particular as no Russian facility has been converted thus far - and the EU to justify the existence of all HEU-fueled facilities, civilian and military, and to establish schedules for decommissioning and conversion. 13 reactors have nominal power levels above 2 MW and require development of new fuel to make conversion to LEU possible while maintaining their main operating properties. The crucial point is then if the development of high-density fuels will continue on schedule. The new deadline for conversion of all eligible facilities is 2018 [14]. Thus, a projection for the reduction of HEU consumption for research reactors has no well-defined milestones as the progress depend on the technical R&D, only parts of the research reactor universe is being addressed and no definitive scope for conversion vs. decommissioning has been established.

At the moment, there are also too many loose ends to present a credible scenario regarding the use of HEU for Mo-99 production. There are no specific plans with the four main producers to convert to LEU targets. The dark horse in these considerations is how soon the planned, large-scale LEU-based production facilities, in particular in the US, will reach significant production levels. As the isotope demand is increasing at approximately 10% pr. year, the argument for having one new high–flux reactor in Europe for isotope production online by 2010-15, and another by 2015-2020 has been made. Recommendations have subsequently been made to the EU and EURATOM to promote LEU technologies for potential new isotope production facilities.

Naval reactors. When considering the future use of HEU for propulsion, not including a sudden revival of HEU-fueled space vehicles, the main issues are two: (1) the implementation of a naval reactor lifetime core, and (2) prolongation of the current force level for attack and strategic submarines, and aircraft carriers. There are no signals indicating any reductions in the HEU-fueled reactor-based military forces, except for Russia where old vessels are regularly taken out of service while virtually no new vessels are being commissioned.

The US long-term plan is to introduce one *Virginia*-class submarine every year until 2020, while reducing the number of *Los Angeles* class by one every year. The influence on the annual use of HEU is none; the overall level reached today will remain constant, despite the differences in core inventory of U-235 and core-life between the *Virginia* and the *LA* class. The UK is currently trying to decide what to do when the operational lifetimes of the naval reactors in its Vanguard-class vessels come to an end in the mid-2020s. When designing the replacement for the PWR-2 in *Vanguard*, the UK should also examine the potential for using LEU, in order to assess the French approach, rationale and relevance for other countries, and complete an independent assessment of fuel design, and the impact on pressure vessel, reactor compartment and ship. If the *Vanguard* class is replaced with LEU-fueled reactors, this will only have an effect well beyond 2020. Regarding the annual use of HEU, the main issue is continued phase-out of the PWR-1 reactor used in the *Swiftsure* and *Trafalgar* submarine classes and the introduction of the *Astute* class, which uses the PWR-2 reactor, one every other year beginning in 2009. A reasonable assumption about the differences between these two installations – PWR-1 and PWR-2 – is that the latter has a considerably larger core inventory. However, as plans call for more vessels to be decommissioned than are being introduced in the coming years, the net effect on the overall use of HEU is limited.

Russia will probably accelerate the construction of new military vessels with higher endurance unless it is convinced otherwise. However, the current decline in the Russian Navy will continue as old vessels are taken out of service and the introduction rate of new vessels stays low. According to current estimates, the strategic submarines (*Delta III*, *Delta IV*, *Typhoon)* are assumed to have a life-span of 30 years after retrofitting. Regarding new classes of vessels, a commissioning rate of two per year from 2010 with a total of six vessels has been suggested. The attack submarines (*Sierra I and II*, *Akula*, *Oscar II*, *Victor*) are assumed to have a life-span of 20 years, somewhat longer than earlier versions of similar vessels. Nevertheless, Russia's nuclear navy will in be down to less than 15 vessels after the year

2015. If more vessels are to be operational, the lifetime of the existing ones will have to be extended, as it is difficult to speed up the rate of commissioning for 2015-20 at this stage.

5. CONCLUSIONS AND RECOMMENDATIONS.

As of August 2007, 294 reactors and isotope production facilities use HEU fuel or target material, of which 154 are used for naval propulsion. The existence of additional facilities cannot be ruled out as there is disagreement as to whether several facilities are HEU-fueled or not. These nearly 300 HEU-fueled facilities annually need more than 10 000 kg of HEU with various enrichment levels, out of which more than 3 500 kg is HEU for naval propulsion, more than 900 kg HEU in civilian research reactors, and more than 80 kg HEU for isotope production in civilian facilities, in addition to 6 000 kg HEU in various other types of reactors, such as breeder facilities, Russian Pu-production reactors and other military reactors. As the facility burn-up levels vary between 1-70%, large amounts of spent fuel with significant amounts of HEU are generated, large parts of which are recovered through reprocessing, especially in Russia. However, significant quantities are stored at multiple facilities worldwide. Top priority should be given to the effort to establish a comprehensive list of all HEU-fuelled facilities and fuel storage facilities.

The establishment of baseline measurements for assessing the results of the current HEU minimization effort calls for additional focus on the scope and methodology for HEU minimization. 48 civilian research reactors, representing a decrease in HEU consumption of 278 kg – or 19% compared to the amount of HEU consumed in 1978 in similar facilities, have completed the conversion to LEU as a result of international assistance over the past three decades. 130 HEU-fueled reactors with HEU consumption of 450 kg have been shutdown. There should be no need to convert all 133 research facilities – or the 73 facilities currently part of the GTRI conversion programs – as decommissioning and dismantling should play a significant role in the future HEU minimization effort as well. The justification for having only 56% of the remaining HEU-fueled research facilities within the scope of the GTRI program should be revisited. The GTRI programs – as the driving force for HEU minimization in research reactors – have not had sufficient means to address decommissioning in the past, and there is little indication how these programs will be able to put an additional emphasis on decommissioning in the future. Several reactors were shutdown within five years after conversion. As the issue of decommissioning touches upon a whole set of other issues, such as different international and national strategies for nuclear research, perceptions of progress and national pride, as well as local and regional issues, it remains an open question as to whether GTRI is the appropriate framework for addressing these issues.

The US naval propulsion fleet outmatches the number of civilian HEU-fueled research reactors worldwide, and currently has annual HEU consumption levels in the range of 2 metric tonnes of HEU, which will remain constant for the foreseeable future. For nuclear propulsion, HEU has long offered unprecedented advantages in terms of core compactness, power outputs and operational modes. Sensitivity concerns are high, keeping nuclear naval propulsion activities in a shroud of secrecy. But such non-explosive applications represent a significant fraction of HEU stocks. The first step to examine these uses could be an international conference examining the justification for eliminating HEU-fueled facilities, that addresses both military and civilian issues. However, this seems impossible within the frameworks of current assistance programs.

6. ACKNOWLEDGEMENTS

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