Components of Naval Nuclear Fuel Transparency

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Chapter 1: Introduction

The primary obstacle to clandestine and unlawful nuclear weapon production is to get access to sufficient quantities and qualities of fissile material. Highly enriched uranium or plutonium is the essential components of any nuclear explosive device. It is considerably easier to make a bomb using enriched uranium than using plutonium.[2] Potential proliferators could therefore try to divert uranium material directly from any weapons-usable source, e.g. from the naval fuel cycle, due to the extremely high enrichment levels and low radiation levels.[3] Highly enriched naval fuel cycles may thus serve as a back door for production of clandestine nuclear weapons.

To increase confidence in non-diversion of naval fuel and to support contemporary nuclear arms control efforts, this report suggests a set of transparency measures that could be introduced on stockpiles of naval fissile material. Particular attention will be given to U.S. and Russian naval fuel stocks, as these are by far the most extensive in the world. The U.S. and Russia are nuclear weapon states and their fissile material is therefore not subjected to safeguards under the Non-Proliferation Treaty.[4]

As international nuclear arms control stands poised to move beyond agreements limiting strategic delivery systems, and the international community tries to shrink the noose around all stockpiles of weapons-grade fissile material, they will, sooner or later encounter the stocks of highly enriched uranium destined for naval nuclear prolusion purposes.[5] Moreover, as Russia is currently evolving plans for the construction and possible export of floating nuclear power plants, using reactors fuel with HEU, new markets for HEU outside international control could, emerge. If this fuel has been enriched to 90 % or higher, as low as 10 fuel assemblies could supply enough highly enriched uranium for a bomb.[6] Yet, the level of international control and transparency on these large and highly proliferation-attractive stockpiles is strikingly low.

The report identifies ways to increase transparency in the naval fuel cycle without conflicting with national security needs or concerns, and argues that such transparency measures will give long-term nuclear security benefits. The report is divided into five chapters and two appendixes. Following this introductory chapter, the next chapter provides a general background on fissile material transparency, including definitions, recent political transparency commitments, and a discussion of obstacles to transparency, both of a justified and of unjustified character. Chapter 3 deals with the current transparency situation – or more correctly, the lack of such measures – regarding naval fuel cycles, both in nuclear weapon states and in non-nuclear weapon states. Chapter 4 suggests a set of transparency components that could be acceptable to the possessors of nuclear submarines, as a foundation for a voluntary naval fuel transparency regime.

Conclusions and recommendations for the implementation of the proposed transparency components are given in Chapter 5. Appendix I provides an analysis of current and future naval fuel consumption levels in the U.S. and Russia, and technical background information on the fuel. The analysis shows that existing naval fuel stockpiles in the two states are substantial and that their fuel needs in the future are diminishing. This could ease the political process of introducing transparency on the highly sensitive naval fuel cycles. In appendix II, the proliferation potential of naval fuel is discussed, including an assessment of the challenges associated with using naval HEU fuel as the fissionable explosives of crude nuclear devices. This assessment is presented to underline the need for increased international focus on all HEU naval fuel cycles, with a future international naval fuel transparency norm as the ultimate goal.

Throughout the text, the term "transparency" is used to cover voluntary measures initiated by the individual state(s) to increase international confidence in non-diversion of naval fuel for nuclear explosive purposes.

Chapter 2: Why fissile material transparency?

While existing arms control agreements do not include any restrictions on the stockpiles of fissile material, the stocks of fissile material place a *de facto* upper limit on the number of warheads that can be produced. Today there is no requirement to eliminate any nuclear warheads: current agreements only require elimination of delivery systems and put limits on the number of warheads each can carry. The existence of large stockpiles of fissile material will create a potential for rapid and large-scale “breakouts” from treaty obligations. Thus, if military nuclear arms reductions are to be made permanent, more information will have to be made available about *all* military stocks of fissile material, and steps must be taken to reduce these stocks so that they cannot be easily re-introduced into nuclear weapon assemblies or used in crude nuclear explosive devises.

Fissile material transparency is therefore likely to become an increasingly important tool for addressing both arms control and nonproliferation issues in the coming decades.[7] Accurate information on the stocks of fissile material is prerequisite for gaining control of and confidence in non-diversion of the material. The considerable uncertainties in fissile material inventories could in fact prove to be the largest obstacle for verifying nuclear disarmament.[8] International transparency of fuel stocks, while protecting proliferation sensitive information, is therefore likely to support both global nonproliferation efforts and the long-term security interests of Russia and the United States.[9]

Until recently, it was assumed that information on plutonium and HEU stocks should be available only to governments, industrial companies and international agencies. In most countries that possess nuclear weapons or that are trying to acquire them, information about HEU and plutonium production is still classified. The latter part of the past decade has seen a political shift and there is now widespread agreement that greater transparency is a desirable goal.[10]

This is reflected both in bilateral transparency commitments and the voluntary stockpile declarations put forward by some of the nuclear weapon states, notably the U.S. and the U.K.

More information is now available about military nuclear programs than only a few years ago, but still there exist no official figures on the military inventories of HEU in the nuclear weapon states.[11] U.S. estimates of the size of the Russian fissile material stockpile have an uncertainty factor of more than a hundred tons.[12] Moreover, hardly any of the measures necessary to verifiably reduce stockpile of nuclear warheads and fissile material to low, agreed levels are in place. These are measures that will have to be developed by the states with the largest stockpiles: the United States and Russia.[13]

Once introduced and in place, transparency measures could have a self-intensifying effect. Voluntary measures will generate increased confidence in the peaceful (non-offensive) nuclear intentions of the adversary, reducing tensions and the perceived need for secrecy. It is to be hoped that they will create a climate of new declaration and openness, producing a positive response to the disarmament and nonproliferation processes. The goal of confidence building is to release information through transparency activities that can corroborate that no clandestine activities are taking place, bolster the validity of material accounting, confirm that nuclear material is adequately protected, and verify that nonproliferation obligations are being met.

Thus there exist several interrelated incentives for increased transparency on all stocks of fissile materials, including materials destined for naval nuclear propulsion:

- to gain confidence in non-diversion,
- to maintain constructive security dialogues,
- to raise awareness of international nonproliferation challenges, and
- to identify the best and most sustainable nuclear security options.

The meaning of transparency

"Transparency" could be understood as measures that *provide confidence* that a activity is taking place. "Verification", however, could be understood as measures that *confirm* that a activity is actually taking place. For arms control, transparency involves for instance measures that build the confidence of each side in its understanding of the size of the other's stockpiles of nuclear weapons and fissile material, and the rate of reduction of these stockpiles.[14] Implementing international verification and transparency measures will not necessarily be the same as applying IAEA safeguards, though some of the measures (e.g. declarations) and techniques employed may have common features.[15]

Nuclear weapons states under the Non-Proliferation Treaty have an obligation not to disseminate sensitive nuclear information to non-nuclear weapon states.[16] However, the internationally most credible way of preventing clandestine and unlawful use of plutonium or uranium is to place surplus stocks under international or bilateral surveillance. Thus, the major incentive for promoting transparency on existing stocks of fissile material is not primarily to supply security to the material itself (which may be adequate in most nuclear weapon states), but to reassure the international community that the material will not be diverted to other uses.

Transparency itself will necessarily be a dynamic process, dependent on the audience, the timing requirements of the activities, the location of the effort (country or facility where activity takes place) and changes in the international environment.[17] Also culture will have an impact on transparency, as cultural characteristics and beliefs will affect how it is interpreted. Bearing in mind the different dynamics of interrelationships, one could define transparency as a: ".... cooperative process that is based on thorough risk-benefit assessments and that (1) increases openness and builds confidence, (2) promotes mutual trust and working relationships among countries, national and international agencies, and the public, and (3) facilitates verification and monitoring measures by information exchanges."[18]

Thus, transparency is more than a description of a nuclear program or a specific site. Based on voluntary measures, it permits the accumulation of data, both direct and indirect, over an extensive period of time to build confidence that behavior of a country or a group of countries is consistent with agreements and norms. Transparency surpasses such required activities as reporting to regulatory bodies. Transparency has been aptly described as “permitted knowledge”.[19] The voluntary release of information is the true measure of transparency. Moreover, taking extra steps of openness beyond expectations will promote even higher levels of trust.

Political transparency commitments

With the end of the Cold War have come substantial changes in how nuclear powers view their stockpiles of weapons and their stocks of fissile material. There appears to be a growing willingness on the part of most of the established nuclear powers to reduce the sizes of their stockpiles and to use the excess material for peaceful energy production, or to provide for their ultimate disposal under stringent safeguards.[20]

As a part of this process, the United States and Russia have launched several bilateral nuclear warhead and material transparency efforts. The first of these was launched at the January 1994 summit when the presidents of both countries agreed on a goal of “ensuring the transparency and irreversibility of the process of reduction of nuclear weapons.” The initiative, dubbed the "Safeguards, Transparency, and Irreversibility (STI)" initiative, was designed largely to ensure that fissile material from eliminated warheads would not be recycled into new weapons.[21]

Despite the good intentions and practical work (such as working groups for spot checks to increase confidence in fissile material declarations, and mutual reciprocal inspections) the STI initiative collapsed when the two countries could not commit themselves to an agreement that would allow the cooperative exchange of sensitive and classified information.[22] All the same, interest in political transparency remained alive, and the issue was resurrected at the March 1997 Presidential Summit in Helsinki when Presidents Yeltsin and Clinton agreed that the proposed START III agreement would include transparency measures.[23]

Moreover, as part of the U.S. Openness Initiative, the Department of Energy released a report on plutonium production, acquisition, and utilization in the U.S. from 1944 through 1994.[24] The United States is expected to release similar information on its HEU stockpile and use in the near future. The extensive production of uranium and the complexity of the uranium fuel cycle render such assessment more challenging than the plutonium account.[25] The intentions behind the 1996 plutonium report were to aid in discussions of plutonium storage, safety and security with stakeholders, as well as to encourage other nations to declassify and release similar data.[26]

Unfortunately, Russia has not released any official information on its fissile material stockpiles. Russian officials and laboratory experts have indicated that the country lacks the funds for compiling such information in a format comparable to that used by the United States concerning its plutonium stockpile. This has led to a proposed lab-to-lab contract, whereby the United States would undertake to pay the cost of preparing an inventory of Russia's plutonium stockpile in return for receiving information at the same level of detail as that already released by the U.S. [27]

Obstacles to transparency

At first glance, transparency and security may seem like incompatible and conflicting interests: it may be argued that any openness is likely to harm the long-term security interests of a nation due to its loss of control of information. Transparency measures could introduce the risk that classified, sensitive or proprietary information might be compromised or released – with adverse impacts on national security and international obligations.[28] Apart from the proliferation risks, this may increase vulnerability and lessen the (political) strength of the nation, as sensitive technical information and weaknesses could be revealed. Moreover, increased openness could make it easier for criminals and sub-national groups to divert fissile material unlawfully, if government details of the physical protection systems and quantities and qualities of fissile material at facilities were to be made available.

Some of the objections to transparency are clearly well founded and justified, based on proliferation risks. Others, however, may be outdated and based more on traditions of "instinctive" secrecy. Secretiveness has traditionally had a special status within nuclear weapon complexes. Divulging technical information has been seen as being on a par with the surrender of status, and has often been viewed as defeat.[29]

Some guidelines would seem necessary to facilitate the delicate processes of transparency. For one thing, a transparency measure should generally not release information that could be damaging to the very nonproliferation interests it seeks to promote. Thus, detailed information concerning sensitive nuclear technology and physical protection of the material at each facility should not be released. Also industrial and proprietary rights could be harmed by far-reaching transparency (e.g. at sites with cutting-edge MPC&A – Material Protection, Control and Accounting – technology), and should be protected to the extent possible. Normally, domestic and international agreements and laws, derived from sensitive nuclear technology and physical protection requirements, have been established to prevent the dissipation of both sensitive information and information containing proprietary secrets.

Moreover, practical limitations may hamper the introduction of transparency measures. Companies already contractors at one or more sites would want to stay in control of their technology and maintain a competitive edge. Nor should one underestimate the costs and possible impact on the operation of the facility that introducing transparency through monitoring could involve. Indeed, it would seem that the more transparency that is requested, the greater the cost.[30]

If transparency measures are to proceed and gain momentum, all these factors must be dealt with in ways specifically designed for that purpose. While the technology applied may limit the negative impacts of increased insight (e.g. by the introduction of verification with information barriers), traditional secrecy could prove to be the most transparency-resistant obstacle, just as it has blocked the progress of joint U.S.–Russian security upgrades of Russia's fissile material.

Chapter 3: The naval fuel cycle and the *lack* of transparency

All the five declared nuclear weapon states under the Non-Proliferation Treaty possess nuclear-propelled submarines. However, as nuclear weapon states, they are all exempted from international (IAEA) safeguards and other monitoring activities.[31] Sensitivity issues and the strategic importance of nuclear submarines have led the nuclear weapon states to maintain a high degree of secrecy around their own nuclear naval operations. Very little is officially known about U.S. and Russian submarine nuclear fuel designs, production technology, operational data and naval fuel stocks.[32]

The lack of transparency on the U.S. naval fuel cycle

No official figures exist on the U.S. stockpiles of HEU for naval purposes or material destined for future naval consumption. Estimates indicate an overall consumption of HEU in U.S. reactors since the dawn of nuclear propulsion of approximately 120 tons – some 12% of the total U.S. HEU production of nearly 1,000 tons.[33]

As the U.S. has stopped enriching HEU, the U.S. Navy relies solely on weapon stocks of HEU for its naval propulsion program. While this may complicate any introduction of transparency measures, portions of the U.S. HEU stockpile are already subject to somoe international verification: As part of its fissile material cut-off initiative launched in 1993, the Clinton Administration offered to allow the IAEA to inspect about 10 tons of HEU at the Y-12 plant at Oak Ridge in 1994.[34] Furthermore, to demonstrate the U.S. commitment to irreversibility and the nuclear disarmament process, President Clinton announced in March 1995 that another 200 tons of fissile material would be permanently withdrawn from the U.S. nuclear weapon stockpile. Of this material, 173.4 tons is HEU, in many chemical forms.[35]

Still, there is only 12 tons of excess fissile material under international safeguards at three U.S. Department of Energy (DOE) facilities.[36] In addition, approximately 50 tons of excess HEU were being down-blended at an NRC-licensed[37] facility under international safeguards.[38] These down-blending operations began late 1999 and will continue for six years. However, none of the material currently placed under international safeguards is designated or suitable for the naval fuel cycle.

In fact, the U.S. Navy has been proceeding with extreme caution, keeping in military reserve *all* the fissile material usable for naval propulsion. The low proportion of higher enrichment levels in HEU declared excess to national security needs stems from U.S. Navy insistence that such material be reserved for its possible future needs. With the exception of the first 10 tons declared excess, all of the HEU that the U.S. has declared excess failed to meet the specifications for use in naval fuel.[39] Of the 174.3 excess tons of HEU, about 33 tons are enriched over 92%, and 142 tons are enriched between 20 to 92%.

Moreover, the pledges given by the U.S. that no fuel ever put under international safeguards will be withdrawn for military purposes do not apply to the Navy. It could withdraw HEU that has been declared excess to national security needs and put under safeguards, to use it as naval reactor fuel.[40] However, the Navy has never evoked its unique pullback option. The U.S. Navy plans well and probably does not intend to use currently safeguarded excess material for its programs; moreover, attempting to do so would a steep uphill political climb. The policy of withdrawal allowance should undergo review, as it is likely to undermine the evolving norm of irreversibility in nuclear arms control.

The lack of transparency on the Russian naval fuel cycle

As is the case for the U.S., no official figures exist today on Russia's stockpiles of fissile material in general, or on its naval stocks in particular. Transparency is extremely limited.[41] Estimates, all of them involving huge uncertainties, indicate a remaining military HEU stock in Russia of 1,010 tons at the end of 1997, including the 500 tons of HEU slated for sale to the United States under the U.S.–Russian HEU deal. Russia's overall HEU naval fuel production through the year 2000 alone is estimated at more than 140 tons.[42] Russia alone may now hold as much as 80 to 85 metric tons of HEU for naval propulsion.[43] This proliferation-attractive material has never been exposed to international or bilateral control or safeguards.

However, as part of ongoing efforts to secure fissile material in Russia, the joint U.S.–Russian MPC&A upgrading at naval facilities has been quite successful, and clearly better able to deal with the sensitivity issues hampering other parts of the assistance program.[44] The DOE has forged close working relationships with officials in the Russian Navy, overcome security concerns about the location of the naval fuel, and gained access to install physical protection systems and accountancy systems at these centralized but still sensitive sites. This may be a sound start for future transparency on the Russian naval nuclear fuel cycle.[45]

The lack of safeguards on naval nuclear cycles in non-nuclear weapon states

Naval nuclear stockpiles outside the nuclear weapon states may also constitute a potential problem. Paragraph 14 of the comprehensive IAEA safeguards agreement under the NPT allows any state to withdraw nuclear material for peaceful uses from safeguards if it is being used for a "non-proscribed military activity".[46] Thus, naval nuclear fuel may represent a loophole for nuclear weapon production even outside the nuclear weapon states. True, the safeguards agreement stresses that, during the period of non-application of safeguards, the nuclear material must not be used for the production of nuclear weapons or other nuclear explosive devices. However, there is no prohibition of the non-explosive use of nuclear material, equipment or technology for a military purpose such as the propulsion of naval ship. Against this backdrop, concerns have been voiced that the naval fuel cycle could be used as a back door to nuclear weapons.[47]

A non-nuclear weapon state under the NPT that wishes to acquire enriched uranium for submarine propulsion could either invoke the paragraph 14 exemption or could avoid IAEA safeguards entirely by obtaining unsafeguarded material from a nuclear weapon state or a non-NPT state.[48] The latter is possible because the NPT requires safeguards only on special fissionable material provided to a non-nuclear weapon state for peaceful nuclear activities.[49]

More far-reaching scenarios could include non-nuclear weapon states under the NPT building uranium enrichment and fuel fabrication plants for the production of submarine fuel and claiming that the material is not subject to IAEA safeguards since it is dedicated to non-proscribed military use. There would be no means for verifying that the material and facilities were not being misused to make nuclear weapons. In either case, the result would be that some of the HEU in a non-nuclear weapon state under the NPT would not be subject to IAEA safeguards. This loophole was deliberately introduced into the treaty to accommodate some of the states involved in the negotiations and who were considering acquiring nuclear-propelled naval craft and wished to avoid foreign inspections, accountable to an international organization, on board such ships.[50]

Increased transparency in the naval fuel cycle can also be paramount for the U.S. goal of prompting a resumption of negotiations on the next key multilateral step in the nuclear disarmament process: a treaty to ban the production of fissile material for nuclear weapons or other nuclear explosive devices.[51] If a future Fissile Material Cut-Off Treaty is to be implemented with a high level of confidence that no clandestine HEU diversion is taking place, and to bolster the HEU stockpile accounting and control under such a treaty, then the non-explosive uses of HEU (e.g. naval uses) must comprise part of the agreement.

The strategic importance of submarines makes probable a sustained interest in nuclear submarine propulsion across the world.[52] Moreover, Russia's emphasis on floating reactors to provide energy to remote areas may lead to increased use and possible future exports of naval reactor technology and HEU fuel. Guidelines and a regime have been proposed and advocated to limit the potential impact of the current HEU loophole in the Non-Proliferation Treaty –without significant political support so far.[53] A related approach for increasing international confidence in non-diversion of naval fuel would involve establishing a norm of increased, voluntary transparency. If implemented, such a norm could boost long-term nuclear safety of both non-nuclear weapon states and nuclear weapon states. In the following, the possible components of such a transparency standard will be discussed.

Chapter 4: Components of a naval nuclear fuel transparency regime

The introduction of transparency on sensitive items will have to balance carefully the information extracted against security and classification concerns. All the same, there seem to be good prospects of such measures being implemented on the sensitive naval fuel cycle, as political acceptance of the concept of transparency is emerging. This could, together with the new technical opportunities of high-quality and non-intrusive verification measures, create an important foundation for new transparency initiatives.[54]

The naval nuclear fuel transparency measures could include the following as part of a more comprehensive, future transparency regime: [55]

- declarations of total HEU quantities dedicated to naval propulsion (including estimates of future needs)
- voluntary, non-intrusive verification on designated parts of the naval fuel cycle
- description of all facilities used for producing naval fuel, including production records and material balances for each facility
- information on the status of each naval fuel batch (whether fresh fuel/spent fuel, in storage, or in operating reactors, and its final disposition) and location of the material
- an account of any fissile material removed from the naval inventory, such as:
    - material consumed during operation
    - material transferred to the national surplus stockpile and/or down-blended to LEU (low-enriched uranium)
- declarations of any naval fuel placed under international safeguards.

Declarations on the status of the fuel batches, estimates of future fuel needs and the accounting of material removed from the naval cycle should be made regularly, perhaps on an annual basis. In the following, each of the items above will be discussed in more detail, and on-going and related nuclear arms-control activities will be presented.

Declarations of the total HEU quantities dedicated to naval propulsion

Due to major uncertainties as to current stocks of fissile material, both initial and regular declarations are particularly important. Confidence in the declarations given would be boosted if non-intrusive spot checks of these declarations were permitted.[56] Information on the mass, chemical and isotopic composition (enrichment) of the fuel is desirable because it promote greater confidence in the declarations, but this may also raise the risk of reveling and disseminating highly sensitive proliferation information.

The total declared quantities of uranium and the annual consumption levels can be estimated on the basis of operating history and other open-source information. Other countries – or, under bilateral U.S.–Russian transparency agreements, the U.S. and Russia – can evaluate whether the quantity declared for naval purposes appears plausible on the basis of its understanding of the number, the power, and operating patterns of the reactors. Their inspectors should verify that the amounts being released into the naval fuel cycle match the declarations.[57]

Moreover, as spent naval fuel will be less proliferation-attractive (due to the high radiation levels), early transparency measures could focus on verifying the status of the spent fuel. At the back end of the fuel cycle, if the spent fuel were reprocessed, inspectors could check the weights and assays of the recovered uranium and plutonium. It would also be possible to assess declarations of the amounts of uranium-235 that had been fissioned by measuring the quantity of uranium-236 in the residual uranium.[58]

Formalized agreements already exist for some fissile material stockpile declarations. One example is the guidelines agreed to by the five declared nuclear weapon states under the NPT, together with Belgium, Germany, Japan and Switzerland, to increase the transparency of the management of civil plutonium by publishing annual statements of each country’s holdings of civilian plutonium.[59] In principle, these guidelines cover all plutonium in all peaceful activities, but focus on the material that poses the greatest proliferation concern: Separated plutonium, whether in storage, in unirradiated mixed oxide (MOX) fuel elements, in other unirradiated fabricated forms, or in the course of manufacture or fabrication into these items. The guidelines also apply to plutonium declared excess to military nuclear programs. Plutonium in spent fuel is not the focus of the guidelines, but each country has agreed to publish annual estimates of the amount of plutonium in its spent nuclear fuel.

The nine nations which have agreed to the guidelines will publish:

- occasional brief statements explaining their national strategy for nuclear power and spent fuel, and their general plans for managing national holdings of plutonium
- annual statements of their holdings of all plutonium subject to the guidelines
- annual statements of their estimate of the plutonium contained in their holdings of spent civil reactor fuel.

These annual publications of the civil holdings have been generally successful in creating more transparency. However, in accordance with the goal of universal membership and adherence, more countries possessing civilian plutonium need to be involved. Still, the plutonium declarations could serve as a useful model for future naval fuel declarations.

Voluntary, non-intrusive verification on designated parts of the naval fuel cycle

Any forms of verification allowed to be performed on the sensitive naval fuel cycles are likely to boost confidence in declarations and the overall transparency. Also here, the challenge is to protect classified information while allowing the inspecting party to draw independent and accurate conclusions.

Some elements of a fissile verification regime for sensitive HEU stocks have already been introduced, both through bilateral and trilateral agreements. The U.S.–Russian HEU deal and the trilateral IAEA–U.S.–Russian cooperation to remove excess material from military stocks have generated verification and monitoring measures, all within acceptable ranges of the nuclear weapon states involved.[60] Such measures, briefly described in the following, may provide an important point of departure for future non-intrusive HEU verification of the naval fuel cycle.

The HEU deal

February 1993 saw the signing of the Agreement between the Government of the United States and the Government of the Russian Federation Concerning the Disposition of Highly Enriched Uranium Extracted from Nuclear Weapons. This HEU deal allowed, for the first time, the conversion of weapon-grade nuclear material from dismantled warheads to commercial reactor fuel for electricity generation. Commonly referred to as "Megatons to Megawatts", the deal had, by the end of 1999, resulted in the dilution of over 35 tons of weapons-usable uranium. In many ways, the HEU deal may constitute the single most important nonproliferation measure introduced bilaterally, covering a significant part of Russia's weapon stockpile of HEU.

After a slow start and organizational difficulties, implementation of the agreement is accelerating and new transparency measures have been installed. For the U.S. Department of Energy (DOE), there are three transparency objectives. Firstly, that the HEU is extracted from nuclear weapons, secondly, that the same HEU is oxidized, and finally that the HEU is blended into LEU.[61] For *MINATOM,*[62] the transparency objective is that the LEU is fabricated into fuel for commercial nuclear power reactors.[63]

Portable instruments are used to confirm the presence of HEU in weapons-component containers; once the component has been removed from the unique shipping container, U.S. monitors use the instruments to confirm that no HEU remains in the container. The portable units determine the level of U-235 enrichment of metal chips that results from the machining of the HEU metal components from the weapons.[64] Even though the choice fell on a system less intrusive and less likely to reveal sensitive information, after over two years of operation, all its measurements had been consistent with the declared enrichment.[65]

The Trilateral initiative

The removal of weapon-origin fissile material from the defense programs of Russia and the U.S. furthers the obligations of the two states under the Article VI of the Non-Proliferation Treaty. The Trilateral Initiative would place both excess U.S. fissile material and excess Russian fissile material stored at the *Mayak* facility (in the Chelyabinsk region) under IAEA safeguards. Progress has been made toward completing a model verification agreement that will serve as the basis for implementing the new verification measures. Unfortunately, progress on these measures has been slow, both because the measures overlap with the U.S.–Russian negotiations on Mayak transparency and because concerns about protecting sensitive information from international inspections remain.[66]

Under the Trilateral initiative, the requirement is not to verify the weapons origin of HEU and plutonium but to promote international confidence in the assurance that the material is not used in the production of new weapons. The aim is to provide transparency on the steps taken to reduce the stocks of fissile material potentially available for the use in nuclear weapon programs.[67] Thus, the commitments to the initiative must be irrevocable, and verification must follow from storage through the disposition activities, remaining in effect until the fissile material is rendered no longer usable in nuclear weapons.

To begin the trilateral IAEA verification as early as possible, special technical provisions are being developed that will allow the two states to submit dismantled nuclear weapon components or other classified forms of fissile material, with the assurance that IAEA inspectors will not acquire information relating to the design or manufacture of such weapons.[68] The U.S. will ensure that the material (and facilities) which it has opened for international inspection will not provide IAEA inspectors with proliferation-sensitive information. This is to be accomplished by vulnerability assessments, by limiting the information given to international inspectors to that has been determined to be safeguard-relevant and mission-essential.[69]

Important progress has been made in developing and testing verification equipment. A prototype verification system for plutonium has been built and demonstrated (under conditions expected in the field) at the Los Alamos National Laboratory. This prototype combines standard non-destructive measurement techniques with a new technology known as “information barriers” designed to allow inspectors to derive sufficient, credible information for verification, while preventing access to classified information. The prototype provides a means to evaluate previously identified concepts. Tests have shown that verification under the security constraints could meet the security exigencies of the states and the verification requirements of the IAEA.[70] As equipment for HEU measurements evolve, the techniques and procedures are probably applicable to the sensitive naval fuel cycle as well.

Description of naval fuel-producing facilities

Better knowledge of the production history of naval fuel-producing facilities ensures against clandestine production, simultaneously raising confidence that no such production is taking place. The introduction of transparency measures on naval fuel production facilities will be challenging, but ongoing international work may support such efforts.

The new Model Protocol, INFCIRC/540 (Corrected) represents an attempt to broaden the scope of international safeguards with much more comprehensive declarations.[71] Under this safeguards protocol, states are required to declare and submit to international control all nuclear material production facilities, whether operating or not. Many of the same set of provisions is likely to be included in a future Fissile Material Cut-Off Treaty, to avoid covert weapon production and suspicion of such activities. Again, it can be worth exploring the symbiotic effects on the naval fuel cycle, concerning naval fuel production facilities in particular.

The status of naval fuel batches

It may be desirable to have descriptions and inspections at such production facilities as the Russian Electrostal's fabrication line for highly enriched uranium fuel, but this is unlikely to be accepted due to sensitivity problems. Alternatives to boost confidence in non-diversion could therefore be explored. By introducing tags and seals on the transportation containers leaving the production facility, fuel batches could be tracked throughout the fuel cycle, from the production line to temporary storage, up to the stage when the fuel is introduced into the reactors. The container tags could be reapplied after submarines have been refueled/defueled, tracking the fuel to the point of final disposition or use (or down-blending).

An account of fissile material removed from the naval inventory

Whether the removal of fissile material occurs through consumption or transfers, any and all material removed from the naval stockpiles should be accounted for. Declared consumption levels may again be checked against estimates based on open-source information and submarine operating history. In the event that naval fuel is put under international safeguards, specific declarations should be made.

Chapter 5: Conclusion and recommendations

The lack of transparency on the naval fuel cycles is likely to be detrimental to long-term nuclear security of both nuclear weapon states and non-nuclear weapon states. The persistent interest in naval nuclear propulsion around the world, possible exports of Russian naval reactor technology, and the tempting naval nuclear loophole in the NPT safeguards agreement – all of these could create new HEU markets beyond international control. The need for an international transparency norm to increase confidence in non-diversion of highly enriched naval fuel to clandestine nuclear weapon production may therefore be stronger than anticipated.

The components of the transparency regime for naval fuel proposed here represent a minimal, non-intrusive approach to avoid the disclosure of sensitive information while at the same time providing a way of increasing the confidence in non-diversion of naval fuel to nuclear weapon production. Today there is growing political interest in nuclear transparency in general. Technical transparency solutions that might be applied on the naval fuel cycle are evolving in related nuclear arms-control arenas.

Thus, a step-wise approach, allowing to increase the confidence of the international community and potential opponents in non-diversion of the highly proliferation attractive naval fuel to clandestine weapon production, should be considered. In particular, such a transparency regime could consist of a combination of voluntary declarations of quantities and qualities of material destined for naval consumption, and, desirably, non-intrusive spot-checks on strategic points along the fuel cycle.

Experience from bilateral nuclear security cooperation with Russia has shown that cooperative programs can succeed only if they are carried out as true partnerships, as ventures serving both Russian and American interests.[72] To create the proper environment for naval fuel transparency measures, the U.S. could take the lead and reiterate and expand U.S.–Russian transparency efforts, tailoring the transparency measures to fit Russia’s own interests by offering strategic, technical and financial incentives. A valuable foundation for non-intrusive transparency on the Russian naval fuel cycle has been created by the highly successful cooperative naval fuel security upgrades, due to the close working relations established and the ongoing consolidation of fuel to a limited set of storages.

To support these efforts, the U.S. could consider allowing surplus naval fuel to be included in the national declarations of excess nuclear material. Additionally, it could abandon its current option of allowing nuclear materials to be withdrawn from international safeguards for the use as naval fuel.[73]

Appendix I: U.S. and Russian Naval Fuel – Current and Future Needs[74]

In this appendix the current and future needs of naval fuel in the U.S. and Russia are assessed, as part of an investigation of how well and how easy a future naval fuel transparency regime may be implemented politically,. The United States and Russia both have extensive naval propulsion programs which use highly enriched uranium (HEU) in the reactor cores. Their naval programs involve by far the largest fleets globally.[75] The naval fuel cycle represents some 10 to 15% of the total HEU economy in both states.

For various reasons, fuel requirements in the two countries are likely to be reduced over the coming decades. While the overall U.S. naval fuel requirement will be reduced mainly due to the introduction of life-time reactor cores and some decline in the number of operating reactors, Russian naval HEU consumption will continue to decrease due to the Russian Navy's reduced operational status and severe fleet reductions. Ideally, such reduced fuel demands could serve to facilitate the implementation of non-intrusive, voluntary transparency measures on proliferation-attractive fresh naval fuel.

This appendix scrutinizes current U.S. and Russian stockpiles and future needs of HEU for naval propulsion. Both navies maintain a high degree of secrecy around their nuclear operations, and very little is declared officially about submarine nuclear fuel designs, production technology, and operational data. However, assessments of the current and future naval fuel economy can be made on the basis of the number of operating vessels and other available open-source information.

U.S. naval program

U.S. naval nuclear propulsion reactors use uranium enriched to at least 93% in U-235.[76] This is material that is directly useable in nuclear weapons.[77] On the basis of estimates during the 1980s, Cochran et al. found that a U.S. submarine reactor core contains an average of 200 kg of U-235 enriched to 97.3%, the rest of the core being U-238.[78] Larger as well as smaller core loads are possible, but such enrichment levels are supported by other open-source information.[79] Over the years U.S. naval reactor technology has improved, increasing both the power output and the overall performance of submarines, and leading to a steady increase in the core lifetimes of reactors.[80] Today's U.S. submarines put to sea with reactors that will last the life of the ship, obviating the need for refueling.[81]

Naval fuel is highly robust and designed to operate for many years in a high-temperature, high-pressure environment.[82] To ensure that it will be capable of withstanding battle shock loads, naval fuel is surrounded by large amounts of zirconium alloy.[83] Further exploitation of the modified fuel process and better understanding of various reactor technologies that permit more optimized designs will further increase the energy density for the next generation of naval reactors. Currently, new structural material, coolant chemistries, reactor plant arrangements, and core configurations are being investigated by the U.S. Naval Reactors.[84]

Forty percent of the combatant ships of the U.S. Navy are nuclear powered, including all U.S. submarines and 75% of the aircraft carriers.[85] Taking into account also the naval prototypes, 103 U.S. naval reactors were operating as of October 1999 (see table A1).[86] This makes the number of U.S. naval reactors comparable to the number of commercial power reactors in the U.S. This is also nearly equal to the number of reactors in the next two largest commercial nuclear power-producing countries, France and Japan, combined. All U.S. naval reactors are of the light-water pressurized type (PWR).[87]

Type of vessel	**Number of vessels**	**Number of reactors in vessel**	**Total number of reactors**
SSBN[88]	18	1	18
SSN[89]	56	1	56
NR-1[90]	1	1	1
Nuclear aircraft carriers[91]	9	2 (8)	16 + 8
Prototypes[92]	4	1	4
SUM	88		103

Table A1. U.S. naval reactors operating as of October 1999

During the 1990s, the U.S. ballistic missile submarine (SSBN) force was reduced from 32 submarines (armed with 584 missiles and 5024 warheads) to 18 submarines (carrying 432 missiles with 3456 warheads).[93] In 1990, 23 of the active submarines dated from the 1960s. In contrast, today's SSBN fleet consists entirely of Ohio-class submarines.

The fleet of attack submarines (SSNs) included more than 90 boats throughout most of the 1980s, and peaked at 98 boats in 1987.[94] The number of operating U.S. attack submarines is dropping as the U.S. Navy is remodeling its submarine force for the 21st century. Today, 82 fast-attack submarines are assigned to the Atlantic and Pacific Submarine Forces,[95] 56 of which are nuclear propelled. The older SSNs, some of them launched back in the 1960s and 70s, will successively be decommissioned and replaced by the New Attack Submarines (NSSNs). In September 1999, the keel was laid for the U.S. Navy's first new nuclear attack submarine, USS *Virginia,* the lead ship in what will be called the Virginia-class submarines.

The U.S. fleet has undergone extensive modernization and reductions in recent decades. Between 1995 and the end of 1999, the number of operating reactors was reduced from 158 to 103. The reactor fuel and core vendor industrial base has shrunk in response to the downsizing of the Navy following the breakup of the Soviet Union, and in response to the reduced requirements due to the continuously increasing lifetimes achieved in HEU-reactor cores.[96] The United States is now disposing of reactors from decommissioned ships at the rate of about six per year.[97]

Future U.S. naval reactors and fuel consumption levels

No new SSBNs are currently projected, but existing U.S. Department of Defense guidelines call for a force of 50 attack submarines, although some studies have called for raising the number to as many as 72.[98] As for the strategic vessels, the same uncertainties in out-year projections of the defense budget render the future SSN manufacture uncertain. Under the most extensive plans, the U.S. Navy plans to spend USD 64 billion to acquire 30 New Attack Submarines by the year 2016.[99] These purchases will allow the Navy to maintain its force-structure goal of 50 boats. Higher numbers would require modifications to current plans.[100]

The future deployment of other types of naval reactors is also fairly constant. The new carrier USS *Ronald Reagan* (CVN 76) and the new CVN77 will replace older, conventional aircraft carriers taken out of operation.[101] The Navy is likely to keep two prototypes for R&D on energy efficiency and training of personnel.[102] In the course of 1999, DOE inactivated and defueled six shutdown prototype reactor plants.[103] The NR-1, a nuclear-powered ocean engineering and research submarine, continues its service to the Navy and many research and educational institutions. This vessel was overhauled and refueled in 1993 after an operating period of 24 years.[104]

The U.S. Navy buys reactor cores many years before they are actually loaded: a ten-year advance procurement seems customary. As of 1995 enough HEU was already available to cover projected U.S. naval requirements until about 2006.[105] As the portion of the Portsmouth enrichment plant that made weapons-grade uranium was closed in 1992, naval reactors now depend on the existing inventory of weapons-grade uranium. The U.S produced 994 tons of HEU from 1945 to 1992, when production ended.[106] However, the amount of HEU already used or incorporated into weapons has yet not been declassified. As part of its openness policy, DOE expects to complete a report in which it will detail the U.S. production, acquisition, uses, inventories and disposition of HEU from 1945.

Over its lifetime, the U.S. naval propulsion program has designed, built and operated more than 30 distinct types of reactors.[107] Early naval reactors had a lifetime of about two to four years. A modern attack submarine (SSN) has a ship life of approximately 30 years. On the basis of statistics of U.S. Navy reactor cores, a study in the 1980s assumed a ten-year average life for reactor cores.[108] This figure is supported by more recent studies[109] that have indicated the need for refueling twice during the normal lifetime of the current vessels. The Navy is currently designing reactor cores to last 50 years for aircraft carriers, 40 years for SSBNs, and 30 years for SSNs.[110] These core developments would eliminate the need for submarine refueling altogether.[111]

The operation modes of strategic nuclear submarines will be on a lower energy output than the faster attack submarines, prolonging the lifetimes of their cores. The cores of the last of the Ohio-class submarines, designed in the late 1970s, will operate for over 20 years without refueling.[112] The last Ohio-class submarine with this core technology was delivered in 1996.[113] If a strategic U.S. force is to be maintained, however, a new class of SSBNs must be built to replace the current Ohio class. By the time this new class of ships is designed, a 45-year HEU core should be feasible for submarines.[114] The same will apply for the new aircraft carriers. Existing core technology and consumption levels for SSBNs and aircraft carriers will remain in the years to come, however, thus requiring at least one refueling during their operational life.[115]

By assuming a lifetime for the submarines of 30 years and a lifetime of 45 years for the aircraft carriers, and assuming compliance with the START treaties, we can derive the expected total number of operating naval reactors. Providing that the U.S. Navy’s most extensive plans are initiated – with 30 new attack submarines – the total number of operating U.S. Naval reactors by 2020 will be 86 (14 SSBNs, 49 SSNs and 10 aircraft carriers, 2 submarines for training, research and development, plus the NR-1). The development of the nuclear-propelled fleet is presented in Figure A1, with the decommissioning of older vessels taken into account.

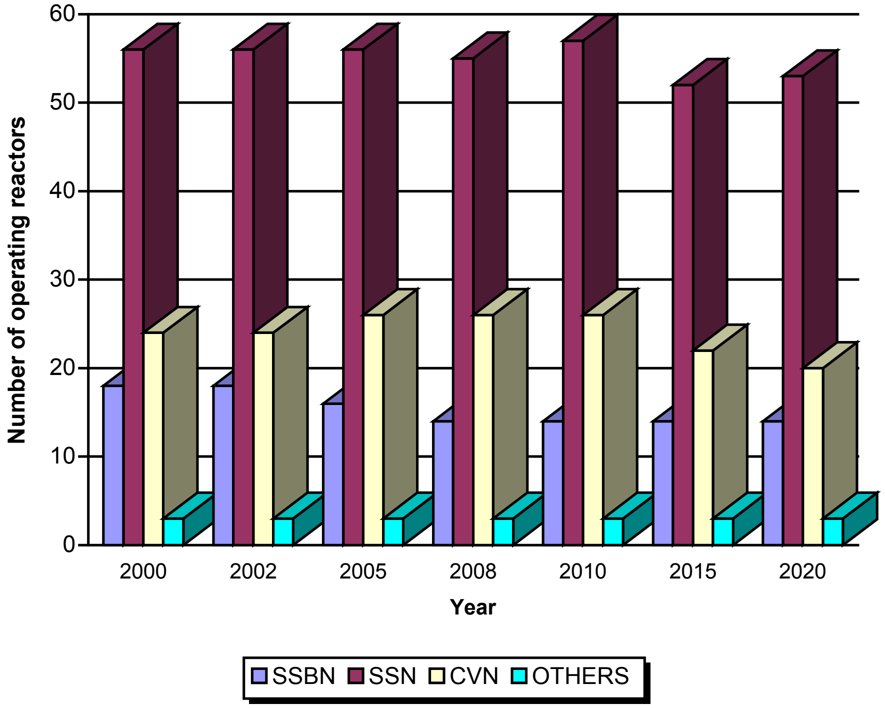

Figure A1. U.S. Naval reactors operating until 2020, given the proposed production of 30 new SSNs

According to current production schemes, the number of operating naval reactors will be reduced to 86 by 2020, as compared to the 103 reactors operating in 1999.[116]

In 1995, with 158 operating U.S. naval reactors, the annual burn-up of U-235 in the entire fleet was reported to be approximately 1.1 tons.[117] Thus, as a crude approximation, on average each U.S. reactor used 7 kg of U-235 during that year of operation. The annual burn-up 20 years from now will be approximately 600 kg of HEU, or slightly more than half of the 1995 burn-up.[118]

Probably more important in the longer term, however, are technical developments in the reactor core. The introduction of life-time reactor core technology will mean new and unparalleled fuel saving benefits. As mentioned, U.S. submarines today put to sea equipped with reactors designed to last the life of the ship, obviating the need for refueling.[119] Thus, even with the most extensive U.S. submarine modernization and production plans, with 30 new attack submarines within the coming two decades,[120] the U.S. Navy will need less HEU.

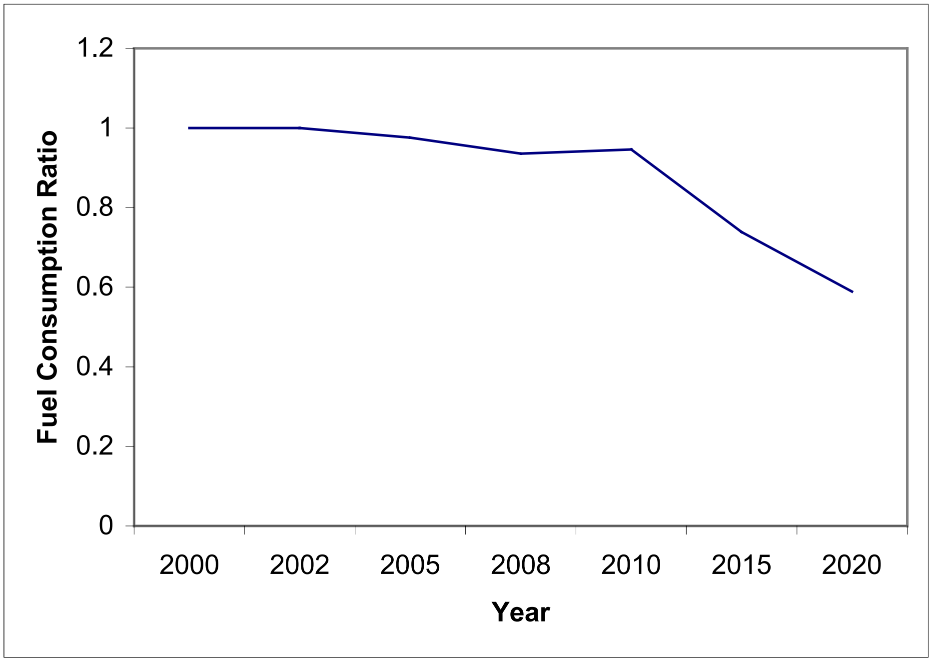

Figure A2: Annual integrated HEU fuel consumption ratio relative to 2000 levels for U.S. attack submarine. The relative decline is mostly due to the introduction of new reactor technology.

By 2020, with the successful launching of all the planned new SSNs with lifetime cores and the decommissioning of 40 old SSNs (due to expired service lifetimes), the annual lifetime integrated naval HEU fuel consumption of U-235 for U.S. attack submarines will be 60% of the levels for the year 2000 (see Figure A2).[121] Beyond 2025, including only the new SSNs, the lifetime integrated fuel loads of HEU will be 6 tons of U-235, contrasted with the 18 tons required to meet the consumption needs if old core technology were still applied.[122]

Russia's naval program

Today's Russian submarines use HEU as well, but with enrichment levels ranging from 40 to 90%.[123] Russia's nuclear-propelled icebreaker fleet uses fuel with the same enrichment levels, as the reactors in these icebreakers were used as test-beds for Russian nuclear submarine reactors. The proportion of incidents of diversion involving naval HEU in Russia has been notably high.[124] Naval fuel seems to have been particularly exposed to theft, and the enrichment levels of the fuel involved make such attempts worrisome.

In the Murmansk region of Russia alone, six known thefts of naval HEU fuel took place between 1993 and 1996.[125] Insiders, either military personnel or contract workers at the shipyards, were often involved in these incidents.[126] In September 1999, thieves disabled a nuclear submarine by pilfering vital equipment.[127] In January 2000, four Russian sailors and a retired officer were arrested for stealing a fuel rod from a nuclear powered submarine.[128] This misdeed was economically motivated, carried out by key personnel with detailed knowledge about the security systems and the necessary protective measures.

In terms of submarines and naval reactors produced, the Russian naval program outmatches that of the U.S. However, Russia's submarines are now at an all-time low in terms of deployment and readiness, spending significant time in port due to the current economic situation in Russia. The severe budget crunch has forced the Russian Navy to retire older attack submarines and ballistic missile submarines prematurely, and to concentrate its limited sources on maintaining only the most modern assets – the *Oscar* and *Akula* attack submarines and the *Delta IV* SSBN.[129] Less frequent deployment at sea helps extend the service lives of existing systems.[130]

For nearly three months starting in early May 1998, Russia had no operational SSBNs at sea.[131] Russia does not have the money to maintain and repair its six huge Typhoon submarines, so these vessels have not been on active duty since 1995. In the Fall of 1999 it was decided to decommission the Typhoons before they reached the end of their operational lifetime.[132] However, in early 2000 news reports indicated that three of six

Typhoon-class submarines would remain in active operation to test new strategic missiles.[133]

Since 1958, the Soviet Union and Russia have constructed 249 nuclear-powered submarines, representing more than half of the submarines produced worldwide.[134] Two thirds of these vessels were delivered to the Northern Fleet, the rest were destined for the Pacific Fleet. In addition to combat submarines, five research and development submarines and several full-sized land-based submarine-training facilities have been produced. Additionally, the eight ships in the Russian icebreaker fleet are nuclear propelled, each with one or two reactors and accompanied by four battle cruisers and a communication ship with twin reactors. Most Russian submarines are equipped with two reactors. The overall number of naval reactors produced by the Soviet Union/Russia is therefore at least 480.The vessels use fuel enriched from below 21% to 90%.[135] Of these, a total of 24 reactors are believed to have been designed to use uranium enriched to 90% U-235.[136]

Deployment peaked in 1989, when approximately 196 submarines were in service.[137] Most of the submarines have now reached the end of their service lives and have been decommissioned. These vessels await dismantlement, a process involving huge safety (environmental) and security challenges.[138] As of early 1999, the Russian force was composed of 26 SSBNs (and SSGNs) and 22 SSNs.[139]

Future Russian naval reactors and fuel consumption levels

The current socio-economic situation in Russia renders the size of the future Russian submarine forces extremely uncertain. A minimum force will probably remain, especially as the strategic role of Russian submarines is likely to increase. If the START II treaty is ever implemented, over half of the remaining Russian warheads will be based on SSBNs.[140]

Russia is therefore likely to maintain a limited number of modern submarines (SSBNs) in the coming decade, eventually replacing the last *Delta IIIs*, built in the mid- to late-

1970s, with the new *Borey* class.[141] The *Delta III* is the only SSBN currently deployed with the Pacific Fleet. If not enough Borey-class submarines are deployed to maintain the number of vessels in both the Northern and the Pacific Fleets, the Russian Navy will have to consolidate its SSBN operations with the Northern Fleet.[142]

According to Russian naval officers, by 2005 or 2006 Russia will retain only 10–12 submarines as nuclear weapon platforms.[143] These figures are supported by members of the Russian Duma who have claimed that the Navy will need 65 to 72 submarines in the 21st century, including 12 to 13 SSBNs, the same number of SSNs to protect these SSBNs, and 10 to 12 SSNs each in the Northern and Pacific Fleets to engage in tactical operations and monitor enemy SSBNs.[144]

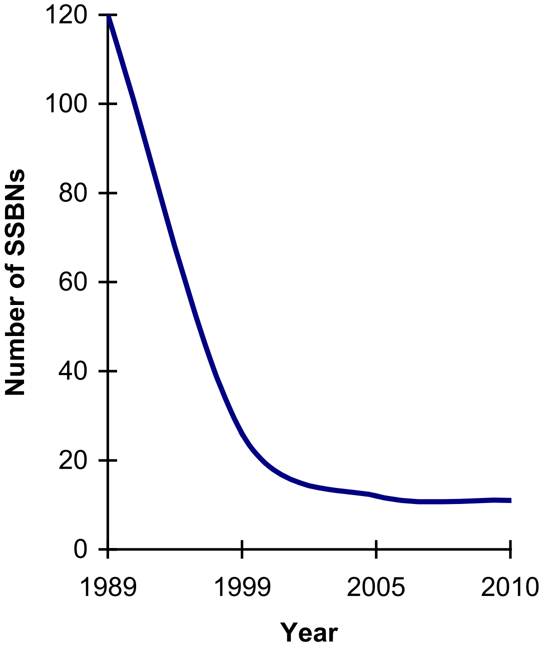

Figure A3. Operating Russian ballistic missile submarines 1989 to 2010. Predicted figures are maximum numbers, depending both on the finalization of projected submarines and on prolonged lifetimes of existing SSBNs.

This figure seems, however, to depend on the production of several new ships. Even if 10 Boreys are produced, the Russian SSBN force could shrink to as few as 4 to 12 ships.[145] The current production plans and actual progress do not support an extensive Russian submarine manufacture. The keel of the fourth-generation strategic missile *Yuriy Dolgorukiy* of the Borey class was laid down in November 1996. However, work on the vessel, the only nuclear-powered ballistic missile submarine under construction, has been halted pending a redesign of the missile system.[146] The submarine was scheduled for launch in 2002, but is now planned to enter service in 2010. Thus, Russia's existing strategic submarines may have to enter more demanding operating schedules, and *decreased* service lives might result.[147]

The keel of the first of the fourth-generation attack submarines, the *Severodvinsk* class, was laid down in late 1993. However, work on the submarine has been suspended since 1996. Currently progress is slow to the point where the program is in doubt.[148] Unless shipyard workers are paid regularly and equipment manufactures supported by industry, these submarines will take a very long time to complete. Between 1999 and 2005 three attack submarines are scheduled for launch – but also here, implementation of these plans remains uncertain.

Despite the economic problems, the Russian icebreaker fleet is likely to continue operating in the coming decades. Given an estimated lifetime of 35 years,[149] six of the eight icebreakers will keep going until 2010 and three, or possibly four, will operate until 2025. The construction of a new icebreaker, *"50 Let Pobedy",* formerly called *"Ural"*, was begun back in 1989, scheduled to enter service in 1994. Scarce funding and a reduction of cargo shipments in the Arctic regions have caused contract delays. However, starting in 2000, limited annual funding for the completion of the icebreaker has been made available.[150]

Moreover, given the success of the Russian naval nuclear propulsion program, the Russian Ministry of Atomic Energy has proposed extending the uses of these reactors to provide electricity and heat to remote communities.[151] This would involve placing the reactors on floating barges to be transported to coastal areas or possibly underground, e.g. in mines, to make extensive sources of energy available locally. These plans have yet to be implemented, and again, the economic situation makes the future deployment of naval reactors as miniature power plants uncertain. However, given Russia's persistent energy needs, particularly in the Far North and Far East, the push for the use of non-propulsion, naval power reactors is likely to increase in the coming years. Russian officials claim that the International Atomic Energy Agency has approved the initial designs for these reactors.[152]

Very limited information is released on the Russian reactor cores, uranium enrichment level, and core lifetimes. Generally, higher enrichment levels will allow longer operating times, and a critical design objective is refueling periods of up to nine to ten years. However, with lower enrichment levels, core lives of approximately seven years are more probable, depending on operating modes.[153] Various different fuel geometries and shapes have been applied for former Soviet, now Russian, nuclear submarine reactor production. The Soviet Union developed four generations of naval pressurized reactors, each generation with improved reliability, compactness, and silence of operation. However, there are no reports to indicate substantially prolonged core lives even in the latest generation of submarines. The third-generation reactors (OK-650) began entering into service in 1987.[154] None of the fourth-generation submarines have so far been put to sea.

First- and second-generation submarines generally have U-235 enrichment levels below 21%, while specific classes (e.g. November and Alfa) reportedly have 90% enrichment levels.[155] The third generation is probably enriched in a range of 21% to 45%.[156] Such enrichment levels correspond well to the operational periods of these submarines, with refueling occurring approximately every seven years. In the past, the Russian Navy and the icebreaker fleet each required five to ten fresh cores annually.[157] In recent years however, the naval fuel requirement has dropped to a few cores per year, as the Murmansk Shipping Company (the operator of the icebreaker fleet) and the Russian Navy each conducts one to two refuelings a year.[158]

Russia's icebreakers and submarines use the same reactor concepts; these icebreakers have been used as test beds for the development of submarine reactors. As the icebreaker reactor core is much more accessible than a submarine core, it is easier to cope with the problems of potential fuel element rupture.[159] Moreover, defueling or refueling an icebreaker does not involve the lengthy processes of opening and sealing the hull, as with submarines. Current icebreakers use enrichment levels ranging from 20 to 90%.[160] Non-homogeneous enrichment levels within each of the cores are possible, for example with a HEU enrichment gradient of 20% from the core perimeter to the center of the reactor core.[161]

Little information is available on the sources, uses and inventories of Russian HEU. Estimates indicate a total Soviet/Russian production of 1,400 tons of weapons-grade HEU from 1950 through 1988, after the production of HEU for defense purposes stopped.[162] The inventory of remaining military HEU stocks in Russia was estimated to 1,010 tons at the end of 1997,[163] including the 500 tons of HEU slated for sale to the United States under the U.S.–Russian HEU deal. This HEU inventory estimate does not, however, include any HEU dedicated to the naval fuel cycle. According to calculations made by Oleg Bukharin, the average amount of U-235 in Russian ship reactor cores is approximately 100 kg.[164] With an estimated need for three (re)fueling sessions per reactor, overall U-235 consumption for all the 478 naval reactor cores produced is thus roughly 143 tons.

By assuming an average enrichment level of 30% and 315 kg of uranium on average in the reactor cores,[165] we can perform simple calculations of the fuel savings in the period 1999 to 2005. As seen, the number of strategic submarines will decrease from 26 to approximately 12. Due to the very limited construction of new submarines, the number of SSNs is, as a conservative approximation, assumed to remain constant. Normally, each submarine uses three batches of uranium fuel, or approximately 950 kg. Thus, due to reduction in the strategic submarine fleet, the impact on naval fuel consumption constitutes a reduction of approximately 13.3 tons of intermediately enriched uranium (30%), or nearly 4 tons of U-235 – corresponding to a reduction in the annual U-235 consumption of approximately 800 kg over the next five years.

Appendix II: U.S. and Russian Naval Fuel – Proliferation Potential

In this appendix the proliferation attractiveness of highly enriched naval fuel is assessed. This is partly done by looking at the enrichment levels of the fuel and partly by assessing the challenges associated with using the fuel in crude nuclear devices. The assessments performed are crude first-order approximations and should be regarded preliminary.

With the end of the Cold War, the vast quantities of nuclear weapon-usable material have emerged as one of the most important threats to international security. At the center of technical proliferation concerns is the direct-use material that can be employed to make nuclear weapons without further enrichment or reprocessing.[166] Plutonium and highly enriched uranium (HEU) are the key ingredients of nuclear weapons. The management and control of this material is essential for reducing the potential for nuclear proliferation, nuclear war, and nuclear terrorism. Unlike plutonium, most of the world's HEU is in military stocks. In addition to its use in nuclear weapons, it is employed to fuel research reactors, reactors that produce tritium, and to produce the fuel that powers nuclear submarines.[167]

It is considerably easier to make a bomb using enriched uranium than using plutonium.[168] With uranium there is essentially no risk of premature detonation due to neutrons from spontaneous fission, as the spontaneous fission rates are far lower than for plutonium. Moreover, as fresh HEU is much less radioactive than weapons-grade plutonium, the material can be handled with limited risk, even without protective measures or shielding. This means that HEU bomb assemblies will be practical, more readily brought together – and more likely to function without prior testing. All these factors make HEU a more attractive material than plutonium for potential proliferators, particularly those with limited access to sophisticated technology.

The ease or difficulty of acquiring sufficient quantities of fissile material is a major factor in the production of nuclear weapons. All stocks with weapons-usable material are attractive targets. This appendix investigates the proliferation potential of HEU – more specifically, the proliferation attractiveness of fresh HEU for naval propulsion and the possible production of crude nuclear weapons based on this material. The final section of this appendix presents a general discussion of the production of crude nuclear weapons. For the purpose of this report, a "crude" design means either of the designs successfully demonstrated in 1945, i.e. the gun-type and the implosion-type weapon.[169]

Proliferation potential of HEU

Shortly after the discovery of nuclear fission in 1939 came the realization that it might be possible to make a powerful nuclear explosive by extracting and concentrating the U-235 from natural uranium. Highly Enriched Uranium (HEU) is a special mixture of isotopes of uranium produced by increasing (enriching) the uranium-235 content of natural uranium. An internationally accepted distinction between "low" and "high" enrichment has been made at 20% enrichment. This is based on the understanding that it is difficult to fashion an explosive nuclear device from uranium enriched to levels of 20% U-235 or less.[170]

The proliferation potential of a fuel cycle, or its proliferation resistance, is determined by the quantity and the quality of the fissile material that could be diverted to military – possibly terrorist – uses. According to Galperin et al. (1999) a decisive barrier to proliferation should be based on inherent properties of the fuel cycle itself in addition to a system of international safeguards measures. The attractiveness of the material, or the weapon quality of the fissile material, can be evaluated by considering the following properties:

- critical mass
- radioactivity levels and the weapon stability degradation by heat emission
- weapon-yield degradation due to pre-initiation caused by spontaneous fission neutrons.

For uranium, both the radiation levels (and thus heat degradation) and the spontaneous fission rate will be very low. Due to the higher rate of spontaneous fissions and stray (background) neutrons, all plutonium-weapons will be more vulnerable to pre-ignition than weapons based on uranium, a material with a lower neutron background.[171] Particularly with reactor-grade plutonium, the probability of "pre-detonation" is very high, raising the probability that the weapon will blow itself apart at an early stage and thus cut short the chain reaction that releases the energy.[172] The reminder of this section will focus on the critical mass needed for a crude uranium weapon and the yield likely to be produced.

Critical mass

During the fission of fissionable nuclides, vast amounts of energy are released together with neutrons and fission products. The neutrons released may induce new fissions in other nuclides. A nuclear chain reaction can sustain itself only if there is an assembly of fissile material large and dense enough to keep many of the neutrons from escaping. An assembly in which, on average, each fission makes one other nucleus spilt, sustaining the reaction at a steady state, is called "critical".

A subcritical assembly would not maintain the chain reaction, and it would die down. By contrast, a supercritical (bomb) assembly causes the reaction to grow exponentially, releasing large amounts of energy before the weapon finally destroys itself. Weapons manufacturers thus need something like a critical mass of the material they intend to use, preferably of metal, although oxide powder might be used.

The critical mass varies for different isotopic compositions. For a particular fissile material, the amount that constitutes a critical mass can further vary widely depending on the enrichment level, the density, and the nature and fractional quantity of any inert diluents present (such as oxygen in uranium oxide, uranium-238 in partially enriched uranium-235, or chemical impurities).[173] Further, the critical mass is highly dependent upon the presence of reflectors surrounding the core to return to the system the neutrons that would otherwise have been lost.

For higher densities of the material, the critical mass decreases significantly. The bare critical masses (without any reflectors) are 52 kg of 94% U-235 metal (density 18.7 g/cc) and approximately 110 kg of uranium-oxide enriched to 94% U-235 (density 11.4 g/cc).[174] Due to the greater cross section of plutonium weapons isotopes, the bare critical mass of 239-plutonium metal with a density of 19.9 g/cc is as low as 10 kg.[175]

Uranium bombs can be made with a wide range of uranium enrichments, but the mass required is greater for lower enrichments. For lower enrichment levels, e.g. 50% enriched metal uranium, the bare critical mass is approximately 160 kg – a threefold increase compared to the 94% enrichment level, given the material of the same density. Not only is very highly enriched uranium preferable for building a compact bomb, less separative work is required to obtain a smaller critical mass (roughly 18 kg) at 90% enrichment than to obtain a larger critical mass (37 kg) at 60% enrichment.[176] This is why high enrichments (and less fissile material) are normally used in uranium bombs.

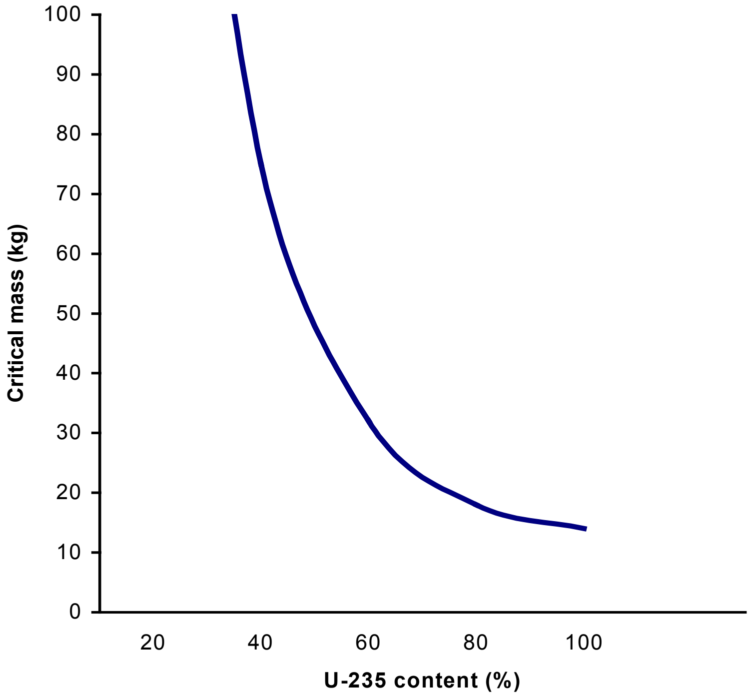

Figure A4. Critical mass of uranium metal in the form of spheres enclosed in thick neutron reflectors of natural uranium, as function of enrichment levels.[177]

The relationship between enrichment levels and critical masses for an assembly with a neutron reflector is illustrated in Figure A4. With a good reflector, the critical mass for 60% enrichment is 22 kg of U-235 and 37 kg of uranium, while only 15 kg of U-235 is required at 100% enrichment levels (pure U-235).[178] Thus, reflectors may reduce the critical mass by as much as a factor of three. As shown in the Figure, material enriched to less than 15–20% U-235 cannot be used in a nuclear weapon, because sufficiently rapid supercritical assembly becomes impractical.[179]

The simplest type of nuclear explosive, a "gun type", in which the optimum critical configuration is assembled more slowly than in an "implosion type" device, cannot be made with plutonium. The Pu-240 content even in weapons-grade plutonium is so large that very rapid assembly is necessary to prevent pre-initiation.[180] Gun-type weapons can thus be made only with highly enriched uranium, in which spontaneous fission is rare. Either material can, however, be used in an implosion device.

Rather than the gun-type assembly, the first Chinese bomb used an implosion design to assemble the critical mass of uranium, necessitating considerably less material to make a weapon. By comparing the 6 kg fissioned in the Nagasaki bomb with the critical mass of 10 kg for naked plutonium not surrounded by a neutron reflector, Garwin and Charpak (1999) predict that it is possible to manufacture an implosion bomb with 34 kg of uranium or less.[181] According to Mark et al. (1987), 25 kg of very highly enriched uranium would be needed for an implosion-type HEU weapon.[182]

The minimum quantities of approximately 25 kg indicated are well in accordance with the Significant Quantities used by the IAEA.[183] However, these significant quantities have been criticized for being too large, as nuclear fission weapons could reportedly be produced with as low as 2.5 kg to 8 kg of HEU, depending on the sophistication of the weapon design.[184]

Weapon yield

The energy yield of nuclear weapons is commonly expressed in kilotons (kt) or megatons (Mt) of TNT equivalent. Yield will depend on the quantity of fissile material available, and, more importantly, on the ability of the nuclear device to maintain a supercritical configuration. The energy output can be devastating even in crude nuclear weapons: the weapons dropped on Hiroshima and Nagasaki produced yields more than 1000 times the biggest conventional bomb ever deployed in warfare.[185]

Even if pre-ignition in a simple nuclear device similar to the Nagasaki bomb occurs at the worst possible moment, when the material first become compressed enough to sustain a chain reaction, the explosive yield will be in the order of one or a few kilotons.[186] While this is referred to as a "fizzle yield", a 1-kiloton bomb would still have a radius of destruction of roughly one-third that of the Hiroshima weapon, making it a potentially fearsome explosive.

The complete fission of U-235 in a reactor releases 8.2×10^{13} J/kg.[187] About 85% of the energy comes from the fission fragments themselves and 5% from prompt neutron and gamma rays. The complete fission of 1 kg of U-235 would give a prompt explosive yield of about 7×10^{13} J/kg, or approximately 17 kt. The actual yield of nuclear weapons is less than 17 kt/kg, because a bomb will disassemble without complete fissioning of all the material. More poorly assembled nuclear devices will produce a smaller yield, because the chain reaction will be aborted as the system rapidly expands. Nevertheless, they may produce a significant radiation burst.

The early plutonium bombs had efficiency under 20%, and this figure probably is even lower for crude uranium bombs. The bomb dropped on Hiroshima had a yield of approximately 15 kt, but only some 700 g of the total of 60 kg of uranium actually fissioned, indicating an efficiency of a little more than 1%. A complete fissioning of 6 kg of HEU will produce slightly above 100 kt, so 1% efficiency would give a yield of approximately 1 kt. This makes feasible the estimates of Cochran and Paine (1995), indicating that 8 kg of HEU, or as low as 2.5 kg for more sophisticated weapons, is sufficient to produce a yield of 1 kiloton.

Part of the energy from the explosives compressing the fissile material will heat the device and the surroundings. The yields produced will depend on how close to the fissile material is to the critical mass prior to the compression, especially for the less compressible oxide material. This means that the willingness of perpetrators to risk potential criticality incidents while preparing the device will be an important factor in determining the yield produced.

Crude nuclear weapon production

Expert opinion differs on the ease of building a clandestine nuclear explosive outside the purview of a traditional state weapons program. The following discussion will argue that such production is feasible. Due to the anticipated limited technical skills of potential would-be-nuclear-terrorists, only crude nuclear weapon designs will be investigated here.

The primary restraining factor in the production of clandestine nuclear weapons is likely to be the difficulty of access to highly enriched uranium or plutonium, the essential ingredients of such weapons. The vast quantities of fissile material produced during the Cold War and the breakup of the Soviet Union may increase the availability of the weapons-usable material. Thus, while the primary barrier may be crumbling, the importance of other barriers against clandestine production and deployment may increase.

The fact that the most substantial problem of a potential bomb-maker is to acquire sufficient amounts of weapons-usable nuclear material has been underlined by John Foster, former director of the Lawrence Livermore National Laboratory:

> *the only difficult part of making a fission bomb of some sort is the preparation of a supply of fissionable material of adequate purity: the design of the bomb it self is relatively easy….*[188]

Luis W. Alvarez, a prominent nuclear weapon scientist in the Manhattan Project, has emphasized the simplicity of constructing a nuclear explosive with highly enriched uranium: [189]

> *With modern weapons-grade uranium, the background neutron rate is so low that terrorists, if they have such material, would have a good chance of setting of a high-yield explosion simply by dropping one half of the material onto the other half. Most people seem unaware that if separated HEU is at hand it's a trivial job to set off a nuclear explosion... even a high school kid could make a bomb in short order.*

While Alvarez does not specify the meaning of "high-yield" explosion, it is probable that a yield in the kiloton range could be established. Thus, the difficulty of designing and fabricating a nuclear weapon from either highly enriched uranium or plutonium may often seem exaggerated. A competent group of nuclear physicists and electronic and explosive engineers would have little difficulty in designing and constructing such a weapon from scratch. Moreover, they would not need access to any classified information.[190]

The nuclear weapons developed in the mid 1940s then represented the "state of the art" in technical engineering and nature science. Today these weapons are regarded as both primitive and outdated. Though no detailed descriptions of nuclear weapons have been released publicly, the principles behind the first fission explosions are widely known and available from the scientific literature and from declassified U.S. documents. Also in the swarm of information on the Internet, description and background information on crude nuclear weapon production can be found.[191]

The simplicity of the gun-type design makes it probable that a workable uranium bomb could be produced without any testing. “Little Boy”, the HEU bomb dropped on Hiroshima, was triggered by a simple “gun” mechanism. A small, slug-shaped piece of uranium was fired down a barrel into a larger, cup-shaped piece of HEU, and the weapon was used without previous testing.[192] And yet this elementary design generated a destructive force of about 15 kilotons — the equivalent of 15,000 tons of TNT.
In 1993 South Africa surprised the world by announcing that the country’s clandestine production of nuclear weapons had ceased, that the weapons had been dismantled and that the country was ready to submit all former weapons activities to the control of the International Atomic Energy Agency. Despite the international embargo posed on the apartheid regime, six nuclear weapons had been produced during a period of four years. These weapons, all developed without any testing, were of the gun-type design. On average each weapon contained about 55 kg of uranium enriched to 94% U-235.[193]

The fact that terrorists may not have to heed many of the restrictions and problems of states’ nuclear weapon programs may further increase the risk of the sub-national production of clandestine nuclear weapons. First, the requirement of knowing the precise yields of the weapons will be superfluous for terrorists. While covert attackers would want predictable weapons-effects, less precision is required than for state military purposes.[194] Further, terrorists will not have to meet the extremely stringent specifications and tolerance required for military weapons production.[195] State military weapons must, to a much larger extent than terrorist weapons, be reliable, safe and optimal. That is, when the weapons are used, they must function with optimal yields with the minimal impact of possible effects of aging or other deteriorating factors, e.g. heat deterioration. Moreover, during long-term storage, state weapons must remain safe and secure, to guard against unintentional or unauthorized detonation.

Weapons for military uses are needed in large numbers, and they must be delivered by conventional military means (missiles, mortars etc.). Due to their limited size and weight, crude nuclear weapons will easily fit into a van, or even automobiles, for subsequent detonation in densely populated areas. Other non-military means of delivery could be trucks or ships in harbors. Crude nuclear weapons will be produced in limited numbers, reducing the costs of manufacture and maintenance. Finally, while state nuclear weapon programs are usually supported by a large infrastructure and perhaps reprocessing facilities for the separation of fissile weapons material, sub-national groups will normally rely on smaller programs and most probably externally acquired weapons-usable material.[196] It is also possible that “rogue” governments unwilling to use weapons of mass destruction due to fear of retaliation could readily supply the raw material or the finished product to terrorists – whether by political design or for commercial gain.[197]

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Morten Bremer Maerli is researcher at the Norwegian Institute of International Affairs, Oslo, Norway. He is a physicist by training with both practical and research experience in the fields of nuclear safety and security.

From 1995 to 2000 he served as a Senior Executive Officer at the Nuclear Safety Department of the Norwegian Radiation Protection Authority, with physical protection and accountancy of nuclear materials as his prime responsibility. Through his work he has gained regional knowledge and hands-on experience of the current situation and practices concerning the handling, storing and security of nuclear materials in Northwest Russia.

In addition to his degree in physics (Master's of Science, MSc), he holds a Bachelor of Arts degree from the Institute of Media and Communication, University of Oslo, focusing on risk communication and perceptions of the risk of radiation. In 1999, Bremer Maerli published the book “Atomterrorisme”, assessing the intentions and the capabilities of sub-national groups to perform acts of nuclear and radiological terrorism.

He has acted as a technical consultant to the Norwegian Ministry of Foreign Affairs, e.g. at the Conference on Disarmament, Geneva, on discussions on the Fissile Materials Cut Off Treaty. Bremer Maerli was a technical advisor to the Norwegian delegation to the 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, New York.

During the 1999/2000 academic year Bremer Maerli was a Science Fellow at the Center for International Security (CISAC) at Stanford University, working on nuclear nonproliferation and the prevention of nuclear terrorism. In August 2000 he started his PhD studies, focusing on Russian nuclear naval fuel and the risk of proliferation.

During the 2000/2001 academic year he was a Visiting Research Scholar at Sandia National Laboratories, California, and affiliated with the Center for International Security and Cooperation of Stanford University. He has now returned to his position at the Norwegian Institute of International Affairs in Oslo.

Endnotes

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[1] This report was produced as part of the NATO-EAPC Research Fellowship, and was largely written during my stay as a Science Program Fellow at the Center for International Security and Cooperation (CISAC), Stanford University, the 1999/2000 academic year. In addition to the NATO-EAPC Research Fellowship, the beneficial stay at CISAC was made possible through the gracious funding of the Fulbright Foundation, the Scandinavian–American Association, the Norwegian Ministry of Defense, and CISAC. The views expressed here, however, are the author's, and not necessary those of the mentioned institutions. The report is slightly revised January 2002, and published by the Norwegian Institute of International Affairs.

[2] Bodansky (1996) p. 271.

[3] In fact, the inherent properties of HEU make the material more proliferation-attractive than plutonium. Cf. Appendix II.

[4] By the end of 1997, the total stocks of military plutonium and weapons-grade uranium in the U.S. and Russia were estimated to be 250 tons and 1700 tons respectively. (Albright & O'Neill, 1999, p. 11.)

[5] von Hippel (1997).

[6] Ibid. The authors assume that about 12 kg of weapons-grade uranium would be needed to produce an implosion-type nuclear device, i.e. half the quantity with which this report operates. Moreover, Bukharin and Potter apparently assume that as much as 300 kg of U-235 is available in the reactor cores. This latter assumption contrasts the quantities given in the Sevmorput Safety report, indicating only 150 kg of HEU.

[7] For useful sets of policy recommendations for nuclear material transparency, see e.g. Task Force VI panel of CSIS (2000), pp. 58–64, Bukharin & Luongo (1999), pp. 11–15, Bunn (2000), National Academy of Sciences (1994), and Fetter (1999).

[8] In his paper "Verifying Nuclear Disarmament" (1996) Fetter outlines the technological possibilities for verifying compliance with a nuclear disarmament treaty. While not explicitly stating the close interrelated relations between nuclear disarmament and nuclear proliferation, he stresses the importance of the nuclear weapon states providing detailed declarations of their stockpiles and allowing these declarations to be verified. Only such actions will lay the necessary foundation for nuclear disarmament, because today's uncertainties regarding existing quantities of nuclear material will be magnified as the world struggles towards minimizing the number of warheads.

[9] Transparent and irreversible nuclear reductions are part of the long term U.S. nonproliferation program for Russia. See e.g. the statement of Gottemoeller (2000).

[10] Albright et al. (1997), pp. 6–7.

[11] The United Kingdom is a noteworthy exception. As mentioned, the U.S. is currently producing a report on its HEU production, along the lines of the national plutonium assessment.

[12] Bunn (2000), p.17.

[13] Ibid, p. 2.

[14] DOE (1997), p. 6 & p. 21.

[15] The safeguards of the Non-Proliferation Treaty are meant to verify compliance with treaty by providing for "the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for the purposes unknown, and the deterrence of such diversion by the risk of early detection". From IAEA INFCIRC/153, article 28. The production of HEU and plutonium for use in weapons and other national defense purposes requires many of the same steps as those involved in the civilian nuclear fuel cycle, and many of the same government facilities constructed for military programs have been used to produce fuel for civilian nuclear-power reactors. The relationship between the civilian and military fuel cycles has prompted international concerns that nuclear material in the civilian sector could be used for manufacturing nuclear weapons. To counter the threat of nuclear weapons proliferation, 185 countries have agreed to implement the nuclear-material safeguards developed and monitored by the International Atomic Energy Agency (IAEA). IAEA's safeguards involve accounting and verification procedures designed to detect unauthorized diversions of nuclear material that could occur in the commercial fuel cycle. To further expand nuclear safeguards, the

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United States has voluntarily agreed to allow the IAEA to inspect certain inventories of U.S. HEU and plutonium no longer needed for national defense purposes. From DOE/EIA (1998), p. 8.

[16] The Non-Proliferation Treaty, article III.

[17] Mochiji et al. (1999), p. 47.

[18] CSIS (2000), p. 53.

[19] Ibid, p. 54.

[20] Unfortunately, many good political intentions have stranded before their practical implementation. For an overview of transparency commitments that never were implemented, see Bunn (2000), p. 88.

[21] Bukharin & Luongo (1999), p.3.

[22] In the area of mutual reciprocal inspections (MRI), the proposed activity was to have U.S. and Russian technical experts develop non-intrusive techniques of confirming that, at the end of the dismantlement process, a declared fissile material container contains a weapons-grade plutonium or highly-enriched uranium (HEU) object the shape and mass of which (in the case of a warhead pit) are consistent with those of a warhead component. During 1994 and 1995, Russian and U.S. experts developed and demonstrated some promising MRI techniques, but no consensus was reached on the scope of fissile material measurements or specific MRI procedures. Bukharin & Luongo (1999), p.3.

[23] Relating to the "transparency of strategic nuclear warhead inventories and the destruction of strategic nuclear warheads and any other jointly agreed technical and organizational measures, to promote the irreversibility of deep reductions including prevention of a rapid increase in the number of warheads." However, according to Bukharin & Luongo (1999), in the U.S. bureaucracy this statement was met with some confusion as to its actual meaning, and resistance to warhead transparency persisted in some portions of Russia's bureaucracy.

[24] DOE (1996).

[25] In February 1996, the U.S. Secretary of Energy, Hazel O'Leary, announced that the United States would produce a report detailing the production, use, disposition and inventories of HEU covering the past 50 years. She said the report would be completed in about one year. As of early 2002, the HEU report has still not materialized.

[26] DOE (1996), p. 5. After considering the arguments for the maintenance of previous levels of confidentiality about the stocks of fissile material required for national security reasons, the British government in June 1988 concluded that there was no longer a need for complete confidentiality about these stocks, and declared their total stockpiles of plutonium and uranium held outside international safeguards. Moreover, a significant amount (4.4 tons of plutonium and over 9.0 tons of enriched uranium) of the stock has been made available for IAEA/Euroatom safeguards. From INFCIRC/570 Attachment. "United Kingdom Fissile Material Transparency, Safeguards and Irreversibility initiatives".

[27] Bukharin & Luongo (1999), p. 23. If this worked well for plutonium, a similar approach could be taken for Russia's HEU stockpiles once the U.S. has released its data.

[28] CSIS (2000), p. 54.

[29] Based on Schaper & Frank (1999), p. 59.

[30] Mochiji et al. (1999), p. 48.

[31] France and China use LEU in their submarines.

[32] See Appendix I for a technical description of U.S. and Russian naval nuclear propulsion programs.

[33] Maerli, unpublished working paper (1999) and Appendix I.

[34] The introduction of verification measures as part of the safeguards agreement with the United States was cumbersome and expensive for both the IAEA and the U.S. While intensive physical protection systems were in place to meet U.S. domestic requirements to protect against theft of the material, extensive modifications were necessary to allow the IAEA to apply containment and surveillance measures. Also, resolving complications associated with the stratification of the material, its packing, and other indigenous parameters or the facilities required time and money. New measurement techniques and instruments had to be developed to provide the required level of measurements accuracy. From Scheifer & Shea (1999).

[35] For a list of the locations and amounts of the excess material, see Albright et al.. (1997), pp. 92–93. See also DOE Office of Fissile Material Disposition. "Surplus HEU Disposition". http://twilight.saic.com/md/disp-1.asp

[36] According to Bukharin & Luongo (1999), p. 18, ten tons of the fissile material under IAEA inspections at DOE facilities is HEU.

[37] The U.S. Nuclear Regulatory Commission.

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[38] Withworth (2000), DOE International Safeguards Division, personal communication. February 4, 2000.

[39] Apparently, some of the first 10 tons of HEU declared as surplus could meet the specifications for use as naval fuel, according to Bunn, (2000), p. 54.

[40] Albright et al. (1997), p. 93.

[41] The HEU covered by the U.S.–Russian HEU deal is an exception where transparency is in place. Cf. the section "Voluntary, non-intrusive verification on designated parts of the naval fuel cycle".

[42] Maerli, unpublished working paper and Appendix I.

[43] Hibbs (1995), p. 12.

[44] Maerli (2000).

[45] Ibid.

[46] INFCIRC/153 Corrected: "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons."

[47] See e.g. Sanders & Simpson (1988), Miller (1992) and Moltz (1998).

[48] Miller (1992), p. 160.

[49] The Non-Proliferation Treaty, article III. 2.

[50] See note 57 above.

[51] On the U.S. commitment to an FMCT, see Speech by John D. Holum, Acting Under Secretary of State for Arms Control and International Security Affairs, and Director, Arms Control And Disarmament Agency (ACDA), Geneva, 21 January 1999. http://www.acronym.org.uk/cdholum.htm

[52] Canada has abandoned its long-term nuclear submarine ambitions, but Brazil has persisted in its nuclear submarine plans. Other interested states are India and Pakistan. An alternative put forward by Moltz and Robinson (1999) is the possibility of states buying decommissioned nuclear Russian submarines. Apparently, India has expressed interest in Russian nuclear submarines, opening up for possible transfers also to other interested states, such as. India's rival Pakistan or others. For the Russians, this could be an attractive option, as it would open the potential of badly needed revenue to Russian shipyards which have been facing deep cuts in orders for the commissioning of new submarines. Revenues would further be secured through subsequent repair contracts and the necessary training of personnel, and of course continuous provisions of naval fuel. Secondly, the early removal of decommissioned ships would ease the pressures on current dismantlement activities and thus on the potential environmental impacts due to leakages and already exhausted storage facilities. All the same, such a "nuclear submarine flea market" does not seem to be a very realistic option. Due to the presence of valuable scrap metals, the recycling value of the submarine may even exceed the price that states would be willing to pay for a second-hand submarine. Estimates (by retired Colonel Aleksandr I. Kurchatov, quoted in Moltz & Robinson (1999)), indicate recoups of only 20 to 30% of the dismantlement costs; however, these figures are uncertain. "Warranty" and liability problems could also complicate future sales. However, the possibility underscores a fundamental and possibly increasing problem associated with the naval components of the NPT.

[53] Guidelines for supply of submarine reactors and submarine launched missiles have been suggested by Sanders & Simpson (1988); a suppliers' "Nuclear Propulsion Reactor Control Regime" has been presented by Moltz (1998).

[54] Maerli (2000).

[55] This section builds partly on Fetter's discussion on transparency for fissile material stocks. See Fetter. (1996), pp. 14–20, as well as the Principal Recommendations given in National Academy of Sciences (1994).

[56] E.g. with inspections performed with equipment with information barriers.

[57] FAS (1991), pp. 15–16.

[58] When a uranium-235 atom absorbs a slow neutron in a reactor, the probability of fission resulting is somewhat less than 90%. Non-fission absorption results in the formation of uranium-236, which has a half-life of 24 million years. The percentage of uranium -236 in a sample therefore reflects the amounts of uranium-235 which have been fissioned. Due to neutron absorption and further decay, more exact estimates of the quantities of uranium-235 fissioned would involve measurements of some other isotopes as well. From FAS (1991) , p. 19.

[59] In 1998, the IAEA published its Guidelines for the Management of Plutonium (INFCIR/549). See also Albright & Barbour (1999b).

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[60] In September 1996, the U.S. Secretary of Energy, the Russian Minister of Atomic Energy and the Director General of the IAEA initiated discussions on practical measures concerning IAEA verification of fissile material of excess weapon origin.

[61] While this is clearly the goal to verify that the LEU shipped originates from Russian weapons, doubts have been raised whether the measurements really can determine if the HEU is of weapons origin.

[62] Russian Ministry of Atomic Energy

[63] Mastal et al. (1999).

[64] Ibid. (1999).

[65] Decman et al. (1999).

[66] Bukharin. & Luongo (1999), p. 10.

[67] Thus, the verification arrangements that will be implemented are likely to involve not so much meeting specific goals in relation to the manufacture of a single nuclear weapon, as is the case for IAEA nonproliferation safeguards, but the amounts of fissile material maintained under monitored storage, use (e.g. down-blended HEU), and immobilization.

[68] IAEA (1999) "IAEA Verification of Weapon-Origin Fissile Material in the Russian Federation and the United States". Press release September 27,1999. http://www.iaea.org/GC/gc43/gc_pr/gcpr9910.html

[69] Withworth, A. (2000), DOE International Safeguards Division, personal communication, February 4, 2000.

[70] IAEA (1999) "IAEA Verification of Weapon-Origin Fissile Material in the Russian Federation and the United States". Press release 09.27.1999. http://www.iaea.org/GC/gc43/gc_pr/gcpr9910.html

[71] IAEA, INFCIRC/54 (Corrected), *Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards*, <http://www.iaea.org/worldatom/Documents/Infcircs/1998/infcirc540corrected.pdf>.

[72] Bunn (2000), p. 4.

[73] The current policy does not violate any written agreements, but it conflicts with the spirit and intentions of voluntary, irreversible declarations of excess material and undermines the (political) impact of these delicate efforts at international control and confirmation of non-diversion.

[74] Thanks to John Finn and Bob van der Zwaan at the Center for International Security and Cooperation, Stanford University, for useful comments during the preparation of this appendix.

[75] As elucidated throughout this text and the text in Appendix II, naval reactors and commercial reactors differ in size, number of fuel assemblies, fuel enrichment, power output and core lifetimes. Naval reactors use uranium fuel enriched in the range 20 to 97.3% U-235; the rectors are extremely compact with active core heights of approximately 1 m. Fuel used in commercial light-water reactors is normally enriched to U-235 concentrations ranging from under 1% to over 4%, with typical enrichments close to 3%. Within the core of a given reactor, enrichments vary with the location of the fuel assemblies. The commercial pressurized water reactor, like other light-water reactors, operates with uranium fuel in the form of uranium oxide ceramic pellets that are stacked in zirconium alloy tubes some 5 m long and 9 millimeters in diameter. Typically 25% of the 50,000 fuel rods of a commercial reactor, which represent 100 tons of fuel in a reactor, are replaced each year (representing about 40 fuel assemblies, each containing 264 fuel rods and some neutron absorbers and positions for control rods). Depending on the core design and operating modes, submarines are generally refueled once every seven to ten years. The power outputs of the huge commercial reactors range from 600 MW to 1500 MW, while compact submarine reactors typically produce outputs between 30 MW to 50 MW, i.e. approximately 5% of the commercial outputs.

[76] Director, Naval Propulsion Program (1995), p. 35.

[77] The HEU used in U.S. nuclear weapons is enriched to 93.5%. (Roser, 1983, quoted in Chow & Solomon 1993, p. 5, footnote 5).

[78] Assuming approximately 20 new fuel cores procured per year, and an annual consumption of 5 metric tons of fuel. (Cochran et al., 1987, p. 71.) In addition to the U-238 fraction, some U-234 remnants from the enrichment process are probable.

[79] E.g. Miller (1992), p. 157, and von Hippel & Levi (1986b), p. 367.

[80] Director Naval Propulsion Program (1995), p. 3.

[81] Naval Nuclear Propulsion Program Classification Review (1995), p. 3.

[82] Cores with a high power density will inevitably face heat-transfer problems. The most practical solution is to use flat plates instead of pins. Such dispersion fuel creates a larger surface area through which the heat released by the fissions can escape, increasing performance and output; it is now widely used as submarine

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fuel. The highly enriched uranium fuel in U.S. submarine reactors is dispersed within another material, called a matrix, and clad with a third material, to make a fuel plate. Material used in the reactor cores needs a low absorption cross section for neutrons, in order not to increase the amount of fissionable material required. The uranium powder can be uranium oxide or uranium aluminides and uranium silicides. From Eriksen (1990), pp. 45–48, and Simpson (1995), pp. 332–333.

[83] Beckett 1998, quoted in DOE appendix: Inventory and Characteristics of Spent Nuclear Fuel, High-Level Radioactive Waste, and Other Material. p. A-29.

[84] DOE (1998). Features sought are enhanced power density, longer life of the cores, decreased weight, increased resilience, reduced corrosion, ease of operation, and affordability.

[85] The reactors in the U.S. Navy's warships have over 115 million miles steamed on nuclear power, or a total of 5,000 reactor years of operation.

[86] Based on Sharpe (1999), pp. 789–838, and personal communication with personnel at the Naval Nuclear Propulsion Program Directorate.

[87] With a machinery output in the range of 26 MW to 45 MW for submarines in the current fleet (SSNs and SSBNs, respectively). From Sharpe (1999), pp. 789–838.

[88] Ballistic missile nuclear submarine.

[89] Nuclear-powered attack submarine.

[90] Deep Submergence Craft, a nuclear-powered ocean engineering and research submarine.

[91] USS Enterprise (the first nuclear aircraft carrier built) has eight reactors. The other eight carriers are of the Nimitz-class with two operating reactors each.

[92] Land-based reactors for training and research and development. There are four facilities, each with one reactor.

[93] Arkin & Kristensen (1998).

[94] The Benjamin Franklin class, the Sturgeon class, the Los Angeles class, the Seawolf class and the Virginia class.

[95] As of September 21, 1999. Source: U.S. Submarine Warfare Division, http://www.chinfo.navy.mil/navpalib/cno/n87/n87.html

[96] Director Naval Propulsion Program (1995), p. 21.

[97] U.S. Secretary of Energy Bill Richardson before the Committee on Armed Services Subcommittee on Military Procurement U.S. House of Representatives, March 4, 1999. http://www.doe.gov/news/testimon/cas3499.htm

[98] FAS (1999).

[99] GAO (1998).

[100] Other options reviewed (October 1999) by the Joint Chief of Staff include: Converting older Ohio-class SSBN submarines to so-called SSGNs at a cost of $420 million; refueling and extending by 12 years the service life of perhaps eight Los Angeles-class (SSN 688) subs at a cost per copy of $200 million; or building new Virginia-class (SSN 774) subs at a rate of at least four over the next five years, at a cost of roughly $2 billion each. From FAS (1999).

[101] Sharpe (1999), p. 801. To maintain a fleet of 12 carriers an additional aircraft carrier, CX1, will be needed by the year 2007.

[102] Albright et al. (1997), p. 87.

[103] U.S. Secretary of Energy Bill Richardson before the Committee on Armed Services Subcommittee on Military Procurement U.S. House of Representatives, March 4, 1999. http://www.doe.gov/news/testimon/cas3499.htm

[104] Sharpe (1999), p. 838.

[105] Schmitt, quoted in National Academy of Sciences (1995), p. 165.

[106] DOE/EIA (1998), p. 13.

[107] Schwartz et al. (1998), p. 140.

[108] von Hippel et al. (1986), p. 3.

[109] I.e. Eriksen (1990), p. 47.

[110] Schwartz et al. (1998), p. 141, footnote 89.

[111] A specific program is getting started on developing a reactor for the Navy's new class of aircraft carriers, called the "CVNX", prolonging their lifetimes. U.S. Secretary of Energy Bill Richardson before the Committee on Armed Services Subcommittee on Military Procurement U.S. House of Representatives, March 4, 1999. http://www.doe.gov/news/testimon/cas3499.htm

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[112] Director, Naval Propulsion Program (1995), p. 9.

[113] Sharpe (1999), p. 794.

[114] Director Naval Propulsion Program (1995), p. 9.

[115] The current reactor core design for the aircraft carriers is more than 30 years old. In fact, by the time the last Nimitz-class carrier is retired, the design will have been in use for nearly 100 years (as the last Nimitz-class carrier is planned to be commissioned December 2002). This technology of the early 1970's has mechanical features that facilitate reactor servicing but make less than fully efficient use of the active core volume. These cores, like the ones in USS Enterprise, operate for over 20 years.

[116] 14 SSBNs, 49 SSNs and 10 aircraft carriers, 2 submarines for training, research and development, and the NR-1. Based on Sharpe (1999) and FAS (1999) and an average lifetime for the submarines of 30 years and a life of 45 years for the aircraft carriers. The decommissioning of the USS *Enterprise* before 2015 comprises a reduction of eight reactors alone.

[117] Office of Naval Reactors, quoted in National Academy of Sciences (1995), p. 166.

[118] Attack submarine reactors are operated at more demanding modes, so the SSN-fraction of annual consumption is somewhat higher than the overall average indicated. However, the annual U-235 consumption of 7 kg is well in accordance with a lifetime core lasting 30 years with a total of 200 kg U-235 in the core.

[119] Naval Nuclear Propulsion Program Classification Review (1995), p. 3. http://www.osti.gov/html/osti/opennet/document/nnppcr/nnppcr.html

[120] According to commissioning schemes in FAS (1999).

[121] The annual integrated fuel consumption is the expected lifetime consumption of HEU, averaged over the operating years. An average lifetime of 30 years for submarines of 30 years and 45 years for aircraft carriers is assumed.

[122] Assuming, in accordance with Cochran et al., an average of 200 kg of HEU in the reactor cores.

[123] Bukharin & Potter (1995).

[124] Bukharin & Potter (1995).

[125] See Maerli (1999).

[126] Thefts of military equipment and fuel by servicemen in Russia's underfunded military became frequent in 1990s. DOE officials report that they made progress with the Russian Navy in installing security systems after several incidents involving sailors led it to take the theft seriously, but the challenges remains, see e.g. GAO (2000). Some of the earlier thefts, such as the diversion of 1.8 kg HEU (36%) from a North Fleet storage site in July 1993 and the theft of 4.5 kg HEU from the Sevmorput shipyard in November the same year, led the U.S. to expand its MPC&A program to the naval fuel cycle. Four more incidents involving naval HEU in the same region were reported during the subsequent three years. (Lee, 1996)

[127] *ABC News*, September 9, 2000. "Thieves Cripple Russian Nuclear Sub".

[128] *New York Times,* February 1, 2000. "Russian Servicemen Accused of Theft".

[129] Wilkening (1998), p. 20.

[130] Handler, quoted in Wilkening (1998), p. 20.

[131] IISS (1998), p. 102.

[132] Litovkin. (1999), p.30.

[133] From Kudrik (2000) "Typhoons to remain in service". http://www.bellona.no/imaker?id=14203&sub=1. This contradicts, however, both the plans announced by the American Co-operative Threat Reduction, or CTR, program and reports that Bark-class missiles will be discarded due to design failures.

[134] 92 ballistic missile submarines (SSBNs), 67 cruise missile submarines (SSGNs), 90 attack submarines (SSNs).

[135] Bukharin & Potter (1995), p. 48.

[136] Bukharin (1996), p. 63.

[137] Bukharin & Handler (1995), p. 246. Based on Sharpe (1990), p. 557, it can be assumed that approximately 120 of the vessels were SSBNs or SSGns. .

[138] For a description of the challenges in decommissioning the Russian submarine fleet, see e.g. Bukharin & Handler (1995) and Moltz & Robinson (1999).

[139] Sharpe (1999).

[140] U.S. Office of Naval Intelligence (1997), p. 11.

[141] Arkin & Kristensen (1998)

[142] Wilkening (1998), p. 22.

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[143] Ovcharenko (1998)

[144] Stated by Duma member Kuznetsov, May 1998, in an article in *Nezavisimoye voyennoye obozreniye*, translated in the Center for Nonproliferation Studies database. According to Kuznetsov, the absence of clear enemies necessitates an "economic" approach to estimating Russia's naval force requirements in the 21st century, in which the "naval order of battle is determined by capacities for regular funding in the form of a certain proportion of GNP". This may explain the discrepancies between the desired numbers of submarines, i.e. 65 to 72, and the actual numbers indicated (adding up to a total of maximum 48 submarines).

[145] Arkin & Kristensen (1998)

[146] Admiral Kuroyedov, quoted in Baker (1999).

[147] This has been claimed by Litovkin (1999), p.30.

[148] Sharpe (1999), p 560.

[149] The economic situation may, somewhat paradoxically, extend the service lives of the ships due to limited operational schedules and no possibilities for replacing ships. Service lives even above 35 years could thus be the result.

[150] In 2000, the Russian government pledged to earmark around USD 3.5 million, but according to the shipyard, some 25 million dollars annually is required to finalize the ship in three years. From Kudrik (2000) "New icebreaker might enter service in three years". http://www.bellona.no/imaker?id=15129&sub=1

[151] From the database of the Center for Nonproliferation Studies (CNS), Monterey Institute for International Studies.

[152] Thein (1997), quoted in the CNS database.

[153] According to Bukharin & Potter (1995), p. 47, most Russian submarines have two pressurized-water reactors which, under normal operating conditions, require refueling every 7 to 10 years.

[154] Bukharin & Handler (1995), p. 249.

[155] Bukharin & Potter (1995), p. 48.

[156] Idem.

[157] Bukharin (1998), p. 319.

[158] Reportedly, the Murmansk Shipping Company has become the principal customer of the Electrostal naval fuel production line. From Bukharin (1998). This is another indication of the financial hardships faced by the Russian Navy.

[159] Eriksen (1990), p.49.

[160] Maerli et al. (1998), p. 262.

[161] Volkov (1997), personal communication.

[162] DOE/EIA (1998).

[163] Weapons-grade equivalent HEU. From Albright, in Albright & O'Neill (eds.) (1999), p. 11. According to Bunn (2000), p. 18, the stockpile is 1050 tons of HEU, or 40 tons more than the estimates given by Albright. As Bunn points out, there are substantial uncertainties associated with the numbers presented. The latter quantity is over 100 tons less than the official estimate of the DOE MPC&A Strategic Plan.

[164] Bukharin (1996), p. 63

[165] Based on Bukharin (1996), p. 63.

[166] In accordance with internationally accepted standards regarding special fissionable and weapons-usable ("direct-use") material, and as reflected in IAEA definitions and practices, the material are plutonium 239, highly enriched uranium (i.e. uranium containing more than 20% uranium 235), uranium 233, and material containing any of the foregoing.

[167] Tritium is a radioactive isotope of hydrogen used to enhance the explosive yield of every thermonuclear weapon. It is normally produced by bombarding lithium with neutrons (e.g. from a U-235 chain reaction in a reactor).

[168] Bodansky, p. 271.

[169] In the gun-type, a subcritical piece of fissile material is fired rapidly into another subcritical piece (the target) such that the final assembly is supercritical without changing the density of the material. In the implosion-type, a near critical piece of fissile material is compressed by a converging shockwave resulting from the detonation of a surrounding layer of high explosive and becomes supercritical because of its increase in density. From Mark et al. (1987)

[170] Director, Naval Propulsion Program (1995), p. 35, see also figure A4.

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[171] Plutonium releases a steady stream of neutrons from spontaneous decay of its nuclei, thus producing a relatively high level of background neutrons. If plutonium is used in a gun-type bomb, these neutrons are almost certain to initiate an early chain reaction, causing a "fizzle" that will destroy the weapon without producing a large nuclear yield. Thus, a quick compression of the fissile material is required, leaving out plutonium as the core material of gun-type devices that represents a "slower" compression rate.

[172] In weapons using plutonium oxide, normally requiring larger quantities of fissile material than metal-based weapons, the device may constitute a powerful radiological dispersion device (because of the scattering of the oxide, due to the chemical explosion) even if the nuclear chain reaction is aborted and the weapon fizzles.

[173] Mark et al. (1987), p. 56.

[174] Ibid, p. 57.

[175] Cross section is a measure of the probability that an incident neutron will interact with a particular nuclide. Cross sections are separately specified for different target nuclides and different reactions. The cross section has units of area and can be, loosely, thought of as an effective target for a specific process. Bondansky (1996), p. 374.

[176] At 60% enrichment, the separative work is 125 SWU/kg, or 4600 SWU for 37 kg (assuming natural uranium feed). This may be compared to 193 SWU/kg and about 3500 SWU total for 17 kg of 90% enriched uranium. From Bodansky (1996), p.271.

[177] From Moniz & Neff (1978), p. 44.

[178] Bodansky (1996), p.271

[179] Moniz. & Neff (1978), p. 42. According to Chow & Solomon (1993), p. 5, the critical mass of HEU enriched to 20% will be 250 kg. Adding the other necessary components of a primitive nuclear weapon (reflector and high explosives) would make a bomb using uranium with less than 20% fissile content very heavy, and it would be impractical to develop a survivable delivery system for it. The bare critical mass of HEU enriched to 20% will be as high as 800 kg. Mark et al. (1987).

[180] This is due to the neutron background from spontaneous fissions.

[181] Based on the assumption that the mechanical properties of the material are similar and on a critical mass of 56 kg for naked uranium (enriched to 93.5% in U-235). Garwin & Charpak (1999), p. I-283**.**

[182] Mark et al. (1987).

[183] A significant quantity (SQ) is defined by the IAEA as "the approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded." For plutonium the significant quantity is taken to be 8 kg; for highly enriched uranium (HEU), 25 kg of contained U-235; for low-enriched uranium (LEU), 75 kg of contained U-235.

[184] Cochran & Paine (1995). With good designs and high-speed explosives, pure nuclear fission weapons could be manufactured with limited amounts of plutonium or HEU.

[185] Named the "Earthquake bomb" and the "Grand Slam", with a conventional yield of 10 tons of TNT.

[186] National Academy of Sciences (1994), p.33.

[187] Bodansky (1996), p. 261.

[188] As cited in Abrams & Pollak (1994), p.1.

[189] Alvarez (1987), p. 125. Although the initial chain reaction would not be sustained and the device would fizzle due to the physical expansion of the fissile material, significant energy could be released.

[190] Barnaby (1993), p. 37.

[191] Maerli (1999) p. 87.

[192] "Fat Man", the plutonium bomb deployed over Nagasaki, had the same design as the bomb used in the Trinity test, the first deployment of a nuclear weapon, performed July 6, 1945 in New Mexico.

[193] Cochran (1993)

[194] Falkenrath et al. (1998), p. 100.

[195] Mark et al. (1987) p. 63.

[196] The Aum Shinrikyo cult is an exception. The cult unsuccessfully tried to develop HEU from natural uranium mined at the cult's premises in Australia.

[197] Laqueur (1999), p. 5.