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Effect of Current and Future Nuclear Navies on an International Agreement over the Limiting of Fissile Materials Production

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EFFECT OF CURRENT AND FUTURE NUCLEAR NAVIES ON AN INTERNATIONAL AGREEMENT OVER THE LIMITING OF FISSILE MATERIALS PRODUCTION

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The most effective way to prevent the development of new nuclear weapons is to prevent the production of fissile materials. However, China, France, Russia, the United Kingdom, and the United States each have naval vessels that are fueled with fissile material. Furthermore, Brazil and India are developing such vessels. It has been argued that a formal cutoff of fissile material production, namely that of highly enriched uranium (HEU), will prevent nuclear navies from being fueled. The reality of the situation is calculated in this work.

It is shown that each current nuclear navy can be fueled for at least 100 years using its country's existing stockpile of HEU. For instance, the United States can fuel its navy for over 500 years. Obviously, a formal cutoff will not hinder the ability of any existing navy, but it may not be amenable to nations that are in the process of developing nuclear navies. To deal with this issue, a production cutoff above 40% HEU is proposed. It is shown that such an enrichment level can still provide adequate power to nuclear vessels, while being essentially useless for a military nuclear weapons program.

With these numbers in hand, a model is developed that determines how likely India and Pakistan, both of which are currently outside many proliferation agreements, can come to an agreement limiting the production of fissile material depending on political pressure put on them by various other key countries. It shows that although an agreement in the short term is unlikely, one is likely to be reached within 25 years. This,

along with the previous calculations, indicates that the countries of the world stand to benefit more strategically by agreeing to a formal fissile material production cutoff than not.

for everyone, everywhere

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Introduction

Previous works have examined stopping the production of uranium highly enriched in the isotope U-235.[1] The motivation is to stop production of material that can be readily converted to the manufacture of nuclear explosives. This would most likely occur in the context of a broader moratorium on the production of un-safeguarded enriched uranium and of un-safeguarded plutonium. If such a moratorium were to have any impact on the explosives production plans of states not currently parties to the Nuclear Non-proliferation Treaty (NPT), they may require as a quid pro quo that the five nuclear-weapons-states NPT signatories place some restrictions on their own future production of highly enriched uranium (HEU). Moreover, many NPT signatories may also wish to avoid having any country develop the sizeable potential for very rapid conversion to nuclear explosives of uranium enriched to very high concentrations of U-235 in declared support of naval propulsion. This may remain reasonably compatible with continuing nuclear navy operations if nations that currently fuel their navies on HEU will still be able to fuel them with weapons-grade HEU stockpiles until they develop vessels that operate on lower uranium enriched levels.

Previous studies have argued that existing stocks of enriched uranium would allow a transition to nuclear naval propulsion without continuing HEU production that takes “many decades”[2] or is “several-decades-long.”[3] Given both the politics surrounding HEU production and the long development times and lifetimes of nuclear navy assets, it is useful to have as much clarity as possible concerning just what the impact of a long-lasting moratorium on the production of very highly enriched uranium for naval fuels would be.

The present work combines estimates of enriched uranium stockpiles and the projected size and configurations of nations' nuclear navies over the next few generations to calculate how long each nation's transition period to a navy fueled with lower enrichment levels could last. Some of the results are on time scales that most would consider to be much longer than "several decades." For instance, it will be shown that Russia may fuel its projected navy on its current stockpile of HEU for at least 1,000 years. For the United States the corresponding timescale may be more than 600 years, while the British Royal Navy may be fueled for well over 300 years. In these cases the phrase "several centuries" more accurately describes how long these transition periods can be.

After examining these questions, this paper presents results from a model of the temporal evolution of the probability that an agreement limiting HEU production will have been reached. It is assumed that such an agreement would provide for a 25–100 year moratorium on HEU production above a given enrichment level of around 40%. This would leave open options for naval propulsion using newly produced moderately enriched uranium (MEU) below the prescribed enrichment limit, existing stocks of more highly enriched uranium, and possible future additional higher level enrichment after the expiration of the moratorium. For the purposes of this paper, these conditions accommodating naval propulsion are assumed to be necessary so that the agreement does not fatally conflict with the perceived essential requirements of countries that would be party to the agreement.

It will be estimated that the likelihood of such an agreement within the next twenty-five years encompassing South Asia and the United States based on current attitudes and efforts is possible, albeit small, being about 45% likely by 2030. However, it is also estimated that if the United States were to take a strong position in pushing for an agreement, the cumulative likelihood of success increases to over 50% by 2025 and rising substantially with time thereafter. The findings of this paper show that the United States, United Kingdom, and Russia will each suffer no strategic loss by agreeing to a limited production agreement and, in fact, benefit from the increased security it provides against materials proliferation. As such, there are no technical barriers preventing the United States or even Britain and Russia, from fully engaging its political will to bring other nations to an agreement limiting the production of fissile materials.

HEU Stockpiles

The following is an outline of the amount of HEU fuel available to each nation that currently has a nuclear navy. A useful starting point for this is Albright, Berkhout, and Walker's *Plutonium and Highly Enriched Uranium 1996*.[4] Using this reference and some more recent material, this section provides country-by-country estimates of HEU stocks, including error estimates where available. In this section the designation HEU is used for all uranium enriched to more than 20% U-235. All levels of HEU are relevant for China, France, and Russia because either their current or proposed ships can all run on the lowest possible level of HEU, 20%, or less. This is a useful break point around the lower end of enrichments for purposes other than fuel for electrical power production in reactors with a predominantly thermal neutron energy spectrum. Since enrichment levels of different stocks vary, it is convenient to also quote values in terms of the equivalent number of metric tons (tonnes) of weapons grade uranium (WGU) with an enrichment of 93%, which is nominally the dominant type in U.S. HEU stocks. However, the HEU stockpiles calculated for the United States and U.K. only account for uranium enriched to at least 93%. While both of these countries have stocks at levels below WGU, they are unsuitable for use in their current naval reactors without further enrichment, which would obviously be in direct conflict with limiting high-level enrichment. The stockpiles calculated for all other countries include all uranium enriched above 20% and is reported in WGU equivalent.

United States: According *Plutonium and Highly Enriched Uranium 1996*, the United States had 749 ± 50 tonnes of HEU at the time that manuscript was prepared.[5] This was listed as equivalent to 645 ± 50 tonnes of WGU. Of this, it is estimated that 127 tonnes is enriched to below 93% with an average of 45% enrichment.[6] This is equivalent to 61 tonnes of WGU. The U.S. Department of Energy has since declared 231.3 tonnes of HEU to be excess to the needs of the military.[7] This excess uranium is to be blended down for sale, reserved for space missions, or transferred to long-term storage. However, only 33 tonnes of WGU were included in this total.[8] This leaves 551 ± 50 tonnes of WGU.

Recent estimates indicate there are 10,350 warheads in the U.S. nuclear arsenal.[9] If the average amount of uranium per warhead is considered to be 20kg, this amounts to an additional 207 tonnes of WGU.[10] This leaves 344 ± 50 tonnes of WGU available for naval propulsion. However, the United States has declared that it will reduce its number of actively maintained warheads to approximately 6,000 by the year 2012.[11] Thus over 4,000 excess warheads could add another 87 tonnes of WGU to the available stocks for naval propulsion. In the relatively near future then, the United States will have 431 ± 50 tonnes of WGU potentially available for naval reactors.

United Kingdom: According to the Royal Navy’s 1998 Strategic Defense Review, the United Kingdom has 21.9 tonnes of HEU.[12] It can be assumed that this is predominantly weapons or higher grade because it is referred to as a “defense stock” and the UK has no defense applications that utilize non-WGU. This review also declared that the UK needs no more than 200 operational nuclear warheads to satisfy its deterrence needs.[13] These 200 warheads account for about four tonnes of WGU. However, this amount is not included in its declared HEU stockpile. Thus, the UK nominally has 21.9 tonnes of WGU potentially available for use in its naval reactors.

Russia: In 1996, Russia had an estimated 1,050 ± 300 tonnes of HEU stockpiled from production and dismantled nuclear weapons.[14] Through a 1993 agreement, Russia is converting 500 tonnes of HEU to low enriched uranium (LEU), which is then being sold to the United States for civilian power reactor fuel. This program has already converted 237 tonnes of HEU and is scheduled to convert the remaining 263 tonnes by 2015.[15] By then, Russia is expected to dismantle another 2,000 nuclear warheads,[16] creating an additional 40 tonnes of HEU in its stockpile. Thus by 2015, Russia will have 590 ± 300 tonnes of HEU potentially available for naval propulsion.

France: France had 26 tonnes of HEU stockpiled in 1996.[17] There has not been any major change in that figure since then. France's estimated 350 warheads account for 7 tonnes of this figure.[18] This number is not expected to change anytime in the near future. Thus, France nominally has 19 tonnes of HEU potentially available for naval propulsion. As will be discussed below, however, this figure is irrelevant unless France adopts a new naval propulsion strategy relying on HEU or transfers HEU to another state with a nuclear navy.

China: China is estimated to have stockpiled 20 ± 5 tonnes of HEU, which are taken here to correspond to approximately the same amount of WGU equivalent.[19] Of this, China's estimated 400 nuclear warheads account for eight tonnes.[20] This leaves 12±5 tonnes potentially available for naval propulsion. As will be discussed later, China's nuclear navy currently does not use HEU fuel, but that could change in the near future.

Table 1 collects the above nominal values and uncertainty ranges in terms of WGU equivalent for the current permanent five (P-5) members of the United Nations Security Council, which are the nuclear weapons states parties to the NPT. Of the two other countries included below because of their nuclear naval plans, Brazil and India, neither nominally has any excess HEU stock.

Table 1. HEU Potentially Available for P-5 Countries' Naval Fuel

Country	**Tonnes of HEU** **(WGU Equivalent)**
United States	431 ± 50
United Kingdom	21.9
Russia	590 ± 300
France	19
China	12 ± 5

Nuclear Navies

This section describes current nuclear navy deployments. Using these numbers as starting points, the future sizes of these navies are estimated for the next few generations of ships. The prospects of additional nations creating nuclear navies are also discussed.

United States: The current U.S. nuclear fleet stands at eighty-two vessels[21]. This fleet consists of ten CVN (carrier vessel nuclear) aircraft carriers, eighteen SSBN (submersible ship ballistic nuclear) submarines (four of which are being converted to SSGN (submersible ship guided missile nuclear) roles,[22] and fifty-four SSN (submersible ship nuclear) attack submarines. These vessels reportedly run their reactors with nominally 97.3% HEU, or above weapons grade uranium.[23]

The United States has been exploring the option of increasing the size of its nuclear submarine fleet. These plans call for seventy-six SSNs in operation by the year 2025.[24] This is a tall order, as many current SSNs will also be retired over the next twenty years. This increase will be accomplished with an aggressive ordering and building campaign of the new Virginia Class SSN, four of which are already built or under construction.[25] The increase in the fleet size would accompany the construction of another CVN to replace the Enterprise, which will retire in 2015.

Assuming that its current reduction to fourteen SSBNs indicates the level of deployment desired by the United States in the future, it can be projected that the U.S. nuclear fleet will stand at 100 vessels, or 130 reactors assuming four reactors in each CVN, for the next few generations of ships. This is more than are likely to be kept operational by all other nations combined in the near future.

United Kingdom: The UK currently has fifteen nuclear submarines in operation. This fleet consists of eleven SSNs and four SSBNs.[26] Like those of the United States, all of the British nuclear vessels are fueled with very highly enriched uranium.[27] The United Kingdom is in the process of downsizing its fleet. All eleven of its SSNs will be retired by 2025, and there are plans to replace only six of them with the new Astute Class SSN.[28] Assuming it maintains a deployment of four SSBNs, this reduction will bring the size of the British nuclear navy down to ten vessels for the next generation of ships.

Russia: It is very difficult to determine exactly how many nuclear vessels Russia currently has operational. Its once large nuclear navy has fallen into considerable disrepair over the past fifteen years. Compared to 197 nuclear submarines nominally in operation in 1990, estimates of its current functional size stand at thirty-nine vessels.[29] However, due to budget constraints it is unlikely Russia will even maintain a fleet of that size for long.[30] Even with its current development of the new Borey Class SSN, two of which are currently under construction, Russia is likely to lose another 25% of its fleet to retirement in the coming years.[31] All of these vessels are assumed to be fueled by 20-45% HEU.[32]

Russia is also in control of seven nuclear powered icebreakers and one nuclear powered transport ship. The icebreakers use 30-40% HEU and the transport ship uses 90% HEU. Icebreakers have a higher power demand than SSN’s. However, the Russian icebreaker fleet has not been economically profitable and recently had only three ships operational. Unless this situation changes, commercial nuclear navy operations are not likely to significantly decrease the lifetime of Russia’s HEU stocks.[33] Thus, a nominal estimate for the future size of Russia’s nuclear navy is under twenty-nine vessels, including three surface vessels with two nuclear cores each.

France: France currently operates eleven nuclear vessels, but only five of these run on HEU. Its six Rubis Class SSNs are fueled by 7% enriched uranium. Its four SSBN’s and one CVN, the Charles de Gaulle, are fueled with up to 90% HEU.[34] France has committed itself to making its entire nuclear fleet operate on LEU, although an additional HEU-fueled SSBN is currently under construction. For the future, France’s *Project de Loi Programmation Militaire 2003-2008* calls for six new LEU fueled Barracuda Class SSN’s to replace the aging Rubis Class and the construction of a second CVN. It is still unclear what type of fuel will run this second carrier.

Each of France’s existing HEU fueled SSBN’s have about one refueling left before they are decommissioned starting in 2025.[35] Furthermore, the Charles de Gaulle will be decommissioned by the year 2050.[36] If France adopts an LEU fuel design for its proposed CVN, 2050 will be the last year it will operate any HEU fueled vessel.

China: China has six operational nuclear submarines in its fleet. Five of these are Han Class SSN’s and one is the Xia Class SSBN.[37] All six of these submarines are reportedly fueled with 5% LEU.[38] These ships are generally considered to be obsolete and hardly ever leave port.[39] However, China has two new types of submarine under construction.[40] Russia has aided China with the development of what is called the Type 093 SSN. The reactor for this ship is reportedly the same shape and size as the Han Class. Following Chinese practice this ship would be fueled with LEU, while following Russian practice it would be fueled with 20-45% HEU.

China has independently been developing the Type 094 SSBN. There have been reported troubles with getting the reactor to work with the ship.[41] This implies that China is not using the type of reactor as the Xia Class. In addition, this submarine is to be an SSBN, which implies a “blue water” role in the navy. As such, it may need much more endurance than the 5% LEU fueled reactors can provide. Regardless of the type of fuel, China is expected to build three Type 093 subs and three Type 094 submarines.[42]

India: India has been developing naval nuclear reactor technology since the 1970s.[43] Although this project has hit many snags along the way, it is currently making stronger progress. It has been suggested that India’s Advance Technology Vehicle, as this project has been named, will be fueled with 20% HEU.[44] However, there is some question as to if that is the actual enrichment of the fuel. From 1988 to 1991 India leased a Charlie Class SSGN from Russia.[45] This class of submarine was fueled with 20% HEU, but recent reports indicate that the Rattehalli enrichment facility, which will provide all the fuel for the ATV program, has been outputting 30–45% HEU.[46]

The first ATV began hull construction in 1997, and its land based reactor prototype began operating in 1999.[47] There have been reported issues with making the reactor small enough to fit into the hull, which might indicate a lower enrichment and thus greater volume for the fuel, but little time is left for major modifications if the ATV is to meet its planned launched for sea trials in 2007.[48] It has been suggested that India wants a total of five of these vessels in the near future.[49]

Brazil: Brazil has been working on a naval nuclear propulsion system since 1979, well before its accession to the NPT as a non-weapons state. The original completion date for this project was 1995, but it has been drastically rescheduled, with the first nuclear powered vessel not planned for commissioning until 2018.[50] If this program continues, Brazil is expected to build a total of three nuclear vessels. There are conflicting reports as to what kind of fuel Brazil’s submarines will use. Some media sources indicate they will be fueled with LEU.[51] However, there are other indications that these vessels may be fueled with HEU, such as Brazil indicating a desire for a “blue water” navy, which may require submarines to have a higher endurance as provided by HEU fuel.[52]

Furthermore, the activities at Brazil’s Resende Enrichment Facility have recently been literally shrouded in much secrecy. Brazil has denied IAEA inspections of certain areas of its enrichment complex by hanging sheets or boards in front of its equipment. Brazil claims it needs to do this to protect proprietary knowledge of a new enrichment technique that will allow it to become a net exporter of enriched uranium.[53] This may be the underlying motivation, but an immediate goal of the enrichment program must be to fuel Navy’s land-based prototype reactor, which is scheduled to come online within the next year.[54] According to U.S. government sources, uranium enrichment is not an indication that Brazil is trying to establish a nuclear explosives program. In October 2004, then Secretary of State Colin Powell said, “'The United States understands that Brazil has no interest in a nuclear weapon, no desire and no plans, no programs, no intention of moving toward a nuclear weapon. They have a nuclear power program. We understand that.”[55] However valid this conviction may be and remain, if Brazil undertakes continuing HEU production it may complicate the process of bringing weapons-grade HEU enrichment in other countries to a halt.

Table 2 gives the nominal projected numbers of naval nuclear cores in next generation navies of the seven countries discussed above. While the boundary between

LEU and HEU from a safeguards point of view is conventionally taken to be 20% enrichment, going from slightly under to modestly over this boundary is of marginal use to the nuclear explosives program of a country with stocks of weapons grade plutonium and previously produced highly enriched uranium. This includes all of the countries listed in Table 2 except for Brazil. Given the well-established political situation in South America particularly with respect to Argentina, it seems unlikely that Brazil will in fact produce weapons grade plutonium or nuclear explosives, and would thus find uranium enriched to the 20-45% range to have little military potential beyond its use for naval propulsion.

Table 2: Current and Projected Number of HEU-fueled Nuclear Cores

Country	**Current # of HEU Fueled Nuclear Cores**	**Projected # of HEU Fueled Nuclear Cores**
United States	112	130
United Kingdom	15	10
Russia	39	32
France	8	0
China	0	3*
India	0	5*
Brazil	0	3*

*Fuel enrichment unknown and assumed here to be 20% for calculations. This figure is the current cutoff between LEU and HEU and is assumed to be below any limit agreed upon for a production moratorium.

In practice India is likely to have a deciding say on where the LEU/HEU boundary is drawn with respect to a future extended moratorium on enrichment to higher levels beyond this boundary, unless Brazil is willing to “take the heat” as a spoiler by insisting on a higher level. As long as this boundary is set well below normal weapons grade, e.g. 45% enrichment or below, the countries already well endowed enough with weapons grade fissile materials to sign on to a production moratorium would gain little additional nuclear explosives potential through safeguarded enrichment up to this boundary. Thus, the question of what if any levels of enrichment within this range India, Brazil, and China choose for their next generation of naval propulsion reactors need not necessarily be critical to prospects for establishing a durable moratorium on the production of fissile materials for nuclear explosives programs.

Endurance of HEU Stockpiles when Used for Naval Fuel

It is possible to estimate how long each country's stockpile of HEU could support its naval needs by using the above information. One approach is to determine how many refuelings (R) are possible out of each country's stockpile by dividing the tonnes of HEU in the stockpile (S) by how many tonnes are used in each reactor core (C). This can then be divided by the ratio of the number of vessels (V) to core life per reactor (L) to give the stocks' endurance in years as:

$$R = \frac{S}{C}$$

$$Endurance = \frac{R}{(V / L)}$$

This method has a number of uncertainties. Most notably, the exact enrichment totals of each country's stockpile are unclear. For instance, each stockpile contains a certain amount of weapons grade uranium and a different amount of, say, 30% enriched uranium for research reactors. It is doubtful that the exact breakdowns of each country's stockpile will soon be fully disclosed. For this reason, previous calculations of stockpile sizes all include an inherent uncertainty.

Another uncertainty in the method used to determine the endurance of each country's HEU stockpile when applied to naval fuel is the exact amount of uranium used in each submarine reactor. The numbers used in the following calculations are the best estimates available for each type of submarine. However, depending on how often a ship goes to sea and how far it travels, the lifetime per core can vary by a few years or more.

United States: The United States nuclear fleet is generally accepted to use 0.2 tonne of uranium enriched to above 93% to fuel each of its submarines.[56] However, there are indications that these reactors will operate at their desired power levels and endurances using a minimum of 93% HEU fuel.[57] Using 93% enrichment to avoid the having to require further enrichment of part of the stockpile to obtain 97% enrichment and thus allowing for the equivalent of a slight blend down of this higher enrichment to WGU, this means that its 431 ± 50 tonnes of stockpile WGU equates to 2,155 ± 250 refuelings. As determined above, the United States is expected to have 100 vessels in its fleet. This includes ten surface vessels, assumed here without significant loss of accuracy to use fuel at four times the rate of submarines. Assuming a WGU-driven design retaining a core life of thirty-three years, or the assumed operational life of the submarine,[58] this will require 3.93 core replacements per year to maintain the nuclear navy. The number of refuelings divided by this ratio equals 548 ± 64 years. Thus, the U.S. nuclear naval fleet is nominally sustainable for at least 480 years without any further enrichment activities if it is run on WGU.

The United States has already declared 260 tonnes of its HEU stockpile to be reserved for use as naval fuel.[59] This declared amount can nominally supply 1,300 refuelings to the U.S. navy. That is still enough to run the U.S. nuclear fleet for 331 years without any further enrichment activities and still have 171 ± 50 tonnes of WGU left over in the stockpile.

United Kingdom: Assuming continuing British use of U.S. nuclear submarine design and also using a fuel enrichment of only 93% as discussed above, 21.9 tonnes of WGU equates to 110 refuelings. The fleet of ten submarines that the UK is expected to retain can be fueled for an estimated 363 years with this material, without the need for transfer of excess WGU stocks from any other country.

The UK has declared five to seven tonnes of its HEU stockpile to be reserved for naval fuel.[60] This amount of uranium can supply twenty-five to thirty-five refuelings. That is enough fuel to supply the British navy for 83 to 116 years without any further enrichment activity and still have 14.9 to 16.9 tonnes of HEU leftover in the stockpile.

Russia: The Russian nuclear fleet uses an estimated 0.315 tonne of uranium enriched to an average of 33% in each of its submarines.[61] The 590 ± 300 tonnes of WGU equivalent in Russia's stockpile then equates to 1663 ± 845 tonnes of naval fuel. This is enough for 5279 ± 2683 refuelings. With an estimated fleet load of thirty-two cores and a core life of ten years,[62] this is enough to fuel the Russian navy for 1,650 ± 838 years.

Russia has declared that forty to seventy tonnes of its HEU stockpile will be used for naval fuel.[63] This is enough uranium for 127 to 222 refuelings. This could supply the Russian navy with fuel for forty to sixty-nine years and still leave 535 ± 300 tonnes of WGU equivalent in the stockpile.

France: The French nuclear navy does not play a role in the discussion at hand because, as mentioned before, it is being converted to an entirely LEU fueled fleet. Assuming that the currently proposed aircraft carrier is LEU fueled, France only needs enough uranium for about eight more refuelings. It clearly has this much in its stockpile of nineteen tonnes of HEU. Should a future French government decide to run a single carrier on HEU using fuel at four times the rate of a nominal submarine, then one-quarter of its HEU stocks would suffice to do this for ninety-nine years.

China: As discussed above, it is somewhat unclear as to what China's future nuclear navy will actually contain. For argument's sake, it will be assumed that the three Type 094 submarines that China wants will be fueled with 400 to 800kg of 20% enriched uranium. With these assumptions, China's current HEU stockpile of 12 ± 5 tonnes equates to 54 ± 23 tonnes of naval fuel. If each core life is ten years like French and Russian cores of the same fuel type, then this is enough fuel for 135 ± 58 years for a 400kg reactor core or 68 ± 29 years for an 800kg reactor core. China has not declared any of its HEU stockpile for use as naval fuel, at least in part because its current fleet operates solely on LEU.

India: Using Russia as a model, for India to operate a planned five nuclear submarines on 33% enrichment would require about 10,000–12,000 separative work units (SWU) per year with a tails assay in the range 0.035–0.023%. (Using the parts of the model of Bunn et al. detailed here in Appendix A, 0.035% value is the economically optimum tails assay for an international market uranium cost of $10/kg, while the 0.023% value is the optimal tails assay if India has to rely on domestic uranium resources at four times that cost.)[64] For the same average naval reactor power output from cores with 20% enrichment HEU, the SWU/yr requirements are lower by about 600. In either case, according to Ramana's *An Estimate of India's Uranium Enrichment Capacity* as a starting point,[65] India does not currently have enough enrichment capacity for its proposed nuclear navy of five ships.

Unlike several other countries, India has not likely built up a large stock of excess HEU given its reliance from the beginning of its nuclear program on plutonium from natural uranium fueled production reactors. Even assuming India continues to use natural uranium to fuel its electricity production, it will need to carry through with increasing enrichment capacity at its Rattehalli facility to meet the HEU requirements for a fleet of five fully operational nuclear submarines. It is implausible that over the next decade India would build up stocks allowing operations for such a fleet for nearly a century after the onset of a production moratorium. Not only would this be unnecessarily expensive from an Indian point of view, Indian accumulation of such large stocks of HEU could easily cause a political reaction in Pakistan that would preclude agreement on a moratorium on production of fissile materials for explosives programs.

Thus, if India insists on at least maintaining the option of providing its own fuel for up to five fully operational nuclear submarines, as seems likely, then the LEU/HEU boundary for any moratorium on production of HEU and weapons program plutonium that encompasses South Asia will likely have to be set by the choice of HEU level India makes for its nuclear submarines.

Brazil: Brazil's Resende Enrichment Facility was estimated to have started operation in 2003 with an enrichment capacity of 20,000 SWU per year and is predicted to be at 100,000 SWU per year by 2010.[66] By linear interpolation, it can be calculated that the facility currently has an enrichment capacity of about 43,000 SWU per year and has produced a current stockpile of enriched uranium containing about 470kg of U-235. If operated at full capacity and used solely for the nuclear propulsion program, the planned capacity of the Resende facility could by 2020 build up enough excess HEU stock to power Brazil's planned naval propulsion program for the rest of the century.

However, it is unlikely that Brazil will invest so heavily in uranium enrichment just to build up excess stocks for naval propulsion. Recent droughts have put more pressure on expanding the nuclear power industry in Brazil.[67] The government has declared that it wants to be able to provide 60% of the country's uranium needs by 2010 and become a net uranium exporter by 2014.[68] Currently, Brazil is operating two commercial pressurized water reactors (PWRs) that can produce electricity at a combined rate of 1,900 MWe.[69] These reactors require about 48 tonnes of fuel each year.[70] Even with its predicted increases in capacity, Brazil will not be able to meet its 60% goal by 2010. At that time, the Resende Facility will only be able to produce 30% of Brazil's fuel needs even if it provides no fuel to the naval program. Thus, if Brazil carries through with its plans for nuclear naval propulsion and for supplying its own electricity production reactors and exporting LEU, then it will need to develop a continuing source of enrichment for naval fuel. Unless it takes the unusual step of relying on an outside source for fuel for its military naval program or diverts enrichment capacity from other purposes to domestic production of naval fuel, Brazil is unlikely to build up enough HEU stocks that allow for a future moratorium, and in any case will not have such stocks until well after a decade from now. Thus, if Brazil insists on a higher enrichment for naval fuel and its participation in an HEU production turns out to be needed politically for such a moratorium to encompass South Asia, then the HEU level chosen by Brazil for its naval reactors would set the uranium enrichment limit for such a moratorium.

Table 3: Endurance of HEU Fueled Navies

Country*	**Years: All HEU Stocks**	**Years: Naval Use Stocks**
United States	548 ± 64	331
UK	363	83 – 116
Russia	1,650 ± 838	40 – 69
France	**	**
China	135 ± 58 for 400kg/reactor 68 ± 29 for 800kg/reactor	***

*India and Brazil are not included because neither has a sizeable HEU stockpile.
** France does not plan to have HEU fueled vessels after 2050.
***China has not declared any stocks specifically for naval use.

Table 3 summarizes the projected length of time that nuclear navies could be fueled with all available HEU stocks, and with those stocks declared excess to weapons use and thus currently reserved for use as naval fuel. The current trajectory of U.S. and Russian nuclear weapons stockpiles makes it highly likely that sufficient additional WGU stocks could be made available for naval fuel if and as needed, even though for current naval planning purposes there is no apparent need to set aside additional WGU for naval propulsion. Thus, provided that the level of enrichment in these stocks is deemed sufficient for naval propulsion, there is no practical limit up to several centuries for the length of an HEU production moratorium that could be supported by these countries. The same is effectively true for the United Kingdom. British HEU stocks set aside for naval propulsion are already adequate for more that a century. Another centuries' worth could readily be set aside from existing UK stocks of WGU or acquired from the United States, France, or eventually possibly even Russia. French HEU stocks are more that adequate for the one HEU-fueled vessel it plans to operate during the first half of the twenty-first century, and could readily be stretched to a full century or two from now if a future government decides to replace that ship with another HEU-fuelled one.

China, on the other hand, has not declared any of its HEU stocks excess to its needs for nuclear explosives and thus available for use as naval fuel. China is not likely to do so unless and until it has a comprehensive nuclear arms limitation understanding with the United States and possibly also with Russia, or it develops sufficient excess HEU stock beyond its perceived need for a minimum deployed deterrent in the absence of such an understanding. Somewhat more explicitly than China, India nuclear doctrine also seeks a "minimum deterrence" rather than parity with larger nuclear arsenals[71]. Although Pakistan's nuclear doctrine is more opaque, something below parity with India is likely for Pakistan in order to avoid continuing build-ups if parity in nuclear explosives holdings turns out to be unacceptable to India. In large part because of generational inertia in domestic political attitudes, the U.S.-Russian builddown in assembled nuclear explosives holdings is unlikely to proceed at a pace faster than that of tritium decay, which reduces stocks by about a factor of four every quarter century in the absence of continuing production. At this rate it will not be until around the end of the twenty-first century that United States and Russia assembled nuclear explosives holding approach parity with China, thus possibly allowing a build-down in Chinese nuclear explosives holdings. Assuming India carries through with its current plans to cap nuclear explosives holdings at less than half of China's, it would take more than another quarter century for Sino-India parity in nuclear explosives holdings to provide the political cover for India to join a global build-down. Thus there is no particular expectation that China, India, or Pakistan will stock a large over-build of WGU that will subsequently be declared as excess and thus available for naval propulsion. This does not preclude institutional inertia producing excess HEU stocks even though they are not needed for nuclear explosive programs. Another possibility is that one or more of these three countries will import enriched uranium for naval propulsion, thus saving indigenously produced material that could be used during a production moratorium. However, these alternatives are fraught with potential political and technical difficulties and cannot be relied upon to provide relief from the conclusion that China, India, and perhaps Pakistan will insist on retaining the option to enrich uranium above 20% enrichment for use in naval propulsion.

As indicated by a recent agreement between the U.S. administration and India, there may be some political incentive for the United States to cooperate on nuclear matters with India.[72] On the U.S. side, in this agreement

> President Bush conveyed his appreciation to the Prime Minister over India's strong commitment to preventing WMD proliferation and stated that as a responsible state with advanced nuclear technology, India should acquire the same benefits and advantages as other such states. The President told the Prime Minister that he will work to achieve full civil nuclear energy cooperation with India as it realizes its goal of promoting nuclear power and achieving energy security. The President would also seek agreement from Congress to adjust U.S. laws and policies, and the United States will work with friends and allies to adjust international regimes to enable full civil nuclear energy cooperation and trade with India, including but not limited to expeditious consideration of fuel supplies for safeguarded reactors at Tarapur…

On the Indian side,

> The Prime Minister conveyed that for his part, India would reciprocally agree that it would be ready to assume the same responsibilities and practices and acquire the same benefits and advantages as other leading countries with advanced nuclear technology, such as the United States. These responsibilities and practices consist of identifying and separating civilian and military nuclear facilities and programs in a phased manner and filing a declaration regarding its civilians (sic) facilities with the International Atomic Energy Agency (IAEA); taking a decision to place voluntarily its civilian nuclear facilities under IAEA safeguards; continuing India's unilateral moratorium on nuclear testing; working with the United States for conclusion of a Fissile Material Cut Off Treaty; refraining from transfer of enrichment and reprocessing technologies to states that do not have them and supporting international efforts to limit their spread; and ensuring that the necessary steps have been taken to secure nuclear materials and technology through comprehensive export control legislation and through harmonization and adherence to Missile Technology Control Regime (MTCR) and Nuclear Suppliers Group (NSG) guidelines.

If fully carried through, over likely opposition from parts of the U.S. Congress and the Indian nuclear establishment,[73] this joint U.S.-India understanding would produce a very different situation than what was the case for negotiating and end to nuclear testing before India's 1998 explosions. At that time, India stood alone in the Conference on Disarmament in blocking reporting of the Comprehensive Test Ban Treaty Text directly to the United Nations. It is questionable whether the "including but not limited to" in this statement by President Bush would in practice extend to transfer of uranium enriched over 20%, even if safeguarded for use in naval propulsion only. On both sides this would likely require years of building trust between successive U.S. and Indian administrations, as it would produce a situation in some respects similar to the "special relationship” on nuclear propulsion matters that exists between the United States and Britain.

However, particularly in the context of a comprehensive global agreement on cessation of production of un-safeguarded fissile materials for nuclear explosives programs, it should be noted that this deal allows for the transfer of LEU to India. Another possible source of such a transfer is Russia, for which the financial reward is larger in proportion to its economy, and the political cost is minimal if occurring with the tacit approval of the other permanent members of the UN Security Council. Transfer of HEU for naval propulsion from the United States to China seems out of the question, particularly if China uses the HEU to power SSBN’s that can target the United States. Such a transfer from Russia to China is more likely, but in this case it would be more likely to engender active opposition rather than tacit support from the United States.

It is less likely that states holding nuclear explosives would strongly object to a transfer of less than weapons-grade safeguarded HEU to Brazil in connection with the establishment of a global moratorium on HEU production, but there could be domestic opposition in Brazil to reliance on outside sources.

For at least the next one or two decades, all of this supports the conclusion drawn above, that the LEU/HEU enrichment level boundary for an expanded extended moratorium on HEU production is likely to be set by the enrichment level chosen by China, India, and possibly Brazil for naval propulsion. Setting this boundary somewhere above 20% in the range 20–45% will run counter to accepted practice and may thus encounter some opposition among the non-weapons-states parties to the NPT. However, the alternative is likely to be no additional multilateral agreement at all on production of fissile materials for nuclear explosives programs.

Medical Isotope Production

There are four other main areas of interest when it comes to HEU proliferation. These are tritium production, space reactors, research reactors, and medical isotope production. Of these, tritium production and space reactors are not of much of a proliferation concern because the HEU used is self-secure. The only HEU fueled reactors producing tritium are two 1000 Megawatt thermal (MWt) reactors at the Mayak facility in Russia.[74] Being of a military purposed operation, some heightened security, as much as can be expected from the Russian programs, can be assumed. Furthermore, the 1000-MWt rating of these reactors will cause the fuel to become impossible to handle in a clandestine way, as would be expected with smuggling attempts. Space reactors can be considered a self-secure use of HEU because once launched, it becomes unrecoverable. Finally, there are many alternatives to direct HEU fuel for both of these reactor systems.[75]

There has been much work in regards to mitigating the proliferation threats of research reactors. The Reduced Enrichment for Research and Test Reactors (RERTR) program at Argonne National Laboratory researches and develops ways to fuel current HEU fueled research reactors with LEU fuel of the same geometry. This is done by increasing the density of the uranium fuel.[76] Current research indicates that a U-Mo alloy fuel can be fabricated to a density of 15.6 g/cc up from the roughly 1 g/cc of standard HEU fuel.[77] These efforts will allow every research reactor still in operation to be converted to LEU fuel. As long as funding remains on target, which appears likely after a short budget slump following the Cold War, the issue of research reactors could eventually solve itself.

This leaves the issue of medical isotope production. Of the many radioisotopes used in nuclear medicine, technetium-99 is the most widely used.[78] It is employed in nearly 80% of all nuclear medicine procedures. Historically, it has been created by irradiating an HEU target with neutrons. This creates a Mo-99 isotope among other fission products.[79] Mo-99 has a half-life of 66 hours and then beta decays into Tc-99, which has a half-life of only 6 hours.[80] However, it has been shown that LEU targets are technically feasible for the production of Mo-99, but they require a different reactor setup.[81] It is estimated that the four producers of Mo-99 worldwide use 85kg of HEU every year.[82]

In 1992, to combat HEU proliferation in the commercial sectors, the "Schumer Amendment" was passed in the United States. Its main goal was to get customers of HEU supplied by the United States to switch their operations to LEU as quickly as possible. It mandated that the NRC could only issue a license for HEU export if the following three conditions were met:[83]

1. There is no alternative reactor fuel or target enriched in the isotope 235 to a lesser percent than the proposed export that can be used in the reactor
2. The proposed recipient of that uranium has provided assurances that, whenever an alternative nuclear reactor fuel or target can be used in that reactor, it will use that alternative in lieu of highly enriched uranium
3. The United States Government is actively developing an alternative nuclear reactor fuel or target that can be used in that reactor

The Energy Policy Act of 2005 relaxed these standards somewhat. Now a license for export may be issued if the following two criteria are met:[84]

> (A) a recipient country that supplies an assurance letter to the United States Government in connection with the consideration by the Commission of the export license application has informed the United States Government that any intermediate consignees and the ultimate consignee specified in the application are required to use the highly enriched uranium solely to produce medical isotopes; and

> (B) the highly enriched uranium for medical isotope production will be irradiated only in a reactor in a recipient country that—
>
> (i) uses an alternative nuclear reactor fuel; or
>
> (ii) is the subject of an agreement with the United States Government to convert to an alternative nuclear reactor fuel when alternative nuclear reactor fuel can be used in the reactor.

The most important distinction between the two is that the newest form does not require the use of alternative targets if they are available. This change is a result of heavy lobbying by the largest medical isotope producer, the Canadian company, Nordion.[85] Nordion had a history of rebuffing the Schumer Amendment. It had originally agreed to develop an LEU target by 1997.[86] Upon requesting another export license in 1997, the NRC reminded them of their obligations under the Amendment and another committee was agreed to. It too was never acted on by Nordion and in response the NRC threatened to revoke its license.[87] Nordion assured many more commitments in the years to follow, but all were broken after citing various reasons including the possible disruption of isotope supplies worldwide and cost restrictions. It even appealed to the IAEA to endorse its HEU use over LEU conversion. The IAEA refused to endorse Nordion and expressed a desire for Nordion to become a world leader not just in production of isotopes, but also conversion of targets.[88]

As it stands now, Nordion can continue applying for and receiving HEU exports from the United States without any move to convert its target. Nordion's three competitor's, Mallinckrodt, the Institute National des Radioelements, and the Nuclear Energy Corporation of South Africa, none of which receive HEU from the United States and thus are not subject to the new Energy Policy Act, have all stated a commitment to switching targets, but like Nordion, it is unclear how committed they really are. However, Argonne National Lab has stated that LEU targets may be economically cheaper to use in the long-term operation of isotope production.[89] This means that there is a potential win-win situation for the first company that fully switches to LEU targets.

The first of the four companies that converts to LEU targets will have the benefit of choosing from many suppliers of target fuel, as opposed to just a few nations as right now. Furthermore, it will provide a huge public relations boost to the company, which can expand sales. Furthermore, once one company switches, the others run the risk of being legislated out of business if they do not convert. It is possible that the United States could reverse the changes made by the 2005 Energy Policy Act or even halt all exports of HEU altogether once a company converts. Although, since Nordion is the only producer in the Western Hemisphere and Mo-99's half-life is only 66 hours, it may be difficult for the other companies to provide adequate supplies to hospitals throughout the United States.

In any case, medical isotope production is not an issue that should complicate an international agreement on fissile materials production. While it affects many nations worldwide, it is strictly an issue that needs to be resolved between the main suppliers of HEU, the United States and Russia, and the four isotope production companies. Economic incentives may resolve the issue in Europe and Russia since Mallinckrodt is in the Netherlands and the Institute National des Radioelements is in Belgium, so they can both supply the same geographic areas with the same expediency required for isotopes with such short half-lives. However, this may not happen in the United States for the reasons described above. A possible solution would be the United States. building its own production facility, which in actuality makes the most economic sense owing to the fact that the United States is the largest consumer of Tc-99 treatments. Even the threat of building its own facility could have enough of an effect on Nordion that it could change its targets to LEU.

Much like how the issue of research reactors will eventually solve itself through the efforts of RERTR and the Global Threat Reduction Initiative, the issue of medical isotope production will also solve itself. Only in its case, it will be due to economics and not nonproliferation efforts. Thus, while a cursory glance at the issue indicates otherwise, medical isotope production, as well as research reactors, space reactors, and tritium production, do not play into the current discussion of establishing an international agreement over a limit in fissile materials production.

Towards an Agreement

A primary goal of an expanded and durable moratorium on production of fissile materials for nuclear explosives programs is that it include India and Pakistan. That such a moratorium is overdue from the point of view of global security is clear enough. It was the absence of such a moratorium in the 1990s that provided the motivation for Pakistan to acquire a new generation of enrichment centrifuges that made an earlier generation excess and thus tempting to transfer to Libya, Iran, and North Korea through the A. Q. Khan network.

Nuclear technology transfers from Pakistan may have also influenced the timing or even the occurrence of the breakdown of the 1994 Agreed Framework with the Democratic Peoples Republic of Korea. Given the remarkable level of popular disapproval of the United States within Pakistan,[90] a breakdown in good relations between Pakistan and the United States and its allies, for instance through a coup on the Musharraf regime, could again lead to a situation where an active fissile materials production program in Pakistan could serve as a source of technology transfer or even nuclear materials export. This seemingly would require the overthrow of Musharraf, which could be possible. Under his rule, however, with current U.S. foreign policy focused on the “war on terror” it seems unlikely that nuclear materials export would be possible considering the severe repercussions for Pakistan by taking such an action. While India has a strong and enduring policy against being a source of nuclear technology transfer, there remains the possibility that this could change when its own nuclear explosives program no longer needs additional fissile materials, but no moratorium on their production has been established. Assuming it comes into full effect, the nuclear fuel agreement India signed with the United States in March 2006 will have interesting ramifications on this. However, without currently knowing the details of this agreement, in depth analysis of its effects is impossible.

From a South Asian regional security perspective, the sooner an enduring moratorium on production of fissile materials for nuclear explosives can be established, the less the nuclear weapons overbuild will need to be managed there for generations to come. Through tense Indo-Pakistani confrontations in 1987, 1990, 2000, and 2002, it has become clear that a state of deterrence already exists in light of the conventional and undeclared, and later declared, nuclear military capabilities on both sides. In parallel with recently accelerated Sino-Indian rapprochement, this suggests that all current and future production of fissile materials for nuclear explosives in South Asia is indeed “overbuild.” As noted above in the case of the United States, Russia, and China, it can and is likely to take generations before such overbuild can be reversed once it is produced. Thus, both from a global and regional point of view, there are potential advantages to an early broadening into South Asia of a durable moratorium on the production of fissile materials for nuclear explosives.

A moratorium that includes limits on HEU production and embraces Pakistan and India may be bilateral, multilateral, or universal. A formal universal agreement would require the cooperation of all countries that are not non-nuclear-weapons states parties to the NPT, all countries with interest in HEU production for naval propulsion, and all countries using HEU for medical and other isotope production and research reactors if they are not willing to rely on outside HEU providers as discussed above. In addition to India and Pakistan, Israel and North Korea are not parties to the NPT. Furthermore, the five permanent members of the UN Security Council (P-5) are not non-nuclear-weapons states parties to the treaty. With respect to nuclear explosives programs, the most likely impediments to a formal universal moratorium on production of fissile materials are Israel and North Korea. By the time Pakistan is ready to sign on to such a moratorium, Israel is likely to have no further need for fissile materials production. However, Israel is likely to want to continue tritium production in the same type reactors used to make plutonium. Both to keep its tritium production low profile in the Middle East and to avoid domestic political opposition to any constraints on its nuclear program, Israel is unlikely to sign on to a formal agreement that requires inspection of its nuclear production facilities. It will require a substantial change in the regional domestic and political situation or in the willingness of the United States to press Israel to cooperate before Israel signs on to any formal universal agreement on nuclear materials production that requires inspections of operating nuclear facilities.

Ending the current standoff on North Korean production of weapons-grade fissile materials will also require a change in North Korean or U.S. positions or in China’s willingness to pressure North Korea to cooperate. What is necessary for a moratorium on fissile materials production is a freeze rather than elimination of North Korea’s nuclear weapons program. The most likely route to this is a change sometime over the next ten to fifteen years in U.S. policy on the grounds that a production freeze is the most than can be achieved, but that such a policy change will materialize is far from certain. What this implies is that entry into force of a comprehensive fissile materials production cut-off treaty (FMCT) is very unlikely for the foreseeable future if it follows the Comprehensive

Test Ban Treaty (CTBT) precedent of requiring the ratification of all potentially relevant countries.

An Indo-Pakistani bilateral agreement halting the production of fissile materials for nuclear explosives programs would avoid the difficulties of achieving a universal agreement, but lacks the political incentives for coming to such an agreement that could accompany a broader-based process. India in particular is strongly vested in the idea of a “non-discriminatory” approach that would also formally constrain China and all other nuclear weapons states equally. Pakistan may also be able to make political gains with some of the P-5 if agrees to a production moratorium in a broader multilateral framework. In both cases multilateral engagement can help provide domestic political cover for governments that might otherwise be accused of simply capitulating to its rival across the line of actual control in Kashmir.

Thus, what is of primary interest here is an arrangement that is multilateral, but not necessarily formally universal. This could parallel the current situation with nuclear testing. In this case, the Preparatory Commission for the CTBT Office has set up much of the verification mechanics without the treaty actually coming into force. This resulted from India allowing the draft of the treaty to be worked out in the Geneva Conference on Disarmament but declining to sign onto the final text. A similar situation on fissile materials production with Israel or North Korea as holdouts on entry into force is quite possible with respect to the FMCT. In this case, the challenge will be to design an arrangement that builds confidence that countries stating a willingness to cooperate have in fact ceased production of unsafeguarded weapons-usable fissile materials.

Assuming that other countries are willing to negotiate a treaty text even knowing that Israel or North Korea are unlikely to sign it (and that the U.S. Senate may be unlikely to ratify it for the foreseeable future), there are three treaty text issues that have been identified at the Conference on Disarmament as potential roadblocks. These include existing stocks, availability of higher than weapons grade HEU, and verification.

Existing stocks: The key issue on existing stocks has been Pakistan's concern over India's weapons grade plutonium. This concern will be somewhat allayed when Pakistan achieves what it considers an adequate minimum nuclear deterrence, which is in any case a prerequisite for Pakistan to agree to a production moratorium. At this point, a likely diplomatic approach is to encourage rather than require signatories to declare and possibly safeguard existing stocks, using U.S.-Russian actions on this as a precedent. Existing stocks of enriched uranium are also a potential concern. However, stocks of LEU are likely to be widely distributed amongst many states with nuclear potential, and the separative work units (SWU) needed to enrich reactor grade LEU to weapons grade HEU is less than that to make LEU from natural uranium (c.f. Fig.1 under "Form of an Agreement", below).[91] For a given technology, the energy requirement for enrichment is about proportional to the SWU requirement (which depends only on the feed, product, and tails enrichment). Moreover as noted above, enrichments up to 45% are likely to be of marginal use for nuclear explosives programs of states not non-weapons-states parties the NPT, as such states will already have access to substantial amounts of weapons grade fissile materials by the time they are ready to sign on to an extended production moratorium. Thus, the most substantive question concerning "breakout potential" is not whether states hold less than weapons grade enriched uranium but how much potential they have for rapidly converting this material to weapons grade. For this mothballed enrichment facilities would be likely to suffice, and it is unlikely that in context of a moratorium rather than an in-force treaty that such mothballed facilities would soon be irreversibly decommissioned.

Naval propulsion: Another potential roadblock concerns the impact that an extensive HEU production moratorium could have on the continuing ability of the United States and Britain to field nuclear navies fueled with WGU. The primary question about using WGU as a base for naval propulsion fuel is not whether this is feasible but whether it is seen to be desirable in the sense of producing compensating security gains. This raises a difficult cost-benefit question, which is addressed quantitatively below. In any case there is a considerable amount of resistance within the U.S. Navy against a switch to lower enriched fuel and thus, by correlation, there is resistance to a permanent halt of HEU production. This is a delicate point that should be understood. It appears that those in the U.S. Navy are only concerned with their fuel supply and not with how it was made. If officials can be convinced there is already an adequate fuel supply for any of their naval needs through current stockpiles, then there would be drastically less resistance to formalizing the already voluntary HEU production moratorium in effect in the US. How much better is WGU for navies than LEU? This assessment regarding the fuel supply needs and convincing officials hasn't been done yet?

Since entry into force of a permanent treaty banning such production seems unlikely, an extended moratorium might be more practicable. A precedent for this was set in the NPT, which was originally written to last for a limited duration of twenty-five years unless and until an extension and review conference extended the treaty either for a limited period of time or indefinitely. This approach allowed countries with nuclear potential but no nuclear weapons, notably Germany and Japan, time to gain confidence in the nonproliferation regime and its benefits in comparison to verification costs and the limits it put on their nuclear programs. The same approach might be useful for the text of an FMCT. However, owing to the extensive HEU stocks of the United States and long lead-time for design as well as operation of nuclear naval assets, an agreement on longer a moratorium might be possible.

Verification: Reversing a standing tradition of pushing for extensive verification in various arms control agreements, the United States recently took a position in the Conference on Disarmament against detailed verification arrangements for an FMCT. While this may reflect a generic skepticism about arms control agreements and reluctance to countenance any international intrusions on U.S. sovereignty, it also reflects the reality that it is likely to be fruitless to negotiate detailed verification arrangements for an FMCT that cannot enter into force without effectively universal ratification. Given the latter very real concern, the challenge particularly for future U.S. administrations will be to help fashion confidence building measures for a broader de facto moratorium on production of fissile materials for nuclear explosives programs without a formal treaty having entered into force.

For the nuclear explosives testing moratorium, it has been possible to build confidence in the universality of the moratorium since 1998 in part through activities of the Preparatory Commission that do not involve challenge inspections. This is particularly convenient for the testing moratorium, because a global network of seismic and other detection systems has been built up and applied to producing useful upper limits on the yield of any explosions world-wide without intrusion into the territory of the few relevant states that decline to cooperate.

As with underground nuclear testing at substantial yields, in practice it is also likely that all weapons-grade fissile materials production programs have been detected well before the level of production that would be significant for the nine countries that are not now non-weapons-states parties to the NPT. This has been done through a combination of national technical means, voluntary on-site inspections, and tracking the intermediaries that have been involved in nuclear technology transfers.

Probably the most useful mechanism that could be developed for encouraging confidence building in a fissile production moratorium is the establishment of voluntary agreements with the International Atomic Energy Agency. Rather than trying in advance to specify a “one size fits all” standard for states not already covered as non-weapons NPT signatories, this would allow each confidence building arrangement to be tailored individually. Assuming that each state signs on to the moratorium with the intention of abiding by it, then the primary advantage to them is to build confidence amongst potential rivals that they are in fact doing so. This applies particularly to India and Pakistan, but also potentially to China as well. Should a succeeding government want to violate the agreement without having appeared to, this might not be so easy, as North Korea discovered. Quite likely the negotiation of such confidence building arrangements could be slow and difficult, but this approach would nevertheless provide political cover for establishing and maintaining a production cutoff without the appearance of sacrificing sovereignty up front by simultaneously signing on to a detailed verification protocol. Thus a production moratorium agreement itself might end up looking more like the simple NPT text rather than that of the very lengthy and detailed Chemical Weapons Convention.

Form of an agreement: To summarize, what is envisioned here is a comparatively simple agreement that calls for an extended moratorium on production of fissile materials for nuclear explosives programs. Participants in the agreement would pledge to eschew all un-safeguarded plutonium production and all HEU production above a given enrichment level. This limit would be defined in the final negotiating process and end up somewhere in the range of 20-45%. This range would effectively define a new category of HEU to be referred to here as moderately enriched uranium (MEU). A limit of 40%, for example, could probably be made adequate for the naval propulsion programs of countries using MEU if they so chose. By itself, MEU in this range would have marginal utility to the nuclear explosives program of any country with the technical capability to produce it, since such a country would also have a supply of fuel for plutonium production, and the capability to rapidly produce higher level uranium enrichment whether or not its existing production was limited to the LEU or MEU range. Fig. 1 and Table 4 illustrate why this is the case. Fig. 1 shows the separative work units per kilogram of uranium-235 in the enrichment product as a function of the enrichment. The SWU requirement depends on the tails assay, which is the percentage of uranium-235 in the depleted uranium discarded after enrichment. A higher cost of natural uranium feed provides an economic incentive to reduce the amount of uranium-235 discarded in the tails, which requires more separative work.

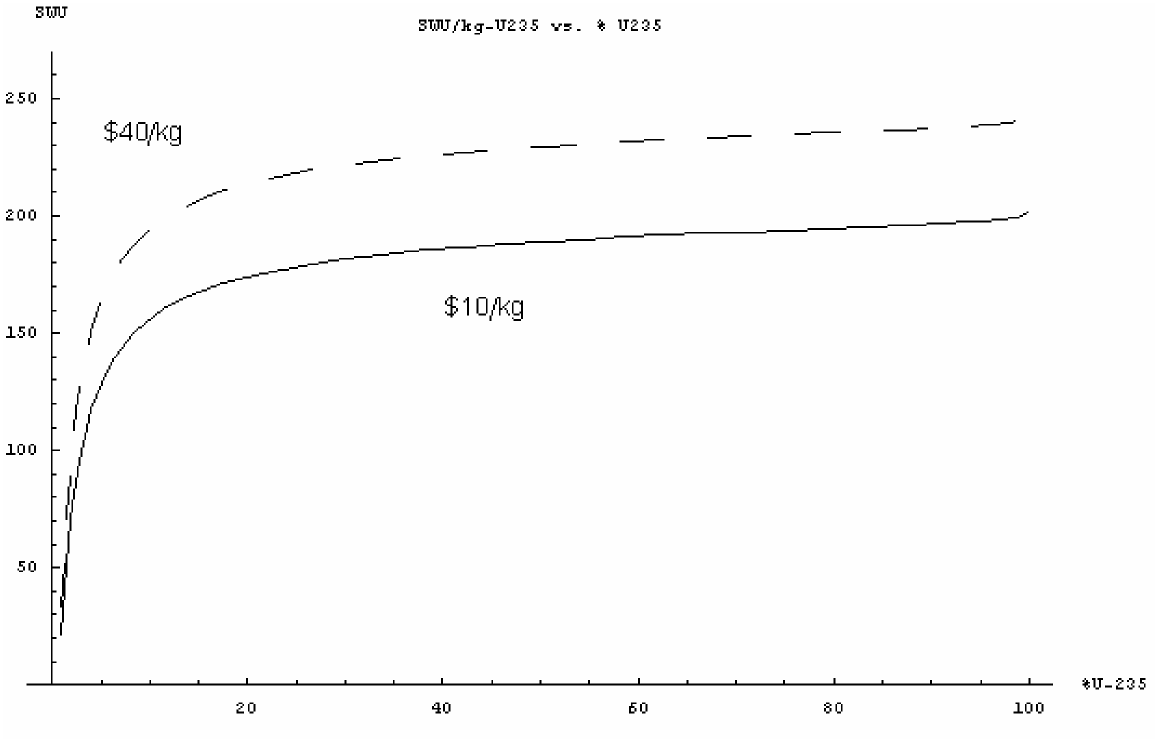

Fig. 1. Separative work units, per kilogram of U-235 in the product, as a function of product enrichment plotted from 1.0% enrichment to 99.8% enrichment, for natural uranium feed at $10/kg (solid curve) and $40/kg (dashed curve).

The assumptions used to estimate optimal tails assays of 0.35% for $10/kg feed and 0.23% for $40/kg feed are detailed in Appendix A. While separative work requirement expressed in terms of the total amount of all uranium isotopes in the product increases nearly linearly with the product assay over a wide range of enrichments, what is relevant to high level enrichment is the separative work requirement expressed in terms of the amount of uranium-235 in the product. This more relevant measure diverges logarithmically with the difference between product assay and 100% uranium-235, but as illustrated in Fig. 1 at the maximum plotted value of 99.8% enrichment, this divergence only starts to become significant when the uranium-238 percentage in the product becomes comparable to the uranium-235 percentage in the tails.

Table 4 gives numerical values for SWU per kilogram of product uranium-235 for various enrichments. These include the c. 1% value to be used in new Canadian design heavy water reactors, an approximate lower limit of 3% used in light water electricity production reactors, the 20% enrichment boundary between LEU and HEU, a possible 40% boundary between medium and high level forms of HEU, 93% nominal WGU, and 97.3% nominal HEU naval propulsion fuel. Evidently a light water reactor program is "over half way there" to WGU, and there is little significance in terms of additional enrichment requirement to the difference between 20% enrichment and WGU vs. the difference between 40% enrichment and WGU. Thus, once a country has acquired enrichment capacity at the level of 4000–5000 SWU/yr needed to make 20 kg/year of WGU, in terms of the additional separative work needed to make weapons grade material, it does not make a lot of difference whether that enrichment capacity is used to make light water reactor fuel or does enrichment for other purposes at either 20% or c. 40% enrichment. Under such circumstances the most that can be managed is adequate verification that the enrichment is being used for declared purposes to build confidence amongst other parties in the absence of more threatening activities and to increase the political cost of breakout.

Table 4: Separative Work per Kilogram U-235 in Product vs. Enrichment

%U-235	SWU ($10/kg Feed)	SWU ($40/kg Feed)
1	22	34
3	100	132
20	174	214
40	186	226
93	197	238
97.3	199	239

Nevertheless, limiting enrichment to less than about 40% range would greatly limit the yield of a nuclear explosive that could be produced by a non-state actors acquiring it, if indeed they could obtain enough such material and the needed technology to fashion into a fast-neutron-driven critical assembly. However, this is still a level at which new naval reactors can operate with high power density.[92]

Table 5 qualitatively shows how the uranium enrichment level dictates both the quantity of enriched uranium and the technological capability a non-state actor would need in order to develop a weapon of equivalent yield. In this comparison, neutron absorption by the U-238 isotopes is ignored for simplicity, so in reality, the mass of uranium needed would be even greater than that indicated in the table for lower enrichments. Furthermore, technological capability refers to such things as scientific knowledge, computational ability, precision machining, etc. Thus, the table shows that if a non-state actor were able to obtain 40% HEU, it would need to have 3 times technological capability and over 2.5 times the physical mass of uranium in order to achieve the same yield of explosion it could get from obtaining WGU. This is shown purely to demonstrate that the difficulty of manufacturing a weapon increases rapidly as the enrichment levels are lowered.

Table 5: Qualitative Comparison of Uranium Enrichment vs. the Amount and Technology Needed to Develop a Weapon of Equal Yield for a Non-State Actor

Enrichment	Technology Capability	Mass of Uranium Needed
93%	1.0	1.0
80%	1.5	1.25
60%	2.0	1.67
40%	3.0	2.50

In order to avoid a permanent disparity between the capabilities of states with and without higher-grade HEU stockpiles, the agreement would initially have limited duration. This would most likely be on the order of the planning and operational lifetime of the next classes of naval nuclear vessels, i.e. about fifty years, but it could be as short as twenty-five years or as long as a hundred years. Given the information in Table 3, a multiple centuries moratorium would in principle be possible if the UK were amenable to lower nuclear explosive stocks or to relying on the United States or France for WGU transfers. However, more than a century is longer than the historical period of stability of many countries' governments and of most international alliances and would thus seem unnecessarily ambitious. Indeed, allowing for possible drastic changes in political circumstances, such an agreement would have extension and review and withdrawal provisions. This and the rest of the wording of the agreement could thus be similar to that of the NPT but preferably be more tightly worded to avoid overreach (as in the NPT's call for universal disarmament) and ambiguity (as in its provision for review and extension "for an additional fixed period or periods").

Pertinent agreements between signatories and the IAEA should ideally increase confidence in the production halt but also confidence that existing HEU stocks, MEU stocks, and production are secure and not being used for purposes other than naval propulsion and perhaps also non-military purposes. The conversion at least of all greater than LEU enrichment burning activities for other than naval propulsion to no more than MEU and perhaps to LEU enrichment levels could also help build confidence in the spirit of the production moratorium.[93]

Probability of Agreement

The following are hypothetical reactions that each country discussed, as well as some key additional nations, may have to such a moratorium on weapons grade enrichment of uranium. These reactions are based on historical actions, current statements, and future goals of each nation. Following this are the results of a quantitative model of the probability as a function of time that Pakistan and India will have assented to a multilateral or bilateral agreement halting the production of fissile materials for nuclear explosives programs.

United States: Provided that the United States, Britain, and Russia are willing to rely on existing HEU stocks for naval propulsion for the duration of a moratorium, the United States and Russia would be the least affected by these agreements. As shown above, the United States has WGU stocks sufficient for naval propulsion nominally sufficient for over 600 years. Furthermore, its stockpile, while being one of the largest in the world, is relatively secure.[94] In principle an agreement to a moratorium as long as a hundred years could discourage the down-blending of some WGU for commercial purposes. For example, a hundred year moratorium starting in 2025 could preclude down-blending some WGU from 2075-2100, followed by subsequent enrichment to naval propulsion grade c. 2100-2125. With sufficiently high discount rates, preventing such an approach could be economically disadvantageous. For this to be economically significant at the time of signing on to the moratorium, however, discount rates would need to increase substantially with time, which seems unlikely. Thus the primary economic consideration for the United States would be whether the benefits of an earlier than otherwise achievable halt to fissile materials production at least in Pakistan and India would compensate for temporary but long term limitations on enrichment beyond WGU grade uranium for naval propulsion purposes, as discussed further below.

United Kingdom: The United Kingdom has shown that it is committed to nuclear nonproliferation through its arms reductions over the past decade.[95] It is also committed to maintaining a nuclear arsenal smaller than it had during the cold war. Furthermore, the UK has voluntarily declared that it will no longer exercise its exemptions from IAEA safeguards for its fissile material stockpile.[96] Finally, it is reasonable to assume that the UK will be able to make a purchasing arrangement with the United States or elsewhere for any HEU that it may need if in the unlikely event its stockpile becomes insufficient. For these reasons, it is likely that the UK will be favorable to any such agreement.

Russia: Russia stands to benefit in several ways from an agreement limiting HEU production. Use or leakage of nuclear technology or fissile materials from Asian countries can be as much or more of a threat to Russia than to other countries that are not non-weapons-parties to the NPT. Tightening up global fissile materials security elsewhere could also bring more emphasis and aid to improving such security within Russia. From a political perspective, Russia's major European Union trading partners would look favorably on Russia's agreement on tightening global nuclear security and conversely be discontent if Russia blocked it. The political incentive Russia has for broader cooperation on nuclear matters will depend to some extent on how its nuclear deterrence relationship with the United States evolves. Furthermore, Russia has enough WGU stocks to provide the world's likely MEU needs for a least a century. Both Russia and potential importers could thus profit economically from the construction of a more globally comprehensive system to restrict enrichment beyond LEU levels elsewhere and build confidence that MEU transfers are being made under adequate safeguards. Given the global survey of naval propulsion plans shown above, it is highly likely that Russia will have ample supplies of HEU for any of its needs even if it fully supplies the MEU requirements of any number of other countries. This includes supplying fuel for its civilian nuclear icebreaker fleet, which needs to be refueled every three to four years.[97] Given these considerations it can be expected that Russia would be favorable to an agreement unless its government converts to a substantially less internationalist orientation than the current one.

France: France does not have much to risk by accepting such an agreement. France will not need any HEU for submarine fuel and it is perceived as having a secure stockpile program.[98] France's only issue with an agreement may be a perceived encroachment on its long-standing policy of independent nuclear defense.[99] While it may never need more nuclear weapons, France may recognize this treaty as limiting its defense potential. However, as long as tritium production is not limited by this agreement, France should be able to work through this issue. Unlike Israel, France has no particular political need to keep its tritium production operation opaque.

Brazil: Its recent droughts combined with current uranium prices should be a clear indication to Brazil that nuclear power is much more beneficial right now than a nuclear navy. At $114 per SWU[100], Brazil stands to save millions of dollars a year for its energy sector if it can enrich its own fuel more cheaply than buying enriched fuel abroad. That is not to say that Brazil will automatically accept an agreement to limit enrichment above an MEU threshold level. With respect to safeguards, Brazil will most likely take issue with increased IAEA access to its facilities, but this is an issue that should be dealt with under NPT safeguards arrangements in any case. This is one of the reasons for a using a two-step process like that for the NPT: first an agreement on the general form of verification will be agreed with the IAEA, followed with country by country negotiation of specific agreements. Using this approach, it is likely but by no means guaranteed that Brazil would be willing to cooperate with an agreement limiting enrichment levels.

China, India, and Pakistan: China, India, and Pakistan will all be linked in their decisions to accept an agreement. China has already declared a voluntary moratorium, but has little to gain by a more formal approach unless it Asian neighbors are willing to sign on. As with Russia, China's relationship with the United States on strategic nuclear delivery systems may have some impact on its willingness to cooperate fully on fissile materials production. In particular, China and the United States took the lead for several years in blocking progress in the Conference on Disarmament on negotiation of an FMCT due to disagreement on whether ballistic missile defense would be covered under parallel negotiations on prevention of an arms race in outer space (PAROS). Presumably after concluding that U.S. national missile defense deployments would not significantly affect the perceived political utility of China's "modernizing" strategic delivery systems, China agreed with Russia on a joint proposal on PAROS that would not preclude U.S. deployment of ground-based ballistic missile interceptors. Should U.S. ballistic missile defenses outrun what is needed to try to counter North Korean deployments, move to space-based systems, or spin off technology or systems transfers to Taiwan, they could yet poison China's willingness to cooperate on more formal limitations of production of weapons-usable fissile materials.

By one account, Pakistan's estimated 48 warheads outnumber India's estimated 35 warheads,[101] but these estimates are highly uncertain and do not account for likely differences in explosive yield, ease of delivery, and differences in overall fissile materials stocks. Moreover, India's conventional forces greatly outnumber Pakistan's forces.[102] For this reason, Pakistan may feel the need to increase its nuclear arsenal to perhaps 100 warheads. Its Kahuta enrichment facility has an estimated capacity of 9,000–15,000 SWU/year, which is enough for three to six weapons every year.[103] With this capacity, Pakistan could reach 100 warheads within 8 to 15 years. In addition, Pakistan is also in the process of producing un-safeguarded plutonium at its Khusab facility. It is the build-up of Pakistan's fissile materials stocks that is the primary determinant of how long it will be until a production moratorium encompassing South Asia can be achieved.

As discussed above, India has an enrichment capability comparable to Pakistan's and plans to use it to enrich fuel for its naval program. If India can fully develop and fuel its Advanced Technology Vessel as well as perfect it as a launch platform for nuclear warheads, then India may be comfortable without numerical warhead superiority over Pakistan in exchange for mobility and stealth. However, India does not currently have the enrichment capacity to fuel its desired nuclear fleet. By the time Pakistan has enriched enough uranium for a hundred warheads, India should just be at an enrichment capacity that can sustain fuel supply for its fleet. This still creates a potential dilemma, as India would not sign and agreement that would preclude it from enriching the uranium to refuel its submarines. India's near and long term naval nuclear plans thus set a limit on the upper enrichment level boundary for MEU, and possibly also on the initial duration of an HEU production moratorium if India wants to keep the HEU option open for a subsequent generation of naval reactors. India’s decisions on fissile material production will depend on Pakistan’s estimated fissile stocks and to some extent also on the extent of China’s nuclear delivery “modernization,” as well as the extent to which the United States and others are willing to push for an agreement and accommodate to India’s overall political and economic concerns in the process.

North Korea, Iran, and Israel: It is not likely that North Korea and Israel will both agree in the near future to comprehensive limitations and inspections of the facilities they have that are capable of producing weapons-grade fissile materials. For North Korea, this is only likely to happen if the ongoing six-party or successor talks covering its nuclear program result in an accommodation that leads to cessation of its fissile materials production. The cumulative chances of this may eventually grow with time as North Korea accumulates nuclear deterrence capability and other countries accommodate to the idea of merely freezing that capability. A comprehensive agreement might conceivably lead to safeguarding or even the removal of North Korea’s fissile materials stocks.

At the time of this writing Iran had managed to avoid an outright break with the IAEA. It is still subject to inspection of its fissile materials production facilities, though it is quite possible that it will either be declared out of safeguards compliance or conceivably even follow the North Korean precedent of withdrawing from the NPT. In any case, Iran may insist on the right to move up to enrichment to MEU levels as defined above. This need not necessarily be for naval propulsion, but could be justified in terms of reactor research or isotope production. If unable to import enriched uranium, except perhaps on a limited basis from Russia for its Bushehr electricity production reactors, Iran may justify production of HEU for medical isotope production by pointing to a provision in the U.S. Energy Policy Act of 2005 that relaxes a previous legislation aimed at banning HEU exports and curtailing HEU use worldwide. However, as discussed above, it is likely that economics will make this a very weak argument in favor of Iranian enrichment capabilities. In any case, depending on the levels of enrichment involved Iran could end up at odds with a moratorium on HEU production even if it is determined that all it needs to do to remain in good standing with the IAEA is to come into compliance with existing agreements even though it previously hid its enrichment program.

The domestic political ramifications of the relations between Israel, the Palestinian Authority, and other countries in the Middle East including Iran can have an influence on Israel’s willingness to be transparent about not producing fissile materials for explosives, even if it decides it has sufficient amounts of such material for its security needs. One key indicator of the state of Israel’s domestic and international political situation is the fraction of the West Bank that it has turned over to control of the Palestinian Authority (assuming a complete and irreversible pullout makes the question of the occupation of Gaza a moot point). Israel’s recently revised “security fence” boundary takes in about half as much of the West Bank as previously planned, but the fraction of the West Bank currently under full control of the Palestinian Authority is substantially less than that outside either of these security fence plan boundaries. Only when the withdrawal to at least the boundaries of the revised fence plan are complete and stable is there much likelihood that Israel’s international relations and domestic politics will settle down to the extent that an Israeli government could take the chance of appearing to compromise Israel’s security through increased transparency of its nuclear program.

The more the difficulties with North Korea, Iran, and Israel can be resolved to the extent that one or more of them would cooperate with an extended multilateral moratorium on high level uranium enrichment, the more attractive such an agreement might be. However, it is unlikely that all three will come into this fold by the time Pakistan has achieved its desired minimum deterrence and thus that the final stages of negotiations on a multilateral fissile materials production cutoff could proceed in earnest. Thus, though the politics of North Korea, Iran, and Israel can have some effect on the probability of achieving a multilateral agreement, any realistic approach must allow a mechanism for progress to be made without all three of these countries fully on board.

Quantitative Model: The above considerations have been brought together in a quantitative model of the cumulative probability that multilateral or bilateral agreements halting fissile material production for nuclear explosives programs will encompass at least Pakistan and India. The results are shown in Fig. 2, and the methodology is explained thereafter.

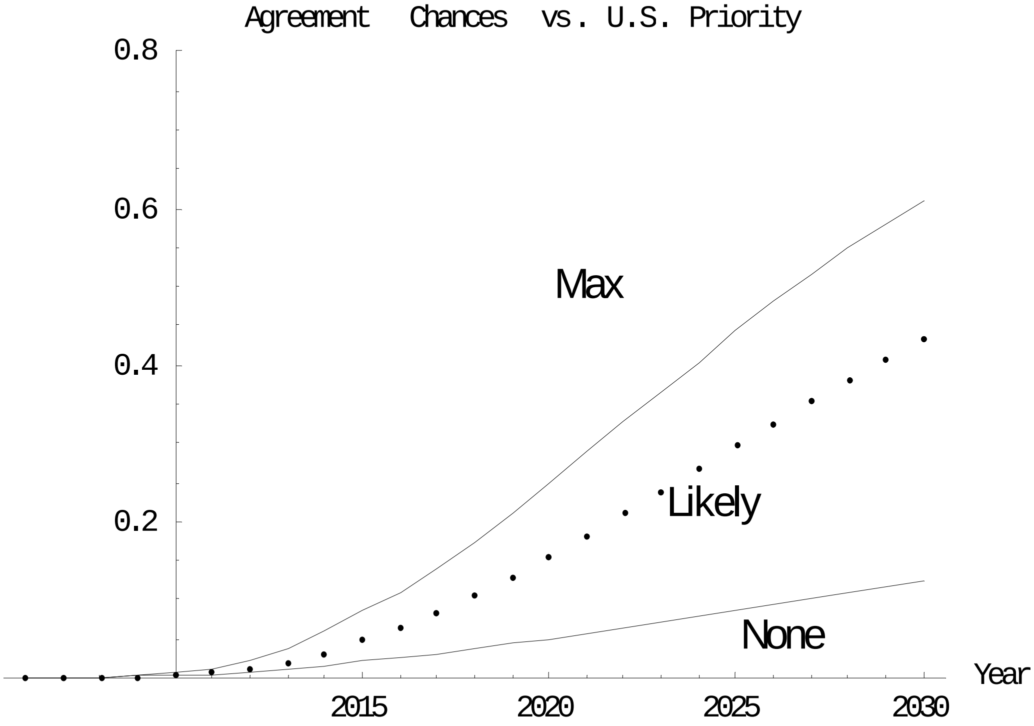

Fig. 2. Cumulative probability of an agreement suspending production fissile materials in South Asia having been reached by the years indicated for a bilateral agreement with no U.S. involvement (lower solid curve), a multilateral agreement with the most likely level of U.S. involvement (dotted line), an agreement with the maximum level of U.S. diplomatic priority assigned to achieving it (upper solid curve).

While an exercise leading to the results shown in Fig. 2 is obviously rife with uncertainty, there is still something to be said for having in hand a graph of the temporal evolution of this probability that is based on a plausible set of assumptions about underlying technical factors and political dynamics. The present exercise is concerned only with the development of agreements that are formal albeit not likely in the form of a new signed and ratified international treaty. It is of course inevitable that Pakistan’s and India’s production of fissile materials for nuclear explosives programs will eventually come to a halt even without any formal agreement in place, but this would likely happen without any coupling to uranium enrichment elsewhere. Since such a bilateral arrangement would rewrite the backdrop for multilateral negotiations, an estimate of its probability is also developed. The difference between the two estimated probabilities is a measure of how much difference outside forces can have on the development of an agreement limiting fissile materials production in South Asia.

The quantitative approach developed here proceeds in three stages. First comes a probabilistic model of the evolution of the "internationalist" vs. "nationalist" outlook of the governments of nine relevant countries: Pakistan, India, China, Russia, the United States, North Korea. France's position is assumed to be essentially independent of the political party in power, and the relationships of the United Kingdom to the United States and France are assumed to be strong enough that the type of government in power in Britain also has little predictable effect on the overall outcome. For simplicity, countries are assumed to face a choice of change of government type at intervals that are regular for a given country but staggered and of different duration for different countries. A continuity probability c in the range of 0.6–0.9 is assigned to each country, and the probability of a change in government orientation at each choice point is taken to be c^n where n is the number of "terms" that type of government has been in office. (That is, the probability of retaining the same orientation of government decreases with the number of "terms" that kind of government has continually been in office.) The probability of each country cooperating with a multilateral moratorium on production of fissile materials for nuclear explosives programs is reduced by a factor r during the time it has remained as or reverted to a "nationalist" oriented government. The example shown here uses these listed in Table 6.

Table 6: Factors Influencing Changes in Governments' Orientation

Country	**Continuity Factor, *c***	**Next Choice**	**Interval (years)**	**Government (Start Type)**	**Nationalism Factor, *r***
Pakistan	0.9	2007	5	int	0.5
India	0.6	2009	5	int	0.6
China	0.8	2008	5	int	0.75
Russia	0.8	2007	4	int	0.6
U.S.	0.7	2009	4	nat	0.75
DPRK	0.9	2018	17	nat	0.5

Note that continuity or change in the internationalist (int) vs. nationalist (nat) orientation of the government in power is not necessarily correlated with continuity or change of the political party in power in democratic systems, so that the continuity probabilities chosen do not correspond exactly to probabilities for continuity of the party in power.

It should be understood that while both India and Pakistan have what can generally be classified as internationalist governments, when dealing with their nuclear arsenals, especially with regards to each other's, they have historically been nationalistic. For the purposes of this model, both countries will start as internationalist government types to reflect steps each has recently taken to become a part of the nonproliferation regime. It is also assumed that India, after brokering its nuclear deal with the United States and likely subsequent deal with France, has enough vested interest in maintaining an internationalist outlook on its nuclear weapons and enrichment complex that it will not automatically switch to a nationalist government type if Pakistan does. However, in this model, if India switches to a nationalist government type, Pakistan automatically switches to it as well even if is not a defined election year. This is done to account for the weaker political situation in Pakistan as well as its greater perceived threat of India, especially if it is able to successfully operate nuclear submarines as a nuclear weapons platform.

The second stage models the development of the evolution of a relevant military indicator for each country. These indicators are used to gauge the state of domestic and international politics in each nation as they relate to the issue at hand. Some of these are as follows—Pakistan, India, and DPRK: nuclear bombs constructible from fissile stocks; China: nuclear warheads deliverable to intermediate and long range; Russia: sustainable level of nuclear warheads deliverable to long range. (Note: this figure is not the total number of warheads available. Many of Russia's long-range missiles are obsolete, but the warheads on these missiles are still counted as deployed in many publications.) Finally—United States: number of long-range ballistic missile interceptors deployed.

Each indicator is taken to be changing monotonically at rate and within a maximum limit determined by the orientation of the government in power. The starting values, internationalists' and nationalists' rates and internationalists' and nationalists' limits for are listed in Table 7.

Two additional bilateral indicators are evolved in addition to the nine single-country indicators just discussed. These deal respectively with U.S./DPRK and U.S/Russian bilateral strategic relationships. These indicators simply have a value of one or zero, depending on whether there has been a presumed irreversible understanding developed concerning bilateral nuclear deterrence. The exact formulas are given in Appendix B and described qualitatively in the following two paragraphs.

Table 7: Military Indicators Start Values, Change/Year, and Limits

	Pakistan Bombs	India Bombs	China Delivery	Russia Delivery	U.S. Defense	DPRK Bombs
Start	50	75	200	800	5	0
Int rate	10	25	30	20	1	0
Nat rate	10	25	30	40	5	2
Int limit	300	350	500	2000	10	40
Nat limit	350	700	1000	2000	200	100

In the case of North Korea, it is assumed that there is an annual probability of developing an understanding about that country's nuclear weapons capability. In addition to the nationalist vs. internationalist orientations of the U.S. and DPRK governments, this probability is taken to depend on two ratios of military indicators. One such dependence depends (strongly) on the square of the ratio of North Korea's stocks of weapons-grade fissile materials to the nationalist limit for these stocks listed in Table 7. The other factor modestly decreases the probability of a bilateral understanding depending on ratio of U.S. missile defense deployments to North Korea's number of bomb's worth of weapons-grade fissile materials. The resulting decrease in annual probability of developing a U.S./DPRK understanding is at most 50% in the limit where the United States has deployed five times as many ballistic missile interceptors as the number of nuclear explosives the DPRK has fissile materials for.

In addition to depending on the orientation of the governments in power, the probability of a durable better cooperation on nuclear matters developing between the United States and Russia depends in each year on the orientations of the governments in power at the time. The precise nature of such an agreement is not specified, but manifestation of such an agreement could be referred to as "START IV," a follow-on to the previously consider third strategic arms reduction treaty but with the number of opposing nuclear weapons on each side comparable the number listed in Table 7 as the starting value for functionally deliverable strategic warheads. Such a bilateral understanding between the United States and Russia would quite likely be accompanied by a stronger U.S. interest and credibility concerning a global cutoff in fissile materials production for nuclear explosives programs. The probability of such a development is also taken to depend strongly on the ratio w_4/h_4 of Russia's long range strategic delivery capability to its maximum saturation limit, and more weakly on the ratio w_5/w_4 of U.S. missile defense deployments to Russia's long range warhead delivery capability. The formula used for the annual probability of such an understanding developing is $0.05r_4r_5(1-w_5/w_4)(w_4/h_4)^2$, where r_4 and r_5 for Russian and the United States respectively take on the values shown in the last column of Table 6 with nationalist-oriented governments and the value of one with internationalist-oriented governments.

With these preliminaries in hand, the third and final stage of the calculation is to find the annual probability of Pakistan and India starting a durable moratorium on the production of fissile materials for nuclear explosives programs. This probability is taken to be the product of a "Pakistan factor" F_1, an "India factor" F_2, and a "U.S. factor" F_5. (The skip in subscripts between F_2 and F_5 occurs because countries are listed roughly in order of the importance of changes in their nuclear postures may have on Pakistan's and India's strategic postures, with China coming third because of its importance to India.) The "Pakistan factor" depends on the type of government in power in Pakistan, the Indo-Pakistani strategic nuclear balance, India's domestically driven view of the adequacy of its nuclear deterrent. The "India factor" similarly depends on the type of government in power in India, the Indo-Pakistani strategic nuclear balance, and India's domestically driven view of the adequacy of its nuclear deterrent; but it also depends on the Sino-India strategic balance. The "U.S. factor" captures not only the type of U.S. government in power but also the influences of relations with China, Russia, North Korea on the overall prospects for international cooperation successfully encouraging Pakistan and India to start a durable moratorium on the production of fissile materials for nuclear explosives program. The impact of these influences is given by the product of a set of factors each with weak linear dependences of the form q=1-0.2(1-f), where the factors f for each of the five countries just mentioned reflect the dependence of those countries' policies on the types of government in power and on relevant military indicators. For China this is a weak dependence on the ratio of China's nuclear delivery capability to U.S. missile defense deployments. For Russia this is a weak dependence on the whether the above-mentioned improvement in U.S./Russian nuclear cooperation has occurred. For the DPRK this is a much stronger dependence on whether the above-mentioned understanding on North Korea's nuclear capability has been reached.

The probability of outsiders successfully encouraging India and Pakistan to establish a fissile weapons materials production moratorium in any given year is taken to be a product of the values of "Pakistan factor" F_1, the "India factor" F_2, and the "U.S. factor F_5" for that year. Thus the probability of an agreement *not* having been achieved that year is the value of (1-$F_1F_2F_5$). The cumulative probability of a moratorium *not* having been reached by a given year is thus the product of the values of (1-$F_1F_2F_5$), for all of the previous years. The value of (1-$F_1F_2F_5$) starts out at nearly one initially, since the values of F_1, F_2 and F_5 start out small (particularly for the "Pakistan factor" F_1). Thus for early times the probability of *not* having achieved a moratorium is the product of a set of numbers each close to 1 and is thus itself near 1, and the corresponding probability of having achieved an agreement is nearly 0. Eventually the value of the product $F_1F_2F_5$ gets larger, primarily because the "Pakistan factor" gets larger as Pakistan approaches its maximum limit desired level of weapons-grade fissile materials stocks. Then the values of $(1-F_1F_2F_5)$ and the corresponding probability of *not* establishing a moratorium gets smaller and the accumulating probability of achieving a moratorium gradually grows, as indicated by the dotted line in Fig. 2. The details of the expected value for how fast this happens are contained in the formulas for the factors F_1, F_2, and F_5 given in Appendix B.

The "U.S. factor" F_5 is particularly complex, because it is the product of the U.S. government type factor and three additional factors of the form $q=1-0.2(1-f)$ as described qualitatively above and quantitatively in Appendix B. The results for each of the f factors are between 0 and 1, so each of the q factors is at least 0.8 and individually has relatively little impact. However, since there are three such factors multiplied together, their combined impact can be quite significant. The upper solid curve in Fig.1 is obtained by setting the "U. S. factor" $F_5=1$, a hypothetical case whose comparison with the dotted line result indicates the importance of the expectation that influences external to South Asia will not always be optimally aligned for the encouragement Indian and Pakistani agreement to a production moratorium.

The probability of an explicit or implicit moratorium evolving that requires only Pakistani and Indian cooperation is assumed to be only a function of the military indicators of Pakistan, India, and China, as described quantitatively in Appendix B. This is plotted as the lower solid curve in Fig. 2. This approach is assumed to be effectively a bilateral understanding between Pakistan and India, with India's willingness to participate depending modestly on China’s nuclear weapons delivery capability. This probability is taken to be lower than for an externally encouraged agreement, because it does not necessarily respond to India’s goal of fully normalizing its nuclear relationship with the rest of the world and it does not provide any substantive external political or economic incentive for Pakistan to overcome domestic political resistance to a nuclear posture very unlikely to provide nuclear weapons parity with India.

For all of the results shown in Fig. 2, a hundred random samples were taken according to the assumptions described above and quantified in Appendix B. The probabilities shown are the averages of those for each of these cases. Over the time period plotted in Fig. 2, in most cases a solution for the North Korean problem occurred and about half the time a significant new bilateral U.S./Russia agreement occurred. These parameters are included to take into account the potential importance of U.S.-Korean and U.S.-Russian relations in the overall approach that the United States takes to nuclear proliferation.

Conclusions

The prospect for a near-term agreement limiting the production of fissile materials is remote, as suggested by Figure 2. Taking a long-term perspective, however, it suggests that such an agreement is likely enough that it may be important to understand its upcoming implications for the politics of HEU management. The United States is capable of sustaining its nuclear navy for at least a hundred years without any further uranium enrichment or re-appropriations of stocks, as shown in Table 3. In reality, the United States will not stand to lose anything strategically by agreeing to a limited production cutoff. This means that there are no barriers preventing it from fully pushing for an agreement between Pakistan and India. This could result in a 50% probability in a resolution by 2025. Again, this is shown in Figure 2. In practice, this 50% probability benchmark could be reached sooner due to factors that are not included in the model above such as diplomatic pressure from other countries besides the U.S. and a resolution to the conflict over the Kashmir region. If, on the other hand, Iran withdraws from the NPT, then the impact of dealing with this, along side the North Korean situation and START IV talks, would need to be included in the model and would reduce the probability of obtaining a moratorium.

From a narrow U.S. perspective, the primary benefit of an earlier halt to production of fissile materials for nuclear explosives programs is likely dominated by the long-term implications of Pakistan otherwise pursuing such production continuously over the next few decades. After the attacks of Sept. 11, 2001, it was suggested that U.S. forces should be involved in securing Pakistani nuclear materials in the event of a regime collapse.[104] Given the extraordinarily low favorable opinion ratings of the United States that have evolved in Pakistani opinion polls in contraposition to current accommodations of Pakistan’s General/President, even a modest probability of a fundamental political upheaval in Pakistan is a cause for concern. If this does indeed lead to a U.S. intervention to secure nuclear facilities, this will be all the more complicated following extensive and continuing production at plutonium and HEU production sites. Under less dramatic circumstances, a change of Pakistani government or simply a relapse into the relaxed attitudes that allowed previous nuclear technology transfers could substantially increase the risk of such transfers to other countries or non-state actors if weapons grade fissile production is continuing at the time. While the dominant risk of nuclear materials transfer to third parties likely continues to be from the former Soviet republics, continuing production of weapons-grade fissile materials in South Asia increases this risk.

Although the probability of large-scale use may be small, the damage from of the use of larger than “minimal deterrence” arsenals within South Asia might produce the largest impact ever in human history in terms of the number of casualties. Even from a narrowly defined U.S. national interest point of view, the magnitude of the needed relief effort and the impact on the global economy would be unprecedented at least since the time of the twentieth century’s world wars. The Lugar Survey on Proliferation Threats and Responses estimated that the chance of a nuclear explosion in the next 10 years is roughly 30%.[105] While the chances of this occurring were estimated as less than 50%, the consequences are sufficiently portentous that the questions it raises are worth serious discussion. There is a danger that the discussion between naval planners and “nonproliferationists” on this issue becomes a dialogue of the deaf, with naval planners discounting the relevance of their preferences to nuclear nonproliferation and the other side placing such emphasis on the possible consequence of catastrophic events that naval concerns seem superfluous. What is presented in this paper suggests that both sets of concerns merit serious discussion and dialogue and are, in fact, compatible with one another.

What appears needed is a serious discussion of the tradeoffs and options available for a cutoff of high-level uranium enrichment that is practicable given the current political and military situations that exist in the world. It needs to be understood that the goal of a complete cutoff of fissile material production is impossible to achieve in the current era. However, those working towards it should not be discouraged, or even worse, fight efforts for an agreement such as the one proposed here. An international agreement limiting the production of enriched uranium to around 40% will do more to stem the tide of materials proliferation than debating the intricacies of a total cutoff verification system ever will. Furthermore, this kind of an agreement should not be seen as an end to the question of fissile materials production; rather, it should be viewed as a necessary step in the right direction. As shown above, any nation that possesses the ability to enrich uranium to 40% can easily enrich it to WGU. This continuing possibility of a nation breaking out of the agreement should be reason enough to continue taking steps to build confidence that additional production of weapons grade fissile material is not in fact occurring.

Future Work

The nature of this work can change drastically with the resolution of current events. For instance, how the U.S. Congress acts on the Bush-Singh nuclear deal later this year may open up similar deals between countries like China and Pakistan. If this occurs, it will be very difficult for the United States to place high priority on a resolution between India and Pakistan, as assumed for the top curve in Figure 2. This curve is purely hypothetical as is, but the influence of these bilateral deals would certainly have an effect on its magnitude and the ability of a future administration to achieve it.

Another current event that will require future study is the situation with Iran's enrichment complex. At this time, it is impossible to predict a likely outcome because the situation seems to evolve on a daily basis. Many questions remain unanswered. Will Russia create a verifiable and amenable plan to enrich uranium on behalf of Iran? Will the UN impose sanctions on Iran? Will Iran break off ties with the IAEA? All of these questions have implications well beyond the Middle East. Any resolution to this situation will have to be broad enough to encompass countries such as Brazil. As discussed above, Brazil's enrichment complex has also been under scrutiny in recent years. While few, if any, believe Brazil will construct a nuclear weapon, the dual-use nature of these technologies requires careful consideration when creating agreements that encompass them.

Appendix A: Separative Work Units vs. Enrichment Level

The model used by Bunn et al. and developed by Steve Fetter to estimate the economically optimal uranium enrichment tails assay for two different costs of natural uranium feedstock is used here[106]. The input parameters are the Bunn-Fetter reference values except for the use of a 10% discount rate here instead of their 5% value (which leads to a slightly higher tails assay at a given feedstock cost). Costs are in 2003$US and do not account for the extra capital investment cost per SWU of enrichment capacity for mastering a new technology, as these extra costs are assumed to be sunk costs that do not affect the choice of tails assay.

In the following equations x_f, x_t, and x_p are the fraction of U-235 in the feed, tails, and product of enrichment respectively and Cu is the cost per kg of uranium feed. As such, the separative work per kg of product, S, is

$$S = V[x_p] - V[x_t[Cu]] - \{R[Cu] * (V[x_f] - V[x_t[Cu]])\} \qquad \text{(A-1)}$$

In this equation, V is called the value function and is defined as

$$V[x] = (2x - 1) * Log[\frac{x}{1 - x}] \qquad \text{(A-2)}$$

and the faction of tails, x_t, can be defined as

$$x_t[Cu] = 10^{-0.1631(lu[Cu])^2 + 0.47055 * lu[Cu] - 2.6453} \qquad \text{(A-3)}$$

In Equation A-3, lu is the log base 10 of the enrichment-to-feed cost ratio and is given by

$$lu[Cu] = Log_{10}\left[(1 - fs) * \frac{Cs}{Cc * j^{ts-tc} + \frac{Cu * j^{ts-tu}}{1 - fc}}\right] \qquad \text{(A-4)}$$

Solving Equation A-4 requires that we know the conversion and enrichment loss fractions (fc and fs), cost per kg of conversion and cost per SWU (Cc and Cs), the years time lag for purchasing feedstock, conversion, and separation (tu, tc, and ts), and finally the interest rate (i) and multiplier (j). These constants are given below:

fc = .005

fs = .005

Cc = 6

Cs = 100

tu = 2

tc = -0.5

ts = 0

i = 0.10

j = 1 + i

Finally, to solve Equation A-1, the ratio of uranium feed to enriched product (R[Cu]) needs to be calculated by the following

$$R[Cu] = \frac{xp - xt[Cu]}{xf - xt[Cu]} \tag{A-5}$$

By substituting Equations A-2, A-3, and A-5 into A-1, one can then determine S. This new equation is divided by x_p to determine the separative work per kg of U-235 in the product as a function of the product enrichment for various costs of feedstock as shown in Figure 1.

Appendix B: Agreement Probability vs. Military Indicators

Defining l_i to be the internationalists' military indicator limits and h_i to be the nationalists' limits as indicated in Table 6, the formulas defining the probability of each country's sufficient interest in fissile material cutoff moratorium dependent on the military indicators are listed below. The probability of a moratorium having been established by a year *J* after the first year in which this probability is non-negligible is

$$\prod_{j=1}^{J}(1-F_{1j}F_{2j}F_{5j})$$

The Pakistan, India, and U.S. factors F_{1j}, F_{2j}, and F_{5j} for each year *j* are

Pakistan: $$F_{1j}=G_{1j}*(\frac{2*w_{1j}}{w_{2j}})*\frac{\left(\frac{w_{1j}}{l_1}\right)^3}{0.05+\left(\frac{w_{1j}}{l_1}\right)^3}$$

India:

$$F_{2j}=G_{2j}*\left(\frac{0.5*w_{2j}}{w_{1j}}\right)*\left(\frac{w_{2j}}{h_2}\right)^2*\frac{1}{1+\frac{0.5*w_{2j}}{w_{1j}}}*\frac{1}{\left(0.5+\frac{w_{2j}}{h_2}\right)^2}*\frac{\left(\frac{4*w_{2j}}{w_{3j}}\right)}{\left(1+\frac{4*w_{2j}}{w_{3j}}\right)}$$

U.S.: $$F_{5j}=G_{5j}*q_{3j}*q_{4j}*q_{6j}$$

Here for *i = 3, 4, and 6,*

$$q_{ij}=1-0.2*(1-f_{ij})$$

The factors f_{ij} for the following countries are:

China: $$f_{3j}=0.8*G_{3j}*\left(1-\frac{w_{5j}}{l_3}\right)$$

Russia: $$f_{4j}=0.9*G_{4j}*(0.9+0.1*S_j)$$

DPRK: $$f_{6j}=G_{6j}*(0.1+0.9K_j)$$

Here the switches S_j describing the state of U.S./Russian relations take on the values 1, except that S_j=0 if the following set of numbers are all less than a set of independent random numbers chosen uniformly on the unit interval for all $k<j$:

$$0.05 * G_{4k} * G_{5k} * \left(1 - \frac{w_{5k}}{w_{4k}}\right) * \left(\frac{w_{4k}}{h_4}\right)^2$$

Similarly, the switches K_j describing U.S./DPRK relations take on the values 1, except that K_j=0 if the following set of numbers are all less than a set of independent random numbers chosen uniformly on the unit interval for all $k<j$:

$$G_{5k} * G_{6k} * MAX[0.5, \left(1 - 0.5 * MIN[1, \frac{w_{5k}}{5 * w_{6k}}]\right)] * \frac{\left(2 * \frac{w_{6k}}{l_6}\right)^2}{1 + \left(2 * \frac{w_{6k}}{l_6}\right)^2}$$

The government type factors switch magnitude, to either -1 or 1, if the following is less than a random number chosen uniformly on the unit interval where pc is the probability of continuity, listed in Table 6, and nt is the number of terms the current government type has been in effect:

$$pc^{nt}$$

The switching constants take on the values T_{ij}=1 or T_{ij}= -1 when an internationalist or nationalist government respectively is in power in country i during year j. The factors r_i are listed in Table 6, and the switching between nationalist and internationalist oriented governments occurs according to the model described in association with the parameters in Table 6.

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