Safeguarding the Military Naval Nuclear Fuel Cycle

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Abstract
In the safeguards agreements between non-nuclear-weapon-state members of the Nuclear Nonproliferation Treaty and the International Atomic Energy Agency, there is a possibility for non-nuclear weapon states, acting with the approval of the agency's board of governors, to remove from safeguards nuclear materials to be used in non-proscribed military activities such as naval nuclear propulsion. This possibility limits the power of the agency to enforce the primary goal of the safeguards agreement, i.e., to verify that nuclear materials are not diverted to pursue the development of nuclear weapons or other nuclear explosive devices. Brazil will soon be the first non-nuclear weapons state to deploy a nuclear submarine and the first to challenge the nonproliferation regime to verify the non-diversion of nuclear material from a military activity. As part of a strategy to address this important issue, and after reviewing the existing legal framework, this paper presents a model for the application of safeguards on the naval nuclear fuel cycle in a military environment. The model could potentially be used for Brazil's naval fuel cycle but also be universally applicable to other non-nuclear weapon states and potentially to nuclear weapon states.

A Discontinuity in the Safeguards Regime?
The consequences for the nuclear nonproliferation regime of the spread of military nuclear-propelled vessels, including nuclear submarines, to non-nuclear weapons states (NNWS) have been a recurring concern for more than twenty-five years.[1] The current concerns focus on Brazil's nuclear submarine program and Iran's declared interest in naval nuclear programs.[2] Germany and Japan, both NNWS, developed nuclear naval propulsion in the 1960s and 1970s but for civilian applications.[3]

At the heart of this apprehension is the interpretation of Paragraph 14 in the standard safeguards agreements between the International Atomic Energy Agency (IAEA) and NNWS parties to the treaty on the Nonproliferation of Nuclear Weapons (NPT).[i] Paragraph 14 is the legal framework for the non-application of safeguards to nuclear material to be used in non-proscribed military activities such as nuclear propulsion:

> "NON-APPLICATION OF SAFEGUARDS TO NUCLEAR MATERIAL TO BE USED IN NON-PEACEFUL ACTIVITIES
>
> 14. The Agreement should provide that if the State intends to exercise its discretion to use nuclear material which is required to be safeguarded thereunder in a nuclear activity which does not require the application of safeguards under the Agreement, the following procedures will apply:
>
> (a) The State shall inform the Agency of the activity, making it clear:
>
> (i) That the use of the nuclear material in a non-proscribed military activity will not be in conflict with an undertaking the State may have given and in respect of which Agency safeguards apply, that the nuclear material will be used only in a peaceful nuclear activity; and
>
> (ii) That during the period of non-application of safeguards the nuclear material will not be used for the production of nuclear weapons or other nuclear explosive devices;
>
> (b) The Agency and the State shall make an arrangement so that, only while the nuclear material is in such an activity, the safeguards provided for in the Agreement will not be applied. The arrangement shall identify, to the extent possible, the period or circumstances during which safeguards will not be applied.

> In any event, the safeguards provided for in the Agreement shall again apply as soon as the nuclear material is reintroduced into a peaceful nuclear activity.
>
> The Agency shall be kept informed of the total quantity and composition of such unsafeguarded nuclear material in the State and of any exports of such material; and
>
> (c) Each arrangement shall be made in agreement with the Agency. The Agency's agreement shall be given as promptly as possible; it shall only relate to the temporal and procedural provisions, reporting arrangements, etc., but shall not involve any approval or classified knowledge of the military activity or relate to the use of the nuclear material therein."

This paragraph, often referred to in the nonproliferation literature as the "NPT loophole," is presented as an opportunity for NNWS to remove nuclear material from safeguards and process it beyond the reach of IAEA verification activities. At the time of negotiations on Paragraph 14, this concern was also raised by the IAEA Board of Governors' Safeguards Committee, who tried: "to avoid a situation where withdrawals of nuclear material from safeguards for non-proscribed military use could become a loophole allowing use for nuclear explosive purposes, beyond the reach of agency verification activities".[5] This "loophole" is depicted by critics as a "threat" to the NPT regime and seen as permitting the indiscriminate spread of non-proscribed nuclear military activities (henceforth NPMA), especially the proliferation of nuclear vessels, among NNWS and so increasing the risk of fissile material diversion for possible nuclear weapon purposes. A careful reading of Paragraph 14 leads to a more nuanced picture, however.

Paragraph 14 identifies a beginning and an end to the non-application of safeguards. It requires the state to keep the IAEA informed on the quantity and composition of nuclear materials withdrawn from safeguards. Paragraph 14 arrangements require the approval of the IAEA. In particular:

- The state must inform the IAEA of the NPMA for which it needs to call for the special dispositions of Paragraph 14 (non-application of safeguards), making it clear that during the period of the non-application of safeguards the materials will not be used for the production of weapons.
- Safeguards must be reapplied on the nuclear material as soon as it is reintroduced into peaceful activities.
- The IAEA must be kept informed of the total nuclear material inventory out of safeguards, including quantities and composition.
- Any such arrangement must be made in agreement with the IAEA and would be submitted to the IAEA Board of Governors for approval.[6]
- The IAEA is prohibited from gaining access to classified information related to the activity in question.

Yet, if Paragraph 14 gives a legal basis to deal with NPMA within the NPT, it also clearly limits the power of the agency to enforce the primary goal of the safeguards agreement, i.e., to verify that the nuclear material is not diverted to nuclear weapons or other nuclear explosive devices. Once safeguards are removed, the verification regime is undermined, and the treaty cannot be fully enforced.

In the case of applications related to naval nuclear propulsion, this situation is of particular concern since most of the current nuclear-powered vessels deployed around the world are fueled with highly enriched uranium (HEU, ≥ 20 percent uranium-235), a directly weapon-usable nuclear material.[7]

Consequently, under the current rules of the NPT safeguards regime, a country wishing to develop an HEU-fueled nuclear-powered military vessel would potentially have the right, if granted by the IAEA, to stockpile unsafeguarded fissile material and process it in unsafeguarded facilities without breaching its safeguards agreement.

While it seems difficult to prevent further countries from acquiring nuclear submarine technology, actions can be taken to ensure that nuclear materials used in naval nuclear reactor fuel cycles are not diverted for weapons purposes. One step forward would be to promote the establishment of an international norm limiting the enrichment of naval nuclear fuel to low-enriched uranium (LEU) level, i.e., enriched to less than 20 percent U-235, and therefore limiting the risks of direct weaponization of diverted fissile material. In this case, assuming that enrichment facilities are under standard IAEA safeguards, a country would need to enrich parts of its naval stockpile of LEU to HEU levels clandestinely, something that could potentially be detected.

Unfortunately, the reluctance of various navies — especially that of the United States — to design their future naval nuclear reactors using LEU fuel, could jeopardize any effort in this direction.[8]

It is important to note that the technology to power nuclear vessels with LEU exists and is already deployed. France is currently operating eleven nuclear vessels (ten submarines and one aircraft carrier), all fueled with LEU, and plans to continue to do so in the future. The next class of French nuclear attack submarines (SSN Suffren, to be commissioned in 2017) is supposed to be fueled with uranium enriched to levels used in civilian light water nuclear power plants.[9] This strategy of using LEU fuel should be encouraged in current and future navies operating naval nuclear reactors.

Ultimately, even if no consensus can be reached on limitation of enrichment to below 20 percent U235 for NPMA, the only way to efficiently and comprehensively guarantee that no naval fuel is diverted for weapons purposes would be to promote the implementation of nonintrusive safeguards in the naval nuclear fuel cycle. This approach, which appears quite challenging at first but would greatly reinforce the verification regime, is the main focus of this paper.

After discussing constraints on the implementation of safeguards in a military environment — especially with regard to the protection of military secrecy — this paper presents a model for the application of safeguards to a military naval reactor fuel cycle. Each step of the fuel cycle is addressed from the enrichment and fabrication of the fuel to spent fuel disposal. Particular attention is given to the design of the naval base and the implementation of safeguards in the fueling/defueling process of the naval reactor while protecting inspectors from gaining access to classified knowledge. Without loss of generality for certain key concepts and because Brazil will be the first NNWS to deploy a nuclear submarine, the application of the model is primarily focusing on the future Brazilian military naval nuclear fuel cycle.

Since the approach proposed here in its most general form applies to monitoring the military naval fuel cycle and does not depend on whether the fuel is LEU or HEU it can be extended to nuclear-powered vessels deployed by weapon states. A future Fissile Material Cutoff Treaty (FMCT) will need to provide assurance that highly enriched uranium intended for military naval propulsion is not diverted for weapons.

The Brazilian Case

In early 2013, Brazilian President Dilma Rousseff declared during the inauguration of the new Brazilian naval shipyard in Rio: "We are entering the select club of countries with nuclear submarines: The United States, Russia, France, Britain, and China."[10] So far this "select club," which also includes India, has been composed of only nuclear weapon states (NWS). Brazil will be the first NNWS to pursue a non-proscribed military application of atomic energy. This poses a challenge to the IAEA to come up with a good strategy to assure the non-diversion of nuclear materials used in NPMA.

Brazil has not signed an INFCIRC/153 comprehensive safeguards agreement with the IAEA. For Brazil, safeguards are defined by an equivalent document, usually referred as "the Quadripartite Agreement," co-signed by Argentina, Brazil, the Brazilian–Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), and the IAEA.[11] Following the accession of Brazil to the NPT in 1998, the IAEA's Board of Governors declared INFCIRC/435 to satisfy the obligation of Brazil under Article III of the NPT.[12]

> The equivalent of Paragraph 14 in INFCIRC/153 is Article 13 in INFCIRC/435:
>
> "Article 13
>
> If a State Party intends to exercise its discretion to use nuclear material which is required to be safeguarded under this Agreement for nuclear propulsion or operation of any vehicle, including submarines and prototypes, or in such other non-proscribed nuclear activity as agreed between the State Party and the Agency, the following procedures shall apply:
>
> (a) that State Party shall inform the Agency, through ABACC, of the activity, and shall make it clear:
>
> (i) that the use of the nuclear material in such an activity will not be in conflict with any undertaking of the State Party under agreements concluded with the Agency in connection with Article XI of the Statute of the Agency or any other agreement concluded with the Agency in connection with INFCIRC/26 (and Add. l) or INFCIRC/66 (and Rev. l or 2), as applicable; and
>
> (ii) that during the period of application of the special procedures the nuclear material will not be used for the production of nuclear weapons or other nuclear explosive devices;

(b) the State Party and the Agency shall make an arrangement so that, these special procedures shall apply only while the nuclear material is used for nuclear propulsion or in the operation of any vehicle, including submarines and prototypes, or in such other non-proscribed nuclear activity as agreed between the State Party and the Agency. The arrangement shall identify, to the extent possible, the period or circumstances during which the special procedures shall be applied. In any event, the other procedures provided for in this Agreement shall apply again as soon as the nuclear material is reintroduced into a nuclear activity other than the above. The Agency shall be kept informed of the total quantity and composition of such material in that State Party and of any export of such material; and

(c) each arrangement shall be concluded between the State Party concerned and the Agency as promptly as possible and shall relate only to such matters as temporal and procedural provisions and reporting arrangements, but shall not involve any approval or classified knowledge of such activity or relate to the use of the nuclear material therein."

From a reading of Article 13, it is not clear if what is mentioned as "special procedures" is equivalent to the non-application of safeguards in Paragraph 14. The IAEA safeguards glossary doesn't specify this term neither does it refer to INFCIRC/435.[13]

However, sub-paragraph (b) specifies the following: "the special procedures shall apply only while the nuclear material is used for nuclear propulsion or in the operation of any vehicle, including submarines and prototypes." This sentence means that only when the fuel is physically in the submarine reactor and the reactor is operating, the fissile material can be potentially exempt from safeguards. Consequently any activities related to fuel fabrication, storage, and disposal should be safeguarded. This would be an important difference between INFCIRC/153 and INFCIRC/435.

Nevertheless, even if the Brazilian case may seem less severe due to this difference, the gravity of the issue and its potential implications for other NNWS should encourage the IAEA to seek a universally applicable agreement to all NNWS in its future arrangement with Brazil. This agreement could take the form, for example, of an additional protocol for the safeguards of non-proscribed military activities. Whether or not Brazil will be treated as a special case by the IAEA, the safeguards model presented here could be applied in a non-discriminatory manner to any NNWS including Brazil and potentially to any NWS. Interestingly, thanks to the particular provisions of INFCIRC/435, Brazil could become a model for NNWS parties to the NPT in showing the possibility to implement non-intrusive safeguards for NPMA.

Military Secrecy Baseline for the Implementation of Safeguards

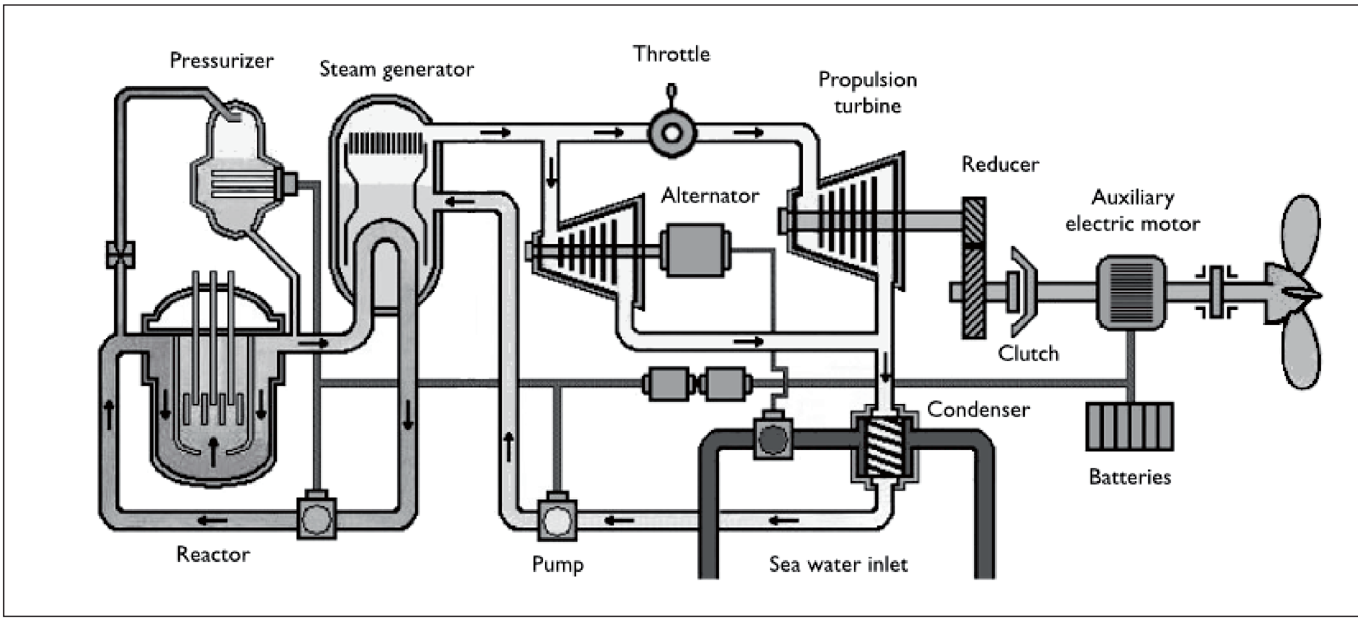
The first obstacle to the implementation of safeguards in the naval nuclear fuel cycle is the need to protect military information considered classified or sensitive by the host state and as required by Paragraph 14. It is therefore important to arrive at a reasonable agreement on what information should stay classified and protected and what information must be shared with the IAEA to ensure effective implementation of safeguards.

Four main issues need to be addressed:

- Information with regard to fuel design and composition;
- Information with regard to the naval reactor designs;
- Information with regard to operational military installations, i.e., naval bases; and
- Information with regard to the military fuel cycle fabrication facilities, i.e., processes.

Naval reactors and their associated fuel are designed to meet certain military requirements that differentiate them from civilian power reactors, such as the ability to allow rapid power transients, to operate in the naval environment (e.g., mechanical shocks from collisions, vibrations from waves while on the surface, changes in vessel inclination while diving) and resist external shocks (e.g., a depth charge explosion close to a submarine), and to operate silently by limiting noise radiation and propagation to the hull. Thus the design of the fuel and the core in general (shape, cladding, and matrix materials together) may intrinsically contain a limited amount of information on the overall military performance of a submarine. It is understandable that the host state will want to minimize access to such information during the implementation of safeguards.

Figure 1. Schematic of a nuclear submarine propulsion system. The propulsion of the submarine can be achieved for example by "direct" coupling of the steam turbine to the propeller shaft or by generating electricity to drive electric motors.[14]



Some information crucial for material accountancy need not be classified, however. For example, while the total uranium-235 inventory of a fresh core can give an upper bound for the maximum lifetime a reactor can achieve before refueling, it gives no indication of the actual tactical performance of the submarine propulsion system.

As any thermodynamic cycle, this performance depends on many parameters including the efficiency in converting heat to mechanical power (see Figure 1).

It is important to also note that the gross external dimensions of a fuel element shouldn't be required to be classified, as they don't by themselves give information on the thermal-hydraulic properties of the fuel.[15]

In what follows, and in line with the reporting obligation of the state, we will assume that the IAEA will be informed of and be able to verify non-intrusively the total U-235 and U-238 inventory of a core.

A "managed access" for inspectors to military fuel storage facilities should be organized in a way to protect both classified fuel design information and sensitive operational information.[16] The term operational information refers here to all information related to a naval base's operational status, such as internal ship design, ship movements, weaponry, and military personnel not easily available from commercial publications and satellite imagery. Inspectors should only have access to the information they need to implement the naval nuclear fuel safeguards agreement. The deployment of local remote monitoring technologies on the naval base in areas where the inspectors are given routine access should be encouraged, as they could provide continuity of safeguards at times of active military operations when physical access of IAEA inspectors could be more limited.

A Model for Safeguarding Military Naval Nuclear Fuel

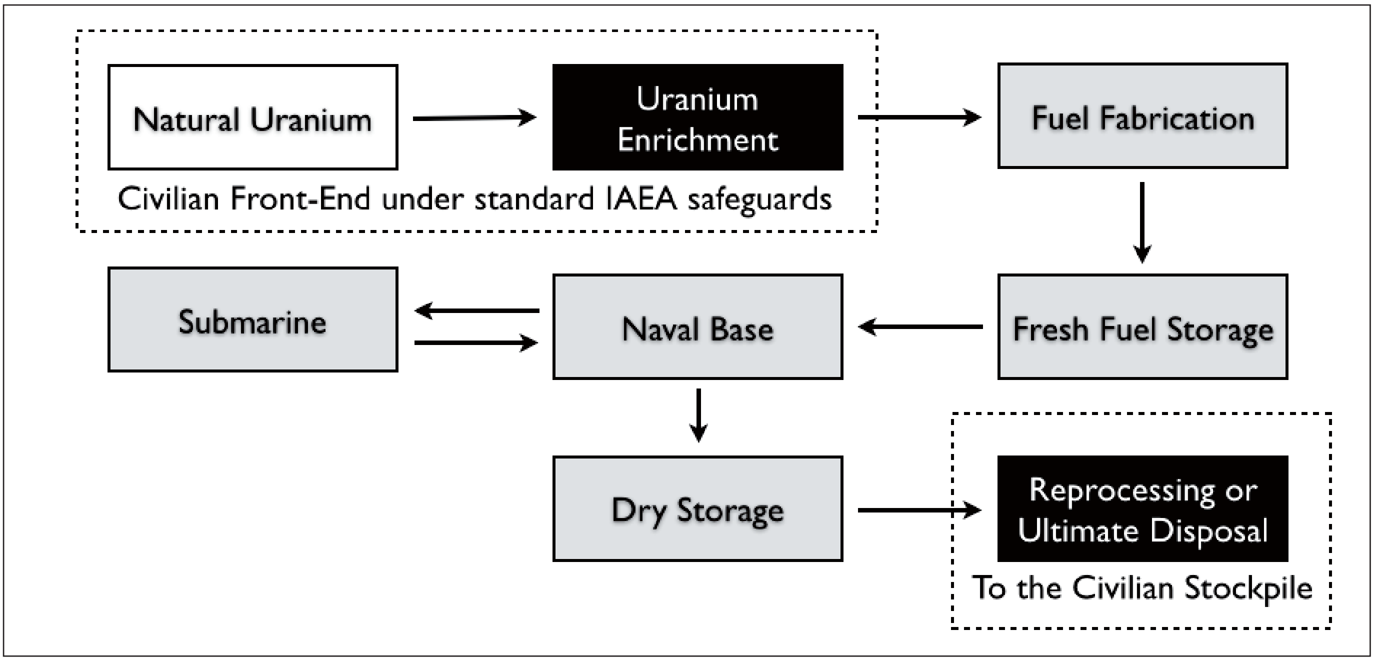
A Fuel Cycle Approach

We approach the problem from a fuel cycle point of view, meaning that we will look at every step in the naval fuel cycle and propose associated safeguards to ensure the non-diversion of enriched uranium for any other purposes.[17]

Figure 2 presents the key steps of the naval fuel cycle: natural uranium procurement, uranium enrichment, fuel fabrication, transfer to a naval base, fueling of the naval reactor, reactor operation, defueling, and pool storage on the naval base, then dry storage followed eventually by disposal or reprocessing. For the potential application of safeguards in a NWS as part of a FMCT, another path for uranium procurement would potentially need to be added: the supply of enriched uranium from pre-existing military stockpiles.

We have defined three different stockpiles between which materials can be transferred (Figure 3): civilian stockpiles subject to standard IAEA safeguards, a safeguarded naval fuel

Figure 2. A simple model of the naval fuel cycle for a submarine in a NNWS



stockpile subject to the rules that will be established in our model, and an unsafeguarded uranium stockpile. The unsafeguarded stockpile is a peculiarity of NWS and represents all the uranium that is not under safeguards such as weapon-grade HEU or previously produced naval fuel. The application of the model to NWS would not require any pre-declaration of unsafeguarded stockpiles.

For NNWS, everything that enters the safeguarded naval fuel stockpile must end up in the safeguarded civilian uranium stockpile as required by Paragraph 14 of the safeguards agreement. This rule could also be applied to NWS in order to avoid "double standards" between NNWS and NWS. This way, if the fuel is obtained from HEU weapon-usable material, NWS can eliminate in a verifiable manner the surplus of their weapon-usable fissile material stockpiles. It is important to note that in the context of a FMCT, NWS will be required to carry out uranium enrichment even for naval application in safeguarded civilian facilities.

In what follows, we will focus on the case of Brazil only and will not pursue the implementation of safeguards in NWS as part of a FMCT. The latter issue is the focus of future research.

Assumptions on the Brazilian Case

We assume that Brazil will use LEU naval fuel and that its reactor core will be composed of several fuel elements as opposed to a one-element core.[18] This assumption is backed up by information published in the literature about Brazil's Labgene prototype naval reactor. The 48-MWth reactor has a cylindrical core of twenty-one standard-size pressurized water reactor (PWR) fuel elements.[19] The Brazilian navy presented several mock-ups of the future SSN, its reactor vessel (code name 2131-R) as well as a 1:1-scale fuel element for the naval reactor during an international defense and security exhibition held in Brazil in April 2013 (see Figures 4 and 5).[20] Table 1 presents the design characteristics of this fuel element. With these characteristics and assuming twenty-one fuel elements, the total uranium inventory of a core would be about 2,700 kg of uranium.

Figure 3. Material flow between national stockpiles. The unsafeguarded uranium stockpile exists for NWS only.

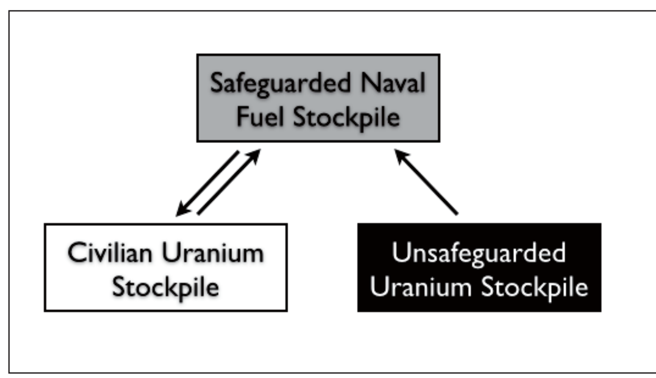


Table 1. Design characteristics of the alleged Brazilian nuclear reactor fuel element. The element is similar to a standard PWR element.

Arrangement	# of fuel rods	# of control rods	# of UO2 pellets	Total mass of UO2 (kg)	Dimensions (mm)
17x17	260	29	24,440	146	220x220x1455

Figure 4. Mock-up of the first Brazilian SSN

Figure 5. Mock-ups of the 2131-R reactor (left) and the first generation fuel element (right)

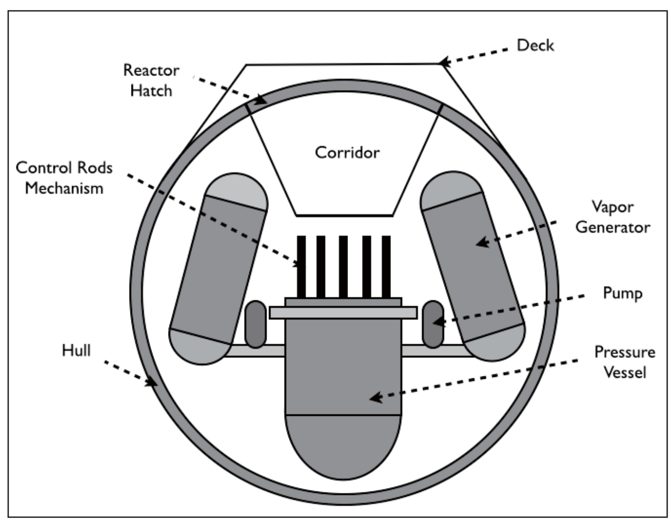
The Labgene reactor features the same equipment and arrangement as a two-loop naval nuclear reactor design that can be integrated in a submarine hull, as seen in Figure 6. The mock-up of the Brazilian SSN features a large hatch in the hull above the reactor compartment (Figure 4).

It seems very unlikely that the naval reactor on board of the first Brazilian SSN will differ significantly from the prototype land reactor. If the presence of standard-size fuel elements (not necessarily having fuel pins but also plates as is the case for cermet fuel) is confirmed in the future, it would be easier for IAEA inspectors to verify the uranium inventory using for example standard measurement methods such as the uranium neutron coincidence collar (UNCL).[21]

The first "typical PWR" fuel element presented above may be too weak from a structural point of view to be used in an operational submarine. Additional information from an official of the Brazilian nuclear power company, Eletronuclear, confirms that Brazil is exploring two alternative types of LEU fuel (caramel and cermet fuel) to produce a second reactor core.[22]

As mentioned above, we assume that the future Brazilian nuclear submarine will feature a large reactor hatch to facilitate fueling and defueling operations based on a model reported in the literature used in French nuclear submarines.[23] This last assumption is based on the fact that the French shipbuilding company, DCNS, will assist Brazil in the construction of its first nuclear submarine, giving advice on the non-nuclear parts of the submarine and potentially the reactor integration in the hull.[24] The Brazilian navy should see this reactor-hatch technology as crucial if it wishes to refuel the reactor in short periods of time (of the order of weeks).[25] All things considered, it is important to note that the model presented here remains mostly hypothetical.

Figure 6. Integration of a two-loop naval nuclear reactor design in a submarine hull



In what follows, we go through each step in the naval fuel cycle and present a strategy for the implementation of safeguards, starting with the civilian front end.

The Civilian Front End

The civilian front end covers activities that are under standard IAEA safeguards in a NNWS, such as uranium enrichment. After uranium enters the naval fuel stockpile, no further enrichment operations are permitted, only the blending of uranium at different enrichments is allowed. Uranium enrichment being one of the most sensitive operations with regard to nonproliferation (together with plutonium extraction from irradiated fuel), it must remain outside any military facility in order to build confidence in the ability to detect any non-declared enrichment activity. Furthermore, this policy towards enrichment implies that an enrichment facility declared to be safeguarded cannot be used to enrich unsafeguarded uranium.[26]

Militarization of the Fissile Material

The militarization of the nuclear material is the crucial step where the uranium leaves the civilian stockpile to enter the naval fuel stockpile. This happens within the naval fuel fabrication plant. All the uranium that enters the naval fuel stockpile must go through this process. Entering uranium is in an unclassified form. Information on the total amount of uranium and its exact isotopic composition would be measured and registered. A document shared with the agency would certify that a certain amount of uranium with a particular enrichment had left the country's civilian stockpile and entered the naval fuel stockpile.[27] This process would require the presence of inspectors.

Fuel Fabrication and Fresh Fuel Storage

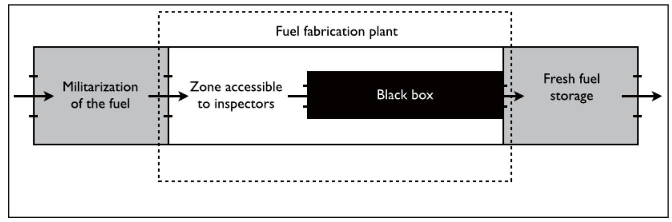
As soon as uranium enters the safeguarded naval fuel stockpile, it can be processed and transformed into fuel elements or a complete core. The fuel fabrication facility is where the material may be converted to a classified form.

In the trivial case where a state decides that the design of its fuel elements is unclassified, it would be easy to implement a safeguards system similar to that in the civil sector that would identify each fuel element. Inspectors could assay the quantity and enrichment of the uranium in the fuel and thereby would be able to verify the material balance between what goes in and out of the fuel fabrication plant. It seems that Brazil may head in this direction.

However, if a state chooses to classify the design of its fuel elements, then performing such material balance checks becomes harder. As discussed earlier, we assume that two main attributes will be classified, the exact composition of a fuel element (including non-fissile materials) and its detailed geometrical shape (for example, its internal dimensions).[28]

Figure 7 describes the layout of a hypothetical fuel fabrication facility that has features that would both facilitate the fissile materials safeguarding process and protect sensitive fuel information. The facility is divided into three principal volumes.

Figure 7. Fuel fabrication facility (hypothetical layout)



One, the "black box," is dedicated to the militarization process of the uranium as explained earlier. The zone is divided in two areas, one that is accessible to the inspectors, the second is the black box and can only be accessed by inspectors when no production is occurring and no uncovered fuel is present. The third area is the fresh fuel storage where fuel elements await shipment to the naval base.

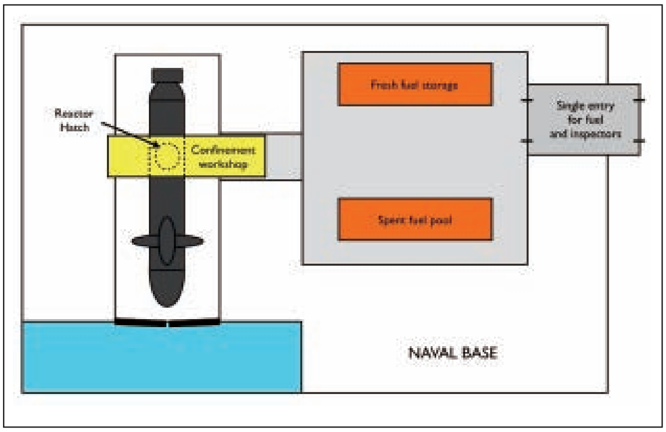
The black box area is the place where the fuel is converted to a classified form. This area, which is not accessible to inspectors during production, must be as simple as possible, for example with a single point-of-access.[29] It is important to stress that not all the fuel fabrication process need be classified; for example, in the case of caramel fuel manufacturing, it is public knowledge that this type of fuel is made of small flat rectangular uranium dioxide tablets; thus the production line of those tablets would not require to be located in the black box.[30]

The black box is connected to the fresh fuel storage area, which is constantly monitored by cameras. Fuel elements exit the black box in a specially designed transportation cask that protects the design of the fuel element from inspectors' eyes. The inspectors could, however, use an active interrogation system to determine the content of U-235 of every cask and apply seals on all of them.[31] One can imagine a measurement technique where, as a fuel element would be placed into a cask, the uranium content could be measured using an adapted UNCL system at the mouth of the cask.

The material balance of the fuel fabrication plant can then be made to ensure that no material has been diverted. This would require the inspectors to verify that no nuclear material is unaccounted for within the black box once fuel elements production has been completed.

Since the complete U-235 inventory of the reactor core will be declared by the state, the IAEA could report any abnormal increase in activity within the plant (i.e., a state manufacturing three cores for only one submarine). A NNWS could be required to agree with the IAEA on a cap on the size of the naval fuel stockpile, for example, limiting the stockpile to two

Figure 8. Model of the naval base. The mobile workshop links the fuel storage building to the submarine (over the reactor hatch) during refueling operations.



cores per reactor operated in the fleet (one in the vessel, and one in the stockpile). A typical 50 MWth naval reactor, working for 600 full power days and assuming a U-235 burn-up of half the initial inventory, has an initial core inventory of 1,125 kg of LEU enriched at 7 percent U-235.

Finally, only fuel elements accounted for and properly sealed can be transported from the fresh fuel storage area to the naval base. The IAEA would be kept informed of the cask movements at all times.

Design of the Naval Base

Figure 8 presents a conceptual layout of the facilities on the naval base. There is only one entry for the naval fuel and for the inspectors on to the base, which leads directly to the fuel storage building. This simple feature limits inspectors' access to other areas of the base, protecting classified operational information.

The fuel storage building is composed of three main areas: a fresh fuel storage area, a spent fuel pool, and a confinement workshop. The guarantee of non-diversion of fissile materials would mostly rely on cask sealing and tagging as well as random assaying of stored casks. Cameras could record the activity within the building as a complementary measure.

Fuel elements waiting to be transferred to the submarine reactor vessel are stored in the fresh fuel area. The amount of material is limited to one complete core. The spent fuel discharged from the reactor is temporarily stored in the spent fuel pool awaiting shipment to a dry cask storage area when residual heat would be low enough to permit transport. The inspection of fuel elements tags and seals in the pool could be conducted using for example the existing IAEA portable underwater television system (UWTV).[32]

The defueling and refueling processes are designed to ensure continuity of knowledge on the use of the fuel elements as well as to protect classified information with regard to the reactor and the submarine. The protocol could be as follows:

> The state would inform the IAEA that a defueling or refueling operation has been scheduled. The state would prepare the operation before the inspectors were allowed to enter the fuel storage building. The confinement workshop would be placed above the submarine located in dry dock right above the reactor compartment (Figures 8 and 9). The workshop would then be connected to the submarine hull to ensure confinement.

We start with the defueling operation. The reactor hatch is presented to the inspectors before being opened. Mechanical seals may have been placed on top of the hatch but under the submarine deck to ensure that the hatch is not opened in the absence of an IAEA inspector.[33] Once the inspectors attest that the seals were not broken, the reactor hatch can be opened. The inspector leaves the facility, and the state can start the operation of opening the reactor pressure vessel.

Once various reactor elements have been removed, for example the pressure vessel top and the control rods mechanisms (see Figure 6), the fuel elements can be removed from the pressure vessel. Figure 9 shows the reactor compartment configuration during defueling operations. A large cylinder is connected to the pressure vessel and filled with water up to the level of the reactor hatch to protect the operators from radiation while spent fuel is transferred from the pressure vessel into a cask under water.

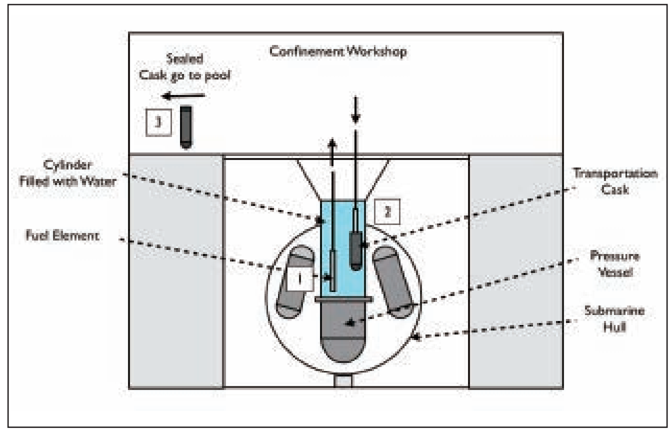
When the state is ready to move the fuel elements out of the vessel, the inspectors can be invited again into the building to follow the operations. Each fuel element is transferred to a cask inside the water (see Figure 9), and the cask is then taken out and moved to the spent fuel pool.[34] The spent fuel cask, which could be different from a fresh fuel cask, protects the operator from radiation during the transfer and guarantees protection for the classified fuel element design. The inspectors seal every spent fuel cask. Before doing so a neutron and/or gamma profiling of randomly selected fuel elements could be made using a cask radiation profiling system.[35] This would allow re-verifying the content of the casks at a later stage by comparing new radiation profiles to the baseline fingerprints. Consistency between fingerprints indicates that the spent fuel elements have remained undisturbed.

At the end of the transfer process, the inspectors verify the absence of irradiated fuel in the pressure vessel, using for example a gamma detector looking for the 757/766 keV line from $^{95}Nb/^{95}Zr$ mounted on a handling pole.[36] No visual check of the interior of the pressure vessel would be required.

The fueling operation works on the same concept but in reverse. At the end of the fueling operation, inspectors affix seals on the reactor hatch.

Submarines are usually fueled with a complete fresh core, but they could also use fuel elements shuffling technique to maximize the fuel burnup of each element.[37] This should not be a problem as the IAEA should be able to keep track of the material inventory of the core and the fuel storage building.

Figure 9. Operations during defueling of the reactor: the fuel elements are removed from the pressure vessel inside the cylinder filled with water and then placed in transportation casks. Once sealed, the casks are transferred to the spent fuel pool.



Spent Fuel Storage and Demilitarization of the Fuel

After spending a certain amount of time on the naval base in the spent fuel pool to allow reduction of their radioactive decay heat, fuel elements could be transferred to another storage area, including both a spent fuel pool and dry storage area. Once the fuel elements leave the naval base, they are not allowed to be fuel again in a submarine.

Again all movement of casks should be declared to the IAEA. It would be convenient if the casks stayed the same throughout the back end of the fuel cycle. Once seals are applied upon discharging the spent fuel from submarine reactor, they would not have to be removed unless the fuel is reprocessed. Thermal imaging techniques could be used to monitor the casks in the dry storage area. This technique measures the decay heat of the spent fuel in the cask, but does not reveal design information.

Earlier, we mentioned that the fissile materials should ultimately go back to the civilian stockpile under standard IAEA safeguards. There would be two ways to do so: first, the spent fuel kept in its original cask could be moved to and permanently sealed and stored in a "civilian stockpile" facility under IAEA safeguards; this material could eventually be prepared for final disposal in a geological repository. Second, the fuel could be reprocessed in a reprocessing facility.[38] The products of the reprocessing process would then go back to the civilian stockpile. In both cases, the material would be transferred back to the civilian stockpile, leaving permanently the naval nuclear fuel cycle safeguards system and keeping the size of the naval fuel stockpile at a reasonable level.[39]

Conclusion

With Brazil on the way to becoming the first non-nuclear weapon state to deploy military naval nuclear propulsion, the right of non-nuclear weapons states to withdraw material from safeguards for use in military applications is a potentially serious proliferation problem. NPT member states wish to ensure that no fissile material is diverted for weapon purposes by any non-weapon state parties of the treaty. To meet this goal in the case of Brazil's naval fuel cycle will require that the International Atomic Energy Agency for the first time extend its safeguards activity into a military environment.

This paper shows that the implementation of safeguards in a military environment, while not easy, may be less challenging than seems to be widely assumed. The model presented shows how it may be possible to track the flow of fissile materials from enrichment through fuel fabrication and fresh fuel storage to the submarine reactor and eventual spent fuel storage and demilitarization of the fuel. It proposes in particular the use of a "black box" approach for fuel fabrication and the careful design of the submarine reactor fueling facility at a naval base to manage the access of inspectors and protect classified information.

The example presented in this paper applies only to a particular submarine architecture and focuses on Brazil. A similar approach could be pursued for other nuclear submarines' designs and surface ships, including those equipped with highly enriched uranium lifetime core, in weapons states and would be relevant for a Fissile Material Cut-Off Treaty.

Since Brazil is not the only non-weapons state interested in military nuclear naval propulsion, the International Atomic Energy Agency should be encouraged to seek a universally applicable agreement on naval nuclear fuel safeguards. This agreement could take the form, for example, of an additional protocol for the safeguards of non-proscribed military activities.

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9. Ministère de la Défense. December 22, 2006. Le Programme Barracuda, Le Sous-Marin d'Attaque du 21ème Siècle, Dossier de Presse. It is important to note that France does not have any military (or unsafeguarded) enrichment capacity since it shut down the Pierrelatte plant in 1996 (HEU) and the "George Besse 1" plant in 2012 (LEU). Naval reactor fuel can thus only be manufactured using uranium previously enriched or freshly produced LEU limited to ≤6 percent U-235 from the civilian plant "George Besse 2".
10. Interestingly, the Brazilian president omits India in her list, see: AFP. March 1, 2013. Brazil to get its first nuclear subs.
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15. By gross external dimensions, we mean, for example, the smallest rectangular box that would contain the fuel element.
16. The definition of "managed access" as given in the IAEA Safeguards glossary (*op. cit.*) is extended here to the protection of military classified information.

17. Common IAEA safeguards techniques and equipment based on material accountancy, containment and surveillance as well as environmental sampling are described in: IAEA. 2011. Safeguards Techniques and Equipment: 2011 Edition.
18. For a description of various naval nuclear reactor concepts see: Fribourg, C. 2002. Réacteurs Nucléaires de Propulsion Navale. *op. cit*. Note that the volume of an attack submarine reactor core is of the order of 1 m^3.
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20. See the website: "LAAD Defence & Security," accessed August 27, 2013, http://laadexpo.com.br/english/. The pictures of the various mock-up are available on the official Brazilian Navy Flickr account: "Flickr: Marinha Do Brasil (Oficial)'s Photostream," accessed August 27, 2013, http://www.flickr.com/photos/mboficial/with/8642496037/.
21. The UNCL is a neutron coincidence counting based measurement device. It features a large collar that encloses a fresh fuel assembly and measure the linear mass density of uranium. It requires knowing the exact length of the assembly. See: IAEA.2011. Safeguards Techniques and Equipment: 2011 Edition, *op. cit*. Note that if the dimensions of the future fuel assemblies become too large, one could measure the uranium inventory on sub-elements before they get assembled in larger ones.
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26. This singular concept has been implemented in France for example in the Eurodif gaseous diffusion enrichment plant. The plant was under Euratom safeguards but unsafeguarded material was also processed in the facility. A 2002 Euratom report states that the "particular status" of the installation continues to limit the safeguards assurance and needs to be addressed." See: Commission of the European Communities. 2003. Report from the Commission to the European Parliament and the Council: Operation of Euratom Safeguards in 2002.
27. This is the "standard" procedure as referred in INFCIRC/153 (revised).
28. Note that as mentioned earlier the external dimensions do not need to be classified, which would facilitate in order the use appropriate measurement devices by the inspectors.
29. The black box area could potentially be accessible by inspectors after the end of any production campaign in order to verify that no quantities of uranium are being held there beyond acceptable losses to waste during the manufacturing process.
30. See, for example, the following advertising brochure for the use of caramel fuel in research reactors: CEA. 1979. *Le combustible caramel pour réacteurs de recherche*.
31. Note that in theory, each fuel element could have a different uranium isotopic composition.
32. IAEA. 2011. Safeguards Techniques and Equipment: 2011 Edition. *op.cit.*
33. This is similar to what is done in standard commercial light water reactors, see: Harms, N., and P. Rodriguez. 1996. Safeguards at Light-water Reactors: Current Practices, Future Directions. *IAEA Bulletin* 38, no. 4: 16–19.
34. Concept adapted from: Fribourg, C. 2001. Navires à Propulsion Nucléaire. *op. cit.*

35. This is a standard IAEA instrument usually used to re-verify the presence of spent fuel in casks following a break in the continuity of knowledge (i.e., gap in surveillance and seals), see: IAEA. 2001. Safeguards Techniques and Equipment: 2011 Edition. *op. cit*.
36. The detector could be the spent fuel attribute tester (SFAT) typically used by IAEA inspectors to detect the presence of spent fuel. Note that activation product such as ^{60}Co are identifiable with this instrument. See: IAEA. 2001. Safeguards Techniques and Equipment: 2011 Edition. *op. cit*.
37. Fribourg, C. 1999. La Propulsion Nucléaire Navale. *Revue Générale Nucléaire* no. 2: 32–49.
38. One could imagine the same "black box" concept as in the fuel fabrication facility. There, the fuel would for example be cut into pieces, leaving the black box in an unclassified form that could be assayed before any heavy metals and fission products would be separated preferably in a dedicated process line.
39. It could be interesting to set a time limit for which the spent fuel casks can be accounted in the naval fuel stockpile. For example, when the last submarine of a particular class is decommissioned, all remaining spent fuel cask in storage should be directly transferred to the civilian stockpile.