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Safeguards and nuclear-powered submarines: a model for special procedures on the nuclear fuel cycle

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ABSTRACT:

This article focuses on the safeguards provided by the International Atomic Energy Agency (IAEA) and how to apply them to nuclear fuel used by nuclear-powered submarines (SSN) developed by a Non-Nuclear-Weapon State (NNWS). Brazil is developing its own SSN, and Australia – supported by the AUKUS partnership – will also operate an SSN around 2030. Countries such as the Republic of Korea, Iran, and Canada have already shown current or past interest in SSN. In this context, it is worth thinking about models to conciliate the safeguards provided by the IAEA and the development and operation of an SSN by an NNWS. The article presents a model in three steps. Firstly, it focuses on the normative framework of the IAEA on this issue. Secondly, it addresses the methodology and structure of the model. The last section presents the model building for each phase of the nuclear fuel cycle. The research outcome was the development of a model, structured following the nuclear fuel cycle, that combines four variables – NNWS interests, proliferation risks, safeguards, and possible key points of application of safeguards. This methodological approach makes the model unique and points out a future pathway of negotiation between the IAEA and an NNWS with an SSN program.

Keywords: Non-Proliferation. Nuclear-Powered Submarines. Nuclear Safeguards.

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INTRODUCTION

This article[2] focuses on the safeguards provided by the International Atomic Energy Agency (IAEA) and how to apply them to nuclear fuel used by nuclear-powered submarines (SSN) developed by a Non-Nuclear-Weapon State (NNWS).

The issue of nuclear material as fuel for the propulsion of submarines, ships and other military platforms is not subject to a ban or prohibition under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) or any other treaty that conforms to the Nuclear Weapons Non-Proliferation Regime (NWNPR). This regime is understood in this article as the integrated network of unilateral, bilateral, regional, and multilateral treaties, as well as rules, norms and procedures that collectively provide a broad framework for the behavior of States and other international players on the issue of nuclear weapons.

In that context, it is relevant to recall that all NNWS parties of the NPT have an express commitment not to use nuclear energy for the development of nuclear weapons or explosives. This commitment is verified through the Comprehensive Safeguards Agreements (CSA) signed by NNWS and the International Atomic Energy Agency[3] (IAEA).

However, the issue of using nuclear energy for submarine propulsion by NNWS has some unique boundary conditions. The first of those is inherent to the intrinsic characteristics of a weapons system, such as a nuclear-powered submarine[4] (SSN). These characteristics were

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3 This commitment to sign a safeguards agreement with the IAEA is established in Article III of the NPT: "Each non-nuclear-weapon State Party to the Treaty undertakes to accept safeguards, as set forth in agreement to be negotiated and concluded with the International Atomic Energy Agency in accordance with the Statute of the International Atomic Energy Agency and the Agency's safeguards system, for the exclusive purpose of verifying the fulfillment of its obligations assumed under this Treaty with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices. […]" (see UNODA, NPT, Text of the Treaty).

4 This article will use the acronym SSN for future conventionally armed nuclear-powered submarines developed or operated by an NNWS (Author note).

summarized by Geoffrey Till (2018, p. 159), and are precisely: "flexibility, mobility, stealth, endurance, reach, autonomy and punch." Its development, construction and operation involve high technological capacity and huge investment. Thus, until this second decade of the 21st century, an SSN is a force multiplier built and operated only by the Nuclear-Weapon States[5] (NWS) recognized in the NPT, plus India, which is a Nuclear-Armed State, but not a signatory of the NPT.

At the beginning of 2024, two countries – Australia and Brazil – have SSN development or acquisition programs. The two programs differ significantly in terms of the indigenous nature and the degree of nuclear fuel enrichment. In the case of Brazil, the program is indigenous and will use Low Enriched Uranium (LEU) as nuclear fuel. On the other side, Australia – within the framework of the Australia, United Kingdom, and United States of America (AUKUS) strategic partnership – will initially receive Virginia-Class SSN, which will be transferred from the US Navy, and will later develop the so-called SSN-AUKUS with British and American support. Both use Highly Enriched Uranium (HEU) and introduce a new variable, thus raising questions about violations of Articles I and II of the NPT by the USA and the UK, as NWS, and Australia, as an NNWS.

The debate arising from the different characteristics of the Brazilian and Australian programs is not the objective of this article. However, in both cases, the application of safeguards will involve reaching a delicate balance whenpreserving the operational characteristics and technology of these weapons systems vis-à-vis the commitments made to the IAEA and the NWNPR, so as to ensure that there will be no diversion of fissile material for proscribed activities.

In addition to those two countries, others may seek to develop or operate an SSN in a medium-term time-frame. In the past, Canada (ROCKWOOD, 2017) has already expressed this interest, and, in the last ten years, the Republic of Korea has also expressed its desire to operate this type of weapons system (see REUTERS, 2021).

The point to be highlighted is that there is a challenge for any NNWS that seeks to develop and/or operate an SSN: technological innovation in line with the commitments assumed within the NWNPR,

5 According to Article IX, item 3 of the NPT, "a nuclear- weapon State is one which has manufactured and exploded a nuclear weapon or other nuclear explosive device prior to 1 January 1967" (see UNODA. NPT, Text of the Treaty). Thus, for all the Parties to the NPT, there are just five NWS: USA, Russia, UK, France, and China (Author note).

especially in the context of the cornerstone of this regime, that is, the NPT.

Therefore, it is worth thinking about models of Arrangements to conciliate the safeguards provided by the International Atomic Energy Agency (IAEA) and the development and future operation of nuclear-powered submarines by the NNWS.

However, regardless of the Arrangement model, some critical and essential issues related to safeguards must be negotiated between an NNWS and the IAEA. Among these issues, the critical point to be negotiated is related to the potential points of withdrawal − or application − of special procedures and reapplication of safeguards in the nuclear fuel of an SSN developed or operated by an NNWS.

In that sense, there is a fundamental framework for thinking about the application of safeguards in the nuclear material used for the propulsion of an SSN or any naval asset: the many similarities between the fuel cycles for submarine propulsion reactors and for use in non-military reactors such as the nuclear power plants for electricity generation or the research reactor (GUIMARAES, 2023). Therefore, concerning the application of safeguards for the nuclear fuel in the SSN of NNWS, it is necessary to think – as in the case of power reactors and research reactors – about applying safeguards throughout the fuel cycles.

Within this framework, the central point is to find ways to guarantee the application of the IAEA safeguards without compromising the sensitive and secret technologies developed by the NNWS and the operational characteristics of a weapons system such as an SSN. It is undoubtedly not something trivial. However, it is far from being understood as impossible. Overreacting to the issue by claiming that nuclear fuel cannot be safeguarded or vowing that it will imply a gap in the NWNPR does not help handle something that will be a reality, sooner or later. The helpful contribution is to find a model for something that is yet to happen, before it happens. In other words, one shall think about a model for safeguarding the nuclear fuel of an SSN which will be developed and operated by an NNWS.

In that context, it is worth questioning: What would be the critical points − of the nuclear fuel cycle − in which to apply the safeguards to ensure the development and future operation of a nuclear-powered submarine of an NNWS and also ensure that this type of program is exactly that and nothing more?

In line with the research question, the objective of the proposed research is to present a model with potential points of withdrawal or application of special procedures and reapplication of safeguards on the nuclear fuel cycle used in the reactor of the nuclear-powered submarines developed or operated by an NNWS, in line with what is provided in their Comprehensive Safeguards Agreements signed with the IAEA.[6]

This article presents the proposed model in three main steps. Firstly, it focuses on the normative framework of the IAEA on this issue and the policy relevance of the model. Secondly, it addresses the methodology and structure of the model. The last section presents the model build for each phase of the nuclear fuel cycle of an SSN of an NNWS.

THE NORMATIVE FRAMEWORK

Brazil and Australia are the current NNWS with SSN programs underway. Despite the differences between the two programs, this research focuses on the CSA of these two countries as a normative framework for the envisioned model.

The Australian CSA is presented in the INFCIRC/217, and its article N°14 has the same content as Paragraph 14 of INFCIRC/153, which is the IAEA`s framework for CSA with NPT`s State Parties. Box 1 compares the texts of INFCIRC/217 and INFCIRC/153 regarding the non-application of safeguards to nuclear material to be used in non-peaceful activities.

6 These CSA follow the framework provided for the INFCIRC/153/Corr – The Structure And Content Of Agreements Between The Agency And States Required In Connection With The Treaty On The Non-Proliferation of Nuclear Weapons (see IAEA, INFCIRC/153).

Box 1 – Comparison between Article 14 of INFCIRC/217 and Paragraph 14 of INFCIRC/153

INFCIRC/217 Article 14	INFCIRC/153 Paragraph 14
14. If Australia intends to exercise its discretion **to use nuclear material** which is required to be safeguarded under this Agreement **in a nuclear activity which does not require the application of safeguards** under this Agreement, the following procedures shall apply:	14. […] 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) **Australia shall inform the Agency** of the activity, making it clear: […].	(a) **The State shall inform the Agency** of the activity, making it clear: […].
(b) Australia and the Agency shall make an Arrangement so that, only **while the nuclear material is in such an activity, the safeguards provided for in this Agreement will not be applied**. The Arrangement shall identify, to the extent possible, **the period or circumstances during which safeguards will not be applied**. […] **The Agency shall be kept informed of the total quantity and composition of such unsafeguarded nuclear material** in Australia and of any export of such nuclear material; and […].	(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**. […] **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. Such agreement […] **shall not involve any approval or classified knowledge of the military activity or relate to the use of the nuclear material therein.**	(c) **Each arrangement** shall be made in agreement with the Agency. The Agency's agreement […] **shall not involve any approval or classified knowledge of the military activity or relate to the use of the *nuclear material* therein**.

Source: Prepared and highlighted by the author based on the contents of INFCIRC/217 and INFCIRC/153 (see IAEA, INFCIRC/217; IAEA, INFCIRC/153 and SILVA, 2023, p. 7).

Considering the content of Article 14 of INFCIRC/217, if Australia intends to exercise its right to develop or operate an SSN, it should be done according to what is provided for in its CSA. Thus, a negotiation with the IAEA should involve "the period or circumstances during which safeguards will not be applied" and the information "of the total quantity and composition of such unsafeguarded nuclear material in the State and of any export of such material". It is worth noting that the definition of such a thing as "the period or circumstances during which safeguards will not be applied" will imply negotiations for achieving an Arrangement with the IAEA.

The point to be highlighted is that, even with the support of the USA and the UK through the AUKUS strategic partnership, Australia must negotiate an Arrangement with the IAEA as provided for in its CSA.

Regarding the Brazilian CSA and its provisions on nuclear-powered submarines, one can observe that there are some singularities on the issue of safeguards. The Brazilian CSA with the IAEA - the INFICIRC/435 - was established by the Quadripartite Agreement[7] and followed the guidance provided for INFCIRC/153. However, there are some remarkable differences between the two documents. Paragraph 14 of the INFCIRC/153 is addressed in Article 13 of the Brazilian CSA, and both provisions are compared side by side in Box 2.

Box 2 – Comparison between Article 13 of INFCIRC/435 and Paragraph 14 of INFCIRC/153.

INFCIRC/435	INFCIRC/153
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:	14. […] 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) that State Party shall inform the Agency, through ABACC, of the activity, and shall make it clear: (i) […] (ii) […].	(a) the State shall inform the Agency of the activity, making it clear: (i) […] (ii) […].
(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, […].	(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**.
c) **each arrangement** shall be concluded between the State Party concerned and the Agency […], **but shall not involve any approval or classified knowledge of such activity or relate to the use of the nuclear material therein**.	(c) **each arrangement** shall be made in agreement with the Agency. The Agency's agreement […] **shall not involve any approval or classified knowledge of the military activity or relate to the use of the *nuclear material* therein**.

Source: Prepared and highlighted by the author based on the contents of INFCIRC/217 and INFCIRC/153 (see IAEA, INFCIRC/435; IAEA, INFCIRC/153 and SILVA, 2023, p. 12).

Considering the comparison presented in Box 2, some singularities are presented in the Brazilian CSA regarding the use of nuclear propulsion for submarines. The first one is that the Brazilian discretion to use nuclear material for the propulsion of submarines is assured. The second one is that the Brazilian CSA does not establish that nuclear material would be withdrawn from the safeguards system. Instead, the CSA provides that an

7 The Quadripartite Agreement is the Agreement of 13 December 1991 Between The Republic of Argentina, The Federative Republic of Brazil, The Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials and The International Atomic Energy Agency for The Application of Safeguards (see IAEA, INFCIRC/435).

arrangement to apply special procedures to the nuclear material used for propulsion shall be negotiated with the IAEA.

Such as the Australian CSA, the Brazilian CSA provides that there is no deadline for the negotiation of such an arrangement to be concluded with the IAEA, and the arrangement to be negotiated does not involve any approval by the IAEA of classified or sensitive knowledge related to the nuclear material used for propulsion of the submarine.

The point to be noted is that, as in the Australian case, there is no possibility, under its CSA in force, that Brazil unilaterally declares that the nuclear fuel of its future SSN will be excluded from the safeguards system. Likewise, as all NNWS with a CSA based on INFCIRC/153, Brazil shall negotiate, with the IAEA, an arrangement to apply Special Procedures to the nuclear material of this kind of propulsion.

In summary, the normative framework provided by the CSA in force in Australia and Brazil, as well as in force in all the NNWS with a CSA in force, demands a negotiation between each of these countries and the IAEA.

The Policy Relevance of the Model

As previously stated, this article aims to present a draft for a model with potential points of withdrawal or application of special procedures and reapplication of safeguards on the nuclear fuel cycle used in the reactor in nuclear-powered submarines developed or operated by an NNWS, in line with what is provided in their CSA signed with the IAEA.

This model is essential because it will lead to a greater or lesser degree of intrusion of IAEA inspections and verifications and, consequently, to the eventual observation of the profile and operational characteristics of the nuclear-powered submarine.

here are a few open studies which address this issue. One was developed by Thomas E. Shea and is quoted as a sample of academic research and proposal on the issue.

Shea presents a proposal with nine recommendations to assure complete transparency for an SSN program of an NNWS. The recommendations comprise confidence-building measures to show what a nuclear-power submarine program is, and the NNWS is interested in avoiding any suspicion. However, the proposal and recommendations – regardless of their good intentions – will not be accepted by most NNWS once they provide many inspections on board the SSN.

> The principal confidence-building measure is to carry out inspector visits to each nuclear-powered vessel shortly after its reactor is started initially, and following each refueling, to confirm that the vessel is, in fact, nuclear-powered. Additional inspector visits would be scheduled when a reactor core is one-third through its life cycle and again at two-thirds. […] Depending on how a ship is configured, once the IAEA has confirmed that the nuclear reactor is functioning, it may be possible to apply IAEA seals to hatches that would have to be opened to allow access to the reactor. The IAEA and the state would come to an agreement on how the needs of transparency could be met (SHEA, 2017, p. 14).

This issue of access on board is so sensitive that Thomas Shea himself points out:

> It is reasonable to anticipate that every state would protect its military secrets, including access aboard its warships and information on its naval reactors including their geometry, dimensions, control mechanisms, and propulsion mechanics. While respecting these wishes, the IAEA and the state will need to agree on the verification procedures, including the possible use of managed access as provided in the Additional Protocol (SHEA 2017, p. 12).

The point to be highlighted is that the model proposed by Shea – and mentioned in this article as a sample of academic research and proposal on the issue – will probably be refused by an NNWS developing or operating a nuclear-powered submarine. This refusal will happen because it provides access aboard the submarine, something unrealistic when discussing a weapon system such as an SSN.

Another well-known model for applying safeguards to a naval (military) nuclear fuel cycle was presented by Sebastien Philippe (2014).

The model proposed by Philippe, like the approach adopted in this research, is structured in the nuclear fuel cycle. However, as in Tomas Shea's model, the model proposed by Philippe implies inspections carried out on board the SSN, mainly to check mechanical seals placed on top of the hatch.

> 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. 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. [...] 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 (Philippe 2014, pp. 48-49).

The point to be noted is that the start of the safeguard exemption or the application of the special procedures can occur at several points, such as when the fuel elements are mounted on the land facility or when the fuel elements are loaded into the submarine's reactor. The same occurs for the restart points of the application of safeguards, which can happen, for instance, when the fuel elements are removed from the reactor or when they are stored on a fuel disposal site.

These points are essential because they are the key to conciliating the development and operation of the nuclear-powered submarine of an NNWS with the necessary safeguards of the IAEA. This definition will not be simple or trivial.

In this context, Australia, Brazil or any other NNWS developing or operating a nuclear-powered submarine must negotiate in detail with the IAEA. Once again, the point to be noted is the necessity of agreeing on the potentialpoints of the exemption – or application of special procedures – and reapplication of safeguards to the nuclear material to be used in the nuclear-powered submarine of any NNWS. It is a fundamental necessity, and there is no more time to ignore how the safeguards provided for CSA based on INFCIRC/153 should be applied in nuclear-powered submarines operated by an NNWS.

METHODOLOGY AND STRUCTURE OF THE MODEL

The model's proposed draft will address four variables: NNWS Interests, Proliferation Risks, Safeguards (Types), and Possible Points to Apply the Safeguards. An overview of the scope of each of these variables is presented below:

NNWS Interests – the model must necessarily consider sensitive and classified technology inherent to the development and operation of an SSN. Some examples of issues at the core of this variable are

- Information on fuel design, composition, and manufacturing of the nuclear fuel;
- Information on the SSN reactor's design, dimensions, geometry, and control mechanisms;
- Information regarding the SSN's shipyard / naval base.

Proliferation Risks – all variables must be integrated within a perspective of minimizing or eliminating proliferation risks.

Five main issues are at the core of this variable:

- Diversion of enriched uranium in bulk form (UO2) from the powder production facility;
- Diversion of UO2 in the fuel rod/plate fabrication facility;
- Diversion of fuel elements from a fresh fuel container;
- Diversion of fuel elements during fueling / refueling;
- Diversion of fuel elements off the cooling pool / fuel disposal site.

Safeguards (Types) – the model shall present the points at which the established safeguards – as provided in the CSA in force – will be applied, as well as the points at which special procedures will be employed, or even the points at which the withdrawal of safeguards may occur.

Three main issues are at the core of this variable:

- "Normal" Safeguards (as established in the CSA in force);
- Special Procedures;
- Withdraw of Safeguards.

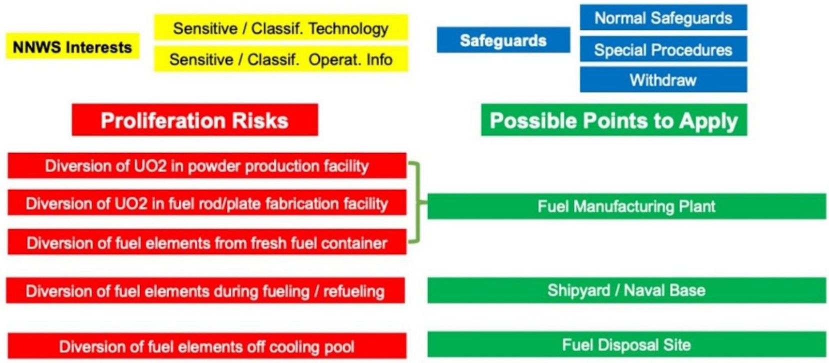
Possible Points of Application – the model shall have as a product the potential points of application for the types of safeguards mentioned — preserving sensitive or classified technologies and ensuring that there will be no diversion of nuclear material for illicit activities.

Four main potential points are at the core of this variable:

- The Fuel Manufacturing Plant;
- The Shipyard / Naval Base;
- The SSN;
- The Fuel Disposal Site.

In summary, this kind of model is not trivial and cannot be conceived with any chance of success if these four variables are not articulated. Figure 1 presents an outline of the four variables addressed.

Figure 1 – Safeguards on Nuclear Fuel – Variables to be integrated: NNWS Interests – Proliferation Risks – Safeguards – Possible Points to Apply.



Source: Prepared by the author.

It is worthy to note that some delimitations were established for the proposed model:

- The reasons leading an NNWS to develop, acquire, and operate an SSN will not be discussed. Instead, the current focus is on the safeguard provisions of the framework of the Comprehensive Safeguards Agreements (CSA) of every NNWS Party to the NPT;

- The existence of a gap or loophole[8] in the Nuclear Weapons Non-

8 As for the issue of the existence (or not) of this loophole or gap, it is suggested to read the following articles: The Naval Nuclear Reactor Threat to the NPT (Kelleher-Vergantini

Proliferation Regime resulting from using nuclear material for submarine propulsion by an NNWS will not be discussed. As a premise, it was assumed that the provisions of Article 14 of the CSA model (INFCIRC/153) provide the necessary framework for special procedures or subsidiary arrangements that the NNWS will have to negotiate with the IAEA;

- The objective of the safeguards negotiated in the Special Procedures Arrangement must be understood strictly in line with the provisions of Paragraph 28 of INFCIRC/153:

> OBJECTIVE OF SAFEGUARDS
> 28. The Agreement should provide that the objective of safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection (see IAEA, INFCIRC/153).

- Negotiations relating to "onshore" prototypes of reactors used for SSN propulsion are not the subject of this research. It is understood that the "IAEA standard approaches for land-based reactors" will be applied to these reactors in line with the accounting and control prescriptions provided in the CSA in force;
- It was assumed that the nuclear fuel used in the SSN reactor is low-enriched uranium (LEU) (degree of enrichment below 20%);
- The possibility of reprocessing nuclear fuel used in SSN reactors was not considered.

Structure of the Model – The Nuclear Fuel Cycle

Before pointing out the structure of the envisioned model, it

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& Thielmann 2013); The Canary in the Nuclear Submarine: Assessing the Nonproliferation Risk of the Naval Nuclear Propulsion Loophole (Kaplow 2015); The Nonproliferation and Disarmament Challenges of Naval Nuclear Propulsion (Shea 2017); Sea Power, Naval Power, Safeguards, and the Brazilian Conventional Nuclear-Powered Submarine (Silva 2023); and IAEA Safeguards, the Naval "Loophole" and the AUKUS Proposal (Carlson 2021).

is worth recalling some past experiences of other countries on reactors for nuclear submarine propulsion. Considering the experience of other countries, such as the United Kingdom, that have been building and operating SSNs for decades, one can observe that experimental reactors have been developed to resolve major uncertainties relating to criticality, control reactivity, and other issues. The first of these reactors in the Royal Navy was the Neptune zero-energy experimental reactor.

> Neptune was devised to operate at one or two watts of power and rarely exceeded ten watts, hence the handling difficulties encountered wit "hot" fuel elements was not a problem. The design of Neptune allowed for fuel elements and control rods to be quickly assembled in a variety of simple configurations to enable calculations to be made and compared with other layouts. Evidence from these calculations would determine the critical size of the reactor and allow for the most favourable arrangement of the fuel elements and control rods (JONES, 2022, p. 119).

Only after this was a shore-based prototype reactor built at the Dounreay complex – HMS Vulcan, Naval Reactor Test Establishment – aiming to resolve any problems encountered with the reactor design and evaluate problems relating to maintenance and assessment of safety and operational problems prior to fitting the reactor into the submarine (JONES, 2022).

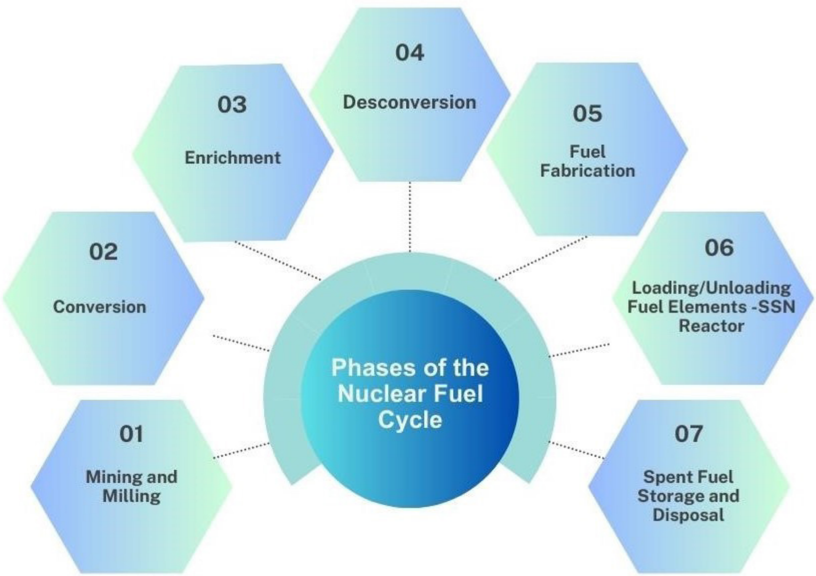
This procedure was applied to the development of the PWR1 reactor that equipped the UK's 22 nuclear-powered submarines after HMS Dreadnought. Likewise, the reactors of the PWR2 series of the Astute-class SSNs and the Vanguard-class SSBNs were developed with this same logic (GATES, 2018)

In summary, only some countries have the technology and resources to produce a weapon system such as an SSN, mainly due to the challenges of designing and building a reactor with these requirements. Thus, the technology to do this is very secretive and sensitive, and no country publishes details of its submarine reactor design.

The point to be highlighted is that the secrecy of the technologies involved in a nuclear propulsion project directly impacts the application of safeguards. The nuclear fuel cycle, with the different phases and facilities involved, is a logical way to consider the variables for the proposed model. This is because, for each phase of the cycle, there are specific technologies, risks of proliferation, types of safeguards, and special procedures to be negotiated at equally specific points. Thus, a separation by phases simplifies the problem and allows for a selective but comprehensive approach to each group of variables considered in the model.

The model adopted the following phases regarding the nuclear fuel cycle: mining and milling (to obtain U3O8 from the ore), conversion (from U3O8 to UF6), enrichment, deconversion (from UF6 to UO2), fuel fabrication and assembly of the fuel elements, loading/unloading fuel elements into/out of the SSN reactor, and spent fuel storage and disposal. Figure 2 presents the phases that this research considers for the nuclear fuel cycle.

Figure 2 – Phases of the Nuclear Fuel Cycle.



Source: Prepared by the author.

It is important to note that, although the nuclear fuel cycle is similar, the reactor design for naval nuclear propulsion reactors differs considerably from that of a civilian nuclear power reactor aimed at generating electricity. A submarine's reactor is designed to operate on a mobile platform that must be ready to combat and survive in combat. Thus, the reactor must be small — to be assembled within a submarine hull — and powerful enough to deal with high speeds and operate through wider power ranges. Besides, it must be safe for the crew and reliable in wartime (BANUELOS, GRAY AND MOORE, 2016).

The point to be highlighted is that the model presented here seeks to be flexible enough to preserve the sensitive and secret technologies developed by the NNWS, regardless of prior knowledge of type of nuclear fuel used, arrangement of fuel elements and reactor design. Thus, thinking along the phases of the nuclear fuel cycle is a way to keep the desired flexibility on this issue, and the proposed model, combining the four variables presented, will be applied to each phase of the nuclear fuel cycle of an SSN belonging to an NNWS.

BUILDING THE MODEL

For the development of the envisioned model, it was assumed that the SSN nuclear reactor has the following hypothetical features:

a) Nuclear fuel: Low-Enriched Uranium (LEU) (degree of enrichment below 20%);

b) The target power rating is approximately 60 MWe with a rapid load following capability from 0 to 100% power;

c) The reference fuel system is monolithic UO2, used in either pellet or plate geometries;

d) Typical operation is expected to be approximately 5-30% of full power, with excursions to 100%;

Box 3 summarizes the main characteristics of nuclear fuel, as reported by the NNWS:

Box 3 – Summary of nuclear fuel characteristics reported by the NNWS.

UO2	
Enrichment	LEU
Fuel Type	UO_2 as rods or plates
Fuel Form	Priority: monolithic (e.g., alloy). Also considered: dispersion[9] (CERMET) or inert matrix[10].

Source: Prepared by the author.

Source: Prepared by the author.

The point to be highlighted is that the model allows its use for reactors with different forms and types of nuclear fuel.

In these first four phases of the nuclear fuel cycle – mining and milling, conversion, enrichment, and deconversion –, safeguards will be applied following the accounting and control prescriptions contained in the current CSA of the NNWS. There are two main reasons for this approach:

- The sensitive and confidential technologies developed by the NNWS relating to these phases of the nuclear fuel cycle have already been negotiated between the NNWS and the IAEA when the CSA was signed between these interested parties;
- There is no SSN operational parameter to preserve at this stage of the nuclear fuel cycle.

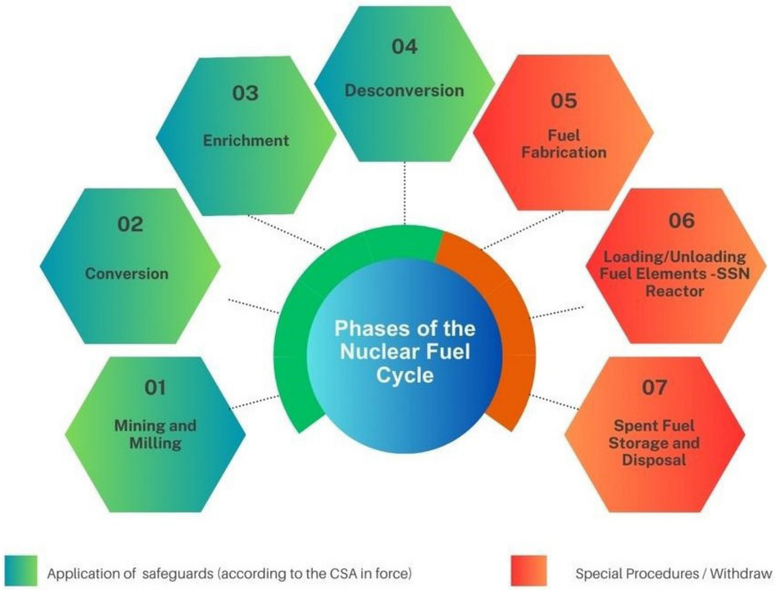
In the other three phases of the nuclear fuel cycle – fuel fabrication, loading/unloading fuel elements into/out of the SSN reactor, and spent fuel storage and disposal – the model prescribes a mix of safeguards as established in the CSA in force, special procedures, and withdraw

9 *Dispersion fuels Ceramic-Metal Composite Material (CERMET) – Compared to a standard oxide fuel rod, a cermet fuel has a higher thermal conductivity, which allows for a reduction by a factor of two of the maximum temperature of the fuel [IAEA 2003]. The use of CERMET fuels reduces the energy stored in the reactor core. It is worth noting that fuel rods with dispersed fuels also have a relatively high operational reliability at variable power regimes. This kind of fuel allows a large accumulation of fission products per fuel volume unit without prohibitive swelling. Dispersion fuels therefore provide for increasing burnup and operational safety in a reactor, and these characteristics allow for a load-following operation. A CERMET example is UO2 in Mg* (MARIANI et al. 2020, p. 22, highlighted by the author).

10 Inert matrix fuels (IM fuels) provide a matrix that does not chemically react with the fuel material and minimally (or not at all) reacts with fission products. Oftentimes, IM fuel designs seek a more structured array of fuel particles in a matrix. Of the three fuel forms, monolithic and dispersion fuels have a high Technology Readiness Level (TRL) in deployment, while inert matrix less so. (MARIANI et al. 2020, p. 7).

of Safeguards. Figure 3 presents the approach to the nuclear fuel cycle phases.

Figure 3 – The Proposed Safeguards Approach to the Phases of the Nuclear Fuel Cycle.



Source: Prepared by the author.

According to the methodology proposed for the model, in each of the three previously mentioned phases the four variables considered will be applied and integrated: NNWS Interests, Proliferation Risks, Safeguards (Types), and Possible Points to apply the safeguards. Therefore, the next topic of this article presents the application of the proposed method in the phase of Fuel Fabrication and Assembly of the Fuel Elements of the SSN Reactor.

Phase: Fuel Fabrication and Assembly of the Fuel Elements of the SSN Reactor

Regarding the variable "NNWS Interests" on sensitive and classified technology, mainly autochthonous technology, at this phase of the nuclear fuel cycle it was assumed that the NNWS would be focused on the type and form of nuclear fuel and the configuration of the fuel bundles.[11]

Concerning the variable “Proliferation Risks”, the main risks are in fuel manufacturing and assembly of fuel element facilities. Box 4 presents the risks of diversion of nuclear material in the fuel manufacturing and assembly of fuel elements phase, considered for elaborating the envisioned model.

Box 4 – Main Risks considered in the Phase of Fuel Fabrication and Assembly of the Fuel Elements of the SSN Reactor.

At the Fuel Fabrication Facility	
Risk	Diversion of enriched uranium in bulk form (UO_2) from the powder production facility
Risk	Diversion of UO_2 in fuel rod/plate fabrication facility
Risk	Diversion of fuel elements from fresh fuel container

Source: Prepared by the author.

As for the “Safeguards (Types)” and “Potential Points to Apply” variables, the adoption of Material Balance Areas[12] (MBA) in the facility for fuel manufacturing and assembly of fuel elements, along with the following safeguards for application arrangement, will minimize the probability of occurrence for the three risks mentioned above. The model proposes the adoption of four MBA, discussed below:

11 A grouping of fuel rods, pins, plates, or other fuel components held together by spacer grids and other structural components to form a complete fuel unit which is maintained intact during fuel transfer and irradiation operations in a reactor (see IAEA 2022, p. 41).

12 According the INFCIRC/153, Paragraph 110 “Material Balance Area means an area in or outside of a facility such that: (a) the quantity of nuclear material in each transfer into or out of each material balance area can be determined; and (b) the physical inventory of nuclear material in each material balance area can be determined when necessary, in accordance with specified procedures; in order that the material balance for Agency safeguards purposes can be established” (see IAEA, INFCICR/153).

• MBA-1 – Receiving Area / Deposit of bulk UO2 already enriched

– Safeguard to be applied: the accounting and control provisions contained in the CSA in force and already enshrined in current fuel manufacturing and assembly of fuel elements carried out in nuclear facilities will be applied.

• MBA-2 – Fuel Manufacturing Area

– Safeguard to be applied: the accounting and control provisions contained in the CSA in force and already enshrined in current fuel manufacturing and assembly of fuel elements carried out in nuclear facilities will be applied.

• MBA-3 – Fuel Element Assembly Area

– Safeguards to be applied: from the moment nuclear fuel enters this MBA, accounting and control measures will be suspended to preserve the geometry and other sensitive and confidential technologies of the fuel elements used in the SSN reactor. The assembled and finished fuel elements will be placed in "transportation casks".

• MBA-4 – Fuel Elements Deposit Area

– Safeguards to be applied: the assembled and finished fuel elements were placed in "transportation casks" when finished at MBA-3, therefore without the possibility of being viewed by IAEA inspectors. However, once the closed casks arrive at the MBA-4, they will be sealed by IAEA inspectors;

– After this, MBA-4 will perform a material balance to ensure that the risks of diversion of fissile material considered at this phase have been minimized.

Figure 3 graphically presents these four proposed MBA for the fuel manufacturing plant and assembly of the fuel elements of the SSN reactor.

Figure 3 – Graphic Representation of the MBA

Subtitles

	Safeguards: accounting and control prescriptions as provided for in the CSA in force.
	Safeguards: Special Procedures – accounting and control measures will be suspended.
	Safeguards: Special Procedures – Visual verification of "casks", followed by the application of seals.

Comments:

- Key flow measurement points have been omitted in this graphical representation.
- Key inventory measurement points have been omitted in this graphical representation.
- Points of transfer of waste and samples have been omitted in this graphical representation.

Source: Prepared by the author.

The possibility of using "active interrogation systems" by IAEA inspectors, aiming to determine the amount of U235 in each "cask", was discarded in the proposed model. Despite being an additional guarantee for a baseline survey of the fissile material in the fuel elements, this type of measurement would also enable an accurate survey of the composition and quantity of fissile material in each fuel element. It would also allow for a reasonable estimate of the interval between recharges of the fuel elements in the reactor, that is, the SSN operational cycle. Therefore, this procedure was assumed to be unacceptable to the NNWS.

Regarding transportation of the assembled fuel elements: once the casks are sealed, they can be transported to the shipyard/naval base. The IAEA inspectors will be informed and invited to monitor the transport of the sealed casks from the fresh fuel storage area to the shipyard/naval base, where they will be loaded into the SSN reactor.

Phase: Loading / Unloading Fuel Elements Into / Out of the SSN Reactor

For the development of the envisioned model, it was assumed that the design information on the part of the nuclear facilities at the SSN shipyard/naval base must be provided by the NNWS in line with the CSA in force (see Paragraphs 42 to 45 of INFCIRC/153).

DESIGN INFORMATION

General

42. Pursuant to paragraph 8 above, the Agreement should stipulate that design information in respect of existing facilities shall be provided to the Agency during the discussion of the Subsidiary Arrangements, and that the time limits for the provision of such information in respect of new facilities shall be specified in the Subsidiary Arrangements. It should further be stipulated that such information shall be provided as early as possible before nuclear material is introduced into a new facility.

43. The Agreement should specify that the design information in respect of each facility to be made available to the Agency shall include, when applicable:

(a) The identification of the facility, stating its general character, purpose, nominal capacity and geographic location, and the name and address to be used for routine business purposes;

(b) A description of the general arrangement of the facility with reference, to the extent feasible, to the form, location and flow of nuclear material and to the general layout of important items of equipment which use, produce or process nuclear material;

(c) A description of features of the facility relating to material accountancy, containment and surveillance; and

(d) A description of the existing and proposed procedures at the facility for nuclear material accountancy and control, with special reference to material balance areas established by the operator, measurements of flow and procedures for physical inventory taking.

44. […].

45. The Agreement should stipulate that design

> information in respect of a modification relevant for safeguards purposes shall be provided for examination sufficiently in advance for the safeguards procedures to be adjusted when necessary (see IAEA, INFICRC/153).

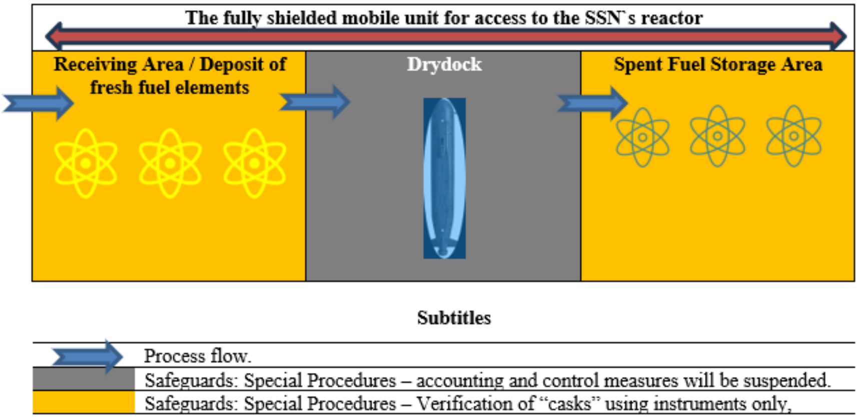
Concerning the variable “NNWS Interests” – at this phase of the nuclear fuel cycle – it was assumed that the preservation of sensitive and classified technology of the NNWS would be focused on the SSN`s reactor design, dimensions, geometry, and control mechanisms as well as the information regarding the SSN shipyard/naval base.

Taking into consideration the variable “Proliferation Risks”, the main risk in this phase of the nuclear fuel cycle is the diversion of nuclear material in the shipyard/naval base during the loading/unloading of fuel elements into/out of the SSN reactor.

As for the variables “Safeguards (Types)” and “Potential Points to them”, it was assumed that the Shipyard / Naval Base would have a radiological complex in which nuclear fuel exchanges would be carried out. This radiological complex will have the following facilities:

- A Receiving Area/Deposit of fresh fuel elements;
- At least one dry dock for the SSN;
- A fully shielded mobile unit structure for access to the SSN`s reactor;
- A spent fuel storage area.

Figure 4 graphically presents these hypothetical facilities of the radiological complex mentioned above.



Source: Prepared by the author.

On the model envisioned, the safeguards during the loading/ unloading of fuel elements into/out of the SSN reactor will proceed according to the following steps.

a) Loading Fuel Elements

The NNWS should inform the IAEA that a fueling operation has been scheduled.

On the date scheduled by the NNWS, the IAEA inspectors will be invited to visit the receiving area/deposit of fresh fuel element casks transported from the fuel fabrication facility to the shipyard/naval base. These visits will occur before the casks arrive and during their unloading in this receiving area.

IAEA Inspectors will be able to check the seals previously placed on the casks when these have been sealed at the fuel manufacturing plant and fuel elements assembly facility. From then on, safeguards will no longer be applied to nuclear material, which will be loaded into the SSN, and inspectors will leave the base.

b) Unloading Fuel Elements

The NNWS should inform the IAEA that a refueling operation has been scheduled.

On the date scheduled by the NNWS to move the fuel elements out of the SSN, the inspectors would be invited again to the radiological complex of the shipyard/naval base.

The inspectors will only have access to the Spent Fuel Storage Area.

Each fuel element will be removed from the SSN reactor and placed into a cask through the fully shielded mobile unit. The casks will be moved to the spent fuel storage area, and once they arrive there, they will be sealed by IAEA inspectors.

It is worth noting that, as in the Fuel Manufacturing and Assembly of Fuel Elements phase of the SSN Reactor the use of "active interrogation systems" by IAEA inspectors was not permitted, its use here would be meaningless.

If this type of procedure had been used previously, it could be used at this stage to determine the amount of fissile material in each cask to compare with the readings taken when loading fuel elements into the SSN reactor. In other words, inspectors would carry out measurements to compare the new measures to the baseline fingerprints and verify if the spent fuel elements are compatible with those loaded during fueling of the SSN reactor.

However, the procedure would also allow for the survey of the burn profile of the nuclear fuel; that is, it would reveal information regarding the operational profile of the SSN. This possibility reinforced the perception that, a priori, the use of "active interrogation systems" by IAEA inspectors would be unacceptable by the NNWS.

Phase: Spent Fuel Storage and Disposal

This is the final phase of the nuclear fuel cycle adopted in the proposed model. It has a critical feature in the facilities, as the final disposal facility can be located inside or outside the shipyard/naval base.

Once again applying the stated method and considering the variable "NNWS Interests", at this phase of the nuclear fuel cycle it was assumed that the preservation of sensitive and classified technology of the NNWS would be focused on the SSN reactor burning profile – as already mentioned – and information regarding the SSN shipyard/naval base.

Regarding the variable "Proliferation Risks", the main risk is diverting irradiated fuel elements from the cooling pool and the final disposal area.

Taking into account the variables "Safeguards (Types)" and "Potential Points to Apply", the adoption of the following procedure will minimize the probability of occurrence of the risk mentioned above:

a) The spent fuel unloaded from the SSN reactor will be temporarily stored in the spent fuel storage area at the radiological complex of the shipyard / naval base.

b) Once the residual heat is low enough to allow transport, the casks could be moved to the final disposal area. This area could be outside the shipyard/naval base, as established by the NNWS.

c) On the date scheduled by the NNWS to move the fuel elements out of the spent fuel storage area in the radiological complex of the shipyard/naval base to the final disposal area, the inspectors would be invited again to the radiological complex of the shipyard/naval base.

d) For the reasons already explained, the use of "active interrogation systems" and "thermal imaging techniques" by IAEA inspectors will not be permitted. However, the IAEA Inspectors will be able to check the seals previously placed on the casks when these have been sealed at the unloading procedure from the SSN reactor.

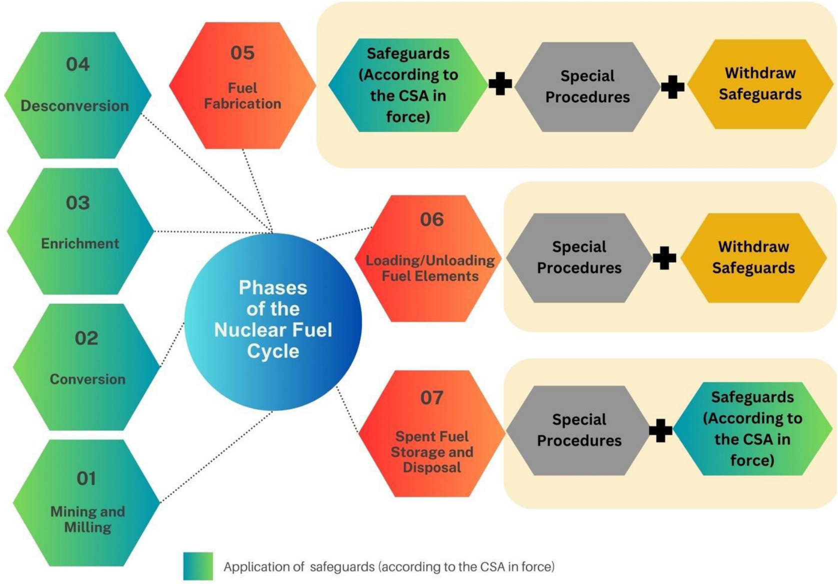
e) The IAEA inspectors will be invited to monitor the transport of the sealed casks from the spent fuel storage area to the final disposal area.

Once in the final disposal area, the casks may be monitored by IAEA inspectors without, under any circumstance, being opened without express authorization from the NNWS.

OUTCOMES AND FINAL CONSIDERATIONS

The research carried out produced a draft of a model with possible points of withdrawal or application of special procedures and reapplication of safeguards on the nuclear fuel cycle used in the reactor of the nuclear-powered submarines developed or operated by a NNWS, in line with what is provided in the Comprehensive Safeguards Agreements signed with the IAEA. Figure 5 presents the synthesis of the model.

Figure 5 – Synthesis of the Model.



Source: Prepared by the author.

The research points out that implementing safeguards in the nuclear fuel of an SSN developed or operated by an NNWS is not impossible, and this kind of use of nuclear power is not necessarily a gap in the nuclear weapons non-proliferation regime.

The model is structured in the nuclear fuel cycle and combines four variables – NNWS Interests, Proliferation Risks, Safeguards (Types), and Possible Points to Apply the Safeguards. This methodological approach makes the model unique and flexible. The presented model points out that minimizing some main risks of diverting significant amounts of nuclear material without compromising the operational information of an SSN is possible. Likewise, the model points to the feasibility of minimizing the risks of the proliferation of nuclear weapons without violating sensitive and confidential technologies developed by the NNWS.

Furthermore, it is worth highlighting that the model can also be used for nuclear-powered surface ships, regardless of the form and type of nuclear fuel adopted.

Undoubtedly, there remains a lot to improve in the presented model. The delimitations made and the data assumed were many.

However, as this topic has so much classified data, the constraints were necessary to achieve the proposed objective.

Regarding the zero-power reactor and the prototype for testing adopted on land – if the NNWS adopts this logical procedure –, it is understood that the model presented here can be used with some adaptations and less difficulty, as it will not require access to the shipyard/naval base.

Finally, it is time to highlight that the opportunity to be connected to the King`s College London (KCL) as a Visiting Professor − in the stimulating environment of the Centre for Science and Security Studies (CSSS) – was a unique opportunity to advanceresearch on the subject. The short period between May 10th and August 31st of 2023, in which this researcher was in person at that prestigious institution, was essential for developing this model. As a Brazilian academic and researcher on safeguards and their application in nuclear-powered submarines, it was a remarkable opportunity to contribute to a non-proliferation issue and the main Brazilian strategic and defense program.

Salvaguardas e submarinos movidos a energia nuclear: um modelo para procedimentos especiais no ciclo do combustível nuclear

RESUMO:

Este artigo tem como foco as salvaguardas da Agência Internacional de Energia Atômica (AIEA) e a questão de como aplicá-las ao material físsil utilizado em um submarino com propulsão nuclear (SSN, na sigla em inglês) desenvolvido por um Estado Não Nuclearmente Armado (NNWS, em inglês). O Brasil está desenvolvendo seu próprio SSN e a Austrália – apoiada pela parceria AUKUS – irá operar um SSN por volta de 2030. Países como a República da Coreia, o Irã e o Canadá já demonstraram interesse atual ou passado em desenvolver um SSN. Nesse contexto, é pertinente pensar em modelos para conciliar as salvaguardas previstas pela AIEA e o desenvolvimento e operação de um SSN pertencente a um NNWS. O artigo apresenta um modelo em três etapas. Em primeiro lugar, coloca-se em evidência o quadro normativo da AIEA sobre essa questão. Em seguida, aborda-se a metodologia e a estrutura do modelo. A última seção apresenta a construção do modelo para cada fase do ciclo do combustível nuclear. O resultado da pesquisa foi o desenvolvimento de um modelo, estruturado no ciclo do combustível nuclear, que combina quatro variáveis – interesses do NNWS, salvaguardas, riscos de proliferação e possíveis pontos de aplicação de salvaguardas. Essa abordagem metodológica torna o modelo único e aponta para um caminho futuro de negociações entre a AIEA e um NNWS com um programa de SSN.

Palavras-chave: Não Proliferação. Submarinos com Propulsão Nuclear. Salvaguardas Nucleares.

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