SAFEGUARDS AT SEA: ENABLING MARITIME NUCLEAR POWER

J. WHITLOCK[1], N. TOMKINSON[2]

[1]Global Nuclear Security Partners (GNSP), Stratford, Canada (jeremy.whitlock@gnsp.global)
[2]Global Nuclear Security Partners (GNSP), London, UK (nick.tomkinson@gnsp.global)

Abstract

Merchant shipping accounts for about 3% of global GHG emissions. Maritime nuclear is a proven, advanced, safe energy source that can tackle this challenge without reducing performance. In 2026 a UK consortium was convened to channel leading expertise from the nuclear, maritime, insurance and regulatory sectors – the goal: a reference solution defining the standards for safe, secure, economically viable nuclear-powered merchant shipping. Non-proliferation will essentially be a first-of-a-kind challenge since there is little experience with nuclear propulsion systems under full international safeguards. Meeting these obligations on a moving vessel without compromising commercial viability is critical, and will require a safeguards-by-design approach that leverages synergies with safety and security requirements, and other innovative solutions. The paper presents an overview of the project and the safeguards assessment (challenges and proposed solutions) developed to date.

1. INTRODUCTION

Nuclear propulsion for civilian shipping has been discussed since the earliest days of nuclear power, but – other than a handful of prototypes (US, Japan, Germany) – implementation has been the preserve of navies and icebreakers (US, Russia, UK, France, China and India, with Brazil and Australia in process). Recently, climate concerns have sparked renewed interest in civilian nuclear marine propulsion, given that merchant shipping accounts for about 3% of global GHG emissions [1] (if it were a country it would be in the top ten of global emitters).

In 2026 a UK-based Maritime Nuclear Consortium was convened by Lloyd's Register to channel expertise from the nuclear, maritime, insurance and regulatory sectors – the goal: a reference solution defining the standards for safe, secure, economically viable nuclear-powered merchant shipping. Non-proliferation will be a first-of-a-kind challenge since no nuclear propulsion system has yet been placed under full international safeguards.

Meeting these obligations on a moving vessel without compromising commercial viability is critical, and will require a safeguards-by-design approach that leverages synergies with safety and security requirements, and other innovative solutions: basically, optimizing safeguards where safeguards were never intended. As the security and safeguards lead in the Consortium, Global Nuclear Security Partners (GNSP) is developing this critical piece, working alongside Lloyd's Register (lead), Rolls-Royce (reactor design), Babcock International Group (ship design), Stephenson Harwood LLP (legal and regulatory), North Standard (marine insurance), and Nuclear Risk Insurers (nuclear insurance).

2. OBJECTIVES OF UK MARITIME NUCLEAR CONSORTIUM

The main objectives of the Consortium are to:

- Demonstrate the viability of a maritime nuclear vessel under all relevant regulatory/oversight regimes: UK-ONR (Office for Nuclear Regulation), UK-MCA (Maritime & Coastguard Agency), IMO (International Maritime Organisation), IAEA;
- Establish the pathway to safety, environmental protection, regulation & classification, security, safeguards, and insurability;
- Publish guidance for industry and government stakeholders; and
- Engage with key stakeholders; e.g.:
  - *UK:* relevant gov't departments, ONR, MCA, UK Chamber of Shipping;
  - *International:* IMO, IAEA (ATLAS), NEMO

The goal is to lead internationally in setting the highest standards for safe, secure and commercially viable nuclear powered merchant vessels.

3. KEY PROJECT ASSUMPTIONS RELEVANT TO SAFEGUARDS

3.1. Technology

The assumed marine platform is a modified research vessel, 124 m in length with integrated full electric propulsion and displacement of 14.5 kt. Two ~3MWe diesel generators complement the on-board reactor.

The assumed reactor is based on Rolls-Royce's Advanced Modular Reactor (AMR): prismatic graphite HTGR, HALEU fuel, 30 MWth nominal power, and 5-10 years refuelling frequency based on duty cycle. No fresh or used fuel is stored on board.

3.2. Legal framework

For the purposes of the project, it is assumed that the vessel is UK flagged and the owner/operator is a UK nuclear licensee. Operation of the vessel is thus subject to the requirements of the UK Office for Nuclear Regulation (ONR) and VOA safeguards agreement, and it is assumed that this situation applies regardless of the vessel's location.

It is further assumed that the UK would include the vessel in its Voluntary Offer Agreement (VOA) Facilities List, and it is thus available for selection by the IAEA for safeguards application (for which it would be a likely candidate due to its novel nature). Regardless of its eventual selection status, the project applies a comprehensive safeguards benchmark encompassing both diversion and misuse scenarios. This is intended to maximise the relevance of the findings to future deployment in non-nuclear-weapon States as well as within the UK context.

3.3. Boundaries

It is assumed that the reactor, and any areas directly associated with it, form both the "facility" in safeguards terms as well as a single Material Balance Area (MBA). For the purposes of the assessment, the hull of the vessel is adopted as a convenient and deliberately conservative working demarcation of the nuclear "site". This assumption enables the implications for Complementary Access (CA) and managed access to be explored, but would need to be tested with ONR and the IAEA against functional boundaries and commercial/security sensitivities.

3.4. Priorities

The key stakeholders will approach the implementation of safeguards from different contexts, and therefore priorities: the State (UK) under its VOA safeguards agreement will focus on maintaining a robust Nuclear Material Accounting and Control (NMAC) system, the operator will focus on complying as efficiently as possible without compromising economic operation, and the IAEA will seek useful operating experience for full-scope safeguards implementation through "safe-haven" prototyping: this would apply to verification of both NMAC and non-misuse of the facility.

For the purposes of the project therefore, the goal is relevance to all key stakeholders through:

- Robust continuity of knowledge and NMAC;
- Efficient implementation in a mobile maritime environment; and
- International relevance through inclusion of both diversion and misuse scenarios.

4. CHALLENGES OF SAFEGUARDING A MARITIME NUCLEAR VESSEL

The novel technical challenges of safeguarding a maritime nuclear vessel can be attributed to its mobility, long core life, and advanced reactor design:

4.5. Mobility

While mobile reactors are not a new concept (particularly in nuclear navies and icebreakers), the application of international safeguards to a civilian mobile reactor remains highly novel. Nuclear safeguards for power reactors have evolved for stationary facilities operating with a verifiable output signature within the national infrastructure of a host State, and refuelling on roughly a 1-2-year cycle or less.

The vessel, on the other hand, will operate beyond the national infrastructure of the UK, with a variable duty cycle backed up by diesel, and for long periods will be inaccessible for inspection. Safeguards will therefore need to rely upon robust remote monitoring and Containment and Surveillance (C/S) measures (resilient in a marine environment), with inspection during UK port visits.

Mobility also introduces a new variable of "location" to facility-based safeguards implementation: the movement of the vessel will be of interest to the IAEA, particularly given the potentially long sailing operations. This has potential a security interface as discussed later.

4.6. Long core life

The advent of advanced reactors with multi-year refuelling cycles will challenge the paradigm of reasonably frequent inspectorate access. In the case of the vessel's reactor, a 5–10-year core life is a long interval between opportunities for direct verification of the core inventory and configuration – which, in combination with the general inaccessibility and mobility of the reactor, will lead to increased reliance upon design verification and robust C/S measures.

4.7. Advanced reactor design

The AMR generally represents a design unfamiliar to the IAEA and ONR. Therefore, the nuclear technology itself will introduce a regulatory/inspectorate learning curve – not only in terms of licensing and safeguards development, but also with regards to core characterisation under normal and off-normal conditions.

5. SAFEGUARDS IMPLEMENTATION

Proposed safeguards implementation that addresses both diversion and misuse scenarios can be separated into port-based and ship-based activities:

5.8. Port-based safeguards activities

- *Design information verification:* The operator must provide design information during construction and any subsequent modifications, and the IAEA has the right to verify (including visiting the factory during assembly);
- *Operational and port-of-call information:* Provision of sufficient information on port visits, refuelling, maintenance and other safeguards-relevant activities to support inspection and verification planning;
- *NMAC verification:* Direct verification of the core inventory and configuration during refuelling outages, supported between outages by NMAC, design information verification, C/S measures, remote monitoring and other agreed activities;
- *Additional Protocol measures:* While in port the IAEA may conduct CA activities on the non-nuclear balance of ship (assumed within the project as the "site").

5.9. Ship-based safeguards activities

- *Containment and surveillance measures:* Provides continuity of knowledge during long sailing schedules and supports verification of non-misuse: C/S measures need to be robust for maritime and reactor environments, accommodate operational access if necessary, and ideally remotely monitored;
- *"Difficult to Access" designation:* Accommodates extended lack of access and difficulty of re-verification, achieved through pre-verification combined with redundancy of C/S measures;

- *Remote data transmission and monitoring (RDT):* Remote, secure transmission of safeguards data to the IAEA during sailing provides strong continuity of knowledge, but will need to address cyber-security risks, and loss of signal due to sailing conditions;
- *Location and voyage information:* Sufficient authenticated information on vessel movement may be required to support verification planning and continuity of knowledge. This should not necessarily be equated with continuous live tracking by the IAEA. The required granularity, latency and recipient of location information would need to be agreed, taking account of commercial and security sensitivities. Options include delayed position updates, authenticated voyage logs, event-triggered reporting, location data provided upon request, and post-voyage verification;
- *Inventory change reporting (ICR):* Accountancy reports would be provided in accordance with ONR requirements. Modelled core inventory, supported by authenticated operating information, could assist ONR and the IAEA in evaluating the declared inventory between direct verification opportunities – the frequency of these updates will be a consideration for discussion, particularly given the long duration between refuelling outages;
- *Thermal power monitoring:* Provides confidence in declared nuclear material inventory changes where core operation is variable and access limited, and is particularly important here given the complementary diesel capability of the vessel and potentially long sailing schedule (addressing the misuse scenario);
- *Inspector access while at sea:* Potential at-sea access could be a contingency verification measure. Its feasibility would depend upon specific legal, safety, security, insurance and operational arrangements agreed between the UK, IAEA and operator. In practice, the preferred safeguards approach should minimise reliance on such access through effective port-based verification, C/S and remote measures.

6. THE IMPORTANCE OF 3S BY DESIGN

The early integration of safeguards considerations with safety and security will be critical if the goals of robustness and efficiency (with minimal operational interference) are to be achieved. The numerous interrelated disciplines and legal frameworks aboard a maritime vessel underscore the importance of this early integration. From the project's perspective, the value of expert elicitation has become clear: obtaining insights from systems experts in order to better navigate the frictions and synergies around 3S interfaces.

Some 3S interfaces highlighted to date include:

- Implementation of effective NMAC;
- Robustness of C/S measures;
- RDT and other cyber interfaces;
- Sharing of vessel location data;
- Inspector access at sea;
- IAEA access for maintenance; and
- Recovery of continuity of knowledge from anomalous or accidental conditions at sea.

7. SUMMARY AND NEXT STEPS

The framework for safeguards application to a theoretical maritime nuclear vessel has been developed within a consortium of key UK industry stakeholders. The consortium's objective is a reference assessment defining the standards for safe, secure and economically viable nuclear-powered merchant shipping. Progress to date indicates that the safeguards objectives can be met, but that conventional implementation will require adaptation to accommodate mobility, extended core life and limited access.

A hybrid model combining port-based verification with resilient ship-based NMAC, C/S and RDT is likely to be required. The most distinctive challenge is not the safeguards technology but maintaining credible continuity across changing jurisdictions while protecting sensitive voyage and security information. Early integration of safeguards with safety, security, ship design and operational planning will therefore be essential to achieving both robustness and commercial viability.

Next steps include engaging ONR to gain clarity on aspects such as facility/site boundaries, MBA, Key Measurement Points (KMPs) and NMAC approach including ICR frequency, the value of the project's target of

broad international relevance in the safeguards assessment, and security implications of location tracking (and possible alternatives). From the technology stakeholders (Rolls-Royce and Babcock), more clarity will be sought around safeguards-relevant design information, joint security/safeguards review of remote monitoring, seals, cameras and information flows, and structured expert elicitation on diversion, misuse and continuity-of-knowledge failure pathways.

REFERENCES

[1] INTERNATIONAL MARITIME ORGANIZATION, Fourth IMO Greenhouse Gas Study, 2020.