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A Tale of Two Disruptive Maritime Technologies: Nuclear Propulsion and Autonomy

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ABSTRACT: Modern industries often attempt to implement innovations that have a disruptive potential. In shipping, this included a largely unsuccessful introduction of nuclear propulsion in late 20th century, among other concepts. Nowadays, introduction of increased autonomy is being associated with prospects of various industry-wide benefits, but is also burdened with serious obstacles. The objective of this study is to investigate reasons behind the failure of nuclear-powered merchant ships introduction and whether lessons learnt from it can be applied to the prospective implementation of autonomous merchant ships. It advocates that three aspects of maritime technology are crucial for its successful implementation: perceived level of safety, economical feasibility, and legal setup.

1 INTRODUCTION

The shipping industry is responsible for securing some 80% of international trade by volume (UNCTAD 2020). Nowadays, it is facing a disruptive change to its traditional setup, which was based on a highly-skilled workforce of seafarers. The disruptive change of introducing autonomous solutions to maritime transportation will affect not only the 1.6-million pool of offshore workers, but is likely to change the way the entire industry works. The expected changes encompass increased safety (Kretschmann et al. 2015), reduced environmental impact (Danish Maritime Authority 2017), increased financial effectiveness, among others. Each of these potential benefits can be contested, primarily for the lack of hard evidence in a form of historical data to support them. Safety-related gains are questionable due to the unknown effect of autonomous ships on maritime operations (Wróbel, Montewka, and Kujala 2017) and difficulty in quantifying or analyzing the effect humans have on maritime safety (Wróbel 2021). Environmental impact will primarily come as an effect of introducing solutions unrelated to autonomy itself, but rather implemented on the occasion of re-shaping the industry. Financial effects of operating autonomous vessels are also difficult to predict (Ziajka-Poznańska and Montewka 2021; Kooij, Kana, and Hekkenberg 2021; Sandvik et al. 2021). On top of these, there is an ongoing discussion on various legal aspects of crewless shipping (Nawrot and Pepłowska-Dąbrowska 2019; Wasilewski, Wolak, and Zaraś 2021) including liability (Mallam, Nazir, and Sharma 2020), lack of clear foundation within the international maritime framework (Bergström et al. 2018), unknown impact of the technology on the workforce (Bogusławski, Gil, et al. 2022), and potential unknown unknowns. As of 2022, the development of the technology is gaining momentum, but its future is burdened with significant uncertainties. These will not necessarily cause it to fail, but may result in significant setbacks.

In order to ensure that the development is smooth, different approaches are proposed. These include close cooperation between the legislator bodies and the industry, as well as learning from other domains where a shift towards autonomy has already occurred (Wahlström et al. 2015). However, it has not been raised until now that the industry can also learn from past attempts to introduce a disruptive technical change. Past failures on the part of maritime industry to embrace a disruptive technology might help prevent their repetition in the case of Maritime Autonomous Surface Ships (MASS) development. One of examples of unsuccessful technologies (that is now again gaining interest) is a nuclear propulsion of merchant vessels.

When first conceptualized in late 1950s, nuclear-powered merchant vessels were viewed as safer, less polluting, and more financially viable than those running on fossil fuels. Note that these are also the main incentives for developing autonomous ships. With only few non-military, nuclear-powered ships in operation today in compare to tens of thousands running on fuel oil, the idea of nuclear-powered maritime transportation has clearly failed to meet the expectations. Noteworthy, it was merely related to the novel mode of propulsion and fuel logistics chain. Meanwhile, introduction of autonomy is believed to impact numerous aspects of shipping operations including fuels used and energy efficiency, human element and crewing, supervision and control, as well as legal regime (Wright 2020).

2 METHOD AND SCOPE

The objective of the present study is to investigate the reasons behind that failure and whether this experience can be applied to promote the development of MASS.

The study has been performed using a comparative analysis method, in which technical and scientific documents pertaining to two technologies in question (nuclear propulsion of merchant ships NPoMS and Maritime Autonomous Surface Ships MASS) have been reviewed. These were collected from scientific documents databases (Google Scholar and ScienceDirect.com) and snow-balled through the references lists to retrieve relevant documents on the development of both technologies. Similarities and differences between them have been disclosed as well as factors governing potential successes and failures. Eventually, lessons learnt from the development of NPoMS and relevant for MASS have been identified.

The scope of this study has been limited to civilian applications of maritime transportation. References to the military applications are only made to maintain the flow of a historical overview.

The reminder of this article is as follows. Firstly, historical overview of both technologies is provided. Then, Section 4 discusses four aspects of the technologies having the greatest impact on their development: legal environment, safety, economic feasibility, and human element considerations. Section 5 presents lessons learned from the development of nuclear merchant ships and elaborates on potential application of these lessons to the development of maritime autonomous systems. Final section concluded the paper.

3 HISTORICAL OVERVIEW

3.1 *Nuclear propulsion*

NPoMS came to reality in 1962 when NS [Nuclear Ship] Savannah has been commissioned, ten years after the launching of USS Nautilus. The purpose of Savannah was to demonstrate the viability and safety of the technology as well as to gain experience in non-military operations rather than to secure financial gains (Freire and Andrade 2015; Dade and Witzig 1974). She was capable of transporting both cargo and passengers. The project proved successful in technical terms, but a complete failure financially (Hirdaris et al. 2014). There were also long disputes over wages for the crew and their qualifications.

In the same year of 1962, construction of NS Otto Hahn was ordered in West Germany. Her primary objective as an ore carrier was to serve as a test bed to gain experience in nuclear ships design by German maritime industry. The ship met many restrictions in calling at certain ports due to perceived nuclear risk, which prevented her operations on certain routes (Ulken, Bianchi, and Kühl 1972; Schøyen and Steger-Jensen 2017).

Ten years later, in 1972, construction of a Japanese NS Mutsu was completed and the vessel was scheduled for sea trials. Due to the protests of local communities, these were postponed until 1974. Due to some design flaws, she suffered from an increase in fast neutrons radiation escaping the nuclear shielding, which was later mis-reported as a 'radioactivity leak' (Nakao 1992). Rectification of this issue and further modifications lasted until 1982 and the ship was finally commissioned in 1991. She was decommissioned a year later, after completing her research objectives (Gabbar, Adham, and Abdussami 2021).

Soviet Union developed a series of nuclear-powered ice-breakers to operate and provide their services in Northern Sea Route. Among them was one that was designed to also serve as a cargo ship, NS Sevmorput. Commissioned in 1988 (two years after Chernobyl Nuclear Power Plant accident), she is still active despite some resistance from port authorities reluctant to accept her entry (Freire and Andrade 2015). The ground for the latter are fears related to nuclear safety. Interestingly, these were even expressed within the Soviet Union during its final years, where Sevmorput has been effectively banned from some Far East ports (Ondir Freire and de Andrade 2019; Schøyen and Steger-Jensen 2017). She is usually employed in a cabotage trade between Russian Arctic ports (Атомфлот n.d.) that can normally be unreachable by other vessels. These are quite unparalleled market conditions.

All in all, except for a minor incident with NS Mutsu, nuclear-powered merchant ships proved technically viable, just as nuclear-powered men-of-war do so. The NS Mutsu incident is said to be a result of dispersed responsibility among entities involved in design and construction.

All projects but Sevmorput were designed to be more of a technology demonstrator and research facility than money-making vehicles, which may have contributed to them being withdrawn from operation. Another contributing factor was safety concerns that prohibited certain operations of ships. It is of note however, that major safety-related obstacles to operation of Savannah, Mutsu, and Otto Hahn (such as denials of port entry) occurred even before the Three Mile Island accident (1979). The event is said to have caused major increase of skepticism and fear towards nuclear industry (IAEA 2004) that has only been exaggerated by later accidents in Chernobyl and Fukushima-Daiichi. If public acceptance for NPoMS was low, these accidents only made it worse. Noteworthy, public does not normally raise similarly big concerns towards nuclear-powered vessels operated by military (Freire and Andrade 2015).

Eventually, nuclear-powered merchant vessels are believed in hindsight to have been a costly exploration of a potentially feasible solution. Their impact was not big enough (primarily due to an inability to create profit, legal restrictions, and public/authority acceptance) to challenge the normal development in shipping (Schøyen and Steger-Jensen 2017).

3.2 *Maritime autonomy*

Although the concept of crewless ships has been put forward as early as in 1898 by famous Nikola Tesla (Tesla 1898), the first regular attempts for designing full scale demonstrators were performed in 1970s (NYT 1970). The development was rather slow, likely due to lagging software and hardware advancements. It was not until around 2014 when initial results of MUNIN (Maritime Navigation through Intelligence in Networks) project were published that the industry began to realize that unmanned ships can be real (Rødseth and Burmeister 2012). Since then, the development in the field gained momentum, both in terms of new studies dedicated to it being published (Wróbel, Gil, and Montewka 2020) but also through prototypes developed (Kongsberg 2017).

The most deployment-ready commercial autonomous merchant ship is Yara Birkeland (Akbar et al. 2021). She will serve a domestic trade within Norwegian waters, operating between a fertilizer factory and an export terminals. The project gained significant public attention and the ship itself will gradually transition towards fully-autonomous operations in order to ensure overall safety. Noteworthy, the assumption behind the development was that it will not only serve as a technology demonstrator but will also generate savings for the operating company. These savings will come from elimination of other modes of transportation from the logistics chain, but Yara Birkeland is nevertheless expected to be economically viable from the beginning (Mannov et al. 2019). She entered into a regular service in spring 2022.

Apart from Yara Birkeland, there are also several other developments across many countries (Kutsuna et al. 2019; Hannaford, Maes, and Van Hassel 2022), but neither has been reported to achieve a comprehensively autonomous operability. Noteworthy, most of those intended for commercial operations are expected to navigate between ports within one country so as to stay within one legal frame and not be involved in international voyages. These would invoke a largely non-existent international regulations designed for MASS.

4 NUCLEAR AND AUTONOMOUS: SIMILARITIES AND DIFFERENCES

4.1 *Legal environment*

Both NPoMS and MASS were initially developed in a legal vacuum. It was not until 1966 (4 years after Savannah has been launched) that the first classification society developed prescriptive Rules for the Classification of nuclear ships (Hirdaris et al. 2014). Code of Safety for Nuclear Merchant Ships was adopted not sooner than in 1981 as a goal-based standard for the design and operation of nuclear-powered ships (IMO 1981). Notably, it was almost 20 years after the Convention on the Liability of Operators of Nuclear Ships was made open for signature (Konz 1963) – clarification of liability issues preceded this of technical ones. Moreover, most of the legal framework for construction and operation of nuclear facilities has been designed to accommodate stationary, land-based structures rather than mobile ones (Hirdaris et al. 2014). Similarly, nuclear regulators were sometimes reported to over-estimate risks related to NPoMS due to their regular interaction with land-based facilities of plate capacity at least an order of magnitude greater than these installed on ships (Edwards 1979).

Lack of stable legislation is one of the factors that keep potential investors away from given industry, just as was the case of NPoMS (Ondir Freire and de Andrade 2019; Edwards 1979). The most notorious aspects of nuclear merchant ships operations were related to the port entry, to which permissions must have been obtained, sometimes with great difficulty. During negotiations related to the safety requirements, shipowners would sometimes withdraw their application should port authorities require the nuclear propulsion be disabled for the time of the port call. This was the case for Savannah and Otto Hahn, purpose of which was to demonstrate the NPoMS technology as a safe one (Edwards 1979). Without being restricted by commercial considerations as much as regular operators would be, neither Savannah or Otto Hahn could accept being deprived of their major purpose and creating a legal precedent. On other occasions, ports would simply not allow nuclear ships to enter (Schøyen and Steger-Jensen 2017). In order to bypass this approach, there were attempts of designing the NPoMS in such a way that it can be detached from the hull and left outside the territorial waters. By doing so, a merchant vessel would enter port under a conventional propulsion and would thus not fall within a complicated nuclear legal regime of a coastal state (Gravina et al. 2012). Similar concept was also raised in terms of maintaining diesel propulsion as a backup for nuclear one in case the latter fails, but having a redundancy in a form of two reactors was also deemed sufficient (Edwards 1979).

Similarly, up until July 2022 there is no legal standard for the design and operation of MASS, even though some prototypes are expected to enter into commercial operation soon. Preliminary guidelines have been published by several classification societies (DNV-GL 2018; Bureau Veritas 2019), but international goal-based Code is scheduled to be implemented by 2028 (IMO 2022). Until then, operations of MASS are left at a discretion of respective coastal states, just as it was with regards to nuclear-powered ones. This setup opened a path towards denying the latter an innocent passage on the grounds of nuclear safety concerns (Lowe 1977; IAEA 1968) in a pre-UNCLOS era. Similar concerns have also been raised in relation to MASS, although these are rather hypothetical considerations for the moment (Allen 2012; Chang, Zhang, and Wang 2020; Veal, Tsimplis, and Serdyc 2019) revolving around the question whether MASS is in fact a ship (Hasan 2022) and as such falls within UNCLOS Article 17. Nevertheless, it has been raised that coastal administrations may legally impose certain legal regime to govern the innocent passage and that such rules may effectively prevent autonomous navigation in territorial waters as well as port calls (Veal, Tsimplis, and Serdyc 2019).

Moreover, it is also reported that current international maritime legal regime contains numerous potential gaps impeding the introduction of MASS into the international trade (IMO MSC 2019). At least some of the legal instruments do not explicitly preclude crewless/autonomous navigation, but may be interpreted that way (Bačkalov 2020).

4.2 *Safety concerns*

NPoMS as well as MASS were originally seen as a way of improving safety at sea. High reliability of a nuclear propulsion (Ulken, Bianchi, and Kühl 1972; Carlton, Smart, and Jenkins 2011) as well as good safety record of military nuclear propulsion were just some of the arguments to support such belief.

As the experience was being gained with nuclear-powered ships operations and MASS research, it was realized that safety improvement expectations may not be easy to meet. Even though no significant nuclear accident had occurred within the merchant fleet, the technology itself proved to be vulnerable in other industries and within military. Although nuclear accidents are relatively rare events due to high technical standards employed (Strupczewski 2003), they do happen as they did on numerous occasions, just to name loss-of-coolant accident aboard NS Lenin and at least two criticality accidents on board Soviet submarines (Reistad, Mærli, and Bøhmer 2005). Consequences of such events are disastrous (Gravina et al. 2012) not only in terms of public health, but also financially. The risk of operating NPoMS may be objectively calculated as low (Folsom et al. 1955; Freire and Andrade 2015), but public does not necessarily see it this way. In particular, Japanese authorities are reported to have failed explaining the radiation leak incident properly (Nakao 1992). It has been clearly stated that the blurring of responsibility among certain parties involved in the design of the vessel and difficulties in interfacing between these were to blame for the incident (Schøyen and Steger-Jensen 2017; Freire and Andrade 2015).

Initially, MASS were also seen as a remedy for maritime accidents, mainly due to potential reduction of at least some of their causes related to human error, such as fatigue. Significant risk reductions were expected (Kretschmann et al. 2015). With the development of the technology and more research being conducted, it has been realized that MASS will not necessarily enjoy safety record as good as initially predicted (Wróbel, Montewka, and Kujala 2017). The ocean passage of Mayflower and problems encountered during it (Maritime Executive 2022) indicate that autonomous ships will be subject to 'childhood diseases'. Other safety-related issues also pertain to ambiguities of navigational situation and environment (Fan, Montewka, and Zhang 2022), situation awareness (Bogusławski, Nasur, et al. 2022), maintenance especially in the case of crewless ships (Pietrzykowski and Hajduk 2019; Bolbot, Theotokatos, and Wennersberg 2022), and remote communication (Wróbel et al. 2021). All in all, lack of quantitative data on MASS safety caused by small number of prototypes operational prevents the research and industry community from concluding on whether this technology will in fact improve safety at sea. Most likely, some setbacks will occur in initial phases of the its introduction to the industry, but the situation will improve with experience gained. Uncertainties comprise the levels of risk associated with early operations and their public acceptability (Goerlandt 2020; Porathe, Hoem, and Johnsen 2018).

Every new technology can potentially introduce new hazards. NPoMS comes with a risk of radioactive leaks (also resulting from non-nuclear accident such as collision or foundering (Edwards 1979)), meltdown, and proliferation. MASS-related hazards are primarily related to new ways of human-machine interactions, also known as 'ironies of automation' (Bainbridge 1983), as well as those stemming from a necessity to maintain real-time communication. Public acceptance is an important factor here, too. Perhaps, the key factor in the development of a technology beyond prototypes and demonstrators is whether the risk exposure in its early stages as perceived by a wider public was big enough to create a strong opposition. If that is the case, any technology beneficial to its stakeholders could develop only if its proponents could overcome the results of early-stage safety incidents. These had a great impact on NPoMS (especially NS Mutsu) but appear to lie ahead of MASS.

4.3 *Economic feasibility*

Contrary to military ships, merchant vessels serve a purpose of making money to their owner or operator. At a time Savannah was built, her upfront costs were estimated to be 2-3 times as much as those of a fuel-burning vessel of a similar size (Schøyen and Steger-Jensen 2017). The calculations were also referred to as 'uncertain' (Namikawa et al. 2011; Dade and Witzig 1974), especially when compared to a fluctuating cost of fossil fuels. Nevertheless, it was argued that NPoMS could reduce operational costs of the vessel due to: lower fuel price, better mobility (no need to make bunkering stops), and improved utilization of space within the hull (no bunker fuel tanks needed (Gravina et al. 2012), but at the expense of dedicating space and deadweight to carrying of containment, shielding etc.). All in all, it was concluded that merchant nuclear-powered ships may be a feasible option for operating larger ships (Panamax+ size) due to high capital costs (Freire and Andrade 2015) in relation to operational ones (Schøyen and Steger-Jensen 2017), economy of scale, and higher energy demand (Ondir Freire and de Andrade 2019). By 'economy of scale', the size of single reactor was understood rather than the number of reactors built, although the latter was also estimated quite optimistically at certain point (Dade and Witzig 1974). However, it was highlighted that there are uncertainties involved particularly pertaining to the costs and technical possibility of maintenance, refurbishments, salvage, and decommissioning of nuclear-powered ships (Schøyen and Steger-Jensen 2017; Gravina et al. 2012). High costs are also said to be associated with liability (Hardy 1963), protection and indemnity issues (Dade and Witzig 1974). Economical feasibility of NPoMS was simply too difficult to reliably calculate in an industry that (1) faced major challenges in calculating life-cycle costs and (2) competed against well-known although variable economics of fuel oils. Again, certain data could be drawn from military applications (Ondir Freire and de Andrade 2019), but the economics of military operations is different than this of commercial ones.

As for MASS, it is clear that their implementation depends on whether they can prove profitable (Tsvetkova and Hellström 2022). Contrary to NPoMS, profitability was in the spotlight from the beginning of the development of the technology in late 2010s. Numerous studies were performed to establish the economic feasibility of the technology. Eventually, it was concluded that MASS can be a profitable alternative to conventional vessels under certain market conditions (Kretschmann, Burmeister, and Jahn 2017; Kooij, Kana, and Hekkenberg 2021), within specific assumptions (Sandvik et al. 2021), and with a significant level of uncertainties. These are associated mainly with an early stage of the development towards autonomous vessels (Kretschmann, Burmeister, and Jahn 2017) and hardly take into account costs of exceptional events such as salvage (Suri and Wróbel 2022). However, it is accepted that economics of MASS will be associated with higher CAPEX in relation to conventional ships. This is due to a need for improved redundancy and additional equipment including sensors. On the other hand, reduction of crew costs as well as improved efficiency among other factors are expected to reduce OPEX. This effect can be reduced by an increase in costs related to the maintenance of the ship (Kretschmann, Burmeister, and Jahn 2017).

Regardless of the expenses side, neither NPoMS or MASS were ever expected to affect the earnings of the ship operators. This was associated with the fact that both concepts will compete for the cargo against their conventional counterparts, be it oil-powered ships or fully-crewed ones. From a business perspective, cargo owners would normally be directed by a price of moving their commodities from A to B, provided that such movement is carried out safely and on time. Technical specification of the vessel involved, that is her type of propulsion or degree of automation are of a secondary importance and do not justify a higher price by themselves. Operators of NPoMS or MASS would also have little incentive to offer significantly lower freight (Sandvik et al. 2021). The relatively small number of either NPoMS or MASS in relation to a global fleet especially in the beginning of their implementation would be unlikely to affect freight costs globally.

Therefore, the only chance for making both NPoMS and MASS economically feasible is by ensuring its life-cycle costs remain lower than those of conventional ships.

4.4 *Human element*

Human element has always been in the spotlight of the maritime industry. Its complexity include the recruitment and retention of workforce, training and related certification, crew-related costs, working conditions, and the effect seafarers have on the conduct of maritime operations.

Within the nuclear ships concept, it was predicted that special training and qualifications for seagoing crews would be needed to operate NPoMS (Hirdaris et al. 2014). For instance, it was argued that officers should be trained in radiation medicine in order to deal with potential emergencies and to monitor radiation doses absorbed by the crew. The complexity of reactor design and operation caused training costs especially of the engineering crew to be high and the training itself was rather lengthy (Dade and Witzig 1974). Moreover, compliment of engineering crew was higher than on conventional ships (Edwards 1979; Gravina et al. 2012) which would increase costs not only through a greater manpower but also through its high and unique competencies. As a matter of fact, at some point the NPoMS community raised several rather interesting concerns (Edwards 1979). Firstly, the quality of training for nuclear engineers was deemed so high that it could introduce self-complacency issues and promote an unacceptable level of experimentalism among the crews through underestimation of risk. Secondly, the industry was warned against reckless automatization of nuclear propulsion, which would promote reduction of highly-trained crews so badly needed in case of an incident.

With regard to human-machine interfaces, basic ergonomics issues were raised upon the review of the Savannah power plant design, including location of consoles and colors of indicating lamps to improve situation awareness (Ebasco Services Inc. 1960) before she was put into operation. Moreover, the importance of simulator training was highlighted particularly in dealing with emergencies, but it was also acknowledged that such training can under no circumstances replace hands-on experience completely (Edwards 1979).

Eventually, particular attention was paid to the issue of human error. In 1968, 38 of 59 (64%) reactor shutdowns (scram can be regarded as a near-miss in a safety terms) onboard Otto Hahn were attributed to it and 13 of 24 (54%) a year later. The proportion is reversed for NS Lenin (one of Soviet nuclear ice-breakers) were human error was at fault in 20 of 64 (31%) scrams (Edwards 1979).

Although the idea of autonomous ships was originally based on the concept of a complete elimination of human element from the system, this proved impossible. Crewless, autonomous, or conventional, ships will involve humans within a predictable time-frame. The only question is the scope and degree of human involvement. Without historical data available, it can be expected that the implementation of MASS will require changes to recruitment and retention policies (Bogusławski, Gil, et al. 2022) as well as training design (Lutzhoft et al. 2019; Pietrzykowski and Hajduk 2019; de Klerk, Manuel, and Kitada 2021; Kennard, Zhang, and Rajagopal 2022). With a reference to the latter, the ongoing discussion is also on the certification scheme for remote operators of ships (Kim et al. 2020) and whether individuals without practical experience gained at sea could be trusted with conning the vessel (Hogg and Ghosh 2016). Significant cost reductions are expected due to increased autonomy replacing costly seafarers that collect wages, must be fed and accommodated on board which consumes space available to store cargo. However, there are also non-trivial effects involved as raised in (Karlis 2018). Namely, global shortage of officers and a need to employ experiences ones may create a competition between traditional crewing agencies and remote control centers to attract suitable personnel. Cost reductions could then be achieved through making individual operator supervise or control several ships at a time (Kari and Steinert 2021), risking a loss of situation awareness.

4.5 *Attitudes of the industry*

Finally, reading the historical documents one could feel that the NPoMS were regarded as a truly disruptive technology back in 1960s and 1970s. Numerous scientific and industry conferences, legal instruments, etc. were focusing precisely on various aspects of nuclear-powered ships even though lack of new findings was acknowledged (Edwards 1979). An overall optimism could be seen in these documents, advocating that the scientific and technical effort was worth taking. The ultimate goal was to widely implement a technology that was regarded as safe, environmentally friendly, and economically feasible and to change the industry for better. Clearly, this never happened.

MASS appear to be in a similar point of development as of October 2022 that NPoMS was at the beginning of its journey. Various advancements of the technology are being announced either by academia or the industry, R&D projects are being funded to advance the progress, prototypes are put into operation, and ideas are being discussed in various community circles, from legal to technical. So far, no high-profile accident involving the technology has occurred that would undermine public trust.

At this point, with historical facts, similarities and differences discussed, questions can be asked whether the tale of nuclear merchant ships failed implementation can be related to the development of MASS. Can conclusions be drawn and potential setbacks averted?

5 DISCUSSION: LESSONS LEARNT

There are some striking similarities between NPoMS and MASS development. Both technologies were introduced to the maritime industry without a clear international legislation in place. This effect reduced operational capability of nuclear-powered ships and is a significant limitation for autonomous merchant vessels. Moreover, both technologies were advertised as economically feasible, but no solid evidence could be presented to support such statements. Similar case was also with regard to safety of the technologies that could not be proven to outpace that of traditional solutions.

On the other hand, failure of full-scale implementation of NPoMS can be analyzed in hindsight. As of 2022, the technology has not been brought back except for isolated applications in Russian Arctic and despite its potential to limit the shipping contribution to climate change. Contrary to NPoMS, development of MASS is an ongoing issue and one that is gaining momentum. Aside similarities, differences between NPoMS and MASS can also be found. The former was only relevant for changing isolated aspects of ships operations, that is their propulsion and fuel supply chain. MASS concept is likely to affect the entire industry to the extent dependent on actual implementation of the ideas. Moreover, MASS takes into account one thing that is crucial for any commercial activity, that is money, from the very beginning of their introduction.

The historical analysis of the development of nuclear propulsion of merchant ships and an analysis of the state-of-art in maritime autonomy allows for listing few lessons that can be learned:

1. Securing favorable legal environment is critical to the development of a disruptive technology in an industry as globalized as shipping. Difficulties and inabilities to obtain administrative permissions for entering ports were one of factors contributing to the failure of the operations of nuclear-powered ships. Uncertainties related to the legal regime also discouraged investors from involvement in the business projects burdened with significant capital costs that might not be allowed to come into operation.
   Legal instruments related to implementation of maritime merchant vessels are also under development as of July 2022. Numerous international legal conventions on maritime issues came into force since the peak of civil nuclear applications in shipping, clearing up some uncertainties that posed obstacles to them. However, prospective autonomous ships are facing legal uncertainty that is only now being addressed by governing bodies;
2. It is perceived safety that matters, not safety itself. Despite nuclear facilities at sea (including military ones) having a relatively good safety record, wider public recognizes risks associated with their operations and appears to apply a precautionary principle whenever possible. That is, to remain skeptical until proven otherwise. Voters unfamiliar with the shipping industry may easily associate nuclear propulsion with multiple risks otherwise non-existent and apply an emotional, skeptical approach (Slovic 1987).
   However, these out-of-trade individuals would hardly see difference in risk levels associated with degree of ship's autonomy. Again, it is a public perception of risk that matters rather than results of its quantitative and objective assessment (Slovic 1987). In turn, those that are in fact maritime professionals might be able to individually assess the risks more accurately, but still be bound by the opinions of a society they belong to;
3. Achieving economic sustainability or reliable prospects of it is crucial for a wide implementation of any technology. Meanwhile, the well-known 'valley of death' of innovations is often associated with uncertainties related to the future market circumstances (Ellwood, Williams, and Egan 2022).

These can only be limited by proving that the concept under development is sustainable in financial terms. NPoMS hardly had economical gains on the agenda and largely focused on other aspects of operations. With economics not being a top priority, uncertainties could not be reduced.

Meanwhile, up-front costs of some simplified analogues of MASS (Unmanned Surface Vehicles - USVs) used for non-commercial purposes is small and can help build up relevant financial models. The technology can also be implemented in an evolutional rather than revolutionary one as was the case of NPoMS. This means that some autonomy functions can be implemented one by one on different ships rather than the sudden and financially demanding removal of diesel engines and implementation of a nuclear reactor. Moreover, full-scale MASS prototypes that are being developed assume at least some financial gains over traditional vessels from the very beginning (Maritime Executive 2021). However, there is so far no evidence of the financial benefits in a life-cycle terms simply because the life-cycle has only just started.

6 CONCLUSIONS

The conducted review and analysis of technical and scientific documents revealed some parallels between the process of development of two potentially disruptive maritime technologies: nuclear propulsion and autonomy. The former held some prototypes as early as in 1960s with only one specimen operational as of late 2022. It did not become widely used due to variety of reasons, including politics, safety concerns, and uncertain financial benefits. The latter is on a rise but is also facing obstacles related to legal, safety, and financial concerns. The ability to overcome these on the part of the industry will be crucial for its successful implementation.

The analysis also allowed for elaborating certain ways of ensuring that the disruptive potential of Maritime Autonomous Surface Ships does not share the fate of merchant ships with nuclear propulsion. That is – oblivion or eccentricity, at best. Just as great hopes were placed on nuclear propulsion to solve some of the problems of the shipping industry, similar hopes are placed on autonomy today. In order to ensure that the technology is implemented successfully, its legal foundations must be secured along with financial benefits. It must also be proven beyond reasonable doubt and communicated to the public that safety of maritime transportation is not reduced in a process. By this, the objective of the study has been achieved.

Limitations of the performed analysis include the fact that only publicly available documents could be analyzed and conclusions based on these. It is possible that some documents especially on the nuclear propulsion of merchant vessels that would contradict the conclusions drawn could not be obtained.

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REFERENCES

Akbar, Abeera, Anna K. A. Aasen, Mohamed Kais Msakni, Kjetil Fagerholt, Elizabeth Lindstad, and Frank Meisel. 2021. " An Economic Analysis of Introducing Autonomous Ships in a Short - sea Liner Shipping Network. " International Transactions in Operational Research 28 (4): 1740–64. https://doi.org/10.1111/itor.12788.

Allen, Craig H. 2012. "The Seabots Are Coming Here: Should They Be Treated as Vessels?" Journal of Navigation 65 (4): 749–52. https://doi.org/10.1017/S0373463312000197.

Bačkalov, Igor. 2020. "Safety of Autonomous Inland Vessels: An Analysis of Regulatory Barriers in the Present Technical Standards in Europe." Safety Science 128 (October 2018). https://doi.org/10.1016/j.ssci.2020.104763.

Bainbridge, Lisanne. 1983. "Ironies of Automation." Automatica 19 (6): 775–79. https://doi.org/10.1016/0005-1098(83)90046-8.

Bergström, M, S Hirdaris, O A Valdez Banda, P Kujala, and O Sormunen. 2018. "Towards the Unmanned Ship Code." In Marine Design XIII, edited by Pentti Kujala, 881–86. Helsinki: Taylor & Francis Group.

Bogusławski, Krzysztof, Mateusz Gil, Jan Nasur, and Krzysztof Wróbel. 2022. "Implications of Autonomous Shipping for Maritime Education and Training: The Cadet's Perspective." Maritime Economics & Logistics 24 (2): 327–43. https://doi.org/10.1057/s41278-022-00217-x.

Bogusławski, Krzysztof, Jan Nasur, Jie Li, Mateusz Gil, Krzysztof Wróbel, and Floris Goerlandt. 2022. "A Cross-Domain Scientometric Analysis of Situational Awareness of Autonomous Vehicles With Focus on the Maritime Domain." IEEE Access 10: 50047–61. https://doi.org/10.1109/ACCESS.2022.3174097.

Bolbot, Victor, Gerasimos Theotokatos, and Lars Andreas Wennersberg. 2022. "A Method to Identify and Rank Objects and Hazardous Interactions Affecting Autonomous Ships Navigation." Journal of Navigation, May, 1–22. https://doi.org/10.1017/S0373463322000121.

Bureau Veritas. 2019. "Guidelines for Autonomous Shipping." Vol. NI 641 DT. Paris.

Carlton, J S, R Smart, and V Jenkins. 2011. "The Nuclear Propulsion of Merchant Ships: Aspects of Engineering, Science and Technology." Journal of Marine Engineering & Technology 10 (2): 47–59. https://doi.org/10.1080/20464177.2011.11020247.

Chang, Yen Chiang, Chao Zhang, and Nannan Wang. 2020. "The International Legal Status of the Unmanned Maritime Vehicles." Marine Policy 113 (January): 103830. https://doi.org/10.1016/j.marpol.2020.103830.

Dade, Thomas B., and Warren F. Witzig. 1974. "Container Ships: Oil Fueled versus Nuclear Powered." Nuclear Technology 22 (2): 196–223. https://doi.org/10.13182/NT74-A31403.

Danish Maritime Authority. 2017. "Analysis of Regulatory Barriers To the Use of Autonomous Ships." Copenhagen.

DNV-GL. 2018. "Autonomous and Remotely Operated Ships - Class Guideline." Høvik.

Ebasco Services Inc. 1960. "NS Savannah Nuclear Merchant Ship Design Review Summary Report." New York, NY. https://www.osti.gov/servlets/purl/4027498.

Edwards, J. 1979. "Report on the OECD Nuclear Energy Agency/International Atomic Energy Agence Symposium on the Safety of Nuclear Ships, Hamburg, 5-9 December 1977." Annals of Nuclear Energy 6: 25–58.

Ellwood, Paul, Ceri Williams, and John Egan. 2022. "Crossing the Valley of Death: Five Underlying Innovation

Processes." Technovation 109 (January): 102162. https://doi.org/10.1016/j.technovation.2020.102162.

Fan, Cunlong, Jakub Montewka, and Di Zhang. 2022. "A Risk Comparison Framework for Autonomous Ships Navigation." Reliability Engineering & System Safety, July, 108709. https://doi.org/10.1016/j.ress.2022.108709.

Folsom, R G, H A Ohlgren, J G Lewis, and M E Weech. 1955. "Nuclear Propulsion of Merchant Ships - an Engineering Summary." Ann Arbor.

Freire, Luciano Ondir, and Delvonei Alves de Andrade. 2015. "Historic Survey on Nuclear Merchant Ships." Nuclear Engineering and Design 293 (November): 176–86. https://doi.org/10.1016/j.nucengdes.2015.07.031.

Gabbar, Hossam A., Md. Ibrahim Adham, and Muhammad R. Abdussami. 2021. "Optimal Planning of Integrated Nuclear-Renewable Energy System for Marine Ships Using Artificial Intelligence Algorithm." Energies 14 (11): 3188. https://doi.org/10.3390/en14113188.

Goerlandt, Floris. 2020. "Maritime Autonomous Surface Ships from a Risk Governance Perspective: Interpretation and Implications." Safety Science 128 (February): 104758. https://doi.org/10.1016/j.ssci.2020.104758.

Gravina, Jonathan, James Blake, Ajit Shenoi, Stephen R. Turnock, and Spyros Hirdaris. 2012. "Concepts for a Modular Nuclear Powered Containership." In NAV International Conference on Ship and Shipping Research. Naples.

Hannaford, Elspeth, Pieter Maes, and Edwin Van Hassel. 2022. "Autonomous Ships and the Collision Avoidance Regulations: A Licensed Deck Officer Survey." WMU Journal of Maritime Affairs, no. 0123456789 (May). https://doi.org/10.1007/s13437-022-00269-z.

Hardy, Michael. 1963. "The Liability of Operators of Nuclear Ships." The International and Comparative Law Quarterly 12 (3): 778–88.

Hasan, Sabrina. 2022. "Analysing the Definition of 'Ship' to Facilitate Marine Autonomous Surface Ships as Ship under the Law of the Sea." Australian Journal of Maritime & Ocean Affairs 0 (0): 1–16. https://doi.org/10.1080/18366503.2022.2065115.

Hirdaris, S.E., Y.F. Cheng, P. Shallcross, J. Bonafoux, D. Carlson, B. Prince, and G.A. Sarris. 2014. "Considerations on the Potential Use of Nuclear Small Modular Reactor (SMR) Technology for Merchant Marine Propulsion." Ocean Engineering 79 (March): 101–30. https://doi.org/10.1016/j.oceaneng.2013.10.015.

Hogg, Trudi, and Samrat Ghosh. 2016. "Autonomous Merchant Vessels: Examination of Factors That Impact the Effective Implementation of Unmanned Ships." Australian Journal of Maritime & Ocean Affairs 8 (3): 206–22. https://doi.org/10.1080/18366503.2016.1229244.

IAEA. 1968. "Safety Considerations in the Use of Ports and Approaches by Nuclear Merchant Ships." Vienna. https://inis.iaea.org/collection/NCLCollectionStore/_Public/43/119/43119051.pdf.

———. 2004. "50 Years of Nuclear Energy." Vienna. https://www.iaea.org/sites/default/files/gc/gc48inf-4-att3_en.pdf.

IMO. 1981. Code of Safety for Nuclear Merchant Ships. London.

———. 2022. "Maritime Safety Committee (MSC 105), 20-29 April 2022." 2022. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MSC-105th-session.aspx.

IMO MSC. 2019. Regulatory Scoping Exercise for the Use of Maritime Autonomous Surface Ships. London: IMO MSC.

Kari, Raheleh, and Martin Steinert. 2021. "Human Factor Issues in Remote Ship Operations: Lesson Learned by Studying Different Domains." Journal of Marine Science and Engineering 9 (4): 385. https://doi.org/10.3390/jmse9040385.

Karlis, Thanasis. 2018. "Maritime Law Issues Related to the Operation of Unmanned Autonomous Cargo Ships." WMU Journal of Maritime Affairs 17 (1): 119–28. https://doi.org/10.1007/s13437-018-0135-6.

Kennard, Alice, Pengfei Zhang, and Sriram Rajagopal. 2022. "Technology and Training: How Will Deck Officers Transition to Operating Autonomous and Remote-Controlled Vessels?" Marine Policy 146 (1): 105326. https://doi.org/10.1016/j.marpol.2022.105326.

Kim, Mingyu, Tae-hwan Joung, Byongug Jeong, and Han-seon Park. 2020. "Autonomous Shipping and Its Impact on Regulations, Technologies, and Industries." Journal of International Maritime Safety, Environmental Affairs, and Shipping, June. https://doi.org/10.1080/25725084.2020.1779427.

Klerk, Yvette de, Michael Ekow Manuel, and Momoko Kitada. 2021. "Scenario Planning for an Autonomous Future: A Comparative Analysis of National Preparedness of Selected Countries." Marine Policy 127 (January): 104428. https://doi.org/10.1016/j.marpol.2021.104428.

Kongsberg. 2017. "YARA and KONGSBERG Enter into Partnership to Build World's First Autonomous and Zero Emissions Ship." 2017. https://www.km.kongsberg.com/ks/web/nokbg0238.nsf/AllWeb/98A8C576AEFC85AFC125811A0037F6C4?OpenDocument.

Konz, Peider. 1963. "The 1962 Brussels Convention on the Liability of Operators of Nuclear Ships." The American Journal of International Law 57 (1): 100–111.

Kooij, C, A A Kana, and R G Hekkenberg. 2021. "A Task-Based Analysis of the Economic Viability of Low-Manned and Unmanned Cargo Ship Concepts." Ocean Engineering 242 (May): 110111. https://doi.org/10.1016/j.oceaneng.2021.110111.

Kretschmann, Lutz, Hans-christoph Burmeister, and Carlos Jahn. 2017. "Analyzing the Economic Benefit of Unmanned Autonomous Ships: An Exploratory Cost-Comparison between an Autonomous and a Conventional Bulk Carrier." Research in Transportation Business & Management 25 (April): 76–86. https://doi.org/10.1016/j.rtbm.2017.06.002.

Kretschmann, Lutz, Hugh Mcdowell, Ørnulf Jan Rødseth, Bénédicte Sage Fuller, Helen Noble, and Jeffrey Horahan. 2015. "Maritime Unmanned Navigation through Intelligence in Networks - Quantitative Assessment." http://www.unmanned-ship.org/munin/wp-content/uploads/2015/10/MUNIN-D9-3-Quantitative-assessment-CML-final.pdf.

Kutsuna, Koji, Hideyuki Ando, Takuya Nakashima, Satoru Kuwahara, and Shinya Nakamura. 2019. "NYK's Approach for Autonomous Navigation – Structure of Action Planning System and Demonstration Experiments." Journal of Physics: Conference Series 1357 (October): 012013. https://doi.org/10.1088/1742-6596/1357/1/012013.

Lowe, A V. 1977. "The Right of Entry into Maritime Ports in International Law." San Diego Law Review 14 (3): 597–622.

Lutzhoft, M, A Hynnekleiv, J V Earthy, and E S Petersen. 2019. "Human-Centred Maritime Autonomy - An Ethnography of the Future." In Proceeding of MTEC/ICMASS 2019. Vol. 1357. Trondheim. https://doi.org/10.1088/1742-6596/1357/1/012032.

Mallam, Steven C., Salman Nazir, and Amit Sharma. 2020. "The Human Element in Future Maritime Operations – Perceived Impact of Autonomous Shipping." Ergonomics 63 (3): 334–45. https://doi.org/10.1080/00140139.2019.1659995.

Mannov, Adrienne, Tiago Fonseca, Jens-Uwe Schröder-Hinrichs, and Dong-wook Song. 2019. "Autonomous Ships: A New Paradigm for Norwegian Shipping." https://doi.org/10.21677/itf.20190715.

Maritime Executive. 2021. "An Early Look at ASKO's Autonomous Freight Ferries." 2021. https://maritime-executive.com/article/an-early-look-at-asko-s-autonomous-freight-ferry.

———. 2022. “Mayflower Autonomous Ship Completed Historic Atlantic Crossing.” 2022. https://maritime-executive.com/article/mayflower-autonomous-ship-completes-historic-atlantic-crossing.

Nakao, Masayuki. 1992. “Radiation Leaks from Nuclear Power Ship ‘Mutsu.’” Tokyo.

Namikawa, Shunichiro, Peter Hoffmann, Morten Maerli, and Erik Brodin. 2011. “Nuclear Powered Ships - Findings from a Feasibility Study.”

Nawrot, Justyna, and Zuzanna Pepłowska-Dąbrowska. 2019. “Revolution or Evolution? Challenges Posed by Autonomous Vessels for the National and International Legal Framework.” Comparative Law Review 25 (December): 239–55. https://doi.org/10.12775/CLR.2019.008.

NYT. 1970. “Japan’s First Computer-Run Large Tanker Ends Maiden Trip,” 1970.

Ondir Freire, Luciano, and Delvonei Alves de Andrade. 2019. “Economically Feasible Mobile Nuclear Power Plant for Merchant Ships and Remote Clients.” Nuclear Technology 205 (6): 766–80. https://doi.org/10.1080/00295450.2018.1546067.

Pietrzykowski, Z, and J Hajduk. 2019. “Operations of Maritime Autonomous Surface Ships.” TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation 13 (4): 725–33. https://doi.org/10.12716/1001.13.04.04.

Porathe, T, Å Hoem, and S Johnsen. 2018. “At Least as Safe as Manned Shipping? Autonomous Shipping, Safety and ‘Human Error.’” In Safety and Reliability–Safe Societies in a Changing World. Proceedings of ESREL 2018, edited by Stein Haugen, 417–25. Trondheim.

Reistad, Ole, Morten Bremer Mærli, and Nils Bøhmer. 2005. “RUSSIAN NAVAL NUCLEAR FUEL AND REACTORS.” The Nonproliferation Review 12 (1): 163–97. https://doi.org/10.1080/10736700500209171.

Rødseth, Ørnulf Jan, and Hans-Chritoph Burmeister. 2012. “Developments toward the Unmanned Ship.” In Proceedings of International Symposium Information on Ships–ISIS. Hamburg. http://www.unmanned-ship.org/munin/wp-content/uploads/2012/08/Rødseth-Burmeister-2012-Developments-toward-the-unmanned-ship.pdf.

Sandvik, Håkon Osland, David Sjödin, Thomas Brekke, and Vinit Parida. 2021. “Ihnerent Paradoxes in the Shift to Autonomous Solutions Provision: A Multilevel Investigation of the Shipping Industry.” Service Business, no. 0123456789. https://doi.org/10.1007/s11628-021-00458-5.

Schøyen, Halvor, and Kenn Steger-Jensen. 2017. “Nuclear Propulsion in Ocean Merchant Shipping: The Role of Historical Experiments to Gain Insight into Possible Future Applications.” Journal of Cleaner Production 169 (December): 152–60. https://doi.org/10.1016/j.jclepro.2017.05.163.

Slovic, Paul. 1987. “Perception of Risk.” Science 236 (4799): 280–85. https://doi.org/10.1126/science.3563507.

Strupczewski, A. 2003. “Accident Risks in Nuclear-Power Plants.” Applied Energy 75 (1–2): 79–86. https://doi.org/10.1016/S0306-2619(03)00021-7.

Suri, Mayank, and Krzysztof Wróbel. 2022. “Identifying Factors Affecting Salvage Rewards of Crewless Vessels — Lessons from a Case Study.” WMU Journal of Maritime Affairs 21 (2): 213–32. https://doi.org/10.1007/s13437-022-00276-0.

Tesla, Nikola. 1898. Method of and apparatus for controlling mechanism of moving vessels or vehicles. 613809, issued 1898.

Tsvetkova, Anastasia, and Magnus Hellström. 2022. “Creating Value through Autonomous Shipping: An Ecosystem Perspective.” Maritime Economics & Logistics 24 (2): 255–77. https://doi.org/10.1057/s41278-022-00216-y.

Ulken, D, H Bianchi, and H Kühl. 1972. “Technical Operation Experiences of the NS Otto Hahn and Problems of Port Entry.” In Symposium on Nuclear Ships. Rio de Janeiro.

UNCTAD. 2020. Review of Maritime Transport 2020. Geneva: United Nations Publications.

Veal, Robert, Michael Tsimplis, and Andrew Serdyc. 2019. “The Legal Status and Operation of Unmanned Maritime Vehicles.” Ocean Development and International Law 50 (1): 23–48. https://doi.org/10.1080/00908320.2018.1502500.

Wahlström, Mikael, Jaakko Hakulinen, Hannu Karvonen, and Iiro Lindborg. 2015. “Human Factors Challenges in Unmanned Ship Operations – Insights from Other Domains.” In 6th International Conference on Applied Human Factors and Ergonomics, 3:1038–45. Elsevier B.V. https://doi.org/10.1016/j.promfg.2015.07.167.

Wasilewski, Wiesław, Katarzyna Wolak, and Magdalena Zaraś. 2021. “Autonomous Shipping. The Future of the Maritime Industry?” Zeszyty Naukowe Małopolskiej Wyższej Szkoły Ekonomicznej w Tarnowie 51 (3): 155–63. https://doi.org/10.25944/znmwse.2021.03.155163.

Wright, R. Glenn. 2020. Unmanned and Autonomous Ships - An Overview of MASS. Abingdon: Routledge.

Wróbel, Krzysztof. 2021. “Searching for the Origins of the Myth: 80% Human Error Impact on Maritime Safety.” Reliability Engineering & System Safety 216 (December): 107942. https://doi.org/10.1016/j.ress.2021.107942.

Wróbel, Krzysztof, Mateusz Gil, Przemysław Krata, Karol Olszewski, and Jakub Montewka. 2021. “On the Use of Leading Safety Indicators in Maritime and Their Feasibility for Maritime Autonomous Surface Ships.” Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, July, 1748006X2110276. https://doi.org/10.1177/1748006X211027689.

Wróbel, Krzysztof, Mateusz Gil, and Jakub Montewka. 2020. “Identifying Research Directions of a Remotely-Controlled Merchant Ship by Revisiting Her System-Theoretic Safety Control Structure.” Safety Science 129 (September): 104797. https://doi.org/10.1016/j.ssci.2020.104797.

Wróbel, Krzysztof, Jakub Montewka, and Pentti Kujala. 2017. “Towards the Assessment of Potential Impact of Unmanned Vessels on Maritime Transportation Safety.” Reliability Engineering & System Safety 165: 155–69. https://doi.org/10.1016/j.ress.2017.03.029.

Ziajka-Poznańska, Ewelina, and Jakub Montewka. 2021. “Costs and Benefits of Autonomous Shipping—A Literature Review.” Applied Sciences 11 (10): 4553. https://doi.org/10.3390/app11104553.

Атомфлот. n.d. “АТОМНЫЙ КОНТЕЙНЕРОВОЗ «СЕВМОРПУТЬ».” Accessed July 8, 2022. http://www.rosatomflot.ru/flot/atomnyy-lihterovoz-sevmorput/.