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Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications

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ABSTRACT

Global marine shipping annually accounts for about one billion tonnes of CO_2 equivalent greenhouse gas emissions. Nuclear power propulsion may be an option to de-carbonise some niches of the merchant ocean fleet. This paper considers the three experimental nuclear-powered merchant ships launched and operated in the world so far; the iconic *Savannah* (USA), *Otto Hahn* (West Germany) and *Mutsu* (Japan). They were independently developed and operated in the 1960s and 1970s for technology demonstration and learning. A fourth ship, *Sevmorput* (Soviet Union/Russia, 1988–to date), is a pioneer in respect of its logistics functions and propulsion system. This paper develops a theoretical framework for the sustainability assessment of nuclear propulsion in ocean merchant shipping and presents a method for exploring nuclear propulsion, relative to flag state, ports, shipping resources and ocean transport services. The experimental ships' transport efficiency is discussed and related to contemporary oil-fired shipping of general cargo, and to recent literature presenting possible future applications of merchant nuclear propulsion in some market niches. Insights provided include: (1) the experiments demonstrate that merchant nuclear propulsion may be technically feasible; (2) port and canal access for merchant nuclear-powered ships may be difficult and restricted; (3) the up-front costs, refuelling and end-of-life decommissioning costs of nuclear-powered ships are vast and uncertain against conventionally-powered ships; (4) because nuclear fuel is comparatively low-cost, the conventional oil-fired ship cost implications of high-speed operations do not apply.

1. Introduction

Global marine shipping annually accounts for about one billion tonnes or 2.8% of the global man-made CO_2 equivalent greenhouse gas (GHG) emissions, combining CO_2, CH_4 and N_2O (IMO, 2014). The demands for maritime transport, and with that GHG-emissions, are envisaged to increase considerably in the coming decades (IMO, 2014). The shipping sector also uses low-quality, polluting fossil fuels - mainly heavy fuel oil (HFO) - and is responsible for about 12% of SO_x and for 13% of NO_x global man-made emissions (IMO, 2014). Emissions include toxic metals (V, Ni etc.) as well as airborne particulate matter (PM), with detrimental health effects (Corbett et al., 2007; Oeder et al., 2015). However, de-carbonising and greening ocean shipping implies a move away from fossil fuels. Over the longer term, the maritime industry seeks to reduce pollution from ships (Eide et al., 2013; Royal Academy of Engineering, 2013). Nuclear propulsion represents one technology that could de-carbonise shipping, as it is the only technology for ocean-going ships where propulsion power generation emits zero CO_2, CH_4, NO_x, SO_x and PM (Eide et al., 2013). This technology deserves to be studied more carefully although small emissions of air pollutants may arise due to the use of fossil fuels in the extraction, processing and handling of nuclear fuel (Vergara et al., 2012).

Three experimental nuclear merchant ships have been built so far: *Savannah*, *Otto Hahn* and *Mutsu*. They were independently developed in the 1960s for technology demonstration and learning (Freire and de Andrade, 2015). A fourth ship, *Sevmorput*, is still in service, and is a pioneer in respect of its logistics functions and nuclear propulsion system (Freire and de Andrade, 2015). These four ships, shown in Table 1, are hereinafter referred to as the experiments. This paper examines the outcomes of these experiments.

Nuclear merchant propulsion applications are a potential future

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Table 1
Experiments: Ship name, flag state, period and objective. Compiled from: Donnelly, 1965; Nakao, 1992; Khlopkin and Zotov, 1997; Freire and de Andrade, 2015; PortNews, 2016.

Ship name and flag state	Period of nuclear powered operation	Objective
Savannah USA	1962–1972	Part of president Eisenhower's civil 'Atoms for peace' program. Demonstrator and laboratory ship to study design, operation and manning
Otto Hahn West Germany	1968–1979	Research ship with the primary purpose of gaining experience on future nuclear ships for transport
Mutsu Japan	1974 1991–1992	Prototype commercial ship for transport of special cargoes and crew training
Sevmorput Soviet Union/Russia	1988-to date	Container and lighter aboard ship (LASH) for cargo freight and icebreaking in remote Arctic areas

pathway in some ocean shipping niches to cut air emissions and/or to provide higher-speed ocean freight services for some high-value cargoes (Vergara and McKesson, 2002; DNV, 2010; Carlton et al., 2011; Eide et al., 2013; Royal Academy of Engineering, 2013; Hirdaris et al., 2014). There is considerable potential push from both military nuclear propulsion applications in USA, the UK, France, Russia, China and India (Hirdaris et al., 2014; Moore, 2015; World Nuclear Association, 2016), and from developing on-shore nuclear power stations (Kessides, 2012; Brook and Bradshaw, 2015; Mu et al., 2015; Rowinski et al., 2015).

This paper extends the literature on ship-owning and propulsion technology. Specifically, it explores the role of the experiments and how the interplay between shipping, port and civilian nuclear industry actors and societal stakeholders can be addressed, for the purpose of assessing the challenges and achievability of nuclear propulsion in merchant ocean shipping. The research questions are:

(1) Are there lessons that can be learned from the experiments relative to sustainable ocean merchant shipping? If so, what are they?
(2) How do these experiments relate to possible future nuclear applications in ocean merchant shipping?

The unit of analysis is the shipowner (private/public/hybrid), seen as the investor and provider of logistic transport services, for long-term strategic decisions on fleet composition.

The contribution of this paper to the sustainable developments research literature is clear; it is the first to examine the role of the experiments within a theoretical framework on sustainable ocean shipping. The backdrop to this study is the current situation facing long-haul shippers and ocean carriers of continued slow speed (@12–22 knots) for ocean transport services (as described in Bows-Larkin et al., 2015). Significantly, it is not the objective of this paper to advocate or predict merchant nuclear propulsion as such, but to provide insight into the use of experimental civilian ships so far, as well as the nuclear potentials in the coming decades, including some considerations for supply chains. Experience shows that the time taken by the shipping industry to adopt new propulsion technologies varies (Henning and Trace, 1975; Geels, 2002; Mendonça, 2013).

The next section develops a theoretical framework. Section 3 devises a method to explore nations, ports, cargoes and routes of merchant nuclear propulsion. Section 4 employs the two previous sections to shed light on the role of the experiments. Section 5 further reflects upon the experiments' transport and CO_2 emission efficiencies, with regard to their historical contexts, contemporary oil-fired shipping and recent literature on potential applications of merchant nuclear propulsion. Section 6 provides a discussion on whether these kinds of experiments should be encouraged. Conclusions and implications are presented in Section 7.

2. Theoretical framework for the sustainability assessment of nuclear propulsion in ocean merchant shipping

The analytical framework developed in this paper assesses the role of the experimental ships and places them in their historical contexts. It relates them to some sectors of contemporary ocean shipping and to the recent literature on nuclear merchant marine applications. It is based on three dimensions. The first dimension deals with the supply chain that is linked to technological niches as unstable sociotechnical configurations in sociotechnical landscapes, evolving slowly over decades. A supply chain can be considered as a series of events including materials conversions, assembling, disassembling, transport and placements (Branch, 2007). Shipping and ports can be seen as supply chain transport service providers (Stopford, 2009; Panayides and Song, 2013). The second dimension reflects the evolution of a maritime regulatory system for governing ocean shipping. The third dimension deals with the life-cycle approach to nuclear civilian propulsion.

2.1. Sustainable supply chain management (SSCM)'s impact on innovations in merchant propulsion

Seuring and Müller (2008) claim that habitual triggers for SSCM are external pressures and incentives on a focal company set by governing agencies, customers and stakeholders. Levels of pressures and incentives can be categorized under: Legal demands, customer demands, response to stakeholders, competitive advantage, environmental and social pressure groups as well as reputational loss (Ciliberti et al., 2008; Seuring and Müller, 2008). In a possible emergence of SSCM practices, the focal company commonly has to take a wider range of issues and a greater part (or life-cycle) of the supply chain into account than what is normally needed for pure economic reasons (Seuring and Müller, 2008; Kovács, 2008). Additionally, variations and possible disruptions to societal demand linked to merchant propulsion may play a significant role; for instance differences in societal demands between flag and port states if they were to host nuclear-powered merchant ships.

2.2. The maritime regulatory system

The current framework of international law has been accomplished by means of international conventions developed by United Nation's International Maritime Organization (IMO) and International Labour Organization (ILO) (Stopford, 2009). IMO has established certain emission control areas (ECA) with more stringent controls on SO_x and NO_x emissions (IMO, 2014). According to Lister et al. (2015) and van Leeuwen (2015), IMO lacks effective implementation of existing international conventions, which results in a situation of growing regulatory fragmentation - e.g. regional regulations - and uncertainty. IMO in 1981 adopted Resolution A.492 (XII), Code of Safety for Nuclear Merchant Ships, but this has not yet been implemented. There are at present no standards for the design, operation and development of nuclear merchant ships (Royal Academy of Engineering, 2013). Although sea-mode shipments of radioactive materials and waste from nuclear power

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