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AN ANALYSIS OF SUBMARINE AIR INDEPENDENT PROPULSION TECHNOLOGIES AS A SOLUTION TO CANADIAN ARCTIC SOVEREIGNTY CONCERNS

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JCSP 44

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SERVICE PAPER

ÉTUDE MILITAIRE

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CANADIAN FORCES COLLEGE – COLLÈGE DES FORCES CANADIENNES
JCSP 44 – PCEMI 44
2017 – 2018

SERVICE PAPER - ÉTUDE MILITAIRE

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Word Count: 2577

Compte de mots: 2577

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AIM

1. The aim of this service paper is to investigate the feasibility of technologies for non-nuclear air independent propulsion (AIP) of diesel-electric submarines as a potential means of addressing the current gap in Canadian undersea operations in the Arctic. In order to fulfill this aim, a brief overview of available, proven AIP technologies in use by the navies of other nations will be provided. Additionally, an analysis of Canadian defence policy and goals for Arctic operations will be provided in order to present further context within which to make a decision regarding the use of AIP capable submarines for Canadian under-ice operations.

INTRODUCTION

2. As climate change leads to increased accessibility in the Arctic, the fields of research, tourism, and commercial activity are all expected to increase in the coming decades.[1] The approximately 5.4 million square kilometers of Arctic territory in Canada's North will present significant challenges in exercising sovereignty, as well as responding to environmental and search & rescue operations.[2] Canada must be ready to respond to the expected increase in Arctic

[1] Canada, Department of National Defence, "Strong, Secure, Engaged: Canada's Defence Policy," Ottawa: 7 June 2017, 51.

[2] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 124.

activity. Strong, Secure, Engaged (SSE) identifies that the largest challenges relating to Arctic activity will be search and rescue missions and disaster response.[3]

3. SSE also identifies the need to defend North America in partnership with the United States. This will require modernized partnerships, such as NORAD, and increased collaboration to provide better situational awareness in the Arctic.[4] SSE calls for an approach to surveillance in the Arctic that is not only collaborative, involving the US as a key partner, but also integrated, combining inputs from land, sea, air, and space systems.[5]

4. As a major strategic chokepoint, the Greenland-Iceland-United Kingdom (GIUK) gap is heavily monitored by US and NATO forces.[6] This monitoring turns the Davis Strait and passages between Canadian Artic islands into alternative pathways for non-allied submarine operations.[7] Canadian sovereignty over Arctic waters implies a national responsibility to provide monitoring of these passages.[8] However, following the end of the Cold War, Arctic submarine activity has decreased significantly; especially on the part of Russian forces. With this decreased submarine activity, the majority of required monitoring will be of economic activity conducted by surface vessels.[9]

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[3] Canada, Department of National Defence, "Strong, Secure, Engaged: Canada's Defence Policy," Ottawa: 7 June 2017, 51.

[4] *Ibid.*, 82-83.

[5] *Ibid.*, 80.

[6] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 123.

[7] Canada, House of Commons, "The Canadian Submarine Acquisition Project," Ottawa: August 1988, 22.

[8] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 124.

[9] *Ibid.*, 120.

5. Submarines provide an outstanding platform for conducting maritime surveillance. However, there are significant challenges when conducting submarine operations in the Arctic. The *Victoria*-class, as a conventional diesel-electric submarine, is not capable of conducting under-ice operations.[10] The US Navy has conducted under-ice submarine operations using nuclear powered submarines (SSNs) since the 1950s.[11] Nuclear power provides the ability to remain submerged for durations limited only by the food stores carried onboard, and ultimately human endurance.

6. Unfortunately, the development or procurement of a Canadian SSN is currently not a politically viable option. As a result, Canada is left with two possible options in the pursuit of Artic surveillance and sovereignty operations. The first is to develop or acquire non-nuclear AIP-capable submarines. The second is to rely on the US Navy to continue to fill this capability gap, choosing instead to focus Canadian efforts on other aspects of a collaborative, integrated approach to monitoring and controlling the Arctic.

DISCUSSION

7. There are several available and proven AIP technologies. For the technologies presented below, the only limiting factor for endurance is the amount of fuel and oxidizer carried onboard.[12] In order to achieve an endurance of two weeks at six knots, a total AIP-system output of approximately 300-400 kilowatts (kW) is required, in combination with a 1000 MW-hour

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[10] Canada, Royal Canadian Navy, "Victoria Class Submarine Interim Concept of Employment Guidance," Ottawa: 28 May 1999, B-6/12, 2.3.2.

[11] William M. Leary, *Under Ice: Waldo Lyon and the development of the Arctic submarine,* College Station: Texas A&M University Press (1999), 186-187.

[12] Konstantinos Psallidas, Clifford Whitcomb and John Hootman, "Design of Conventional Submarines with Advanced Air Independent Propulsion Systems and Determination of Corresponding Theater-Level Impacts," *Naval Engineers Journal*, 1. (2010): 113.

storage battery. Only 60-75 kW are required for propulsion, and the remainder is needed for hotel loads.[13] Further analysis would be required in the design and procurement phases; however, these values serve as a baseline for an initial assessment of available technologies.

8. At present, there are four primary AIP technologies in service with different navies throughout the world. Any these four technologies could be adapted for use in Canadian submarines, either through a retrofit of the existing *Victoria*-class, or more likely through a new construction project. A significant advantage of doing so during new construction would be a considerable cost savings. Implementation during new construction also offers the advantage of being able to account for other design changes that would be required.

Current AIP Technology

Closed-Cycle Diesel

9. The closed-cycle diesel (CCD) system operates by utilizing the standard diesel engine found on a conventional submarine in order to generate electricity and charge the battery bank. During CCD operations, the engine is operated without having access to the atmosphere.[14] This requires the creation of an artificial atmosphere to support combustion. The exhaust gases are recycled and combined with an inert gas to serve as the basis of this artificial atmosphere, to which pure oxygen must be added.[15] Carbon dioxide and other exhaust products are systematically removed from the false atmosphere through the use of seawater scrubbers.[16]

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[13] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 173.

[14] Lesley Ullyett, "Air independent propulsion: the new generation submarine threat," *Exercise Leonardo da Vinci.* (1992): 5.

[15] K.A. Heemskerk, "Air-independent Propulsion for Submarines: A Canadian Perspective," *Maritime Engineering Journal,* October (1991): 9.

[16] *Ibid.,* 7.

10. CCD systems offer several advantages, the most significant being the ability to utilize existing submarine diesel engines. This leads to dramatically lower infrastructure costs compared to other available technologies.[17] Utilizing proven diesel engines also contributes to high reliability.[18] Another advantage is the ability to switch between open-cycle and closed-cycle modes of operation. This provides the ability to conserve stored fuels when possible to greatly extend the operational length of reserves held onboard.[19] However, the usefulness of this ability during under-ice operations would be limited due to limited opportunities to access the atmosphere.

11. There are also some significant disadvantages of CCD systems, including the need for storing oxygen and inert gas, as well as high wear rates caused by the intake of highly corrosive combustion products.[20] Initial wear rates utilizing CCD were extremely high, but the use seawater scrubbing has largely addressed this problem.[21] The last issue requiring attention is the high generated noise as compared to other AIP technologies.[22] The impact of this limitation would require further analysis regarding the method of employment and design requirements for under-ice submarine operations.

[17] Lesley Ullyett, “Air independent propulsion: the new generation submarine threat,” *Exercise Leonardo da Vinci.* (1992): 5-6.

[18] K.A. Heemskerk, “Air-independent Propulsion for Submarines: A Canadian Perspective,” *Maritime Engineering Journal,* October (1991): 7.

[19] Lesley Ullyett, “Air independent propulsion: the new generation submarine threat,” *Exercise Leonardo da Vinci.* (1992): 5-6.

[20] *Ibid.,* 6.

[21] K.A. Heemskerk, “Air-independent Propulsion for Submarines: A Canadian Perspective,” *Maritime Engineering Journal,* October (1991): 7.

[22] *Ibid.,* 7.

Stirling Engine

12. The Stirling engine is an external combustion engine, and it has the longest history of use for AIP in submarines. It was first used full-scale by the Royal Swedish Navy in 1988, and they have continued refining their systems since that time. As an external combustion engine, it functions through the use of a working fluid, which is typically an inert gas, contained inside of a heat exchanger. As the working fluid is heated, it expands and is forced into the second chamber of the heat exchanger. Work is extracted by harnessing the volumetric changes of the working fluid.[23]

13. Stirling engines offer the advantage of a long history of use within submarine applications, making it a truly proven technology. Additionally, the external combustion process allows a great deal of flexibility when choosing the fuel source. The Swedish applications of Stirling engines use diesel fuel, since it is already carried onboard for normal diesel engine operation. As with other AIP systems, liquid oxygen (LOX) must be carried onboard to support the combustion process.[24]

14. Another advantage of Stirling engines over internal combustion engines is a reduced sound signature However, they do suffer from low efficiencies. Additionally, the engines operate at extremely high temperatures. Typical combustion chamber temperatures are in excess of 750°C. This can cause problems with materials failure and combustion. These issues are partially mitigated through the use of low-sulfur diesel fuel. A substantial design consideration in employing this technology is a low power output per unit. The typical output of the Sterling

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[23] *Ibid.,* 7.

[24] K.A. Heemskerk, "Air-independent Propulsion for Submarines: A Canadian Perspective," *Maritime Engineering Journal,* October (1991): 7.

engine employed in Swedish submarines is only 75 kW. While this limitation can easily be overcome through the use of additional units working simultaneously, the obvious trade-off is additional required storage space.[25]

Steam Turbine (MESMA)

15. The French-designed MESMA (*Molule d'Energie Sous-Marine Autonome*) utilizes stored ethanol and LOX which are combined in a combustion chamber in order to heat a steam generator.[26] As in a conventional steam plant, the produced steam is used to drive a turbine that powers an electrical generator.[27] The combustion gases, which are maintained a separate loop from the steam system, are discharged overboard at pressures up to approximately 60 bar.[28] MESMA is designed to be installed either in new constructions and it is also available as a stand-alone unit that can be retrofitted into existing platforms.[29] The current system is engineered to provide power across a range of 150-600 kW and is in use on submarines of the Pakistani Navy.[30]

16. Although MESMA is quieter than CCD, the reciprocating machinery in the system does still create a significant level of noise.[31] The most significant disadvantage is the low efficiency;

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[25] *Ibid.,* 7.

[26] Peter Hauschildt, Lars Larsson and Ezio Bonsignore, "Air-Independent Propulsion for Submarines," *Military Technology*, 27, no. 8/9 (2003): 99.

[27] *Ibid.,* 99.

[28] Gerd Wursig, Lorenz Petersen and Lloyd Germanischer, "AIP-Technologies for Submarines: Some basic design aspect related to fuel and LOX storage," *Naval Forces,* 24, no. 5 (2003): 128.

[29] Antony Preston, "Non-nuclear Submarine Propulsion," *Armada International,* 24, no. 5 (2000): 70.

[30] Peter Hauschildt, Lars Larsson and Ezio Bonsignore, "Air-Independent Propulsion for Submarines," *Military Technology*, 27, no. 8/9 (2003): 99.

[31] *Ibid.,* 102.

at only 20-25%, it provides the lowest efficiency of all available technologies.[32] However, this system does provide a large power output and ease of integration due to its modular design.[33]

Fuel Cell

17. One of the most promising AIP-technologies is the electrolytic fuel cell. The most popular of these are polymer electrolyte membrane (PEM) units, such as those installed on German Type 212 submarines.[34] Fuel cells operate by combining oxygen and hydrogen and collecting the released energy.[35] This process is nearly silent since there are no moving parts, it operates at low temperatures of about 80°C, and the only waste product is water.[36] Fuel cells are also extremely efficient, especially when operated at partial loading.[37] At 10% loading, a peak efficiency of approximately 70% can be achieved, compared to typical peak values of 25-35% for other AIP-systems.[38] Fuel cell systems also offer the advantage of great flexibility; additional units can be added in series and parallel in order to achieve the desired output.[39]

18. The Canadian company Ballard constructed a 50 kW fuel cell prototype and was contracted to develop a 400 kW unit for use in submarines.[40] However, Maritime Command failed to renew the contract in 2003, leading to cancellation of the project.[41] The exact

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[32] *Ibid.,* 102.
[33] *Ibid.,* 99.
[34] Antony Preston, "Non-nuclear Submarine Propulsion," *Armada International,* 24, no. 5 (2000): 66.
[35] Thomas Kreck, "Energy from AIP-systems," *Naval Forces,* 21, no 6 (2000): 12.
[36] Antony Preston, "Non-nuclear Submarine Propulsion," *Armada International,* 24, no. 5 (2000): 66.
[37] *Ibid*., 66.
[38] K.A. Heemskerk, "Air-independent Propulsion for Submarines: A Canadian Perspective," *Maritime Engineering Journal,* October (1991): 11.
[39] Thomas Kreck, "Energy from AIP-systems," *Naval Forces,* 21, no 6 (2000): 13-14.
[40] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 177.
[41] Peter Hauschildt, Lars Larsson and Ezio Bonsignore, "Air-Independent Propulsion for Submarines," *Military Technology*, 27, no. 8/9 (2003): 103.

circumstances of this contract are outside the scope of this paper, but further investigation into the matter would be required prior to proceeding with the procurement of fuel cell AIP technologies.

Additional Required Improvements

19. In addition to changes to the propulsion system, there are a large number of other changes required to enable a submarine to conduct under-ice operations. For example, the US-design *Los Angeles*-class was not initially designed for under-ice operations, and required significant modifications once the need for this capability was identified. These changes included alterations to the diving planes, added hardening of the sail and exposed sonar systems, the installation of ice-detection sonars, and improved navigation and communications equipment.[42] Similarly, a partial list of modifications for the *Victoria*-class would include alterations to the mast, fin, hull, weapons, and life support systems.[43] If new construction was chosen over retrofitting the *Victoria*-class, the new design would also have to incorporate considerations for all of these systems. Additionally, since all presented AIP technologies utilize LOX, storage facilities and infrastructure would be required.[44] These facilities would have need to be near operational areas to prevent the loss of LOX through boil-off during transit.[45]

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[42] William M. Leary, *Under Ice: Waldo Lyon and the development of the Arctic submarine,* College Station: Texas A&M University Press (1999), 255.

[43] Canada, Royal Canadian Navy, "Victoria Class Submarine Interim Concept of Employment Guidance," Ottawa: 28 May 1999, B-6/12, 2.3.2.

[44] *Ibid.,* 128-129.

[45] K.A. Heemskerk, "Air-independent Propulsion for Submarines: A Canadian Perspective," *Maritime Engineering Journal,* October (1991): 13-14.

Canadian Submarine Employment

20. According to the Interim Concept of Employment, the maximum theoretical platform availability for the Victoria class is 280-300 days per year per submarine. This availability presents an operational schedule that is in excess of anticipated available resources for employment.[46] A theoretical employment schedule for four Canadian submarines could include one submarine undergoing intensive maintenance, one operational submarine in the Northwest Atlantic, one in the Northeast Pacific, and one available for contingencies.[47] In order to exercise Arctic sovereignty, this third operational submarine would need to be employed in the Arctic.

21. Utilizing the third operational submarine for Arctic operations presents two distinct but connected problems. The first relates to the effectiveness of using one ship to cover the vast area of the Canadian Arctic (over 5.4 million square kilometers).[48] Undoubtedly, this would not result in sufficient surveillance of the entire area. The second problem this would create is the resulting inability for operational flexibility that allows Canadian submarines to remain "Engaged in the world" on dynamic missions.[49] Relying on the submarine fleet for Arctic sovereignty would risk the submarine fleet becoming relegated solely to under-ice operations.[50]

22. There is another problem associated with the use of submarines to exercise Arctic sovereignty. Navies are excellent tools for protecting sovereignty and responding to maritime

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[46] Canada, Royal Canadian Navy, "Victoria Class Submarine Interim Concept of Employment Guidance," Ottawa: 28 May 1999, B-10/12, 6.3.2.

[47] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 203.

[48] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 124.

[49] Canada, Department of National Defence, "Strong, Secure, Engaged: Canada's Defence Policy," Ottawa: 7 June 2017, 14.

[50] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 140.

crises.[51] Although Canadian submarines have previously conducted sovereignty operations against commercial fishing vessels, such as during the Turbot War, the visible presence offered by surface vessels would be a more effective tool in this situation.[52] Submarines are extremely capable tools for a myriad of naval functions, but are not particularly well-suited to sovereignty operations involving non-military forces.

Alternatives to Submarine Operations

23. There are means of exercising sovereignty in the Arctic other than under-ice submarine operations which merit consideration. One of the key investments in the Royal Canadian Navy (RCN) as identified in SSE is the procurement of five or six Arctic Offshore Patrol Ships (AOPS) that are ice-capable.[53] The AOPS will be used to conduct armed surveillance in "Canadian waters, including in the Arctic."[54] If utilized in its intended role, the AOPS will provide a viable alternative for exercising sovereignty in the Arctic. Additionally, a surface vessel such as the AOPS would be better suited for search and rescue or disaster response missions.

24. Satellite surveillance systems present another alternative to under-ice operations. These systems offer widespread coverage, but have significant limitations. Subsurface detection capabilities are not yet available. Adverse weather conditions, which are common in the Arctic, can prevent information gathering. Monitoring Arctic latitudes requires polar-orbit satellites;

[51] *Ibid.*, 65.
[52] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 205.
[53] Canada, Department of National Defence, "Strong, Secure, Engaged: Canada's Defence Policy," Ottawa: 7 June 2017, 108.
[54] *Ibid.*, 35.

geostationary surveillance systems can not be used. The polar-orbit used by RADARSAT has a revisit time of three days, which prevents conducting real-time surveillance. Finally, the cost of these platforms is also prohibitively expensive. One RADARSAT satellite costs approximately the same as four new *Victoria*-class submarines.[55]

25. Perhaps the most promising option as an alternative to under-ice operations is the implementation of an undersea surveillance system, such as the US-operated SOSUS array.[56] A fixed array such as this could provide continuous monitoring of a large portion of the Arctic for both surface and subsurface contacts. An experimental array, the Canadian Arctic Underwater Sentinel Experiment (CAUSE) is currently being developed.[57]

CONCLUSION

26. Canada must make a conscious decision about how to utilize the RCN to exercise sovereignty in Arctic waters, particularly as interest and activity in this area of the world continues to grow. Submarines do present one possible option for surveillance and sovereignty operations, and the AIP technology that presently exists could be adapted to enable Canadian submarines to operate in the under-ice environment. However, developing or procuring under-ice propulsion is only one part of a complex problem. There are many engineering and logistical challenges that would have to be overcome. Ultimately, there are also several other options for exercising Canadian sovereignty in the Arctic. This will be a difficult decision, especially in

[55] Julie H. Ferguson, *Deeply Canadian: New submarines for a new millennium,* Port Moody: Beacon Publishing (2000), 115.

[56] Whitman, Edward. "SOSUS: The 'Secret Weapon' of Undersea Surveillance." *Undersea Warfare,* 7, no. 2 (2005). http://www.public.navy.mil/subfor/underseawarfaremagazine/Issues/Archives/issue_25/sosus.htm

[57] Jimmy Thomson, "Canadian military developing surveillance system to monitor Arctic waters," *CBC News,* 2 August 2017, http://www.cbc.ca/news/canada/north/cause-array-drdc-test-1.4232348

today's fiscally-constrained environment. However, this decision must be based not only on the technical aspects of the available platforms, but also the political impact and follow-on effects that they will create for the rest of the RCN.

RECOMMENDATION

27. Due to the small number of available RCN submarines and the planned acquisition of the AOPS, it is recommended that no AIP-systems are procured for the purpose of under-ice operations. The AOPS will provide a visible symbol of Canadian sovereignty in the Arctic, and will be well-suited to responding to rescue and disaster relief missions that are likely to accompany increased commercial activity. It is also recommended that development of an undersea surveillance system continues. Implementing a system such as this, in combination with a US partnership providing under-ice SSNs as required, will provide an effective deterrent while allowing for Canadian monitoring of sovereign waters. Additionally, pursuing this course of action will allow RCN submarines to remain engaged on operations throughout the world.

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