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AIR-INDEPENDENT PROPULSION: AN ENABLER FOR CANADIAN SUBMARINE UNDER-ICE OPERATIONS?

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AIM

1. This service paper discusses the technologies, other than nuclear propulsion, that might allow Canada to operate submarines under sea ice, and the feasibility of conventional submarines (SSKs) filling this role. The paper will concentrate primarily on propulsion considerations, this being the most significant impediment to under-ice operations, but will also identify other concerns. It will be a review of existing and near-future technologies, and will relate them to a defined problem.

BACKGROUND

2. The Royal Canadian Navy's (RCN's) *Victoria*-class submarines are capable platforms for surveillance, deterrence and other missions. As conventional vessels, their propulsion system comprises diesel electric engines, batteries banks, and a propulsion motor. This gives them the advantage of being extremely quiet when submerged and running on batteries, when there are few moving machinery parts. However, they become vulnerable when, every few days, they must rise to periscope depth and raise the snorkels, both to run the engines in order to charge the batteries and to vent fresh air into the submarine. This increases the probability of detection, but also precludes operation under sea ice – to do so would require an ice-strengthened sail in order to frequently break through ice, which would anyway be an impractical method of operation.

3. Operation under sea ice would be a valuable capability for a number of reasons. For decades, other nations – notably the US, the UK and the USSR/Russia – have operated under the sea ice with impunity.[1] Also, access to the Northwest Passage is increasing as the navigable season lengthens over time, and Canada, which asserts that this is internal waters, finds it difficult to patrol and to control this route.[2] Finally, Canada is expected to submit its arctic exclusive economic zone (EEZ) claim this year, which may extend considerably west and north of its archipelago.[3] Once granted in part or in whole, it will be very difficult to exert control over this area other than by air and by under-ice submarine patrols.

4. An obvious solution to this is nuclear-powered submarines (SSNs). Their practically limitless source of energy leads to no limit to patrol range or speed, and also allows oxygen to be produced from seawater in an energy-intensive process, precluding the need to surface for fresh air.[4] Thus they are only practically limited by the stores, particularly food, that they can carry. However, SSNs are very costly, and nuclear power may be politically unpalatable with respect to public sentiment. Canada thus has a unique problem set: a large, ice-covered arctic sea area; a disputed strait, the Northwest Passage (NWP), and overlapping contested EEZs and territorial waters; but a low probability of procuring SSNs. No other arctic nation has all three of these issues.

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[1] Bob Weber, "Russian maps suggest Soviet subs cruised Canadian Arctic," *The Canadian Press*, last modified 11 December 2011, http://byers.typepad.com/arctic/2011/12/russian-maps-suggest-soviet-subs-cruised-canadian-arctic.html#more; David Szondy, "Rising tide: Submarines and the future of undersea warfare," *New Atlas*, last modified 5 July 2017, https://newatlas.com/future-submarines-modern-warfare/49896/; RT, "British subs eye resuming Arctic patrols after decade-long pause," last modified 10 April 2016, https://www.rt.com/uk/339128-uk-submarines-deployed-arctic/.

[2] David K. Dunlop, "Canada's Future Submarines," *Canadian Naval Review*, last modified 25 September 2017, http://www.navalreview.ca/2017/09/canadas-future-submarines/.

[3] Levon Sevunts, "Canada to submit its Arctic continental shelf claim in 2018," *RCI*, last modified 3 May 2016, http://www.rcinet.ca/en/2016/05/03/canada-to-submit-its-arctic-continental-shelf-claim-in-2018/.

[4] Szondy, "Rising tide: Submarines and the future of undersea warfare."

5. The problem, then, is to determine if there is another propulsion system that could overcome the limitations of a conventional diesel-electric submarine adequately to operate under sea ice.

DISCUSSION

Problem Definition

6. The first step is to define the problem clearly, that is, to generate requirements based on expected missions. There are likely two significant reasons for putting submarines in the arctic: surveillance and control, so that Canada can establish a clear maritime picture in the arctic and exert control over vessels operating there; and deterrence, where the threat of armed Canadian submarines in the arctic convinces other actors that they cannot operate there with impunity. Another important consideration is against whom these missions are executed, whether against other nations' ice-capable submarines, commercial shipping, or some other threat.

7. These missions established, the two main requirements can then be asserted. First, any submarine conducting a meaningful patrol must be capable of travelling great distances. From Victoria, BC to Halifax, NS via the NWP is approximately 6,940 nm, and the North Pole is about 3,800 nm from Victoria and 3,220 nm from Halifax. Varying portions of these routes are ice-covered, depending on the season – about 3,400 nm of the NWP in the winter, and parts of the 1,300 nm transit through the archipelago itself in the navigable season in late summer. Perhaps 1,000 nm of the transit to the North Pole from the Bering Strait could be ice covered in late

summer, and 2,000 nm in the spring.[5] Second, in order to conduct surveillance of vessels or submarines of interest, Canadian submarines would need to transit at commensurate speeds. Commercial shipping can transit upwards of 25 kt, but often slower, at about 18 – 22 kt, and much slower if escorted through ice by an icebreaker, perhaps as low as 3 kt or lower.[6] Nuclear submarines, taking US submarines as indicative, are advertised as be capable of speeds over 25 kt.[7] So, then, it can be seen that there are three rough mission sets:

a. **Surveillance of arctic shipping routes in the navigable season**. This could require under-ice transits of a few hundred miles or even the majority of the 1,300-nm NWP archipelago transit, at speeds up to 24 kt, though 20 kt would likely allow surveillance of most shipping. Ships' speed through ice would be slower still, depending on ice thickness. A subset of this mission could be passive surveillance, where the submarine merely positions itself in a shipping route, but does not necessarily follow individual ships persistently. This would allow for very slow under-ice mission speeds;

b. **Surveillance of Canadian territorial waters and EEZ at all times of year**, including against other nations' SSNs. Properly accomplished, this would require under-ice transits in the range of 4,000 nm at speeds of 24 kt or even greater; and

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[5] Distances are approximate, calculated using the tool at: "Sea-Seek – Google Maps Distance Calculator," last accessed 4 February 2018, https://www.sea-seek.com/tools/tools.php. Under- ice distances are approximate, calculated based on median monthly sea ice extent for 1981 – 2010, for appropriate months, as given at: National Snow & Ice Data Center, "Sea Ice Index Animation Tool," last accessed 4 February 2018, http://nsidc.org/data/seaice_index/archives/image_select. It should be noted that these sea ice concentration extents represent 15 percent ice concentration, so in fact the sea ice extent at lesser concentrations would be even greater.

[6] Jean-Paul Rodrigue, "The Geography of Transport Systems," last accessed 4 February 2018, https://people.hofstra.edu/geotrans/eng/ch8en/conc8en/fuel_consumption_containerships.html; U.S. Coast Guard, "The Cutters, Boats, and Aircraft of the U.S. Coast Guard," last accessed 4 February 2018, http://www.overview.uscg.mil/Portals/6/Documents/PDF/CG_Cutters-Boats-Aircraft_2015-2016_edition.pdf?ver=2016-10-19-153700-540.

[7] U.S. Navy, "U.S. Navy Fact Sheet: Attack Submarines – SSN," last accessed 4 February 2018, http://www.navy.mil/navydata/fact_print.asp%3Fcid%3D4100%26tid%3D100%26ct%3D4%26page%3D1.

c. **Deterrence**, where Canadian submarines are capable of reaching any part of the arctic under ice, but not necessarily of matching the speeds of vessels or submarines of interest.

Potential Solutions

8. The most important consideration is of potential non-nuclear, non-diesel electric propulsion systems, which are presented here. These are referred to as air-independent propulsion (AIP) systems, in that each system is self-contained and does not require snorkeling for fresh air. AIP systems are typically limited by the special fuels and/or the oxygen they require, and so are normally fitted in addition to, rather than replacing, a conventional diesel-electric system. This gives a certain length of fully submerged patrol capability, on the order of a few weeks, while allowing a total patrol length of two or three months while snorkeling on the diesel engine(s).

a. **Stirling engines** are ‘external combustion engines’ that burn fuel separately from the working fluid, to which heat is transferred. The primary contemporary example is the 75 kW Kockums Sterling V4-275R engine. Sweden’s 1,240-ton (surfaced) *Götland*-class submarines are each fitted with two of these engines, burning diesel fuel with liquid oxygen along with inert helium. They can travel two weeks at 5 kt without surfacing, giving them a range of 1,680 nm submerged.[8] Japan’s 4,200-ton (submerged) *Sōryū*-class, are fitted with four of these engines.[9] Their estimated range is around 6,000 nm,

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[8] Naval Technology, “SSK Gotland Class (Type A19),” last accessed 4 February 2018, https://www.naval-technology.com/projects/gotland/.

[9] David Hamon and Christine M. Leah, “Australia’s Submarines: The US Option,” *The Diplomat*, last modified 1 November 2015, https://thediplomat.com/2015/11/australias-submarines-the-us-option/; Naval

depending on the source, and some sources cite that this is the range that can be achieved while submerged and running on AIP at 6.5 kt, though this value is suspect, as it greatly exceeds the submerged range of other modern AIP submarines. This type of engine is also fitted in a number of Chinese conventional submarines.[10]

b. **Steam turbines** function in a manner similar to the Stirling engine in that the combustion process occurs separately from the working fluid. The 2,050-ton (submerged) Pakistani *Khalid*-class submarines, designed by France's DCN (now DCNS), are fitted with the *Module d'Energie Sous-Marine Autonome* (MESMA) system, a 200 kW steam turbine fueled by the combustion of ethanol and liquid oxygen. DCNS also offers this technology using diesel fuel rather than ethanol. The submarine's submerged endurance is somewhere between 21 and 28 days. The submerged endurance speed is not published, but is likely around 5 kt.[11]

c. **Fuel cells** generally have fewer moving parts than the other types of engines, making them much quieter. Rather than using combustion, the electro-chemical process introduces oxygen and hydrogen on opposite sides of a membrane that is impermeable to electrons, thereby forcing electrons through an electrical circuit where useful work is performed. In its basic form, the only output is fresh water. A number of German submarine designs incorporate proton-exchange membrane (PEM) fuel cells. The Type 212 and 214 submarines use metal hydride to supply the hydrogen, which is safer than

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Technology, "SS Soryu Class Submarines," last accessed 4 February 2018, https://www.naval-technology.com/projects/sssoryuclasssubmarin/; Kosuke Takahashi, "Japan to equip future Soryu-class submarines with lithium-ion batteries," last modified 29 February 2017, http://www.janes.com/article/68275/japan-to-equip-future-soryu-class-submarines-with-lithium-ion-batteries; Gabriel Dominguez, "Japan launches 10th Soryu-class submarine," last modified 7 November 2017, http://www.janes.com/article/75484/japan-launches-10th-soryu-class-submarine; Szondy, "Rising tide: Submarines and the future of undersea warfare."

[10] Naval Technology, "SSK Gotland Class (Type A19)."

[11] Naval Technology, "SSK Agosta 90B Class Submarine," last accessed 4 February 2018, https://www.naval-technology.com/projects/agosta/; GlobalSecurity.org, "Khalid Class (Fr Agosta 90B)," last accessed 4 February 2018, https://www.globalsecurity.org/military/world/pakistan/khalid.htm;

pure hydrogen, but incurs a weight penalty as only two percent of the fuel weight is hydrogen.[12] The proposed 4,300-ton (submerged) Type 216 submarine would use methanol for fuel, which is converted to hydrogen and carbon dioxide in a reformer. This design has a submerged range of 2,600 nm at 4 kt.[13] France's DCNS recently unveiled its FC-2G (second generation fuel cell) AIP system, which will be fitted in the Australian Shortfin Barracuda Block 1A design, based on the DCNS's SMX®-Océan design. This system uses diesel fuel and reformers to produce hydrogen, as well as liquid oxygen and nitrogen to create a synthetic atmosphere which increases fuel cell life. The system is predicted to achieve a submerged endurance of about 3 weeks which, assuming a speed of 5 kt, puts the submerged range at approximately 2,520 nm.[14]

9. Table 1 summarizes the pertinent characteristics of selected AIP submarines.

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[12] Vincent Groizeleau, "Submarines: DCNS unveils fuel cell AIP," *Mer et Marine*, last modified 7 October 2017, https://www.meretmarine.com/fr/content/submarines-dcns-unveils-fuel-cell-aip.

[13] Dunlop, "Canada's Future Submarines,"; Naval Recognition, "Type 216 U-216 Conventional Submarine SSK AIP TKMS HDW Submarine Class 216 ThyssenKrupp marine Systems Royal Australian Navy datasheet pictures images photos video specification," last modified 29 December 2011, http://www.navyrecognition.com/index.php/oceania/australia/submarines/264-type-216-u-216-conventional-submarine-ssk-aip-tkms-hdw-submarine-class-216-howaldtswerke-deutsche-werft-thyssenkrupp-marine-systems-royal-australian-navy-datasheet-pictures-images.

[14] Groizeleau, "Submarines : DCNS unveils fuel cell AIP."; Naval Group, "DCNS Unveils SMX®-Océan, A New Blue-water SSK with Expanded Capabilities," last modified 28 October 2014, https://www.naval-group.com/en/news/dcns-unveils-smx-ocean-a-new-blue-water-ssk-with-expanded-capabilities/.

Table 1: Characteristics of Selected AIP Submarines

Class	**Displacement (tons surfaced/ submerged)**	**AIP System**	**Fuel and combustion process inputs**	**AIP Range (submerged)**	**AIP Speed (submerged)**
Götland (Sweden)	1,240/*	2 x 75 kW Kockums V4-275R Stirling Engine	Diesel fuel Liquid oxygen Helium	1,680 nm	5 kt
Sōryū (Japan)	*/4,200	4 x 75 kW Kockums V4-275R Stirling Engine	Diesel fuel Liquid oxygen Helium	6,000 nm‡	6.5 kt
Khalid Agosta 90B (Pakistan)	1,510/2,050	DCNS MESMA 200kW steam turbine	Ethanol Liquid oxygen	2,520 – 3,360 nm?	5 kt†

Type 216 (proposed, HDW, Germany)	4,000/4,300	4 x 120 kW PEM fuel cell modules	Methanol Liquid oxygen (presumably)	2,600 nm	4 kt
Shortfin Barracuda Block 1A (Australia, planned)	*/5,300	DCNS FC-2G fuel cell system	Diesel fuel Liquid oxygen Nitrogen (liquid?)	2,520 nm?	5 kt†

*unknown

†assumed/estimated

‡value suspect, discounted in this analysis

Achieving the Missions

10. Considering the above, it can be seen that AIP systems vary considerably. Most basically, they all require propulsion inputs other than diesel fuel – typically liquid oxygen as a minimum. Some fuels, such as methanol and hydrogen, can be dangerous if mishandled. Though most would increase the logistics burden and cost of refueling, metal hydride in particular requires special handling facilities, greatly further reducing flexibility in refueling locations.[15] None of these is an actual ‘closed system’, in that they all require discharging waste gases overboard, though a straight hydrogen-oxygen fuel cell would not have waste products other than water.

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[15] Groizeleau, “Submarines : DCNS unveils fuel cell AIP.”

DCNS, in particular, claims that its systems dissolve the gases into seawater so that there is no signature, but it is conceivable that these signatures will become detectable with future technology developments.[16]

11. With respect to the specific missions, a few conclusions become immediately obvious:

    a. **High-speed, long-range submerged missions are well beyond the capabilities of current AIP systems**. The problem is effectively one of energy density of fuel components. The relationship between submerged speed and propulsion power is roughly cubic, so that proceeding at twice as fast requires eight times the power, and thus fuel is consumed eight times faster.[17] As an approximation, this means that proceeding at 20 kt using an AIP system designed for a 5 kt endurance speed would cut an endurance time of three weeks to perhaps eight hours, or, as a corollary, would require 64 times as much fuel for the same endurance range. This is likely prohibitive in terms of the increase in size and cost of a submarine;

    b. **Limited under-ice transits in support of a deterrence mission could be feasible**. Most of the submarines surveyed, above, have submerged ranges of approximately 2,600 nm. Assuming that a Canadian submarine would operate under ice with a fuel reserve of 30 percent, this would make transits of 1,800 nm feasible. This would allow for a somewhat direct passage through the NWP in the summer, but would not leave much margin for patrolling at will; and

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[16] A similar property, the Debye effect, has been investigated for its usefulness in detecting submarine wakes: "Hunting submarines with magnets," *The Economist*, last modified 12 November 2016, https://www.economist.com/news/science-and-technology/21709948-new-way-detect-even-quietest-boats-hunting-submarines-magnets; Groizeleau, "Submarines : DCNS unveils fuel cell AIP."

[17] Edward C. Whitman, "Air-Independent Propulsion: AIP Technology Creates a New Undersea Threat," *Undersea Warfare Magazine* 4, no. 1 (Fall 2001), last accessed 4 February 2018, http://www.public.navy.mil/subfor/underseawarfaremagazine/Issues/Archives/issue_13/propulsion.htm.

c. **Long-range deterrence transits would be unfeasible**. With a useful range of 1,800 nm under ice, deterrence patrols under the ice cap would be limited to 900 nm, from the ice edge, or even less, considering that sea ice extent could change while a submarine is patrolling, leaving it a longer transit back to the ice edge. Thus, even in late summer, a direct transit of only a portion of the northern EEZ could be made at slow speed, and no useful patrols could be conducted in the winter and spring.

12. Another important consideration is structural ice strengthening of the submarine so that it is able to surface through thick sea ice, whether in an emergency or for a specific task. Typically, as only nuclear-powered submarines have the endurance for ice operations, these are the only ones that are so strengthened. Work would need to be done to confirm that a conventional, lower-displacement submarine could be adequately strengthened and that it would have adequate buoyancy to break through sea ice.

13. There are a few other important aspects with respect to arctic operations in conventional submarines. It may be necessary to develop refueling facilities, which for AIP systems would need to include non-standard combustion inputs such as liquid oxygen, inert gasses, and possibly specialty fuel such as ethanol or methanol. Nuclear submarines generally produce oxygen from seawater to allow for long submerged patrols, which is possible due to their practically limitless energy source; in AIP submarines, this is not feasible, and consideration must be given to both the crew and the AIP system consuming stored oxygen, compounding the endurance problem. Appropriate sonar and navigation systems would be required, as well as training and experience in under-ice navigation, for which Canada might have to rely on allies. Furthermore, this is

compounded by the fact that charting of the arctic is fairly minimal, increasing risk in navigation.[18] Though submarines are designed to operate with minimal communications, the difficulty of communications transmissions in the high arctic would need to be addressed. Next, aside from the navigation aspect, operation of a new type of propulsion system is likely to increase training and maintenance costs over those for a standard conventional submarine. Finally, the overall cost of procurement and operation of an AIP submarine would be higher than for a diesel-electric submarine – but with a commensurate increase in capability.

14. One last note concerns batteries. In a diesel-electric submarine, batteries are used as an energy storage medium to allow submerged operations. For submarines also fitted with AIP, batteries serve a second function: they can allow bursts of speed while operating submerged on AIP at slow speeds. However, contrary to what is published in some literature, they are an energy storage device and not a 'power source'. Investing in high-capacity battery technology such as the lithium-ion batteries installed on the Japanese *Sōryū*-class and the future Australian Shortfin Barracuda Block 1A will add capability in terms of increased speed bursts and longer submerged times in non-AIP operation; however, it is not likely to have an impact on the problem of the long-range under-ice patrol.

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[18] Department of the Navy, "The United States Navy Arctic Roadmap for 2014 to 2030," February 2014, http://greenfleet.dodlive.mil/files/2014/02/USN-Arctic-Roadmap-2014.pdf, 8.

CONCLUSION

15. Given Canada's unique problem with respect to patrolling and exercising sovereignty in the arctic, it is incumbent upon the RCN to attempt to address this gap in capabilities. Based on the above analysis, it can be seen that existing AIP submarines would provide only a limited solution to the problem, that is, relatively short-range, slow-speed deterrence patrols. Considering this, Canada's solution to its unique problem is likely to be unique as well: the RCN's ideal AIP submarine would have a much greater submerged endurance than is typical, and would also have the ability to surface in ice. If pursued, this implies increased risk in procurement, as any solution, even if provided by an established submarine designer, would be bespoke and thus unproven.

16. Given this, Canada needs to be bold in exploring conventional submarine under-ice operations. As the *Victoria*-class is likely to be in service no later than the mid-2030s, and thus a replacement project would need to start in the 2020s, it is important that the RCN quickly acquire a strong understanding of the design space within which solutions to this problem may be found.[19]

RECOMMENDATIONS

17. The following are recommendations for immediate action:

    a. The Department of National Defence (DND) should establish relationships with existing AIP submarine and propulsion system designers;

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[19] Department of National Defence, "Strong, Secure, Engaged: Canada's Defence Policy," 2017, 65.

b. DND, either directly or through contract, should conduct concept design exercises to explore the design space and trade-offs with respect to faster, longer-range under-ice AIP submarines.

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