National Defence Défense nationale

Canadian Forces College

Collège des Forces Canadiennes

CANADA’S UNDER-ICE OPTIONS: SUBMARINE AIR-INDEPENDENT PROPULSION

LCdr Iain Meredith

JCSP 44	PCEMI 44
SERVICE PAPER	**ÉTUDE MILITAIRE**
Disclaimer	**Avertissement**
Opinions expressed remain those of the author and do not represent Department of National Defence or Canadian Forces policy. This paper may not be used without written permission.	Les opinons exprimées n’engagent que leurs auteurs et ne reflètent aucunement des politiques du Ministère de la Défense nationale ou des Forces canadiennes. Ce papier ne peut être reproduit sans autorisation écrite.
© Her Majesty the Queen in Right of Canada, as represented by the Minister of National Defence, 2018.	© Sa Majesté la Reine du Chef du Canada, représentée par le ministre de la Défense nationale, 2018.

Canada

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

SERVICE PAPER - ÉTUDE MILITAIRE

CANADA'S UNDER-ICE OPTIONS: SUBMARINE AIR-INDEPENDENT PROPULSION

LCdr Iain Meredith

Word Count: 2526

Compte de mots: 2526

CANADA'S UNDER ICE OPTIONS: SUBMARINE AIR INDEPENDENT PROPULSION

AIM

1. This service paper aims to inform senior Royal Canadian Navy (RCN) Leadership on submarine Air Independent Propulsion (AIP) systems for Arctic under-ice operations. RCN Leadership will be able to use this information to advise the Government of Canada for consideration in assessing options to replace the VICTORIA Class submarines.

INTRODUCTION AND BACKGROUND

2. Canada's Defence Policy, Strong, Secure, Engaged (SSE), states that the VICTORIA Class submarines will remain fully operational until the mid-2030s, at which time the Class should be decommissioned.[1] SSE further highlights the Arctic in a larger global context and articulates Canada's requirement to enhance its northern capabilities with Arctic Offshore Patrol Vessels and increased surveillance systems among other initiatives.[2] As in previous defence policies, SSE states Canada will exercise its Arctic sovereignty and increase its presence.[3,4,5] Absent from SSE is a VICTORIA Class replacement programme and a capability for under-ice operations.

3. During the Cold War, the Canadian Government realised their strategic vulnerabilities in the Arctic. If left unprotected, the Soviet navy's submarine programme was capable of

[1] Government of Canada, *Strong, Secure, Engaged*, *Canada's Defence Policy,* (Ottawa: 2017), 65.
[2] *Ibid*, 79-80.
[3] Government of Canada, *Challenge and Commitment, A Defence Policy for Canada,* (Ottawa: 1987), 52.
[4] Government of Canada, *Canada First Defence Strategy*, (Ottawa: 2006)
[5] Canada, *Strong, Secure, Engaged* …60.

threatening Canada, NATO, and invaluable merchant shipping in the Pacific and Atlantic oceans via Canadian Arctic under-ice sea channels. The 1987 Defence Policy, Challenge and Commitment, stated "… the Canadian navy must be able to determine what is happening under the ice in the Canadian Arctic, and to deter hostile or potentially hostile intrusions."[6] As nuclear powered attack submarines (SSN) were the only option in 1987, the defence policy announced a program to acquire 10-12 SSNs.[7] However, the environment in which this decision was made rapidly changed. The Canadian Government faced fiscal shortages, the RCN significantly underestimated the infrastructure costs associated with supporting an SSN program, and with the decline and potential collapse of the Soviet Union, public support for SSNs dissipated. By May 1989, Canada's SSN project was cancelled.[8]

4. Although the Cold War ended, Russian submarine operations in the Arctic and potential incursions into Canadian water space continues today. In 2007, Russia planted a flag in the North Pole seabed and currently conducts routine patrols under the Arctic sea ice.[9,10] More recently, China announced that they are a "Near Arctic State" with the issuance of their Arctic policy.[11] While China does not exclusively state that they will operate submarines in the Arctic, they do possess the capability with long range SSNs. Both of these Canadian adversaries have the

[6] Canada, *Challenge and Commitment …*, 50.

[7] *Ibid,* 53.

[8] GlobalSecurity.org, "1987, Submarine Acquisition Program". https://www.globalsecurity.org/military/world/canada/hmcs-ssn-1987.htm, accessed 31 January 2018.

[9] CBC, Russia plants flag staking claim to Arctic region http://www.cbc.ca/news/world/russia-plants-flag-staking-claim-to-arctic-region-1.679445, updated 2 August 2007.

[10] CBC, How Russian advances in the Arctic are leaving NATO behind http://www.cbc.ca/news/canada/north/russia-arctic-military-build-up-1.3926162, updated 9 January 2017.

[11] The Diplomat, *China Issues Its Arctic Policy*, https://thediplomat.com/2018/01/china-issues-its-arctic-policy/, updated 26 January 2018, and Xinhua, *Full text: China's Arctic Policy*, http://www.xinhuanet.com/english/2018-01/26/c_136926498.htm, updated 26 January 2018.

capability and demonstrated the intent to operate in the under-ice environment of the Canadian Arctic.

DISCUSSION

5. The Report of the Standing Senate Committee on National Security and Defence agrees with the statement in Leadmark 2050, the RCN's Future Capabilities document, that "[s]ubmarines are likely to remain the dominant naval platform for the foreseeable future, and hence are an essential component of a balanced combat effective navy."[12,13] The Canadian Senate report concluded that Canada requires a fleet of modern submarines with an AIP system as these submarines would meet Canada's strategic requirements in the Atlantic and Pacific oceans with an "… option to deploy vessels into Arctic waters as required."[14]

6. There are four AIP systems in development or in service with Canadian Allied submarines, none of which are designed for prolonged under-ice service.[15] As all four AIP systems require stored oxygen (pressurised liquid oxygen (LOX)), LOX storage capacity is currently the limiting factor for prolonged submerged operational time. However, with advances in submarine battery technology and enhancements to LOX/fuel storage capacity that would come with a larger submarine, these AIP systems may have the potential for prolonged submerged capability to meet Canada's strategic submarine and Arctic under-ice requirements.

---

[12] Daniel Lang, and Mobina Jaffer, *Reinvesting in the Canadian Armed Forces, A plan for the future,*(Ottawa: 2017), 35.

[13] Royal Canadian Navy, *Canada in a New Maritime World, LEADMARK 2050*, (Ottawa: 2015), 50.

[14] Lang, *Reinvesting in the Canadian Armed Forces* …, 37.

[15] Norman Jolin, "Future Canadian Submarine Capability: Some Considerations", *Canadian Naval Review,* V 11, No. 1, (N.P.: 2015), accessed 31 January 2018, http://www.navalreview.ca/wp-content/uploads/public/vol11num1/vol11num1art3.pdf, 17.

7. Potential AIP systems that may meet Canada's requirements include: closed cycle diesel engines; closed cycle steam turbines; fuel cells; and Stirling cycle engines.[16] Details of each system can be found below, together with current limitations and requisite advancements to meet Canada's potential under-ice requirements.

Closed cycle diesel engines

8. Closed cycle diesel (CCD) engine AIP systems have been researched since World War II, and other than a 1993 experimental 300 horsepower demonstration by Germany, no CCD system has been used in a modern submarine.[17] The CCD AIP system works by creating an artificial air intake environment for the fitted diesel engines, and exhausting the gases into the undersea water. The artificial intake environment is created using stored LOX, partial exhaust bleed off (carbon dioxide, nitrogen) and a stored inert gas (such as Argon of Nitrogen) to create the required volumetric demands of the engine with optimal oxygen concentration for combustion.[18]

9. As the CCD AIP system uses the submarine's fitted diesel engines for power and propulsion, any submarine with this AIP system would not be ideal for covert operations as the acoustic signature generated by operating a diesel submerged would be quite large. Furthermore, as no modern submarine operates this type of AIP, comparable submerged specifications, ranges and speeds are not available to determine its suitability for the RCN's requirements. Therefore, more research and design advancements are required for CCD AIP, including a large R&D investment, to determine its suitability for Arctic under-ice operations.

[16] *Ibid,* 18-19.

[17] Edward C. Whitman, Air Independent Propulsion – AIP Technology Creates a New Undersea Threat http://www.public.navy.mil/subfor/underseawarfaremagazine/Issues/Archives/issue_13/propulsion.htm, accessed 31 January 2018.

[18] *Ibid.*

Closed Cycle Steam Turbines

10. The most common design for this AIP system in development/employment is the French Module d'Energie Sous-Marin Autonome (MESMA) system. It utilises the same steam propulsion plant that the SSN uses, with heat being generated by burning stored ethanol and liquid oxygen instead of utilising a nuclear reactor.[19] The closed cycle steam turbine is argued to be "…inherently inefficient and has the highest rate of oxygen consumption of the four types of AIP."[20] The MESMA system is currently operational in the French export version of the AGOSTA 90B Class submarine and the MESMA system extends the submerged operational time by approximately four times the non-AIP version of the AGOSTA SSK.[21] As the non-AIP AGOSTA 90B has a range of 350 nautical miles at a speed of 3.5 knots,[22] this would give the AIP version a range of approximately 1400 nautical miles and submerged operational time of just over 16 days.[23]

11. The AGOSTA 90B submarine is a relatively small SSK, displacing approximately 1980 tonnes, and designed for the littoral waters off coastal nations.[24] While a smaller submarine requires less power to propel, and hence is more efficient, the smaller hull greatly limits its LOX storage capacity. Meanwhile, a submarine designed for greater patrol ranges would displace a greater volume, and thus have additional capacity for fuel storage. The larger LOX and ethanol

---

[19] *Ibid.*

[20] Jonlin, *Future Canadian Submarine Capability* …, 18.

[21] Naval Technology, SSK Agosta 90B Class Submarine Project Overview, https://www.naval-technology.com/projects/agosta/, access 31 January 2018.

[22] Jane's, Jane's Fighting Ships, , https://janes.ihs.com/Janes/Display/jfs_2272-jfs_, last updated 5 May 2017.

[23] All submarine operational specifications in this paper are cited from open source and unclassified documentation.

[24] Jane's, Jane's Fighting Ships, https://janes.ihs.com/Janes/Display/jfs_2272-jfs_, last updated 5 May 2017.

fuel reserves would greatly extend the submerged range while under AIP, thereby potentially meeting the RCN's operational requirements to operate under the ice in Canada's arctic.

Fuel Cells

12. Fuel cells have been used in practical power generation applications for several decades, commencing with NASA's space programmes in the 1960s. Similar to a battery, a fuel cell consists of an anode, cathode, and an electrolyte. Fuel cells differ from batteries in that fuel cells use an external fuel source (usually hydrogen) and an oxidant (usually oxygen) to generate electricity and will continue to generate electricity as long as fuel and an oxidant are supplied. A battery is different in that the electrical potential between the anode and cathode is inherent within the chemicals that comprise of the battery, and regularly requires reversal of the chemical process through the induction of energy to restore the battery's electrical potential, commonly known as "charging".

13. Similar to the other three AIP systems, fuel cells require stored LOX. Of the four AIP systems, fuel cells are the most efficient in oxygen consumption, consuming approximately 0.4 kilograms of oxygen per kilowatt hour (kgO_2/kWh), compared to ~0.75 kgO_2/kWh for the CCD, ~0.95 kgO_2/kWh for the Stirling system, and ~1.1 kgO_2/kWh for the MESMA system.[25] Furthermore, as fuel cells have no moving parts, their acoustic signature is significantly less than the other three AIP systems discussed.

[25] Dr J B Lakeman, Dr D J Browning, *The Role of Fuel Cells in the Supply of Silent Power for Operations in Littoral Waters*, (Gosport: 2004), 47-3.

14. Despite the advantages fuel cells have, a disadvantage from their AIP system counterparts is that they require hydrogen storage and generation. For submarine applications, the most practical hydrogen storage systems are reversible metal hydrides, carbon nanofibers, or hydrocarbon (methanol, diesel, gasoline, etc.) reformation.[26] The German Navy has had great success with the proven reversible metal hydride technology. While carbon nanofiber technology is still an unproven technology, researchers claim a significant increase in hydrogen storage capacity and efficiency over reversible metal hydrides.[27] Hydrocarbon reformation has its advantages, however, when applied to long term submarine AIP systems there are several disadvantages that would render them impractical.[28]

15. There are several types of fuel cells commercially available, with the Proton Exchange Membrane Fuel Cell (PEMFC) being the most suitable for submarine AIP applications.[29] The German Navy operates the Type 212 submarine with a PEMFC AIP system which uses a Siemens PEMFC stack assembly capable of generating 300 kW of electricity. The Type 212 stores its oxidant as LOX and its hydrogen fuel source as reversible metal hydride.[30] Similar to the AGOSTA 90B, the Type 212 is a relatively small submarine (displacing 1860 tonnes) designed for the littoral waters off the coast of Europe. The Type 212 has a submerged operational time of three weeks, and U32 conducted an ~1600 nautical mile transit solely on AIP in April of 2016.[31]

---

[26] *Ibid*, 47-7 – 47-9.
[27] *Ibid*, 47-7.
[28] *Ibid*, 47-8 – 47-9.
[29] *Ibid*, 47-3.
[30] *Ibid*, 47-4.
[31] Jane’s, Jane’s Fighting Ships, https://janes.ihs.com/FightingShips/Display/1355524, updated 15 February 2017.

16. The range and submerged operational time of the Type 212 is insufficient for prolonged Arctic under-ice operations. However, with platform modifications and rapidly developing advancements in fuel cell technology, this AIP system could meet the requirements. Similar to the argument made in favour for the closed cycle steam turbine AIP, a submarine designed for greater patrol ranges would have additional LOX and fuel storage capacity that would significantly extend the submerged range while on fuel cell AIP. Thus, a larger submarine design for a fuel cell AIP may potentially meet the RCN's operational Arctic under-ice requirements.

Stirling engine

17. A Stirling engine uses an independent heat source to heat the working gas of an engine in a closed loop cycle. The energy from the heated working gas is then transferred into mechanical energy, usually through pistons or turbines, to operate a generator.[32] For submarine AIP applications, the heat source comes from a combustion chamber which burns diesel fuel with LOX and an inert gas (such as helium or argon).[33] A significant advantage of the Stirling system is its ability to use a conventional submarines' traditional fuel source, diesel. Unlike an internal combustion engine which has several thousand explosions per minute, the combustion chamber in a Stirling engine has a constant supply of fuel which burns much quieter (similar to a boiler), reducing the acoustic signature. All waste by products produced by the combustion chamber are expelled into the underwater environment through a pressurised exhaust system.

[32] Saab Solutions, The Stirling Engine, An engine for the future, https://saab.com/naval/Submarines-and-Warships/technologies/The-Stirling-Engine/, accessed 31 January 2018.

[33] Naval Technology, SSK Gotland Class (Type A19), https://www.naval-technology.com/projects/gotland/, accessed 31 January 2018.

18. The Stirling engine is currently installed in two Allied submarines designed for AIP propulsion; the Swedish GOTLAND Class and the Japanese SORYU Class. Both classes of submarine use the Kockums V4-275R, a 75 kW engine. The GOTLAND Class has two Stirling engines fitted for a total of 150 kW, while the SORYU Class is fitted with four, totaling 300 kW of electrical power generation.

19. The Swedish GOTLAND Class is designed and built for similar purposes as the German Type 212 and French AGOSTA 90B (export version); patrolling the littoral waters off a coastal nation. The GOTLAND Class is relatively small, displacing 1625 tonnes and has a limited LOX storage capacity.[34] Therefore, the Class can only sustain AIP operations for two weeks at five knots, giving it an approximate range of ~1700 nautical miles.[35]

20. In contrast to all the other AIP submarines discussed, the Japanese SORYU Class is a much larger submarine, displacing 4100 tonnes submerged and designed for long range patrols in the distant waters from Japan.[36] There is limited open source technical specifications on the SORYU Class from reliable sources, however, one source does openly estimate that the range of the SORYU while on AIP is 6100 nautical miles at 6.5 knots.[37] If accurate, the SORYU could remain submerged for ~40 days. While the source cannot be verified, the range and speed under AIP would be consistent with a submarine of that size and propulsion plant. Before these specifications can be used in any decision making brief, further research and study on the hull

---

[34] Jane's, Jane's Fighting Ships, Gotland (A19) Class, https://janes.ihs.com/FightingShips/Display/1354579, updated 14 December 2017.

[35] Naval Technology, SSK Gotland Class (Type A19), https://www.naval-technology.com/projects/gotland/, accessed 31 January 2018.

[36] Jane's, Jane's Fighting Ships, Souryu Class, https://janes.ihs.com/FightingShips/Display/1356886, updated 13 November 2017.

[37] Global Security.Org, SS-501 Soryu, https://www.globalsecurity.org/military/world/japan/2900ton-specs.htm, accessed 31 January 2018.

form and fuel/LOX storage capacity is required to verify the information. Given its potential capabilities it is probable that the Stirling engine AIP system would meet the RCN's requirements for Arctic under-ice operations.

Additional AIP Considerations

21. All AIP designs are currently limited in their under-ice range due to their limited capacities to store LOX, and in the case of fuel cells, hydrogen. As a result of their LOX/hydrogen storage limitations, any AIP submarine needs to drive on a conventional means of propulsion (diesel and battery) until the operational requirements dictate AIP use is necessary. For Arctic operations, this would be when the vessel is required to go under the ice.

22. There have been recent advancements in submarine battery technology, the most notable being Lithium Ion (Li-Ion) batteries. The last two SORYU Class submarines to be built in 2020 and 2021 will be fitted with Li-Ion batteries. These batteries will result in an increase in the electrical storage potential of the battery and an extension of the underwater range.[38] Li-Ion batteries have many advantages, including being small and having four to five times greater volumetric and gravimetric density.[39,40] This means that a lead acid battery cell can physically be replaced by four to five Li-Ion battery cells, resulting in the electrical potential of the battery increasing by over four-fold. If the RCN intends to operate their next generation of submarines in

[38] Jane's 360, Japan to equip future Soryu-class submarines with lithium-ion batteries, http://www.janes.com/article/68275/japan-to-equip-future-soryu-class-submarines-with-lithium-ion-batteries, updated 27 February 2017.

[39] Joeseph P. O'Connor, Battery Showdown: Lead-Acid vs. Lithium-Ion, *an except from: Off Grid Solar: A handbook for Photovoltaics with Lead-Acid or Lithium-Ion batteries*, https://medium.com/solar-microgrid/battery-showdown-lead-acid-vs-lithium-ion-1d37a1998287, 23 January 2017.

[40] Relion Battery, 7 Facts Comparing Lithium-ion With Lead Acid Batteries, http://www.relionbattery.com/blog/7-facts-and-figures-comparing-lithium-ion-vs.-lead-acid-batteries, updated 29 August 2015.

the Arctic under-ice environment, it would be wise to utilise the latest battery technology to ensure that the RCN selects the best battery for its needs.

CONCLUSION

23. The technology required to design an Arctic under-ice capable AIP SSK exists today. Three of the four AIP systems discussed in this paper have demonstrated the potential to meet possible Arctic under-ice submarine requirements. They are the closed cycle steam turbines, fuel cells, and Stirling engines, with the latter two showing greater potential.

24. A fuel cell or Stirling engine AIP system, enhanced with Li-Ion batteries in a larger SSK (4000 tonnes or more) designed for long range and under-ice environments, will meet Canada's requirements as discussed in the Report of the Standing Senate Committee on National Security and Defence.

RECOMMENDATION

25. As a major capital project to design and build a warship takes 15-20 years to achieve full operational capability (FOC), it is recommended that the Government of Canada and the RCN immediately establish a major capital project to replace the VICTORIA Class submarines before divestment in the mid-2030s.[41] The project, with industry experts, should create a detailed statement of requirements (SOR) for an Arctic under-ice AIP SSK specifying the required range, speed, and minimum submerged time while on AIP. Once requirements are identified, a request for proposal (RFP) to design and build an Arctic under-ice capable AIP SSK should be issued to

[41] Canada, *Strong, Secure, Engaged* …, 65.

industry with planned delivery to coincide with the divestment strategy for the VICTORIA Class submarine. Canada is well suited to be a world leader in Arctic capable SSKs and should seize the opportunity to lead our Allies with the next generation of AIP attack submarines to deter potentially hostile intrusions from our adversaries in Canadian Arctic waters.

BIBLIOGRAPHY

CBC. "Russia plants flag staking claim to Arctic region" http://www.cbc.ca/news/world/russia-plants-flag-staking-claim-to-arctic-region-1.679445. Updated 2 August 2007.

———. "How Russian advances in the Arctic are leaving NATO behind." http://www.cbc.ca/news/canada/north/russia-arctic-military-build-up-1.3926162. Updated 9 January 2017.

GlobalSecurity.org, "1987, Submarine Acquisition Program." https://www.globalsecurity.org/military/world/canada/hmcs-ssn-1987.htm. Accessed 31 January 2018.

———. "SS-501 Soryu." https://www.globalsecurity.org/military/world/japan/2900ton-specs.htm. Accessed 31 January 2018.

Government of Canada. "Strong, Secure, Engaged, Canada's Defence Policy." Ottawa: 2017.

———. "Challenge and Commitment, A Defence Policy for Canada." Ottawa: 1987.

———. "Canada First Defence Strategy." Ottawa: 2006.

Jane's. "Jane's Fighting Ships." https://janes.ihs.com. Accessed 31 January 2018.

Jane's 360. "Japan to equip future Soryu-class submarines with lithium-ion batteries." http://www.janes.com/article/68275/japan-to-equip-future-soryu-class-submarines-with-lithium-ion-batteries. Updated 27 February 2017.

Jolin, Norman. "Future Canadian Submarine Capability: Some Considerations", *Canadian Naval Review, V 11, No. 1*, (N.P.: 2015), , http://www.navalreview.ca/wp-content/uploads/public/vol11num1/vol11num1art3.pdf. Accessed 31 January 2018.

Lang, Daniel, and Jaffer, Mobina. "Reinvesting in the Canadian Armed Forces, A plan for the future." Ottawa: 2017.

Lakeman, J B, and Browning, D J. "The Role of Fuel Cells in the Supply of Silent Power for Operations in Littoral Waters." Gosport: 2004.

Naval Technology. https://www.naval-technology.com. Access 31 January 2018.

O'Connor, Joeseph P. "Battery Showdown: Lead-Acid vs. Lithium-Ion." An excerpt from: *Off Grid Solar: A handbook for Photovoltaics with Lead-Acid or Lithium-Ion batteries*. https://medium.com/solar-microgrid/battery-showdown-lead-acid-vs-lithium-ion-1d37a1998287. Updated 23 January 2017.

Relion Battery. “7 Facts Comparing Lithium-ion With Lead Acid Batteries.” http://www.relionbattery.com/blog/7-facts-and-figures-comparing-lithium-ion-vs.-lead-acid-batteries. Updated 29 August 2015.

Royal Canadian Navy. “Canada in a New Maritime World, LEADMARK 2050.” Ottawa: 2015.

Saab Solutions. “The Stirling Engine, An engine for the future.” https://saab.com/naval/Submarines-and-Warships/technologies/The-Stirling-Engine/. Accessed 31 January 2018.

The Diplomat. “China Issues Its Arctic Policy.” https://thediplomat.com/2018/01/china-issues-its-arctic-policy/. Updated 26 January 2018,

Whitman, Edward C. “Air Independent Propulsion – AIP Technology Creates a New Undersea Threat.” http://www.public.navy.mil/subfor/underseawarfaremagazine/Issues/Archives/issue_13/propulsion.htm. Accessed 31 January 2018.

Xinhua. “Full text: China's Arctic Policy.” http://www.xinhuanet.com/english/2018-01/26/c_136926498.htm. Updated 26 January 2018.