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China Maritime Report No. 31: China's Submarine Industrial Base: State-Led Innovation with Chinese Characteristics

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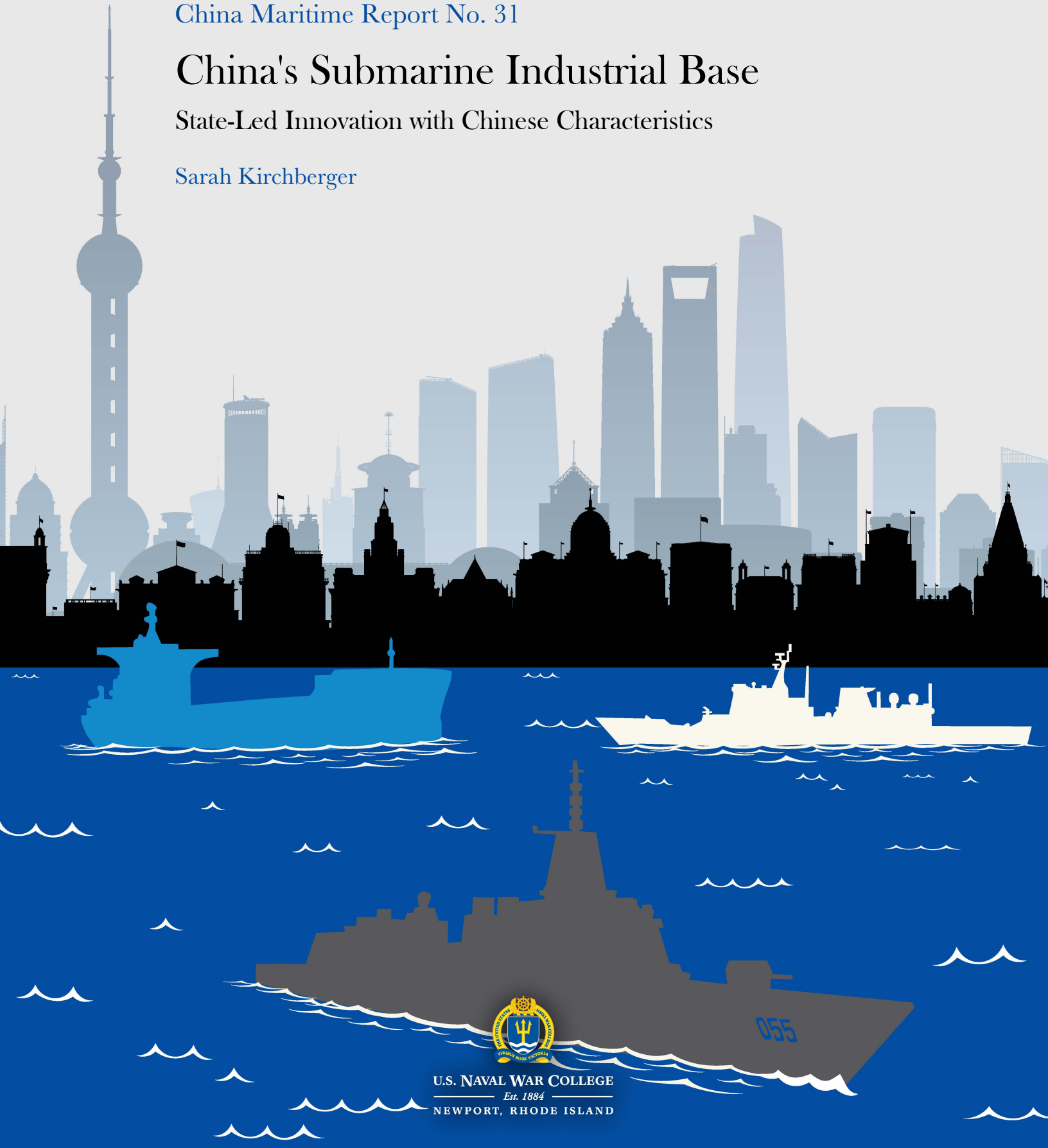

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Summary

In recent years, China's naval industries have made tremendous progress supporting the modernization of the People's Liberation Army Navy (PLAN) submarine force, both through robust commitment to research and development (R&D) and the upgrading of production infrastructure at the country's three submarine shipyards: Bohai Shipyard, Huludao; Wuchang Shipyard, Wuhan; and Jiangnan Shipyard, Shanghai. Nevertheless, China's submarine industrial base continues to suffer from surprising weaknesses in propulsion (from marine diesels to fuel cells) and submarine quieting. Closer ties with Russia could provide opportunities for China to overcome these enduring technological limitations by exploiting political and economic levers to gain access to Russia's remaining undersea technology secrets.

Introduction

The sprawling yet opaque ecosystem of industrial and research facilities engaged in the design and production of China's subsurface warfare systems is not easy to quantify, let alone analyze. Long hampered by the 1989 (post-Tiananmen) arms embargo, it has profited from an avalanche of state funding; is characterized by a maze of cross-shareholdings that includes state-owned banks and listed private businesses within China and abroad; connects deeply with the academic research and development (R&D) community; and is engaged in a vast effort to overcome critical arms technology bottlenecks via ingenious methods beyond traditional espionage.[1] Undersea warfare technologies are of strategic priority for the Chinese government, and R&D connected to it enjoys the highest level of political backing.[2]

Technical details of submarine production, including of critical subsystems, are classified in all submarine-operating countries. In the People's Republic of China (PRC), a culture of extreme secrecy in military affairs extends to even far less critical issues. Given the lack of public budgets, opaque and monopolistic procurement processes, and secret build schedules, PRC submarine procurement is shrouded in a greater degree of obscurity than that of most other countries. Sometimes, analysist discover the existence of a new submarine type only after its construction is already complete—on satellite imagery or accidentally filmed footage. This lack of transparency makes it difficult to evaluate China's true capability at building undersea warfare systems. At the same time, China's leaders are eager to project an image of stunning technological progress. Advances in arms production are regularly used to this end. Beijing is therefore trying to balance contradictory aims: preserving technical secrets of submarine production, while advertising breakthrough successes to signal military prowess, all the while routinely using disinformation about progress in advanced arms programs as a tool in information warfare.[3]

These caveats notwithstanding, there is a wealth of open sources containing hints about the arms-industrial base that is contributing to China's submarine and anti-submarine warfare (ASW) technology programs. Even job advertisements posted on Chinese university websites targeting technical degree graduates can provide valuable detail about a particular company's or research

[1] For a detailed breakdown of the various legal, illegal, and extralegal strategies employed by China see William C. Hannas and Huey-Meei Chang, "Chinese Technology Transfer—An Introduction," in William C. Hannas and Didi K. Tatlow (eds.), *China's Quest for Foreign Technology: Beyond Espionage* (N.Y.: Routledge, 2021), pp. 3-20.

[2] Sarah Kirchberger, "China's Undersea Warfare," Testimony before the U.S.-China Economic and Security Review Commission Hearing on China's Pursuit of Defense Technologies: Implications for U.S. and Multilateral Export Control and Investment Screening Regimes on 13 April 2023,

https://www.uscc.gov/sites/default/files/2023-04/Sarah_Kirchberger_Testimony.pdf.

[3] James Bussert and Bruce A. Elleman, *People's Liberation Army Navy Combat Systems Technology, 1949-2010* (Annapolis, MD: Naval Institute Press, 2011), p. 2.

unit's facilities, staffing, and business areas. Further, information from foreign subsystem suppliers to China and experiences reported by China's submarine export customers in Thailand, Pakistan, or Bangladesh can yield interesting first-hand accounts of the actual vs. the advertised capabilities of Chinese undersea warfare systems. This report relies mostly on these and other types of openly accessible source materials supplemented with a number of background conversations with Western industry executives and submarine warfare experts.[4] By combining this information with the already existing knowledge on the functioning of the Chinese arms-industrial base, and extrapolating from submarine-building experiences in other countries, this report seeks to construct at least a partial picture of the current trends, successes, and remaining technical bottlenecks characterizing China's submarine industrial base. It also offers some cautious assessments of the operational implications for China's future fleet development.

China's Submarine Shipbuilding Infrastructure

China's naval shipbuilding has made remarkable progress during the past twenty years.[5] Though overcapacities and bureaucratic inefficiencies continue to exist, overall, the sector has been thoroughly modernized—not least through foreign technology partnerships in commercial ship design and construction. Facilities in the major shipyards have been upgraded to nearly the level of the world's leading shipyards in Japan and South Korea, and modern design and construction methods such as modular construction and the use of advanced design software are now standard practice.[6] In the past few years, satellite imagery analysis has shown that several of the leading naval shipyards have been massively enlarged with new production facilities.

Apart from the shipyards building submarine hulls, a great number of design, R&D, and production facilities contribute to naval shipbuilding, including undersea warfare systems (see Figure 1 below).

[4] Sources relied on include published reference works; analyses based on satellite imagery and other visual evidence; Chinese scientific journal articles; Western, Chinese, and Russian news reports; official websites of Chinese industries and R&D units; job advertisements; industry brochures and presentations shown or collected at arms fairs and conferences on naval weapon systems; and background interviews with undersea warfare experts and practitioners from the industry and military communities.

[5] Sue Hall and Audrye Wong, "Key Factors in Chinese Shipyards' Development and Performance: Commercial-Military Synergy and Divergence," in Andrew S. Erickson (ed.), *Chinese Naval Shipbuilding: An Ambitious and Uncertain Course* (Annapolis, MD: Naval Institute Press, 2016), pp. 75-106, p. 81ff.

[6] Andrew S. Erickson, "Introduction: China's Military Shipbuilding Industry Steams Ahead, On What Course?", in Erickson (ed.), *Chinese Naval Shipbuilding*, pp. 8-10.

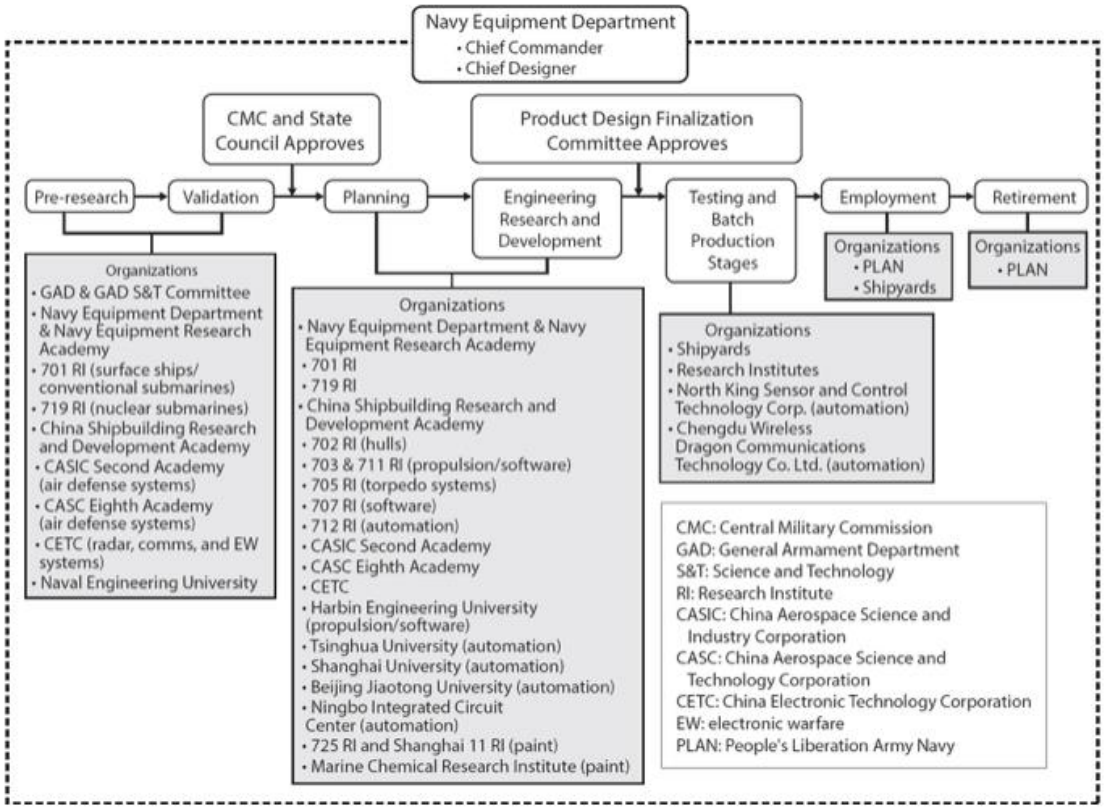

Figure 1: Primary organizations involved in China's military shipbuilding[7]

Shipyards that Build Submarines

Out of the six major Chinese shipyards engaged in naval shipbuilding, three build submarines. Two of these, Bohai Shipyard in Huludao, Liaoning province and Jiangnan Shipyard in Shanghai, are located on the coast, while the third—Wuchang Shipyard in Wuhan, Hubei province—lies further inland, on the Yangzi River, upstream from Jiangnan Shipyard.

Bohai Shipyard, Huludao

All nuclear-powered submarines are constructed at the Bohai Shipbuilding Heavy Industry Company (BSHIC) shipyard in Huludao. According to an archived 2017 snapshot of its official website, it encompasses a total area of 3.6 km^2, and the yard is equipped with China's largest covered berths, two 300,000 DWT dry docks, a 150,000 DWT semi-dock building berth, and a 50,000 DWT flooding dock, among other facilities. BSHIC is capable of building various types of ships up to a size of 400,000 DWT, and its annual shipbuilding capacity can reach 4,000,000 DWT. Aside from performing the full spectrum of naval and commercial shipbuilding, BSHIC also engages in ship repair; steel structure processing; the construction of metallurgic and hydropower equipment; and nuclear power equipment fabrication. Interestingly, the shipyard describes itself as an "official research base" for "localizing […] important technical equipment," alluding to its role in Military-Civil Fusion (军民融合, MCF), a core Chinese military-

[7] Kevin Pollpeter and Mark Stokes, "China's Military Shipbuilding Research, Development, and Acquisition System," in Erickson (ed.), *Chinese Naval Shipbuilding: An Ambitious and Uncertain Course* (Annapolis, MD: U.S. Naval Institute Press, 2016), p. 183.

technological innovation strategy that aims to leverage civilian technological innovation to achieve more rapid military modernization and turn China into a technological superpower.[8]

Bohai Shipyard has recently seen enlargement on newly reclaimed land, and the hasty addition of a large covered hall in 2016 promptly gave rise to speculations that it might be intended for accelerated submarine production, which was later confirmed by the first launch of a submarine from that hall in January 2023.[9] By early 2022, satellite images had begun to show construction work on a new harbor that may offer additional capacity in a future accelerated submarine construction process.[10]

Though construction of next-generation SSNs (Type 095) and SSBNs (Type 096) has already commenced, satellite imagery of the early construction stages is scarce, as it takes place inside covered halls, even though sometimes individual segments can be observed outside the halls.

Wuchang Shipyard, Wuhan

Design and construction of conventionally powered submarines is centered around Wuhan, where a new shipyard downstream of the old shipyard site in central Wuhan has only recently been erected. According to satellite imagery analyses, the new Wuchang shipyard's area is about 10 times as large as the old Wuhan shipyard and extends for about 1.5 miles along the Yangzi River bank.[11] The new site seems to have been under construction since 2012, started active work on surface vessels in 2015, and has since added covered halls for the construction of "Yuan" (Type 039A)-class submarines. Here, Sutton has observed evidence of "several boats… being constructed at once," indicating a possible mass production line akin to those developed for

[8] See https://web.archive.org/web/20170420112250/http://www.bsic.com.cn/Home/CorpSummary/. BSHIC's official website (bsic.com.cn) seems to have been offline for years, though it is still listed on its holding conglomerate CSSC's website directory (http://www.cssc.net.cn/n11/index.html). On MCF, see Richard A. Bitzinger, "China's Shift from Civil-Military Integration to Military-Civil Fusion," *Asia Policy*, Volume 16, No. 1 (January 2021), pp. 5–24; pp. 7-8. https://www.rsis.edu.sg/wp-content/uploads/2022/05/Asia-Policy-16.1-Jan-2021-Richard-Bitzinger.pdf.

[9] A short clip from the TV series "World Strategy" shows interesting footage of the Bohai Shipyard's state-of-the-art welding and construction facilities. See 环球战备 [World Strategy],中国原子弹大踏步向前，渤海造船厂暴露秘密：六艘核潜艇同时建造! ["China's Atomic Bomb is Making Great Strides Forward, and the Bohai Shipyard Reveals its Secrets: Six Nuclear Submarines are Built at the Same Time"], 25 October 2020, 00:03:20, https://www.youtube.com/watch?v=K-nyrGTZSZU. Christopher P. Carlson has revised his initial assessment that this particular hall might be tied to commercial build projects instead of submarines. Carlson based his analysis on satellite imagery that suggested—among other problems—that the hall's foundation would be too weak to support the full weight of a nuclear submarine. According to a personal communication by Carlson received on 23 April 2023, all reasons cited in the above analysis to doubt the function of the hall as a submarine construction facility have by now dissolved. In particular, writes Carlson, "1) The approx. 6 meter wall blocking access to the graving dock was removed by mid-2017; 2) The Chinese produced a launch barge from Nov-Dec 2019 that aligns with the transfer system rails from the construction hall; 3) The width or gauge of the transfer system is 6.8 meters, not the about 6 meters in the original analysis. This is sufficient to move a completed submarine from the construction hall to the launch barge; 4) China has been using reactive powder concrete, also called ultra high performance concrete, which is at least twice as strong as the high strength concrete I assumed in my original analysis; 5) The Chinese launched a submarine from the new construction hall in January 2023—the proof is in the pudding as they say." (Christopher P. Carlson, Personal Communication, 23 April 2023.). For Carlson's original assessment, see Christopher P. Carlson, "Bohai Shipyard Expansion: New Assembly Line or Nuclear Submarine Production?", Admiralty Trilogy website, 20 July 2017, http://www.admiraltytrilogy.com/pdf/Bohai.pdf.

[10] H.I. Sutton, "Further Expansion Of China's Nuclear Submarine Shipyard," Covert Shores, 5 January 2023, http://www.hisutton.com/Chinese-Navy-Huludao-Expanding-202301.html.

[11] H.I. Sutton, "China Increases Production Of AIP Submarines With Massive New Shipyard," *Naval News*, 16 February 2021, https://www.navalnews.com/naval-news/2021/02/china-increases-production-of-aip-submarines-with-massive-new-shipyard/.

surface vessel construction, pointing to a "much greater capacity than many other submarine yards around the world."[12]

The leading organization in charge of conventional submarine design is the China State Shipbuilding Corporation (CSSC)'s 701st Research Institute, located in Wuhan. The design of nuclear-powered submarines is also led from Wuhan, by the CSSC's 719th Research Institute—but construction of all nuclear submarines takes place at Bohai Shipyard in Huludao.

Jiangnan Shipyard, Shanghai

The enormous new Jiangnan Changxing shipyard in Shanghai covers an area of about 11.5 km^2, compared with the old shipyard site of about 7.3 km^2—an increase of roughly 64 percent.[13] The naval shipyard covers about 1.4 km^2 and is located within the commercial shipyard area. Here as well, submarine construction takes place in a covered assembly hall.[14] Despite only being operational since 2008, Jiangnan has already been involved in several remarkable large-scale naval surface warship construction projects, in particular the Type 003 aircraft carrier.[15] In December 2019, satellite images showed at least nine newly built major warships plus one Yuan Wang-class satellite tracking ship concurrently moored at Jiangnan Changxing shipyard.[16]

Next to its heavy commercial and naval surface building workload, Jiangnan has constructed half of the Type 093B Yuan-class submarines in parallel to the construction ongoing in Wuchang. It is also involved in the building of the new Type 039C series, and seems to play a role in the design and/or outfitting of various prototype submarines. In October 2018, the launch ceremony for an unknown "sailless" submarine of about 46m length was publicized by Jiangnan Shipyard. According to analysts, it may be an extra-large unmanned undersea vehicle (XLUUV) or a manned test submarine influenced by other sailless designs, such as the Swedish A21 "Flundran," the French Naval Group's SMX-31 concept, or the older Soviet Pr. 673.[17] Remarkably, those designs have remained on the drawing board whereas the Chinese sailless submarine has actually been built.

Since Jiangnan Shipyard is located downstream from Wuchang, this sometimes allows for observation of other hitherto unknown submarines on the river while they are being moved for outfitting in Shanghai. In February 2022, for example, video footage showed an unknown type of

[12] Ibid.

[13] H.I. Sutton, "Chinese Navy Growth: Massive Expansion Of Important Shipyard", *Naval News,* 15 March 2022, https://www.navalnews.com/naval-news/2022/03/chinese-navy-growth-massive-expansion-of-important-shipyard/.

[14] "Analysis of Jiangnan Shipyard," CSIS, 17 December 2018, https://www.csis.org/analysis/analysis-jiangnan-shipyard.

[15] A TV documentary on CCTV-7's Military Channel (军事频道) that premiered on 14 November 2020 titled 揭秘中国最大军工造船厂：走进江南造船探秘国之重器 ["Demystifying China's Largest Military Shipyard: Walking into Jiangnan Shipbuilding to Explore the Country's Most Important Weapons"], 00:26:22, https://www.youtube.com/watch?v=HywtBF29n68, showcases the shipyard's remarkable build capacity and world-class construction facilities.

[16] H.I. Sutton, "The Chinese Navy Is Building An Incredible Number Of Warships," *Forbes,* 15 December 2019, https://www.forbes.com/sites/hisutton/2019/12/15/china-is-building-an-incredible-number-of-warships/; Vinayak Bhat, "High-Speed Production: Chinese Navy Built 83 ships in Just Eight Years," *The Print,* 20 September 2017, https://theprint.in/defence/chinese-navy-built-83-ships-8-years/10416/.

[17] 中国公开疑似新型"无头"潜艇 外媒：它只用锂电池 ["China Publicly Unveils a Suspected New Type Of 'Headless' Submarine—Foreign Media: It Runs on Lithium-Ion Batteries"], *Sina Military,* 10 July 2019, https://web.archive.org/web/20230328143835/https://mil.news.sina.com.cn/jssd/2019-07-10/doc-ihytcitm0912066.shtml; H.I. Sutton, "The Chinese Navy's New Mystery Submarine," *Forbes,* 9 October 2019, https://www.forbes.com/sites/hisutton/2019/10/09/china-navy-new-mystery-submarine/.

smaller submarine with outer lines and general appearance resembling the "S200 Midget Submarine" and "S600 Coastal Submarine" design models shown at defense exhibitions, e.g., the Defense & Security 2017 in Bangkok.[18] In case the small new submarine is not intended for the People's Liberation Army Navy (PLAN), one possible explanation could be that it might have been built as a tech demonstrator to boost the design's export chances. This is not unheard of in the naval export market, where having a "built and proven" design makes marketing considerably easier, as navies tend to be cautious about adopting prototype designs, and more so in the case of unproven submarine technology.[19]

In 2021, yet another hitherto unknown type of larger conventional submarine was observed on the river between Wuhan and Shanghai, displaying a distinct flattened sail form.[20] In July 2022, this was confirmed to be the newest version of the Yuan-class, the Type 093C, when a submarine with precisely this sail shape was commissioned into the PLAN and assigned to the Daxie Dao (大榭岛) submarine base.[21] Its flattened sail form is likely intended to reduce the radar signature, as in the case of the Swedish next-generation A26 "Blekinge"-class which is optimized for stealthy missions in the Baltic Sea's crowded and shallow littorals.[22]

Shipyard Expansion

All three submarine-building shipyards have undergone technical infrastructure upgrades and seen considerable enlargements and facility extensions in recent years. As the U.S. Secretary of the Navy Carlos Del Toro remarked in February 2023, some individual Chinese naval shipyards may have a greater build capacity than all American naval shipyards combined.[23]

One further general characteristic of Chinese military shipbuilding is a high level of military and commercial shipbuilding integration in all yards. That is unusual, as the industrial base, skillsets, and materials required for warship construction are quite distinct from commercial standards. The difference is even more pronounced in submarine construction. In China, this integrated build strategy is likely intended to enhance technical and organizational standards of shipbuilding in general, not least via joint ventures with partners from the leading commercial shipbuilding nations—in particular Japan and South Korea. This ultimately led to China's technically upgraded and massively subsidized yards surpassing even South Korea as the leading producers

[18] H.I. Sutton, "China's New Submarine Is Unlike Anything In Western Navies," *Naval News*, 15 February 2022, https://www.navalnews.com/naval-news/2022/02/chinas-new-submarine-is-unlike-any-fielded-by-western-navies/. The images are provided in "China's CSIC Unveils Three New Submarine Designs for Export," *Navy Recognition*, November 2017, https://www.navyrecognition.com/index.php/news/defence-news/2017/november-2017-navy-naval-forces-defense-industry-technology-maritime-security-global-news/5719-china-s-csic-unveils-three-new-submarine-designs-for-export.html.

[19] After a period of unsuccessful marketing, French naval shipbuilder DCNS in 2011 financed and built a demonstration version of its "Gowind" OPV design and offered it for lease to the French Navy to boost its export chances. That strategy proved successful. See D-Mitch, "L'Adroit Offshore Patrol Vessel of the French Navy", *Naval Analyses*, 12 January 2015, https://www.navalanalyses.com/2015/01/ladroit-patrol-vessel-of-french-navy.html.

[20] H.I. Sutton, "Image May Reveal A New Type Of Submarine for the Chinese Navy," *Naval News*, 12 May 2021, https://www.navalnews.com/naval-news/2021/05/image-may-reveal-a-new-type-of-submarine-for-the-chinese-navy/.

[21] H.I. Sutton, "China's Newest Attack Submarine Now Stationed Near Taiwan," *Naval Analyses*, 11 August 2022, https://www.navalnews.com/naval-news/2022/08/chinas-newest-attack-submarine-now-stationed-near-taiwan/.

[22] Interview with a submarine designer, 24 March 2023.

[23] Brad Lendon and Haley Britzkey, "US Can't Keep Up With China's Warship Building, Navy Secretary Says", *CNN*, 23 February 2023, https://edition.cnn.com/2023/02/22/asia/us-navy-chief-china-pla-advantages-intl-hnk-ml/index.html.

of commercial ships starting in 2018. Another likely aim is to reduce technical bottlenecks in military shipbuilding via Military-Civil Fusion.[24]

Apart from facility upgrades and area enlargements, China's naval shipyard have massively augmented their warship output by reportedly following unusual build-schedules.[25] With a construction output that is more or less unparalleled, one remaining bottleneck concerns the area of warship design. According to researchers from the China Ship Design and Research Center (a.k.a. the CSSC's 701th Research Institute), design is the "main obstacle to speeding up warship production rather than shipyard capacity." China's military is planning to tackle this bottleneck with the help of artificial intelligence (AI). Using an AI algorithm, these researchers were reportedly able to design a warship's entire electrical systems in just one day, a task that normally required 300 human work days to complete. According to the report, "the AI works by consulting a database of Chinese ship designs from past decades and then comes up with a design that is checked against the database, with this approach drastically reducing computing resources and eliminating errors."[26]

Key Organizations Involved in Submarine Warfare Systems Design and Production

The leading facilities involved in submarine design, production, and R&D—i.e., shipyards, production plants, design bureaus, and research institutes—are subsidiaries of China's sole state shipbuilding conglomerate, CSSC. In addition, the leading state-owned conglomerate in the defense electronics sector, China Electronics Technology Group Corporation (CETC), is also heavily involved in R&D and production of various products needed for anti-submarine warfare. In particular, CETC has the lead in the construction of China's vast ocean surveillance network and its related infrastructures, including many unmanned underwater systems, as well as in naval electronics.[27]

The report Appendix lists some key organizations involved in the production of China's submarine and anti-submarine warfare capabilities.

Based on the affiliations of researchers listed in the published Chinese research literature, some PLA units are also highly active in submarine-related R&D. These include Unit 92730 in Sanya, Hainan, whose members seem to be conducting research on supercavitating torpedoes;[28] Unit 92578 in Beijing, whose members have published on lithium-ion and fuel cell power systems for submarines and subsurface unmanned vessels, as well as on fiber-optic hydrophones;[29] and Unit

[24] "How is China Modernizing its Navy?" CSIS China Power Project, 17 December 2018; updated 20 April 2022. https://chinapower.csis.org/china-naval-modernization/.

[25] Bhat, "High-Speed Production."

[26] Gabriel Honrada, "AI Warship Designer Accelerating China's Naval Lead," *Asia Times*, 19 March 2023, https://asiatimes.com/2023/03/ai-warship-designer-accelerating-chinas-naval-lead/.

[27] See Asia Maritime Transparency Initiative, "Exploring China's Unmanned Ocean Network," with assistance from J. Michael Dahm, CSIS, 16 June 2020, https://amti.csis.org/exploring-chinas-unmanned-ocean-network/; J. Michael Dahm, "Inter-Island Communications", South China Sea Military Capability Series, Johns Hopkins Applied Physics Laboratory, July 2020, p. 8, https://www.jhuapl.edu/sites/default/files/2022-12/Inter-IslandCommunications.pdf.

[28] 覃辉 [Qin Hui] and 翁辉 [Weng Hu], 超空泡射弹对反鱼雷作战体系贡献率的评估 ["Evaluation of Contribution Rate of Supercavitation Projectile to Anti-torpedo Combat System"], 数字海洋与水下攻防 [*Digital Ocean & Underwater Warfare*], vol. 4, no. 5 (October 2021), pp. 372-379.

[29] 宋强 [Song Qiang], 水下无人航行器燃料电池技术浅谈 ["Discussion on Fuel Cell Technology for Underwater Unmanned Vehicles"], 舰船科学技术 [*Ship Science and Technology*], vol. 42, no 12 (2020), pp. 150-154; 宋 强 [Song Qiang], 赵满 [Zhao Man], and 毛柳伟 [Mao Liuwei], 浅析日本"凰龙"号潜艇动力系统技术状态 ["Analysis

No. 91001 in Beijing, whose members seem to be researching remote sensing and oceanography for submarine operations and other military purposes.[30]

Most of the organizations listed in the Appendix have at some point been added to the U.S. Entity List. Only some have publicly accessible websites, and many have undergone several name changes over the years that can make it hard to keep track of their work over time. Much like the shipyards that have been relying on commercial orders for as much as 90 percent of their revenue, some of the production and R&D facilities listed in the Appendix conduct submarine warfare-related business next to other, unrelated business activities. This is typical of China's defense industries in general.[31]

Apart from Huludao, Wuhan, and Shanghai, the port city of Qingdao in Shandong province is another key hub of China's undersea warfare systems development. It is home to the PLAN's Naval Submarine Academy, the PLAN's 2nd Submarine Flotilla, and the nearby strategic submarine base Jianggezhuang (姜各庄). Besides these military functions, Qingdao is also a hub of underwater robotics R&D and a noted center of foreign technology transfer.[32] Based on studies of future submarine command and control systems design, China anticipates next-generation submarines to integrate embarked unmanned vehicles, making undersea robotics development prospectively an integral aspect of submarine design.[33] Elsa Kania reports that in 2017 an "Underwater Vehicle Intelligent Equipment Base" (水下无人航行器智能装备基地) was established in Qingdao that is "undertaking research and development, as well as the design and manufacture, for a range of marine robotics and engineering equipment, including the white Dolphin (白豚) autonomous underwater vehicle." In April 2018, Qingdao hosted the "first forum on military-civil fusion in the AI industry." Convened by Harbin Engineering University (HEU), the forum discussed intelligent underwater robots, high-speed unmanned boats, smart ships, and target recognition.[34]

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on Technical Status of the Power System of the Japanese Oryu Submarine JS"], 船电技术 [*Marine Electric & Electronic Engineering*], vol. 42, no. 12 (December 2022), pp. 22-29.

[30] 樊旭艳 [Fan Xuyan], 何锡玉 [He Xiyu], 杨亮 [Yang Liang] and 王叶 [Wang Ye], 海洋遥感在军事海洋环境保障中的应用研究 ["Research on Application of Ocean Remote Sensing in Military Marine"], 海军工程大学学报 [*Journal of Naval University of Engineering*], vol 17, no. 3 (September 2020), pp. 39-42; and 孟荻 [Meng Di], 袁延艺 [Yuan Yanyi], and 刘平香 [Liu Pingxiang], 声诱饵对尺度目标的回波模拟方法 ["Echo Simulation Method of Acoustic Decoy to Scale Target"], 声学技术 [*Technical Acoustics*], no. 3 (2015), pp. 275-278. Though listed here as a member of the Naval Equipment Research Institute in Shanghai, Meng Di was later identified in other articles as a member of the PLA Unit No. 91001.

[31] Daniel Alderman and Rush Doshi, "Civil-Military Integration Potential in Chinese Shipbuilding," in Erickson (ed.), *Chinese Naval Shipbuilding*, p. 145; Hall and Wong, "Key Factors in Chinese Shipyards' Development, p. 104.

[32] 青岛科技的"引进来"和"走出去 ["The 'Bringing In' And 'Going Out' of Qingdao's Science and Technology"], *Sina.com.cn*, 19 May 2018, https://web.archive.org/web/20221005222519/http://news.sina.com.cn/c/2018-05-19/docihaturfs5184650.

[33] 张严 [Zhang Yan], 武志东 [Wu Zhidong], and 张玉玲 [Zhang Yuling], 美英潜艇指控系统发展历程及启示 ["Development of U.S. and British Submarine Command Systems and Enlightenment"], 数字海洋与水下攻防 [*Digital Ocean & Underwater Warfare*], no. 6 (2022), p. 558. Slightly corrected machine translation.

[34] Elsa Kania, "Chinese Military Innovation in Artificial Intelligence", Testimony before the U.S.-China Economic and Security Review Commission Hearing on Trade, Technology, and Military-Civil Fusion on 7 June 2019, p. 25, https://www.uscc.gov/sites/default/files/June%207%20Hearing_Panel%201_Elsa%20Kania_Chinese%20Military%20Innovation%20in%20Artificial%20Intelligence_0.pdf.

Besides these locations, numerous other R&D and production facilities involved in areas related to submarine and anti-submarine warfare are scattered throughout the country. See the report Appendix.

Market Size and Capital Flows into China's Submarine Industry

Naval shipbuilding, like arms production in general, is effectively monopolistic in China. Due to a functional differentiation, this was the case even before the 2019 merger of the two large state-owned shipbuilding conglomerates, China Shipbuilding Industry Corporation (CSIC) and CSSC, into one entity named "CSSC." The sector remains characterized by "balkanization," which likely leads to some inefficiencies and an unexpected lack of profitability—despite the world's fullest order books.[35] To blame may be exceptionally high development costs of several ambitious prototype projects: two different aircraft carrier types, the latest equipped with EMALS catapults; two new classes of nuclear-powered submarines; plus, the build-up (together with the defense electronics conglomerate CETC) of a vast ocean information network (海洋信息网络) that likely costs CSSC and its subsidiaries significant funds to co-develop.[36]

How are the funds necessary to sustain such a gigantic effort provided? All naval shipyards attract commercial orders globally that might offset some of the cost of naval R&D.[37] More impactful than that, however, has been a consistent state strategy of providing extensive credit lines from state-owned banks to the defense sector and tapping domestic and foreign securities markets via asset securitization and other vehicles, often by listing a state-owned defense conglomerate's subsidiaries on stock exchanges.[38]

In Xi Jinping's China, naval shipbuilding has continuously enjoyed strong political and financial backing, and capital as the "critical enabler" of defense modernization has been made available in abundance to China's shipyards. The maze of cross-shareholdings between Chinese defense industries, semi-private subsidiaries, and state-owned banks created since the mid-2000s has been dubbed a "military-industrial-financial complex."[39] And despite a recent economic downturn following Xi's "zero-COVID" policy, China's latest state budget showed that defense spending continues to outpace economic growth as well as other spending priorities.[40]

A market analysis conducted in 2020 as part of a securities firm's company evaluation of the listed underwater communication electronics firm China Haiphong (中国海防) unsurprisingly predicted strong growth in naval procurement funding for the mid-term. Based on an analysis of official Chinese documents, the study predicted a total domestic naval equipment expenditure volume of 214.5 billion RMB (ca. $30.7bn) for the year 2025 alone. Total market size for naval equipment expenditures during 2020-2025 was estimated to amount to 1 trillion RMB (ca. $143.4bn), including newly procured warships, R&D cost for experiments, ship modifications,

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[35] Sarah Kirchberger and Johannes Mohr, "China's Defence Industry," in Keith Hartley and Jean Bélin (eds.), *The Economics of the Global Defence Industry* (London: Routledge, 2019), pp. 35-68; see in particular pp. 55, 59-60.

[36] "Exploring China's Unmanned Ocean Network," CSIS AMTI, 16 June 2020, https://amti.csis.org/exploring-chinas-unmanned-ocean-network/.

[37] Matthew P. Funaiole, Joseph S. Bermudez Jr., and Brian Hart, "China's Opaque Shipyards Should Raise Red Flags for Foreign Companies," CSIS, 26 February 2021, https://www.csis.org/analysis/chinas-opaque-shipyards-should-raise-red-flags-foreign-companies.

[38] Tai Ming Cheung, *Fortifying China: The Struggle to Build a Modern Defense Economy* (Ithaca, NY: Cornell University Press, 2009), p. 125; IISS, *The Military Balance 2018* (London: Routledge, 2018), p. 234.

[39] Kirchberger and Mohr, "China's Defence Industry," pp. 52-53.

[40] Kathrin Hille, "China's Military Budget Outpaces Other Spending in Shift to Security," *Financial Times*, 5 March 2023, https://www.ft.com/content/66790beb-bd5b-4025-b12e-5d0e7dd8bbfb.

naval weapon systems, support facilities construction, as well as maintenance and upgrades.[41] In light of the heavy financial burden that warship procurement imposes on future generations in terms of lifetime maintenance and operation costs, experts have expressed skepticism regarding the sustainability of such an aggressive shipbuilding trajectory. Maintenance alone typically costs as much over the entire life-cycle of a warship as the initial procurement.[42] Submarines, and in particular nuclear-powered submarines, are among the costliest weapon systems that can be procured, as they require extensive R&D on multiple technical frontiers. The same is true for next-generation aircraft carriers that China is building simultaneously. In line with the financial requirement, total R&D funding has massively increased over the past three decades, growing by a factor of 35 between 1991 and 2018 to a level of $462.6bn, or more than the combined total R&D funding spent by Japan, Germany, South Korea, and France.[43]

An unknown, but likely sizeable portion of China's R&D funding has been funneled into undersea warfare systems, including submarines. Evident from models and brochures shown at defense exhibitions, a wide variety of unmanned and robotic underwater vehicles are under development in China.[44] Sometimes developments are deliberately leaked. In 2018, for example, the lead designer of a hitherto unnoticed "Project 912" disclosed the ongoing development of XLUUVs for defensive and offensive purposes, "from reconnaissance to mine placement to even suicide attacks against enemy vessels." The timeframe named for their deployment was "the 2020s."[45] Kania in 2019 assumed this to be more signaling than imminent development.[46] By early 2023, however, an image of a heavily armed Chinese XLUUV had been unveiled at the NAVDEX 2023.[47] While it remains unclear whether this XLUUV image corresponds to "Project 912," it was identified as a product of CSSC's 705th Research Institute, a.k.a. the Xi'an Precision Machinery Institute (XPMRI), a torpedo maker. In its company brochure, XPMRI claims to be China's "only institute capable of overall design of underwater weapon and matched launcher in China [sic]" and being "mainly engaged in the development of lightweight torpedo [sic] for ships, heavyweight torpedo for submarines, launchers for ships and submarines and underwater special equipment," having developed more than ten types of torpedoes and launchers for the PLAN. While headquartered in Xi'an, it has branches in Kunming and Shanghai, with 2,470 employees, one doctoral program (in hydroacoustic engineering) and two master's degree programs, as well

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[41]浙商证券有限公司 [Zheshang Securities Co. Ltd.], 舰船水声防务龙头,内生外延双轮驱动──中国海防深度报告 ["A Leader In Naval Hydroacoustic Defense, On A Two-Wheel Drive From Domestic Origins to Outward-Looking Expansion—In-Depth Report About CSSC China Marine Information Electronics Company Ltd./China Haiphong"], Hangzhou: Zheshang Securities (https://www.stocke.com.cn/), 7 February 2021, https://pdf.dfcfw.com/pdf/H3_AP202202081545678276_1.pdf?1644326407000.pdf, p. 17.

[42] Christopher P. Carlson, "China Maritime Report No. 10: PLAN Force Structure Projection Concept, A Methodology for Looking Down Range," China Maritime Studies Institute, November 2020, pp. 11-12, https://digital-commons.usnwc.edu/cmsi-maritime-reports/10/.

[43] "How Developed Is China's Arms Industry?", CSIS China Power Project, 18 February 2021, Updated February 25, 2021, https://chinapower.csis.org/arms-companies/.

[44] See the collection of Chinese industry brochures on underwater warfare systems, including gliders, UUVs, submarine decoys, the "FishBot" UUV, export submarines, and ocean surveillance network technologies published by Wendell Minnick in 2019: W. Minnick, *Chinese Submarines and Underwater Warfare Systems,* independently published, https://www.amazon.com/-/de/dp/1794009442/.

[45] Stephen Chen, "China Military Develops Robotic Submarines to Launch a New Era of Sea Power," *South China Morning Post,* 22 July 2018, www.scmp.com/news/china/society/article/2156361/china-developing-unmanned-ai-submarines-launch-new-era-sea-power.

[46] Kania, "Chinese Military Innovation," p. 13.

[47] H.I. Sutton, "China Reveals New Heavily Armed Extra-Large Uncrewed Submarine," *Naval News,* 23 February 2023, https://www.navalnews.com/naval-news/2023/02/china-reveals-new-heavily-armed-extra-large-uncrewed-submarine/.

as advanced test and simulation facilities.[48] Developing XLUUVs nonetheless seems to be a new venture for this institute.

Performance of China's Submarine-Related Industries: Implications for China's Future Submarine Force

Since the 1970s, China's shipbuilding industries have succeeded—with Russian design assistance—in producing the indigenous "Han" (Type 091) and "Shang" (Types 093, 093A and 093B)-class SSNs, while work on the next-generation Type 095 class SSNs is already ongoing. China has also succeeded in developing a single indigenous "Xia" (Type 092) class SSBN, as well as the "Jin" (Types 094 and 094A)-class SSBNs—again with Russian design assistance. Meanwhile design work and perhaps construction on the next-generation Type 096 is reportedly underway.[49] In the field of smaller, conventionally-powered submarines, China has indigenously produced the Type 035G/035B "Ming," the Type 039 "Song," and Types 093A, 093B and 093C "Yuan"-class submarines, all the time copying and adapting various foreign technologies. The latest designs have demonstrated marked improvement over earlier submarine classes.

Lingering Problem Areas: Propulsion and Quieting of Nuclear Submarines

Recent stunning advances in UUVs and other undersea warfare-related emerging and disruptive technologies (EDTs) notwithstanding, China's submarine design and construction system has long struggled with producing some fundamental technologies that determine the value of a submarine as a weapon system, most notably reactor design, advanced air-independent propulsion systems (AIP), and quieting technologies.[50]

In January 2018, a Type 093A "Shang"-class SSN was reportedly detected and tracked continuously for two days by Japanese ASW aircraft and ships near the Senkaku Islands before it surfaced in full view of the pursuers. Beijing-based commentators considered this "a shame," pointing out that this "too noisy" boat's acoustic signature would now have been recorded and its physical features observed in detail by the Japanese. Why it surfaced remains unclear, but it may have been due to technical problems or the need to communicate. In 2004, another incident was reported where an earlier-generation (and much noisier) Type 091 "Han"-class SSN had been detected in the same area and "chased by Japanese ships and planes dropping sonobuoys."[51] And in the summer of 2021, a Russian analyst commented on reports that when transiting the South China Sea in July, British ASW forces aboard the HMS *Kent* and HMS *Richmond*, working in tandem with an *Astute*-class SSN to protect the aircraft carrier *Queen Elizabeth II*, had detected and identified three Type 093B/G "Shang"-class SSNs that were following the carrier within tens of kilometers distance. Deeming this account plausible, given the estimated hydroacoustic characteristics of the Chinese SSN (which he supposes to fall somewhere between 80-100db when traveling at the speed necessary to follow a transiting carrier, given they have propellers and no pump-jet), and given the reported sensitivity of the passive ASW sensors carried by the British ships, the seemingly knowledgeable analyst remarked that "it is well known that Chinese

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[48] Minnick, *Chinese Submarines,* p. 15.

[49] U.S. Department of Defense, *Military and Security Developments Involving the People's Republic of China 2022: Annual Report to Congress*, https://media.defense.gov/2022/Nov/29/2003122279/-1/-1/1/2022-MILITARY-AND-SECURITY-DEVELOPMENTS-INVOLVING-THE-PEOPLES-REPUBLIC-OF-CHINA.PDF, p. 96.

[50] See the detailed discussion of Chinese reactor design related issues in Andrew S. Erickson, Jonathan Ray, and Robert T. Forte, "Underpowered: Chinese Conventional and Nuclear Naval Power and Propulsion," in Erickson (ed.), *Chinese Naval Shipbuilding*, pp. 242-244.

[51] Liu Zhen, "Is China's Nuclear Attack Submarine Too Easy To Detect?", *South China Morning Post,* 28 January 2018, https://www.scmp.com/news/china/diplomacy-defence/article/2130870/chinas-nuclear-attack-submarine-too-easy-detect.

specialists have much less experience in designing specialized sound-absorbing coatings than, for example, specialists of the [Russian design bureau] SPMBM Malakhit, which developed the 885 Yasen nuclear multi-purpose submarine, or General Dynamics Electric Boat/BAE Systems, which designed and regularly upgrades the *Virginia*-class submarine." Deficiencies in anechoic coating would render the Type 093B more vulnerable to detection by active sonar as well, even at lower speeds.[52]

Discussion of Chinese SSN and SSBN classes in Russian military publications generally tend to emphasize their shortcomings in comparison to their far more advanced Russian and Western counterparts. Regarding the Type 093 "Shang"-class SSN's acoustic profile, one Russian commentator highlights its lack of a pump-jet and notes that "Chinese engineers struggled for a long period with vibration suppression issues from the shock absorption platform that houses the steam turbine along with circulation pumps, turbo charger and other equipment."[53]

Academy of Military Science researcher Colonel Ma Hongwei (马宏伟), the author of a 2020 book on China's navy, claims that the next-generation SSN—the Type 095—will overcome such deficiencies by adopting a whole series of "six world-leading new technologies": a new pump-jet propulsion system; ultra-high-strength steel (presumably allowing for greater diving depths); a single-double hybrid hull structure; a new integrated shock-absorbing floating raft for improved quieting; a vertical launch system (VLS) for cruise missiles; and China's "third-generation submarine reactor."[54] Another Chinese commentator likewise mentions the "new generation of reactor technology" of the new submarines, and points out that China has the world's largest 80,000-ton forging hydraulic press as well as "super steel with a yield strength of 2,000 MPa, which is the world's top level"—presumably a precondition for more pressure-resistant hulls and deeper diving depths.[55]

Colonel Ma gives the following concrete performance data for the Type 095-class SSN: A maximum underwater speed of no less than 33kn, silent speed of no less than 18kn, and a maximum diving depth of no less than 600m. This would put the Type 095 in a different league than its predecessors. He also indicates that on the basis of the Type 095 SSN, China also intends to develop a cruise missile-armed nuclear submarine carrying multiple integrated cruise missile launchers.[56]

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[52] Евгений Даманцев [Evgeny Damantsev], Инцидент с игрой в кошки-мышки между британской АУГ и китайскими МАПЛ типа 093 обрастает подробностями ["The Cat-And-Mouse Game Between the British Carrier Strike Group and China's Type 093 SSNs In Greater Detail"], Военное обозрение [*Military Review*], 27 August 2021, https://web.archive.org/web/20230328200957/https://topwar.ru/186287-incident-s-igroj-v-koshki-myshki-mezhdu-britanskoj-aug-i-kitajskimi-mapl-tipa-093-obrastaet-podrobnostjami.html, transl. O. Husieva.

[53] Евгений Даманцев [Evgeny Damantsev], Операция НОАК по выдворению ВМС США из Южно-Китайского моря. Детали «Бьендонгской зоны A2/AD» - часть 2 ["PLA Operation to Expel the U.S. Navy from the South China Sea. Details of the Bien Dong A2/AD Zone—Part 2"], Военное [*Military Review*], 5 July 2017, https://web.archive.org/web/20230326165817/https://topwar.ru/119466-operaciya-noak-po-vydvoreniyu-vms-ssha-iz-yuzhno-kitayskogo-morya-detali-bendongskoy-zony-a2-ad-chast-2.html, transl. O. Husieva.

[54] 马宏伟 [Ma Hongwei], 走向深蓝的中国海军 [*The Chinese Navy on the Way Towards Deep Blue*], (Shanghai: Fudan University Press, 2020), pp. 169-170.

[55] "JL-3 Missile to Change China's Emphasis of Nuclear Triad," *China-Arms*, 24 June 2019, https://web.archive.org/web/20230323111129/https://www.china-arms.com/2019/06/jl-3-missile-to-change-chinas-emphasis-of-nuclear-triad/.

[56] Ma, *The Chinese Navy on the Way Towards Deep Blue*, pp. 160-170. The same performance data is cited in a 2021 piece by another Chinese military commentator on Zhihu, see: 候博士 [Hou Boshi], 中国 096 型核潜艇，号称"海洋杀手"，达到世界先进水平 ["China's Type 096 nuclear submarine, known as the 'ocean killer', has reached the world's advanced level"], 知乎 [*Zhihu*], 12 March 2021, https://zhuanlan.zhihu.com/p/356559941; an English

Hull-Related Innovations

So far, China's nuclear submarines have been double-hulled. Evidence potentially supporting Colonel Ma's claim of a single-double hybrid hull design of the future Type 095-class SSN was discovered in November 2022 by submarine expert Tom Shugart using satellite imagery. He noted pressure hull segments of two different diameter sizes at Huludao Shipyard—about 9m, as previously used in the Type 093, and a larger diameter size of roughly 12m. These could be intended for the Type 095 SSN or the Type 096 SSBN.[57]

The hull design of the latest currently operational SSBNs—Type 094/Type 094A "Jin" —has been criticized for its so-called "turtle shape," which has been described as "fundamentally flawed in that the large missile compartment at the rear of the vessel and the flood openings below the missile hatches create a detectable sonar signature" at higher speeds, making the acoustic signature of these boats even worse than 1970s Soviet-era designs such as the Delta III-class SSBNs and Victor III-class SSN.[58] Chinese commentators blame the less-than-ideal turtle shape on "poor technical strength at the time" and on the need to integrate the JL-2 SLBM that was longer than its predecessor, the JL-1. By contrast, the Type 096 SSBN is expected to be much quieter, with military expert Chen Guangwen giving it an expected noise value of less than 105db.[59]

Apart from quieting concerns, hull strength and stability for potential operations in ice-covered waters seems to have become another, relatively recent R&D concern, as at least two studies by researchers from the School of Ship Engineering at Harbin Engineering University indicate. They discuss the mathematical modeling of submarine contact with ice sheets. In the abstract of the 2018 study "Peridynamic Model for Submarine Surfacing Through Ice," Ye Liyu (叶礼裕) and colleagues note that

> the political and military value of submarines in the [Arctic] region has been well recognized. Although the thick ice in the Arctic provides natural protection, it also poses a risk to submarines during the surfacing process. A method for accurately predicting the ice surfacing process and transient ice loads can be the most important issue in the design of submarine shells and choice of ice thickness.[60]

A 2020 article by the PLA naval engineer Huang Jiaqiang (黄加强) confirms suspicions that Chinese researchers have indeed begun to systematically look into the detailed technical

translation of that article by MEMRI is available at https://www.memri.org/reports/chinese-commentator-chinas-type-096-nuclear-submarine-paired-jl-3-third-generation.

[57] Tom Shugart @tshugart3, "Submarine pressure hull sections seen here in the past have mostly been 9-10m in diameter, as used in the Shang & Jin class SSNs/SSBNs. But this imagery shot shows what looks like another pressure hull section that is roughly 12m in diameter. Could this be for the 095/096?", Twitter, 9 November 2022, 07:10 pm, https://twitter.com/tshugart3/status/1594030283279503361/photo/1.

[58] Christian Conroy, "China's Ballistic-Missile Submarines: How Dangerous?", *The National Interest*, 18 November 2013, https://nationalinterest.org/commentary/chinas-ballistic-missile-submarines-how-dangerous-9414.

[59] "JL-3 Missile to Change China's Emphasis of Nuclear Triad."

[60] 叶礼裕 [Ye Liyu], 王超 [Wang Chao], 郭春雨 [Guo Chunyu], and 常欣 [Chang Xin], 潜艇破冰上浮近场动力学模型 ["Peridynamic Model for Submarine Surfacing Through Ice"], 中国舰船研究 [*Chinese Journal of Ship Research*], vol. 13, no. 2 (2018), pp. 51-59; and 叶礼裕 [Ye Liyu], 王超 [Wang Chao], 常欣 [Chang Xin], and 张洪雨 [Zhang Hongyu], 冰桨接触的近场动力学模型 ["Peridynamic Model for Propeller-Ice Contact"], 哈尔滨工程大学学报 [*Journal of Harbin Engineering University*], vol. 39, no. 2 (2018), pp. 222-228.

requirements of constructing submarines capable of operating under an Arctic ice sheet.[61] To what extent such an ambition is condoned or even supported by Russia remains an open question. Research by Frank Jüris points to an intense research collaboration between Chinese R&D institutions with strong military ties and Russian counterparts on sensitive subjects including hydroacoustics, undersea communication, and fiber-optic hydrophone development in Arctic waters for use under the ice. So-called "China-Russia Polar Acoustic Symposia" (中俄极地声学与信息技术论坛) have been organized at least three times since mid-2019, involving over 100 experts from Russia and China from 30 military research facilities and companies, indicating a surprising openness on the part of Russia to collaborate with China in such fields. The collaboration seems to also encompass underwater communication and underwater robotics.[62]

Survivability and Reliability Concerns: No More Accident-Prone Subs?

The focus on hull strength and survivability is not surprising, given that China's earlier diesel-electric submarines seem to have been particularly accident-prone. In April 2003, an entire crew of 70 suffocated aboard the Type 035G "Ming"-class submarine No. 361 due to a malfunction with the diesel engine, in China's worst known submarine accident to date.[63] Other Type 035 and Type 033 submarines seem to have been lost as well in previous accidents, although public reporting about the causes has been scarce.[64]

One relatively recent incident concerned the Pr. 636 Kilo-class submarine No. 372, which narrowly escaped destruction in the South China Sea when it was pulled into a "deep eddy" and plunged uncontrollably nearly until crush depth. Giant undersea eddies have been found by scientists to form frequently within the Xisha Trough (西沙海槽) between Hainan Island and the Paracel Islands, and the accident is therefore thought to have occurred in that area.[65]

A dramatic report in the *People's Daily* details the accident:

> On that day, the 372 submarine was diving silently in the ocean […] when it suddenly made a "deep fall" and sank rapidly. In the blink of an eye, the submarine was approaching its maximum diving depth […]. At the same time, […] the water pressure on the submarine steeply increased, and a pipe in the main engine room ruptured, causing seawater to spurt into the room. The main engine room is the "heart" of the submarine;

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[61] 黄加强 [Huang Jiaqiang], 北极航行对潜艇航行性能影响研究 ["Research on Submarine Navigation in the Arctic"], 舰船电子工程 [*Ship Electronic Engineering*], vol. 40, no. 9 (September 2020), pp. 62-66.

[62] For further detail on the involved organizations, see Frank Jüris, "Sino-Russian Scientific Cooperation in the Arctic: From Deep Sea to Deep Space," in Sarah Kirchberger, Svenja Sinjen, and Nils Wörmer (eds.), *Russia-China Relations: Emerging Alliance or Eternal Rivals?* (Bonn, Germany: Springer, 2022), pp. 189-90, 192-195. For a report on the 3rd "China Russia Polar Acoustics and Information Technology Forum" on 6 May 2023, see Harbin Engineering University's press release "The Key Laboratory of Polar Ocean Acoustics and Technology Applications of the Ministry of Education was unveiled and established," Harbin Engineering University, 8 May 2023, archived version available at https://web.archive.org/web/20230601161440/https://english.hrbeu.edu.cn/info/1101/3515.htm.

[63] John Pomfret, "Chinese Submarine Accident Kills 70," *Washington Post*, 3 May 2003, https://www.washingtonpost.com/archive/politics/2003/05/03/chinese-submarine-accident-kills-70/755b8587-e1b2-4eba-a1fc-e88e4eb9c016/.

[64] See the compilation of presumed PLAN accidents due to technical malfunction in Sarah Kirchberger, *Assessing China's Naval Power: Technological Innovation, Economic Constraints, and Strategic Implications* (Berlin, Germany: Springer, 2015), p. 224.

[65] Stephen Chen, "'Underwater Tornadoes' Found Near China's Nuclear Submarine Base By Paracels That Could Sink U-Boats In Treacherous Abyss," *South China Morning Post*, 10 December 2015, https://www.scmp.com/tech/science-research/article/1889226/underwater-tornadoes-found-near-chinas-nuclear-submarine-base.

> once flooded, this will paralyze the power system, cause electrical short circuits and fire, and accelerate the speed of the submarine's descent.

Describing heroic efforts by the crew to save the boat, the article continues:

> The commanding officer, Wang Hongli […] made bold decisions and commanded calmly, giving dozens of instructions to each station in less than a minute; [crew members] Chen Zujun, Zhu Zhaowei and Mao Xuegang reacted instantly, cutting off their own "escape way" by closing the main cabin door to plug the leak; mine bomb class squad leader Zeng Gang grabbed the ventilation insert handle in the dark, […] with only 20 seconds to complete an action that normally takes one minute to complete […]. In the critical moment of such a close call, with life and death hanging in the balance, the whole boat's officers and men worked together in unity, calmly and collectedly, […] struggled to remove the danger, finally getting the submarine to float, and avoided a major disaster that would have destroyed the boat and killed everyone on board."[66]

The South China Sea saw another incident in October 2017, when a Type 094 "Jin"-class SSBN suddenly surfaced amidst Vietnamese fishing vessels near the Paracel Islands. The cause for this unusual maneuver was not made public, but would most likely have been related to technical difficulties of some kind.[67]

The Impact of Russian and Western Design Assistance and Technologies

Soviet, and later Russian, expertise has been the most consistently available to China's submarine design community. Therefore, assessments from Russian industry and military experts who have had close contact with that community and its products are often revealing. The Russian Rubin Design Bureau in particular was reportedly heavily involved in assisting the designers of the Type 093 "Shang"-class SSN in the areas of hull design, instrumentation, acoustic stealth improvement, and development of acoustic countermeasure systems.[68]

In the field of conventionally-powered submarines, Russian support has likewise been crucial. Not only were China's earliest indigenous submarines modeled on the Russian "Romeo"-class, Russia later exported two Pr. 977 EKM "Kilo" and ten Pr. 636 "Improved Kilo"-class submarines to China as complete weapon systems including all sensors and armament and provided extensive support and training and maintenance services, with Russian personnel reportedly stationed in a permanent "support cocoon."[69] The purchase of these Kilos gave Chinese experts access to a wide range of new weapons and sensors that formed the basis of later indigenous developments.

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[66] 372 潜艇成功排险，带伤突破外军舰机立体反潜网 ["Submarine 372 Successfully Defeats Danger, Breaks Through Foreign Ships' and Aircraft's Three-Dimensional Anti-Submarine Network While Wounded"], 人民日报 [*People's Daily*], 18 December 2014, https://web.archive.org/web/20230324231812/http://military.people.com.cn/n/2014/1218/c1011-26231738.html. Slightly corrected machine translation.

[67] Jamie Seidel, "'Highly Unusual Event': Chinese Nuclear Sub In 'Embarrassing' South China Sea Incident," *News.com.au*, 17 October 2019, https://www.news.com.au/world/asia/highly-unusual-event-chinese-nuclear-sub-in-embarrassing-south-china-sea-incident/news-story/650d17f451e27338e912f4b072cfcb02.

[68] Richard D. Fisher, Jr., "The Impact of Foreign Technology on China's Submarine Force and Operations," in Andrew S. Erickson, Lyle J. Goldstein, William S. Murray, and Andrew R. Wilson (eds.), *China's Future Nuclear Submarine Force* (Annapolis, MD: Naval Institute Press, 2007), p. 135; Damantsev, "PLA Operation to Expel the U.S. Navy from the South China Sea."

[69] Bussert and Elleman, *People's Liberation Army Navy Combat Systems Technology*, p. 33.

In addition to these Russian transfers, some Western transfers have also been impactful for submarine design, such as Stirling engine technology from Sweden. And rather ominously, the above quoted Colonel Ma Hongwei writes that the Chinese Navy has "conducted technical exchanges with Western countries through certain channels, obtained relevant technologies in the line design of modern surface ships and submarines, and received important technical support in the overall layout of ship modernization" even after the imposition of the arms embargo in 1989.[70] It is unclear which countries and technologies this remark refers to. Before 1989, U.S. and European surface warfare weapons, sensors including radars and sonars, C2 systems, and propulsions plants such as German and French marine diesels and American naval gas turbines were transferred to China. Various Chinese and Russian sources furthermore state that during the 1980s Swedish naval shipbuilder Kockums AB provided China with Stirling engine technology, which was then copied and developed further, forming the basis for China's later indigenous development of a more powerful Stirling AIP system.[71]

Conventional AIP Propulsion and Its Impact in the Chinese Context

Given conventional submarines' far shorter endurance and slower speed compared with nuclear-powered submarines, some observers wonder why nations capable of building nuclear subs such as China, Russia, or France still engage in conventional submarine development at all, investing considerable resources into advanced conventional AIP systems. However, considering the maritime geography of complex and shallow littorals that make up much of China's directly accessible waters, this seems far from surprising, as such environments are suitable for smaller, quieter submarines operating in an area-denial role. AIP makes a key difference here, giving China's conventional submarine fleet the ability to operate more effectively in the presence of advanced U.S. and Japanese airborne ASW assets. As a Chinese military commentator noted in 2014, China's older diesel-electric boats can submerge no longer than 2-3 days and cover no more than about 200 nm before having to recharge their batteries at snorkeling depth, a process which takes 6-14 hours and exposes them to U.S. and Japanese ASW assets.

Furthermore, a difficult maritime geography poses additional operational challenges to China's East Fleet submarines:

> After leaving Zhoushan base […], the sea […] is relatively shallow. The shallowest part is only 20 meters, and the average water depth is less than 50 meters. The East Sea Fleet's conventional submarines need to sail about 200-300 nm on the sea surface to reach diving sea areas with a safe depth for submarines. Therefore, in the face of […] anti-submarine operations by Japan and the United States, the exposure rate of our country's submarine forces is very high. Japan and the United States rely on […] a developed and perfect space-based intelligence support system to quickly obtain the movement situation and maneuvering direction of our submarine force. On this basis, Japan and the United States can use the world's largest and most advanced P-3C fixed-wing anti-submarine fleet to cover the Okinawa Trough and the first island chain area from east to west in the submarine breakthrough area of our conventional submarines, with a depth of 300 to

[70] Ma, *The Chinese Navy on the Way Towards Deep Blue*, pp. 70-71.

[71] Евгений Даманцев [Evgeny Damantsev], Допрыгались! 7-й флот ВМС США попадёт на мушку уникальной модификации «Палтуса» ["You've had it! US 7th Fleet Hits the Target of a Unique Modification of the Project 877 Paltus"], Военное обозрение [*Military Review*], 18 September 2018, https://topwar.ru/147131-doprygalis-7-j-flot-vms-ssha-popadet-na-mushku-unikalnoj-modifikacii-paltusa.html; 中国 AIP 潜艇为何强：发动机功率超国外 117% ["Why China's AIP Submarine Is Strong: Engine Power Exceeds Foreign Countries by 117%"], 军事要闻观察者网 [*Military News Observer Network*], 5 May 2015, https://web.archive.org/web/20150726040029/http://news.qq.com/a/20150505/050443.htm.

> 400nm. […] This to a large extent curbs the conventional submarine force of our East China Sea Fleet, the ability to break through the island chain eastward, enter the Taiwan Strait area southeast, and enter the Japanese coastal area northeastward.[72]

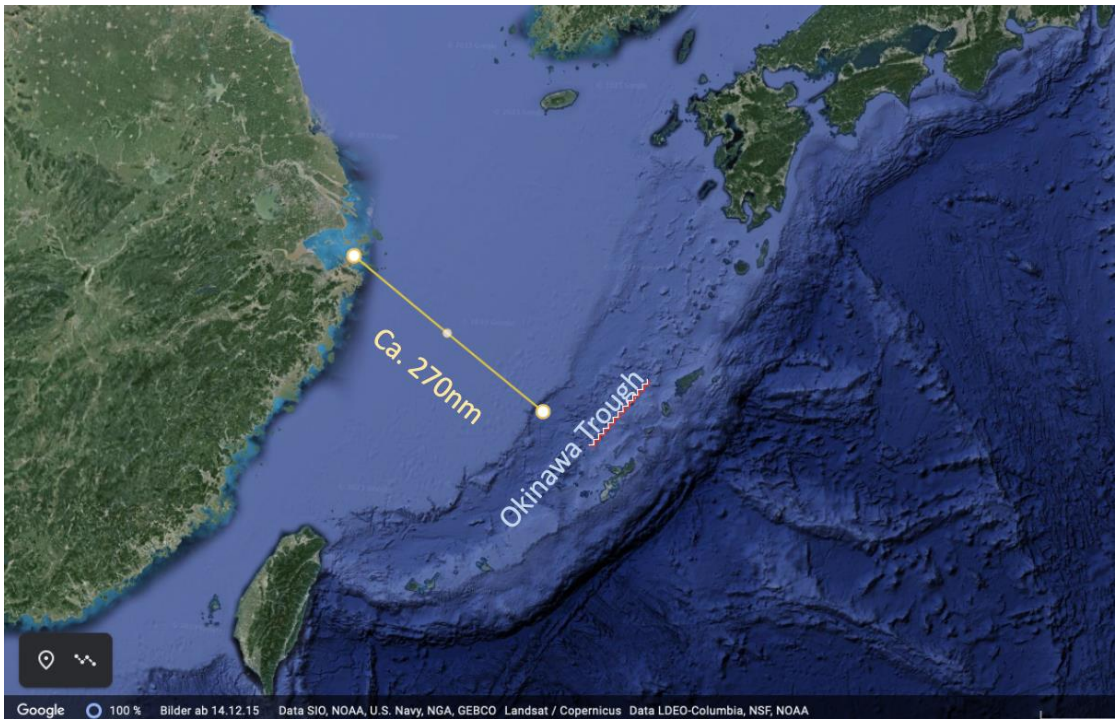

Figure 2: Distance from the PLAN submarine base in Zhoushan to safe diving depths in the Okinawa Trough

AIP propulsion, which gives conventionally-powered submarines the ability to charge their batteries while submerged and stay submerged for up to 20 days, immediately changes the parameters of this tactical situation. Noting the great difficulty of detecting small, quiet AIP-equipped submarines in a complex littoral environment with fixed-wing aircraft using airborne radar and infrared sensors, the above cited commentator claims that:

> [the Type 039A/B "Yuan"-class's] AIP has allowed the Chinese submarine force to secretly sneak into Japan's Kyushu, Shikoku and Honshu to the southwest, and it can also quickly rush to the central part of the Philippine Sea. In fact, thanks to AIP, the combat range of the Chinese submarine force has expanded nearly 10-fold, and a series of new doctrine and tactics have emerged as the times require. […] This means that the submarines of our two main fleets will be able to gain the mobile combat capability to attack dense commercial routes near the eastern part of Japan after breaking through the island chain in a covert manner. Such a strategic posture has far-reaching significance for the deterrence and combat effectiveness of the PLAN's submarine force.[73]

Nonetheless, Chinese commentators also note that the limitations on China's earlier AIP performance still posed problems that needed addressing through further R&D:

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[72] 深度:浅谈中国海军 039 潜艇 AIP 技术成战略意义 ["In Depth: Talking about the Strategic Significance of the Chinese Navy's 039 submarine AIP technology"], *Sina Military*, 18 February 2014, https://web.archive.org/web/20230325232533/https://mil.news.sina.com.cn/2014-02-18/1533764810.html. Slightly corrected machine translation.

[73] Ibid.

> Due to the small power of the Stirling engine, the underwater charging speed of the Type 039B submarine is relatively slow. After a few hours of cruising underwater at 20kn, it may take days of "wandering" underwater at around 2kn to recharge the main battery. It can be seen that increasing the power of the Stirling engine is a key technology to improve the performance of the Type 039B and the new generation of AIP submarines in the future.[74]

Further Progress on China's Indigenous Stirling AIP Development

Chinese commentators note that work on a Stirling engine for submarines began after first acquiring the technology from Sweden during the early 1980s. In 1998, the 711th Research Institute succeeded in developing the first prototype with "completely independent intellectual property rights," and by 2002 it managed to develop a first engineering prototype, finalized by 2005, that came "close to the performance of Sweden's V4-275R series."[75] If that timeline is correct, then the first fully functional Stirling engine AIP system could not have been integrated into submarines built before 2005, which apparently excludes the Type 039A "Yuan"-class (unless they were fitted with it retroactively). And indeed, the above quoted source states that: "It is speculated that after adopting AIP power, the *Type 039B boat* can continuously submerge 2,300 to 2,500nm at a speed of 4kn, which is several times that of the early type 039A" (emphasis added).[76] Another commentator also explicitly mentions the Type 039B-class as the first submarine to be fitted with the newly developed Stirling AIP engine, and credits the "special engine team" of the 711th Research Institute's Heat Engine Division for at least a decade of hard work, noting that their engine yields about 117 percent more power than comparable engines on the market.[77]

In 2021, official Chinese media announced the creation—again by the 711th Research Institute—of an even more powerful Stirling engine, noting that "the prototype ran at a rated power of 320 kilowatts with a power conversion efficiency of 40 percent, making it the most powerful Stirling engine known around the globe." Notably, this development could also improve China's nuclear propulsion systems. As the press release notes, this breakthrough lays the groundwork for the development of "megawatt-class Stirling engines in the future" that, "when used together with a sodium-cooled fast reactor, […] can eliminate the risk of sodium-water reaction" and make it suitable for development into a "portable micro reactor power generator used in special environments such as polar regions, remote islands and Gobi Desert regions"—or, as it is also noted, for use in future submarine propulsion.[78] Could a Stirling engine indeed enhance future nuclear submarine reactors? At least theoretically, this seems possible:

> Stirling engines have been considered as a substitute for the steam turbines that generate electricity in most nuclear power plants. *Interesting Engineering* notes "liquid sodium could be used as coolant and water may not be required at all, Stirling engines can also increase the output of a nuclear reactor and decrease the amount of radioactive waste generated by the same."[79]

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[74] "Why China's AIP Submarine Is Strong: Engine Power Exceeds Foreign Countries by 117%."

[75] "In Depth: Talking about the Strategic Significance of the Chinese Navy's 039 submarine AIP technology."

[76] Ibid.

[77] "Why China's AIP Submarine Is Strong: Engine Power Exceeds Foreign Countries by 117%."

[78] Liu Xuanzun, "China Develops World's Most Powerful Stirling Engine," *Global Times,* 22 December 2021, https://www.globaltimes.cn/page/202112/1243157.shtml.

[79] "China Eyeing Deadlier Submarines, Safer Nuclear Reactors With New Stirling Engine?", *The Week,* December 2021, https://www.theweek.in/news/sci-tech/2021/12/24/china-eyeing-deadlier-submarines-safer-nuclear-reactors-with-new-stirling-engine.html.

Russian commentators have noted the Chinese Stirling AIP engineering success with envy, Russia not having managed to deploy any AIP-equipped conventional submarines so far despite years of multi-pronged R&D and despite having far more experience designing and constructing submarines. Writes Evgeny Damantsev,

> According to knowledgeable sources [in China], the Chinese prototypes were able to be upgraded to 220hp, which is unique. The next step announced by the Chinese experts is to bring the power of these prototypes up to 352hp. Hence, the four Stirling engines installed on Type 039B/C submarines will provide a total power of 1,408hp, which is only 42 percent less than the output from two diesel generators on the Varshavyanka [Pr. 636 "improved Kilo"]-class submarines. This means that the battery recharging time of Chinese Type 039B/C submarines in submerged mode will be as close as possible to that of Varshavyanka and [Pr. 877 "Kilo"] Paltus.[80]

The same observer credits the success of the 711th Research Institute to concentrating their efforts on one type of technology instead, like Russia's Rubin Design Bureau, "spreading themselves too thinly" by researching fuel cells and lithium-ion battery technology in parallel.[81] The manufacturer of the Stirling AIP system for the Yuan-class subs seems to be a subsidiary of the 711th Research Institute, Shanghai Qiyao Power Technology, Ltd. alias MicroPowers (齐耀动力).[82]

The Curious Case of Lacking Indigenous Diesel Engines for Export Submarines

Chinese submarines rely on an imported, license-produced marine diesel from the German engine-maker MTU, whose 396 SE84 diesel seems to power all the Song- and Yuan-class submarines that China currently operates.[83] That this is indeed the case became apparent recently in the course of China's submarine export project with Thailand. After China in 2017 won a contract for one S26T "Yuan"-class submarine to be delivered to Thailand in 2023, the deal ran aground in 2022 once it became clear that the German government would not grant an export license for the MTU engine. After Thailand threatened to cancel the contract, China offered its indigenous CHD620 diesel engine, but Thailand was as of April 2023 still hesitant to accept this "unproven" engine technology, which implies it has never been integrated into a submarine before. The inspection and negotiation process remains ongoing as of this writing.[84]

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[80] Damantsev, "You've had it! US 7th Fleet Hits the Target of a Unique Modification of the Project 877 Paltus."

[81] Ibid.

[82] The company homepage of Shanghai Qiyao alias MicroPowers states that in 2002, ownership of the Special Engine Engineering Research Center of SMDERI (alias the 711th Research Institute) was transformed to create Shanghai MicroPowers Ltd., whose shares are jointly held by CSIC and the 711th RI and which describes itself as "the only manufacturer of the Stirling engine generator unit in China". See the MicroPowers company profile on the official homepage's About section as archived on 5 June 2023, https://web.archive.org/web/20230605143720/http://micropowers.com/en/company.aspx.

[83] Amanda Rivkin, "German technology found in China's warships: report," *Deutsche Welle*, 11 June 2021, https://www.dw.com/en/german-engine-technology-found-in-chinese-warships-report/a-59740301; Franz-Stefan Gady, "Why China's Submarine Force Still Lags Behind," *The Diplomat*, 28 May 2015, https://thediplomat.com/2015/05/why-chinas-submarine-force-still-lags-behind/.

[84] Sebastian Strangio, "Thailand's Navy Chief Says Country Could Cancel Chinese Sub Contract," *The Diplomat*, 23 November 2022, https://thediplomat.com/2022/11/thailands-navy-chief-says-country-could-cancel-chinese-sub-contract/; "Wuhan Trip To Clear Engine Doubts," *Bangkok Post*, updated 30 January 2023, https://www.bangkokpost.com/thailand/special-reports/2494147/wuhan-trip-to-clear-engine-doubts.

This situation points to a rather puzzling bottleneck in what a German submarine design expert interviewed for this study considers a "relatively old" technology that is "not too complicated to master" and poses a "manageable" technical risk. Asked to speculate what elements of an unproven diesel engine might specifically be considered risky from the point of view of a submarine customer, the expert offered that the worries might be related to the exhaust back pressure system for discharging diesel exhaust below the surface when operating at snorkeling depth. As the maker of the MTU diesel engine explains, to discharge exhaust below the surface, for every meter of water depth, an additional 100mbar of exhaust pressure must be provided to avoid water entering the engine, for which MTU has developed a "special charge air system."[85] Malfunctions or bad performance in this area would pose a safety hazard for the crew, and reliability is therefore a key concern.[86]

Fuel Cell AIP Systems Research in China

Apart from Stirling AIP, Chinese researchers have also worked intensely on other AIP concepts, including the technically more advanced fuel cell realized first by Germany's Siemens and TKMS. Due to higher energy density and the absence of moving parts, fuel cell AIP is even quieter and more powerful than the Stirling variant, but also technically more challenging to copy. Despite researching fuel cells for many years, there is so far no evidence that China has mastered the technology sufficiently to deploy it aboard manned submarines, and China may yet conclude that it is more cost-efficient to leapfrog over this technology entirely and concentrate on the next-generation type of submarine AIP based on lithium-ion batteries.[87]

Fuel cell technology seems, however, to be attractive for civilian ships and particularly for powering long-endurance UUVs—a key element of China's ambitions to develop a vast ocean surveillance network. An article by Song Qiang (宋强) of PLA Unit 92578—an organization that seems to work on fuel cells, lithium-ion AIP, and fiber-optic hydrophone technologies, judging by its members' publications—points out that they are "the first choice for improving the underwater endurance of UUVs."[88]

A Focus on Lithium-Ion Battery Development

Japan first adopted the new lithium-ion technology for its submarines in 2018, followed by South Korea in 2021, with Germany, France and others also working on prototypes. Chinese researchers have likewise been highly interested in its potential for powering submarines.[89]

A 2022 article by researchers affiliated with PLA Unit 92578 examined the Japanese model of adopting lithium-ion submarine propulsion in the 11th submarine of the Sōryū-class. It concluded that "lithium-ion power battery is the development direction of conventional submarine power battery system [sic], and the enlightenment [sic] of lithium battery safety research and engineering application should be accelerated."[90] It seems therefore that China's own attempts at

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[85] MTU Website, "Underwater," https://www.mtu-solutions.com/cn/zh/stories/marine/military-governmental-vessels/underwater.html, accessed 27 March 2023.

[86] Interview on 21 March 2023.

[87] Interview with a shipbuilding industry executive, 24 March 2023.

[88] Song, "Discussion on Fuel Cell Technology for Underwater Unmanned Vehicles," p. 154.

[89] Baba Tamim, "China: Lithium Batteries May Soon Power 'World's Largest Fleet' Of Submarines," *Interesting Engineering*, 30 October 2022, https://interestingengineering.com/innovation/lithium-batteries-to-power-china-submarines.

[90] Song, Zhao, and Mao, "Analysis on Technical Status of The Power System of the Japanese Oryu Submarine Js," p. 22.

creating lithium-ion battery-based power systems for submarines are still in the stage of trouble-shooting, but making progress. In a 2022 issue of the journal *Marine Electric & Electronic Engineering*, three authors affiliated with the PLAN Submarine Academy discuss China's attempts to switch to lithium-ion batteries in submarine propulsion, noting the expected operational advantages:

> In 2020, Japan's Taigei-class submarine was successfully launched. This is the world's first true lithium battery submarine. Compared with the previous Sōryū-class submarine equipped with lead-acid batteries, the energy density has more than doubled and the weight has been reduced by half, which has qualitatively improved its maneuverability and concealment.[91]

Discussing the feasibility for China to adopt this propulsion technology, they point out that:

> Lithium-ion batteries in our country are widely used in portable electronic devices, new energy vehicles, aerospace, and national defense and military fields. Examples include individual soldier systems, army combat vehicles, and military communications equipment for the Army, mini-submarines and underwater vehicles (UUVs) for the Navy, and unmanned surveillance aircraft for aviation. Especially in terms of new energy vehicles, [China] has successfully developed a large-capacity lithium-ion battery and its performance ranks among the top in the world.[92]

However, when it comes to submarine operations, they note safety risks that have yet to be managed, particularly related to the danger of thermal runaway:

> "*There are still a number of issues that need to be resolved* […]. To deploy lithium electronic batteries for conventional submarines, we must *first develop testing methods to ensure the safety performance* of the batteries under the conditions of electrochemical action, mechanical action, thermal action and environmental action […]. Thermal runaway is the most important factor affecting the safety of lithium-ion batteries. Overcharging, short circuit and heating may cause thermal runaway. (emphasis added).[93]

The way forward they outline indicates that there may yet be a few issues left to resolve:

> In order to prevent thermal runaway of Li-ion batteries, analysis and research on surface cell structure design, manufacturing process, raw material selection, and battery pack management are the main approaches […]. From the safety point of view, it is recommended to use lithium iron phosphate for the positive electrode and lithium hard carbon or lithium titanate for the negative electrode, and to develop a high-safety lithium electronic battery for conventional submarines by integrating the active material, SEI film, plus new electrolyte and ceramic coated diaphragm technology […]. *After solving the above mentioned problems, lithium electronic batteries replacing lead-acid batteries to equip conventional submarines is just around the corner"* (emphasis added).[94]

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[91] 王峰 [Wang Feng], 张栋 [Zhang Dong], and 孙飞龙 [Song Feilong],锂离子电池装备于常规潜艇可行性分析 ["Feasibility Analysis of Lithium-ion Batteries in Conventional Submarine"], 船电技术 [*Marine Electric & Electronic Engineering*], vol. 42, no. 10 (October 2022), p. 153.

[92] Ibid., p. 153.

[93] Ibid., pp. 153-154.

[94] Ibid., p. 155.

A commentator reporting on this article concluded that the exact type of China's lithium-ion technology for submarine propulsion may also be determined by the availability of raw materials within China, with China likely preferring to use the iron and phosphate variant rather than nickel and cobalt, being reliant on imports for the latter.[95]

EDTs in Submarine Development and Related R&D

One area of keen research activity concerns submarine defense electronics, in particular command & control (C2) systems. Shipboard electronics seems to be an area of comparable weakness in the PLAN in general.[96] Many technical journal articles discuss issues of digitalization or "informatization" (信息化) and "intelligization" (智能化) of naval C2. Judging from relatively recent research output, it seems that China is still in the midst of developing intelligent support for shipboard C2 systems. A 2021 article published in the journal *Ordnance Industry Automation* analyzes the application of AI in command information systems, e.g. in the American "Deep Green" project, and notes that "command information system [intelligization] […] is currently in the stage of theoretical research"; the authors aim only to "provide some ideas to solve the problems in the research of command information system intelligization."[97] Another 2021 article by a team from the Naval Equipment Department and the Jiangsu Automation Research Institute on the topic of 5th generation command information systems and AI application in C2 systems likewise remarks, "There is not much technology validation for the fifth generation system in the international arena, so we should not be in a hurry and still need to study it fully."[98]

Even in more traditional "informatized" (or digitalized) rather than fully "intelligized" combat management system development aboard submarines, China seems to still lag behind American and British standards—at least in the estimation of Zhang Yan (张严), Wu Zhidong (武志东), and Zhang Yuling (张玉玲) of the PLAN Submarine Academy, who analyze U.S. and British submarine command systems in a 2022 article. Comparing the American AN/BYG-1's and the British ACMS's system architecture, information processing capability, integration of commercially available technologies, redundant design, user-friendly displays, ability to integrate third-user applications, and other capabilities, the article concludes:

> Based on the study of the technical characteristics of the development of foreign submarine C2 systems, several insights are drawn for the future development of submarine C2 systems around supporting unmanned equipment, system structure, system intelligence, and intelligent display, which have certain reference significance for the development of future submarine C2 systems.[99]

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[95] Tamim, "China: Lithium Batteries May Soon Power 'World's Largest Fleet' of Submarines."

[96] For a detailed discussion, see Leigh Ann Ragland-Luce and John Costello, "PLA Shipboard Electronics: Impeding China's Naval Modernization," in Erickson (ed.), *Chinese Naval Shipbuilding*, pp. 221-237.

[97] 丹华 [Sun Danhua], 王 琛 [Wang Chen], and 苏焕焕 [Su Huanhuan], 指挥信息系统智能化问题探讨 ["Discussion on Intelligence Problem of Command Information System"], 兵工自动化 [*Ordnance Industry Automation*] vol. 40, no. 8 (2021), p. 6.

[98] 张志华 [Zhang Zhihua] and 王凡 [Wang Fan], 第五代指挥信息系统总体及其智能化技术设想 ["The Fifth Generation Command Information System and Its Intelligent Technology"], 指挥控制与仿真 [*Command Control & Simulation*], vol. 43, no. 5 (October 2021), pp. 1-7.

[99] 张严 [Zhang Yan], 武志东 [Wu Zhidong], and 张玉玲 [Zhang Yuling], 美英潜艇指控系统发展历程及启示 ["Development of U.S. and British Submarine Command Systems and Enlightenment"], 数字海洋与水下攻防 [*Digital Ocean & Underwater Warfare*], no. 6 (2022), p. 558. Slightly corrected machine translation.

For future development, they note the need to enhance data processing capacity to support a commander's tactical decision-making:

> The command system needs to be equipped with a more intelligent tactical auxiliary decision-making system. The system combines various training data and marine hydrological data to form big data. The command and control system should use intelligent algorithms based on big data and maritime maps to make graphic maneuvering routes and attack method recommendations for attacking targets when making auxiliary command decisions.[100]

AI support for submarine commanders' tactical decision-making seems to be a key concern. A report from 2017 detailed Chinese research on an "on-board forecasting system of water conditions for submerged submarines" which "uses algorithms to predict water conditions even if the vessel's sensors can gather only tiny amounts of data."[101] Reporting on another related research project, the *South China Morning Post* notes that "an AI assistant could support commanding officers by assessing the battlefield environment, providing insight into how levels of saline in the ocean and water temperature might affect the accuracy of sonar systems. It also could recognise [sic] and flag threats from an enemy faster and more accurately than human operators. An AI assist also could help commanding officers estimate the risks and benefits of certain combat manoeuvres [sic], even suggesting moves not considered by the vessel's captain." Describing AI as a potential "game-changer" in undersea warfare, Zhu Min of the Institute of Acoustics with the Chinese Academy of Sciences (CAS) argues, "In the past, the technology was too distant from application but recently a lot of progress has been achieved. There seems to be hope around the corner." Funding is apparently not an issue, as according to a researcher interviewed for the report, "Beijing […] takes the AI submarine programme [sic] very seriously [and] is ploughing abundant resources into the undertaking."[102]

A further area of advanced research that seemingly draws a lot of interest, judging by the number of articles in recent years, is supercavitating and nuclear-powered torpedoes. However, most of the Chinese research articles that can so far be found on the topic tend to discuss related research projects in the U.S. and Russia only, concluding that those countries' high-speed torpedo technology is not yet really mature and more or less untested—but pointing to this as an inspiration for "high-technology three-dimensional naval warfare of the future."[103] However, in a 2022 article published in the *Journal of Unmanned Undersea Systems* researchers from the China Institute of Atomic Energy presented a design for a nuclear reactor that could be installed on

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[100] Ibid., p. 557. Slightly corrected machine translation.

[101] Stephen Chen, "China's Underwater Surveillance Network Puts Enemies In Focus Along Maritime Silk Road", *South China Morning Post*, 31 December 2017,

https://www.scmp.com/news/china/diplomacy-defence/article/2126296/chinas-underwater-surveillance-network-puts-enemies.

[102] Stephen Chen, "China's Plan To Use Artificial Intelligence To Boost The Thinking Skills Of Nuclear Submarine Commanders," *South China Morning Post*, 20 July 2018,

https://web.archive.org/web/20190228194123/https://www.scmp.com/news/china/society/article/2131127/chinas-plan-use-artificial-intelligence-boost-thinking-skills.

[103] See e.g. Dalian Naval Academy's 寇祝 [Kou Zhu], 刘晓 [Liu Xiao], and 光李伟 [Guang Liwei],世界超高速鱼雷发展现状与关键技术 ["Current Status And Key Technologies Of Supercavitating Torpedo Development in the World"], 飞航导弹 [*Aerodynamic Missile Journal*], no. 7 (2019), pp. 56-58.

underwater vehicles launched from submarine torpedo tubes—in essence, a miniature version of Russia's "Poseidon" UUV.[104]

Conclusion

Due to a combination of political will, strategic funding, and ruthless exploitation of all available means to overcome technical bottlenecks, China's naval industries have made stunning progress in the build-up of the PLAN's submarine force and also in the upgrading of related production facilities and R&D infrastructure. The picture of technical progress is however uneven, with somewhat surprising weaknesses remaining in certain technology areas that China could be assumed to have long mastered—mostly related to propulsion (from marine diesel engines to fuel cells) and to some quieting technologies. The performance of China's next-generation SSNs, SSBNs, and conventional AIP submarines will show how much China's naval industries continue to be impaired by lack of access to Western technology. Further export projects of conventional submarines such as the one in Thailand may yield more data to analyze in the future.

At the same time, China is likely already a leader in some areas of great future potential, such as AI applications in the ship design process, data exploitation for situational awareness, and potentially also in AI support for submarine commanders in their tactical decision-making.

Compared with Russia, China seems to be ahead in some areas of submarine-building—such as conventional AIP propulsion, and especially in those EDTs that require a lot of funding—but seems also still to lag behind Russia in others, in particular in quieting and nuclear propulsion. This leads to a situation of potential synergies between these two submarine-producing countries. Driven by a lack of funding, Russia's design bureaus and industries could soon face a brain drain towards China, but the Russian state might decide to halt this trend by entering into mutually profitable synergies, e.g. related to joint production, where Russia would supply essential know-how on submarine acoustic signature quieting, nuclear propulsion design, and hydrodynamic hull design, while China's giant and recently modernized shipyards might supply the industrial capacity to build a lot of hulls very fast, fully exploiting economy of scale effects. A Chinese news article reported that on July 5, 2023, the Commander-in-chief of the Russian Navy, Admiral Nikolai Yevmenov, visited a naval shipyard in Shanghai. The article speculated that this might indicate Russian interest in ordering hulls from China's yards to replenish its strained naval forces, thereby overcoming Russian shipyards' lack of production capacity and leveraging economy of scale effects, which would be possible if an existing Chinese ship design is chosen.[105]

Reports of a planned joint conventional submarine design project that surfaced in mid-2020 have so far not yielded any further public information, but that does not mean it has necessarily been shelved.[106] In any case, sensitive ASW and undersea warfare-related technologies including hydroacoustic sensors, underwater communication, and underwater robotics are already being jointly researched by Russian and Chinese institutes, including in the context of the "Association

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[104] Stephen Chen, "Chinese Scientists Plan 'Disposable' Nuclear Reactor for Long-Range Torpedo," *South China Morning Post*, 20 July 2022, https://www.scmp.com/news/china/science/article/3185980/chinese-scientists-plan-disposable-nuclear-reactor-long-range.

[105] 愤怒熊猫 [Fennu xiongmao], 055 大驱升起俄方国旗，俄海军司令造访上海船厂：有大生意要做吗？["The Large Type 055 Destroyer Hoisted The Russian Flag, And The Commander Of The Russian Navy Visited The Shanghai Shipyard: Is There Any Big Business To Do?"], 观察 [*Guancha*], 8 July 2023, https://web.archive.org/web/20230721233848/https://user.guancha.cn/main/content?id=1035574.

[106] Caleb Larson, "Russia and China Want To Build a Non-nuclear Submarine Together," *The National Interest*, 28 August 2020, https://nationalinterest.org/print/blog/buzz/russia-and-china-want-build-non-nuclear-submarine-together-167911.

of Sino-Russian Technical Universities" (中俄工科大学联盟, abbreviated ASRTU) that was formed in March 2011 and is headquartered in China's submarine hub Qingdao. At the very least, this research collaboration points to a diminishing Russian resistance to cooperation with Chinese entities both in ASW and in undersea warfare-related systems development.[107]

One further area of Russian-Chinese cooperation with potential repercussions for submarine-building concerns nuclear fuel deliveries. On December 12, 2022, the Russian state-owned Rosatom Corp. supplied 6,477kg of highly-enriched uranium (HEU) to China's fast-breeder reactor CFR-600 on Changbiao Island. The weapons-grade plutonium it will soon produce could be used for warheads, but alternatively, commentators from the submarine research community have discussed the possibility that it could also be intended as fuel for future nuclear-powered submarines.[108]

Time will tell how far the Russian-Chinese "friendship without limits" can go in the highly sensitive area of submarine production, but it is safe to assume China would be highly interested in catching up with Russia's remaining technological advantages, and willing to use its political and economic levers to obtain Russia's submarine technology secrets.[109]

[107] The ASRTU's Russian homepage is https://misis.ru/university/struktura-universiteta/association/aturk/; its Chinese web page is available as archived in May 2022 at https://web.archive.org/web/20220630081856/http://www.asrtu.cn/. A list of topics presented at the 2nd "China-Russia Polar Acoustics and Communication Technology Forum" on Nov. 28, 2020 contains distributed sensor networks, arctic sea-floor mapping, undersea communication, among other sensitive technology areas. See: "China-Russia Symposium on Hydroacoustics and Information Technologies—Nov, 28, 2020", https://marinet.org/china-russia-symposium-on-hydroacoustics-and-information-technologies-november-28-29/.

[108] Patrick Senft @SenftPatrick, "The #US @DeptofDefense just announced that #Russia was supplying "highly enriched Uranium" to #China. Now, why would China do that? A brief…", Twitter, 9 March 2023, 7:22 pm, https://twitter.com/SenftPatrick/status/1633896095515328534.

[109] Andrew S. Erickson and Gabriel Collins, "Putin's Ukraine Invasion: Turbocharging Sino-Russian Collaboration in Energy, Maritime Security, and Beyond?", *Naval War College Review*, vol. 75, no. 4 (2022), https://digital-commons.usnwc.edu/nwc-review/vol75/iss4/8.

Appendix

Key Organizations Contributing to Chinese Submarine Warfare Design and Construction

Business area	Enterprise or unit		Related military business
	Short Name	**Full name / Alias**	
General submarine design, ship hull development, and construction	701st Research Institute** 七〇一所	China Ship Design and Research Center** 中国舰船研究设计中心	The only general research & design unit in China that develops small and medium-sized submarines. Has national defense key laboratory for electromagnetic compatibility and acoustic stealth technology. Also active in marine dynamic environment monitoring buoys, etc.
	719th Research Institute 七一九所	Wuhan Second Ship Design Research Institute 武汉第二船舶设计研究所	The only overall design institute for nuclear-powered ships in China; develops all nuclear-powered submarines, including reactors.
	702nd Research Institute* 七〇二所	China Ship Scientific Research Center (CSSRC)* 中国船舶科学研究中心	Applied basic research of hydrodynamics, structural mechanics and vibration, noise, impact resistance and other related technologies in ship and ocean engineering, as well as research, design and development of high-performance ship and underwater engineering.
	725th Research Institute* 七二五所	Luoyang Institute of Ship Materials* 洛阳船舶材料研究所	Development of ship materials and engineering application research. Has 4 seaport test stations.
	11th Research Institute+ 一一所	Shipbuilding Technology Research Institute (STRI)+ 上海船舶工艺研究所 上	Research on shipbuilding technology and marine engineering; R&D on hull welding technology and equipment; large-scale CNC cutting and automation equipment production lines; coating technology and equipment; application and process R&D of marine non-metallic materials; development of shipbuilding software systems and information technology integration platforms; non-destructive testing of metal materials, technical testing of non-metallic materials.
	(formerly: Bohai Shipyard)+ 渤海造船厂	Bohai Shipbuilding Heavy Industry Co., Ltd. (BSHIC) 渤海船舶重工有限责任公司	Constructs all nuclear-powered submarines.

	438 Factory+ 438厂	Wuchang Shipbuilding Industry Group Co. Ltd. 武昌船舶重工集团有限公司	Main shipyard for building conventionally-powered submarines.
	Jiangnan Changxing+ 江南长兴	Jiangnan Shipyard (Group) Co., Ltd. 江南造船（集团）有限责任公司	Secondary shipyard for building conventional subs.
Propulsion	711th Research Institute* 七一一所	Shanghai Marine Diesel Engine Research Institute (SMDERI) 上海船用柴油机研究所	Main research institution for conventional submarine power systems. Has developed power systems for multiple types of submarines, including Stirling AIP systems.
	Micro Powers+ 齐耀动力	Shanghai Qiyao Power Technology, Ltd. (上海齐耀动力技术有限公司)	Maker of the Stirling AIP system for conventional submarines; a wholly-owned subsidiary of the 711th Research Institute.
	/	Shaanxi Diesel Engine Heavy Industry, Co. Ltd. (陕西柴油机重工有限公司)+	License-producer of German MTU 396-series marine diesel engines for submarines.
	(719th Research Institute 七一九所 – see above – develops all nuclear propulsion plants)		
Detection and Countermeasures **探测与对抗**	7th Research Academy 七院**	China Naval Research Institute** 中国舰船研究院	Research and design of submarine and ship-borne weapons and equipment.
	/	Haiying Enterprise Group Co., Ltd.+ 海鹰企业集团有限责任公司	China's first underwater acoustic equipment manufacturer. Hydroacoustic equipment, marine engineering special equipment and other special equipment, diving and underwater salvage equipment, navigation, meteorological and marine special instruments and meters.
	715th Research Institute** 七一五所	Hangzhou Institute of Applied Acoustics** 杭州应用声学研究所	Develops acoustic, optical and magnetic detection equipment. Has key laboratory of sonar technology, a first-level hydroacoustic measurement station, an underwater acoustic product testing center, and a second-level radio measurement station.

	/	Haisheng Technology Co., Ltd.+ 海声科技公司	Underwater acoustic detection, navigation, rescue, and underwater security. and underwater acoustic transducers; a subsidiary of the 715th RI.
	716th Research Institute** 七一六所	Jiangsu Institute of Automation** 江苏自动化研究所	Engaged in the research and development of electronic information transmission systems, etc.
	726th Research Institute** 七二六所	Shanghai Ship Electronic Equipment Research Institute** 上海船舶电子设备研究所	R&D of underwater acoustic countermeasures and anti-countermeasure systems, underwater acoustic navigation and marine development application instruments and equipment.
	723rd Research Institute** 七二三所	Yangzhou Marine Electronic Instrument Research Institute** 扬州船用电子仪器研究所	Engaged in the development of electronic engineering systems and equipment.
	704th Research Institute** 七零四所	Shanghai Marine Equipment Research Institute (SMERI)** 上海船舶设备研究所	Application research of special auxiliary electromechanical equipment and systems for ships; vibration reduction and degaussing.
	368 Factory+ 三六八厂	Hebei Hanguang Heavy Industry Ltd.+ 河北汉光重工有限责任公司	Complete sets of ship instruments, packaging machinery, optical sighting equipment, low-light sighting equipment, scopes, photoelectric sighting equipment.
	662 Factory+ 六六二厂	Chongqing Qianwei Technologies Group Co. Ltd.+ 重庆前卫科技集团有限公司	Has key experimental facilities such as anechoic pools, and is a key research and development base for national underwater weapons.

Command, Control and Computers **指挥控制与计算机**	709th Research Institute** 七〇九所	Wuhan Digital Engineering Institute** 武汉数字工程研究所	Integrating information technology, computing technology, and automatic control; research direction is command & control system technology and high-performance computer system technology.
	724th Research Institute** 七二四所	Nanjing Ship Radar Research Institute** 南京船舶雷达研究所	Engaged in the development and production of large-scale device data detection and intelligent systems such as ship radar systems.
	/	Institute of Acoustics (IOA) at the Chinese Academy of Sciences (CAS) 中科院声学研究所	Engaged in research on AI in command & control systems aboard submarines (intelligent support for submarine commanders).
	5th Research Institute 五所 / Academy of Systems 系统院*	CSSC Systems Engineering Research Institute* 中国船舶工业系统工程研究院	Ship combat command system, formation command system, joint combat command system, aircraft carrier aircraft automatic landing system.
Navigation and Communication **导航与通信**	707th Research Institute** 七〇七所	Tianjin Navigational Instrument Research Institute** 天津航海仪器研究所	Technology research and equipment supply in inertial navigation, ship control systems, and hardened computers.
	722th Research Institute* 七二二所	Wuhan Ship Communication Research Institute* 武汉船舶通信研究所	R&D and manufacturing of communication electronic engineering, such as integrated data communication systems, broadband high-speed data transmission, high-frequency adaptive instantaneous communication systems, high-speed optical fiber integrated service transmission networks, special antennae, information security equipment, communication control and distribution, ship internal communication systems.
	717th Research Institute** 七一七所	Huazhong Photoelectric Technology Research Institute ** 华中光电技术研究所	Engaged in photoelectric detection information processing and photoelectric system integration, astronomical navigation and inertial navigation.

	453 Factory 四五三厂+	Chongqing Huayu Electric Group Co., Ltd+ 重庆华渝电气集团有限公司	Marine instrumentation, equipment and supporting products, inertial navigation, positioning and orientation devices.
	455 Factory 四五五厂+	Changjiang Technology Co., Ltd+. 长江科技有限公司	R&D and production of communication, navigation, positioning and orientation equipment.
	/	Xi'an Dongyi Technology Group Co., Ltd.+ 西安东仪科工集团有限公司	Underwater acoustic testing, inertial navigation systems, radio assembly, debugging, reliability testing.
	China Haiphong 中国海防+	CSSC China Marine Information Electronics Company Ltd.+ 中国舰船重工集团海洋防务与信息对抗股份有限公司	R&D, production and manufacturing in information electronics, including underwater information transmission equipment, special equipment for underwater weapon systems and other special equipment, series of special marine power supply products, testing services.
	/	Chongqing Qingping Machinery Co., Ltd.+ 重庆清平机械有限责任公司	Manufacture of special instruments for navigation, meteorology and oceanography; also special precision equipment for gear production and gear testing; high-precision special gears and gearboxes

*On the US Entity List; **Newly added to US Entity List in Dec. 2020; + Apparently not on the US entity list as of this writing (April 2023)

Sources: Based on 浙商证券有限公司 [Zheshang Securities] 2021, 舰船水声防务龙头,内生外延双轮驱动──中国海防深度报告 [A Leader In Naval Hydroacoustic Defense, On A Two-Wheel Drive From Domestic Origins To Outward-Looking Expansion—In-Depth Report About CSSC China Marine Information Electronics Company Ltd./China Haiphong], Hangzhou, 7 February 2021, p. 30; supplemented with company information from various company websites.

About the Author

Dr. Sarah Kirchberger is Academic Director at the Institute for Security Policy at Kiel University (ISPK), a Nonresident Senior Fellow at the Atlantic Council, and Vice President of the German Maritime Institute (DMI). She was previously Assistant Professor of Sinology at Hamburg University and before that, a naval analyst with shipbuilder TKMS. She is the author of *Assessing China's Naval Power: Technological Innovation, Economic Constraints, and Strategic Implications* (Springer, 2015), co-author of *The China Plan: A Transatlantic Blueprint for Strategic Competition* (Atlantic Council, 2021) and co-editor and contributor of *Russia-China Relations: Emerging Alliance or Eternal Rivals?* (Springer, 2022). Her research focuses on China's undersea warfare technologies; PLAN modernization; Chinese defense-industrial development; military-technological co-operation between China, Russia, and Ukraine; EDTs in the maritime sphere; and on the strategic importance of the South China Sea. She has testified on Chinese undersea warfare before the U.S.-China Economic and Security Review Commission. Kirchberger holds a Ph.D. and an M.A. in Sinology from the University of Hamburg.

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