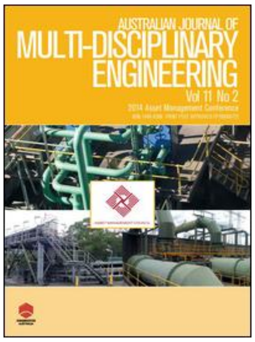

Taylor & Francis
Taylor & Francis Group

Australian Journal of Multi-Disciplinary Engineering

ISSN: (Print) (Online) Journal homepage: https://engineersaustralia.tandfonline.com/loi/tmul20

Nuclear propulsion roadmap for Australia(r) – a systems engineering approach

Christopher skinner

To cite this article: Christopher skinner (2021): Nuclear propulsion roadmap for Australia(r) – a systems engineering approach, Australian Journal of Multi-Disciplinary Engineering, DOI: 10.1080/14488388.2021.1876585

To link to this article: https://doi.org/10.1080/14488388.2021.1876585

Published online: 20 Jan 2021.

AUSTRALIAN JOURNAL OF MULTI-DISCIPLINARY ENGINEERING
https://doi.org/10.1080/14488388.2021.1876585

ENGINEERS AUSTRALIA

Taylor & Francis
Taylor & Francis Group

Check for updates

ARTICLE

Nuclear propulsion roadmap for Australia(r) – a systems engineering approach

Christopher skinner

DISplay Pty Ltd, NSW, AUSTRALIA

ABSTRACT
This paper describes the development of an Australian roadmap for the acquisition of nuclear propulsion for submarines and selected other vessels. This paper reports on the goals of the working group and an outline of the projected roadmap. Australia first operated naval submarines in 1914 and has maintained amodern fleet continuously since 1967. Now embarking on the third generation of conventionally powered boats, attention is shifting to nuclear propulsion for future generations. Nuclear propulsion confers two significant advantages on anaval submarine: increased speed for sustained periods and removal of the requirement for periodic recharging of batteries using air-breathing diesel generators. Development of the nuclear propulsion roadmap is being undertaken by avoluntary working group of nuclear scientists, submarine designers, builders, operators and maintainers, and multidisciplinary engineering and project management professionals, following asystems engineering, disciplined approach to consider all possible options for essential infrastructure, safety assurance, workforce training and development, economic and geopolitical constraints.

ARTICLE HISTORY
Received 25 May 2019
Accepted 12 January 2021

KEYWORDS
Nuclear propulsion; submarine nuclear reactor; nuclear power; nuclear engineering; nuclear systems engineering

1. INTRODUCTION

> 'Nuclear power gives total independence from the surface, meaning submarines can operate under the polar ice cap, circumnavigate the globe submerged, and in all respects – except communication – remain hidden under the sea. Diesel-electric propulsion, when operating submerged on batteries, provides mechanical quietness and compact mechanical spaces; but eventually must come to the surface for battery recharge' (Zimmerman 1999) p13

1.1. *Background*

In August 2013 University College, London [UCL] published a Green Paper entitled *'Could Australia's Future Submarines be Nuclear Powered?'* (UCL 2013). The paper argued persuasively that, yes, they could be nuclear powered, but there were (and still are) formidable hurdles to be overcome for this to happen. This paper is about a grass-roots initiative to identify and overcome those hurdles.

That Australia, a quintessential maritime power, needs to progress its capability to participate in nuclear propulsion is clear to maritime commentators, and in a general way also to the community at large. However for the community the fears of the consequences of nuclear accidents, the hazards of nuclear material misuse and the safe disposal of radioactive wastes for future millennia must first be addressed.

This initiative places Australia beyond the envelope of other countries who possess already or who aspire to acquire nuclear submarines such as Brazil and India because these countries already employ nuclear power for the generation of electrical energy. Australia has not only avoided this step but has actively legislated to prohibit such a step.

Last year the Australian Financial Review [AFR] carried the story '*US wants our help with nuke submarines*' (Greber 2018). This story arose from the early stages of their well-practised process of considering the next generation of nuclear attack submarines (SSN) to follow the current, highly successful USS VIRGINIA (SSN-774) class, which is still in production in a series of successive incremental modernisation baselines.

The next generation, typically labelled SSN(X), will have a number of new capabilities, including the capability to operate unmanned underwater vehicles (UUV), some of them Autonomous Underwater Vehicles (AUV), for various roles including intelligence, surveillance and reconnaissance (ISR), or as countermeasures to attacks.

1.2. *Nuclear propulsion overview*

Nuclear propulsion for a submarine confers essentially unlimited energy that may be employed at a higher power level than any conventionally fuelled propulsion system and without the need to recharge energy storage batteries generally requiring compromise of the submarine's presence through the exposure of a so-called 'snort mast'.

CONTACT Christopher skinner cjskinner@optusnet.com.au

Nuclear propulsion for submarines was pioneered by the USA and first fielded in the submarine USS NAUTILUS. (SSN-571) (Rockwell 1992) (Cross and Feise 2003). Since then several other countries have acquired or are working to acquire nuclear-powered submarines. In the case of USA and UK, their navies have adopted nuclear propulsion for all their submarine force. The US Navy also employs nuclear propulsion for its fleet aircraft carriers. Russia employs nuclear propulsion for ice breaker ships also.

1.3. Australian nuclear legislation

The Australian attitude towards nuclear power of any kind, including submarine propulsion, has been complex. On the one hand, we have agreed to mine and export uranium ores for nuclear power, with some restrictions, but, on the other hand, we have enacted legislation that comprehensively prohibits any form of nuclear power to be undertaken in Australia.

The Minerals Council of Australia in 2017 published a pamphlet '*Removing the Prohibition on Nuclear Power*' (Minerals Council of Australia 2017) and specified the need to delete Section 140A of the *Environmental Protection and Biodiversity Conservation Act 1999*, which states:

1.4. Section 140A No approval for certain nuclear installations

> The Minister must not approve an action consisting of or involving the construction or operation of any of the following nuclear installations:
>
> (a) A nuclear fuel fabrication plant;
> (b) A nuclear power plant;
> (c) An enrichment plant;
> (d) A reprocessing facility.

This Act prevents Australia from acquiring nuclear fuel enrichment and processing capability and the more obvious nuclear power plants but does not specifically mention fuelling, refuelling or defuelling of nuclear reactors *per se*.

Further analysis is planned to determine whether this section legally precludes the acquisition of a nuclear propulsion reactor if the Act could be interpreted as inapplicable to submarines.

An alternative step would be to assess whether the Act could be amended in part rather than removed altogether in order to increase community support for nuclear propulsion for submarines. This could be based on the reactor vessel construction and fuel enrichment being undertaken outside of Australia, with fuelling and refuelling to be either in Australia or in another country, and with spent fuel returned there for necessary reprocessing to minimise the quantity of High-Level Waste (HLW) to be stored long term in a geological repository.

In October 2018 Rear Admiral Peter BRIGGS AO CSC RAN (retired) published a Special Report *'Can Australia afford nuclear submarines? Can we afford not to?'* (Briggs 2018) in which he said

> 'The options for Australia to develop an SSN capability would be limited to building the nuclear submarines offshore or consolidating the submarines in Australia, incorporating reactors purchased offshore.' (Op. Cit)

1.5. Australian submarine development

Australia first acquired submarines in the First World War and continued to acquire and operate them until the 1930's when this capability was discontinued due to economic constraints. The subsequent experience of the Second World War when allied submarines operated with great effect from Brisbane and Fremantle showed the short-sightedness of the earlier decision.

After the war, the UK Royal Navy [RN] agreed to operate a squadron of submarines from Sydney for some years, until in 1967 the RAN re-acquired its own submarine capability with the arrival of HMAS OXLEY on 18 August 1967 at the newly-created submarine base HMAS PLATYPUS in Neutral Bay, Sydney. Australia's six Oberon-class submarines operated with extraordinary effectiveness throughout the remainder of the Cold War including a major upgrade called the Submarine Weapons Upgrade Project [SWUP] that was developed at the Submarine Warfare Systems Centre [SWSC] in Watson's Bay, Sydney.

In 1987 the Government approved the New Construction Submarine Project to design and build the next generation of Australian submarines, the COLLINS Class. The story of the COLLINS Class development and implementation has been endlessly told and retold due to the intense scrutiny it has received and the convoluted process followed to ultimately deliver a regionally superior submarine capability that Australia now has. (Yule and Woolner 2008)

The current program termed SEA 1000 Future Submarine Program [FSP and recently named ATTACK-class] is intended to replace the six COLLINS Class and expand the submarine fleet to double its current size to 12. The FSP timescale that has been published makes it inevitable that the extension of the service life of some or all of the COLLINS Class boats will be required to avoid any reduction in Australia's submarine capability until the FSP program has delivered sufficient numbers of the contracted total.

1.6. Nuclear propulsion roadmap working group

On 31 October 2018 in Adelaide, 14 active and retired scientists, technologists, engineers and industrialists met to discuss and ultimately agree unanimously to develop a Nuclear Propulsion Roadmap for Australia® [NPRM4A] which is the primary focus of this paper. The ultimate goal of this work is to support a government decision to acquire nuclear-powered submarines to follow the ATTACK-Class program now underway.

In doing so we will also consider the evolving philosophy of the modular open systems approach in shipbuilding and especially current submarine building programs, as discussed in (Castelle, Dean, and Daniels 2019). The following key tenets of the COLUMBIA class submarine program are pertinent to the roadmap:

- Stable operational and technical requirements
- Reuse of design to increase affordability
- Higher design maturity at construction start
- Manufacturing and construction readiness, including extensive prototyping of manufacturing technologies and approaches
- Identification of facility and infrastructure requirements
- Development of test sites to conduct integration testing, verification and validation of systems and mitigation of technical risk. (Ibid)

1.7. Working hypothesis

The working hypothesis for the Roadmap is that nuclear propulsion is both necessary and feasible in the period in which the FSP delivers some or all of the projected 12 new ATTACK-class submarines. The rationale for developing the Roadmap is to explicate how this can be achieved – that is that nuclear propulsion can be accepted and approved for Australian submarines in time for the next generation of submarines after the ATTACK class to be nuclear powered.

1.8. Systems engineering approach

Systems engineering (SE) is a discipline especially well suited to the analysis of complex requirements and to synthesise optimised solutions to meet these requirements within a series of sometimes conflicting constraints. (Blanchard 1998) The further consideration of factors outside the classical scientific, technological, engineering and mathematical [STEM] domains has led to the augmentation of SE with so-called system-of-systems (SoS) engineering, which has been addressed in this paper.

1.9. Classical systems engineering

Systems engineering has matured as a powerful engineering discipline that offers a structured process to conceive, design, construct, verify and validate a complex engineering solution.

Systems Engineering provides a process for successive stages of problem-solving, comprising problem definition, conceptual approach to solution design, feasibility analysis; statement of operational requirements; development of the sustainment concept; identification of technical performance measures; functional analysis; requirements allocation to functional elements and systems; analysis, synthesis and design optimisation; design integration; predictive test and evaluation; construction and integration; commissioning and acceptance into service (Ibid)

Within the systems engineering model, there is a series of steps and processes, some of which are repeated in cyclic or spiral sequences to arrive ultimately at an acceptable design point where a balance has been achieved among competing functions.

In 2011, the RAND study '*Australia's Submarine Design Capabilities and Capacities*' described systems engineering as follows:

> 'In the context of submarine design, systems engineering technically develops, integrates and optimises all systems in the ship and prepares technical deliverables by: (1) developing and evaluating system concepts and new components; conducting trade-off studies; and developing system diagrams, class drawings, component speifications, etc. and (2) performing safety analyses on new and significantly modified legacy ship systems and components.' (Birkler 2011) p235

More recent experience has noted the complexity and lack of predictability in most real-world problem domains. This has led to the development of so-called system-of-systems engineering (Jamshidi 2009) that deals not only with the complexity of such systems but also the emergence of external factors including the exponential increase in relevant information; increasing interdependence between systems and their environments; pressure for accelerated development; and expectations that exceed the current capabilities of hardware and software technology.

The challenge addressed in this paper is to apply the complex systems models to nuclear propulsion in a manner that is accepted within the Australian community which may be unaware of what or how systems engineering contributes to such processes.

1.10. Complex systems

The field of complex systems has been proposed as a discrete field for research and application. (Jamshidi 2009). Further development of the body of knowledge attached to complex systems has been undertaken, for example, by Charles Keating who has investigated the governance of such systems. (Keating and Katina 2015)

Table 1. Applicability of System Concerns to Nuclear Propulsion.

Management Concern	System of Systems (SoS)	Applicability to Nuclear Propulsion
Stakeholder involvement	Added levels of complexity; stakeholders at differing levels have competing interests and priorities	Applicable in absence of central management authority such as the Office of Naval Reactors in the USN
Governance	May have funding and management lines of responsibility at the SoS level and also at the level of individual systems	As above
Operational Focus	SoS must meet operational objectives using systems for which their individual objects are not aligned	A significant challenge that must be addressed by the overall design authority
Acquisition, Testing and Validation	No established process for these essential processes to be completed comprehensively. Differing life cycles for component systems makes this more difficult	Again a central authority must ensure that all component systems are considered and competing criteria are reconciled and integrated
Boundaries and Interfaces	In SoS the focus is on identifying the systems that contribute to the SoS and enabling the flow of data, control and functionality of the SoS within the various constraints	Very applicable
Performance & Behaviour	Ensure end-to-end performance of the SoS, within the context and constraints of all the systems	Very applicable again

Keating and Katina have described the central role of governance in complex systems as follows:

> ' … the governance field is appreciative of more diverse and potentially conflicting pluralist perspectives on problems. In addition the governance field has a long history of having to deal with conflicting stakeholder perspectives, shifting boundaries (e.g. time, geography, and conceptual), and politically charged positions. Therefore we conclude that the *complex systems* and *governance* fields have much to gain from exploration of joint development at their intersection.' (ibid) p2

More recently Keating et al. have extended this research to complex systems pathologies, defined as '*violations of underlying system principles*' (Keating 2018), as applied to major acquisition programs. Keating proposes six system perspectives for such programs:

sprawling complexity exceeds the capacity of the system to absorb or respond;

process and event centricity;

complication of responses to emerging challenges;

output focus rather than on outcomes which are less amenable to verification;

control emphasis to minimise constraints on achieving potential efficiencies; and

holism to replace reductionism as a driving paradigm, focussing on '*the central notion that understanding of a system performance or behaviour is achieved by understanding the interactions among components, rather than the components themselves*'. (Ibid)

1.11. Nuclear propulsion as a complex systems domain

The working group asserts as self-evident that safe and practical implementation of nuclear propulsion with all its attendant infrastructure to meet safety, environmental, operational and sustainment demands constitutes a complex system. The publicly visible concerns expressed by political and community stakeholders confirm the classification of nuclear propulsion at the system-of-systems level as outlined above. This leads to the application of the heuristic principles and approaches that have been proposed and demonstrated for such complex systems.

For example, in Table 1 we consider what (Dahmann 2009) says of System of Systems in several areas of concern, based on ((USD AT&L) Under Secretary of Defence for Acquisition, Technology & Logistics 2008).

2. Roadmap proposed structure and work plan

2.1. Roadmap general structure

The proposed Roadmap Structure is based on six proposed major work areas as follows:

(1) Rationale and business case development, consultation and publication
(2) Communications and consultation with community, media, government, academia
(3) Design and integration; lifecycle approach, especially decommissioning
(4) Source of reactor and reactor fuel cycle
(5) Safety and regulatory requirements; legislative framework
(6) Workforce for design, safety assurance, installation, commissioning, operation, sustainment, refuelling, decommissioning, waste recycling and disposal.

2.2. Concurrent work streams

This work is proposed to be developed in three concurrent streams:

(A) Public policy and legislative advocacy to establish a legal framework for the Roadmap to be ratified and then implemented.

(B) Nuclear power as a carbon-free source of energy through the introduction of small modular (nuclear power) reactors, known as SMRs (see Case Study below). Special attention will be given to the design, manufacture and life-cycle management of the nuclear fuel chosen for use.

(C) Nuclear power for submarine propulsion with all the complex issues this entails, especially decommissioning of the submarines at the end of their service lives.

Together these form a 6 × 3 matrix of summaries of research, analysis, interpretation and discussion from which we expect to discern linkages and internal conflicts and ambiguities, to be resolved or reported as alternative views.

3. Case studies relevant to the roadmap

We have noted a case study relevant to the Roadmap and we expect to identify and analyse others.

3.1. Case study: small modular reactors (SMR) for Canada but not nuclear submarines

The Canadian Small Modular Reactor (SMR) Roadmap Steering Committee published the Roadmap in November 2018 (Op. Cit) declaring:

> *'Nuclear energy in Canada is a strategic asset. Canada is a Tier 1 nuclear nation, with a full spectrum industry that we leverage for significant economic, geopolitical and social and environmantal benefits.' (Ibid)*

> *'Through the SMR Roadmap, representatives from industry, governments, utilities and enabling partners have come together to chart a vision for the next wave of nuclear innovation. (Ibid)*

In stark contrast, Canada decided in 1987 that it should acquire 10 to 12 nuclear-powered attack submarines (SSN) under the Canadian Submarine Acquisition Program (CASAP) in order to patrol Canada's three oceans including under the ice capability for the Arctic Ocean. (Canadian White Paper on Defence 1987) These submarines were to meet requirements that could be met by modifying British or French designs but the program was ultimately cancelled due partly to political pressure from the USA, and partly to the projected costs of new infrastructure for the submarine construction, fuelling, refuelling, related maintenance activities and ultimate decommissioning, defuelling and disposal.

Insight Economics makes the following observation (Insight Economics 2017) p79:

> *'… the Canadians also became aware of the very high costs required to create and maintain the hard and soft infrastructure to operate and maintain a fleet of SSN's.'*

As a droll sidebar to the nuclear submarine decisions, Canada is currently considering the acquisition of 12 modern non-nuclear submarines for the same roles as in 1987 but with non-nuclear Air Independent Propulsion (AIP) to permit the under-ice operations. (Dunlop 2018) (Pugliese 2017)

3.2. Role for INCOSE/SESA/ITEA

This paper has been developed specifically for presentation at the Systems Engineering, Test and Evaluation [SETE] conference in Canberra in April 2019. As such this paper extends the pre-defined scope of the Nuclear Propulsion Roadmap for Australia® [NPRM4A] to consider the role that systems engineering could play in the development and implementation of the roadmap.

The three professional organisations supporting SETE are International Council on Sytems Engineering [INCOSE], Systems Engineering Society of Australia [SESA], a technical society of Engineers Australia (SESA is also affiliated with INCOSE), and the International Test and Evaluation Association [ITEA].

As has been discussed, the classical approach to systems engineering as described, for example, by (Blanchard 1998) comprises a series of processes from requirements to acceptance for development and delivery. Complex systems engineering, also known as system-of-systems engineering has extended this classical model to consider the external environment in which the process must operate (Keating).

To be accepted, the development of the Nuclear Propulsion Roadmap for Australia® must take into consideration all of the factors in system-of-systems engineering. There must therefore be a role for the three named organisations to contribute to NPRM4A to ensure its scope covers the full range of issues, and the related analysis accords with accepted standards and practices set by those organisations. The means to accomplish this will be further discussed at the SETE conference.

4. CONCLUSIONS

4.1. Submarine nuclear propulsion is inevitable, but faces hurdles to be overcome

Calls are increasing for due consideration of nuclear propulsion for Australia's next-generation submarine. This is especially important if as has been asserted the option has not been formally studied by Australia as was done in Canada.

4.2. Legislative changes are required

The Environmental Protection Act may well need to be amended although this is subject to investigation by or on behalf of the NPRM4A working group.

4.3. Small modular reactors advocacy for Australia

There is already some advocacy in Australia to acquire Small Modular (Nuclear Power) Reactors (SMR), and this is part of the Roadmap work scope. However, there is not yet any evidence of this being a precursor for nuclear propulsion.

4.4. The nuclear propulsion roadmap is a useful approach because all options are considered

Development of the Roadmap is not time-critical. It is needed in time to plan for the next submarine class following the current ATTACK-Class program.

5. Further work

The development of the Roadmap will continue until ready to publish for community information and ultimately for formal consideration, we hope.

Disclaimer

The views expressed in this paper are entirely those of the author and do not reflect the views of any other person or organisation.

Nuclear Propulsion Roadmap for Australia® is a Registered Business Name of DISplay Pty Ltd ABN: 30 074 858 129

Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

Christopher Skinner is a retired electrical engineer with a master's degree in software engineering from the University of New South Wales. He served 30 years in the Royal Australian Navy as a weapons and electrical engineering officer, which included service at sea in six naval ships, managing the test and evaluation of the guided-missile frigate USS Oliver Hazard Perry (FFG-7), and first project director of the ANZAC frigate program. More recently he has been active in defence and transportation industries and related academic lecturing, Skinner is a life member of IEEE and of the Association for Computing Machinery (ACM).

References

Birkler, J. 2011. *Australia's Submarine Design Capabilities and Capacities, Challenges and Options for the Future Submarine*. Santa Monica: RAND Corp.

Blanchard, B. S. 1998. *Systems Engineering Management. 2nd Ed*. ed. New York: John Wiley & Sons.

Briggs, P. October 2018. 'Can Australia Afford Nuclear Propelled Submarines? Can We Afford Not To?'. *Special Report*, Canberra: Australian Strategic Policy Institute.

Canadian Government. 6 June 1987. *White Paper on Defence*. Ottawa: Candian Government.

Canadian Small Modular Reactor (SMR) Roadmap Steering Committee. November 2018. *A Call to Action: A Canadian Roadmap for Small Modular Reactors*. Ottawa, Canada.

Castelle, K., A. W. Dean, and C. B. Daniels. 2019. *'Benefits and Challenges of Implementing Agile Development in Modular Shipbuilding'*. Naval Engineers Journal. Alexandria. ASNE. June 2019.

Cross, W., and G. W. Feise jr. 2003. *Encyclopedia of American Submarines*. New York: Facts on File .

Dahmann, J. S. 2009. *Systems Engineering for Department of Defense System of Systems*, MITRE Corporation, McLean, VA. 2009 in (Jamshidi 2009) Chapter 9.

Dunlop, D. 1 October 2018. *The Case for Canadian Submarines*. Canadian Naval Review.

Greber, J. 15 December 2018. *US Wants Our Help with Nuke Submarines*. Australian Financial Review.Sydney

Insight Economics. September 2017. '*Australia's Future Submarine. Getting This Key Capability Right*'. Melbourne: Insight Economics Pty. .

Jamshidi, M. 2009. *System of Systems Engineering. Innovations for the 21st Century*. New York: John Wiley & Sons.

Keating, C. B. 2009. '*Emergence in Systems of Sysems*' in (Jamshidi 2009) Chapter 7.

Keating, C. B. 30 March 2018. 'A Method for Identification, Representation, and Assessment of Complex System Pathologies in Acquisition Programs'. *Proceedings of the Fifteenth Annual Acquisition Research Sympsium*, Monterey, CA: Naval Postgraduate School.

Keating, C. B., and P. F. Katina. 2015. "'Editorial: Foundational Perspectives for the Emerging Complex System Governance Field'." *International Journal of Systems Engineering* 6: ½.

Minerals Council of Australia. September 2017. *'Removing the Prohibition on Nuclear Power'*. www.minerals.org.au.

Pugliese, D. 9 May 2017. '*Report Calls for 12 New Subs for Canada - $50 Billion Price Tag*'. Ottawa Citizen.

Rockwell, T. 1992. *The Rickover Effect. How One Mam Made a Difference*. iUniverse Inc., Lincoln.

UCL. August 2013. *"Could Australia's Future Submarines Be Nuclear Powered?"*. London: Green Paper, University College.

(USD AT&L) Under Secretary of Defence for Acquisition, Technology & Logistics. 2008. *System of Systems System Engineering Guide: Consideration for Systems Engineering in a System of Systems Environment*. U.S Department of Defense, Washington, DC. *V1.0* Pentagon.

Yule, P., and D. Woolner. 2008. *The Collins Class Submarine Story. Steel, Spies and Spin*. Port Melbourne: Cambridge University Press.

Zimmerman, S. 1999. *Submarine Technology for the 21st Century. 2nd Ed*. ed. Victoria B.C.: Trafford Publishing.