Nuclear Reactor Integration for Maritime Applications Through the Lens of Defense in Depth

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Hal Berdichesky & Thomas McKenney

MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN

Contents

1. Introduction 3
2. Background in reactor design 4
3. Integration complexity 6
4. Defense in depth as a binary indicator 13
5. Visualizing the Problem 16
6. Discussion and conclusion 21

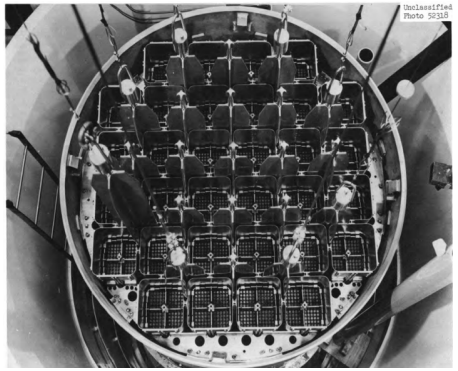


Introduction: Why Nuclear?

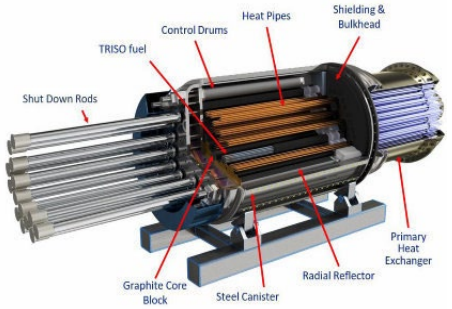
Some key points

1. Challenge of climate change & energy reliability
2. Decarbonization & sustainable solutions
3. Challenge of alternative fuels
4. New reactor technologies are emerging – approaching feasibility
5. New threat environment & significant jurisdictional variation

How do we address the resulting complex design space with novel and uncertain designs towards operation in a treacherous environment to create effective solutions that compete with fossil fuels?



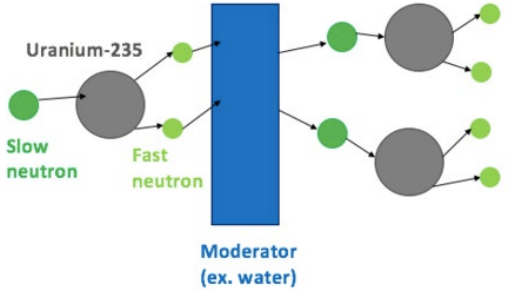
Top View of NS Savannah Core (Source: Gross et al. / Oak Ridge National Laboratory)



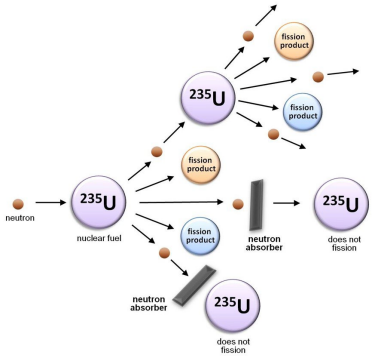
e-Vinci Micro Reactor (Source: Westinghouse)

Background in Reactor Theory - Neutronics

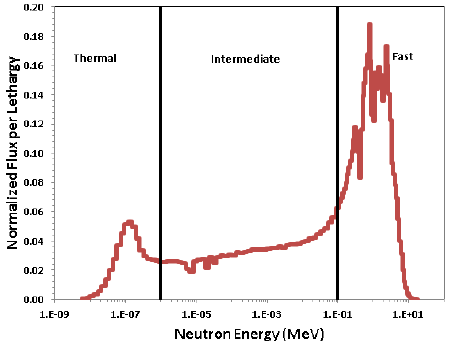
- Fission → Neutrons → Scatter, Absorb, or Escape → Absorb → Fission or Decay
- Fissile & Fertile Isotopes: U-235 vs Th-232 and U-238
- Thermal and Fast Spectra
- Control



Nuclear Fission & the Role of Moderators
(Source: Energy Education)

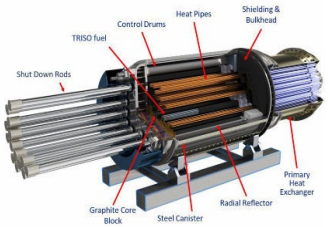


Controlled Nuclear Fission
(Source: McMaster University)

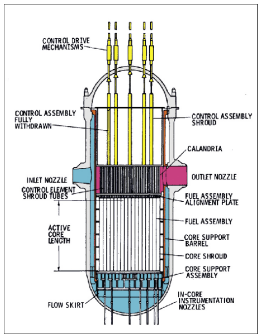


Neutron Spectrum in a PWR Fuel Pin
(Wootan et al. 2015)

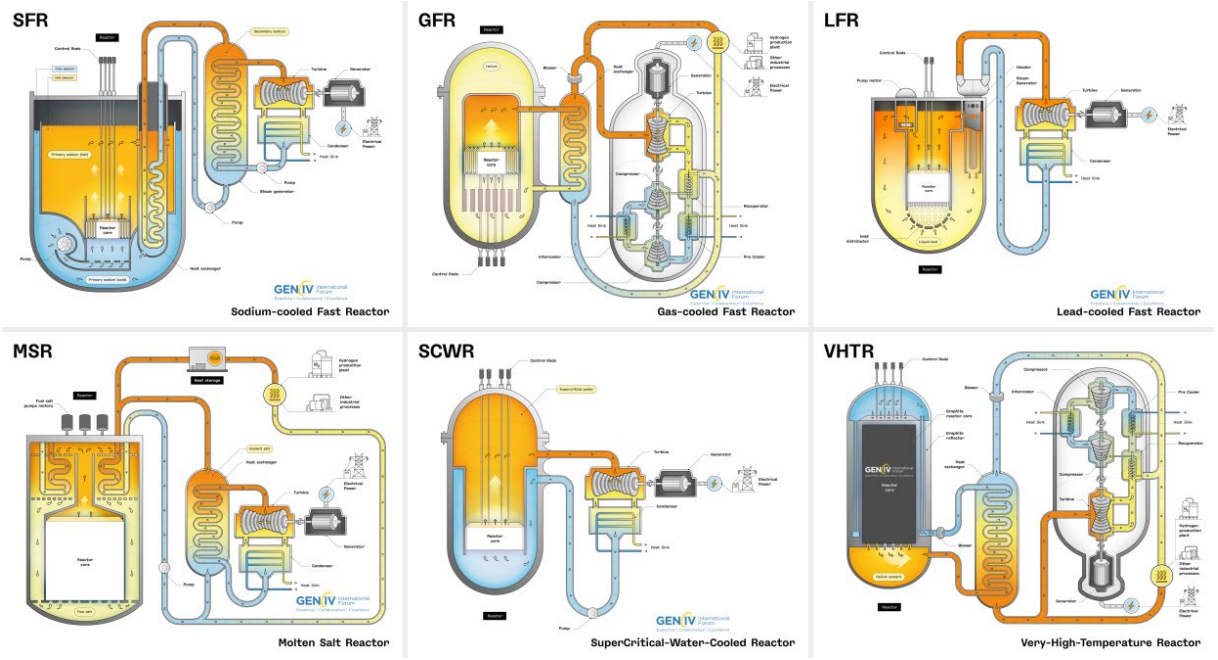
Background in Reactor Theory - Reactor types in context



e-Vinci Micro Reactor
(Source: Westinghouse)



Pressurized Water Reactor
(Source: Yadigaroglu 2005)



Gen IV Reactors
(Source: Gen IV International Forum)

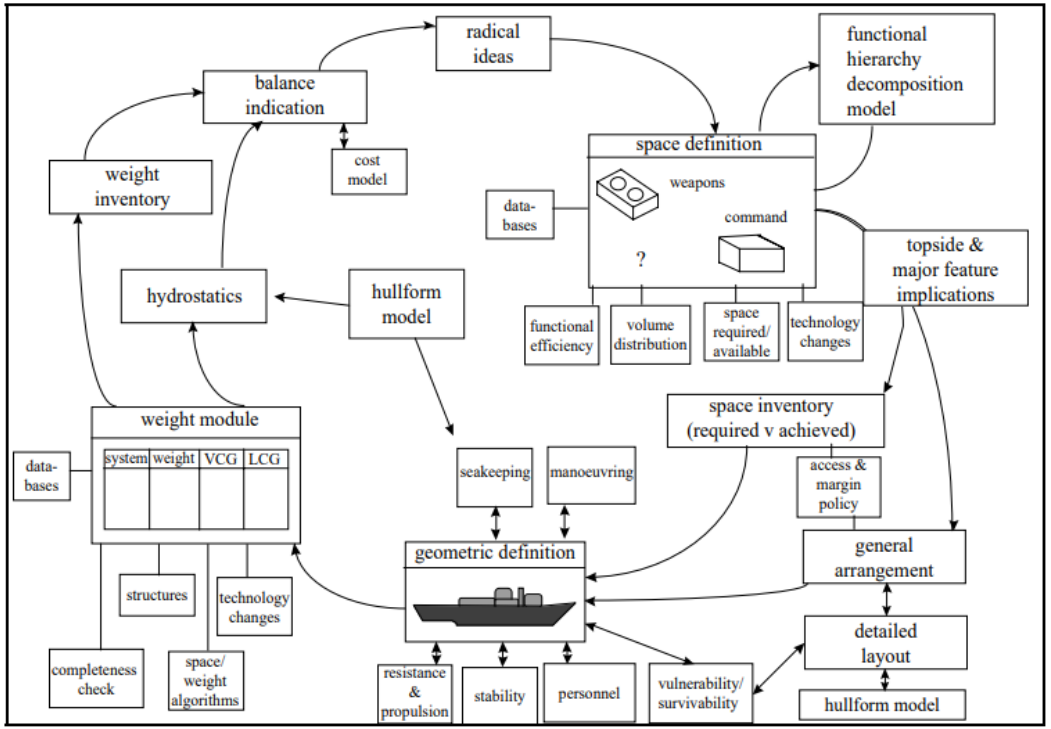
Why a New Lens: Naval Reactors Not the Same Problem

- Using PWRs
- High enrichment: proliferation?
- High pressure: Large EPZ
- Large crews
- Function over cost
- We are starting from scratch



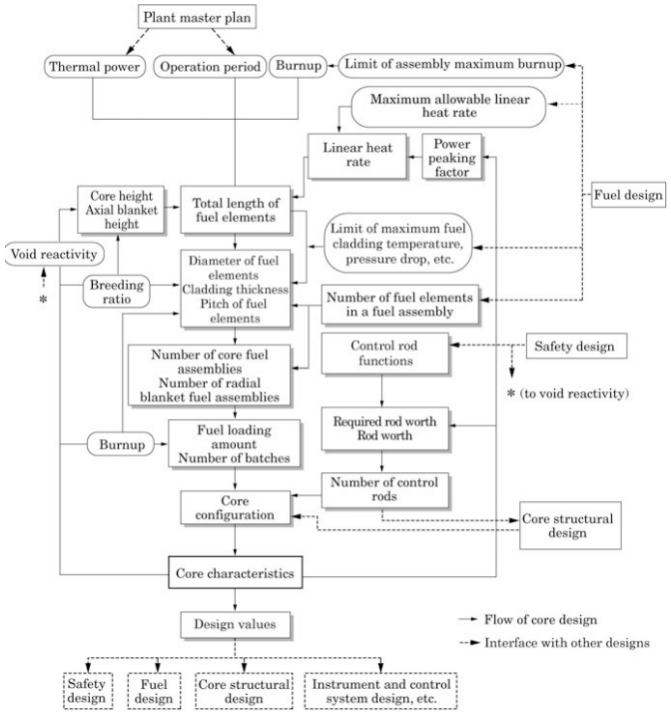
Virginia Class Submarine
(Source: U.S. Navy / GD Electric Boat)

Integration Complexity: Ship

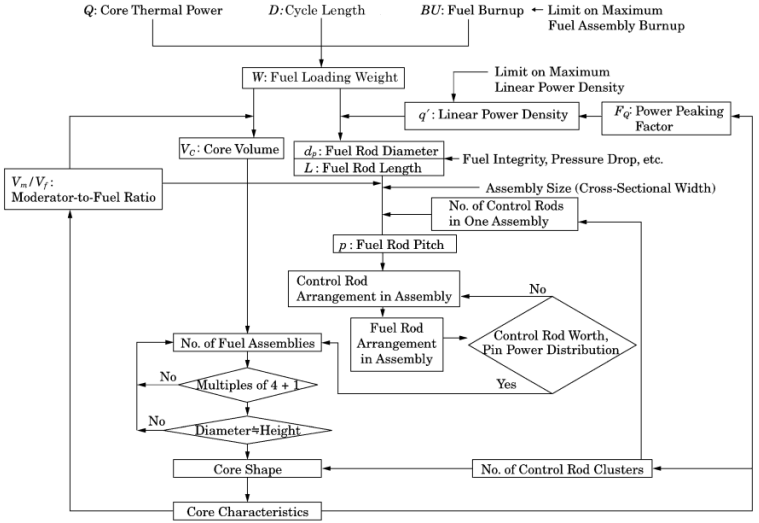


The Design Building Block Approach
(Source: Andrews)

Integration Complexity: Reactor

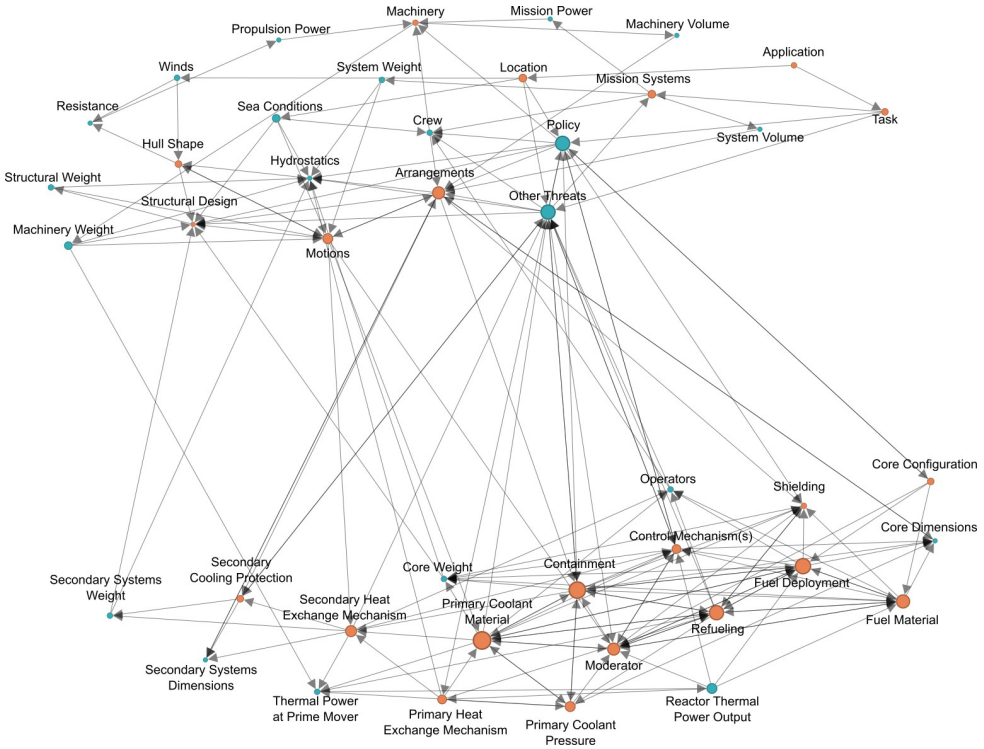


Fast Reactor Core Design Flowchart
(Source: Oka et al.)



PWR Core Design Flowchart
(Source: Oka et al.)

Crude Logical Map of the Interface



A directed map of interactions between ship and reactor, weighted by outdegree.
Components in Orange, Performance Metrics in Blue.

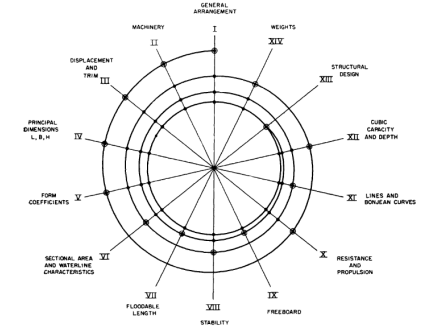
The State of the Art

Ship Design [Singer 2009]

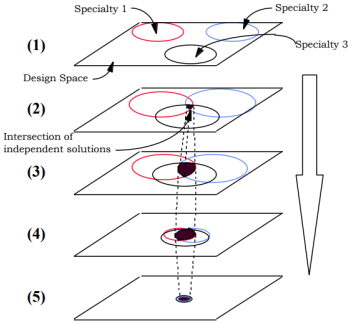
- Point Based
- Set Based

Current Marine Reactor Research

- Point-based integration with ship requirements
- Reactor as a black box
- Assume ship modified to meet reactor needs
- Emblemsvag:
  - Promising because of selection process
  - But selection based on known information & down selection on assumptions

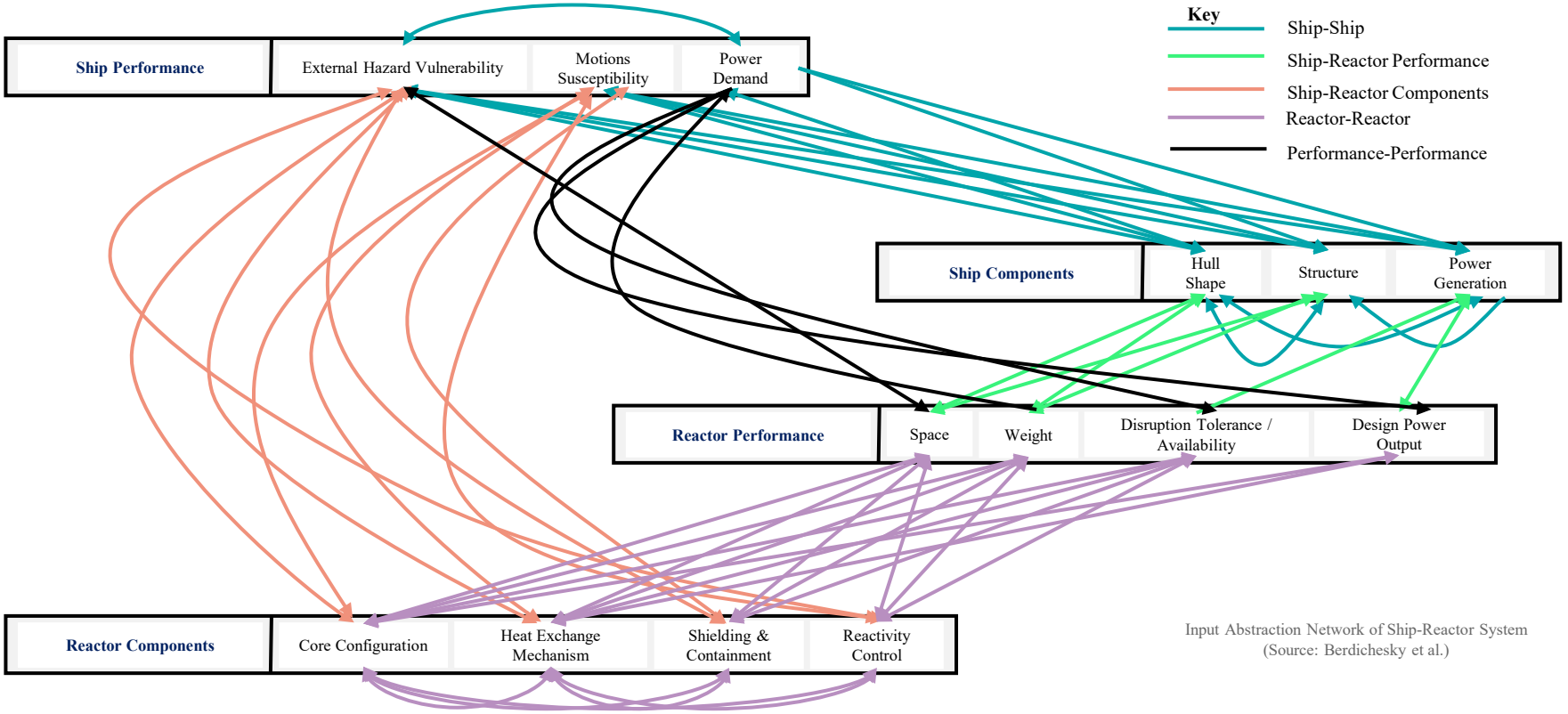


Design Spiral
(Evans 1959)



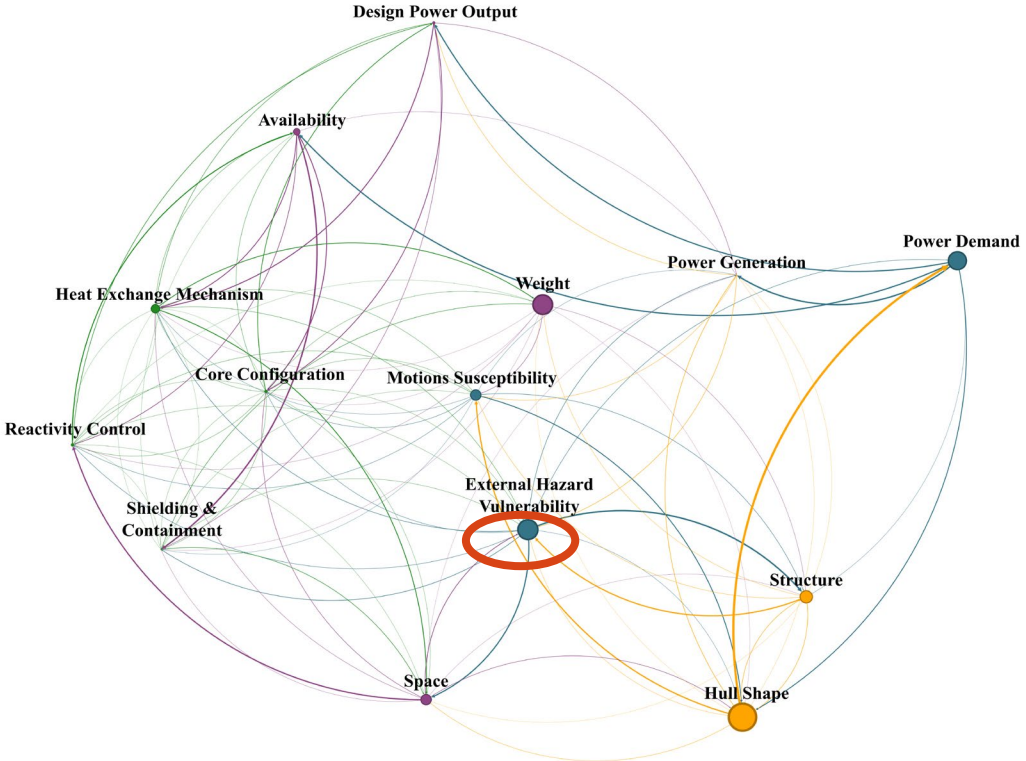
Set Based Design
(Bernstein 1998; Singer 2009)

ANP Abstracted Network: Mapping Through Performance



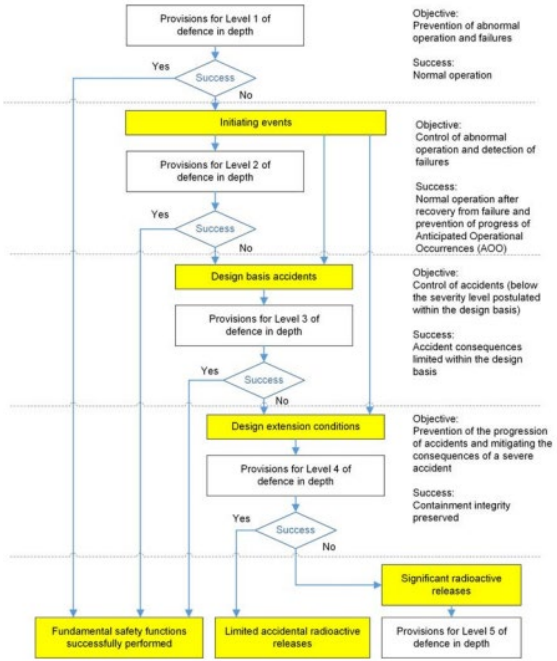
Input Abstraction Network of Ship-Reactor System
(Source: Berdichesky et al.)

Output Network: Ship Requirements Pull



Input Abstraction Network of Ship-Reactor System Under Requirements Pull Assumptions
(Source: Berdichesky et al.)

Defense in Depth: A Binary Indicator



IAEA Flowchart for Defense in Depth (Source: Clark and Rowland)



Wood Splinter Driven Through a Concrete Curb
(Source: Marshall et al.)



1999 Bridge Creek-Moore Tornado, 300+ mph winds
(Sources: Maxwell; Edwards et al.)

Ships in this Context

Avg. 6019 ships 2014-2024, of which 24 sank [Allianz 2024; Gresser 2024]

- Occurrence of about 4×10^{-4}
- Threshold for design basis between 10^{-5} and 10^{-7} (context dependent) [“Final Rule 2019”; 10 CFR Part 50; “Design Features” 2009].
- Russian KLT-40S Reactor on FNPPs: Damage frequency $\leq 10^{-5}$, major radiation release $\leq 10^{-7}$ [“Design Features” 2009].
- **Ship sinking could be a Design Basis Event!** … And even if not, radiation effects still need mitigation for Beyond Design Basis Events.

- Design Basis Event (DBE) vs Design Basis Threat (DBT)
  - DBE based on “appropriate consideration” [10 CFR Part 50]
  - DBT based on what *the operator* can reasonably ensure [“Development… design basis threat” 2009; “National Nuclear Security” 2009]

- Added complications: Remoteness and moving location



Sinking Container Ship (Source: Schuler)

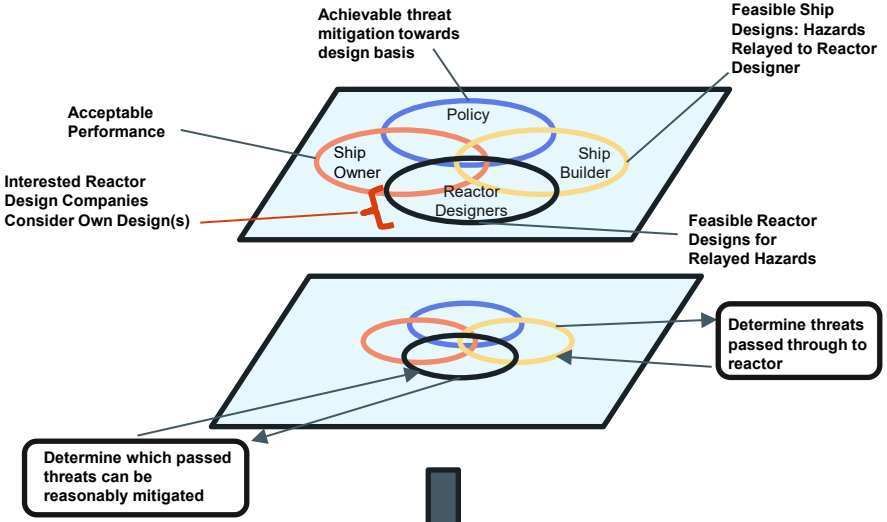


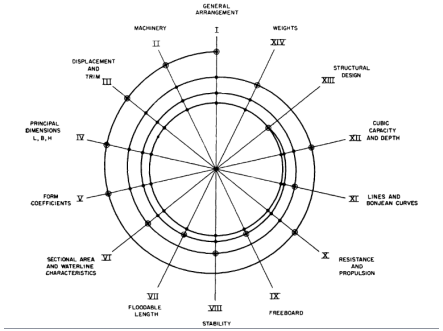
Tanker Marlin Luanda after Houthi Missile Strike (Source: Babb)

Literature Review

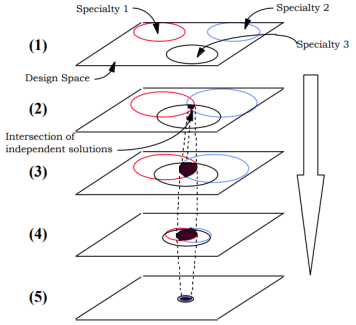
1. Giorsetti (1977). *Analysis of the technological differences between stationary & maritime nuclear power plants.*
2. American Bureau of Shipping (2024). *Requirements for Nuclear Power Systems for Marine and Offshore Applications.*
    a. *References design basis but does not specify*
3. Fialkoff et al. (2020). “Harmonizing Maritime and Nuclear Security for the Physical Protection of Floating Nuclear Power Plants”.
    a. *Identification of relevant parallels, but no established design basis*
4. Valiaveedu et al. (2025). “Nuclear Ship Safety Handbook.”
    a. General principles based on PWR experience
    b. Very PWR-heavy and no established design basis

Visualizing the problem



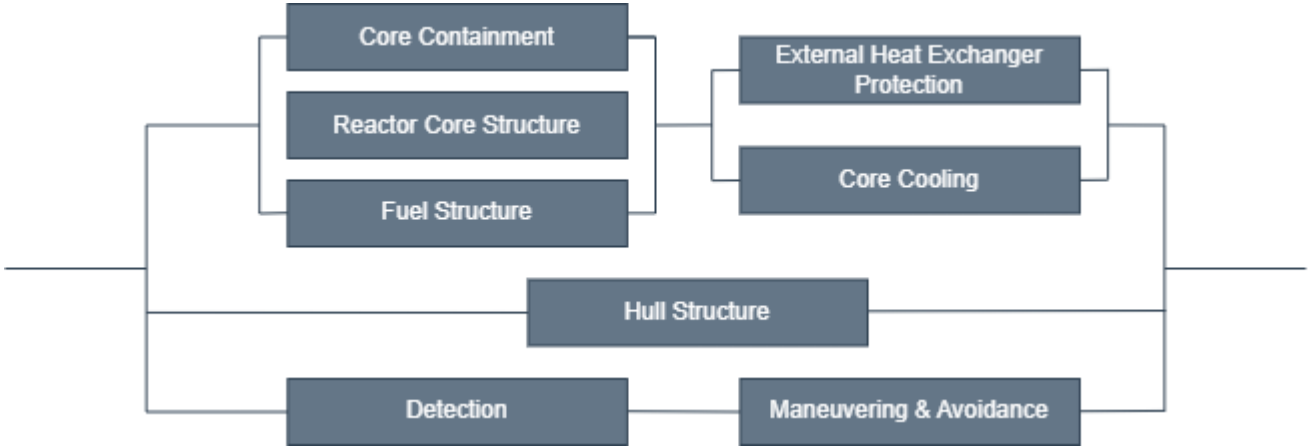


Design Spiral
(Evans 1959)



Set Based Design
(Bernstein 1998; Singer 2009)

Example 1 – Passed-Through External Hazards

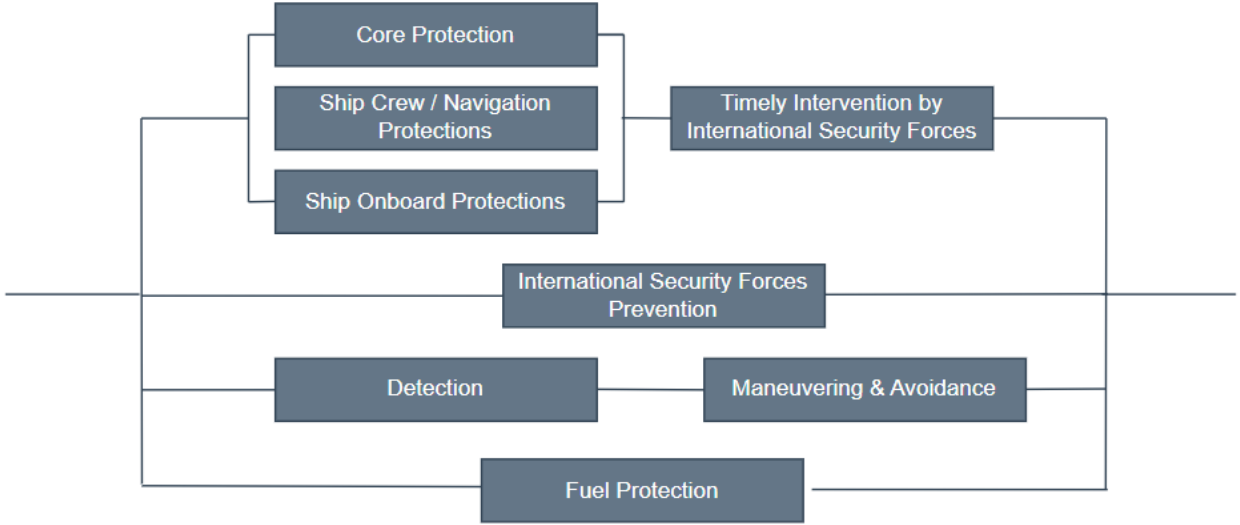


The designer of the ship could probably stop this hazard before or at damage to containment, before the core was impacted. But what if it were a missile? Do such hazards deserve special consideration?

Example Interactions – Fuels & Coolants

Coolant	Benefits (General)	Hazards in Context
Sodium (Gen IV IF)	- High boiling point, low pressure, long thermal response time - Negative temperature coefficient - Atmospheric Pressure	- Violently reactive with water (Emblemsvag) - High temperature → explosive reaction w/ water
Lead (Gen IV IF)	- Doesn't react with water & innate shielding - Dense & high boiling point, high heat of vaporization, thermal capacity	- Corrosive with steel (GIF Proceedings 2009) - High temperature → explosive reaction w/ water
Water ((Umasankari & Mohanakrishnan 2021, U.S. NRC)	- Natural moderator & Affordable - Negative temperature coefficient - Affordable	- High pressure operation - Natural mixing with seawater
Fuel	**Benefits (General)**	**Hazards in Context**
TRISO (Electric Power Research Institute 2019)	- Very Safe; self contained	
MSF (Gen IV International Forum)	- Convention + Dump tanks? - Negative temperature coefficient - Efficiency / low waste	- High temperature → explosive reaction w/ water - Information gap on long-term exposure effects - Corrosive water interactions? (Park, 2024)
UOx Fuel (Buschow et al., 2001, Gen IV IF)	- Affordability / availability - Compatible with most reactor types	- Corrodes with water, releasing soluble uranyl $(UO_2)^{2+}$ (Armstrong et al. 2012)

Example 2 – Proliferation



What policy or operational measures can make this scenario infeasible? Can ship security measures further reduce the risk or delay access to radioactive material? How far do you have to go before this is beyond design basis?

Example Interactions – Fuels & Coolants

Coolant	Benefits (General)	Proliferation Context
Sodium (Gen IV IF)	- High boiling point, low pressure, long thermal response time - Negative temperature coefficient - Atmospheric Pressure	- Opaque, freezes when temperature decreases
Lead (Gen IV IF)	- Doesn't react with water & shielding - Dense & high boiling point, high heat of vaporization, thermal capacity	- Opaque, freezes when temperature decreases
Water ((Umasankari & Mohanakrishnan 2021, U.S. NRC)	- Natural moderator - Negative temperature coefficient - Affordable	
Fuel	**Benefits in Context (General)**	**Proliferation Context**
TRISO (Electric Power Research Institute 2019)	- Very Safe; self contained	- Very hard to extract fuel (Forsberg & Kadak 2025) - But typically higher enrichment
MSF (Gen IV IF)	- Convection + Dump tanks, Efficiency - Negative temperature coefficient	- Would have to separate out from fuel
UOx Fuel (Buschow et al., 2001, Gen IV IF)	- Affordability / availability - Compatible with most reactor types	- Proliferation resistance just from complexity of handling plus often low enrichment

Discussion & Conclusion

1. Mounting threats from climate change, resource uncertainty.
2. Existing methods fail to account for uncertainty, making commitments to concepts that may prove unfavorable. Need to know what is and isn't feasible.
3. For this, we need reconciliation between domains: Ship, Reactor, Owner, Policy
4. Defense in Depth is a starting point because it MUST be achieved and cannot be compromised. Beyond Design Basis insights may guide additional selection criteria.



Questions?

Contact Info
Hal Berdichesky, haberd@umich.edu

Thomas McKenney, tmckenne@umich.edu



References

- Andrews, D. J. (2006). Simulation and the design building block approach in the design of ships and other complex systems. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *462*(2075), 3407–3433. https://doi.org/10.1098/rspa.2006.1728
- Armstrong, C. R., Nyman, M., Shvareva, T., Sigmon, G. E., Burns, P. C., & Navrotsky, A. (2012). Uranyl peroxide enhanced nuclear fuel corrosion in seawater. *Proceedings of the National Academy of Sciences*, *109*(6), 1874–1877. https://doi.org/10.1073/pnas.1119758109
- Berdichesky, H., Willat, R., & McKenney, T. (October 19th-23rd). *Mapping Dependencies and Prioritizations in Maritime Advanced Nuclear Reactor Integration using an Analytical Network Process*. 16th International Symposium on Practical Design of Ships and Other Floating Structures, Ann Arbor, MI.
- Bernstein, J. I. (n.d.). *Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices*.
- Boiling water reactor—BWR | Definition & Components | nuclear-power.com. (2014, October 31). *Nuclear Power*. https://www.nuclear-power.com/bwr-boiling-water-reactor/
- Clark, A., & Rowland, M. (2021). *Safety and Security Defense-in-Depth for Nuclear Power Plants* (Nos. SAND2021-14591, 1832309, 701906; pp. SAND2021-14591, 1832309, 701906). https://doi.org/10.2172/1832309
- Controlling Fission. (n.d.). *Nuclear @ McMaster*. Retrieved October 9, 2025, from https://nuclear.mcmaster.ca/resources/how-does-it-work-2/controlling-fission/
- Domestic Licensing of Production and Utilization Facilities, 10 Code of Federal Regulations § 50 (1956). https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/full-text.html
- Edwards, R., LaDue, J., Ferree, J., Scharfenberg, K., Maier, C., & Colbourne, W. (2013). Tornado Intensity Estimation: Past, Present, and Future. *Bulletin American Meteorological Society*.

References

- Electric Power Research Institute (EPRI). (2019). *Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance: Topical Report EPRI-AR-1 (NP)* (Topical Report No. 3002015750). Electric Power Research Institute.
- Emblemsvag, J., Ordonez, C., Tamm, C., Ortigosa, J., Perez, A., Thoresen, H., Ovrum, E., Jordahl, M., Laanke, L., Reistad, O., Brodin, E., Lien, H., Rygh, B., Rodset, A., Hilland, S., Baptista, L., Trovag, J., Pareliussen, B., Bjornevik, E., & Ribeiro e Silva, S. (2025). *Final Report of the Nuclear Propulsion for Merchant Ships I (NuProShip I) project*. NTNU.
- Emblemsvåg, J., Ordoñez, C. H., Tamm, C. G., Strand, T., Ortigosa, J. S., Pérez, A., Colilles, Y. M., & Esteban, A. (2024, August 4). Criteria for selecting nuclear reactors for merchant shipping. *Proceedings of the ASME 2024 31st International Conference on Nuclear Engineering*.
- Forsberg, C., & Kadak, A. (2025). Reducing Proliferation Risks with High-Assay Low-Enriched Uranium Fuels in Reactors with Coated-Particle (TRISO) Fuels. *Nuclear Technology*, *0*(0), 1–8. https://doi.org/10.1080/00295450.2025.2462378
- Internationale Atomenergie-Organisation (Ed.). (2009a). *Design features to achieve defence in depth in small and medium sized reactors*. IAEA.
- Internationale Atomenergie-Organisation. (2009b). *Development, use and maintenance of the design basis threat: Implementing Guide*. Internat. Atomic Energy Agency.
- Marshall, T. P., Davis, W., & Runnels, S. (2011, May 22). *Damage Survey of the Joplin Tornado: 22 May 201*. 26th Conference on Severe Storms, Nashville Tennessee.
- *Moderator temperature coefficient of reactivity | Nuclear Regulatory Commission*. (n.d.). Retrieved October 10, 2025, from https://www.nrc.gov/reading-rm/basic-ref/glossary/moderator-temperature-coefficient-of-reactivity

References

- *National Nuclear Security Threat Assessment, Design Basis Threats and Representative Threat Statements: Implementing Guide*. (2021). International Atomic Energy Agency.
- Oka, Y., Madarame, H., & Uesaka, M. (Eds.). (2014). *Nuclear Reactor Design: An Advanced Course in Nuclear Engineering* (Vol. 2). Springer Japan. https://doi.org/10.1007/978-4-431-54898-0
- Park, J. (2024). *Studies on Molten Salt Fuels: Properties, Purification, and Materials Degradation*. Virginia Polytechnic Institute and State University.
- *Proceedings of the GIF Symposium, 9-10 September 2009*. (2009). OECD/NEA Publishing.
- *Safety and Shipping Review 2024*. (2024). Allianz Commercial.
- Schuler, M. (2018, March 13). Photos: The Worst Containership Disasters in Recent History. *gCaptain*. https://gcaptain.com/the-worst-containership-disasters-in-recent-history-in-photos/
- Sherrill, M. (2024, May 22). Trade Fact of the Week: A new container ship launches every day. *Progressive Policy Institute*. https://www.progressivepolicy.org/trade-fact-of-the-week-a-new-container-ship-launches-every-day/
- Umasankari, K., & Mohanakrishnan, P. (2021). Chapter 3—Types of nuclear reactors. In P. Mohanakrishnan, O. P. Singh, & K. Umasankari (Eds.), *Physics of Nuclear Reactors* (pp. 155–191). Academic Press. https://doi.org/10.1016/B978-0-12-822441-0.00003-0
- A. Valiaveedu, N. Edmonds, and J. Izurieta, "Nuclear Ship Safety Handbook," MIT Maritime Consortium, Oct. 2025.
- Wootan, D., Burns, K., Gates, R. K., Longoni, G., & Schmitt, B. (2015, June). *A Concept for a Flexible Neutron Source*. American Nuclear Society Summer Meeting 2015.
- Yadigaroglu, G. (2005). Nuclear Reactors: Physics and Materials. *CHIMIA*, *59*(12), 877. https://doi.org/10.2533/000942905777675318

