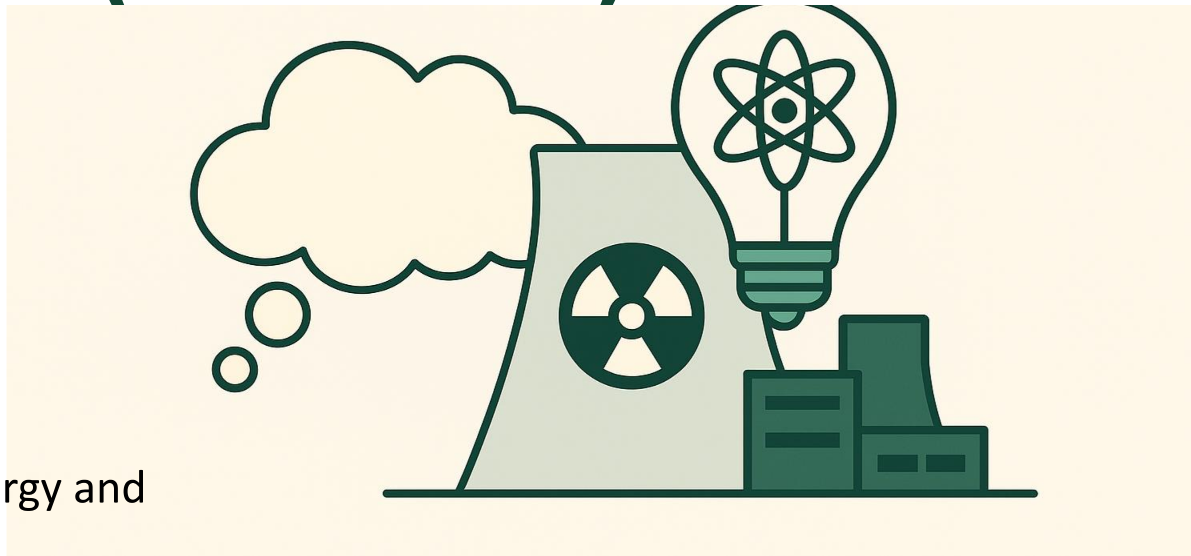
Advanced Nuclear and Small Modular Reactors (SMRs)

Esam Hussein, PhD, PEng, FCSSE



The Energy Council

2026 State and Provincial Trends in Energy and the Environment Conference, Regina, Saskatchewan

2026-06-12

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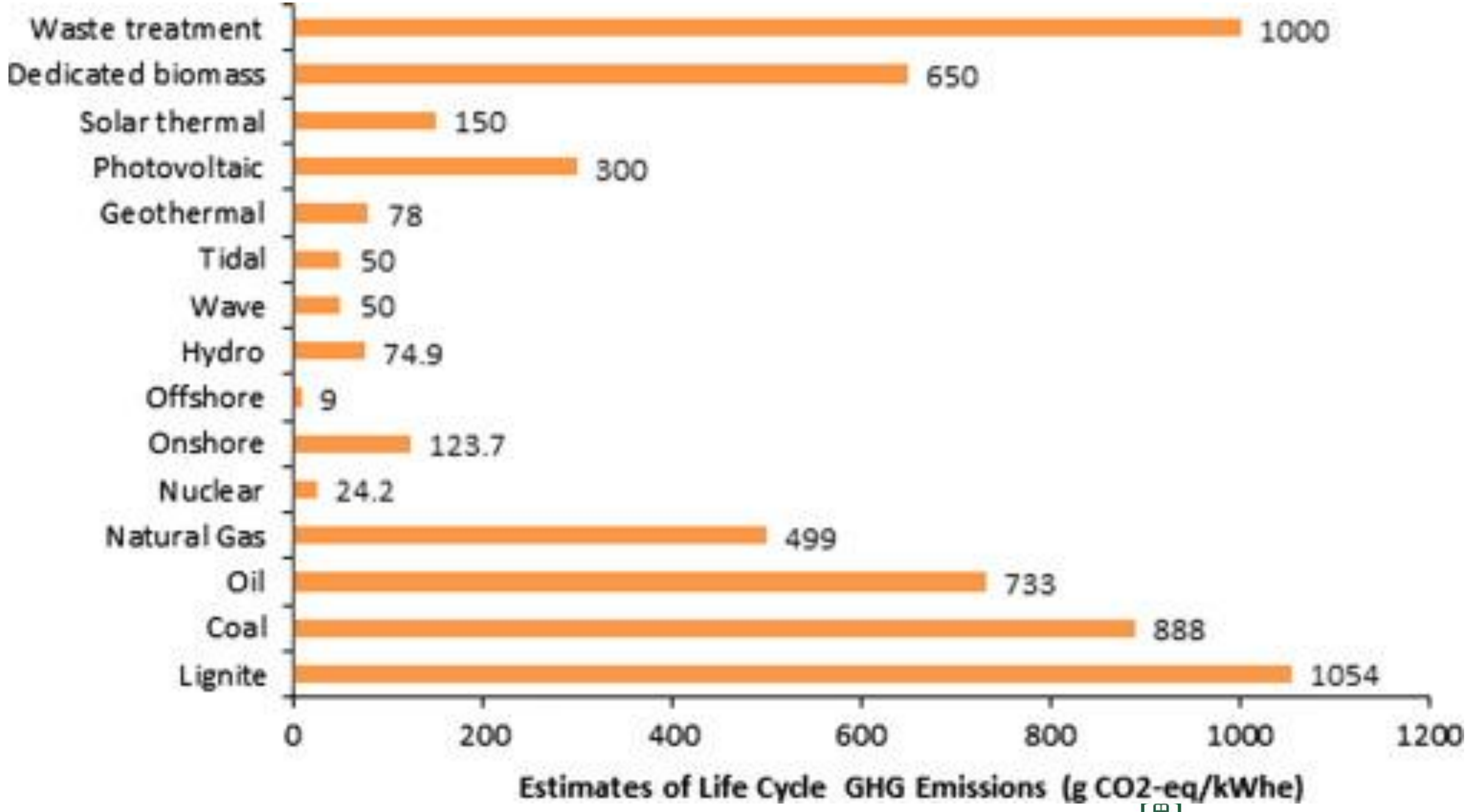
Nuclear Power: Role in Decarbonization



https://doi.org/10.1016/s.rser.2014.07.087

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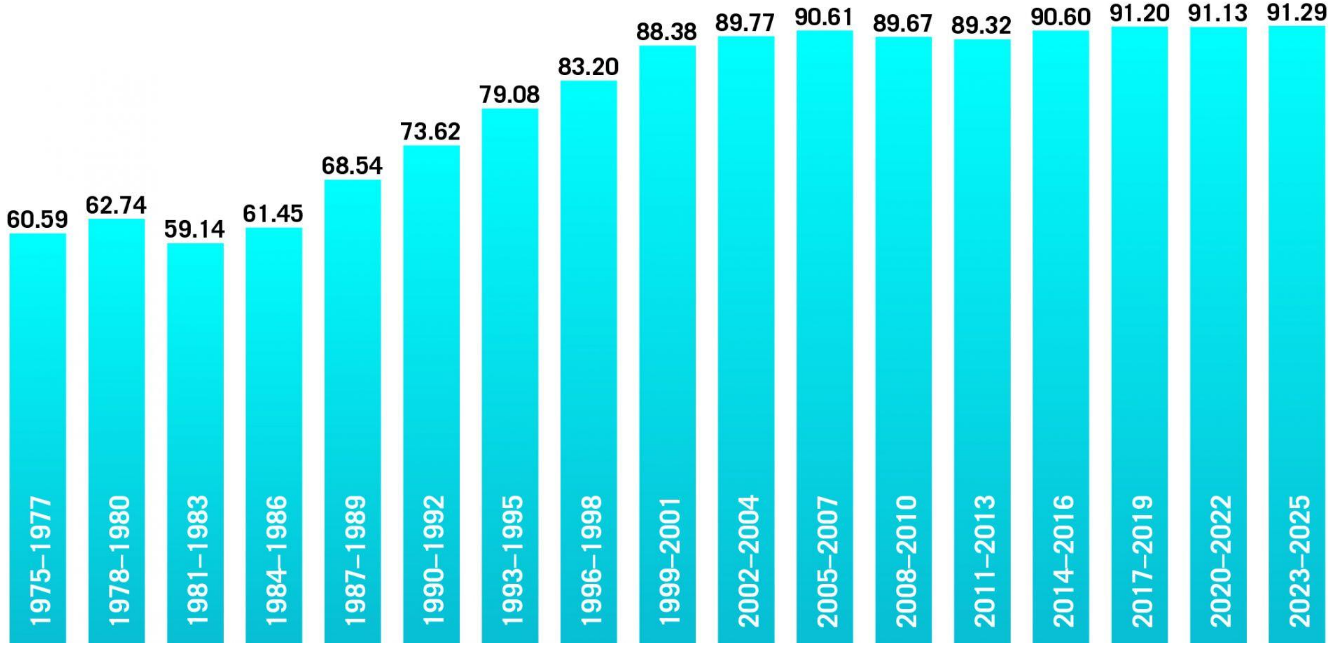
Nuclear Power: Capacity Factor

Capacity factors for selected energy sources in the United States in 2024

https://www.statista.com/statistics/183680/us-average-capacity-factors-by-selected-energy-source-since-1998/

Nuclear	92.3%
Geothermal	65.0%
Natural gas -combined cycle	59.7%
Other biomass	59.0%
Wood	55.6%
Other fossil fuels	45.5%
Coal	42.6%
Hydroelectric	34.5%
Wind	34.3%
Solar thermal	24.6%
Sola photovoltaic	23.4%
Natural gas - steam turbine	20.5%
Natural gas - internal combust	20.2%
Natural gas - gas turbine	14.6%
Pumped storage	11.3%
Battery	7.5%
Petroleum - internal combusti	2.1%
Petroleum -gas turbine	2.1%

EIA
© Statista 2026
United States; 2024; Provisional figures
statista



U.S. fleet's median capacity factor of all reactors

https://www.ans.org/news/article-7959/us-nuclear-capacity-factors-more-power-on-order/

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The Cons of Nuclear Power

- New Constructions: High Capital Cost; susceptible to Budget overruns and Schedule delays
- Radioactive Waste for thousands of years.
- Accident Risk (Low Probability, High Consequence): Public perception.
- Complex Decommissioning
- Proliferation Concerns

Are SMRs the answer? (where did the "N" in Nuclear go?)

Will discuss the implications of being **S**mall, **M**odular and inherently and or passively safe **R**eactor.

Accident Risk

Radioactive Waste

Nuclear Weapons

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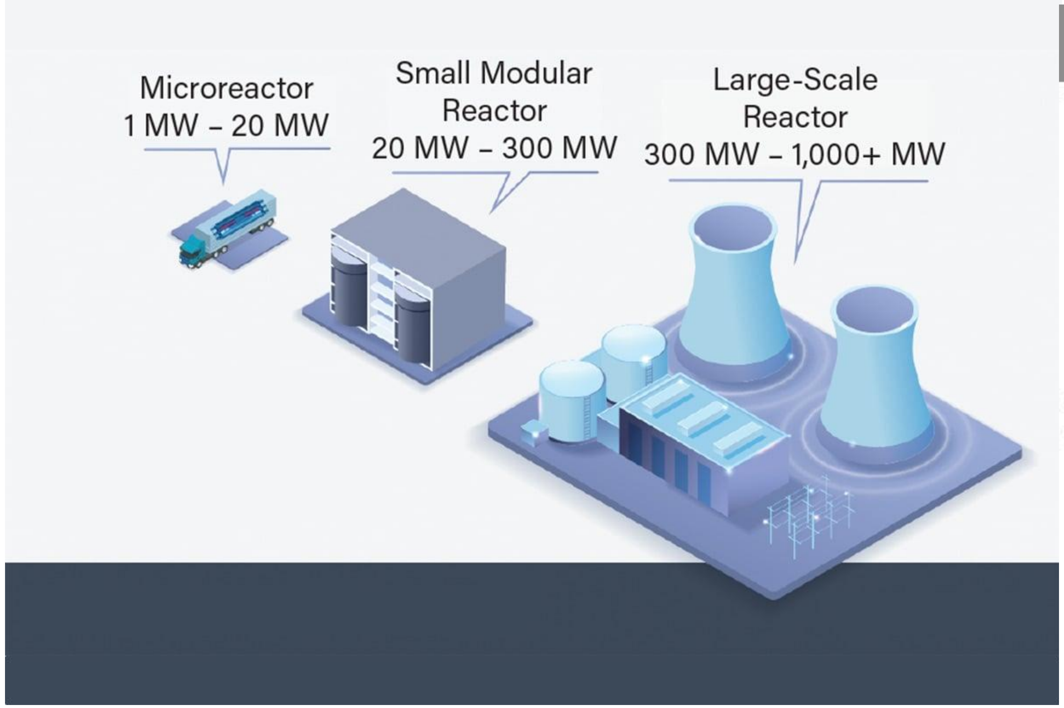
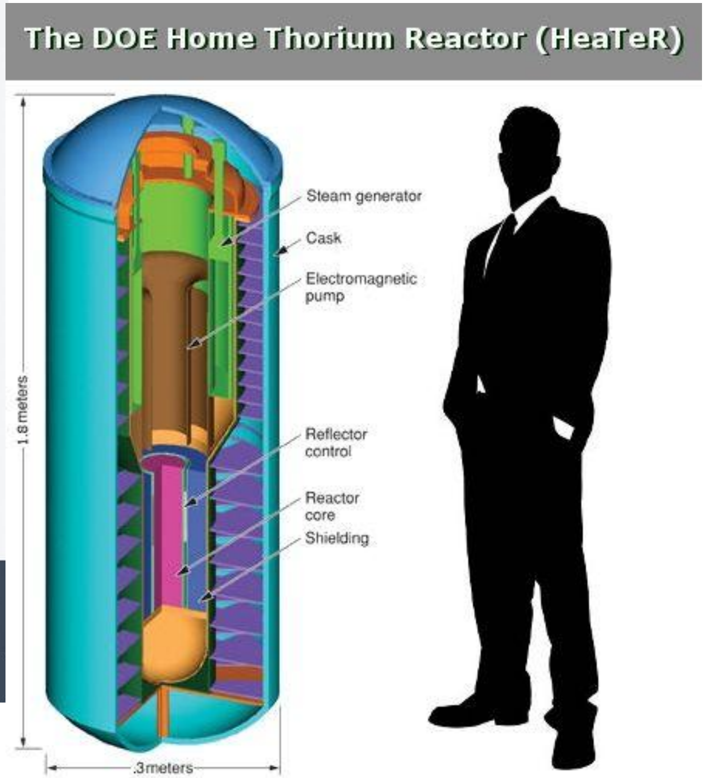
Small, Micro, Large Reactors

In terms of Size: IAEA: small reactor having "physically a fraction of the size of a conventional nuclear power reactor."

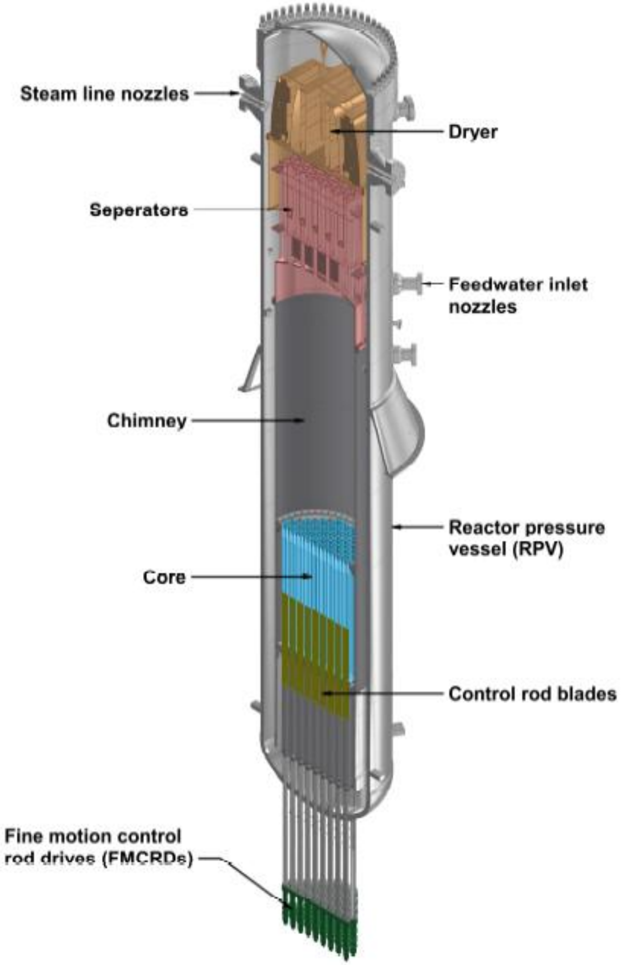
In terms of MW(e) Power:



https://mezha.media/wp-content/uploads/2022/11/smr-1.jpg



https://i.pinimg.com/736x/d8/44/76/d844762a6684c659493d58d199d99241--thorium-reactor-nuclear-reactor.jpg



Reactor Pressure Vessel
Height: 26 m
Diameter: 4 m
Plant footprint: 9,800 m^2

https://aris.iaea.org/Publications/SMR_booklet_2022.pdf
How was the BWRX-300 designed to keep construction costs in check? -- ANS / Nuclear Newswire

Modularity

ELSEVIER

Nuclear Engineering and Design

Volume 417, February 2024, 112809

Generation modular reactors: A framework

Esam M.A. Hussein

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https://doi.org/10.1016/j.nucengdes.2023.112809 Get rights and content

Highlights

- Arguing that a reactor module is not necessarily a modular reactor.
- Asserting that an integral reactor is a module that incorporates process intensification.

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Scale Modularity

- Building a large plant in installments of small units or modules (Small Reactor Modules: SRMs).
- Offers Economy of Multiples, lowers financial risk.
- Sharing of facilities, may impact independence of operation.
- Failure of more than one module due to external or common hazards (common cause failures) may present operational and safety challenges.
- Large Scale Modularity is not uncommon.

https://mechtechtutorials.com/future-of-nuclear-energy/

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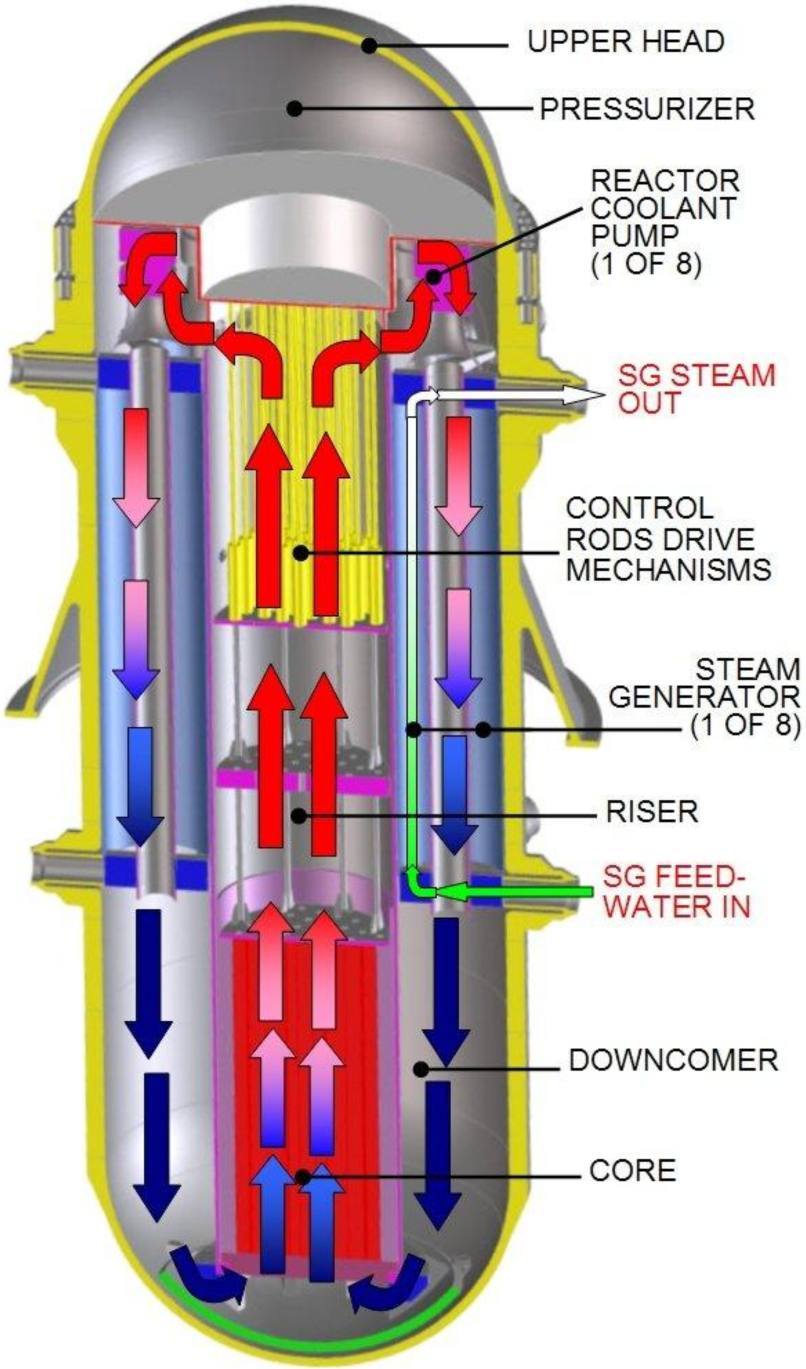
Integral Reactors

Process intensification: combining “multiple operations into fewer devices (or a single apparatus)”[1].

- Reactor core and primary cooling system within the same vessel.
- More intensification by natural circulation, no coolant pumps.
- Minimum pipe penetrations through reactor vessel: eliminating loss-of-coolant accidents, but less accessibility.
- Smaller size, lower capital cost, may be fabricated offsite and transported to site, reducing construction time.

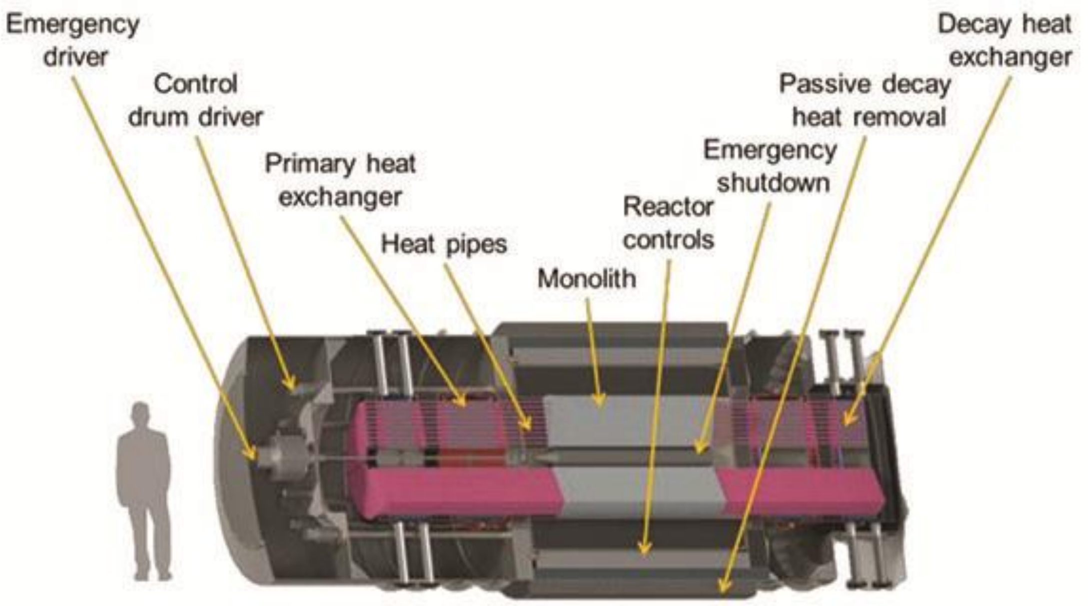


1 Babi et al., 2016, doi:10.1007/978-3-319-28392-0_2.

https://www.researchgate.net/publication/236538819_Reactor_Technology_Options_Study_for_Near-Term_Deployment_of_GNEP_Grid-Appropriate_Reactors/figures?lo=1

Microreactors: up to 10 MW(e)

- Power less than 20 MW(th) classified in the USA as "Category B reactors", within "Hazard Category 2": A hazard with consequences limited to onsite, because the quantities of fissile materials present in such reactors are "not in sufficient quantities to pose significant off-site impacts".[1]
- Reduce or eliminate size of exclusion areas and emergency planning zones. Closer to users: stringent defense-in-depth measures.
- Three features: (1) factory fabrication, (2) portability/transportability and (3) self-adjustment and control.
- Use HALEU fuel (5 to < 20% enrichment)➔ increased security and proliferation risks, mitigated by a well-sealed reactors.



https://prometheus.org/2021/12/23/how-microreactors-could-change-the-nuclear-power-industry-and-the-world/

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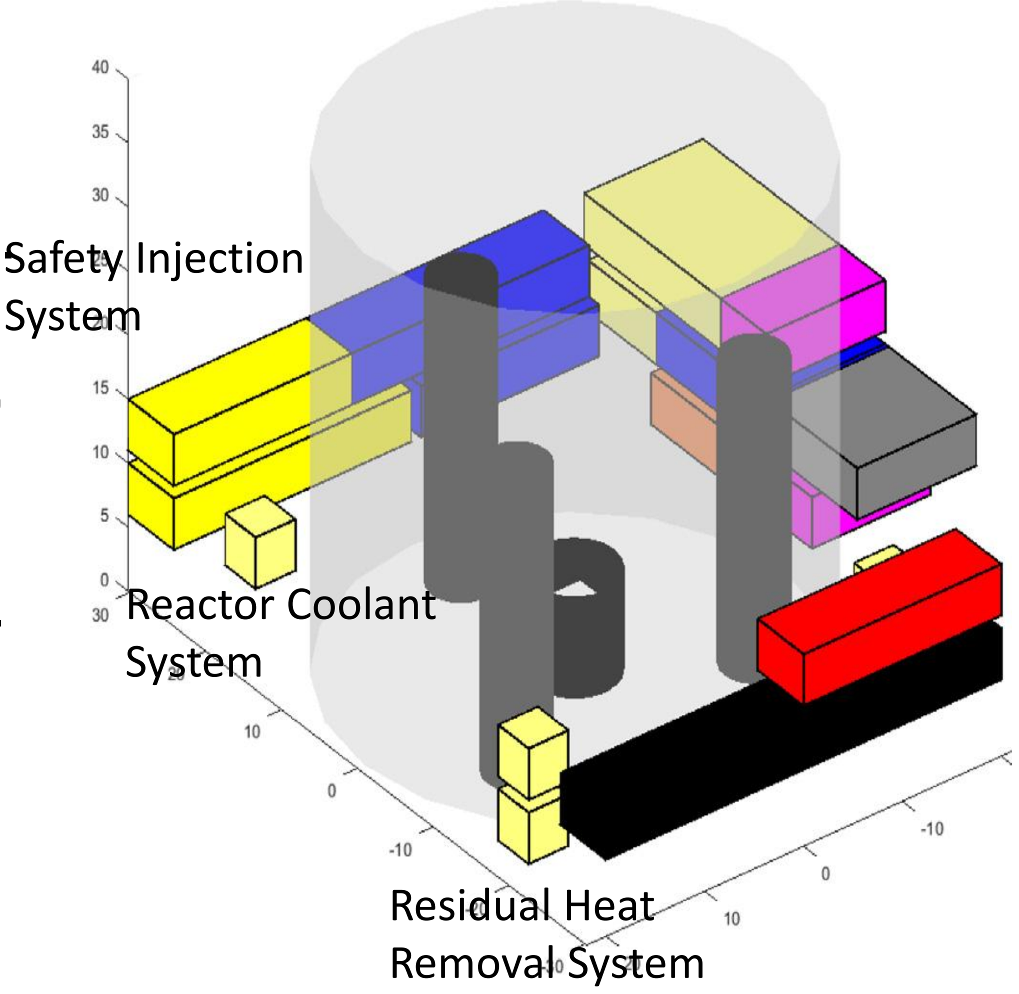
1 DOE-STD-1027-2018, Hazard Categorization of DOE Nuclear Facilities

Modular Design

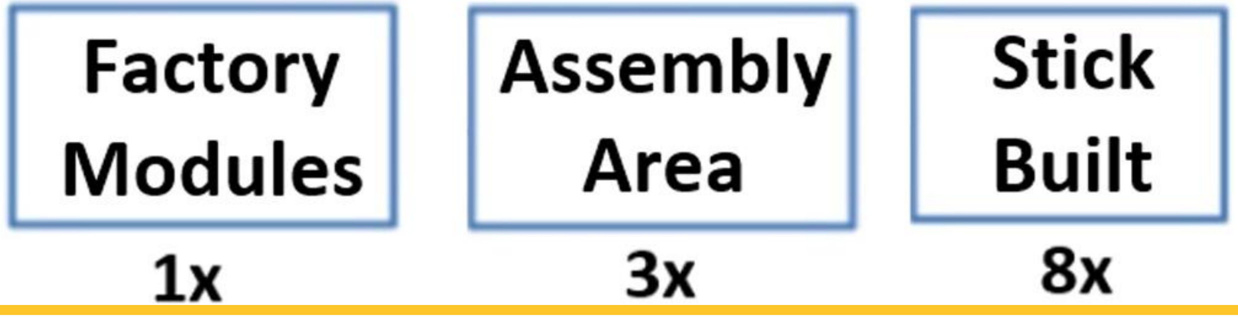
- For a system to be truly modular it should be deliberately designed to be so from its inception.
- Designed modules should be devised so that they can be manufactured in a modular manner, i.e., in shops ready for assembly on site. Modular construction can readily follow: Design modules for manufacture and assembly (DfMA).
- Design separate but interconnected modules/components.
- Applied mostly to Balance of Plant (auxiliary) systems.
- Modules can be designed either to "fit the system", or to "fit modules" to system.



http://www.pesri.net/blog/wp-content/uploads/2018/11/module-layout-optimization.pdf

Modular Manufacturing

- Facilitated by modular design.
- Modules pre-fabricated in a shop, to be assembled and interconnected onsite, with minimal effort ➔ "1-3-8 rule" goal.
- A reactor manufactured offsite as a single module benefits from this rule, e.g., microreactors.
- Multi-Module Manufacturing, best achieved when components and processes of a module are independent from those of other modules, but similar to each other within module, while allowing interchangeability between modules.



https://doi.org/10.1016/j.nucengdes.2018.10.023

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Modular Construction

- Shop-assembled on skids for clipping together using standard connections and interfaces, or for mounting on open or closed 2D panels and/or full-fixture volumetric (3D) units.
- Reduce build schedule by avoiding long-duration tasks in the critical path of the construction plan: “a series of assembly activities, with only the final stages of construction remaining on the critical path“, Lloyd, 2020[1].
- Fewer workers onsite, better workplace health, safety and security, improved quality and less reworking, diminished interruptions due to inclement weather, and lower environmental impact.
- Lapp & Golay, 1997[2] cost saving is “almost equally split between the design for modularity and the modular construction process”.

Ohma Nuclear Power Plant Reactor Building, Japan

Obata, Tatsuya, et al., 2010.. ICONE18-□□□□□/

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1 doi:10.17863/CAM.46941. 2 doi:10.1016/ s0029-5493(97)00031-9..

Modular Construction: CANDU

Two CANDU PHWR (Qinshan, China), 728 MW(e), completed in 2002 and 2003:

- ≈ 80% of its volume installed as modules or prefabricated assemblies.
- Completed in then a record time of 51.5 months.

Unloading Calandria
http://nuceng.ca/canteach-rev2/library/20031701.pdf

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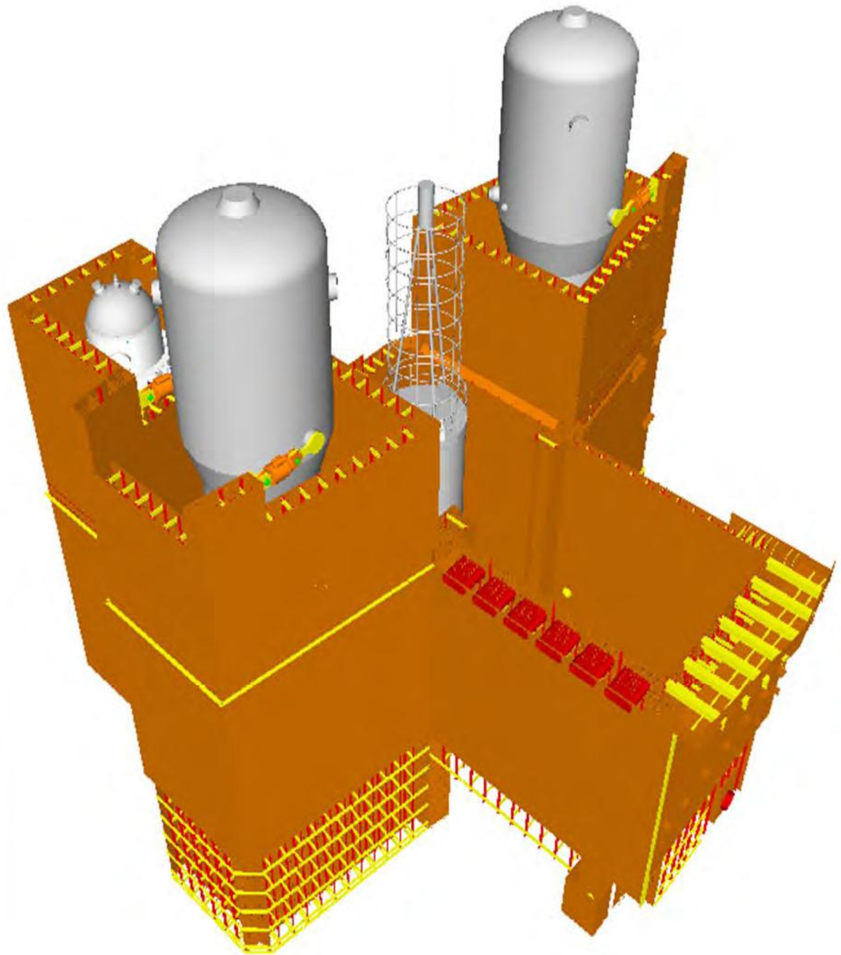
Modular Construction: AP1000 Cont.

- Two AP1000 units 2 and 3 in Virgil C. Summer, South Carolina, started in 2013, suspended in 2017 due to cost overruns, attributed to "issues of managing the quality along the supply chain" (Locatelli, 2018[1]) and inexperience and management challenges (Wrigley, 2021[2]).

- China had four operating AP1000 reactors since 2018, Haiyang 1 and 2 and Sanmen 1 and 2, and four units are under construction, first four operating reactors faced delays and cost overruns, as they were to begin operation in 2013 and 2014, but came online in 2018.

AP1000 Structural Module

https://files.asme.org/Events/NTS2011/28766.pdf



1 https://arxiv.org/ftp/arxiv/papers/1802/1802.07312.pdf. 2 doi:10.1016/j.pnucene.2021.103664..

Generation IV Reactors

GOALS (www.gen-4.org)

Sustainability:

- Long-term availability, effective fuel utilization.
- Minimize and manage nuclear waste, reduce long-term stewardship burden.

Economics:

- Life-cycle cost advantage over other energy sources.
- Level of financial risk comparable to other energy projects.

Safety and Reliability:

- Excel (*inherent & passive safety*).
- Very low likelihood and degree of core damage.
- Eliminate need for offsite emergency response.

Proliferation Resistance:

- Very unattractive and least desirable route for diversion or theft of weapons-usable materials.

Physical Protection

- Increased physical protection against acts of terrorism.

Inherent safety: Avoid hazards by design.

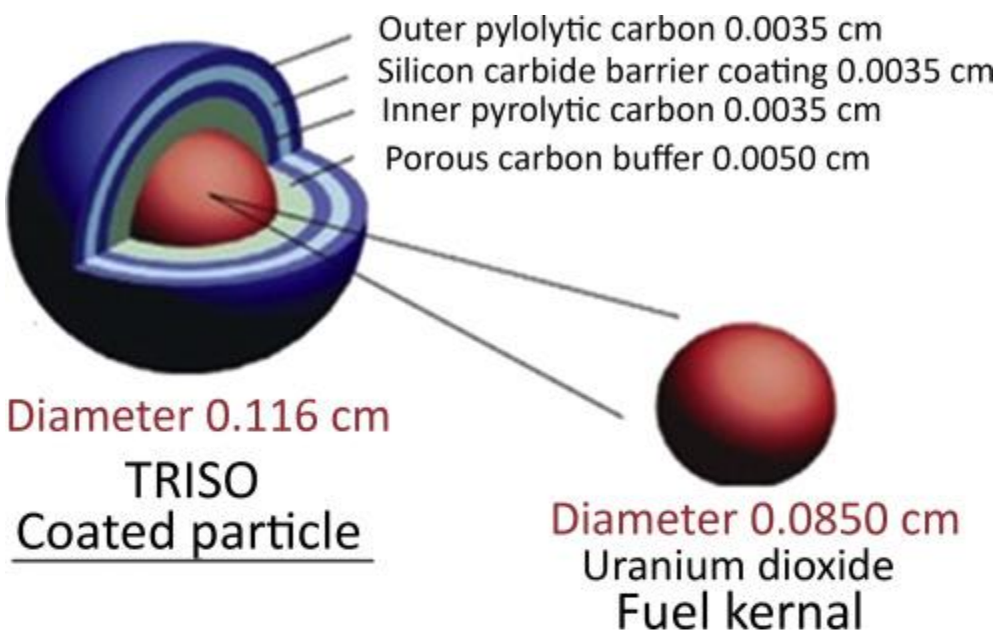
Passive safety: Rely on natural phenomena.

Gas-Cooled Fast Reactors (GFRs)
Lead-Cooled Fast Reactors (LFRs)
Molten Salt Reactors (MSRs)
Sodium-Cooled Fast Reactors (SFRs)
Supercritical-Water-Cooled Reactors (SCWRs)
Very-High-Temperature Reactors (VHTRs)

Inherent safety: Avoid hazards by design

Ultimate Hazard is accidental release of radionuclides by fuel failure➔ Source term (type & amount), avoided by[1]: (i) minimization, (ii) substitution, (ii) moderation (tempering), (iv) simplification

- Minimization:
  - Lower Power ➔ less fuel ➔ lower source term.
  - Reduce reactor size ➔ lower volume-surface-ratio ➔ easier heat dissipation ➔ avoid fuel failure by over heating.
  - Integral Reactor: no Loss of Coolant Accidents.
- Substitution: Use Accident Tolerant Fuel/Cladding:
  - Fuel: TRISO particles, oxides doped with Al_2O_3, CaO, Cr_2O_3, Nb_2O_5, TiO_2, carbides, nitride, metallic.
  - Coated Cladding: Zr alloys coated with chromia, alumina, and/or silica.
  - Cladding: FeCrAl, SiC/SiC composites, Mo-Zr and Mo-FeCrAl (refectory).



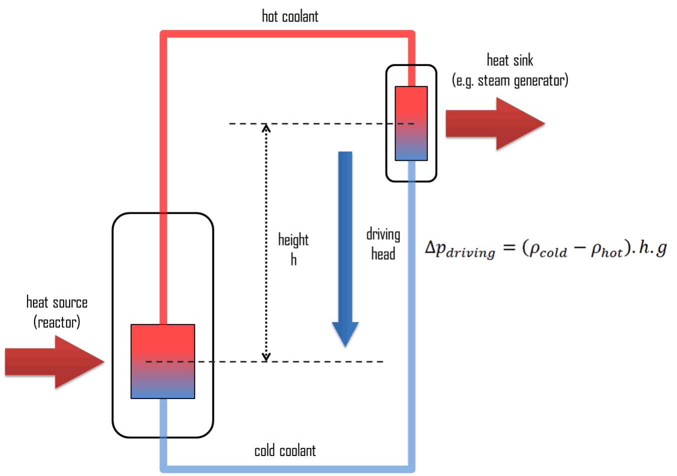
doi: 10.1016/j.net.2016.02.007

1 Amyotte & Khan, 2021, doi:10.1002/cjce.23987.

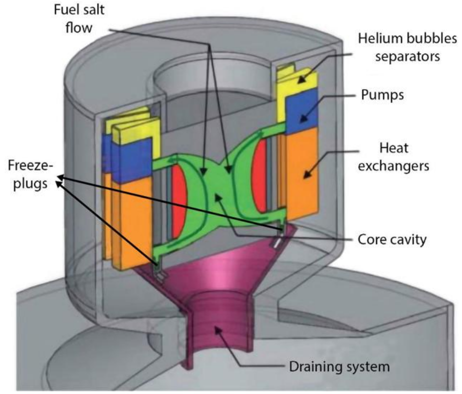
Passive safety: Rely on natural phenomena

Natural circulation and thermosyphon, Gravitational force, Spring force, Centrifugal force, Buoyancy, Liquid metal freezing, Freeze valves/plugs.

- Passive safety does not necessarily ensure absolute safety, as such passive safety systems can fail.
- Passive systems may be difficult to deactivate, once triggered, do not depend on externally imposed driving forces.
- Their failure tend to be gradual due to their inertia ➔ margin of safety.



https://www.nuclear-power.com/nuclear-engineering/heat-transfer/convection-convective-heat-transfer/natural-convection-free-convection/natural-circulation/



Tiberga et al., 2019, doi:10.1016/j.anucene.2019.06.039

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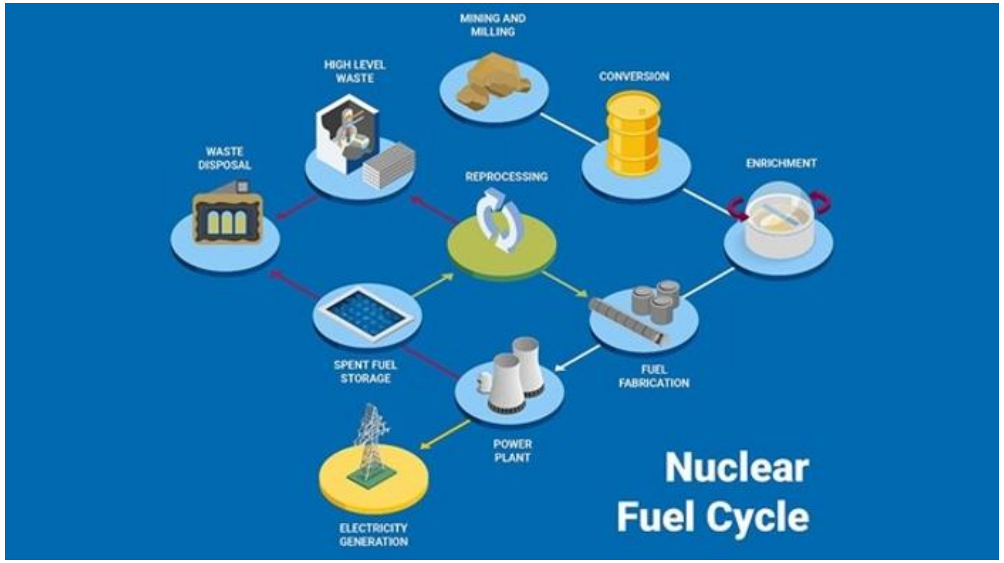
Fuel Supply Chain Challenges

- In the U.S. the "nuclear, the fuel supply chain is often overlooked. This dynamic is shifting as the industry wakes up to critical choke points and a heavy reliance on countries like Russia for enrichment: [Building a domestic nuclear fuel supply chain | Latitude Media]
- [How a post-Cold War uranium program proved even old foes can work together - The Globe and Mail]
- Reactor using plutonium or uranium-233 require reprocessing of spent fuel or a thorium blanket, respectively.
- Canada relies on natural (unenriched uranium) in CANDU reactors, emerging systems rely on uranium enriched up to ≤ 20% in ^{235}U.



[Canada needs policies to fill the gap in its nuclear fuel cycle - Graduate School of Public Policy]

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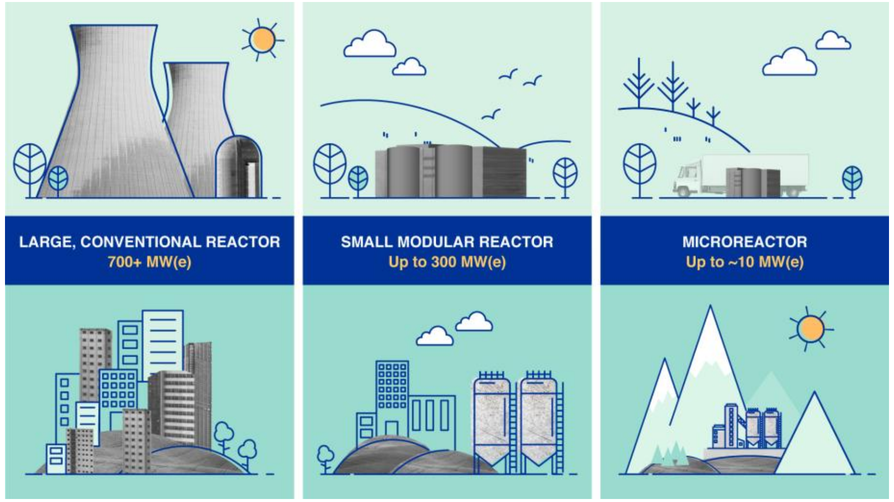
Closing Remarks

- Modularity is mostly in balance-of-plant systems (reactor core is one module), and in Integral Reactors “intensified modules”.
- For a system to be truly modular, it should be designed to be so, to benefit from the “1-3-8 rule” of Modular Manufacturing and enable Modular Construction.
- Inherent and passive safety enhance the defense-in-depth against accidents, but assessment of the performance of passive systems may be challenging. It is, therefore, imperative to test the functionality of such systems, under normal and upset conditions, before implementing them, and to be able to inspect and maintain them during service.[1]



Scratching the surface of SMR history: What’s in a name? -- ANS / Nuclear Newswire

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1 Maio et al., 2021, doi:10.3390/en14154688.

For more details

Esam M.A. Hussein, Advanced Fission Reactors Technology, Nuclear Engineering and Technology for the 21st Century – Monograph Series, The American Society of Mechanical Engineers (ASME), New York, upcoming.
http://asmepress.org/nuclearmonographs.html