Generation IV (very) Small Modular Reactor Technology for Future Surface Combatants

COMMIT
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Materiel and IT Command
Ministry of Defence

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  - Naval nuclear technology
  - (very) Small Modular Reactor
  - Generation IV
  - Future Surface Combatants
- Methodology
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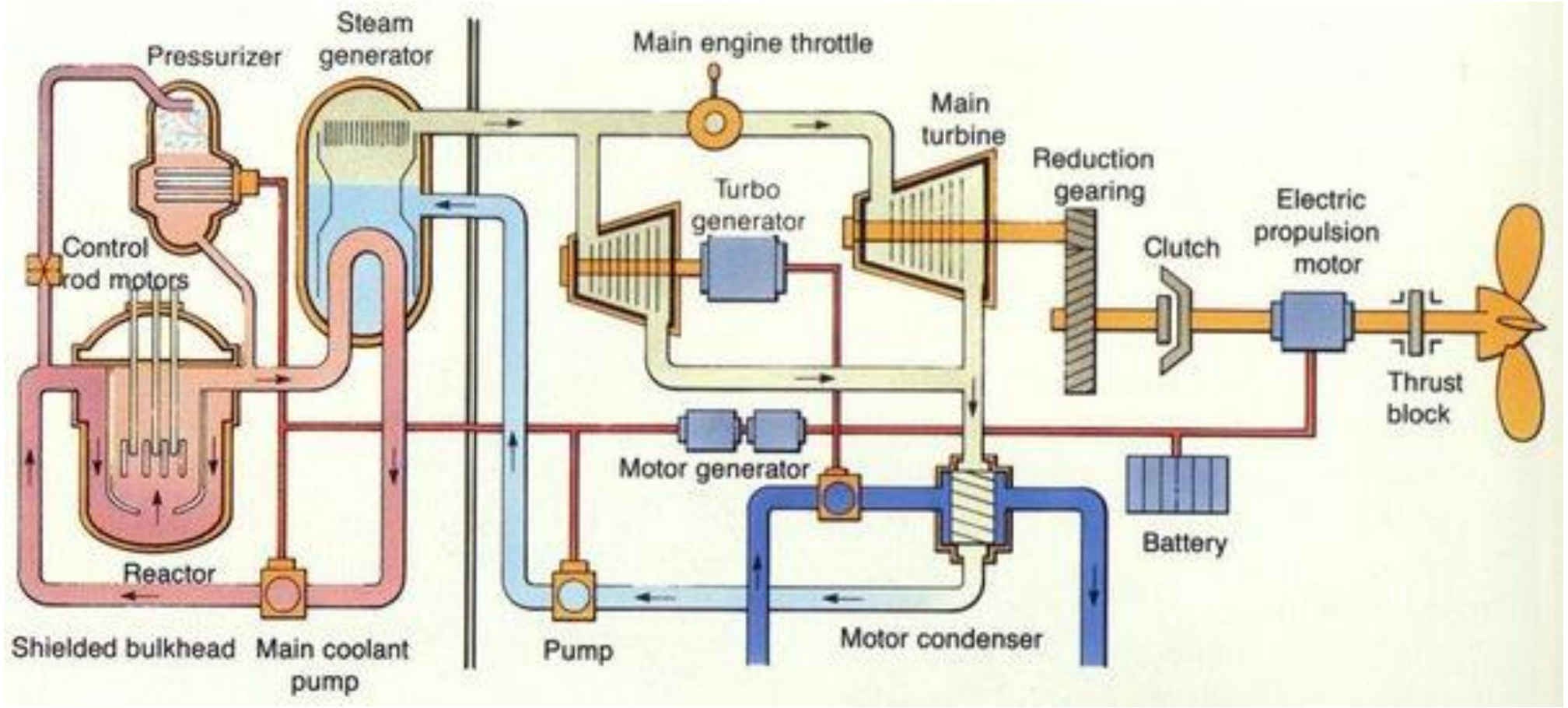
  - Case study
- Conclusion

Introduction

Naval nuclear technology

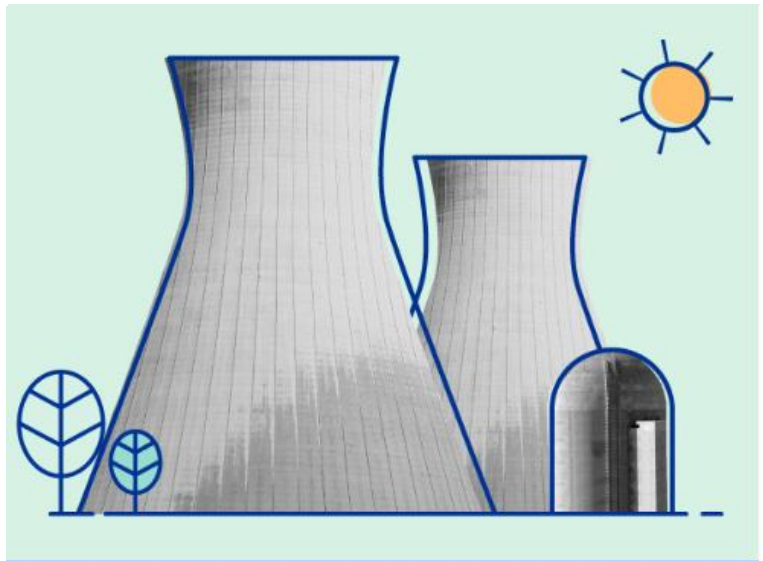


Introduction

(very) Small Modular Reactor

SMR

vSMR



LARGE, CONVENTIONAL REACTOR
700+ MW(e)

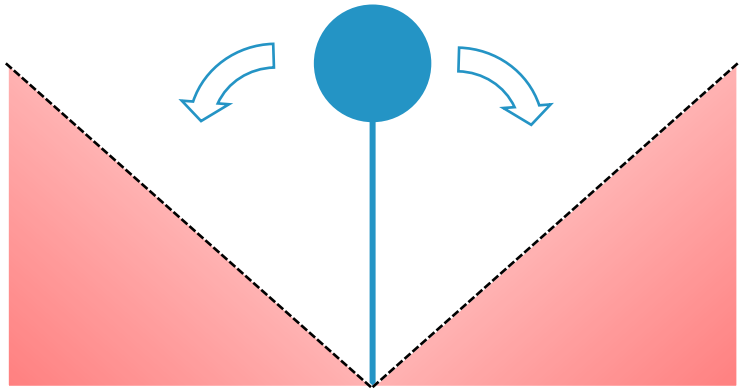
SMALL MODULAR REACTOR
Up to 300 MW(e)

MICROREACTOR
Up to ~10 MW(e)

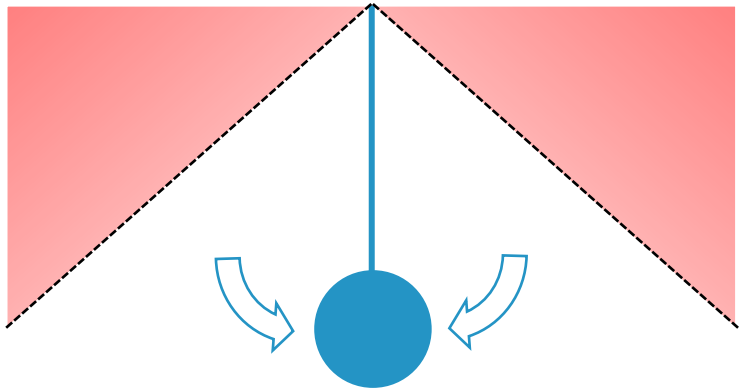
Introduction
Generation IV

- Sustainability
- Economic competitiveness
- Proliferation resistance
- Safety

Conventional Nuclear Reactor
"Active safety"



Generation IV Reactor
"Passive safety"



Introduction

Future Surface Combatants

- Next generation
- Multi-mission operations
- Naval-directed energy weapons
- Increased SEnsors, WEapons and COmmand systems (SEWACO) load

Introduction

Motivation

Generation IV (very) Small Modular Reactor technology has been proposed for future surface combatants:

- to increase strategic autonomy
- to meet future power demand
- to comply with climate goals regarding CO2 emission

While

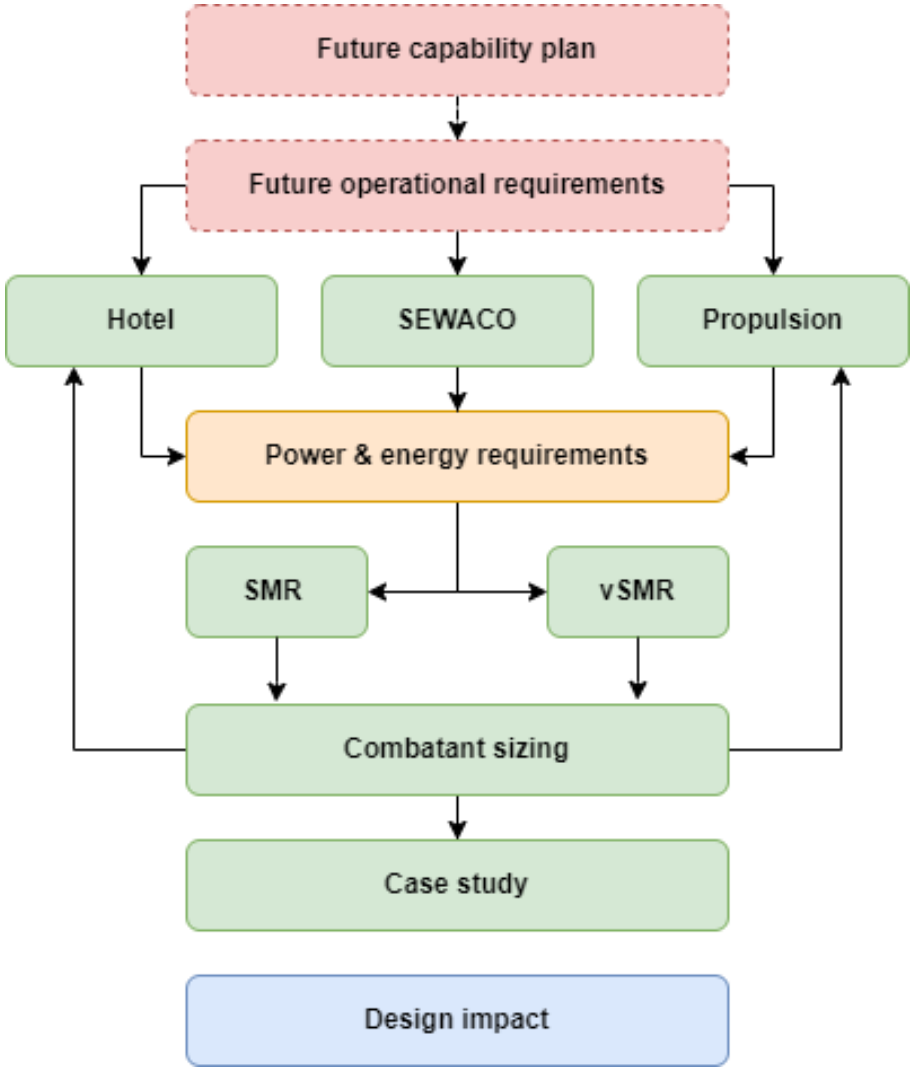
- maintaining or increasing operational effectiveness

RESEARCH QUESTION

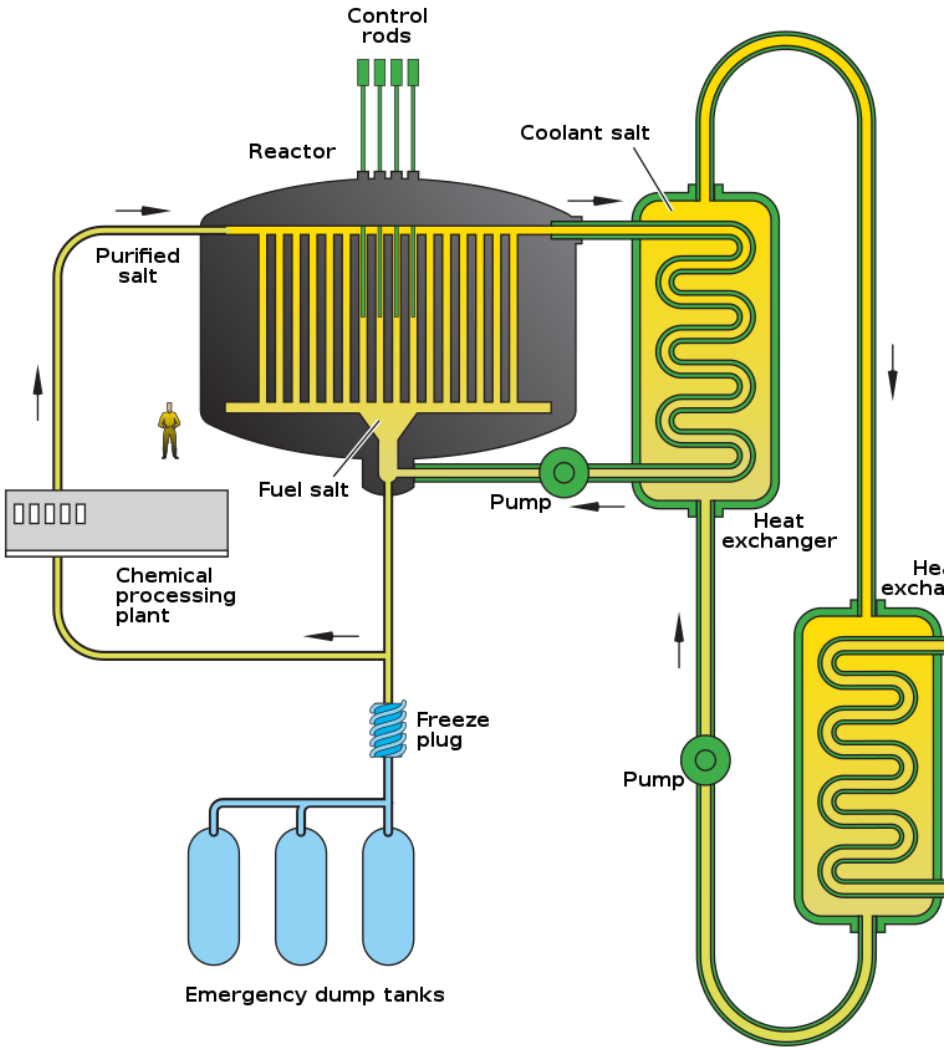
"What are the implications of using generation IV (very) Small Modular Reactor technology for power generation on the design of a future surface combatant?"

Methodology
Research approach

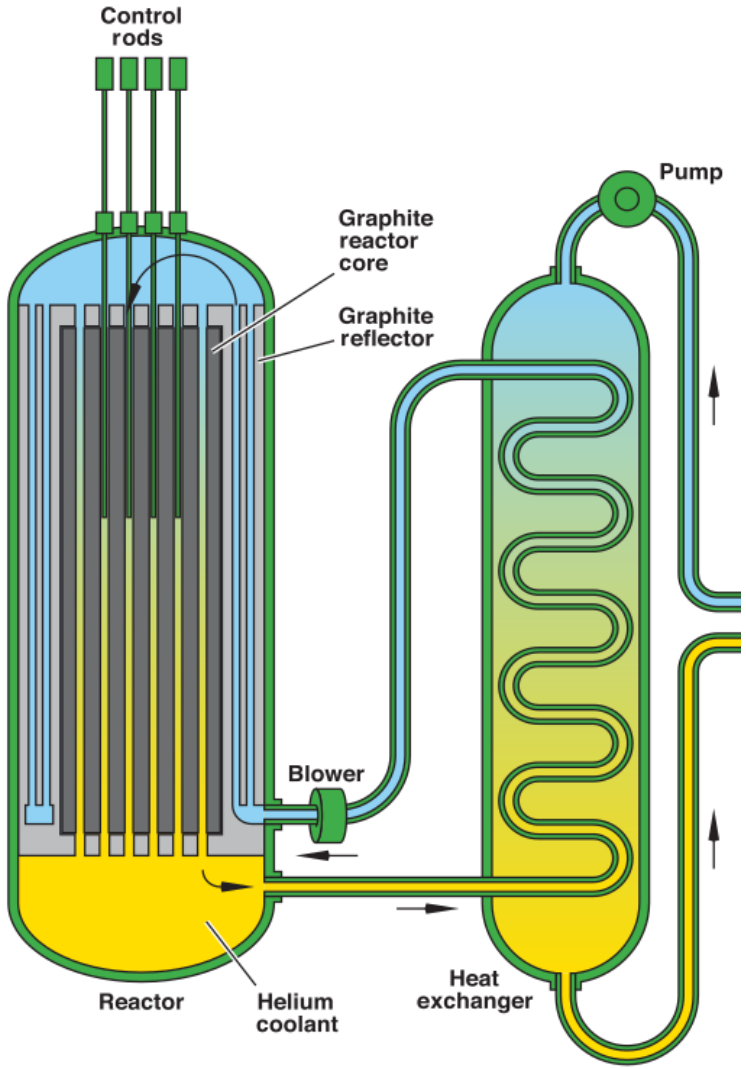
- Power
- Energy storage
- Volume
- Weight



SMR: Molten Salt Reactor



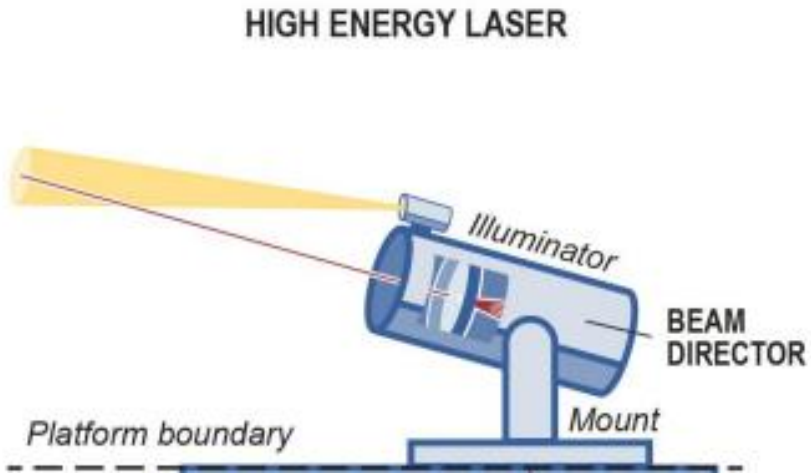
vSMR: (Very) High Temperature Reactor

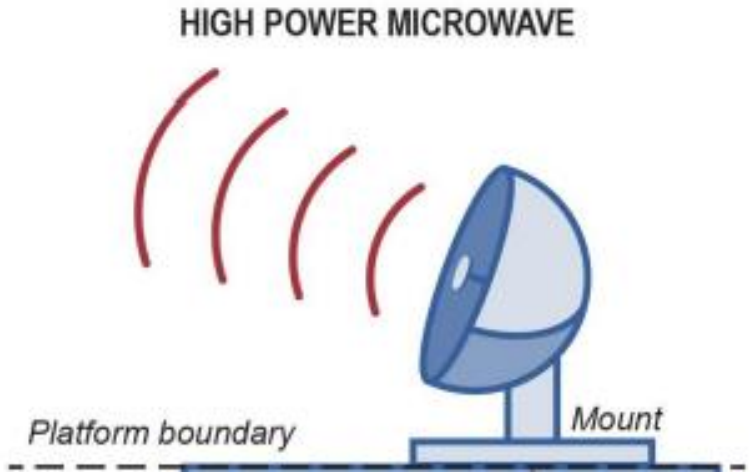


Methodology

Power & energy requirements

- SEWACO
  - Naval-directed energy weapons
  - Advanced radar
  - Total: 11 MWe
- Hotel
  - Scaled, variable
- Propulsion
  - Scaled, variable

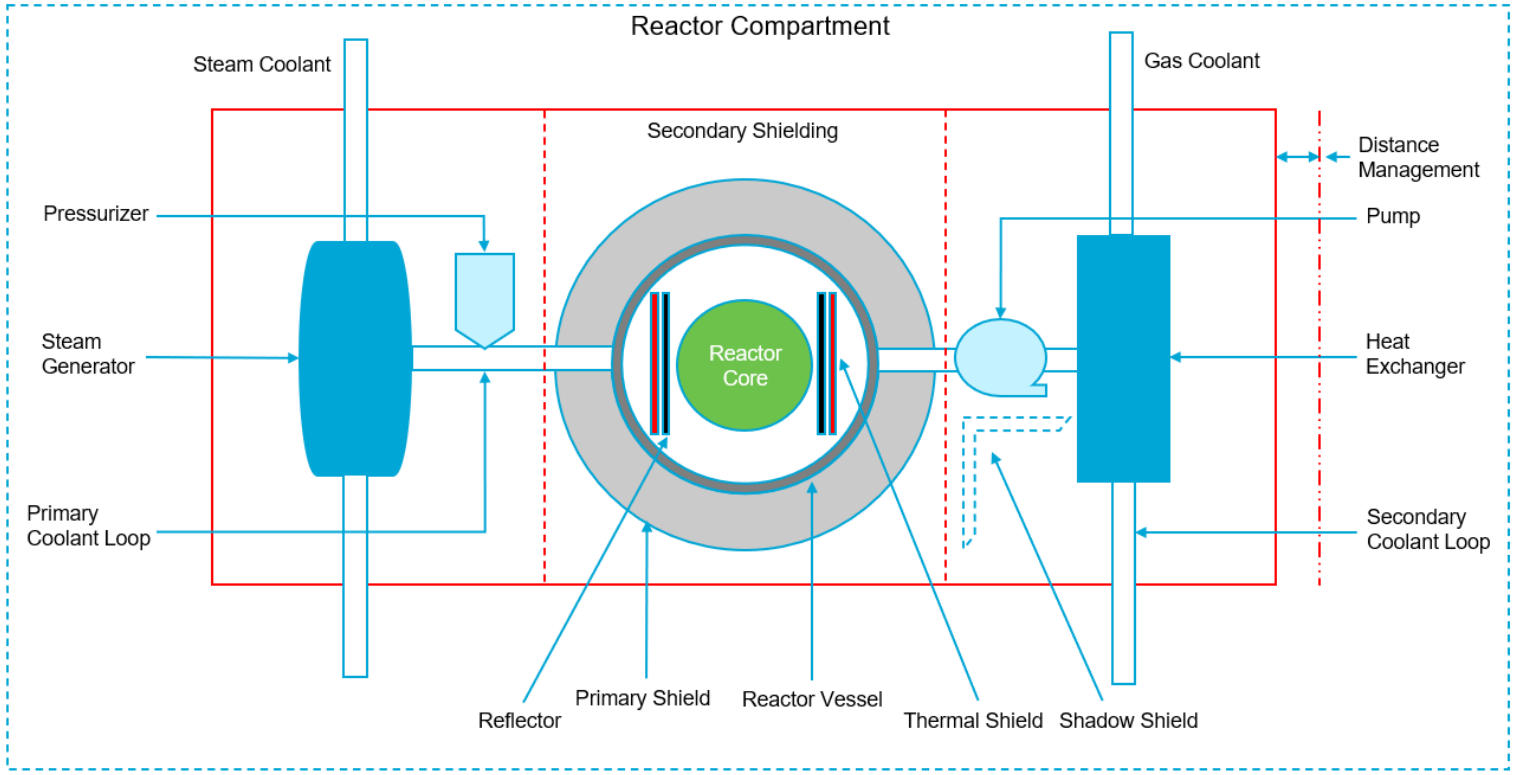




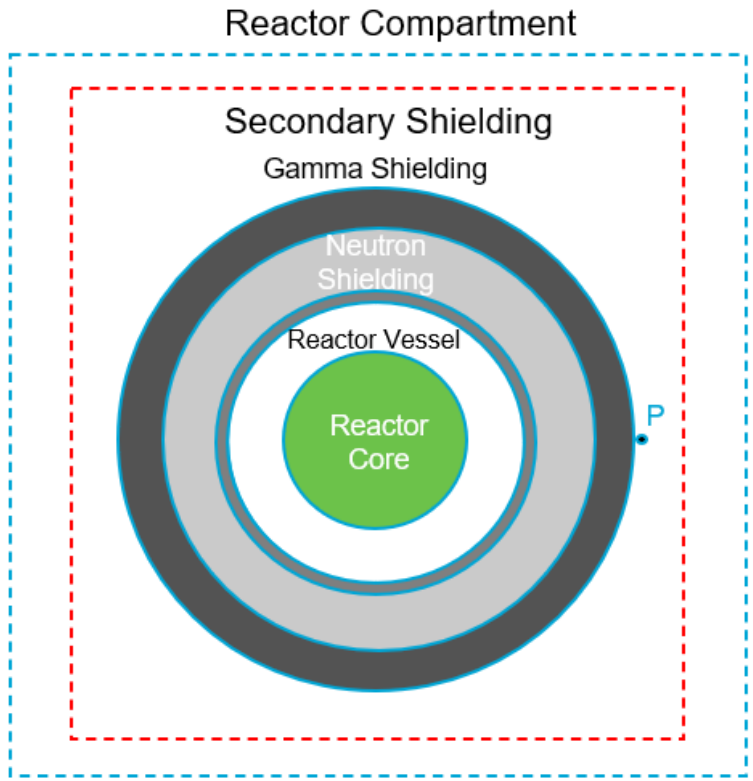
Methodology

Reactor compartment

Reality

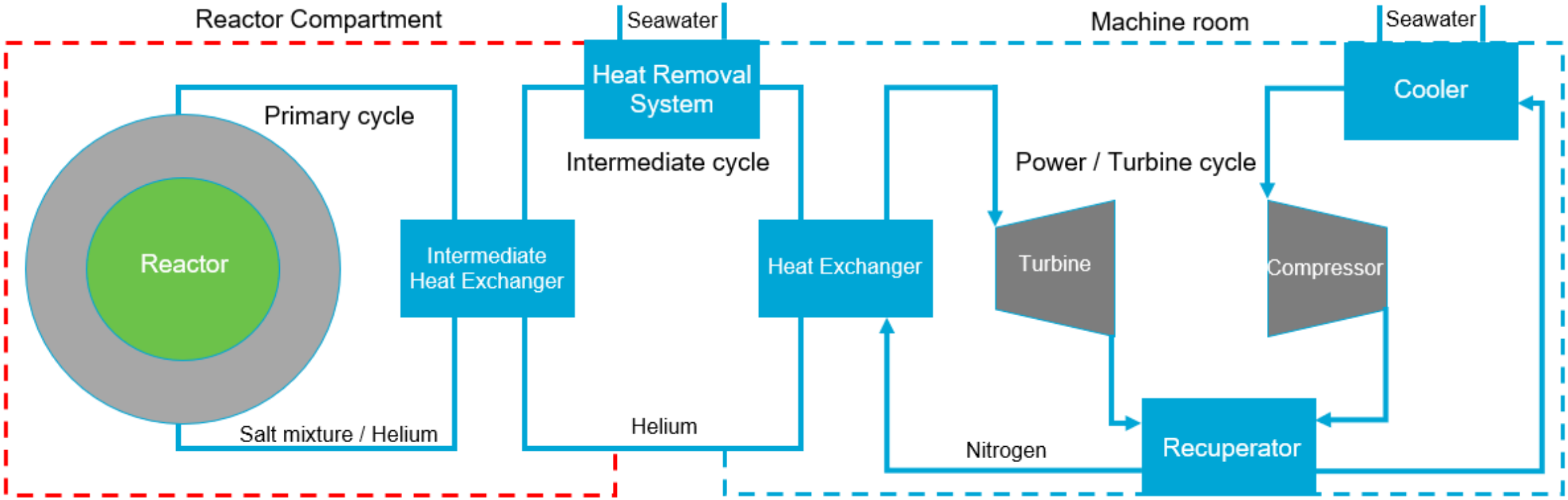


Model



Methodology

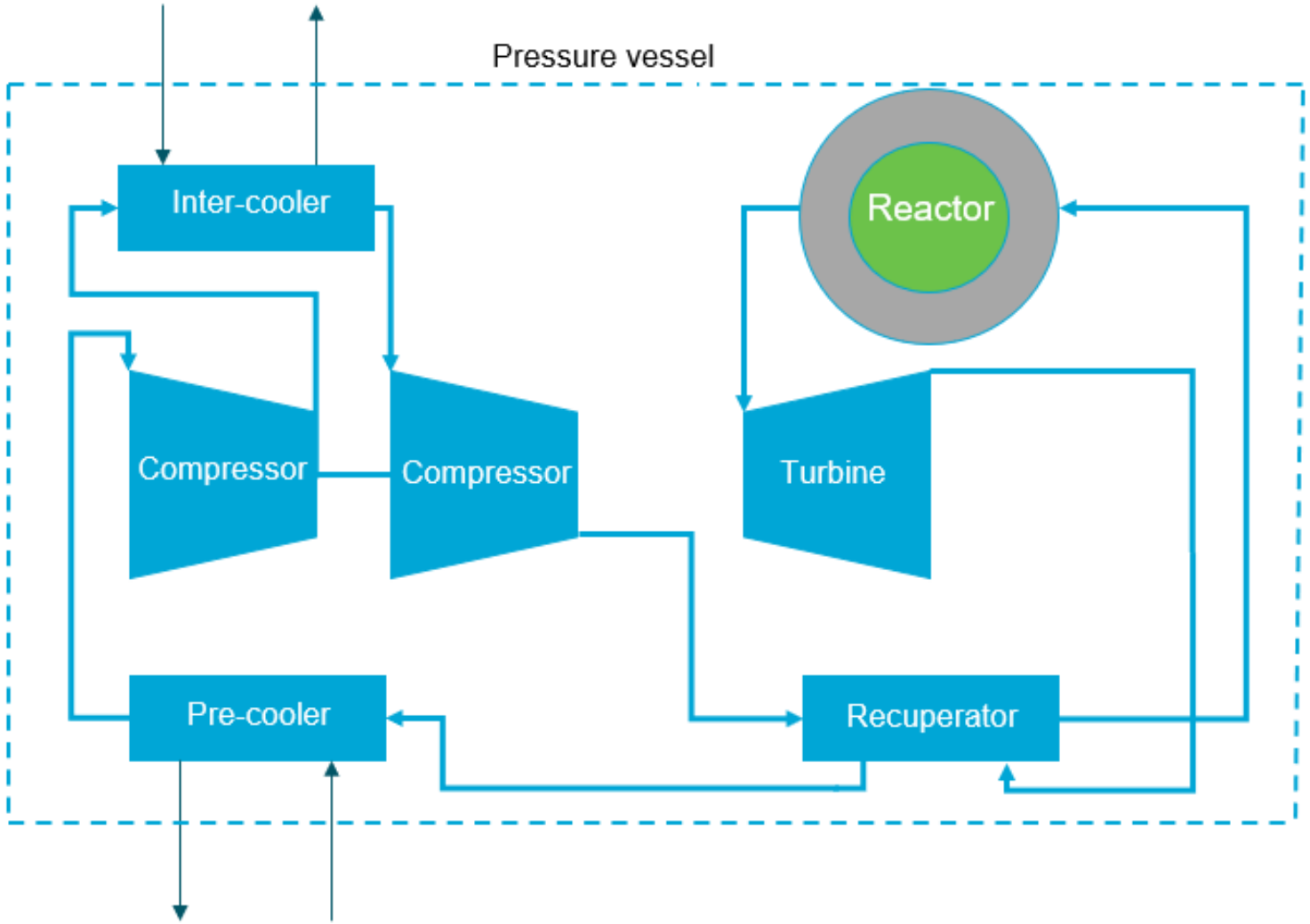
Cooling & heat transfer - SMR



Methodology

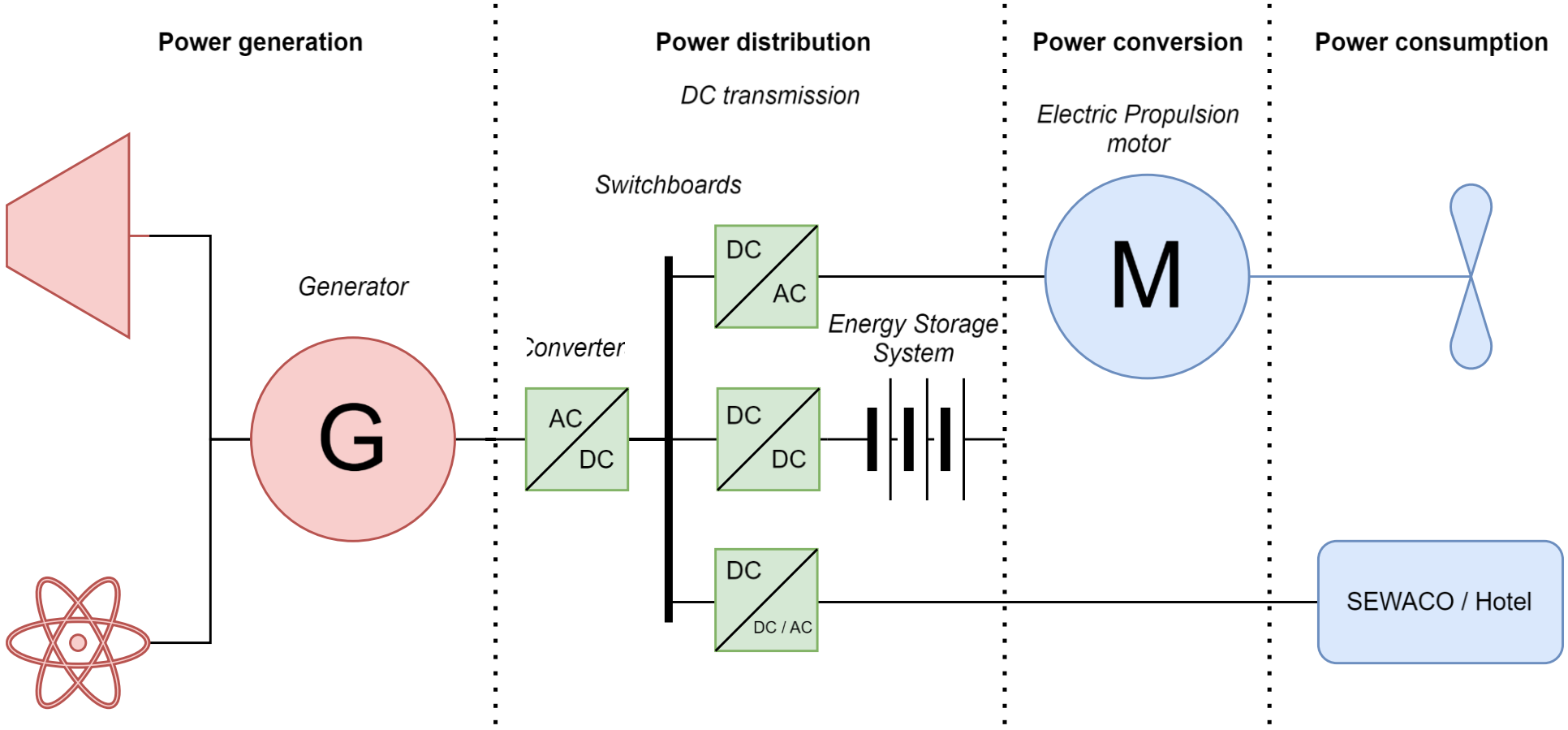
Cooling & heat transfer - vSMR

- Direct cycle
- No Heat Removal System



Methodology

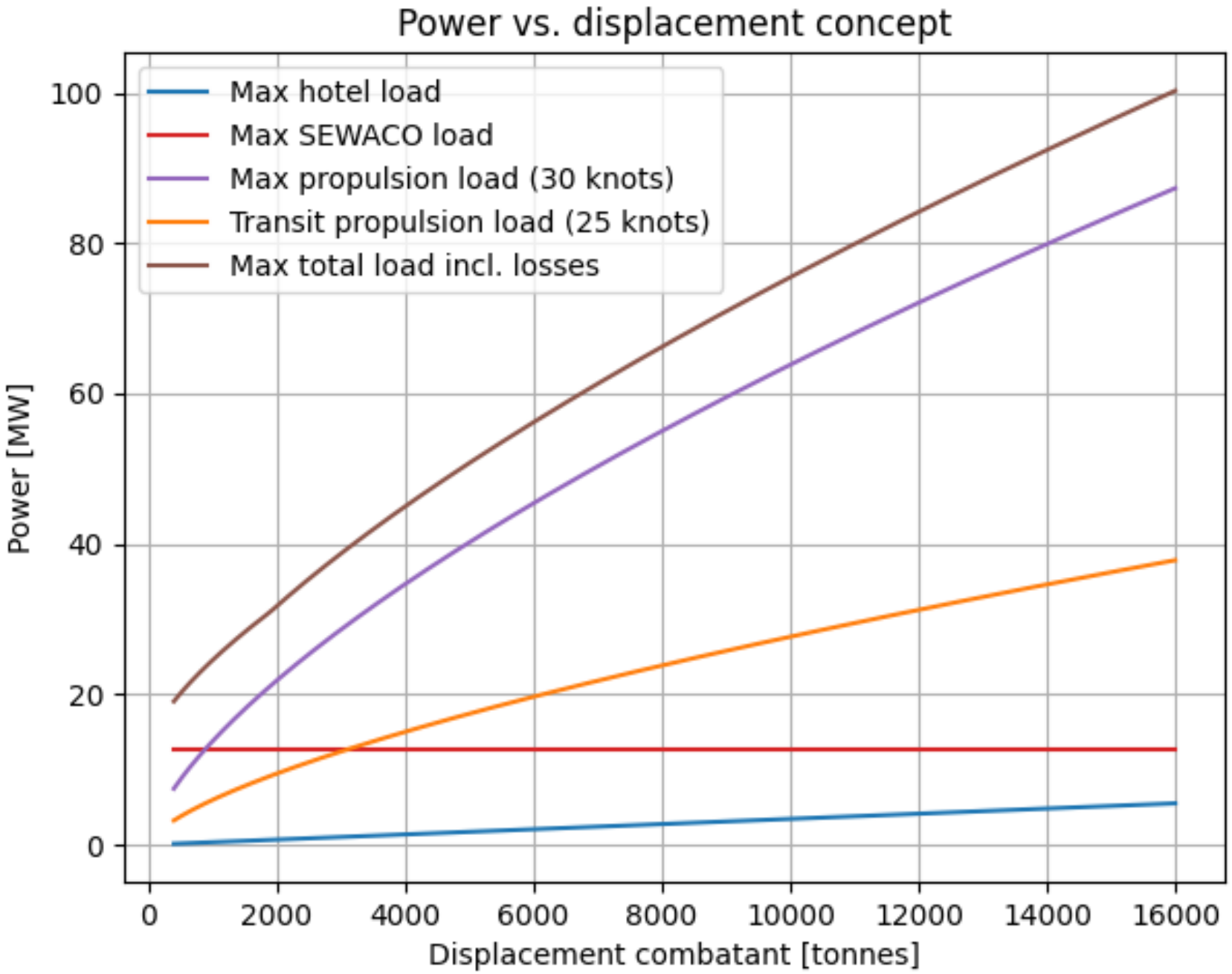
Power generation, distribution & conversion



Model results

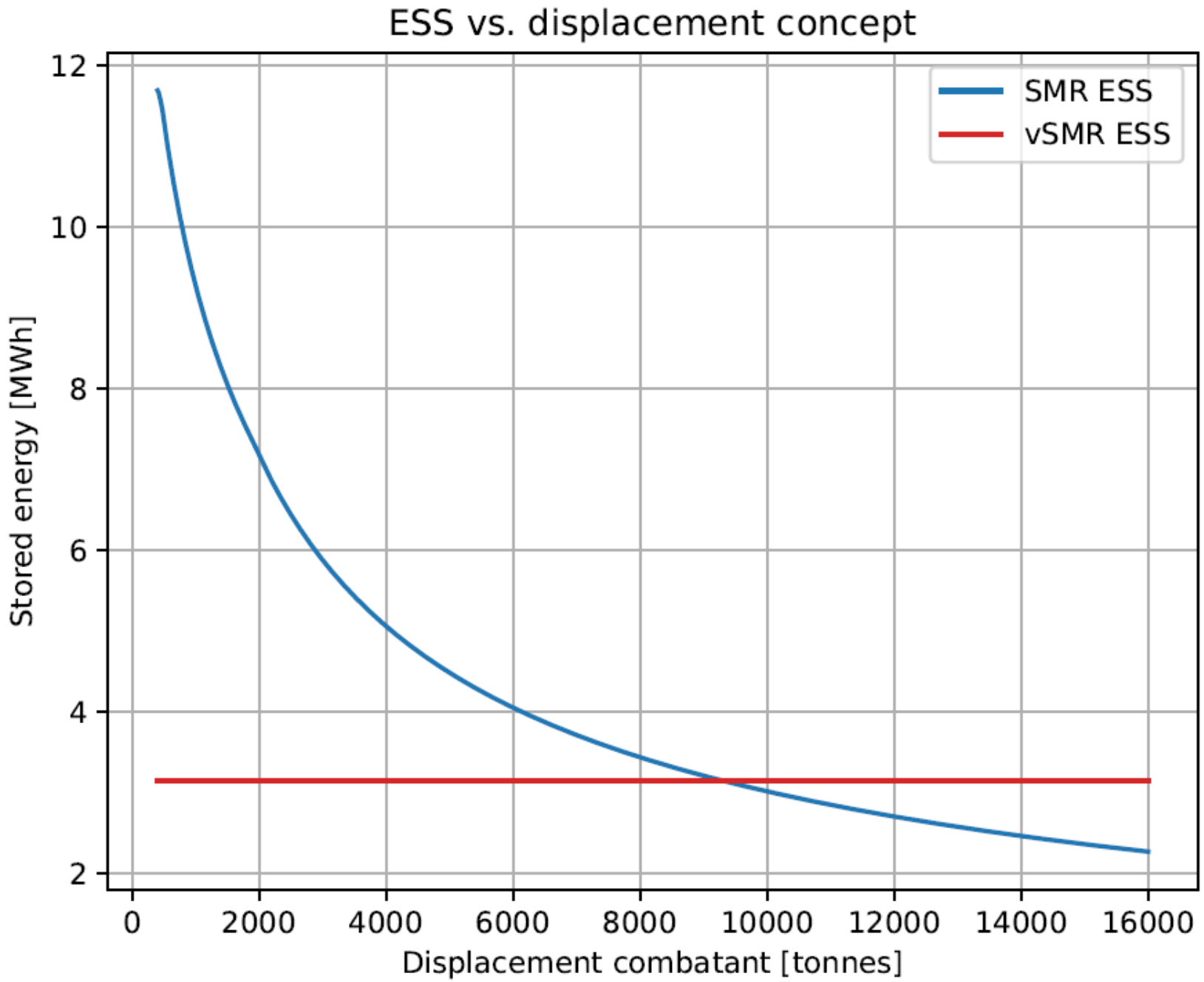
Model results

- **Power**
- *Energy*
- *Volume*
- *Weight*



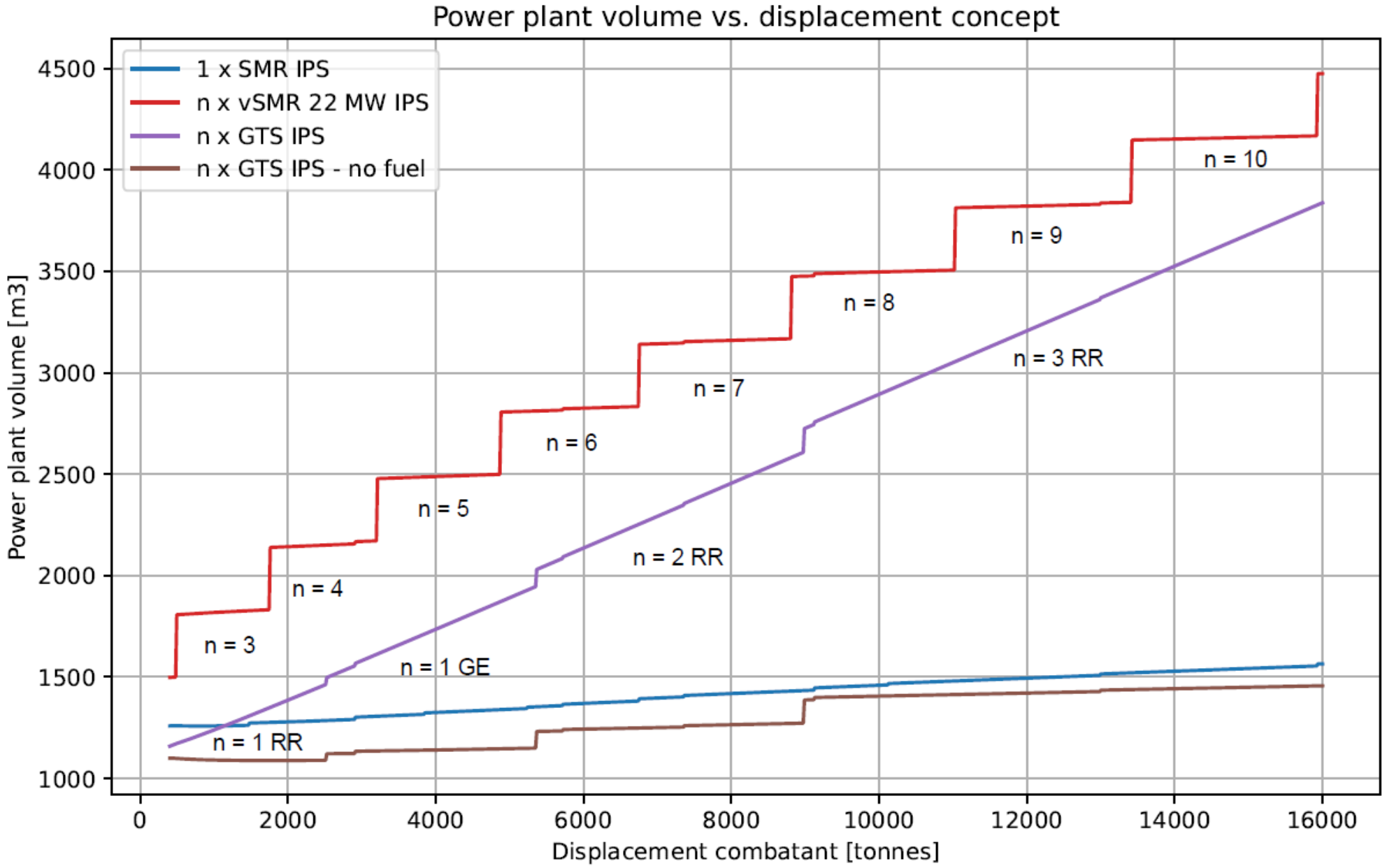
Model results

- *Power*
- **Energy**
- *Volume*
- *Weight*



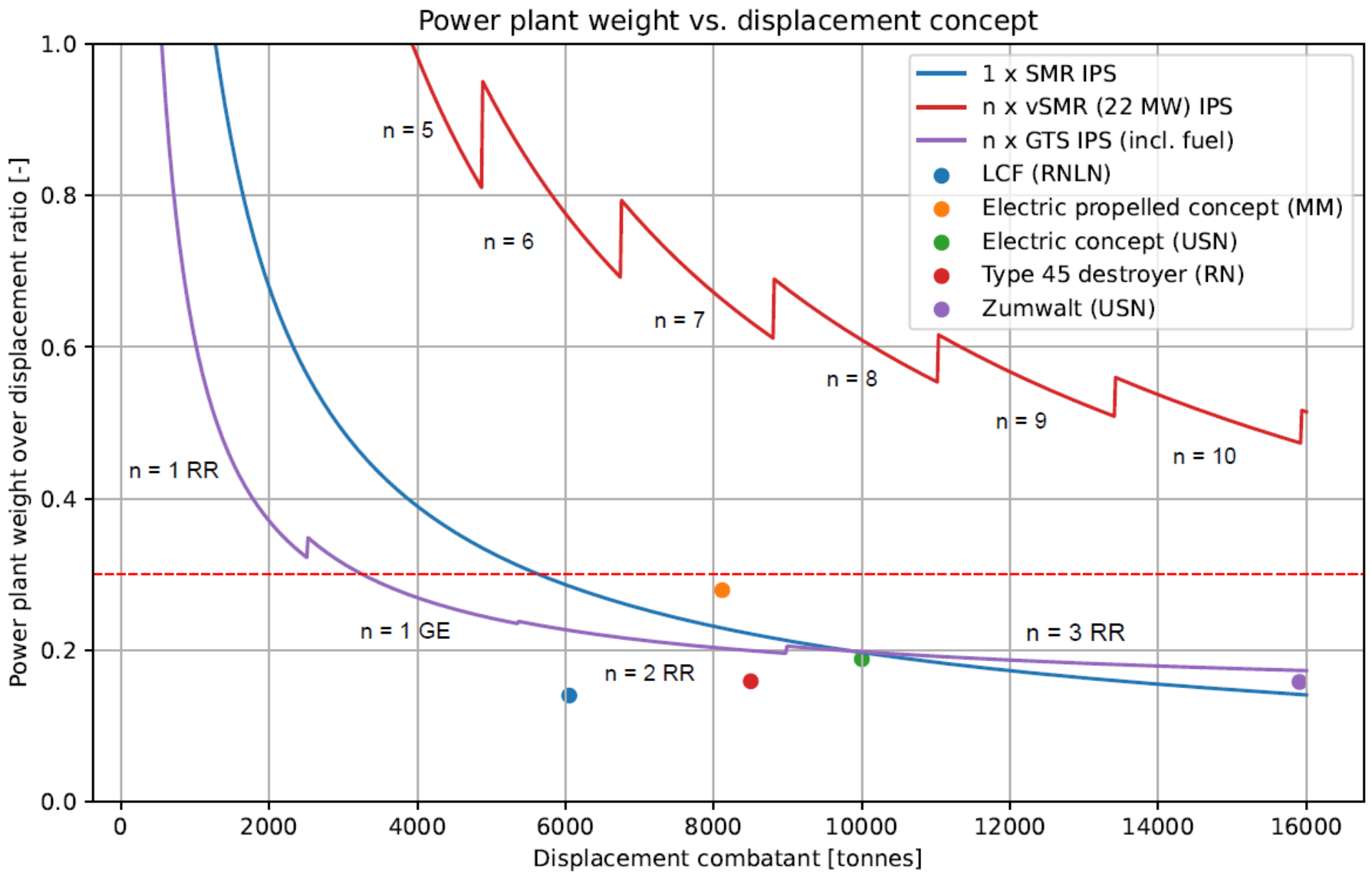
Model results

- *Power*
- *Energy*
- **Volume**
- *Weight*



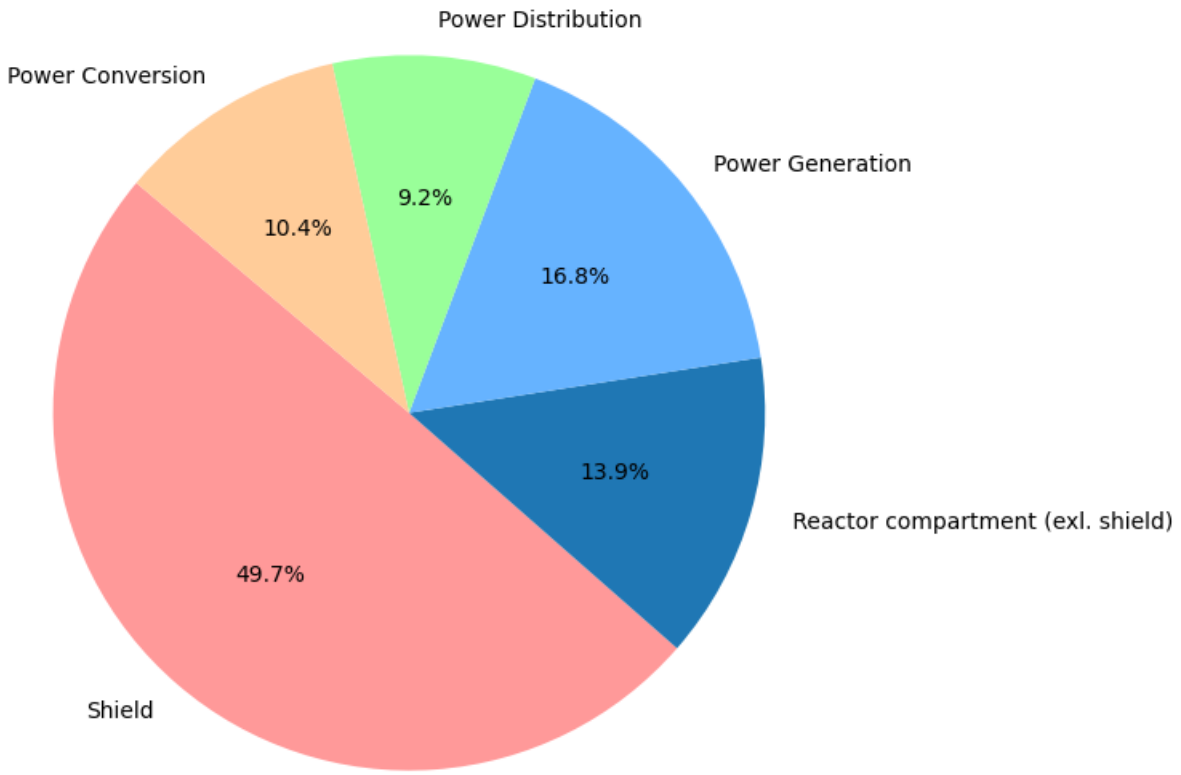
Model results

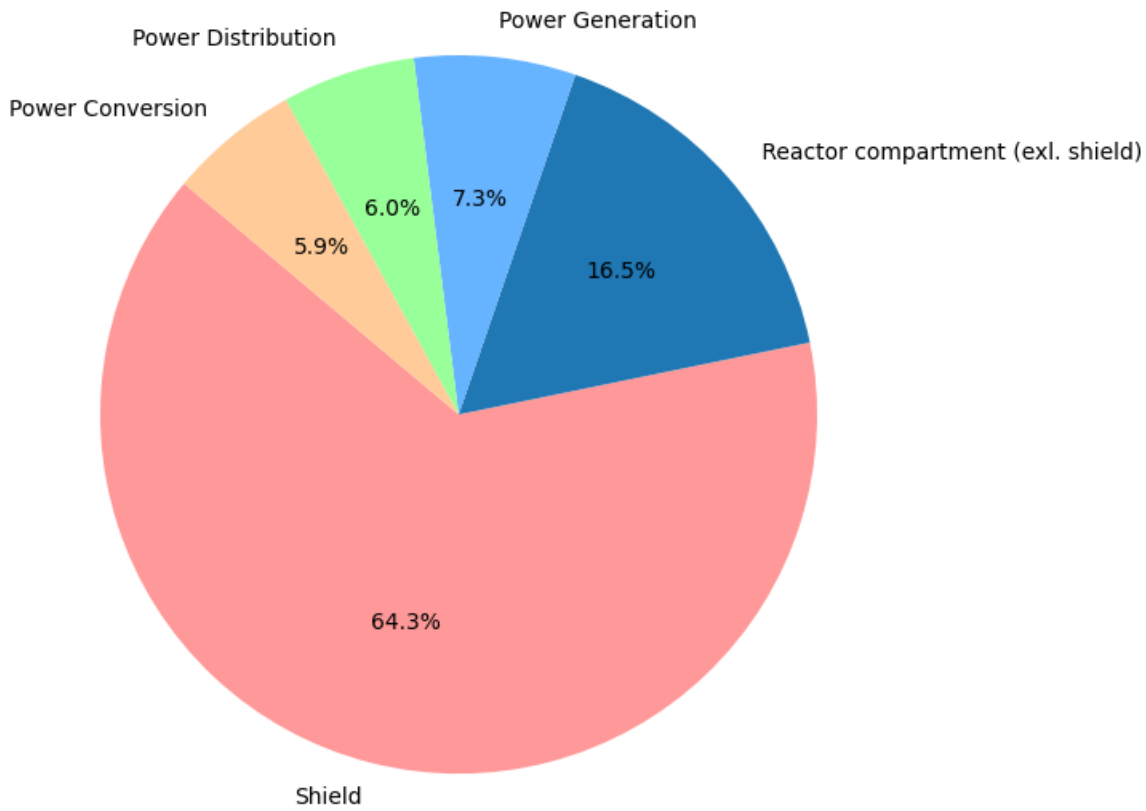
- *Power*
- *Energy*
- *Volume*
- **Weight**



Model results

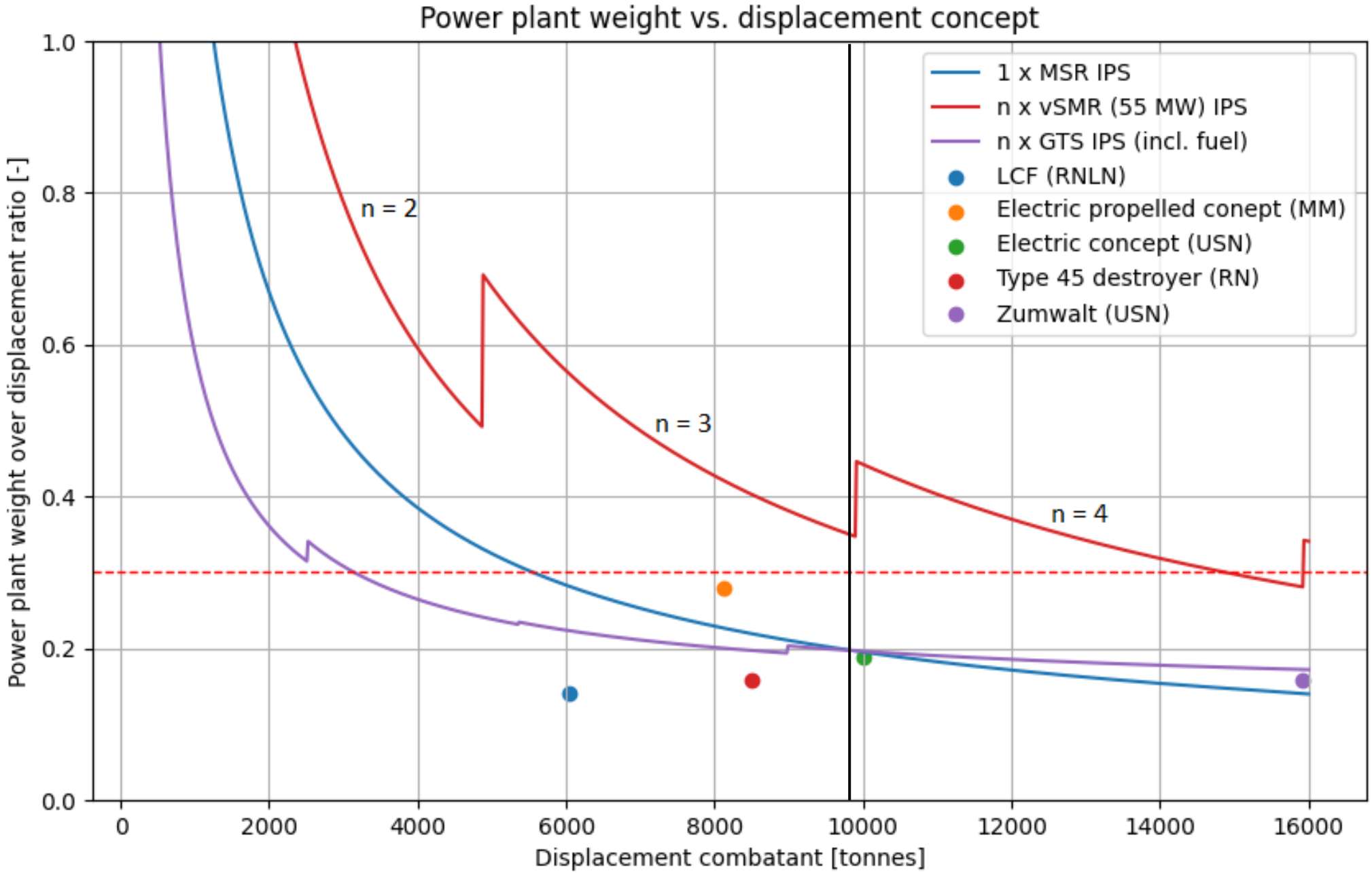
Weight





Model results

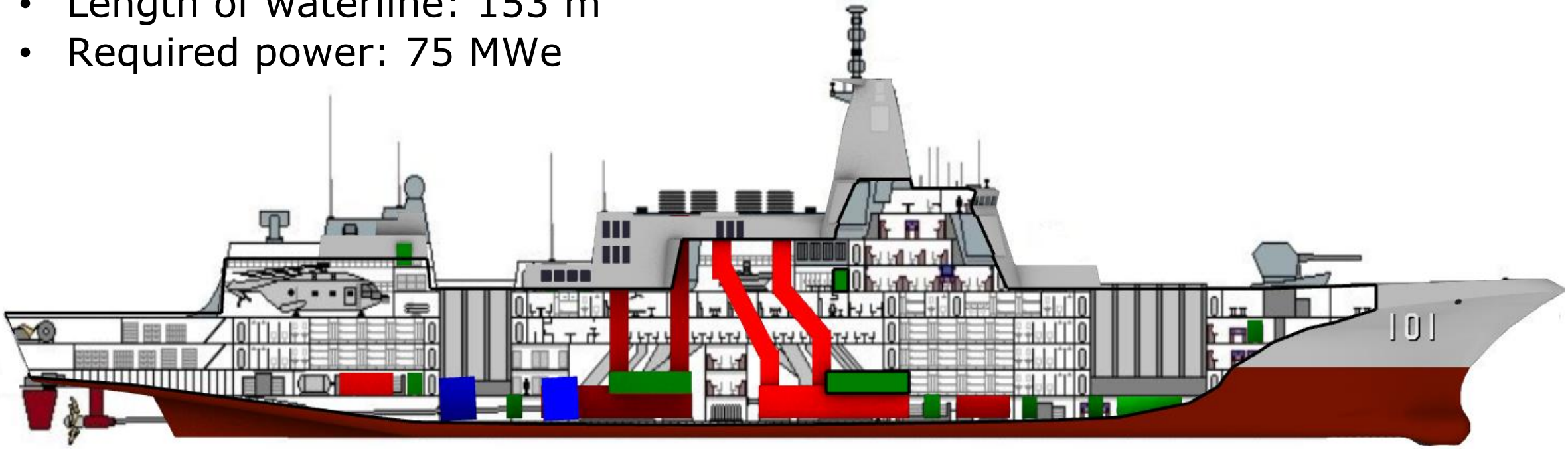
- *Power*
- *Energy*
- *Volume*
- **Weight: new**



Case study results

Case study results

- Displacement: 9,800 tonnes
- Length of waterline: 153 m
- Required power: 75 MWe



Case study results

Volume & size

Conclusion

"What are the implications of using generation IV (very) Small Modular Reactor technology for power generation on the design of a future surface combatant?"

- **Integration:** feasible while increasing autonomy & meeting future power loads 
- **SMR vs vSMR:** compactness  or load response 
- **Design Impact:** Δ = 

Recommendations

- Generation IV (v)SMR technology
- Shared shielding & optimalisation
- Hybrid configuration
- Structures
- Effectiveness

Generation IV (very) Small Modular Reactor Technology for Future Surface Combatants

References

Slide 1: Dutch Navy Details Future ASW Frigates.
https://www.defense-aerospace.com/dutch-navy-details-future-asw-frigates/

Slide 3: What energy do submarines use?
https://www.quora.com/What-energy-do-submarines-use

Slide 4: What are Small Modular Reactors (SMRs)?
https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

Slide 6: Options for the Royal Navy's Future Air Dominance System and the Type 83 destroyer
https://www.navylookout.com/options-for-the-royal-navys-future-air-dominance-system-and-the-type-83-destroyer/

Slide 10: MSR & (V)HTR
IAEA, "Advances in small modular reactor technology developments," 2022.

Slide 11: HEL & HPM
United States Government Accountability Office, "Directed energy weapons, dod should focus on transition planning," 2023

Questions?

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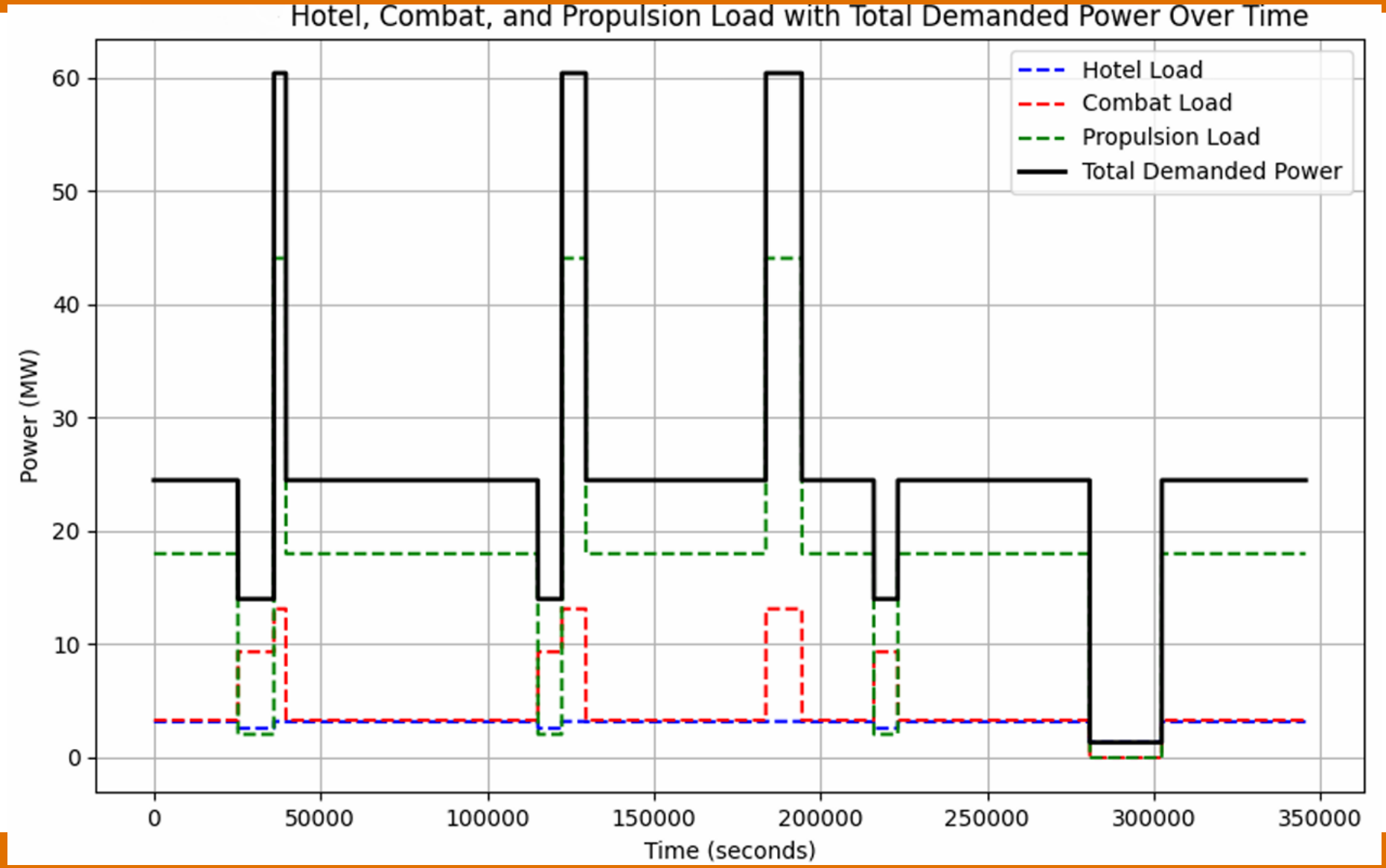
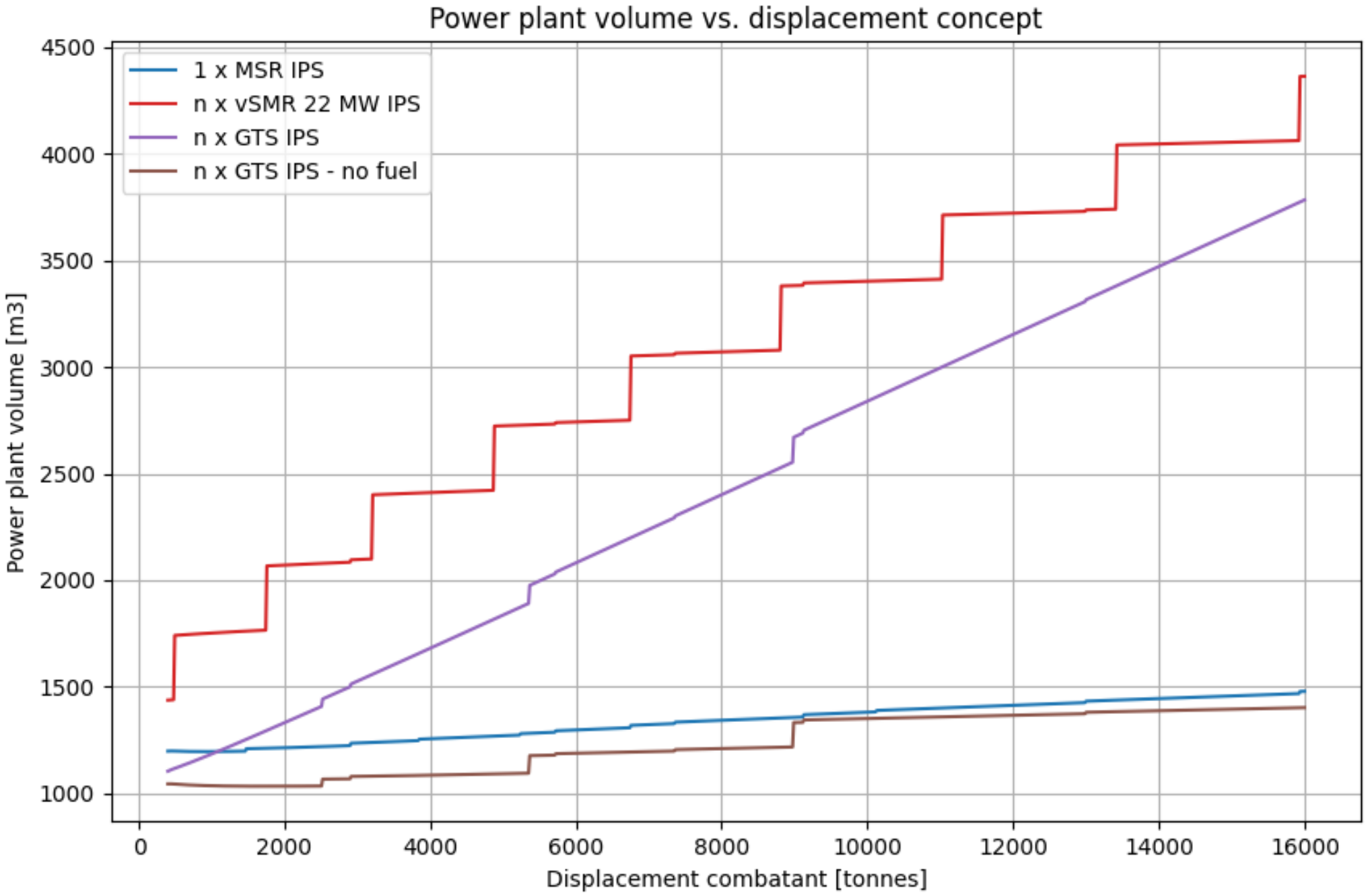
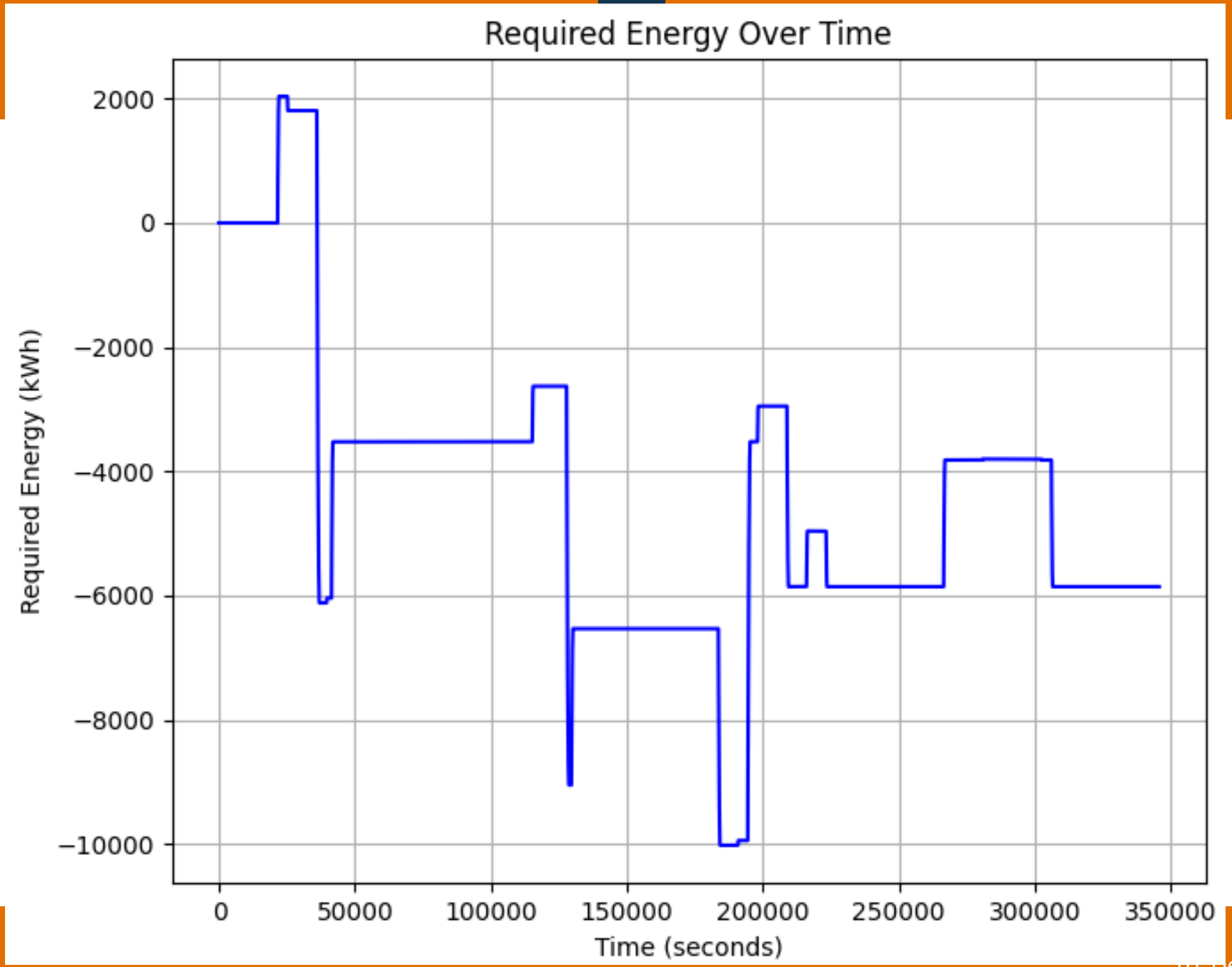
Attachments

Hotel & SEWACO

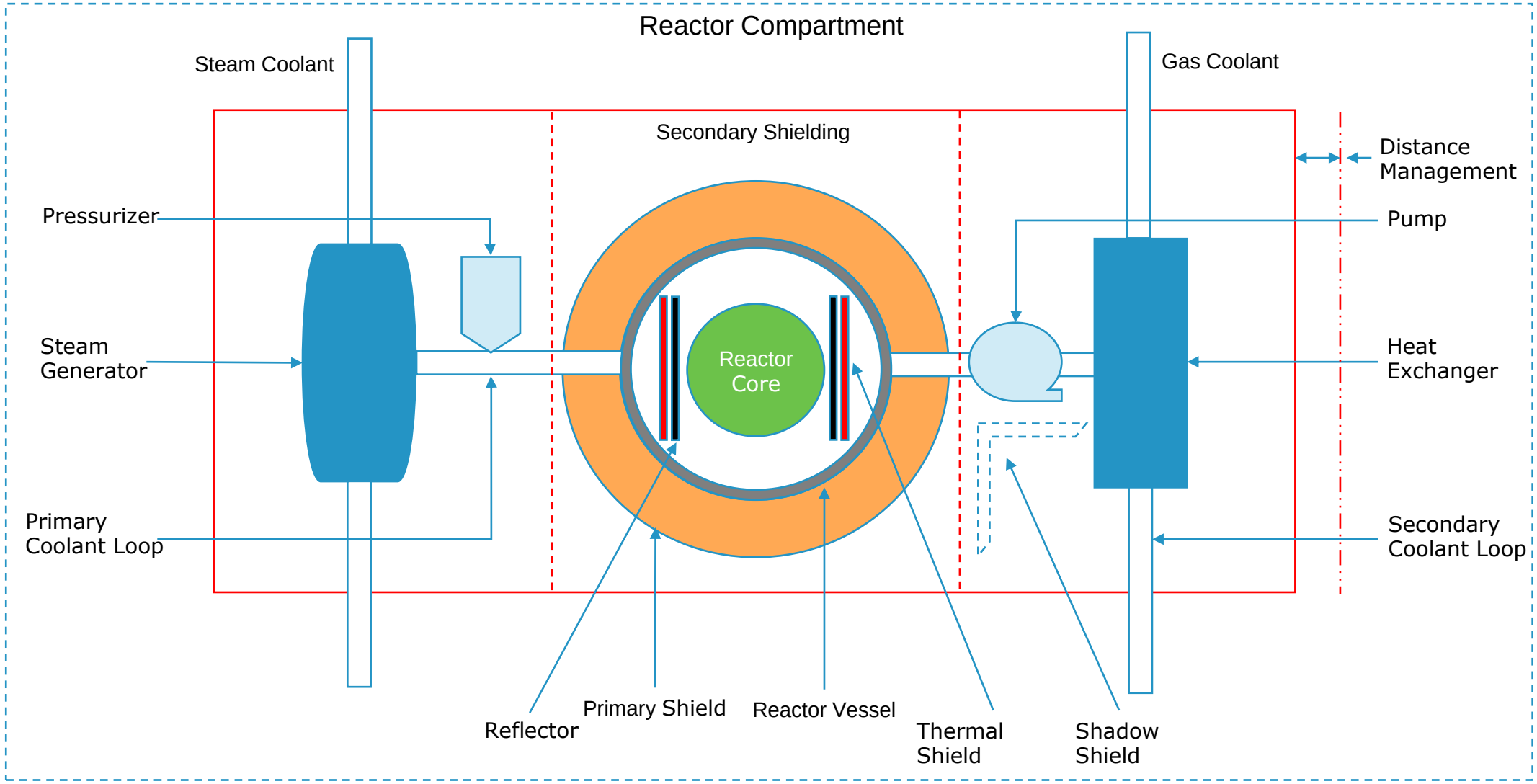
Mission Mode	Combat (C)	Sprint (S)	Transit (T)	Patrol (P)	Slow Transit (ST)	Berth (B)	Emergency (EM)
Bop (kW)	variable	variable	variable	variable	variable	variable	variable
Electric Plant (kW)	300	300	300	300	300	100	150
Aux+HVAC (kW)	800	800	1600	800	1600	1600	150
Outfit & Furnishings (kW)	100	300	300	100	300	200	0
P_{hotel} (MW)	1.20	1.40	2.20	1.20	2.20	1.90	0.30
Conv. Armament (kW)	125	62.5	62.5	125	62.5	0	0
HEL (kW)	1200	240	0	240	0	0	0
HPM (kW)	1820	364	0	364	0	0	0
UXV (kW)	0	0	200	200	0	0	0
VLS	850	500	0	500	0	0	0
Radar L Band	6000	6000	3000	6000	0	0	0
APARD X Band	600	600	300	600	100	0	50
Sonar	400	400	0	400	0	0	0
P_{SEWACO} (MW)	11.00	8.17	3.56	8.43	0.16	0.00	0.05
$P_{h,SEWACO}$ (MW)	12.20	9.57	5.76	9.63	2.36	1.90	0.35
Converter Efficiency	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Design Margin	1.1	1.1	1.1	1.1	1.1	1.1	1.1
$P_{e,tot}$ (MW)	13.84	10.85	6.54	10.93	2.68	2.16	0.40


Hotel, Combat, and Propulsion Load with Total Demanded Power Over Time
Hotel Load
Combat Load
Propulsion Load
Total Demanded Power
Power (MW)
Time (seconds)
0
10
20
30
40
50
60
0
50000
100000
150000
200000
250000
300000
350000


Power plant volume vs. displacement concept
1 x MSR IPS
n x vSMR 22 MW IPS
n x GTS IPS
n x GTS IPS - no fuel
Power plant volume [m3]
4500
4000
3500
3000
2500
2000
1500
1000
0
2000
4000
6000
8000
10000
12000
14000
16000
Displacement combatant [tonnes]


Required Energy Over Time
Required Energy (kWh)
2000
0
−2000
−4000
−6000
−8000
−10000
0
50000
100000
150000
200000
250000
300000
350000
Time (seconds)

	Conventional	SMR	vSMR
Survivability			
Susceptibility	- -	++	++
Vulnerability	-+	-	-
Recoverability	+	-	- -
Total	-+	-+	-+
Mobility			
Top speed	+	+	+
Manoeuvrability	+	-	+
Acceleration	++	- -	-
Deceleration	++	- -	-
Total	++	-	-+
Range & endurance	- -	++	+
Effectiveness	-+	-+	-+

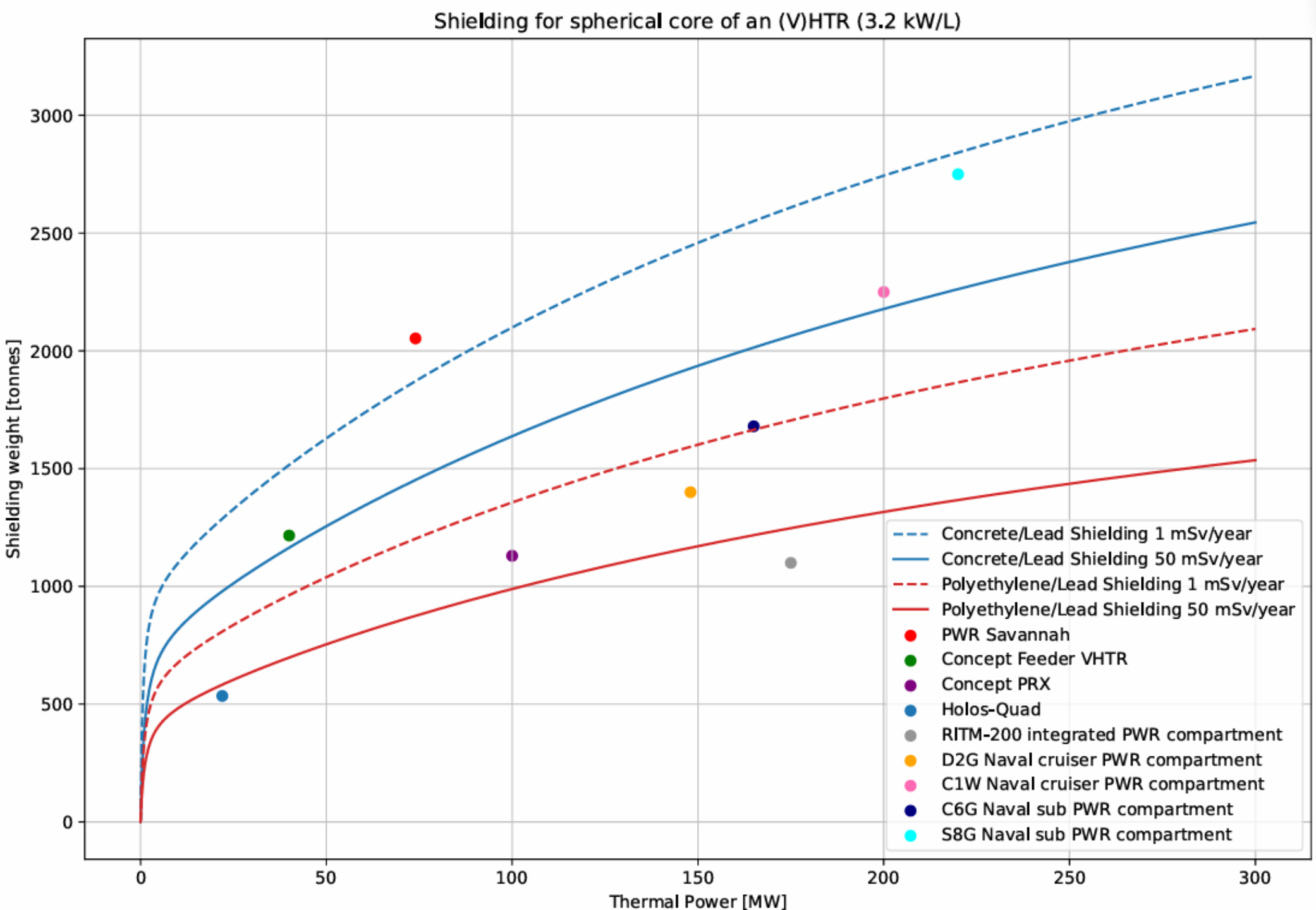

Reactor Compartment
Steam Coolant
Gas Coolant
Secondary Shielding
Distance Management
Pressurizer
Pump
Steam Generator
Reactor Core
Heat Exchanger
Primary Coolant Loop
Secondary Coolant Loop
Reflector
Primary Shield
Reactor Vessel
Thermal Shield
Shadow Shield

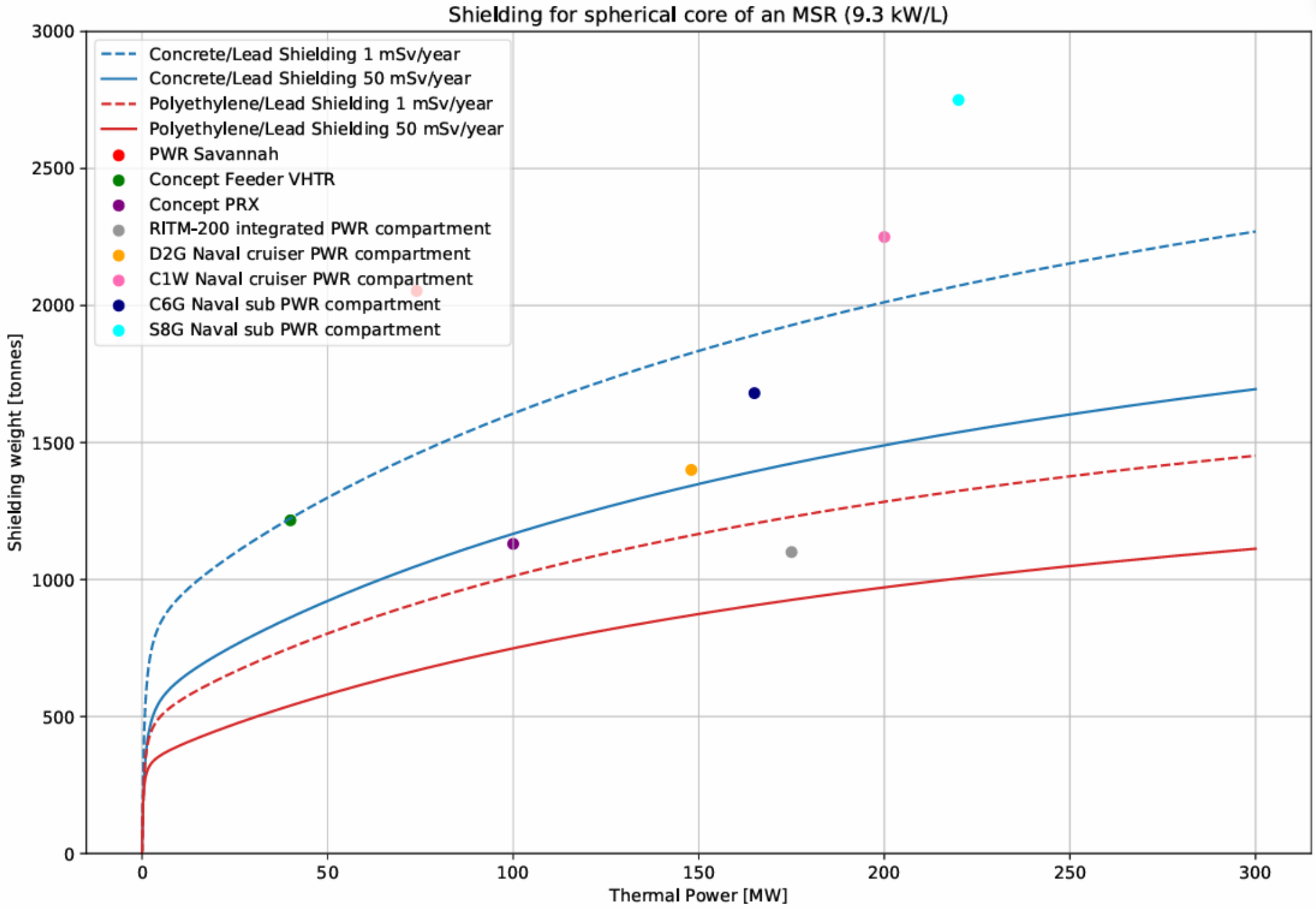
Reactor	SMR (V)HTR
Power output	$10 - 300 MW_e$ [36]
Power range	$100\% - 15\% - 100\%$
Power ramp rate	5%
Power range in fuel cycle	$15\% - 100\%$ $\frac{2 \cdot FC}{3}$, $70\% - 100\%$ $\frac{1 \cdot FC}{3}$
Length of fuel cycle	16-18 months or online
Burnup	90 - 200+ GWd/ton [36]

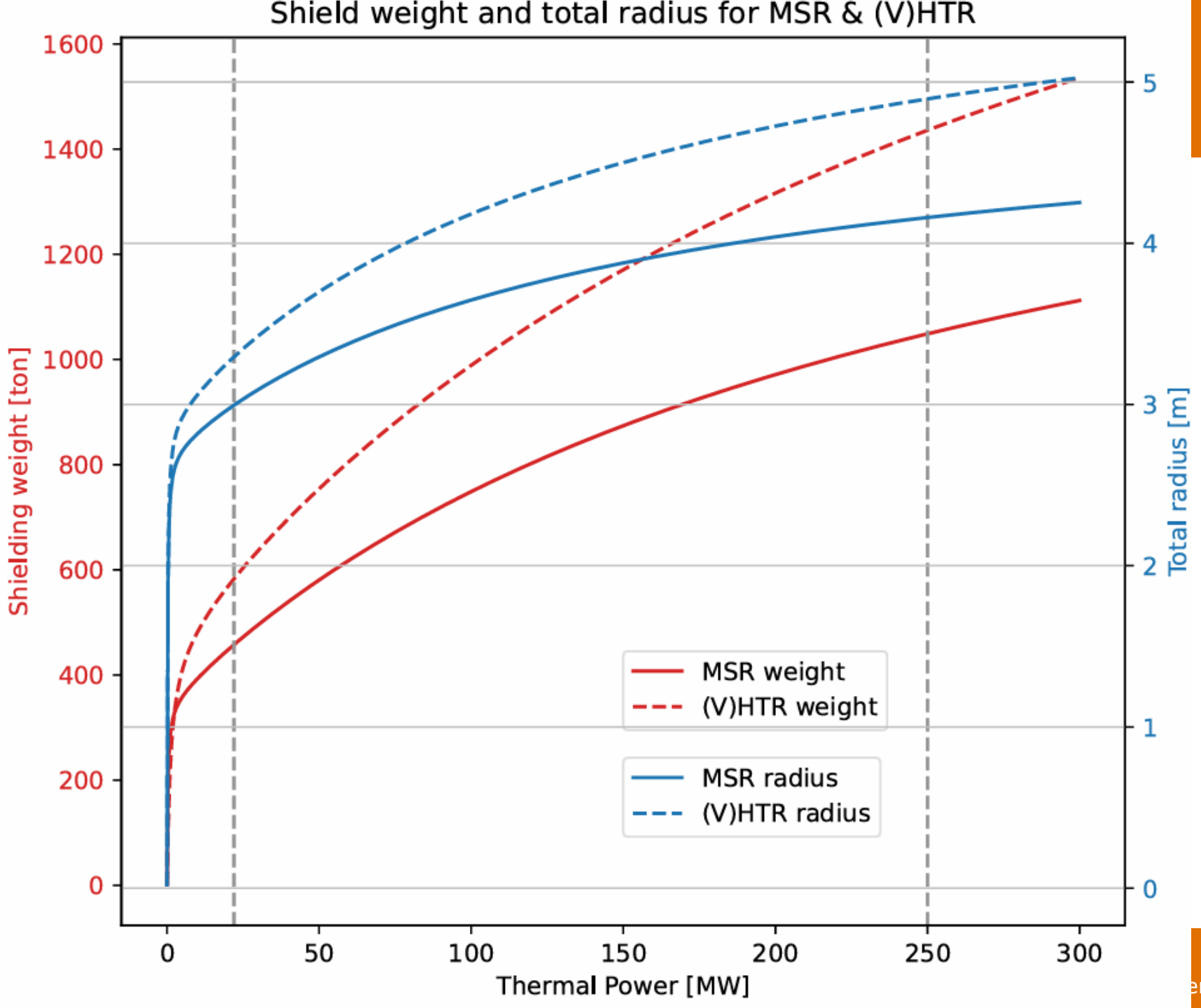
Reactor	SMR MSR
Power output	$16 - 300 MW_e$ [36]
Power range	$100\% - 20\% - 100\%$
Power ramp rate	5%
Power range in fuel cycle	$20\% - 100\%$
Length of fuel cycle	4 days (online)
Burnup	90+ GWd/ton [36]

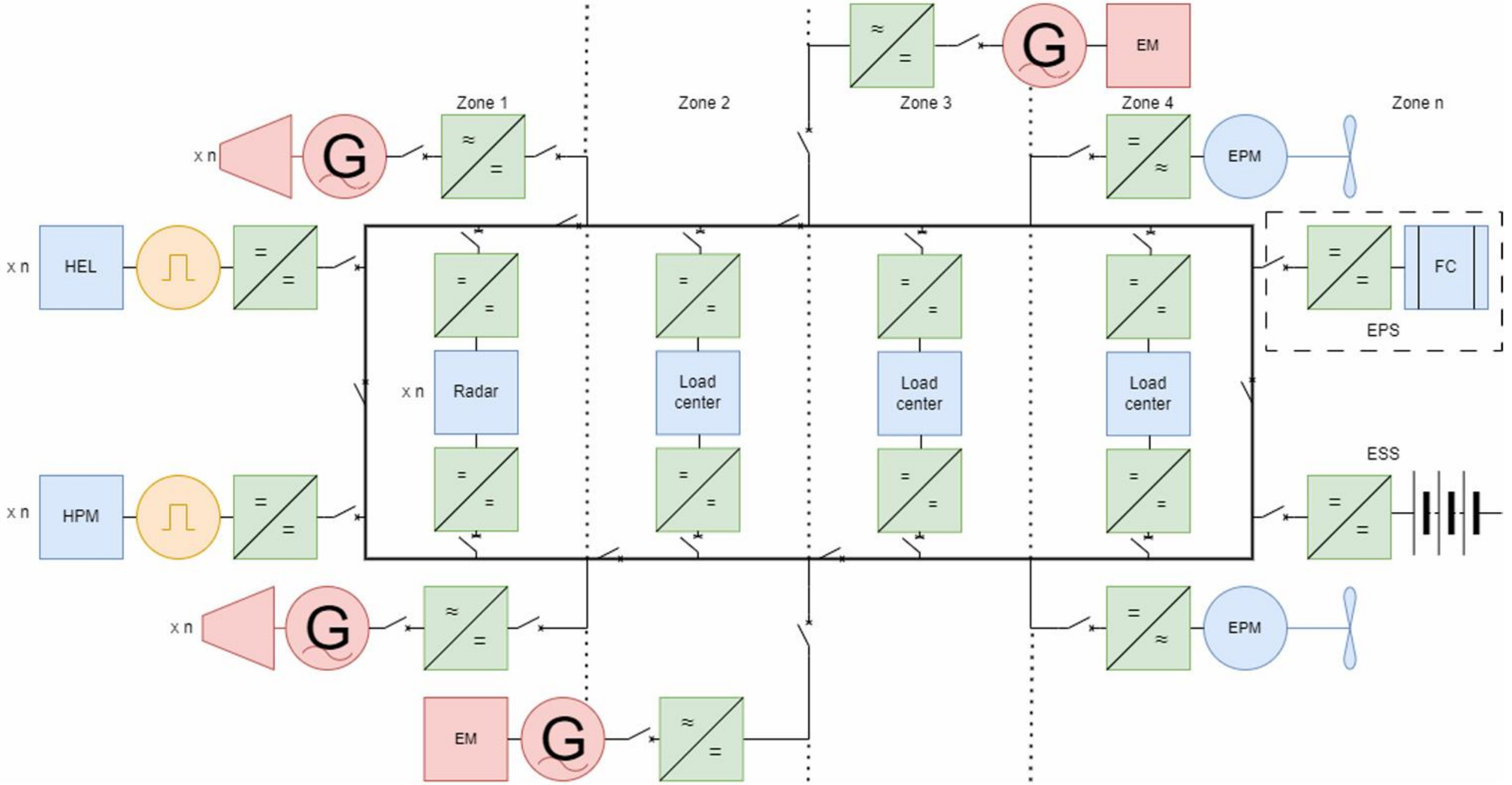
Reactor type	(V)HTR	GFR, LFR, SFR	MSR
+	- Passive & active safety - High burnup - TRISO fuel - High TRL - High temperatures - Online or prismatic - Many vSMR concepts	- Passive & active safety - High burnup - No xenon poisoning - High temperatures - Good load following - vSMR application	- Passive & active safety - Very high burnup - Online refuelling, long fuel cycle - High temperatures - No Xenon poisoning - Good load following
–	- Susceptible to movement and vibrations (pebble bed) - Susceptible to xenon poisoning - High operating pressure - Lower power density due to graphite	- Lower TRL - Liquid coolant hazards - Irradiated coolant - Coolant corrosion - Increased fissile load	- Low TRL - Corrosion issues by the salt - Increased fissile load - Irradiated salt - No vSMR application

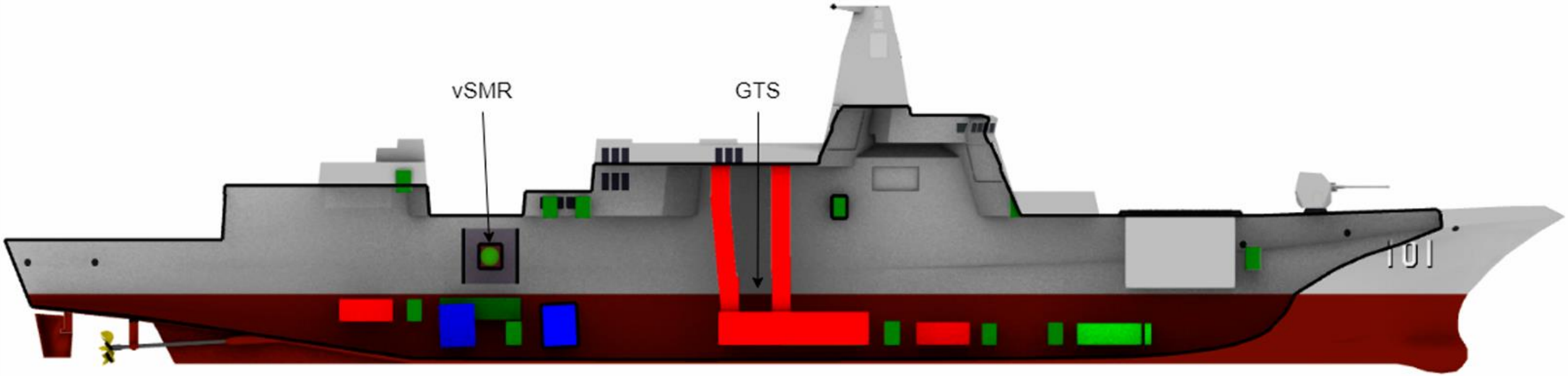
Reactor type	**MSR**	**(V)HTR**	**vSMR**
Neutron spectrum	thermal/fast	thermal	thermal/fast
Fuel cycle	open/closed	open	open
Burnup [GWd/ton]	$90+$	$90-200+$	$60-80$
Refuelling process	online/offline	online/offline	offline
Min refuelling cycle	4 days	$1.5-2$ years	3 years
Max refuelling cycle	lifetime	lifetime	$5-8+$ years
Safety	active/passive	active/passive	active/passive
TRL	4-6	7-8	7-8
Load following	Good	Average	Good
Load range	$20-100\%$	$15-100\%$	$(0)20-100\%$
Load response (ramp rate)	$5\%/\,\mathrm{min}$	$5\%/\mathrm{min}$	$10\%/\mathrm{min}$
Operating temperature	$<800°\mathrm{C}$	$<700-1000°\mathrm{C}$	$500-800°\mathrm{C}$

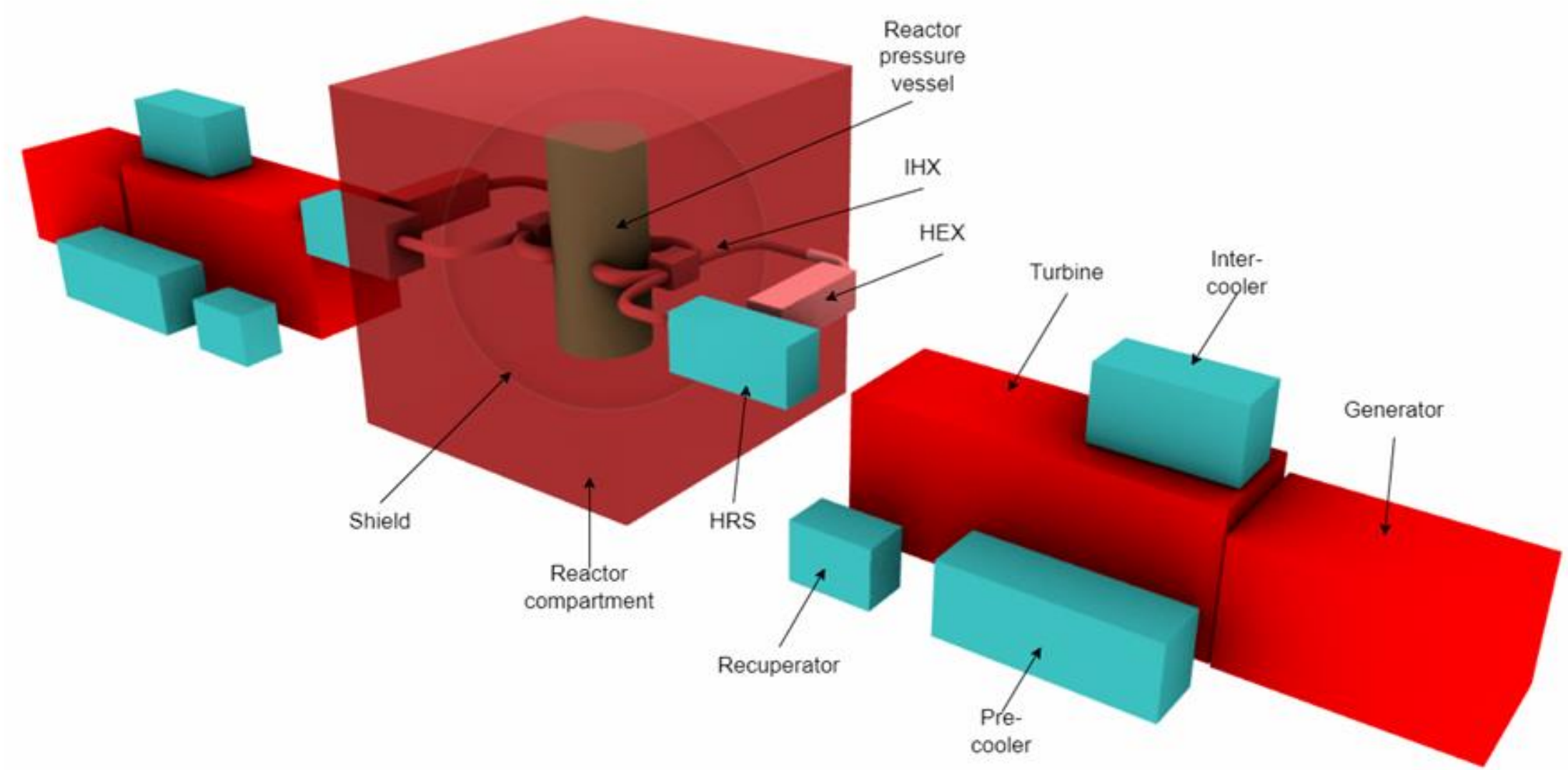

Shielding for spherical core of an (V)HTR (3.2 kW/L)
Shielding weight [tonnes]
Thermal Power [MW]
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300
Concrete/Lead Shielding 1 mSv/year
Concrete/Lead Shielding 50 mSv/year
Polyethylene/Lead Shielding 1 mSv/year
Polyethylene/Lead Shielding 50 mSv/year
PWR Savannah
Concept Feeder VHTR
Concept PRX
Holos-Quad
RITM-200 integrated PWR compartment
D2G Naval cruiser PWR compartment
C1W Naval cruiser PWR compartment
C6G Naval sub PWR compartment
S8G Naval sub PWR compartment


Shielding for spherical core of an MSR (9.3 kW/L)
Concrete/Lead Shielding 1 mSv/year
Concrete/Lead Shielding 50 mSv/year
Polyethylene/Lead Shielding 1 mSv/year
Polyethylene/Lead Shielding 50 mSv/year
PWR Savannah
Concept Feeder VHTR
Concept PRX
RITM-200 integrated PWR compartment
D2G Naval cruiser PWR compartment
C1W Naval cruiser PWR compartment
C6G Naval sub PWR compartment
S8G Naval sub PWR compartment
Shielding weight [tonnes]
Thermal Power [MW]
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300


Shield weight and total radius for MSR & (V)HTR
Shielding weight [ton]
Total radius [m]
Thermal Power [MW]
MSR weight
(V)HTR weight
MSR radius
(V)HTR radius
0
200
400
600
800
1000
1200
1400
1600
0
1
2
3
4
5
0
50
100
150
200
250
300


Zone 1
Zone 2
Zone 3
Zone 4
Zone n
x n
G
EM
EPM
HEL
HPM
Radar
Load center
FC
EPS
ESS


vSMR
GTS
101


Reactor pressure vessel
IHX
HEX
Turbine
Inter-cooler
Generator
Shield
HRS
Reactor compartment
Recuperator
Pre-cooler