Design of a small modular pressurised water-cooled reactor core for application in commercial ships

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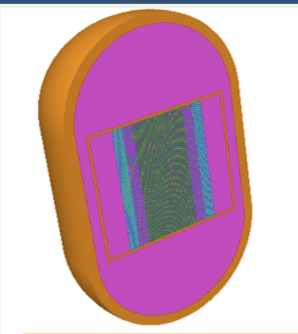
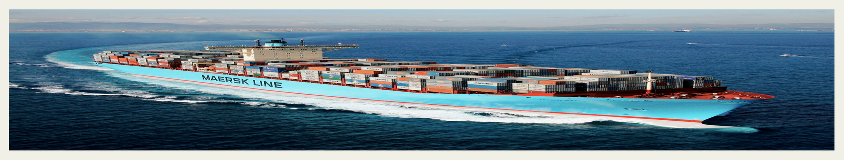


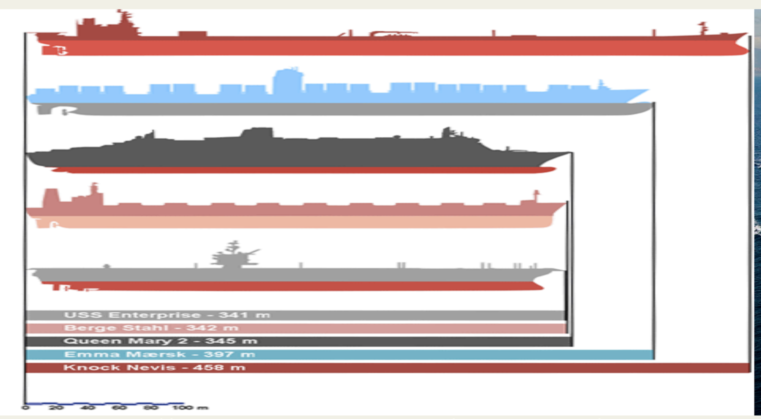


Summary

- The feasibility of replacing conventional diesel powered propulsion systems of large container vessels by small modular reactors (SMRs) has been studied.
- The Emma Maersk, one of the largest container ships in the world, was chosen for the study because of the availability of information such as engine power requirements, engine room dimensions etc.
- A well-validated commercial code MONK 10A that utilises Monte Carlo method was selected for designing the model and for the criticality and burn-up calculations.
- Review of the available SMR technologies was done and the mPower SMR from Babcock and Wilcox was chosen due to its appropriate fuel cycle, power output, safety features and the long experience of the developer in marine applications
- The mPower core was then modelled and made critical. Utilizing the model, criticality and burnup calculations were done for different enrichments of uranium-235 ranging from 3% to 19.5%.
- After analysing the results, a combination of 4.95%, 3.85% and 3% was recommended for the application

Choice of ship to apply the SMR

- Emma Maersk chosen
- Largest container ship until 2013
- Availability of information such as engine power requirements, engine room dimensions etc.



Source: http://www.emma-maersk.com/specification/

Choice of analytical method

- In deterministic method there are measurement uncertainties in the nuclear data, discretisation of space, angle, energy and geometry modelling approximations.
- In contrast to that, statistical methods do not require various approximations as required by the deterministic calculations and are more accurate.
- Statistical methods like the Monte Carlo method can work with any geometry consisting of discrete material no matter how complex it is.

- Among statistical methods, MONK version 10A was chosen because:
- MONK is a commercial code that is widely used in the nuclear industry around the world
- The entire package of MONK consists of the code, a range of nuclear libraries, validation data, visualization tools, productivity tools and user support hotline service[1].
- MONK is a Monte Carlo code used for assessing criticality safety problems and is very well acknowledged with over thirty-five years of successful application across the entire fuel cycle[2].

Choice of reactor design

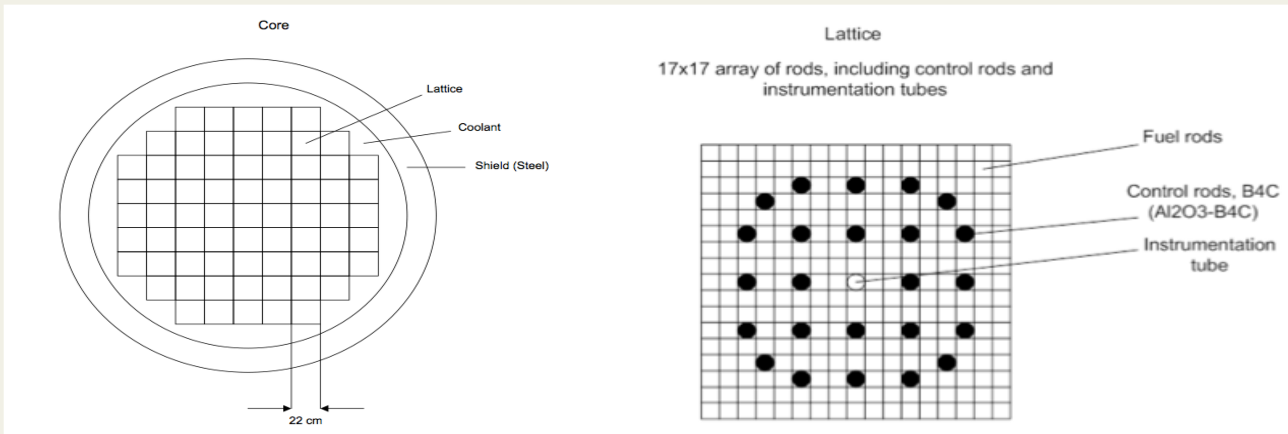
SMR chosen for application because of the following advantages[3]:

- Modularity.
- Scalability
- Lower capital investment
- Flexibility
- Passive safety
- Integral Design
- The reactor containment of SMRs is physically small, suitable for limited space of ships.
- The designs have long fuel cycle, convenient for ships.

mPower design chosen for SMR for the following reasons:

- PWR design SMR, most widely used and most likely to be deployed in near future.
- 4 years fuel cycle of mPower
- Designer company Babcock and Wilcox have a lot experience in the nuclear ship propulsion business starting from 1946

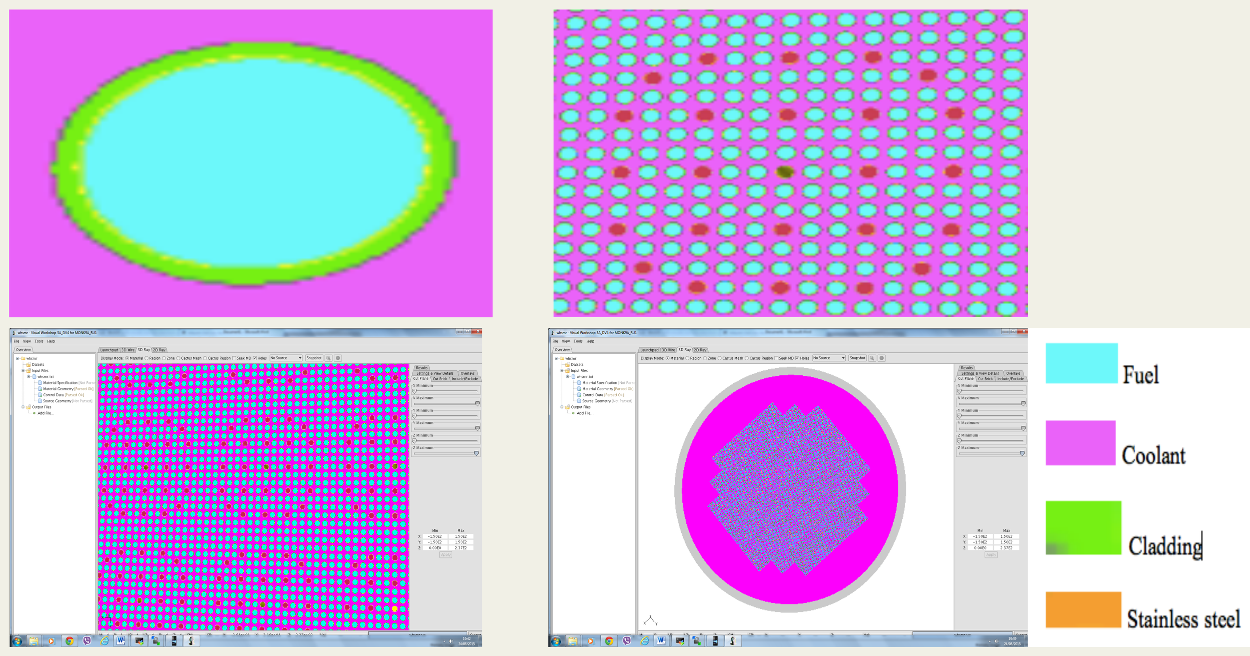
Modelling the core



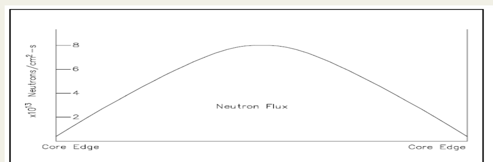
Parameter	Value/Material
Thermal output	500MWt
Electrical output	180MWe
Coolant	Light Water
Fuel	UO_2
Core radius	118cm
Active fuel length	241.3cm
Number of fuel assemblies	69
Fuel density	10.45g/cm^3
Fuel pin radius	0.3922cm
Fuel rod pitch	1.239cm
Fuel cladding	Zircaloy-4
Fuel cladding thickness	0.0491cm
Helium gap thickness	0.0157cm
Absorber	B_4C
Absorber rod dimensions	Same as fuel rod
Absorber cladding	Steel
Fuel assembly thickness	21.063cm
Fuel assembly height	241.4296cm
Mass of fuel	23.3 tonnes
Reflector	Steel
Reflector thickness	5cm

Source: https://www.nrc.gov/docs/ML1015/ML101550512.pdf and Houston et al[6].

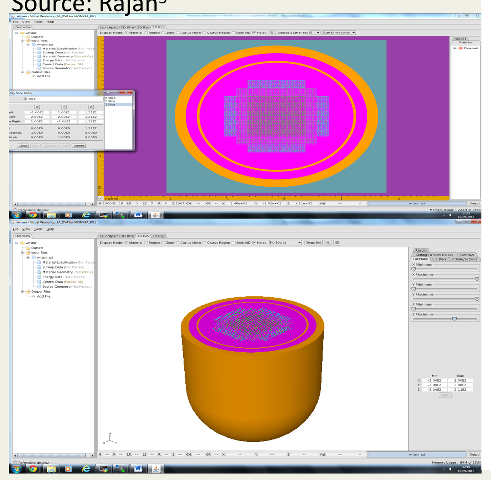
- Geometry of core built using specials functions called NEST and CLUSTER
- NEST is used when one material is inside another material followed by another.
- In our model NEST was used to model fuel rods, control rods etc. where the actual fuel or boron carbide was inside the helium gap that was again inside the cladding.
- The rods were brought together using CLUSTER geometry and repeated using ARRAY command to from an array of rods, which is the fuel assembly. Then the process was repeated but this time repeated with the fuel assemblies formed from previous step to build the core.

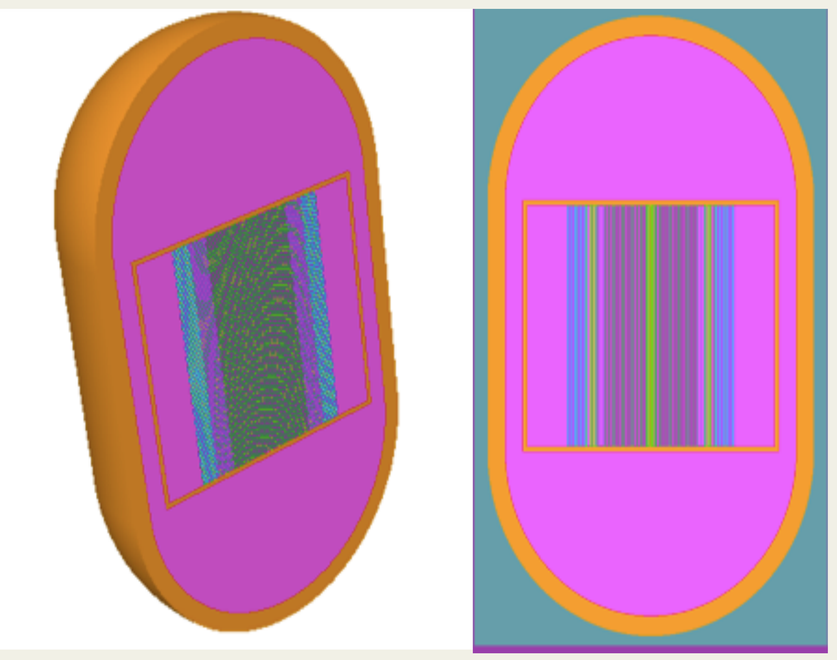


If uniform enrichment was used then heat generation at the centre would be very high compared to the boundary and would generate hot spots near the centre[4].
To flatten the heat flux across the core, variable enrichment can be used with highest enrichment at the boundary where the neutron flux is minimum and lowest enrichment at the centre where the neutron flux is the maximum[4].



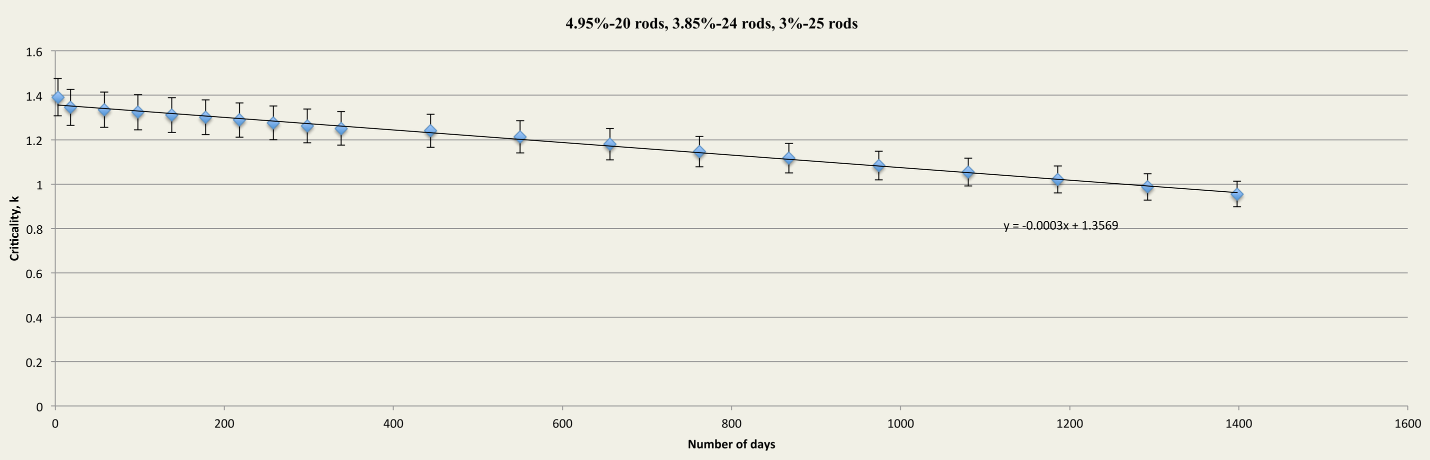
Source: Rajan[5]





	Criticality, k	
Enrichment (% of uranium-235)	With all control rods in	Without any control rods
3	1.3654	0.8561
3, 2.35, 2	1.2741	0.7787
3.6	1.4102	0.8995
3.6, 2.8, 2.4	1.3252	0.8233
4	1.4337	0.9235
4, 3.2, 2.8	1.3651	0.8571
4, 2.5, 1	1.2617	0.7986
4.95	1.4762	0.9727
4.95, 3.85, 3	1.3931	0.8943
10	1.5726	1.1097
10, 7.75, 6.5	1.5306	1.0476
19.5	1.6270	1.2187
19.5, 15.5, 13	1.6048	1.1693

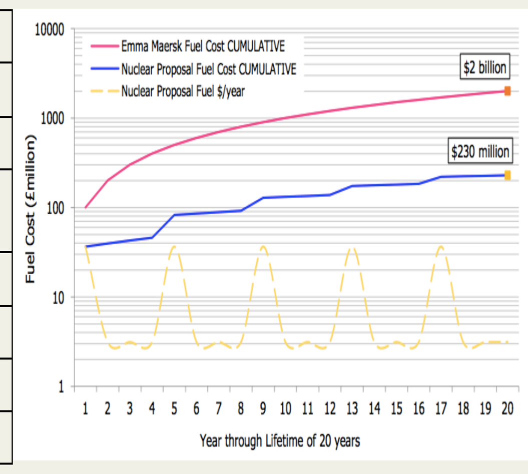
Enrichment (% of uranium-235)	Time taken for criticality (k) to reach 1 in number of years
3	2.932
3, 2.35, 2	1.667
3.6	3.338
3.6, 2.8, 2.4	2.638
4	3.545
4, 3.2, 2.8	2.97
4.95	5.851
4.95, 3.85, 3	3.259
10	14.712
10, 7.75, 6.5	6.781
19.5	17.842
19.5, 15.5, 13	15.326

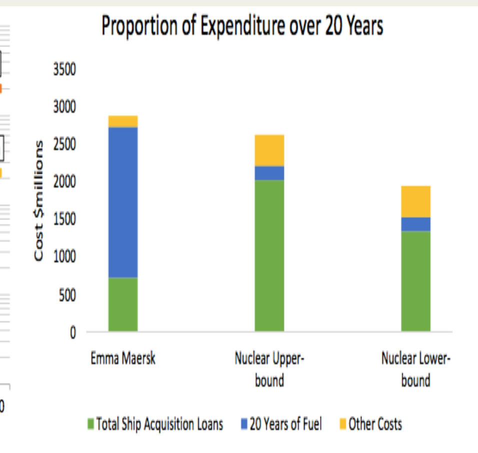


Among different combinations , enrichment of 4.95%-20 rods, 3.85%-24 rods and 3%-25 rods enrichments is very much suitable for marine application The core's criticality is 1.3931 and 0.8943 with and without control rods respectively and has a lifetime of 3.259 years that can be further improved by applying burnable poisons inside the core.

Economic Assessment

	Emma Maersk	Nuclear Propelled
Acquisition (US $million)	145	1260
Maintenance (US $million/year)	0.8	1.6
Maintenance every five year (US $million/five year)	0	2
Crew (US $thousand/day)	10	25
Security (US $ million/year)	1	3
Decommissioning (US $million)	0	20
Refueling (US $million/4 years)	0	2





Source: Houston et al.[6]

An economic assessment was made previously based on the model considering 5% uniform enrichment throughout the core. It was found that:

- The overall cost of running a nuclear powered ship as big as Emma Maersk for a lifetime of 20 years will be several hundred million US dollar less than that of the conventional diesel powered Emma Maersk.
- With an increase in the number of nuclear powered ships built and higher lifetimes than 20 years, its cost will go down further.

Conclusion

- Considering the long fuel cycle, availability of vendors and transport systems for supplying the fuel, a combination of 4.95%, 3.85%, and 3% was recommended for the Emma Maersk.
- A fuel cycle of 3.259 years (and criticalities of 0.8943 and 1.391 with and without control rods in) can be further improved by using burnable poisons. Burnable poison like gadolinium mixed with the fuel is recommended instead of the ones used in coolants.
- Finally taking into account, the long-term environmental benefits and the cost savings that large nuclear powered container vessels can achieve, a SMR with fuel configuration of 4.95%, 3.85%, and 3% is deemed very much feasible.

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Acknowledgements:
- Professor Timothy Abram from University of Manchester
- Nuclear Technology Education Consortium (NTEC)

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