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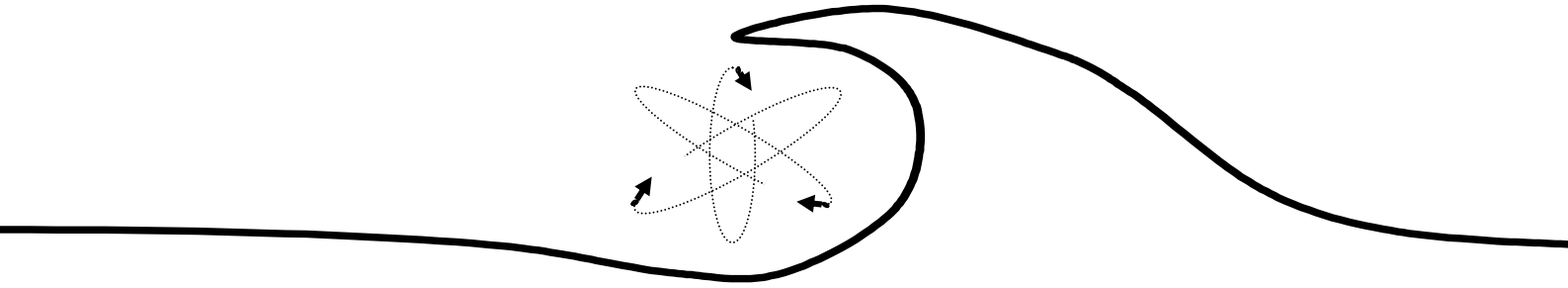
Nuclear Short Sea Shipping

The integration of a helium cooled reactor in a 800 Teu Container Feeder



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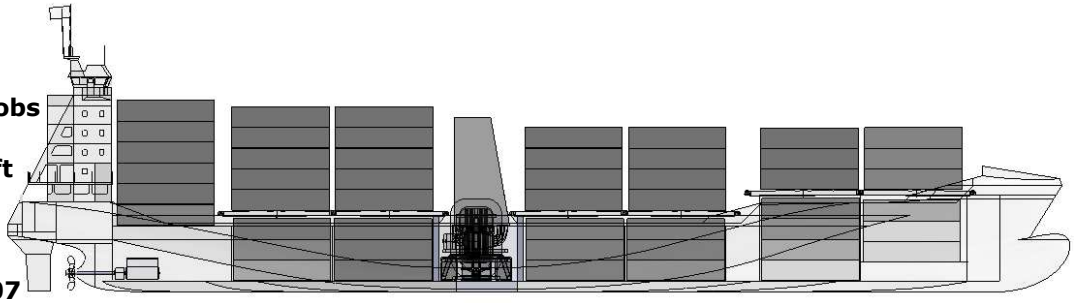

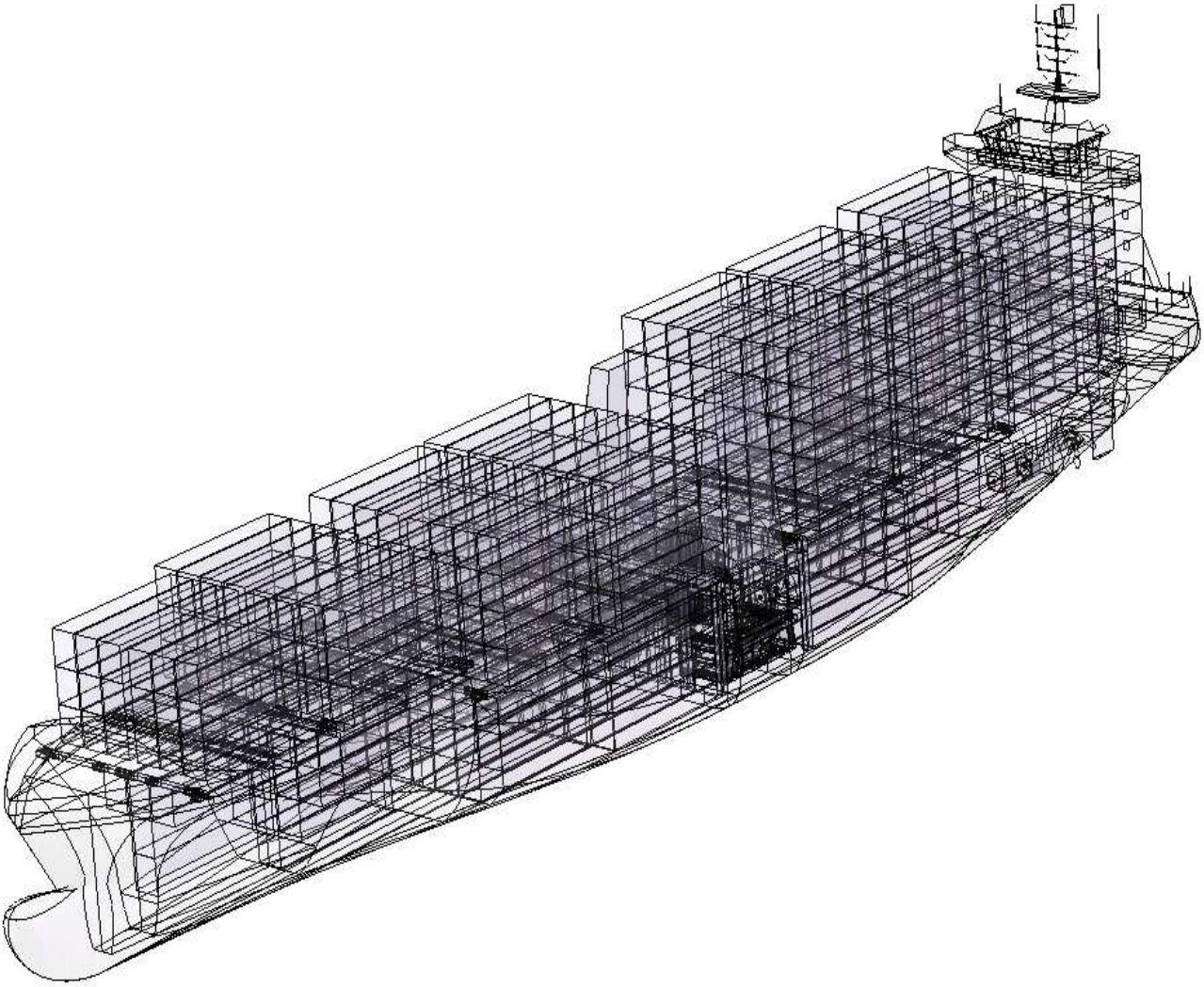

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Summary

"For the best results, a nuclear reactor can't simply be plopped into a hull which was designed originally for a conventional power source. Ultimately, the greatest progress will be made by fleets of vessels which are conceived from the keel up to get their driving force from the atom. Marine engineers and nuclear engineers must work together. That is the way to reach full potential of nuclear energy and to minimize its problems. That is the way to expand and improve the nuclear ships of the world." Joseph M. Dukert [1973]

For this thesis it was chosen to simply insert a nuclear reactor in an existing hull to maximize the opportunities for easy comparison. This will not lead to the best results for a nuclear ship, but provides insight in the pros and cons of placing a reactor on board the ship due to the possibility of eliminating a lot of other differences.

The 'plopping' was done in a suitable coaster, an 800 TEU Container Feeder (CF800). This was chosen as a platform on which to base the design for nuclear propulsion. Multiple ships have been constructed of this design and these can be designated as a serie, which is not common in the ship building. Different nuclear concepts were evaluated for their applicability in the ship, from which the Prismatic-block Gas Cooled reactor filled with HTR fuel compacts was chosen, in combination with an open cycle gas turbine. The reactor and gas turbine in this option are connected via two heat exchangers, ensuring isolation of the reactor from the environment.

Short sea shipping optimizes for shorter loading periods which results into problems with the Xenon poisoning of the reactor, a passive reactor operated on the laws of physics is out of the question in the case of a container ship with a loading period of approximately 12 hours. A necessary higher reactivity will solve this problem but will create the need for active control. Longer loading periods will not lead to this exception and will provide the possible application of a passive reactor, although the dynamic interaction with a gas turbine can still lead to the necessity of active control.

The theoretical models used for this evaluation are static models; the dynamic behavior can result into a different outcome then presented in this evaluation. Off design conditions for gas turbines lead to drastically lower efficiencies which could add to extra fuel costs for a nuclear ship.

The influence of the heat exchanger on the system is very high (great volume, high weight and high costs) when a shell and tube heat exchanger is chosen. Lower weight can be achieved if a plate heat exchanger is applied, but these have to comply with extreme conditions and should be specially developed for this application. The material for such heat exchanger may form a problem in this case no suitable metal was found with sufficiently high creep strength. Still a plate heat exchanger was chosen, because of the lower size and cost in comparison to a shell a tube heat exchanger.

The obtained efficiency from the static model, applying 2 heat exchangers with a simple cycle gas turbine is not as high as reported in different sources. The stated efficiency mounts up to 40% which is almost impossible taking into account pressure losses. Using the static model leads to a total system efficiency of approximately 21 %, including the increase in resistance of the ship and the consumption of the auxiliary equipment.

Small size reactors in small ships will be more voluminous than the conventional diesel plant. Enlarging the ship to maintain the same cargo carrying capabilities will be necessary. The impact of a slightly larger ship, additional resistance, is relative low due to the low impact of the fuel costs on the total costs. This was also the case for the Container Feeder in this case, the elongation was necessary to properly fit the reactor amidships. The elongation results in extra costs for construction and fuel, but these are still relatively small in comparison to the total costs of a nuclear reactor itself.

The construction surrounding the reactor can be made to comply with all current regulations. Safety can further be ensured by taking all precautions which are possible, the cost of structural safety measures in comparison to the total price of a reactor are several orders of magnitude lower. The chance that the primary loop has a breach in combination with the flooding of the reactor compartment, in the case of a sinking ship, could result in a steam explosion; this effect should be investigated for acceptance in all conditions. Designing the reactor as such that it can easily be lifted when a ship is totally lost at sea will keep the environment safe.

Political acceptance of nuclear power as a safe and environmental friendly method of producing necessary energy is essential. The operational costs in the form of permits and compliance to regulation can become impossible when unreasonable demands are formed. The industry needs stable regulation and cost reliability before it will agree to invest. Acceptance of the Sevmorput for example in the harbors, if all current safety demands are met, would be a start.

The initial capital investment is the problem with nuclear ships in comparison to conventionally powered ships and costs will be at lowest in the order of 5; especially the first of a kind will be very expensive.
It is economically profitable to sail with a nuclear short sea ship if fossil fuel triples in price. Additional taxes on emissions or even a ban on sulfur containing fuel can be foreseen, following from the concern for the climate, having the same effect on the fuel cost. Nuclear propulsion for coasters will not be economical viable if this fossil fuel price explosion does not occur.

1 Introduction

With the current concerns for the climate higher demands regarding to emissions can be foreseen. This might open the short sea shipping market for alternative solutions for propulsion, higher demands and more strict regulations will give higher costs for prime movers based on fossil fuels. Increasing oil prices and decreasing resources of fossil fuels can make nuclear propulsion an economically viable alternative.

Short sea shipping seems a good option for nuclear propulsion because of the large amount of vessels, on routes frequently visiting the same harbours. Small unique nuclear designs cannot compete in the current market, off the shelf parts and equipment in larger volumes would lower the cost considerably. A fleet of multiple nuclear coasters could decrease the costs for the surrounding infrastructure and reduce the building costs because of standardized designs. Extended bunker interval and the low impact of the fuel price on the costs are extra stimuli, guaranteeing stable predictable costs. The goal of this report is to research the feasibility of a fleet of nuclear coasters based on one standard design.

The report consists of the following; in the first chapter a brief overview of old nuclear merchant ships will be given. Conditions that need to be met are mentioned in the second chapter. A basis for designing a nuclear reactor for merchant ships will be made in the following chapters.
From the demands to which a nuclear ship has to comply, a ship will be chosen for which an evaluation is done of the different possible concepts. A reactor in combination with a heat engine will be chosen from the evaluation. A static model for the system will be designed to evaluate the properties of such system assuming a refuelling interval of 5 years. This system will then be integrated in the ship. Safety and environmental issues will also be discussed. The necessary infrastructure to support this design will be discussed and an estimation will be made of the different costs. The recommendations ending this report will be based on the chosen design.

2 History Nuclear Merchant Ships

Nuclear fission occurred long before humans interfered with it: in Gabon, Central Africa in the current Oklo mine. 1,5 billion years ago, self-sustaining nuclear reactions took place in the uranium deposit located there. (Cole [1988]) After the discovery of the possibility of nuclear fission in 1938, the search for the control of this form of energy had begun and evolved rapidly into the nuclear science as we know it today.

Pressurized water reactors (PWR's) have been specially developed for marine applications and found their way to land based installations. All maritime reactors up till now have been PWR's and this is logical due to the then known technology. Steam had long been the way to propel ships and enough knowledge was available to accomplish a total working nuclear maritime power plant only 17 years after the discovery of the splitting of the atom.

Nuclear power for ship propulsion was first achieved for the submarine; the "Nautilus" constructed in 1955. A numerous amount of nuclear military ships has been produced and operated for many years. Accidents have happened with these ships and submersibles, but never evolved to global disasters (See appendix I)
Four nuclear propelled ships were produced for merchant purposes: NS Savanah (US), Otto Hahn (Germany), Mutsu (Japan) and the Sevmorput (Russia). There were some rumors about the Republic of China building 2 nuclear ships. The ships were thought to be: the coaster "Zan Than"; launched 1967; 22,000 GRT; 3400 Passengers; 23,5 knots; 60.000 SHP PWR and the general-purpose "Pai-feng"; 70.000 SHP PWR. This was never officially confirmed and is badly documented as stated in ISPRA Vol. 1 [1976]. Murmansk Shipping company has still active nuclear ice breakers in its service, 8 were build from which its known that one is put out of service; the "Lenin". Names of the other icebreakers: "Artika", "Sibir", "Rossija", "Tajmyr", "Sovjetski Sojuz", "Vaigach", "Yamal". The Yamal is currently known to undertake commercial cruises to the North Pole.
Icebreakers are left out of the equation here, the special construction and arrangements on board makes them hard to compare with cargo carrying ships.

2.1 NS Savannah

The NS Savannah proved the technical feasibility of nuclear propulsion in ships, but had too high costs being a unique ship, needing unique support and for the need of a large educated crew. The Savannah sailed over 450.000 miles during her active life only refueling once after 336.000 miles. Many Naval architects still think of this ship as the most beautiful bulk cargo ship ever built (see figures 1 and 2).

Figure 1 NS Savannah

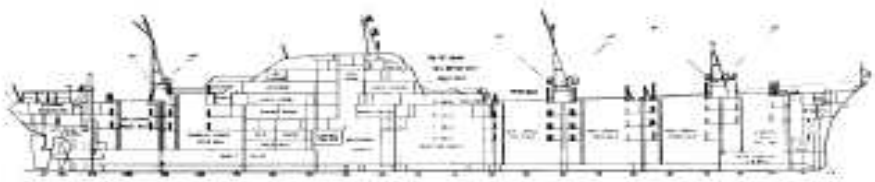

Figure 2 NS Savannah overview

2.2 Otto Hahn

The Otto Hahn also proved the technical feasibility, but again the uniqueness of the ship together with the need of highly educated personnel caused it to be not economical and was converted to a diesel powered ship. She was last seen sailing under the name Madre. The Otto Hahn sailed 650.000 miles visiting 33 ports in 22 countries(see figures 3 and 4).

Figure 3 NS Otto Hahn

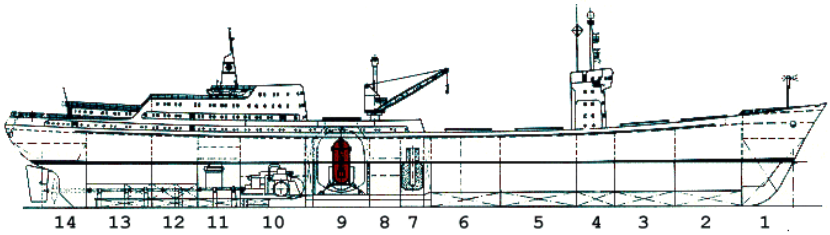

Figure 4 NS Otto Hahn overview

2.3 Mutsu

The Japanese test ship was originally built with cargo holds but these were never used (See figure 5). During the build there were radiation leaks and other severe problems delaying the delivery date. She only made 4 journeys, after a 20 year build, testing the installation and was decommissioned after this.

Figure 5 Mutsu

2.4 Sevmorput

The Sevmorput is a LASH (Lighter Aboard Ship) containership (figures 6 and 7) still in service by the Murmansk Shipping Company, because of being nuclear it has problems getting permission to enter most harbors. The ship is still being operated, but is heavily subsidized. Currently there are plans to convert this LASH carrier into a drilling ship to probe the Arctic sea for its viable resources.

Figure 6 Rear of Sevmorput

Figure 7 Sevmorput in ice conditions

2.5 Compared nuclear merchant ships

All the ships above have pressurized water reactors, which heat water to run it through a heat exchanger, which boils water in a secondary loop. The steam produced is run through a turbine connected to a shaft leading to the propeller. After the turbine, the steam is condensed and fed to the condenser. Steam and condense is formed back into water which is fed back into the heat exchanger. The configuration of the first two ships is almost identical, the reactor somewhat before the middle of the ship and the shafts directly connected to the turbine. The space necessary for the nuclear plant occupies almost one third of the ships in a relative wide part of the ships.

Nuclear Civil Ship	NS Savannah	Otto Hahn	Mutsu	Sevmorput	Units
purpose	bulkcarrier	orecarrier	testship	containership	
start build	1959	1963	+/-1968	1982	
Start Date	1961	1968	1991	1988	
End Date	1971	1979	1992	-	
Length	180	172,05	130	260	m
Width	23,8	23,4	19	32	m
Depth to upperdeck	18	14,55	13,2	18,3	m
Draught	-	9,22	6	12	m
Designspeed	21	15,75	16,5	20	knots
Topspeed	24	17		20,8	knots
Displacement	-	25790	8242	33980	tons
Gross tonnage	10000	14040	-	-	tons
Thermal output	74	38	36	135	MW
Effective output	15,14	8,2	10	30	MW
Crew	124	63	-	-	
Passengers	60	35	-	-	
cargo weight capacity	8500	-	-	-	tons
Cargo space capacity	18000	-	-	-	m3

Table 1 Comparison Historical nuclear ships

As can be seen from the diagram, the efficiency of the ships is rather low. Multiple design studies have been undertaken throughout whole Europe, but did not result in a more profit generating design compared with the conventional prime movers. The studies were primarily around tankers and fast containerships. High capital cost, high (proper educated) crew costs and additional cost for unique infrastructure were the main reasons for these ships to fail economically.

3 Conditional Demands

3.1 Reactor Design Demands

A reactor aboard a ship has to cope with the harsh conditions that can be expected at sea. These conditions or functional demands are given by an internal report of the AES platform [2005]:

All equipment needs to withstand:

- A steady inclination of 15 degrees sideways and 5 degrees forwards.
- Approximately 22,5 degrees amplitude of roll motion and approximately 10 degrees amplitude of pitch motion, this in combination with peak accelerations of 0,6 g for ships larger then 90 m.
- A main engine room temperature of 0-45 degrees Celsius.
- Relative humidity up to 96 %, non-condensing
- Salt density in air up to 1mg/m^3
- Oil contamination (greasy fingers, oil fog and grease oil).
- Outside temperatures ranging form -30 to +50 °C

Further:
Seawater cooling must be able to cope with a seawater temperature range of between 32 °C and -2 °C.

Maximum noise rates: Sound Source 110 dB

The radiation dosis received on board should be according to the ALARP-principle (As Low As Reasonably Practicably) but at maximum:

Maximal cumulative radiation dose	1 year	5 year	
Radiation Workers	50	100	mSv
Individual Members of the public	5	-	mSv

Table 2 Maximal radiation doses

See appendix B.

3.2 Ship Design Demands

The ship design must comply with the specific characteristics of a nuclear reactor, this results in a series of design demands which must be met.

After a certain operation period, the reactor has to be refueled or replaced. Therefore the reactor must be reachable for maintenance purposes, preferable with the possibility to pull the reactor completely out of the ship.

The reactor must survive impacts or collisions from other ships, without serious contamination of the environment.

The reactor should be easily retrievable from the ships hull in case of a total loss of the ship.

The radiation level inside the ship should be at an acceptable level, to make sure the maximum radiation doses will not be exceeded. This has a lot to do with the time spent in certain places aboard the ship. An estimation has to be made for how long the crew maintains in certain zones aboard the ship.

The ship also has to comply with current legislation, this gives a problem only IMO has adopted a specialized section describing demands for nuclear ships. Further legislation has not been developed yet.

3.3 Radiation protection

Radiation protection can be done in several ways:

- Reducing the exposure time has a linear proportional effect on the dose received.
- Increasing the distance to the source of radiation, assuming a point source, will reduce radiation according to the inverse square law. So the dose received will drop with an inverse quadratic function of distance.
- Adding shielding between the source and the receiver will also reduce the received dose.

Reducing the exposure time can be done by lowering the need for maintenance and check ups, offsite monitoring and control.

Increasing the distance can be done by placing the reactor at a larger distance from the accommodations and workspaces onboard.

Biological shielding is of course very important around a nuclear reactor. Harm-full radiations with which should be calculated are neutron radiation and gamma radiation. Alpha and Beta particles are charged particles which do not penetrate far into material due to the electromagnetic counter forces of the nuclei. Neutrons are neutral and are only capable of interaction through collision; they can travel through several centimeters of material before colliding with another particle. Gamma-radiation or photons also do not have a charge and can penetrate very far. See appendix A and figure 8.

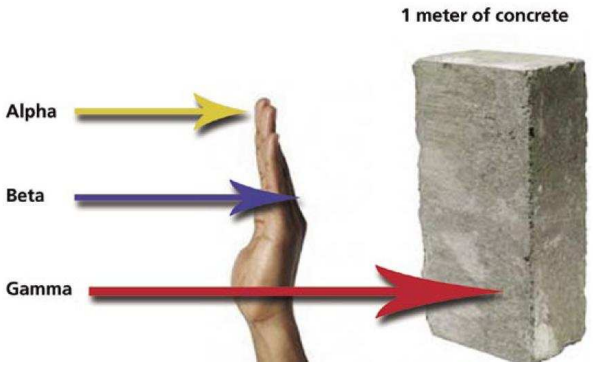

Figure 8 Radiation Penetration Courtesy of Miller [2006]

Gamma shielding can consist of many materials and is often calculated by using a halving thickness as parameter:

- 9 cm for packed soil or
- 6 cm for concrete,
- 1 cm for lead,
- 0,2 cm for depleted uranium,
- 150 m for air.

Problem with this halving thickness that is doesn't take into account the gamma-rays raised by the captured neutrons in the material. The gamma shielding capability is primarily dependent on the materials density. The following graph, figure 9, gives the mass of the shield for a cylindrical core, where the radius of the reactor is 1,18 m and where the variable shield thickness times density is considered as the radiation stopping power. The density of concrete is taken as 2,3 T/m^3, steel as 7,62 T/m^3, lead as 11,34 T/m^3 and tungsten as 19,25 T/m^3.

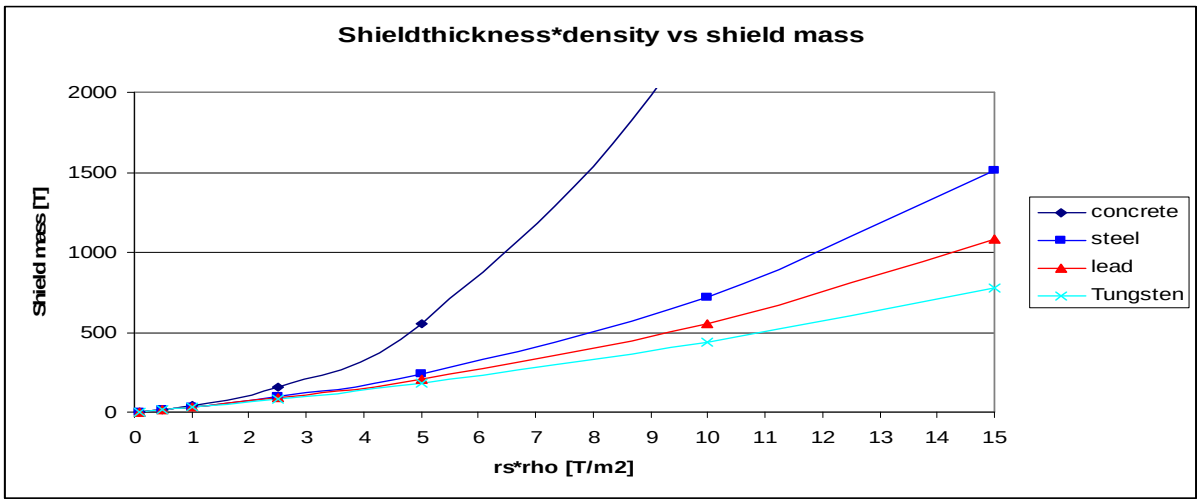

Figure 9 Simple geometry shielding thicknes versus pathway times density

The ability to stop gamma rays will not imply that a material also has the ability to stop neutrons. Lead for example is an excellent protective material against gamma-rays, but is almost useless against neutrons. That is why it is used as a coolant in some fast breeder reactor designs.

Neutron radiation is reduced by scattering and absorbing materials in other words materials with a high absorption cross section for neutrons, or a material with a small nucleus, this gives more effective scattering (more kinetic energy lost). Neutrons cause gamma radiation on absorption, so it is important to shield the neutrons first and then shield de rest radiation.

The shielding design will be based on the neutron flux of a working reactor and gamma radiation, not taking into account possible shut down in harbors.

3.4 Legislation for Dutch harbor visit

A conversation with the authorities of the Port of Rotterdam resulted in the conclusion that no clear defined regulation is applicable, although it is obliged to obtain a permit to visit the harbor with a nuclear ship should be obtained according to the KEW (Kern Energie Wetgeving; Nuclear Energy Legislation).

HBR (Haven Bedrijf Rotterdam; Harbor Company Rotterdam) conducted a research after a question from Mourmansk Shipping Company investigating a shipping route from Rotterdam to the Far East for the nuclear ship Sevmorput. The conclusion was that a single permit would at least cost an estimated € 522.000 (2001) not taking into account the possible political aversion and forming of policies for a visit.
Information on the arrival and protocols during the visits of the Otto Hahn and NS Savannah was no longer available.

Nuclear Submarines from different Navies (NATO Allies) are being permitted in the harbor, for which permits are arranged by the Ministry of Defense (which in theory should be arranged by the Ministry of Economic Affairs).

Dutch legislation provides the KEW in which is stated in article 15: that a permit is necessary to run a ship with a nuclear installation. Ministers of VROM, EZ, SZW, V&W are authorized to give such a permit.
Such permit can be refused on the following grounds:

- -Protection of people, animals, plants and goods.
- -Safety of state
- -Storage and security of fissionable material and ore
- -Energy supply
- -Ensuring proper indemnification in case of damage or injury to a third party
- -Enforcing international obligations

An AMvB (Algemene Maatregel van Bestuur; form of dutch temporal fast legislation) can also make additional demands, which should be made law within 3 months or this will be withdrawn.
Article 21 sub 3 demands insurance for proper indemnification in case of damage or injury.
In the KEW a lot of space is left for AMvB's making the law highly unpredictable when applied, making momentary and temporary political influence very large.

3.5 International Legislation

Nuclear merchant ships have already sailed the earth thus a series of rules and recommendations already have been developed for this class of ship.

IMCO (Inter-Governmental Maritime Consultative Organization) Code of International convention for safety of life at Sea 1960 and 1974 Chapter VIII and attachement 3, supplemented by the Code of Safety for Nuclear Merchant Ships (resolution A.491(XII)) describes demands for the ship design, operation and control. This regulation is based on conventional ship types with a PWR on board. The differences between a reactor filled with TRISO elements compared to a PWR will probably not influence the demands on the design of the structures. Groot [2003] summarized the most important conditions of the code:

IMO defines 4 different conditions for which plant process conditions (PPC's) in the code apply:

1. Normal operation situations such as start-up operation, power operation and manoeuvring.
2. Infrequent unplanned situations or special operations such as turbine trip, control rod withdrawal error and temporary loss of electrical power.
3. Unplanned situations with remote likelihood such as leakage of radioactive substances through primary boundary and consequent shutdown, or collision followed by flooding any two adjacent watertight compartments.
4. Extremely remote situations such as loss of coolant, stranding with intermitted loss of heat sink, grounding, collision and even capsizing and sinking.

Sub-paragraph 2.7.5 to 2.7.7 mention that the ship has to withstand pressure shocks from explosion, missile impacts from rotary devices (like a turbine shaft).

Chapter 3 of the Nuclear Ship Code states that the total reactor compartment must be separated from the cargo by means of air- and watertight cofferdams or bulkhead, extending from the double bottom to the bulkhead decks (3.1.1). It also has to be located or protected to minimize damage in

case of collisions, groundings and hazards arising from cargoes, missiles and other sources specifically identified by the safety analysis (3.1.2).

Damages are defined by IMO as:
Side damage:

1. Longitudinal extent: $\frac{1}{3}L^{\frac{2}{3}}$ or 14,5 m whichever is less.
2. Transverse extent: $\frac{B}{5}$ or 11,5 m whichever is less
3. Upwards from the moulded line of the bottom shell plating at centreline without limit.

Bottom damage:
For 0,3L from the forward perpendicular from the ship:

1. Longitudinal extent: $\frac{1}{3}L^{\frac{2}{3}}$ or 14,5 m whichever is less.
2. Transverse extent: $\frac{B}{6}$ or 10,0 m whichever is less
3. $\frac{B}{15}$ or 2 meter, or whichever is less, measured from the moulded line of the bottom shell plating at centreline.

For any other part of the ship:

1. Longitudinal extent: $\frac{1}{3}L^{\frac{2}{3}}$ or 5,0 m whichever is less.
2. Transverse extent: $\frac{B}{6}$ or 5,0 m whichever is less
3. $\frac{B}{15}$ or 2 meter, or whichever is less, measured from the moulded line of the bottom shell plating at centreline.

The international classification societies have not yet produced rules for nuclear ships, which should be devised to create boundaries in which the possibilities can be evaluated. This should be done to ensure the possibility for insurance.

3.6 Regulations for harbour visits

In May 1979 the IAEA (International Atomic Energy Agency) and IMCO created a joint technical committee to draw up port entry requirements for nuclear merchant ships(IMCO, [1979]), clearly stating that this is not applicable for nuclear naval ships.
These requirements were devised based on ships with pressurized water reactors on board. Main demands to the port in this document are:

- Berth of Nuclear ship should provide easy access for fire-fighting and other emergency services.
- Adequate lighting of the berth should be provided for security surveillance and safety purposes.
- Adjacent hydrants, to supply water for fire-fighting or other emergency connections and any special couplings required between the ship and shore should be provided.
- A shore power connection for the ship's electrical system should be available.
- Suitable communication facilities between the ship and port authorities should be provided.
- Health physics equipment and decontamination services should be available within the immediate port area.
- Where disposal of liquid or solid radioactive wastes from a visiting nuclear merchant ship is permitted by the Host Governmental Authority, or where refueling is permitted, suitable facilities should be provided in the port.

Additional Radiation monitoring is prescribed for background radiation at the berths visited by Nuclear Ships, which data should be retained for record purposes.

Before and during cargo handling the level of radiation in the cargo holds or at the ships bottom should be checked.

And a remote ship anchorage should be found in advance, isolated from concentrations of population and sufficiently distant from normal navigational routes so that other ships are not affected. In case of emergency or radioactive materials release the ship should be towed to this area.

Procedures and emergency plans should be devised and ready before any nuclear ship enters the harbor.

Further demands to personnel on board are also prescribed:

- A senior officer should available on board at all times.
- Sufficient crew members should be on board to ensure that all emergency procedures can be carried out in the event of an accident.
- An adequate fire watch should be maintained on board the ship.
- At all times, when there is fuel in the reactor, the nuclear power plant should be supervised by qualified personnel keeping continuous watch in the main reactor control room.
- Personnel in charge of radiation protection, as defined in the Code, should be on board the ship at all times.

If the Netherlands want to stimulate nuclear propulsion in its fleet these regulations should be evaluated and met. The responsibility of a nuclear shipping company should be clear long before entering the harbor. The arrangements prescribed in these recommendations should be met and these recommendations should be developed into rules so objective evaluation is possible.

Another concern is the insurance necessary; these are issued only on basis of certificates. Known certifying companies have not readily available rules from which it is possible to derive a design, which would slow down the process of designing and producing the necessary installations. Current KEW does not demand a specific contribution in the costs of observance of the legislation, but additional costs for the pursuer of a permit are possible.

Nuclear submarines sometimes visited the Rotterdam harbor, these submarines also have to comply with the KEW. The advantage of the submarines is that security is arranged by their own Navy, and that they evade a lot of international law. If there is no political goodwill, for a visit of a nuclear merchant ship, it can get a problematic and expensive if not an impossible happening. Acceptance of a visit is probably easier if the berth place is not near or in the middle of a densely populated city like a berth place in "De Waalhaven". "De Maasvlakte" is a fairly remote area which is more plausible as possibility for possible berthing (see figure 10 below)

Figure 10 Rotterdam Harbor Area

So concluding: at this moment it is possible, if there is political good will, to visit a Dutch harbor with a nuclear merchant ship. The costs of such visit though can be a surprise.

4 Possibilities

4.1 A Nuclear Coastal Containership

From the history of nuclear merchant shipping can be seen that single application of nuclear powered ships, have the disadvantage of being unique and serviced in one place. The ships had their own infrastructure; NS Savannah even had its own support ship. It also had extreme high cost of a large educated crew, because of complex design with high maintenance and operational demands. Special education only applicable for one ship is also very expensive.

Several design studies were done for fast nuclear ships, which resulted in designs for single and unique ships, with all the additional costs that come from unique objects.

When the design of the nuclear reactor with propulsion plant can be standardized and made feasible for smaller more frequently used ships in the order of 150 m length, then it might be possible that the market grows to an acceptable economic number of ships supported by a central infrastructure, decreasing the cost.

Figure 11 Container Feeder 800 TEU

A large number of Coastal Container ships sailing at harbors in Northern Europe, the routes of these ships are standardized making a central infrastructure possible. Rotterdam can be seen as a sort of hub for these container ships which would be an ideal location to create a central infrastructure from where they can be serviced.

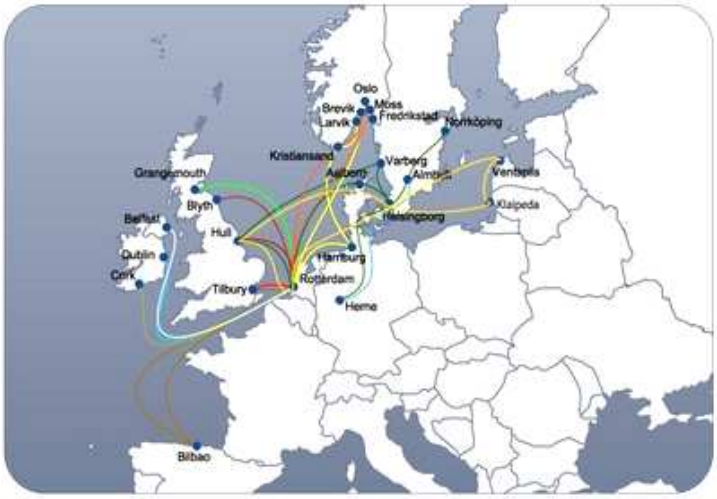

Figure 12 Samskips Sea Trade Routes

A coastal tanker could have additional advantage, as part of the generated heat can be used for cargo heating. This would generate extra efficiency. Only propulsion is considered in this case for easy comparison.

There is a standardized design for a containership which has an 8,4 MW main engine on board, with place for approximately 800 TEU containers, and a cruising speed of approximately 18 knots. This standard design is called: Container Feeder 800 (CF 800 see figure 11). This will be the basis for the design and the model to compare with (see appendix M). Samskip uses this ship and was kind enough to give us information about their trade routes and ship profile. (See figures 12 and 13)

4.2 Samskip Trade Routes

Samskip is one of the largest players on the coastal container transport market and delivers cargo from Rotterdam to other important container receiving harbors in Northern Europe. Here Rotterdam is primary used as a hub from where the transatlantic and transpacific containers are distributed. Samskip also offers container railway services ensuring delivery throughout most of Europe.

Figure 13 Samskip England Sea Trade Routes

As a benchmark one route is chosen from which the cost can be calculated to evaluate the design of the different concepts. The trade route Rotterdam – Tilburry is chosen. Which is a relative short line, but which can easily be varied to see the different impacts on several variables.

Samskip has a line which delivers 6 times a week containers from Rotterdam to Tilburry and vice versa. Only on Friday there is no service between the container terminals. This route is done with 3 ships. Where loading is done on the first day and unloading is done on the third day. Loading and unloading is done within 6 hours. The turn-around-time is 12 hours. The distance from Rotterdam to Tilburry is 166 nautical miles.

From the Power Load Balance from a CF800 a power profile can be made, assuming a maximum shaft power of 6000 kW for propulsion (see figure 14). With this the performance of the reactor can be evaluated to see if it is suitable to deliver the needed power.

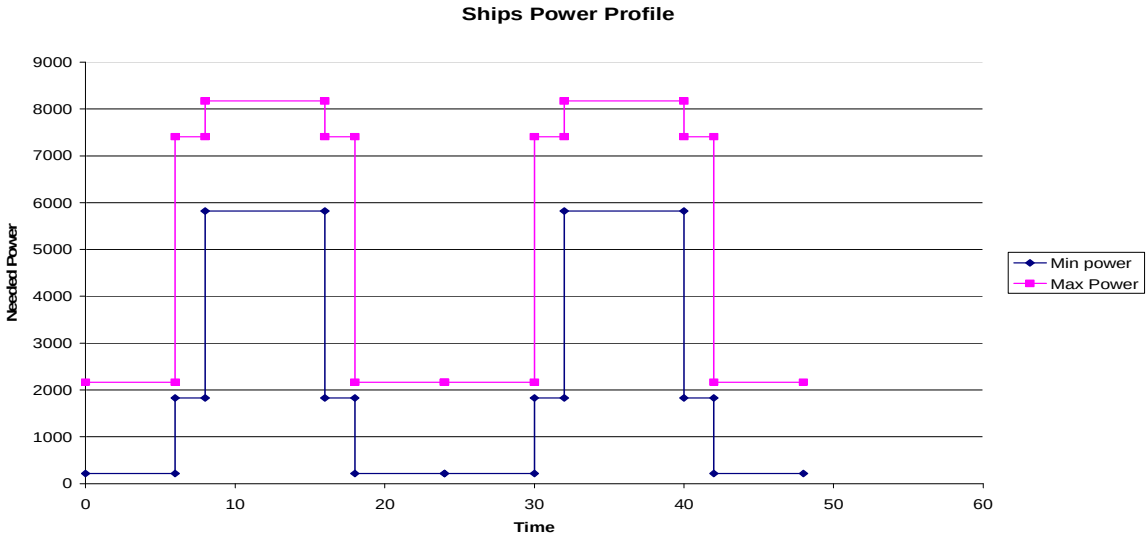

Figure 14 Power Profile

The resulting profile can lead to problems with Xenon poisoning. After shutdown of a reactor Xenon will form from several reaction products. The Xenon absorbs neutrons better then Uranium which leads to problems restarting the reactor. Xenon has a halftime reasonable short halftime so after a period of time, ranging between 12 or 30 hours depending on the design, the reactor will be able to restart, see appendix G. In this case an active controlled reactor with sufficient reactivity available is chosen as the solution to this problem.

4.3 Reactor Choice

Before choosing a reactor type, it is important to make requirements to which it must comply. Safety is the most important factor, but size and cost do also count. The reactor system must also be quite simple and predictable, Keep It Simple Stupid (kiss) as popularly said or Idiot Proof (IP). The reactor must fulfill its purpose in sea motions and must be able to cope with the different load conditions.
Exotic materials like liquid metals and salts should be avoided because of this simplicity and predictability, although the Russian navy has experience with 8 reactors cooled with a lead bismuth alloy according to Nuttall [2005]. Problems can be foreseen when reactors are stopped. Liquid metals or salts will convert to a solid state, making maintenance virtually impossible.

From the available reactors (see appendix C) the following are chosen: the BWR, PWR, PBR and PR, because they can be produced in smaller size, which makes them suitable for application on board a coaster, See table 3 below.

Reactor	BWR	PWR	PBR	PR
Moderator	H_2O (L+G)	H_2O (L)	Carbon	Carbon
Coolant	H_2O (L+G)	H_2O (L)	Inert gas	Inert gas
Control (P = Passive, A = Active)	A	A	P / A	P / A
Coolant Temperature (℃) approx.	285	315	800	950
Pressure (bar) approx.	75	150	40	40

Table 3 Properties candidate nuclear reactors

The Boiling Water Reactor (BWR) has the advantage that the steam produced in the reactor is immediately used in a turbine, so there is little energy wasted on heat exchangers. The BWR stands out in simplicity. Disadvantages are active controlled reactor and all equipment is in contact with primary coolant flow giving problematic repairs caused by the radioactivity, sea motions could cause disturbances in the evaporation and moderating process, which are hard to predict.

The Pressure Water Reactor (PWR) has a pressurized primary water flow which is design to be kept in the liquid phase at high pressure. There is a secondary coolant system which produces steam from the energy extracted from the primary flow by heat exchangers. This is run through a turbine. The problems with the maintenance of all the equipment in the secondary system are avoided in this system. Disadvantage is that heat losses are introduced in the heat exchanger and it is an active controlled reactor.

PWR's are already used in several navy ships especially aircraft carriers and submarines, PWR's are smaller then BWR's, less then half the size and give a more easier maintenance procedure, rendering BWR less suitable for being a primemover in a ship.

The PebbleBed Reactor (PBR) and Prismatic-bock gas cooled Reactor (PR) both have a pressurized primary helium flow to exchange the heat with the reactor, this is run through a heat exchanger with various systems to form usable energy from the heat. The advantage of the system is that the TRISO particles regulate the temperature in the reactor all by themselves, up to and especially down to a certain level. Another advantage is that the coolant is not activated. Disadvantage of the system is the larger amount of waste: if stored in the same way as normal nuclear fuel it can be 13 times the volume of conventional spent fuel assemblies. Xenon poisoning can shutdown the reactor (See appendix G). The waste of the reactor is not yet designed to be reprocessed; it is based on a once through cycle as promoted by MIT [2003].

Cost can be reduced by allowing for fewer personnel through a self regulating system. A PWR can be made in such a way that it is automatically regulated. But when the operator fails it must be scrammed, a lot of reactor knowledge should be present aboard the ship. A PBR or PR can be made self regulating on basis of a temperature balance with negative coefficients, instead of active control. A PWR has the same effect but the temperature differences are not so high, so it has less effect on the reactivity.
Another factor which has to be taken into account is the amount of maintenance, according to Dr.ir. J.L. Kloosterman a PWR needs more maintenance then a Reactor with TRISO elements, caused by the saturated steam in the system. Complex turbines with condensation removal systems are necessary and turbine blade erosion is still a problem.

The Burn up rate for a Pebble bed reactor is reported to be 100 MWd/kg (in extreme cases even up to 174 MWd/kg) versus a 30-60 MWd/kg for a PWR. So fuel is more efficiently used in comparison with a PWR.

The higher temperature of the PBR and PR result in a higher efficiency for the heat engine behind the reactor. The ideal Carnot efficiency is defined as $\eta = 1- T_{low}/T_{high}$ from which follows that a higher temperature from the reactor delivers much more usable energy from a heat engine.

A PR has a larger core density then a PBR resulting in a more compact core, but with the same positive characteristics. The larger core density results from the inefficient stacking of fuel balls, compared to the prismatic block type fuel. Plus the Prismatic block is more solid generating less radioactive graphite dust into the coolant. Application of the Prismatic-block Reactor seems the most promising solution for now, regarding the arguments above.

4.4 Concepts for heat engines

Several variations can be made to extract the energy of a nuclear reactor, combining the promising heat engines from the appendices and a helium cooled high temperature reactor can lead to the following concepts:

- Indirect Single Steam turbine closed cycle
- Indirect Single Gas turbine closed cycle
- Indirect Single Gas turbine open cycle
- Direct Stirling cycle
- Indirect Stirling cycle

These concepts are based on the first two blocks of the following scheme (figure 15):

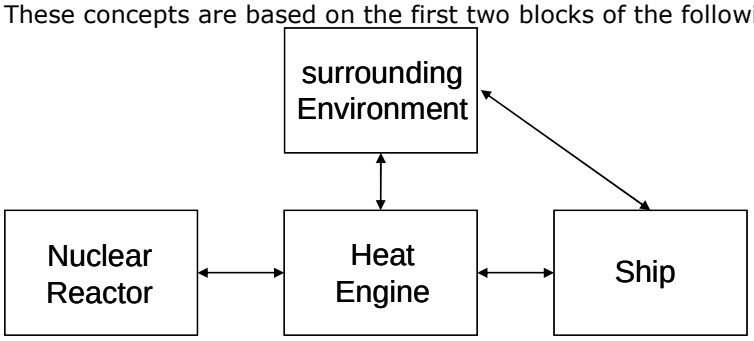

Figure 15 Model building blocks

The combination of the reactor with the heat engine is one of the most important issues to be addressed, because this has the most influence on the parameters it gives for the rest of the design. One of the basic requirements which the system has to for fill is the separation of the environment by 2 barriers, which should result in a system with no single point of failure.

Indirect Single Gas turbine closed cycle (Figure 16)

An inert gas like carbon dioxide is circulated in the secondary loop through a closed Gas turbine cycle. Heating is done by a large heat exchanger between the compressor and the turbine. Cooling is done by a large heat exchanger after the turbine to the lowest possible temperature to get maximum efficiency.
The advantage of this system is a theoretical high efficiency, but turbines for these cycles are not readily available.

Indirect Single Gas turbine open cycle (Figure 17)

In an open cycle the outside air is used as the fluid in the Gas turbine, after the compressor the air is heated by a large heat exchanger, which is in a tertiary loop. The energy is extracted by the turbine and after the turbine the air is blown off. The secondary loop is an extra barrier against possible contamination when a leak occurs in one of the heat exchangers.
The turbine can be based on available aerospace turbines, disadvantages are high losses due to the controllability of the temperature after the exhaust, large volume needed for air intake and exhaust and the high dependency on environmental temperature.

Direct Stirling cycle (Figure 18)

The helium with which the reactor is cooled is directly used to heat the primary head of the cylinder of the Stirling engine. The secondary cylinder is cooled by another medium which is cooled with the outside environment. The disadvantage of this system is that the primary loop is exposed in the Stirling engine, with the probability of contamination. Advantage is a high efficiency. Although a small amount of engineering information is available it is to be expected that a Stirling engine is a lot heavier then a Gas turbine or even a steam plant.

Indirect Stirling cycle (Figure 19)

The primary head of the cylinder of the Stirling engine is heated by a secondary loop. The secondary cylinder is cooled by another medium which is cooled with the outside environment. Risk of contamination with radioactive material is minimized through the use of a secondary loop. Disadvantage is slightly less efficiency and a slightly larger plant then with the direct cycle.

Indirect Single Steam turbine closed cycle (Figure 20)

The water is pressurized in this cycle to get a decent efficiency, a heat exchanger creates superheated steam with a temperature of about 850 °C with the heat from the reactor. The steam is driven through a Steam turbine which delivers kinetic energy. After the steam turbine the remaining steam and condensate is cooled in a condenser to a temperature just below the boiling punt, from which it is delivered to the boiler.
The advantage of this cycle is that it is known technology, apart from the reactor
Steam cycles are still used in LNG tankers, which use the boil off from the gas to propel the ship. The disadvantage is the phase change within the cycle, consuming quite a lot of energy.

Conclusion

The Indirect Single Gas turbine open cycle seems the best solution for now, although not all components are available off the shelf, the heat engine is relative small and light and seems producible in the near future. There are countless more options like addition of recuperators, intercoolers etc. to achieve higher efficiencies, but these will not change the basic configurations of the above mentioned cycles. ROMAWA, an advising company run by G.A.K. Crommelin also advocates this concept.

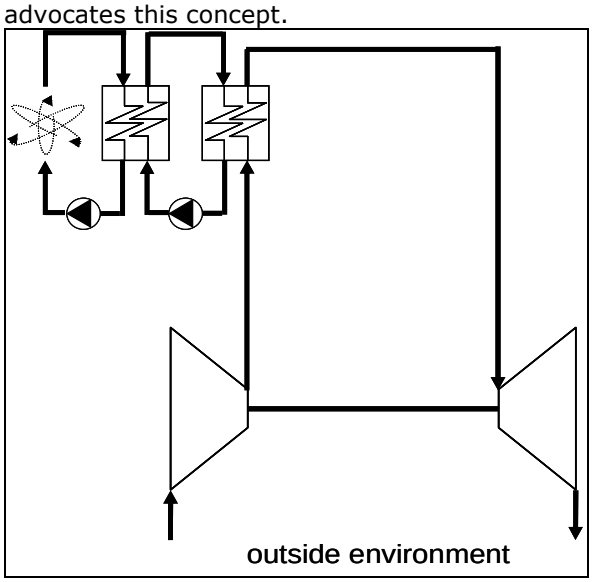

Figure 16 Indirect Open Gas turbine Cycle

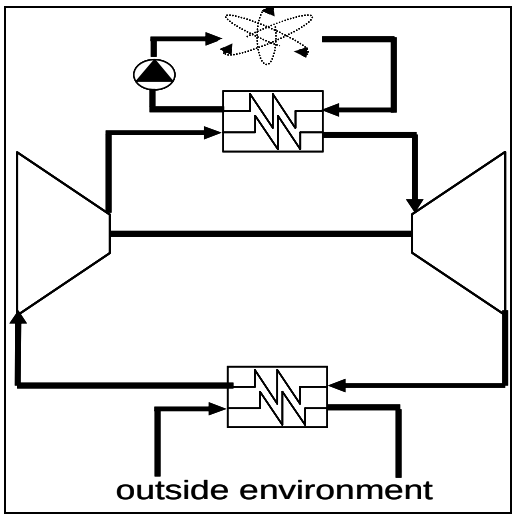

Figure 17 Indirect Closed Gas turbine Cycle

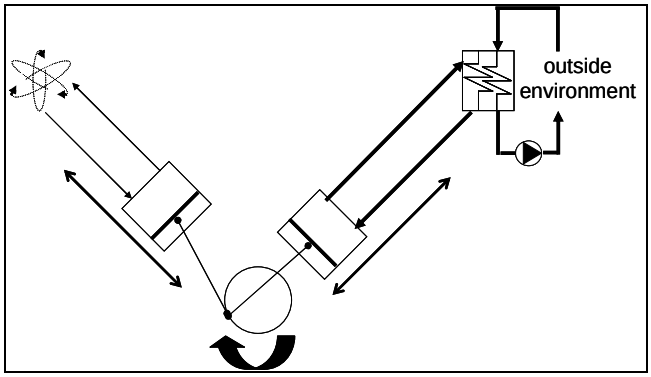

Figure 18 Direct Stirling Cycle

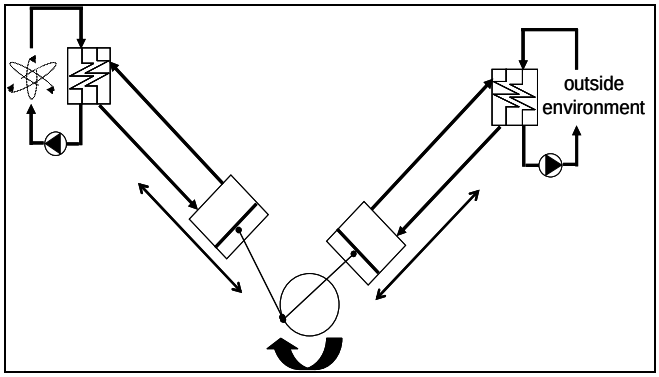

Figure 19 Indirect Stirling Cycle

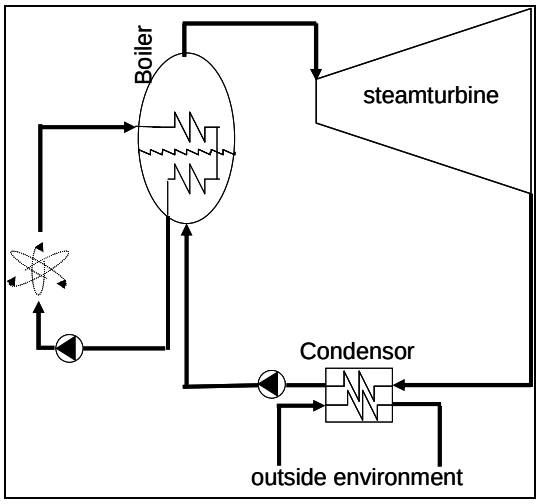

Figure 20 Indirect Steam Cycle

4.5 Assumptions for further development of concept

The Prismatic Block gas cooled Reactor is chosen as the basis for the design seems the best solution; having the best characteristics for now. A passive reactor following the demand of the external machinery would be the most ideal situation, but currently this is not yet feasible for existing transient reactors according to the simulations of Verkerk [2000], although after adaptation of the lowest part of the reactor this might be possible.

Assuming active control following the advice of Verkerk, we need only 1 reactor to comply with the power profile of the ship, also preventing problems with Xenon poisoning. Gas turbines are used to convert the heat into usable energy. Gas turbines normally have an optimum point in which they have their maximum efficiency besides that point the efficiency drops. Using more then one turbine makes the system more redundant and will allow for higher efficiency by driving the turbines more near their most efficient point. Reviewing the load balance it becomes clear that half of the time less than 25 % of the power is needed, one third of the time full power is needed and the rest is in between. A logical choice would be to install a small turbine capable of handling the max of 25 % of the full power and a larger Turbine to handle the other 75 % of the power.

A second gas loop is added as an extra barrier between the outside environment and the primary loop. Some radioactive dust from the graphite is produced which should not escape, the primary loop will be filtered to keep the loop as clean as possible.

Assuming an efficiency of 95 % for the heat exchangers, and an efficiency of 30 % for the Gas turbines, taking the power output of the diesel plant in the CF800 as the basis for the needed output results, the first estimated needed thermal power of the nuclear plant will be 8400/0,95/0,95/0,30 ≈ 31.000 kW. This is relative close to the Japanese HTTR of 30 MWth (See figures 21 and 22).

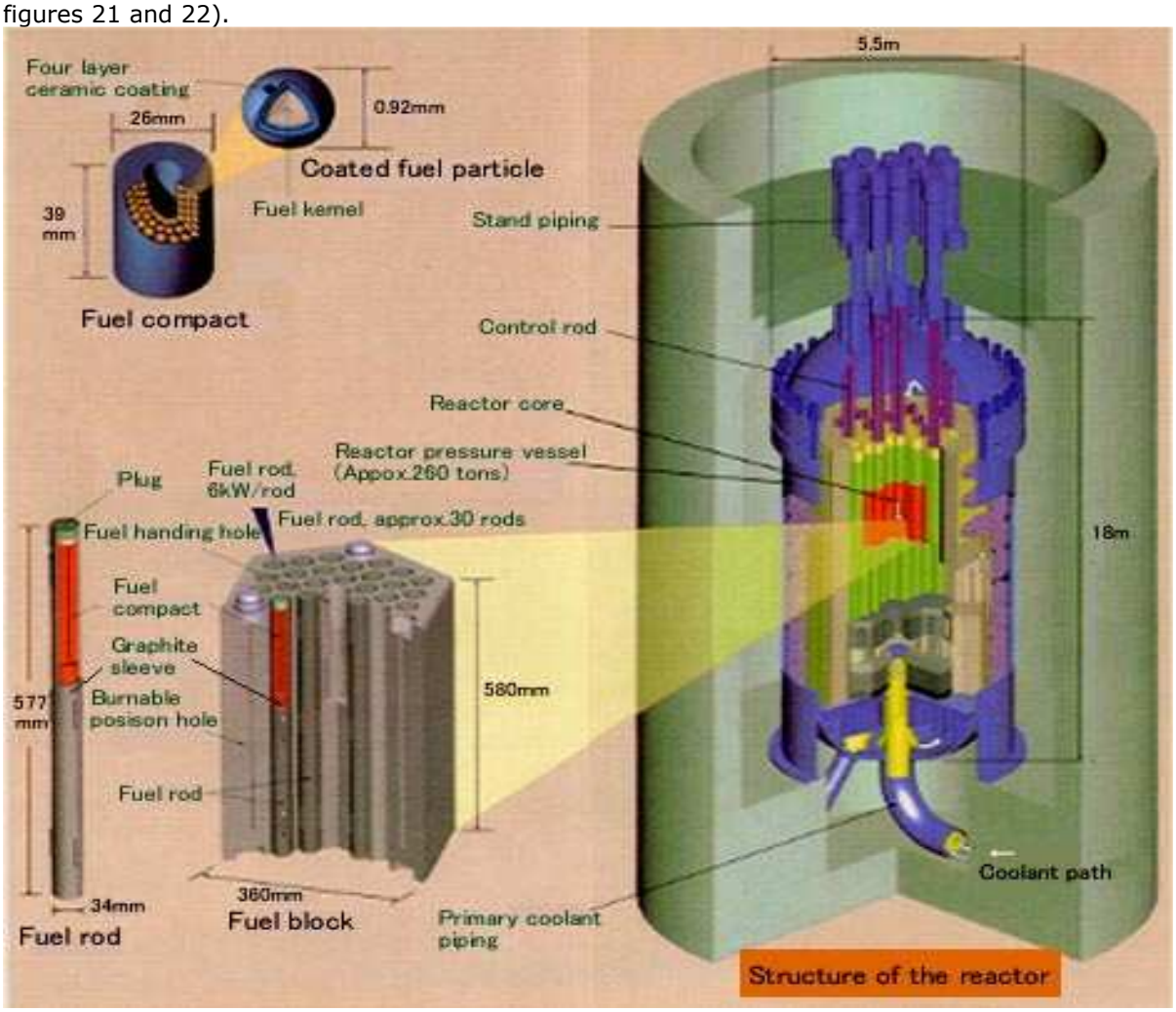

Figure 21 Japanese 30 MWth HTTR http://www.jaeri.go.jp

Normally a ship has a docking period of 5 years, so it is the most practical to have reactors which last these 5 years and then can be replaced or refueled. Gas turbines have higher periodic maintenance checks but these highly depend on the operating temperature, amount of running hours and the conditions of the air used.

The achievable burn up rate for TRISO Fuel is reported to be 174 MWd/kg; Verkerk [2000]. This is of course the maximum what is pressed out of a part of the fuel. Assuming a lower usage of the maximum burn up rate the burn up rate with which the amount of fuel is estimated to be 100 MWd/kg, resulting in combination with the load profile in a total necessary amount of fuel of 385 kg for 5 year. See appendix K.

As can be seen from the figures the used reactor system is not readily applicable for a coastal vessel; including the containment the height of the reactor is 30 m and a diameter of 18,5 m, which could be reduced using other materials as shield and reconfiguring the different standard sizes used in the reactor.

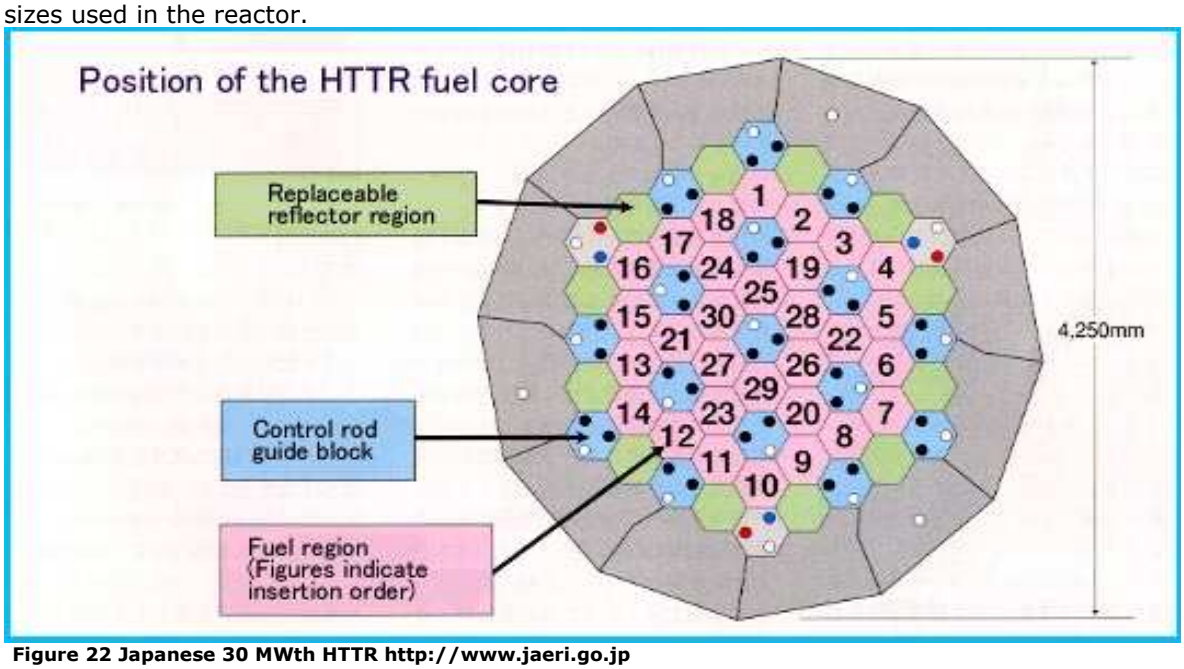

Figure 22 Japanese 30 MWth HTTR http://www.jaeri.go.jp

The Japanese HTTR-vessels weighs approximately 260 tons, where a diesel engine weighs approximately 130 tons. The weight of the reactor vessel is excluding the weight of the Biological shielding, the weight of the heat exchangers and the weight of the Gas turbines. First estimation for the shielding is over 1000 tons, so it deems necessary to place the reactor amidships.

4.6 Concept propulsion format

With the reactor relative distant from where the propulsion is located, the question is how to get the power from the reactor to the propeller. Distributing the power to the propulsion system can be done in multiple ways, the 3 most practical are: electricity generation by Gas turbines with electrical propulsion, direct drive with heat transported across the ship and a long shaft connecting the gas turbines near the reactor directly with the propeller. See figure 23.

When electrically driven the gas turbines can be placed everywhere because of the low weight of these machines. Losses in efficiency by long piping transporting the heated medium from the reactor to the gas turbine and back can be large due to resistance and heat loss along the route through the ship. The disadvantage of using indirect propulsion is the drop in efficiency of 5 % per conversion, with an extra loss for this concept of somewhat over 10 %. Positioning the gas turbines directly besides the reactor the losses of transporting the medium to the gas turbine can be made negligible.

The additional weight is approximately 2 x 30 tons for the generators coupled to the gas turbine and 24 tons for the electro motor driving the propulsion system, with a gear between the propeller and the electro motor of approximately 30 tons.
Direct drive of the propulsion system does also have considerable losses the medium must be transported over approximately 32 meters, when the gas turbines are directly coupled and placed at the traditional place of the diesel engine. Losses are directly related to the quality of the

insulation and the resistance in the piping. Leading high temperature piping through the ship gives additional safety problems.

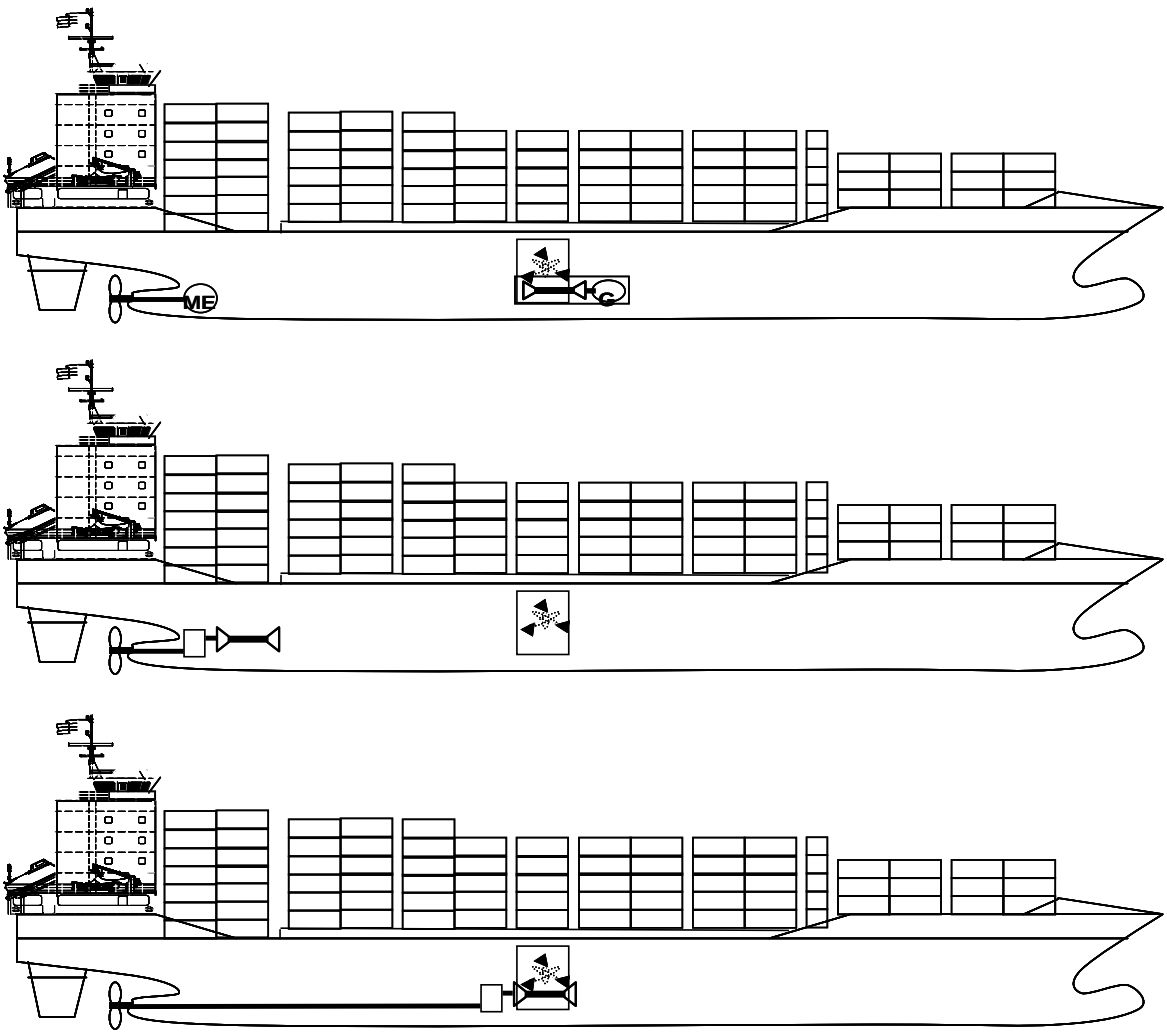

Figure 23 Concepts for power delivery to propeller

Another possibility is a direct drive in combination with the positioning of gas turbines near the reactor by using an extreme long shaft. This would add in weight; assuming a diameter of 500 mm and a length of 48 m the weight of a shaft would be:

$$M = \rho V = \rho \frac{\pi}{4} D^2 L = 7{,}87 \cdot \frac{\pi}{4} \cdot 0{,}5^2 \cdot 48 \approx 74 \text{ ton}$$

This would keep the efficiency loss relative low. A long shaft like this would also mean additional supporting bearings with their maintenance problems.
The additional weight for the gear connecting the 2 gas turbines renders the shaft arrangement a slightly more heavy option.

Further evaluation of the spatial distribution within the ship delivers an extra problem, as illustrated in the following drawing (figure 24): valuable container positions are lost when a solid shaft runs through half of the ship. The position of the gas turbines is also prescribed by the main gear connecting the shaft to the gas turbines. Additional space is lost because the funnels (not illustrated) of the gas turbines need to be led straight upwards. Besides the reactor is no decent place for extra containers, so by using this layout a lot of container positions are lost.

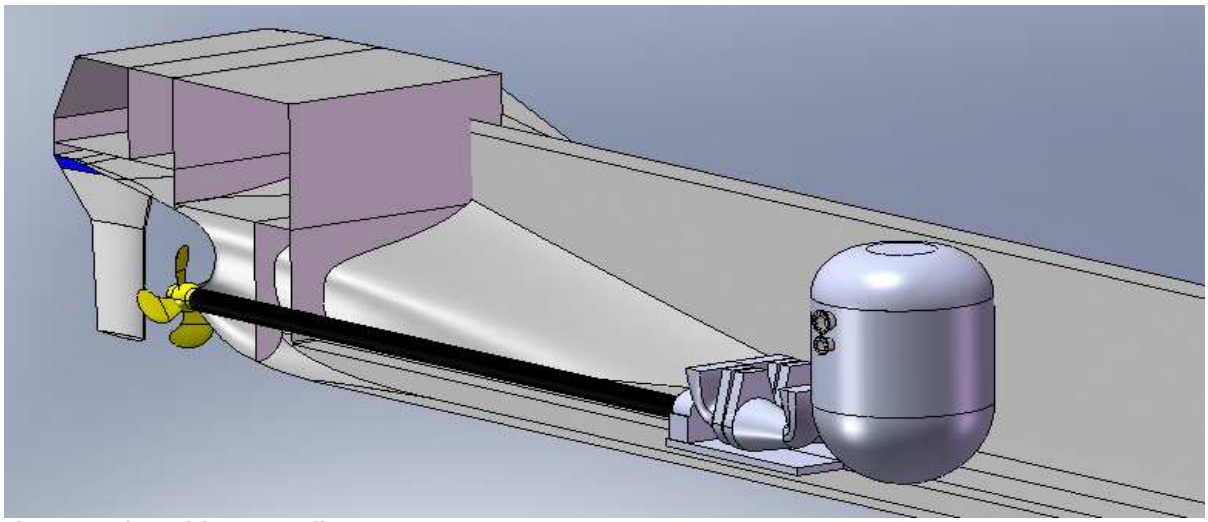

Figure 24 Direct driven propellor

Efficiency losses do have an effect on the size of the reactor increasing the radius slightly, when in scale approximated; if α is the additional loss in efficiency α^{-3} will give the extra diameter and $\alpha^{2/3}$ will give the additional weight so 10 % extra loss will lead to a 2,2 % increase in diameter with 4,6 % additional weight).

Although the slight increase in core size the option with generator sets and an electromotor is preferable above the direct driven option because of the freedom in positioning the gas turbines resulting in less lost container slots and an easier access to the turbines for maintenance overhauls. Another reason for choosing the option is the comparability in this report, changing the structure and layout to support a long shaft will make the comparison with the original design hard. This does not mean that indirect electrical propulsion is always the best way, a dedicated design for a nuclear ship can have other results.

5 Selected system design

5.1 Gas turbine

A gas turbine system of approximately 8400 kW is necessary to replace the original diesel engine, the auxiliary equipment will probably have approximately the same necessary power.
To deliver this amount of power, air is compressed using energy, then heated by a heat exchanger it drives the turbine and the turbine drives the compressor and a load.

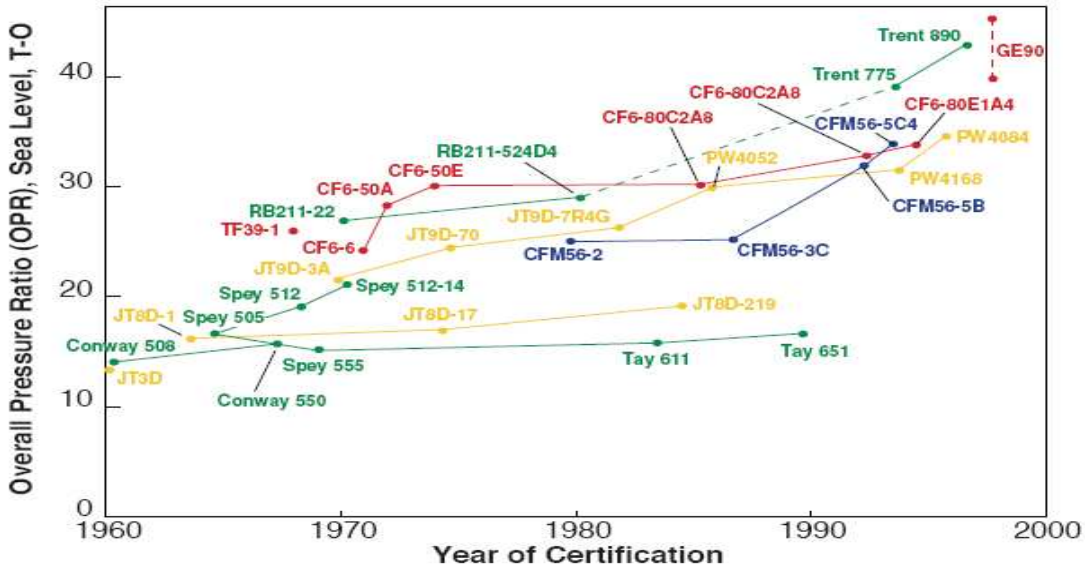

Figure 25 Gas turbine engine pressure ratio trends (Jane's Aeroengines, 1998)

From the trends in pressure ratios for gas turbines (figure 25) it can be concluded that it is possible to construct a commercial compressor, which can deliver a pressure ratio of up to 40. But after evaluation of the gas turbine performance the most efficient point for the pressure ratio of the compressor lies in the region of 9-12 at the given temperature levels (800-900 °C) and pressure drops in the system (0,5 - 1,5 bar).

Application of a recuperator normally increases the efficiency of the Gas turbine and with this a high theoretical efficiencies can be reached. Further improvements can be made by: adding one or more intercooler between different compressor stages, adding one or more reheaters between different turbine stages where efficiencies of just below 60 % are possible (Stapersma [1999]), but these are calculated for the higher temperatures obtained in a combustion chamber. Addition of these parts to the installation will highly increase capital cost and these additions to the gas turbine are not state of the art for this moment.

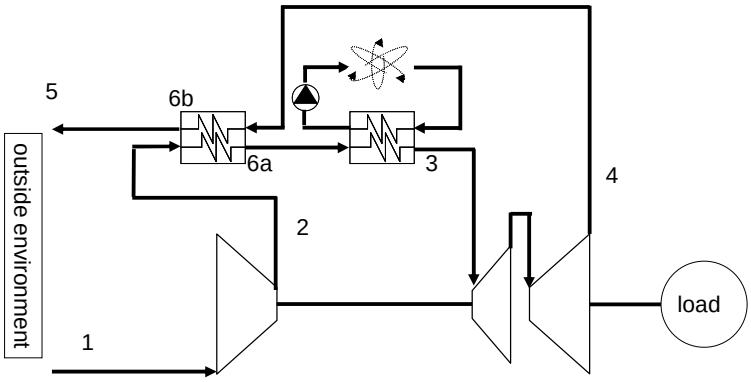

Figure 26 Gas turbine model with recuperator

The power can be delivered directly from the shaft that also connects the compressor and the turbine, but another possibility is to make a second turbine that drives the load (See figure 26), this last solution allows for better control of the system. The gas turbine modeling is done in appendix L.
The direction of the placing of the gas turbine needs some consideration, the gas turbine acts somewhat like a gyroscope. Vertical positioning is out of the question due to the motions of the ship. Positioning the shaft in the longitudinal direction of the ship will be necessary to ensure the lowest wear on the bearings.

5.2 Position of the reactor

The position of the reaction should not change the center of gravity, the easiest assumption is to place the reactor in the center of gravity of the diesel engine combined with the fuel. Fully loaded the center of gravity lies on 57,5 meters, with fuel tanks fully empty this lies on 18 meters. The reactor should have the same impact on the center of gravity of the ship as the diesel engine in combination with the fuel, to ensure that there will be no trim effect during fully loaded conditions. This results in a formula for the position of the centre of gravity of the reactor, where the mass of the reactor is the only variable:

$$COG_{reactor} = \frac{COG_{total}(M_{rest} + M_{reactor}) - M_{rest}COG_{rest}}{M_{reactor}}$$

Which is for the CF800 in fully loaded condition:

$$COG_{reactor} = \frac{60,41(11890 + M_{reactor}) - 11890 \cdot 60,70}{M_{reactor}}$$

The Japanese HTTR-vessel weighs approximately 260 ton, where a diesel engine weighs approximately 130 tons. The weight of the reactor vessel is excluding the weight of the Biological shielding, the weight of the heat exchangers and the weight of the Gas turbines. For a 1000 tons reactor this results in a centre of gravity (cog) for the reactor of 57 m and for a 3000 tons reactor this results in a cog of 59 m. Variation of the reactor position delivers the following table:

Table 4 Variated position of the reactor

	center of gravity reactor [m]	10	20	30	40	60	80	90	100
ballast Condition	Draft fore [m]	3,0	3,5	3,9	4,4	5,3	6,3	6,7	7,2
	Draft aft [m]	7,8	7,5	7,2	6,8	6,0	5,1	4,6	4,1
	Draft mean [m]	5,4	5,5	5,5	5,6	5,6	5,7	5,7	5,7
Fully loaded Condition	Draft fore [m]	5,5	5,9	6,2	6,6	7,0	7,1	7,1	7,1
	Draft aft [m]	8,9	8,6	8,1	7,8	7,4	7,2	7,2	7,4
	Draft mean [m]	7,2	7,2	7,2	7,2	7,2	7,1	7,1	7,3
	Stability requirements	Failed	Complies	Complies	Complies	Complies	Complies	Complies	Complies
	Strength requirements	Failed	Failed	Failed	Complies	Complies	Complies	Failed	Failed

The impact of the reactor location on the ship is clearly visible from table 4. The table goes no further than 100 meter because the ballast condition already has the propeller above water. Approximately between 40 and 70 meters from the aft perpendicular is the best location for the reactor.

Advantage of placing the reactor in the middle of the ship is the available width which is available to place the reactor and other necessary equipment. 18,6 meter is available in width and 7,7 meter is available in height. The length necessary to place the reactor can be varied by replacing containers on another position. It is logical to change the normal orientation, as depicted in Figure 21, of the reactor 90° to accommodate to the space available, although this will give extra problems with on site refueling.

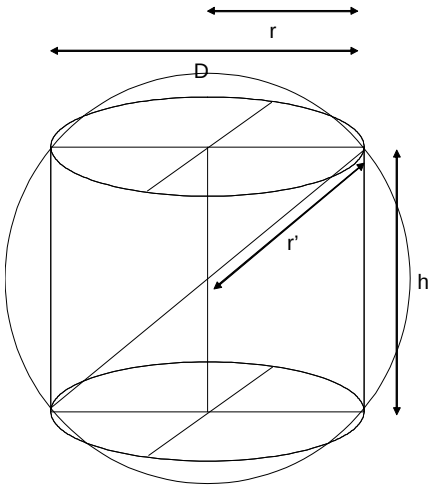

Figure 27 Simpel reactor representation

5.3 Reactor dimensions

From the table in appendix E can be concluded that power densities up to 8 MW/m^3 are possible, strangely enough the Japanese HTTR reactor has a low power density of 2,5 MW/m^3.

The dimensions aspects should resemble the shape of a sphere as much as possible to favor ideal situation to maintain as much neutrons as possible in the core:

r'-r=r'-h/2 resulting in h=2r. This would results in a total volume of V=2πr^3. From the power density the approximate size of the core can be calculated.

From here relations between the volume of the core, the diameter of the core and the surface of the core can be established. The inverse of the surface of the core will give an incentive for the flux on the surface. These relations are visualized in figure 28.

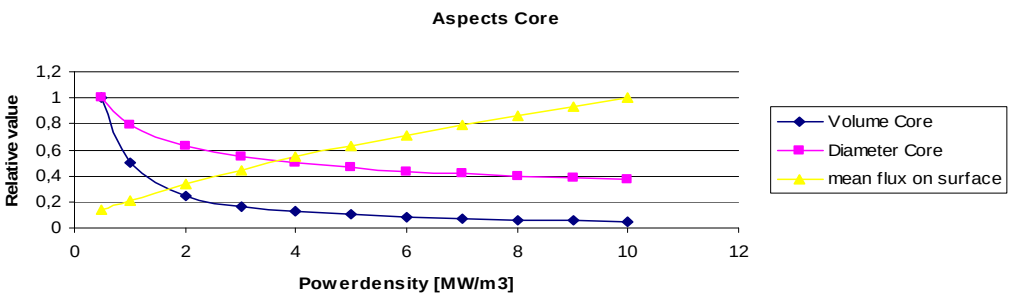

Figure 28 different core properties versus Power density

From the graph can be concluded that a power density between 2 and 4 gives the best effects. A low flux is necessary to limit shielding thickness and a low diameter is needed to keep the dimensions of the reactor as limited as possible. Another factor which needs to be taken into account is the need to get rid of the decay heat from the reactor (see sub chapter:"6.3 Decay Heat"); a more slender body has a greater surface enabling more heat to be transferred.

Another critical item influenced by the shape of the reactor is the weight, changing the radius of the reactor to a more elongated cylindrical shape can have a positive effect on the weight. The weight is mainly depending on the volume of the shield. The shield also consists of a reflector which cannot be neglected in the calculation. The reflector will be like a cylinder around the core with a disc on top and at the bottom. The shape of the shield is chosen as a cylinder topped with two halve spheres (See figure 33).
Cylindrical core:

$$V_{core} = \left(H + t_{refl}\right)\pi R^2$$

Cylindrical shield with sphere shaped ends:

$$V_{shield} = \pi\left(\left(R+t+t_{refl}\right)^2 - \left(R+t_{refl}\right)^2\right)\left(H+t_{refl}\right) + \frac{4}{3}\pi\left(\left(R+t+t_{refl}\right)^3 - \left(R+t_{refl}\right)^3\right)$$

If the proportionality between H and R is defined as α.

$$H = \alpha R \rightarrow V_{core} = \alpha\pi R^3$$

$$V_{shield} = \pi\left(\left(R+t+t_{refl}\right)^2 - \left(R+t_{refl}\right)^2\right)\left(\alpha R+t_{refl}\right) + \frac{4}{3}\pi\left(\left(R+t+t_{refl}\right)^3 - \left(R+t_{refl}\right)^3\right)$$

The volume of the core is known by assuming the power density.

$$\alpha = \frac{V_{core}}{\pi R^3} \rightarrow V_{shield} = \pi\left(\left(R+t+t_{refl}\right)^2 - \left(R+t_{refl}\right)^2\right)\left(\frac{V_{core}}{\pi R^2}+t_{refl}\right) + \frac{4}{3}\pi\left(\left(R+t+t_{refl}\right)^3 - \left(R+t_{refl}\right)^3\right)$$

Assuming a V_{core} of 14,1 m^3 (powerdensity 3 MW/ m^3) and a reflector thickness of 75 cm results in the following graph:

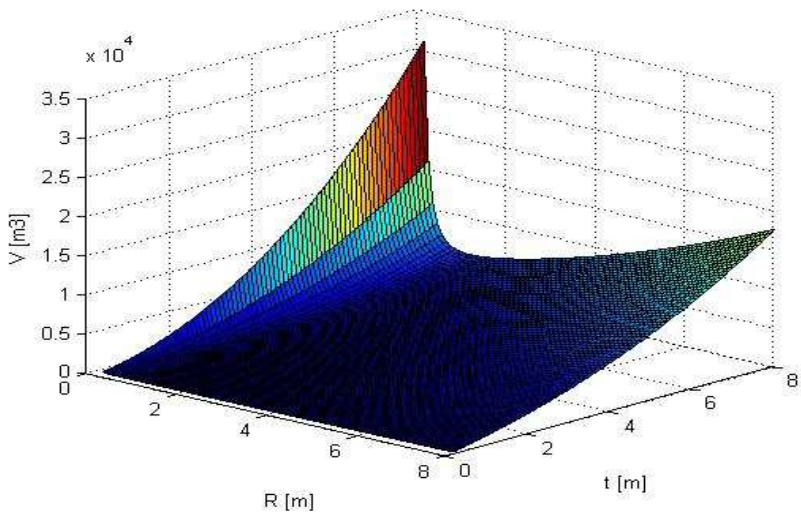

Figure 29 Shield Volume versus radius and Thickness

The volume of the shield of the reactor seems the smallest when R is kept constant on approximately 1,2.

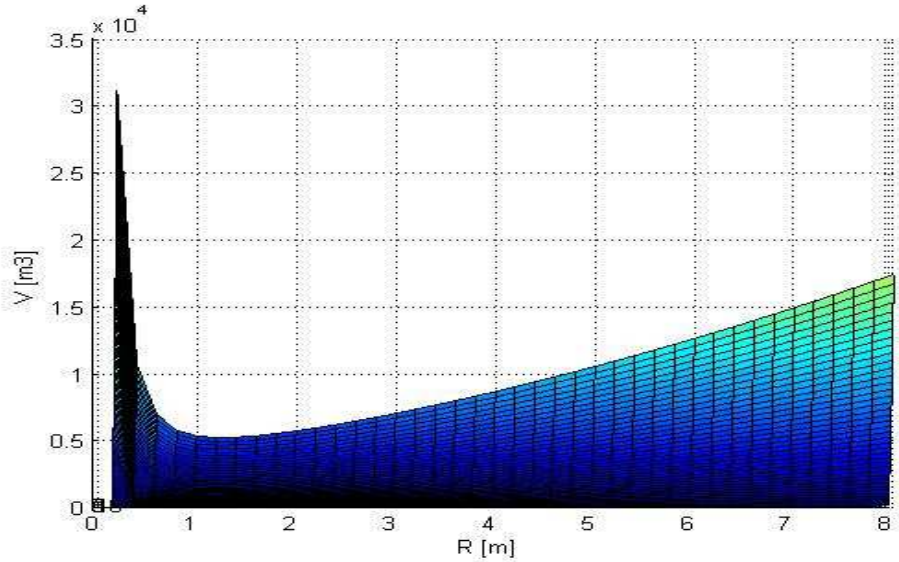

Figure 30 Shield Volume versus radius

Resulting in a α of approximately 2,8 to 2,5 depending on the thickness of the shield, for this α -range 1-3 m.

5.4 Shielding

The effectiveness of the shield can be calculated using Sabine 3. Sabine is a fortran code originally written by C. Ponti, H. Preusch and H. Schubart and was written in 1967. The Program was written for a IBM 7090 (see picture) or 360 (Ponti [1967]). A shield geometry as well as a core description can be inserted and the program calculates the fluxes and the doses throughout the shield. The program uses removal-diffusion techniques for neutron calculation, build-up factors are used to calculate the gamma-radiation. The program was originally designed for BWR's and PWR's but seems applicable for a HTR as well, not all materials are fully available for calculation, but with some estimations a good result can be obtained.

Figure 31 IBM 7090 computer

The core is set at a radius of 1.23 meter and with a height of 2,97 meter, see also figure 32. The reflector has to be simulated first in the design of the shield. The reflector is assumed to be 1 m. wide. The Fission rate density is assumed as 1,04 x 10^{11} Fissions/cm^3/s, which is equal to 3 MW/m^3. The core and shield are assumed to be cylindrical. These assumptions are kept constant and further only the shield geometry is changed.

The maximum dose for a radiation worker should be 100 mSv per 5 years.
Assuming that the personnel does only come up to 2 meters from the reactor shielding wall in the reactor room delivers an reduction in radiation level:

$$\frac{\dot{D}_{r_2}}{\dot{D}_{r_1}} = \frac{r_1^2}{r_2^2} = \frac{4^2}{6^2} = \frac{16}{36} \approx \frac{1}{2}$$

The personnel employed on the ship are not always aboard the ship, the assumption is made that they are only about two third of the time aboard the ship.
The time they spend near the reactor will also be smaller if it is positioned in the middle of the ship. Assuming that they spend 70 % of the time in the superstructure of the ship at a distance of approximately 50 meters from the reactor will result in additional reduction. This results into the following:

$$\frac{\dot{D}_{max.allowed}}{\dot{D}_{actually\ received}} = \left(\frac{1}{2/3}\right)\frac{1}{\left(70\,\%\,\frac{4^2}{50^2} + 30\%\,\frac{4^2}{6^2}\right)} = 10,88$$

So the maximum dose rate at the edge of the reactor can be approximately 11 times higher than maximum allowed dose rate for a radiation worker this results in a dose rate of 218 mSv/year at the edge of the shield which is equal to 0,02485 mSv/hr. This should be a pessimistic figure according to expert opinions.

A simplified model will be used to estimate the weight of the shield: consisting of a cylinder topped by two half spheres:

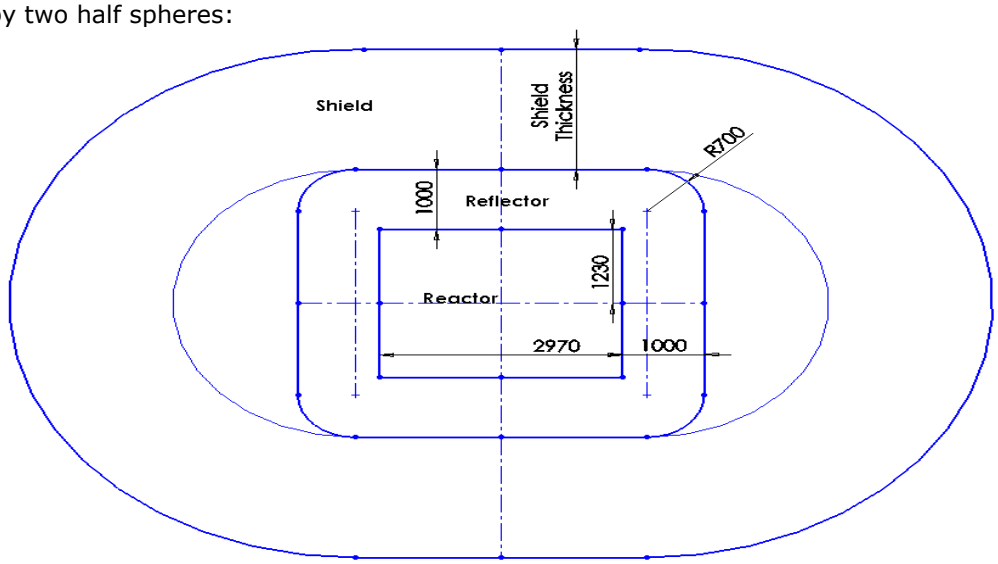

Figure 32 Simplified shield geometry

The weights produced from this calculation will divert from further estimations because of the simplified geometry.

A shield Geometry with more variation can give more insight in the different influences of material. The following graph is of a shield (with the reflector) composed of: 100 cm of graphite (reflector), 30 cm of boron, 10 cm of iron, 120 cm of water, 30 cm of iron and 10 cm of lead.

Figure 33 Graph of neutron flux in shield of combined materials

The boron gave the large dip in the thermal neutrons, as can be seen this is not really effective and the effect can be obtained with iron as well. Water seems not so effective but keeping in mind that

the density is only 1,00 ton/litre and very low cost of this material it is still a serious option for usage in a reactor.
A strange effect occurs in the end where more 'mid area' neutrons are created; this is exactly the part where iron is used as end shielding with a last layer of lead.

Keeping in mind the high temperature of the reactor (1000 °C), renders the option of water as a shield as a troublesome option. A leakage in the shielding or overheating resulting in loss of shielding, can result in non-workable situations due to high radiation levels.
First attempt was a shield combined of graphite and steel:

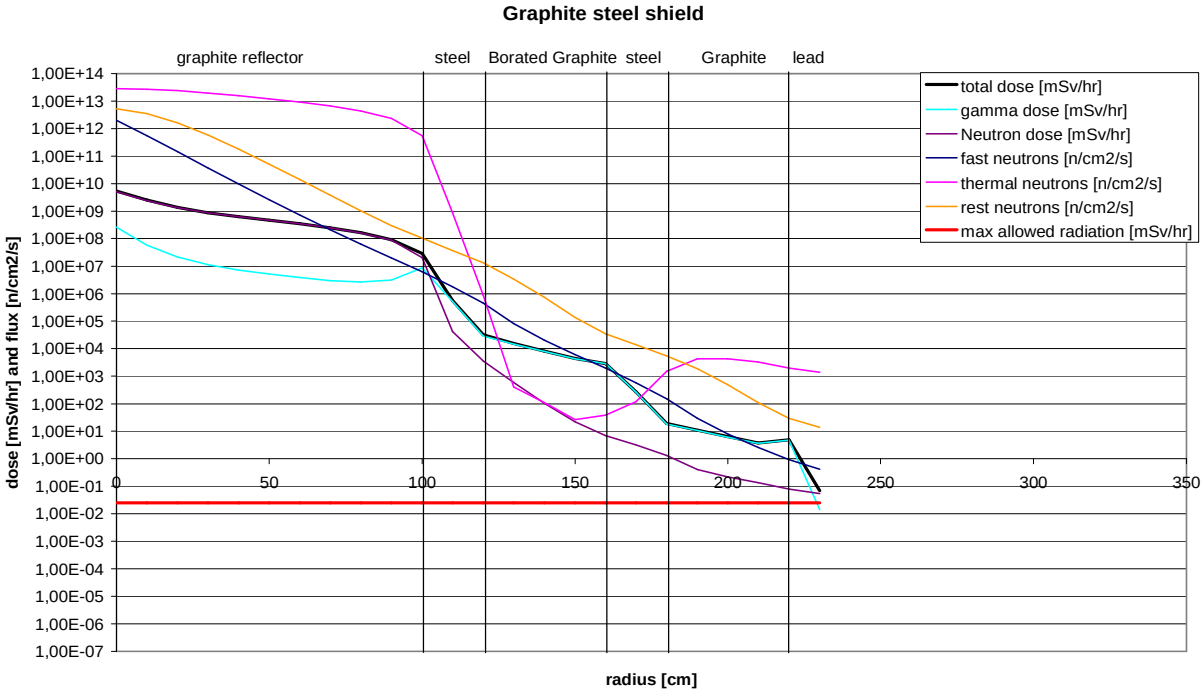

Figure 34 Graph of radiation doses for Graphite steel shield

Layer	material	density	thickness	inner x	outer x	Cor H	volume	weight	remark
		ton/m3	m	m	m	0,8	m3	ton	
Core	Mix	1,895	1,23	0	1,23		14,10	26,72252722	
1	Graphite	2,267	1	1,23	2,23		63,50	143,95	reflector
2	Steel	7,87	0,2	2,23	2,43	3,37	23,51	185,03	
3	Graphite +	2,3	0,4	2,43	2,83	3,37	57,09	131,31	
4	steel	7,87	0,2	2,83	3,03	3,37	33,98	267,44	
5	Graphite	2,267	0,4	3,03	3,43	3,37	79,84	181,00	
6	steel	7,87	0,1	3,43	3,53	3,37	22,58	177,72	
7	Graphite	2,267	0,4	3,53	3,93	3,37	101,57	230,25	
8	steel	7,87	0,1	3,93	4,03	3,37	28,33	222,93	
9	Graphite	2,267	0,4	4,03	4,43	3,37	125,80	285,19	
10	lead	7,87	0,1	4,43	4,53	3,37	34,70	273,09	
	total		4,53					2125	ton

Table 5 Weights for reactor with graphite steel shield

Combining Graphite with a material with a high Z-value (protons in nucleus) does not give a satisfactory solution. Graphite does not lower the neutron dose in a satisfactory manner to result in a low weight, small sized shield. As can be seen from the graph the neutron dose is leading and is not shielded satisfactory to get obtain a smaller shield geometry.

The second attempt was a shield constructed of a steel vessel to contain the core. After this steel vessel 2 kinds of concrete were used. The first layer is a heavy concrete: a Magnetite combination with steel with a density of 4,634 ton/m^3.
The second layer was a standard lightweight concrete (NBS 03) with 2,393 ton/m^3 resulting in the following graph.

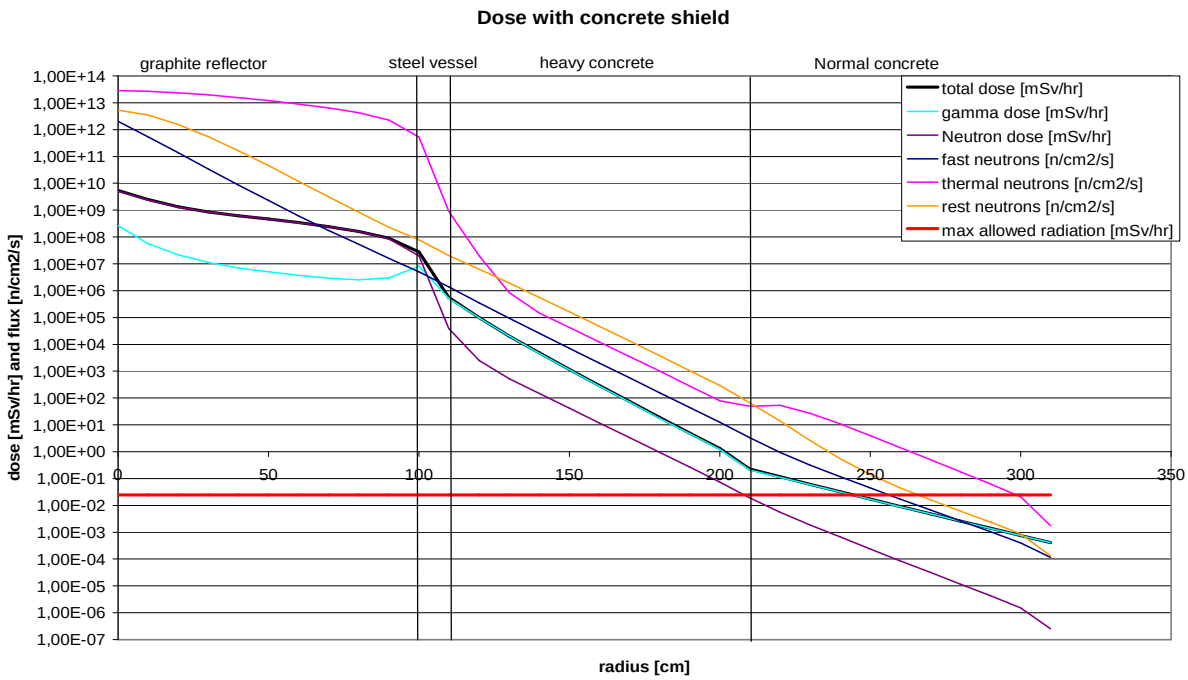

Figure 35 Graph of radiation doses for combined concrete shield

Table 6 Weights for reactor with combined concrete shield

Layer	material	density	thickness	inner x	outer x	Cor H	volume	weight	remark
		ton/m3	m	m	m	0,8	m3	ton	
Core	Mix	1,895	1,23	0	1,23		14,10	26,72253	
1	Graphite	2,267	1	1,23	2,23		63,50	143,95	reflector
2	steel	7,87	0,1	2,23	2,33	3,37	11,36	89,38	
3	heavy concrete	4,65	1	2,33	3,33	3,37	161,56	751,25	
4	normal concrete	2,393	0,35	3,33	3,68	3,37	80,03	191,51	
	total		3,68					1203	ton

Using only heavy concrete results in the following graph.

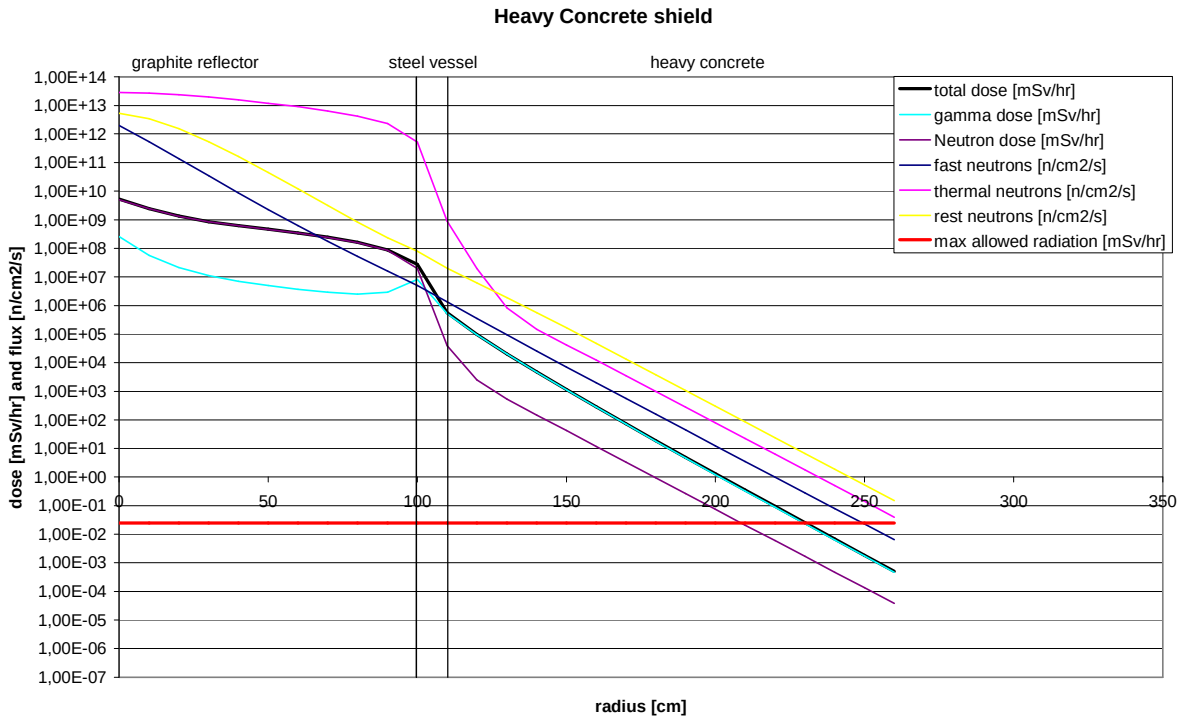

Figure 36 Graph of radiation doses for heavy concrete shield

Table 7 Weights for reactor with heavy concrete shield

Layer	material	density	thickness	inner x	outer x	Cor H	volume	weight	remark
		ton/m3	m	m	m	0,8	m3	ton	
Core	Mix	1,895	1,23	0	1,23		14,10	26,72253	
1	Graphite	2,267	1	1,23	2,23		63,50	143,95	reflector
2	steel	7,87	0,1	2,23	2,33	3,37	11,36	89,38	
3	heavy conc	4,65	1,2	2,33	3,53	3,37	205,65	956,27	
	total		3,53					1216	ton

Conclusion: the concrete shielding delivers the most compact and light weight geometry for the reactor using normal concrete at the outer radius gives an additional reduction of 10 ton.

As can be concluded from the graphs the gamma radiation is still the determining factor for the total dose. Adding another material in the concrete with a high Z-value could further decrease the size/weight, for example lead could be used.
This might be material for further research. For further research it is also recommended to use a more up to date method; for example a code based on the Monte Carlo method, this should give a more precise prediction of the dose rate. The Sabine code is a good start for estimation, but for further variation on shielding not sufficient.

In the first part of this chapter certain assumptions are made in accordance to the radiation to be received by the crew. These assumptions are pessimistic according to expert opinion, for example crewmembers will only be in the vicinity in the reactor in the harbour when the reactor is on low power or shut down. Still the question remains is this as low as reasonable practicably?
Lower radiation levels are achievable by adding more shielding material. The price that is paid for adding extra shielding material is extra volume and extra weight, so less income and extra construction costs. It is not practical to add more weight because it will become too hard to transport the reactor for refuelling.

5.5 Reactor Design

Following the examples of the reactors all ready in use, the helium will first loop through the reflector before entering the central core, cooling the externals of the reactor. The reflector is assumed to be 1 meter wide. The lower reflector edges are rounded to keep everything as small as possible.

The PBMR design from South Africa uses an 18 cm thick reactor vessel, this leads to a stress level of approximately 88 MPa with a pressure of 40 bar within for this design, when using a pure cylinder as estimation. The PBMR design delivers more power with a larger reactor so this thickness will be used although this leads to high stresses according to the estimation.

Using the geometry as calculated for the shielding results in a steel vessel with 1,2 m concrete around it. While sketching the forms for the reactor, the size was kept as small as possible. In the upper part of the reactor, room is reserved to withdraw the control rods. Control of the reactor is obtained by rods that can be inserted into the reactor by pneumatic pressure limiting the height of the construction(the software used to model this was Solidworks). Caution should be taken; this is a mere estimation of the overall sizes of the reactor. An actual design will result in a different geometry, because of multiple possibilities for optimization. The used method resulted in the following model for reactor including the shielding on the following page:

Figure 37 Reactor with concrete shielding

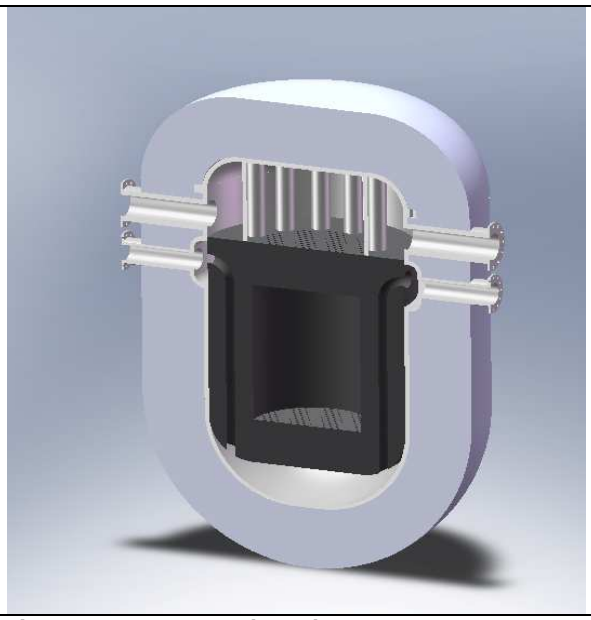

Figure 38 Reactor Cut through

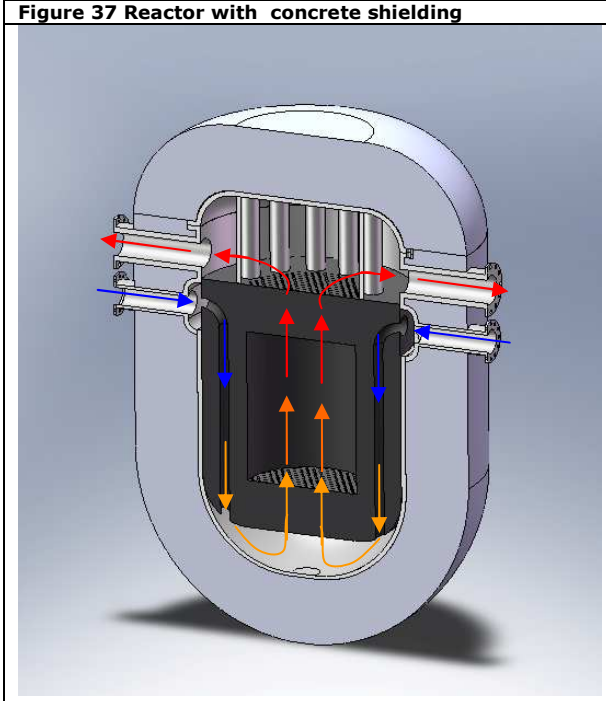

Figure 39 Reactor Cut Through with flows indicated

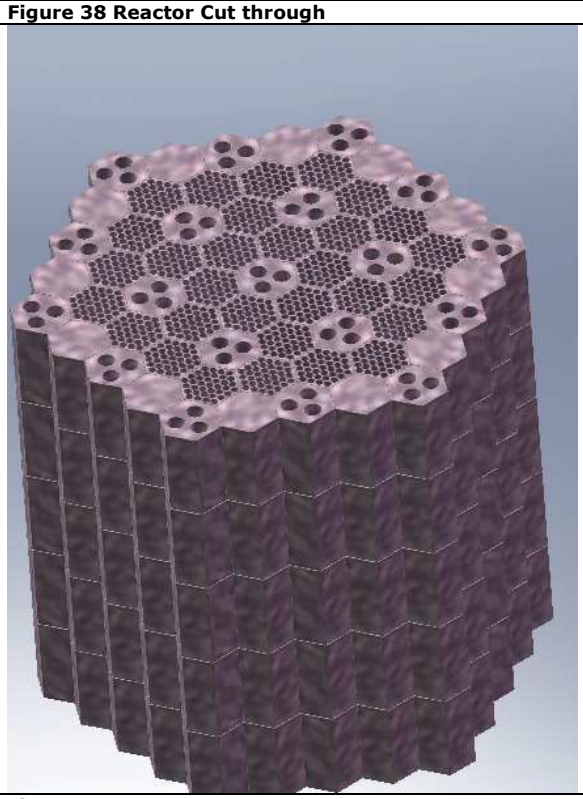

Figure 40 Reactor core

Resulting in a total height of 11,55 meter and a width from flange to flange of 8,7 meter, where the rest of the shielding has a diameter of 7,22 meter. Next are some exploded views of the whole assembly:

Figure 41 Exploded view reactor

Figure 42 Exploded view reactor

This design leads to the following weight list:

Table 8 Weightlist Reactor

Part	Material	Volume	density	Weight	
unit		[m^3]	[ton/m^3]	ton	
Vessel Bottom	steel	24,6	7,87	193,6	ton
Vessel Top	Steel	8,65	7,87	68,1	ton
Shield Bottom	Heavy concrete	161,6	4,634	748,9	ton
Shield Top	heavy concrete	45,87	4,634	212,6	ton
Reflector	Graphite	52,84	2,267	119,8	ton
	Mix	14,1	1,895	26,7	ton
	graphite	11,6	2,267	26,3	ton
	U235	0,001	19,1	0,02	ton
Core	U238	52,83	19,1	0,36	ton
					+
Total				1370	ton

The reactor design can be further optimised by acknowledging that less shielding will be necessary at the bottom of the reactor. Another possibility to further decrease of the size of the reactor is

possible in the variation in thickness of the reflector, this was estimated fairly high with 1 m. Thicknesses for other larger reactors are reported as 80 cm. Smaller control rods will also decrease the height of the reactor.

5.6 Heat exchanger design

5.6.1 Heat exchanger type

The heat exchangers must be capable of coping with the high temperature that comes from the reactor. According to Verkerk [2000] peak core temperatures of 1400 °C can be reached in extreme conditions for a direct cycle, although this could be prohibited by applying active control rods.

Figure 43 Schmidt heat exchanger SIGMA 156 http://www.apischmidt-bretten.de

There are sources which state that it would be possible to have plate heat exchangers at higher pressures: Smeding [2001]. Here the maximum values are mentioned to be higher then found anywhere else posted on the websites of heat exchanger manufacturers. Smeding states that a plate heat exchanger can have a maximum pressure of 25 bar and a maximum temperature of 900 °C, these figures were based on numbers from Alfalaval and Thonon according to the source.

Shell and tube Heat exchangers are definitely capable of handling the necessary high pressures and temperatures.
There are also solid block heat exchangers available, but these are not yet reported with high pressures and high temperatures. This seems simple in production but is likely to be very heavy. Material used in these type of heat exchangers is graphite.

Figure 44 Solid Blok Heat exchanger

The only problem with these heat exchangers is that part of the high temperature is lost. A recuperator does not have such high peak temperatures and can be made of plate type heat exchangers, which have a higher efficiency thus higher end temperature, but also higher pressure losses.

5.6.2 Material Selection

High Temperature Resistant steel, or also known as Hasteloy, Inconel or 2111 HTR, will be able to handle these high temperatures, but the yield strength will drop at higher temperatures to significantly lower numbers, but still feasible to work with. The figures found for creep strength render it nearly impossible to make a commercial heat exchanger with maximal creep strength of 15 N/mm^2 at 900 °C and 29 N/mm^2 at 800 °C. Creep strength at higher temperatures is subject for further investigation.

Graphite as a material would be nice because of the high thermal conductivity, but gives problem due to oxidation with normal air and is not able to cope with high stresses caused by the high pressure differences.

There are large ongoing research programs busy (for example Hechanova [2005]) which investigates the possibility of ceramic materials in heat exchangers like Silicon Carbide (SiC). These investigation give promising results for the future, even oxidation is prevented by using coatings. Using this material in a plate heat exchanger could result in a lightweight and highly efficient heat exchanger. But this is surely not state of the art at the moment. For now HTR steel is chosen because of proven technology, although the problems with creep need to be investigated further.

5.6.3 Modeling a shell and tube heat exchanger

Assumptions for modelling a heat exchanger:

-the thermal conduction is assumed linear over the material in the direction in which the heat is transferred.
-no heat conduction in the other directions

From these assumptions, a model for the heat exchange can be constructed and an approximation of the dimensions and weight can be made. (See appendix N)

The free variables which can be altered are length of the tubes(L_t), Amount of tubes (N_{tubes}), the Outside diameter (D_o), and the distance between the centers of the tubes (P_t). The pressure loss in the heat exchanger should not be too high or no power would be left for the propulsion of the ship. Weight is another limiting factor because of the high price. An evaluation between weight and pressure loss should be made to obtain a reasonable solution.

The tube lengths will be set at 10 meter, shortening does not have a positive effect on the heat exchanger and elongating results in troubles fitting the heat exchanger into the ship. Varying the tubes for commercial tube sizes and a required heat transfer of 19,4 MW (required heat transfer not taking into account any pressure losses) delivers the following table for the 2 heat exchangers:

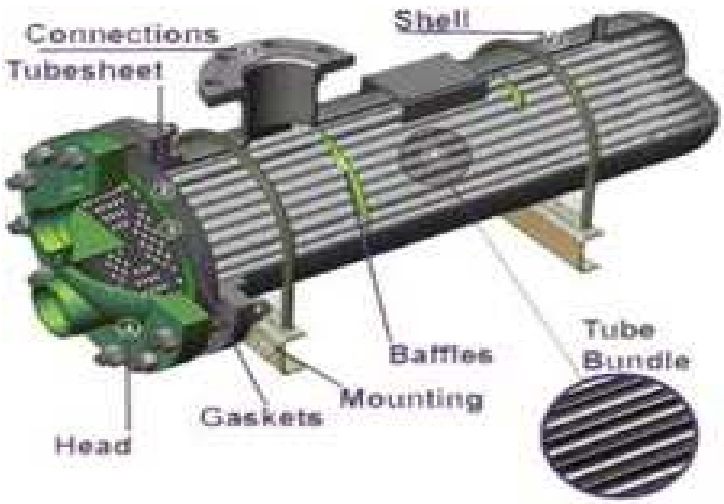

Figure 45 Shell and tube Heat exchanger

Table 9 Different sizes Shell and Tube heat exchangers

Helium-Nitrogen heat exchanger					
Length tube	Lt	m	10	10	10
Outer Diameter	Do	m	0,0127	0,0254	0,0508
Thickness tube	tt	m	0,000253	0,000507	0,001013
Inner Diameter	Di	m	0,012447	0,024893	0,049787
Shell thickness	ts	m	0,024326	0,063579	0,162737
Total weight	mtotal	ton	8,364694	95,40742	1259,75
amount of tubes	N_{tubes}		3302	5635	9236
Nitrogen-Air heat exchanger					
Length tube	Lt	m	10	10	10
Outer Diameter	Do	m	0,0127	0,0254	0,0508
Thickness tube	tt	m	0,000121	0,000242	0,000484
Inner Diameter	Di	m	0,012579	0,025158	0,050316
Shell thickness	ts	m	0,019212	0,062199	0,18081
Total weight	mtotal	ton	11,9388	270,2485	5703,368
amount of tubes	N_{tubes}		7571	19748	41913
Pressure drop	dP	bar	4,63	1,04	0,144586

From table 8 the problem is clearly visible that the weight dramatically increases for decreasing pressure drop. Another observable fact is that the helium-nitrogen heat exchanger is significantly smaller than the nitrogen-air heat exchanger.

1 inch tubing seems the most feasible although this also results into a very high weight, the pressure loss results into additional losses in the gas turbine increasing the weight even more. A recalculation taking the pressure losses into account with the 1 inch tubing delivers one set of heat exchangers of 585 ton => 1170 ton for the total set.

This is not a feasible solution at 60 € per kg material this would result into a total cost of 70,2 M€ for the heat exchangers alone.

Changing to a helium-helium-air loop with 1 inch tubing could significantly lower the weight reducing cost for the heat exchangers. Using this results into a weight of 286 tons which results in a cost price of approximately 17,2 M€ is still very high. Smaller tubing results into losses that can not be compensated.

5.6.4 Modeling a plate heat exchanger

A plate heat exchanger should be more compact because of the enlarged heat transfer area. Various designs are possible here, but these are not yet state of the art. After evaluation of the model prescribed by Kakaç [2002] (see appendix O), it became clear that the pressure drop and

heat transfer are highly dependent on the port diameter, the amount of plates, the amount of passes through the heat exchanger, the angle of the channels in the plates and the length an width of the plates.

Assuming the height and width of the plates, the pitch of the channels, thickness of the plate and the port diameters the same as for the maximum reported by Smeding [2001], and trying to keep the length of the heat exchanger below 10 m, again using the helium-helium-air loop results in 2 light weight heat exchangers. 35,29 ton per set, thus a 70,58 ton. Using the same material price as the shell and tube heat exchanger leads to a cost price of 4,23 M€, in this case a small addition for the labor must be added. The size of the small heat exchanger (helium-helium cycle) would be approximately 3,1 meter long (with the given maximum height of 3 meter and a width of 2 meter). The second heat exchanger (helium-air) would result into a length of 9,4 m.

The maximum output reported by Smeding is 10500 kW, which is half the power as needed for this system. This can be evaded by using 4 sets of heat exchangers. Using 4 heat exchangers adds some weight; 4 plate heat exchangers would result in a total weight of 75 ton with a material price of 4,5 M€, labor costs should also be added here. The size of the small heat exchanger (helium-helium cycle) would be approximately 1,7 meter long. The second heat exchanger (helium-air) would result into a length of 5,1 m. Note the large difference in size, the heat transfer in high pressure helium is far more greater then in the low pressure air. This same effect is seen for a comparison between helium and nitrogen.

The pressures in combination with the temperatures in the system are still too high for this kind of heat exchangers additional research will be necessary to prove the feasibility of this type of heat exchanger in this case.

From these evaluations it seems that 2 additional heat exchangers for recuperating the exhaust heat, would add significantly in weight and pressure loss because of the low temperature difference in comparison to the other heat exchangers. Brugiere et al [2007] came to a design of a 200 ton recuperator for an 80 MWth reactor for a closed cycle. The system evaluated in the report is a closed direct cycle; higher pressures and higher temperature differences and less pressure losses by a heat exchanger. A recuperator in the system used in this report would increase the pressure drop, lowering the efficiency more then it improves by the recuperation of the energy in the exhaust.

5.7 Exhaust

The distance from the main deck to the top of the container stacks is 15,82 m. The exhaust stack has to overcome this distance to blow out the high temperature without heating the containers or surrounding materials.

Pressure drop is calculated using the formula for piping:

$$\Delta p = 4 f \frac{L}{d_i} \frac{\rho U_m^{\ 2}}{2}$$

With Reynolds defined as:

$$\mathrm{Re} = \frac{U_m \rho d_i}{\mu}$$

Where the fluid velocity is given by the mass flow:

$$U_m = \frac{\dot{m}}{\rho A_{exhaust}}$$

With the fanning factor as shown in the figure 46.

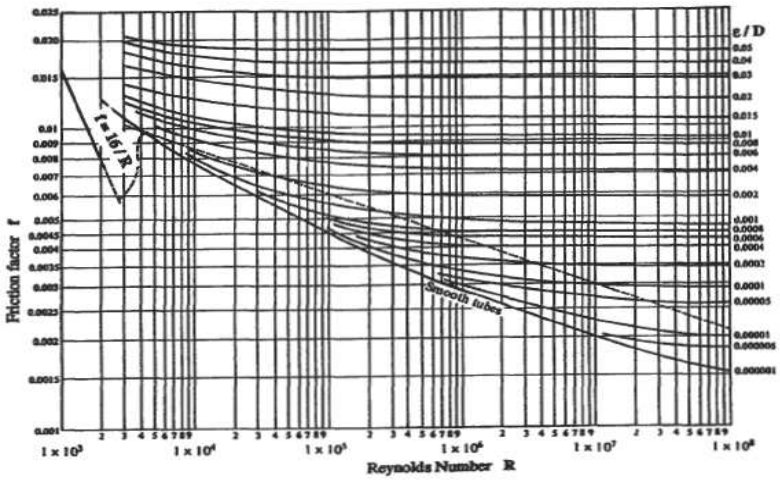

Figure 46 Fanning Factor vs Reynolds (Pope [1996])

This results into a pressure drop $1{,}57 \cdot 10^{-4}$ bar for a 2 meter diameter exhaust, which is equal to a pressure drop ratio of 0,99985.

The high temperature (380 °C) exiting from the exhaust can lead to problems, sailing in the harbour underneath a bridge or crane with small clearance could lead to damage or even injury if someone stand on the overlapping construction. Special consideration for this should be taken

possibly preventive measures by mixing extra cool air with the air coming from the turbine lowering the overall exhaust temperature. Operation below overhanging cranes and bridges could lead to safety issues. An exhaust temperature of 390 °C in the vicinity of other construction which are not constructed for this load can lead to unacceptable situations and should be considered during design. Normal exhaust temperature of a diesel can also be high and is not considered to be a problem.
It might be necessary to install an extra blower cooling the exhaust flow, this will considerably add in the resistance of the pipe, doubling the mass flow leads to a resistance increase of 250 % and quadrupling the mass flow leads to an increase of 1100%. Still the pressure ratio for the exhaust will only be 0,998, which is low in comparison to the estimated pressure losses for the silencer and exit velocity.

Additional pressure loss can be expected due to a silencer and the exit velocity loss this is normally estimated as a loss of 0,01 bar.

5.8 Inlet

Gas turbines are highly sensitive for the salt and water content of the air used, filters are necessary to remove water and salt from the air inlet. The flow velocity through such a filter should be between 3 and 5 m/s. This leads to a necessary surface of 2 x 15,8 m^2. Pressure drop is normally between 0,015 and 0,03 bar.

5.9 System integration

Combining the different models leads to the total static system interaction for full power.
For the heat exchanger a plate type is chosen because of the large difference in weight, although these heat exchangers will have to be developed specifically for this purpose.
The necessary output of the gas turbines is corrected for the additional power needed to pump around the fluids in the primary and secondary loop minus the necessary power for the main engine support for the conventional diesel system which requires an additional 125 kW for the chosen size of the heat exchangers.
Pressure losses in the tubes between the reactor, the heat exchangers and gas turbines are considered to be small enough to be not considered at all.
The total system efficiency results into 20,76% using the variables as given for the different models in the appendices, including the added resistance due to a necessary ships elongation. The ideal pressure ratio in this case for the compressor of the gas turbine is 10,4, which is a normal pressure ratio for gas turbines in this power range. In this case a normal conventional gas turbine without combustion chambers can be applied no exotic solutions will have to be found to make it work. Extending the model with a recuperator, see Figure 26, leads to an extreme large recuperator or unacceptable pressure losses leading to lower or even negative efficiencies, which is off course unacceptable for a costly addition to the cycle. This is only valid for this configuration, a closed cycle with recuperator may have a different effect on the overall efficiency.

To comply with all the demands the gas turbines will have to be insulated to dampen the high frequency sound. Constructional vibrations passed on will be high frequency and will normally be out of range of the eigen frequencies of the construction. The reactor compartment needs to be cooled to comply with the maximal room temperature of 45 °C, all parts will radiate heat and this should be dissipated to stay below the prescribed temperature. The reactor compartment will probably also need to be sealed air tight to comply with foreseeable regulations creating an additional barrier between the outside environment and the reactor. Further demands will probably have small influence.

6 Safety & Emissions

6.1 Safety

The safety of a nuclear reactor on board a ship depends on events that can damage the reactor in a certain way and is quantified by the risk that is involved, where risk stands for the probability that an event occurs times the damage of the outcome. Possible events will be described in the following text:

6.1.1 Stranding

Stranding of the ship will deform the hull, if the reactor is fully attached, or integrated into the hull the vessel can be damaged by the forces exerted on it (See figure 47). Placing the reactor in some sort of pedestal, combined with rupture disks in the connecting pipes, will prevent this from happening.

Figure 47 grounded "Alva Star"

6.1.2 Hull penetration by incoming object

Penetration of the hull by a bulbous bow can have different effect: It can punch through the hull or/and locally deform the hull. Additional measures can be taken to prevent damage. The Otto Hahn had "cutting decks"; the decks surrounding the reactor were so ridged that they would cut an incoming object into pieces, creating a larger surface resulting in less penetration (Dukert [1973]). Another possibility is to use Y-shaped frames. Multiple tests have been undertaken for this sort of sandwich material and the elastic energy absorption has been proven (for example Pedersen [2006]). These forms of protection are very case specific so to evaluate these requires a finite element evaluation which is not in the scope of this report.
Hull penetration by rock beneath the water can result in leaks along the ship with the risk of flooding the reactor compartment.
A falling container from above can also damage the reactor compartment. The ceiling of the reactor should be able to handle the impact of a falling container without damaging the reactor. The maximal weight is 30,5 ton for a 45 foot container, also 30,5 ton for a FEU (Forty foot Equivalent Unit) and 24 ton for a TEU (Twenty foot equivalent Unit). Limitations on weight are mostly caused by the limitations for road transport.

Damages exerted on a ship like the cases above can be made less dangerous by applying a strong sandwich construction which can handle a large deformation before collapsing entirely.

There are Japanese rules developed to which a cargo ship for nuclear fuel/waste has been developed. PNTL (Pacific Nuclear Transport limited) has special designed ships to meet all the stringed demands for the transport of nuclear fuel and waste, which should be comparable to the demands to a nuclear ship in case of hull damage.

6.1.3 Capsizing & Sinking

Capsizing as a result from for example damaged tanks or an uneven cargo distribution will result in a heeling angle plus the risk of flooding or even sinking.
Heeling is not a particular worrying phenomenon, changing the direction of the reactor will have no effect on the reactor itself.
Sinking caused by above or other reason can result in a flooded reactor compartment with high pressure build up from the outside environment. A reactor should be able to cope with the pressure build up without exposing the primary loop, or should be able to take in water without damaging the fuel.

Figure 48 Capsize of "Dongedijk"

6.1.4 Fire

Fire should be suppressed as soon as possible. The reactor should be able to cope with high temperature without collapsing and exposing the primary loop. An additional fire resistant layer can give a solution, together with the normal necessary fire fighting equipment for an engine room

such as automatic CO_2 fire extinguishers, or maybe even a normal sprinkler installation no burnable fuel is present. When applying water based fire suppressing systems, the dangers of spraying on oil from the surrounding machinery should be investigated

6.1.5 Terrorism

Terrorism can be expected in different ways from small missile attack to explosives or kidnapping of the crew and vessel. This is hard to predict because people are very innovative in finding ways to destroy things. The double hull in combination with the thick radiation shielding gives a good protection against single small missile attacks. Explosives placed on the reactor shielding should not damage the internal structure of the reactor, the thickness of the radiation shield should be sufficient to cope with this kind of threat. If the terrorist have knowledge about the operation procedures of the reactor, they could short circuit the safety measures and if the reactor has a surplus of reactivity they could cause extreme temperatures of above 2000 °C in the reactor. This will damage the fuel particles and will release fission products into the primary loop in combination with a leak these could escape into the environment, resulting in danger for the public health. The possibilities of shortcutting the installation from its safety measures should be made practicably impossible. A fully passive reactor (without regulating control rods, only on/of rod) would not have this problem, but for coastal services it is not practical to have a passive reactor, because of the Xenon poisoning and thus the start up availability. The Royal Dutch Navy has done extensive research on the effects of shocks and blasts and the prevention of these, although classified this knowledge could be obtainable.
Alarms with a connection to shore should be placed to warn for kidnapping or other terrorist activities, so preventive measures can be taken from ashore.

6.1.6 Safety wrap up

In all events above the reactor should scram. Several buttons to manually scram the reactor should be placed aboard, as well as automated scram signals on measurable events not belonging to the normal operating conditions. Automated triggers could for example be: reactor temperature, reactor compartment temperature, Heel angle in both directions of the parallel plane, pressure in reactor, pressure in secondary loop, pressure in reactor compartment, radiation measurements across the ship, abnormal accelerations etc.

Additional quick emergency valves where the primary loop leaves the reactor vessel could prevent the contamination of the environment. Gašparović [1971] describes in his promotion articles the pro's and cons of a direct helium cycle, resulting in a negative advice because of the probability of insulation that could shatter due to sudden temperature changes in the primary loop, raising the need for quick shutting valves. And quick means here: closing in the order of milliseconds, this was considered by Gašparović as impossible. It might not be necessary to use such quick valves when using a material capable of handling such high temperatures without insulation, research to the available valves in combination with necessary shut down time should be done.

6.2 Salvaging the reactor

As part of the safety, it should be possible to salvage the reactor when all measures have failed and the ship is lost, without polluting the environment. To salvage a reactor there are 2 possible scenarios: salvage a reactor when it is still in the wreckage or salvage a reactor that is kept afloat in the sea.

6.2.1 Pulling the reactor from the wreckage

When the reactor must be pulled from the wreckage the reactor should be able to withstand the pressures differences underneath the sea without collapsing entirely and it should be able to isolate the reactor from the sea environment. The pressure build up from the outside is ρgh, approximately 1 bar per 10 meter. The ship operates only in the North Sea where the maximum depth is 660 m. sinking completely to the bottom a maximum pressure of 66 bar can be build up. It is easily possible to construct a vessel that is capable of handling these pressures. Disconnecting the pipes to the primary heat exchanger will keep the primary loop closed, this can be done by tactically placing rupture discs in the piping. Constructing the restraints of the reactor to collapse under a certain force, not expected during normal operation, can decouple the reactor from the wreck. Hoist rings to connect the pulling mechanism should be positioned on accessible places to ensure easy access for a diving robot. Disadvantage is that a part of the original construction surrounding the reactor should be removed to extract the reactor. And specialized equipment is

necessary to execute such an operation. The vessel would not be suitable to operate in deep waters, this will not be acceptable in a lot of cases.
If the fuel is capable of handling water ingress the reactor could be fitted with salt plugs to enable the ingress of water when submerged.

6.2.2 A floating reactor compartment

The reactor by itself is too heavy to stay afloat; it is possible to construct a vessel around it which can keep the whole afloat. To keep a reactor of 1500 ton afloat a volume of 1463 m^3 is necessary in seawater, for fresh water this off course would be 1500 m^3. A sphere would be ideal, but is too difficult in integrate within a conventional ship.
Disadvantages of a separate construction are; the possibility that it cannot break loose from the wreckage while sinking, when it also leaks due to deformation or some other reason, it will sink with the rest of the ship. And the extra weight of the construction for the compartment in combination with the extra construction necessary to support the extra gap in the ships construction. The floating compartment should also be picked up as soon as possible before something happens to it, collision with an unsuspecting ship or being washed against the shore or rocks.

Another possibility to create extra volume to keep the reactor afloat is making a collar of inflatable cushions that generate the extra needed volume, like a sort of airbag (See figure 49). The volume of the reactor components is 364 m^3 with a total reactor weight of 1520 ton a minimum additional volume of 1156 m^3 is needed in fresh water. To keep the system redundant 6 different cushions can be installed and with which the reactor can keep afloat with two third of the cushions still intact. Making six cushions adding an extra 4,5 meters to the diameter of the reactor results in an extra volume of 1880 m^3. It is necessary that the reactor will be outside the ship when these airbags fill up, for this system to work. Another possible risk in the system is failure due to the continuous radiation exerted on the cushion material and possible changes in it. Although this is outside the shielding due to the design life of 25 years this should be researched.

Creating rupture discs in the pipelines and some small explosives to create overpressure to eject the reactor from the containing structure will help the reactor to exit the ships structure. After the ejection the cushions should inflate rapidly, this can be done in the same way airbags in cars are filled: with small explosives.

The last solution would result in the lowest effort to retrieve the reactor when the ship is lost, but has the possibility that the system might not work in all conditions. It is easier and more feasible to salvage the reactor by pulling it from the wreckage.

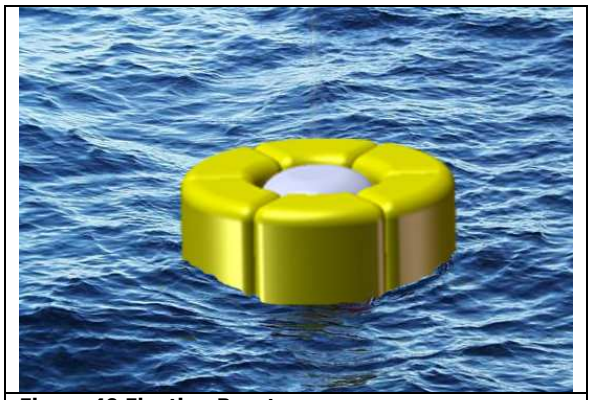

Figure 49 Floating Reactor

6.3 Decay Heat

After complete shutdown considerable heat is produced, which must be removed to ensure the safe continuity of the reactor. Decay heat produced is given by the following formula (Knief [1992]):

$$\frac{P(t)}{P_0} = 6,6 \cdot 10^{-2} \left(t^{-0,2} - \left(t + t_0 \right)^{-0,2} \right)$$

Table 10 Heat Generation after shutdown reactor

Time after shutdown	% of original heat
1 second	5,82%
10 seconds	3,38%
1 minute	2,13%
1 hour	0,515%
1 day	0,053%
1 week	0,0063%
1 year	0,000006%

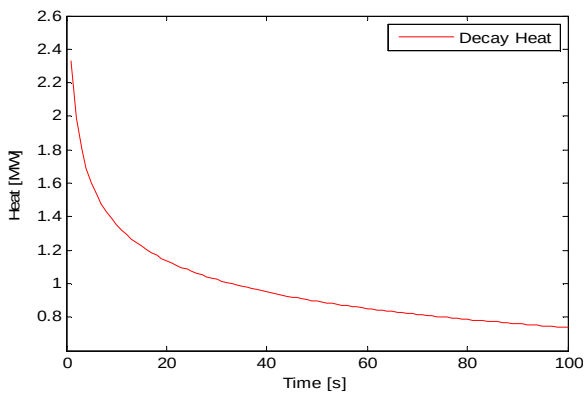

Figure 50 Graph of decay heat

For a 40 MW reactor running for 12 hours with a sudden shutdown this results in figure 50; Graph of decay heat.

This heat should be removed in a passive way, during normal operation this can be done by building ventilation shafts allowing for air running along the sides of the reactor. During normal operation this would result to losses in the order of approximately 2 %, although this can be reduced by using active valves on the venting shafts.

After an accident which results in the sinking of the ship, the heat should still be removed. This heat removal can be done through the same ventilation shafts which are now filled with seawater which has a much larger heat capacity, so no problem expected here. Possible pressure build up by steam creation should be avoided by allowing it to escape using a duct geometry which allows volumes with an upward draft to escape positioned in every possible angle.

6.4 Steam production in a flooded reactor

There is approximately 150 tons of graphite in the reactor, if water rushes into the reactor due to an accident steam can be formed, this can have dramatic consequences due to the sudden pressure rise or even a steam explosion. A first estimation of the production of steam is presented here.

The International Nuclear Safety Center has a formulation for the enthalpy [kJ/kg] of graphite on its website:

$$h(T) - h(298{,}15) = -1446{,}04454 + 2{,}023145T + 3{,}9322 \cdot 10^{-5}T^{2}$$
$$+4{,}26709 \cdot 10^{5}T^{-1} - 6{,}60145 \cdot 10^{7}T^{-2} + 3{,}9963 \cdot 10^{9}T^{-3}$$

If the mean temperature of the core would be 1000 °C the available energy to boil water would be:

$$E = \Delta h_{graphite} m_{grafite} = (981{,}11 - 60{,}71) \cdot 10^{3} \cdot 150.000 = 138{,}6 \cdot 10^{9}\,\mathrm{J} = 138{,}6\,\mathrm{GJ}$$

Water needs to be heated to 100 °C and should evaporate to form steam. The heat of vaporization is 2.260.000 J/kg + difference in enthalpy heating the water from 25 – 100 °C . This results in:

$$\frac{E}{m_{water}} = \Delta h_{T} + \Delta h_{vaporization} = (419{,}84 - 63{,}937) \cdot 10^{3} + 2.260.000 = 2.615.903\,\mathrm{J/kg}$$

So the latent energy in the graphite could boil approximately:

$$m_{water} = \frac{138{,}1 \cdot 10^{9}}{2{,}616 \cdot 10^{6}} = 52790\,\mathrm{kg\ water} = 52{,}8\,\mathrm{ton\ water}$$

This is a rough approximation not keeping in mind the extra pressure. This will have only little effect on the difference in enthalpy, the heat capacity coefficient c_p is relative small for water in comparison to the necessary heat for vaporization. The overall temperature of the graphite is chosen high; the outer reflector will have a lower temperature then the inner core which will decrease the effect of steam formation. In this case the decay heat is not taken into account, which adds to the effect of steam formation.

The formation of Carbon monoxide from the reaction between water and Graphite is not taken into account:

$$C + H_2O \rightarrow CO + H_2$$

This reaction can form additional gas and by that also additional pressure.

The formation of such a gargantuan amount of steam indicates the possibility of steam explosions which could destroy the containment of the fuel if water rushes into a hot reactor. Proper research should be conducted to investigate the dangers of a steam explosion if the reactor is suddenly flooded.

A reactor cooled with a liquid metal would actually perform better here, the metal would quickly solidify and seal of the reactor. A pressurised water reactor would also perform better, it is designed to operate at lower temperatures and to withstand extreme high pressures, reducing the risk of perforation or some other cause of leak and when the primary circuit has a leak the water in the primary circuit will form steam at the leak blowing outward.

6.5 Emissions

Nuclear power is known for its emission free energy production, but normally a nuclear power plant has a fully closed cycle and only exchanges heat through a cooling medium with the environment.
Air is heated in the open cycle gas turbine to temperatures higher then normally done for only cooling. Normal constituents of air are nitrogen, oxygen, argon and carbon dioxide. Heating of air is known to promote NO_x formation, but as a rule of thumb (Turns [2000]) a temperature below 1800 K is considered as an unimportant contribution. Checking this rule of thumb:
The greatest impact would be formed one of the formulas; the nitrous oxide formation reaction rate from the extended Zeldovich mechanism, the reverse reaction would be negligible because the total concentration mixed in the environment is too small.

$$\frac{d[NO]}{dt} = 2k_{1f}\left(\frac{K_p P^o}{R_u T}\right)^{1/2}[N_2][O_2]^{1/2}$$

With

$$k_{1f} = 1{,}8\cdot 10^{11} e^{\frac{-38{,}37}{T(K)}}\left[\frac{m^3}{kmol\cdot s}\right]$$

Equilibrium concentrations given in [kmol/m^3]:

$$[N_2] = \chi_{N_2}\frac{P}{R_u T} = 0{,}79\frac{10\cdot 101325}{8315\cdot 1100} = 8{,}752\cdot 10^{-2}\left[kmol/m^3\right]$$

$$[O_2] = \chi_{O_2}\frac{P}{R_u T} = 0{,}21\frac{10\cdot 101325}{8315\cdot 1100} = 2{,}326\cdot 10^{-2}\left[kmol/m^3\right]$$

$$k_{1f} = 1{,}82\cdot 10^{14} e^{\frac{-38{,}70}{1100}} = 9{,}57\cdot 10^{-5}\left[m^3/kmol\cdot s\right]$$

$$K_p = \frac{P^2{}_O}{P_{O_2}p^o} = e^{\left(\frac{-\Delta G^o{}_T}{R_u T}\right)}$$

$$\Delta G^o{}_T = \left[2g^{-o}_{f,O} - 2g^{-o}_{f,O_2}\right]_{1100K} = 2\cdot 181{,}263 - 0 = 362{,}526\,kJ/kmol$$

$$K_p p^o = e^{\left(\frac{-362{,}526}{8315\cdot 1100}\right)} 1[atm] = 6{,}12\cdot 10^{-18}[atm] = 6{,}20\cdot 10^{-13}\,Pa$$

Resulting in:

$$\frac{d[NO]}{dt} = 2\cdot 9{,}57\cdot 10^{-5}\left(\frac{6{,}20\cdot 10^{-13}}{8315\cdot 2500}\right)^{1/2}\cdot 8{,}752\cdot 10^{-2}\cdot\left(2{,}326\cdot 10^{-2}\right)^{1/2} = 6{,}649\cdot 10^{-16}\left[kmol/m^3\cdot s\right]$$

As can be seen this is time dependent, long time in high temperature will lead to NO formation, but is still of no significant contribution here. The residence time in the system will be somewhere between 2 to 10 seconds. One mole of nitrous oxide is 30.006 g. Assuming a 10 second cycle results in:

$$10[s]6{,}649\cdot 10^{-16}\left[kmol/m^3\cdot s\right]30{,}006[kg/kmol]\frac{41{,}23[kg/s]}{1{,}1691\left[kg/m^3\right]} = 7{,}04\cdot 10^{-12}[kg/s]@\,4370kW$$

In this case there are 2 such gas turbines which results per energy unit:

$$\frac{2\cdot 7{,}04\cdot 10^{-12}[kg/s]}{4{,}370\cdot 10^6[J/s]2{,}78\cdot 10^{-7}[\text{kWh/J}]} = 1{,}16\cdot 10^{-11}[kg/kWh] = 1{,}16\cdot 10^{-8}[g/kWh]$$

For a diesel engine this is 11,78 [g/kWh]. A diesel engine normally must comply to the ISO 8217 standard which demands for fuel a maximum of 5 % $mass_{emissions}/mass_{fuel}$ sulphur, 0,15 % Ash content and 22 % Carbon residue with a fuel consumption of 178 g/kWh.
All in all is the NO_x emission of the nuclear installation not significant in comparison to a diesel engine. Normal operation will not lead to further polluting emissions, except for the emissions caused by construction.

CO_2 emissions are said to be 1 ton per ton concrete, the shielding consists of 961,4 ton concrete. For 25 years of sailing an energy amount of $1{,}92\cdot 10^8$[kWh] is necessary; this results into 5,02

g/kWh. For steel this is approximately 1,85 ton CO_2 per ton steel, the weight of the reactor vessel is 261,7 ton, the weight of the heat exchangers is 74,9 ton plus some additional piping and the additional weight of the extra construction minus the weight of the original diesel engine this is approximately 535 ton extra steel which delivers 2,79 g/kWh. A grand total of 7,81 g/kWh is to be expected in comparison to the 3.114 ton CO_2 per ton HFO of the diesel engine which uses 178 g/kWh HFO thus 554 g/kWh CO_2 on fuel alone.

There is large discussion about the fairness of these kinds evaluation, concrete production with energy from nuclear power plants could be emission free, but unfortunately concrete factories are still equipped with fossil fuel fired burners and steel is still fabricated from cokes. Normally a nuclear plant also has a design life of longer then 25 years extending the life of the reactor by placing it in a new hull will also lower the emissions by extending its productive life. Still the CO_2 emissions would decrease significantly in comparison with the diesel plant, for a larger nuclear plant this increase would even be greater because of the relative more delivered power in comparison with its size.

7 Changes in ship design

The original Container Feeder: 800 TEU, 140,6 m long and 21,8 m wide (see for other main dimensions appendix M) has to be changed to fit the complete installation, the different demands have to be met, which are evaluated in the following paragraphs.

7.1 Ship dimensions according to IMO

Placing the reactor at least outside the by IMO pre-described damage zones will ensure the containment of the reactor.
So the minimum longitudinal distance from the moulded shell to the reactor should be:

$\frac{1}{3}L^{\frac{2}{3}}$ =9,33 m.

The minimum transverse distance from the moulded shell to the reactor should be:

$\frac{B}{5}$ = 4,36 m.

And the minimum vertical distance from the moulded shell to the reactor should be:

$\frac{B}{15}$ =1,453 m.

The height of the double bottom is 1,5 m which has the necessary tolerance.
With a diameter of approximately 8 meter the reactor will have 6,9 meter tolerance on both sides of the ship.
Placing the reactor amidships will meet the longitudinal requirement easily.

Further advice is given on calculations for collisions with a ship of equal size and speed, a very large crude carrier (VLCC), a high speed ship with a fine bow and a collision with a fixed object of infinite mass. These are not unreasonable demands as can be seen from figure 51; The 337 m long MSC Joanna crashing its bulbous bow in the Fairway of 232 m long.

Figure 51 Collision of large Container Ship with large dredger

A finite element calculation would be necessary to evaluate the damage caused by such collisions. Following such evaluation the structure can be altered to partially resist these types of damages, with for example y-shaped frames or cutting decks as with the Otto Hahn.

Current class societies have not yet produced regulation under which a nuclear vessel can be certified. New certification rules with objective regulations are necessary for a workable environment. The industry cannot produce a nuclear vessel when it does not know exactly to what rules it must comply. Uncertainty about regulations which are the design boundaries will not lead to a satisfactory design.

7.2 Ship Design

Altering the configuration of the ship, while keeping the same hull form, can lead to multiple concepts. Positioning the superstructure a bit backwards so there is room for extra hatches will allow for some additional container slots in the first hold right before the superstructure, see figure 52. Placing the superstructure more forward will result in extra possible container slots at the stern. Another possibility is to set the superstructure above the forward fuel tanks from the conventional ships. For the last two concepts the hull construction, has to be changed, strengthened, to accommodate the additional moment and shear force created by the extra containers at the stern. The ship is always in hogging modus due to the sharp form of the hull, putting additional

containers on the stern will add extremely to this hogging modus, which is already is a tight fit in the original conventional diesel powered ship.

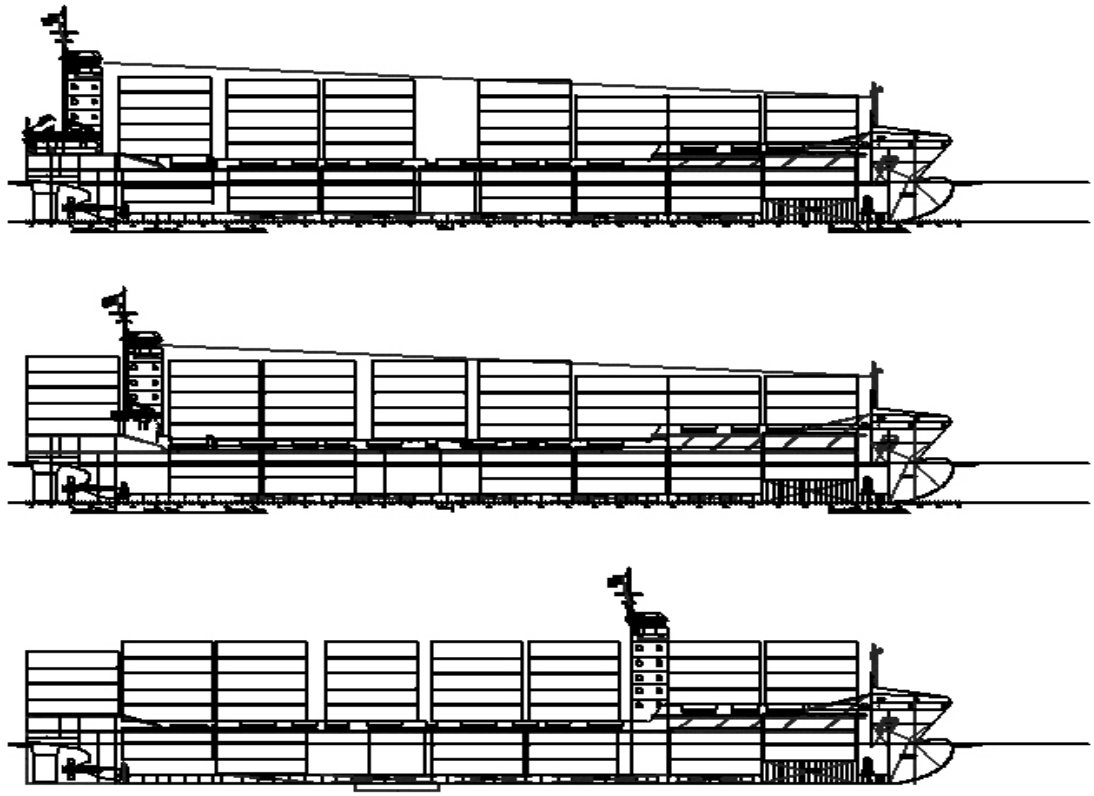

Figure 52 Possible Configurations

For simple cost comparison the configuration of the ship will be kept the same as much as possible. The ship should be slightly altered to fit the necessary equipment in the middle of the ship. The reactor should be approachable from above for the refuelling sequence. The hatch covers need room above the main deck to give space for the folded condition.

To meet these demands we need to elongate the ship for at least the diameter of the reactor. This results in an elongation of the midship section of 11 frames mounting up to 8,69 meter. This results in a total length of 149,3 m, an additional displacement of 1350 m^3 and an estimated extra 183,5 ton construction weight. Elongating the ship midsection also has a slight effect on the resistance; it increases with 2,5 %. This was recalculated using the Holltrop and Mennen module from the program PIAS (designed by SARC).
The elongation results in the following geometry, see figure 53, in comparison to the original design:

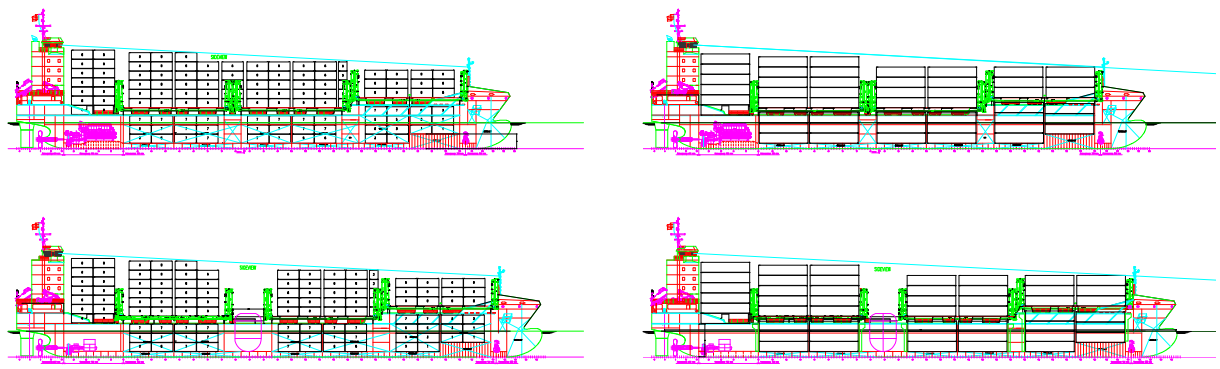

Figure 53 Original configuration and Elongated model

With the extra space created, the gas turbines and heat exchangers can be fitted alongside the reactor. The gas turbine should be at least above the heat exchangers, preferable just below the main deck, to ease the possibility of necessary periodic overhaul. Pumps for the flow will be integrated in the pipelines, these are not modelled in the figures from the engine room. The layout

of the engine rooms is made to fit within the additional available space. The layout is depicted in the figures (54-56) below.

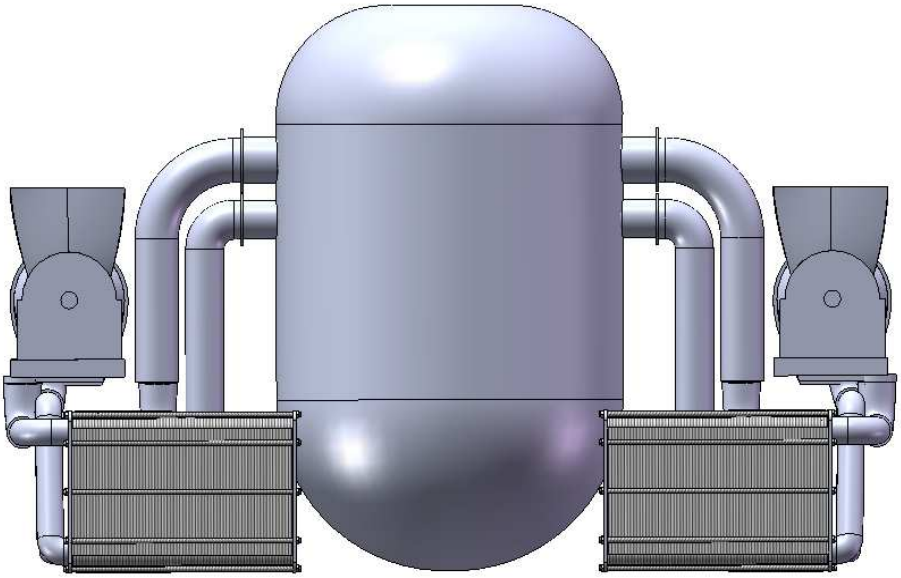

Figure 54 engine room model front

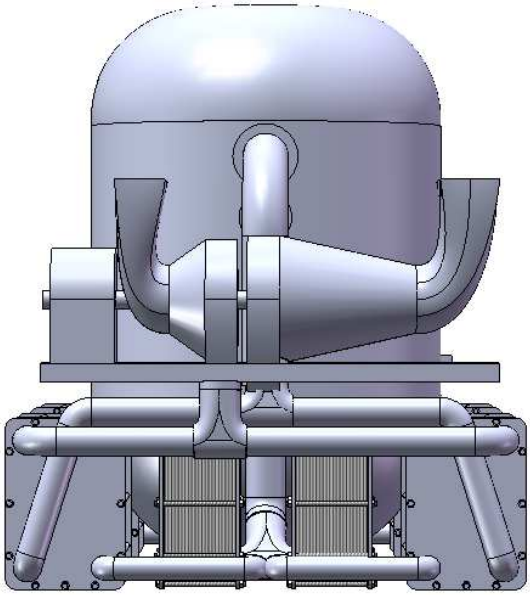

Figure 55 Engine Room model sideways

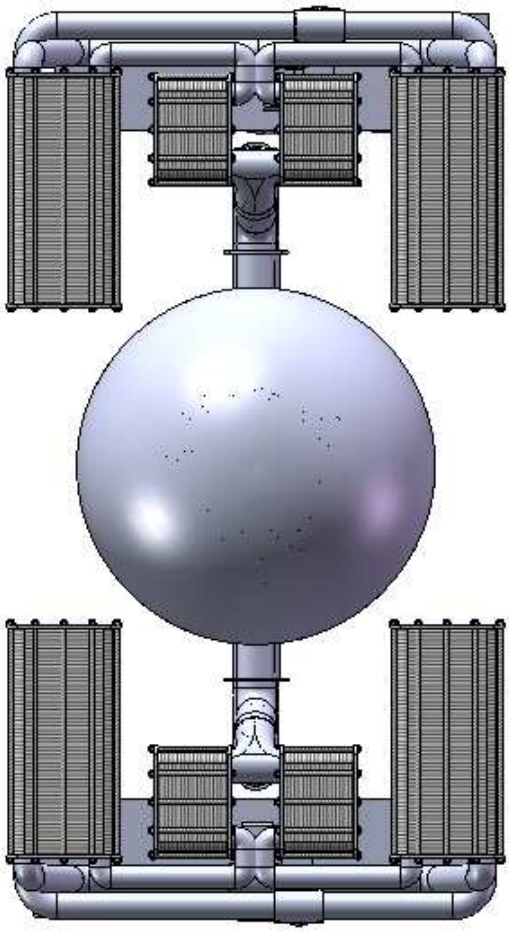

Figure 56 Engine room model bottom

Adding this to the elongated hull results in the following (figure 57) 3d-design:

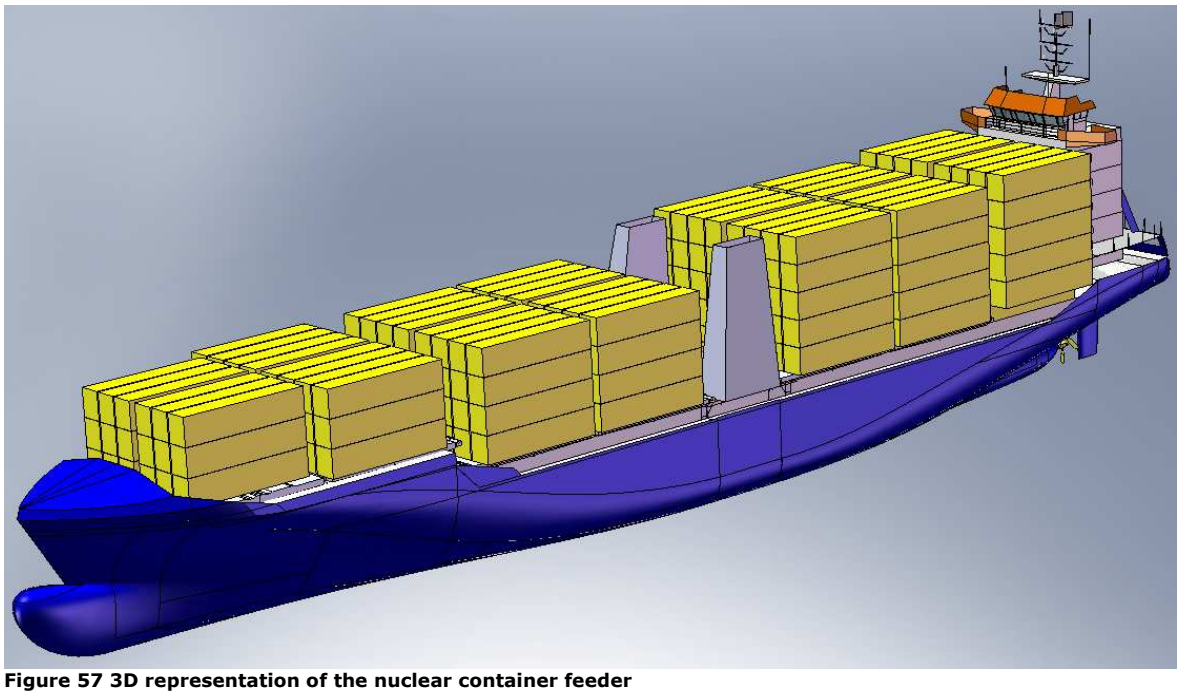

Figure 57 3D representation of the nuclear container feeder

The dense layout of the reactor compartment is not clearly visible but there is not a lot of space available when all necessary equipment is placed in the reactor compartment. The entrance to the reactor compartment is pretty tight; just before the funnel construction above the generator connected to the gas turbine is space to position a stair downwards.
The reactor compartment compared to the historical nuclear ships is a lot smaller the reactor compartment itself takes only about 10 % of the length of the ship.

The necessary power for propelling the ship at 6 knots is 555 kW, approximately 230 kW is necessary for emergency condition during maneuverings. The 685 kW can be provided by the 2 433 kW originally installed generators and the emergency generator, in case of emergency this will be adequate.

Using this geometry delivers a ship has almost the same characteristics as the original design. 9 TEU container slots were lost, but the design of this ship is based on 45 foot containers and the amount of these slots are the same.

The moment in the ships hull is actually less then the original design, due to the sharp form of the ship and the large water plane area amidships it is always in hogging modus. The extra weight in the middle of the ship lowers the moments exerted on the ship. The shear force in the hull is also lower due to less hogging, see appendix R.

A lot of space is created at the place of the original location of the diesel engine, see figure 58. A large part of this space is not really necessary aboard the ship, and is not large enough to fit extra containers. It is necessary to maintain the main deck because of dynamic stability, applying extra hatches, just in front of the super structure, would result in an additional necessary elongation of the ship for only 4 additional 45' containers, which is not really worth while.

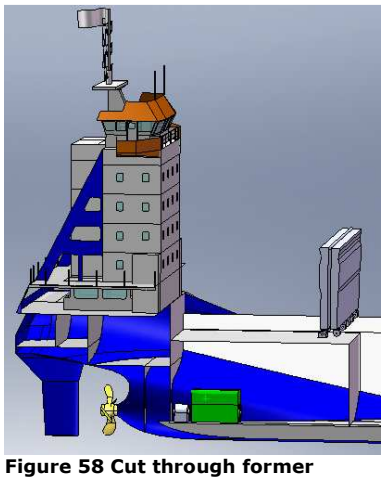

Figure 58 Cut through former engine room

A possibility to fit extra containers above the electro motor exists, but has the disadvantage that the ship has to be elongated for an extra 2,5 meters to fit the extra hatch covers necessary for this configuration. An open configuration resulting in a possible "swimming pool" is not desirable because of the possibility of stability loss and capsize as happened with the "Dongedijk" (See figure 48).

Moving the superstructure to another position could result in a

more efficient distribution.
Another possibility would be to alter the propulsion to 2 pods. This would add in manoeuvrability and redundancy. For this propulsion the stern of the ship would be altered into a more barge like form. After a short inquiry this seems for now a too expensive solution; an approximate extra € 4.000.000 investment would be necessary for such configuration.

To obtain the most optimal design for a nuclear ship it should be redesigned from the keel upward and not derived from an existing ship. The configurations used are optimized for diesel engines, for example: the locations of the hinges of the hatches are right above the fuel tanks, which leads for the nuclear coaster to a void space which is not optimally used. If the reactors height was lower or the main deck higher the hatches could be folded above the reactor, which leads to less void spaces.

8 Necessary infrastructure

8.1Building the ship

The ship can be build in a normal yard, only the nuclear reactor itself needs extra facilities. A conventional ship of this size is produced to be fully operational when it leaves the yard where it was build. Towing a ship of 149 m LOA over a long distance is an expensive business, but not uncommon. Everything up to the reactor vessel can be installed in a normal shipyard without additional problems. Only the insertion of the fuel should not be attempted at a normal shipyard, because of the necessary highly specialized equipment and trained personnel.

8.2 Refueling

For refueling there are 2 options: refueling in the ship itself or changing the reactor for a spare one which then can be refueled in a special land based installation.

In case of the first option, an installation is necessary to fill the core with the hexagonal blocks containing the fuel. The installation should be positioned on top of the reactor, to be able to replace and rearrange the core composition.
This installation should be installed on the ship in an enclosed building to minimize the contact with the outside world. Or the installation should be able to remove the top of the shielding and the top of the reactor vessel. It is hard to automatically remove the shield top and vessel top with the two funnels besides the reactor. Removing one of the funnels would allow for extra operation room.
Removing the top of the reactor can prove problematic because nobody can come near the vicinity to check the operation and solve problems when they occur. In a PWR or BWR the reactor can be flooded with water with an additional shielding layer of water on top. This enables the possibility to look into the reactor and work above the reactor without the problems of high radiation.
The graphite should not be flooded with water because of possible problems when not all the water is extracted afterwards.
The refueling installation should be operated by remote control, because of the hazardous radiation when the top of the shield is no longer in place. The hexagonal blocks are easy to remove and place because of the fuel handling holes in the top of the blocks.
This is an elaborate way to refuel and hard to control when parts of the refueling engine fail.

The second option involves a land based installation, like a normal nuclear plant as in figure 59. A crane will be necessary in the dock to change the reactor, and a platform on which the reactor can be transported to the land based refueling installation. A spare reactor will be needed to minimize the time of the ship in the dock.
The land based installation should be able to take of the top of the shielding and remove the top of the reactor vessel. Some sort of overhead crane could be constructed to enable this ability; the fuel can be easily hoisted from the reactor using a specialized tool which fits exactly in the holes prepared in the hexagonal blocks. Placing the reactor on a mobile platform enables an extra safety feature; the reactor can be transported to another room within the building, where the radiation will not do any damage in case of failure of the refueling installation. Redundancy is key in a refueling installation; the installation cannot be repaired if some part of it fails because of the radiation levels. The building containing the refueling installation can also hold the radioactive waste until its ready for permanent storage.
Building this installation near the vicinity of the dry dock will evade the foreseeable problems with transport of the reactor to the refueling installation.

Figure 59 Fuel handling floor HTTR

The additional costs will be: a building holding the refueling installation with additional room for spare reactors, this can be compared to building a new HABOG (Hoogradioactief Afval Behandelings en Opslag Gebouw, High radioactive waste treatment and storage building), the costs of a 1600

tons crane (or a set working in tandem to create the same capacity) and the purchase of a heavy transport vehicle possibly on rails for transport.

For the cost of HABOG (figure 60) different values are mentioned: from 120 to 230 M€ in publicized news articles (NRG website). HABOG is based on an already existing French design (2 build in France and 1 in Belgium and 1 in The Netherlands: Vlissingen). Additional design costs should be incorporated for the design of the building and the necessary installations. This will probably lead to approximately 300 M€ including the refueling installation.

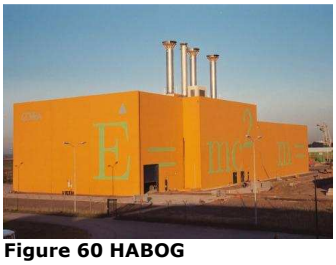

Figure 60 HABOG

The reactor weighs approximately 1550 tons. A crane with that capacity would be a large cost post in the infrastructure. Cost of such crane capacity would be in the order of 30 to 40 M€. Dividing the shield into 2 parts, from which the inner part can shield the radiation which comes from an inactive reactor can reduce this weight, this option will need further research; it could dramatically decrease transport costs.

Figure 61 Scheurle heavy transport

A heavy transport vehicle including capable of carrying the necessary weight over a short distance would be some sort of modular transporter consisting of 4 to 6 modules (like produced by Kamag or Scheuerle, see figure 61) capable of carrying the reactor and a construction holding the reactor like a sort of saddle. This would cost approximately 20 to 30 M€. Ground preparation will also be necessary to ensure stable transport.

All together this results into an approximate cost of 350 to 500 M€ for the necessary infrastructure.

After refueling the fuel is not necessary totally depleted. A land based reactor which re-uses the fuel and is able to extract the remaining energy to the maximum could be profitable. In this case this possibility is not investigated further.

8.3 Location

Combining production and maintenance facilities in one yard would be the most ideal situation with the lowest infrastructural costs. Disadvantage is the higher cost of producing a Casco in The Netherlands.

To fit the whole ship in a dock it would be necessary to have a dock of at least 160 meters. But keeping in mind that it could become a growing business it is preferable to have a larger dock for future prospects.

Location of infrastructure will also be expensive in the Rotterdam harbor area. Another location, preferably an existing yard in an area with low population density would be better. A possibility is dock 2 of the Royal Schelde in east Vlissingen (see figure 61 and 63), with a length of 215 meter a width of 30 meter and a depth of 13 meters it would easily fit the coasters. Additional advantage is that the dock is covered by a hall, keeping the weather elements outside. The hall is equipped with 2 x 75 ton cranes which can be combined for a hoist of 150 ton.

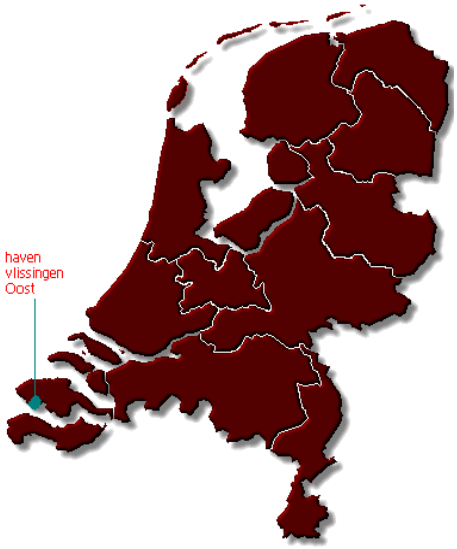

Figure 62 Location Harbor Schelde Oost

Figure 63 Overview Harbor Vlissingen Oost

Updating this dock with new cranes to be able to place the reactor in the vessel would increase the capabilities of the dock. Question off course is if this is possible in combination with the rest of the structure. Some extra buildings to repair and keep the reactor components will be necessary; the COVRA is near the location which would be ideal for eventual waste and intermediate fuel storage.

In the harbor no extra infrastructure is necessary; there would be no refueling or maintenance what so ever on the reactor. Safety measures are a different story.

The necessary equipment in short: a building with installation for the refueling, a crane capable of placing the reactor machine and a heavy transport vehicle with a saddle to transport the reactor from the dock to the refueling station.

8.4 Disassembly

After a productive life of about 25 years the ship will have to be disassembled, fatigue and corrosion will have taken their toll. The hull and superstructure can be scrapped without any problems.
After removing the used fuel the reflector, the reactor vessel and the shield will still be radioactive and should be treated as light radioactive waste. The materials used will be affected by the neutrons which were captured, activating the atoms inside. A proper evaluation should be performed to asses the radioactivity and the duration of the decay inside the different components. Normally in a land based plant the reactor and all the equipment will be kept onsite until the radioactivity of the different parts is dropped below a prescribed level. Some parts will be ready for demolishing after a short period. The reactor and directly surrounding equipment will take longer; as in multiple years.

For the closed nuclear plant at Dodewaard this is for example 40 years, after this the building and all the equipment will be fully demolished and the land will be available for new build or other purposes.

A safe rest place for the reactor should be found for such duration. The terrain of Covra would be ideal again to temporarily store the reactor parts until the radiation is negligible. Only problem is the transportation to the site due to the enormous weight.

8.5 Waste Treatment

The used fuel needs to be stored. This can be done in different ways. The fuel elements can be packed and stored immediately without reprocessing. This will ensure a more voluminous package of waste because of the additional graphite stored extra in this way.

Another possibility is pulverizing the compacts and reprocessing them as it is done in la Hague for fuel elements from conventional nuclear plants. Separation of the different elements will greatly reduce the volume of the high level waste. At this moment no method to do this is devised, because the availability of fuel wrapped in TRISO elements is too low for a specialized reprocessing plant.
The advantage of using a reactor with low power density is that no special arrangement has to be made to transport the internal generated heat. This makes storage much easier.

8.6 Permanent storage

Dumping radioactive waste into the sea was done from 1946 up to 1993 and from then on forbidden by the so called "London Dumping Convention" signed by Countries members of OSPRA consisting of Belgium, Denmark, Finland, France, Germany, Iceland,
Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom. The last reported dump was done by the Russian federation in the Japan Sea/East Sea. High dangers of corrosion and erosion and no possibility to check and retrieve failing containments, are huge disadvantages of dumping at sea.

At this moment there is an on going discussion about the pollution of reprocessing plants into the nearby environment. All though not at the same scale as nuclear waste is produced this is still a problem.

Underground storage is a largely debated subject. There exist plans for storage in salt domes in the Netherlands. These salt domes appear to be the most stable underground layers. Protests against this form of storage are large. The environmental movements argue that storing below grounds will eventually stop the controlling of the waste due to for example budget cuts. Storing above grounds would give an extra incentive to search for a better solution. There are also reports found on salt reacting and destabilizing due to the radiation. And of course there are a large number of protests about the locations proposed, also known as NIMBY's (Not In My Back Yard).

Supporters of the idea of storing below grounds argue that the risks of something happening to the waste below grounds are less then above ground, if stored in a stable environment. Changes over a period of thousands of years are unpredictable, complete cultural or climate changes can be expected. Permanent storage should be able to cope with all these changes and still protect the environment from its contents.

Former head of CORA (Commission Storage Radioactive Waste) Ir. Hageman suggested in 2000 a storage facility in salt layers in the North Sea by building an artificial island. When this is forgotten or swept away by natural disasters the waste will be stored in a location which is very hard to reach for future unknowing passing parties.

Main stream thought is that the radioactive waste should be retrievable. This serves many purposes: Possible repair of the containment in case of damaged containment; possible transmutation of the waste in the future; possibility to measure the effects (hard in laboratories); possibility to alter storage when a better solution is found.

There is also an incentive towards an international joint radioactive waste storage facility to lower the cost for such a facility, but larger difficulties can be foreseen for the choice of a location for such an international storage.

At this moment there is no acute need to store nuclear waste underground for the Netherlands, because of the low volume. A part of the cost of the nuclear fuel is the waste management of the fuel and is paid in advance to funds which use this for permanent solutions when these are decided upon. There is at least enough money available to store the waste in salt domes for now.

8.7 End solution?

Some people say that the nuclear waste of today is the fuel of tomorrow. This could be partly true, but then new reactors that use U^{238} should be used; so called breeder reactors. These reactors give

a very durable system, but have also greater risk when operated. Research is done to accelerate protons into a reactor where it shatters another atom into multiple atom fragments (spallation) to maintain the process with a reactor which is in nature subcritical, this system is called an Accelerator driven system (ADS). This could provide a safer reactor which could "burn" the nuclear waste of today.
But this is not yet state of the art. The reactor which was build (and never used) in Kalkar was a fast breeder reactor, the plant was closed due to incomplete safety procedures and political aversion. Another part of the problem is that plutonium is bred which can be used for nuclear weapons, when segregated from the rest of the material.

There is a Global Nuclear Energy Partnership (GNEP http://www.gnep.energy.gov) trying to set up a system delivering and retrieving nuclear fuel; reprocessing, separating and burning (with a fast breeder reactor) the waste in the USA ensuring non-proliferation in the countries it services. This might be the solution for tomorrow and beyond, ensuring a low impact on the environment.

9 Costs

The cost comparison is done on the cost differences in the installation and fuel, the rest of the ship costs are not taken into account, except for the additional costs for the elongation. Cost estimates are calculated in euros.

9.1 Cost Build up

The costs are depending on a various amount of variables which all interconnect in some way, an overview of some connections (figure 64) between the main components illustrates this fact.

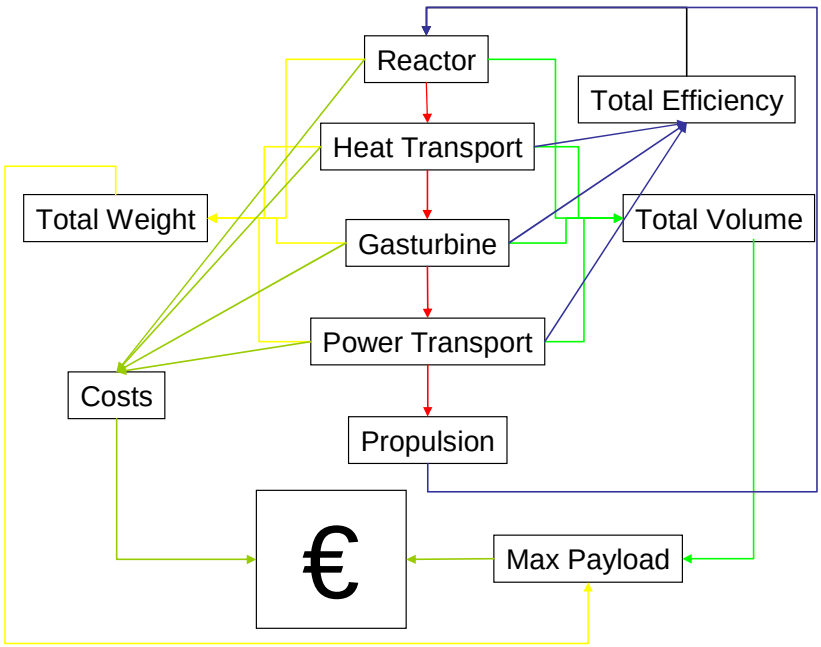

Figure 64 Schedule Possible Cost buildup

The costs for the nuclear power unit can be divided in different ways for example in operational, capital, maintenance and interest cost. These can be further subdivided to different parts, for example capital costs: fuel, shielding, piping, reactor control apparatus, gas turbine, heat exchangers and safety measures. Further subdivision is also possible.

Additionally to this, the difference in the amount of cargo carrying capability is very important calculating the profitability for commercial use. Less containers onboard is less income per trip. The design is adopted in such a way that the amount of 45 ft. containers is the same as in the design for the conventional containership, no difference in income will interfere cost comparison. Some positions of 20 ft. containers were lost, but these ships are specially designed to contain the maximum amount of 45 ft. containers.

Scaling available figures is necessary, because source information is scarce and based on reactors of different size or with other capacity factors etc. Fuel costs will be scaled by the amount of energy generated by the plant. Capital cost should be scaled by the output power of the plant. Operational and Maintenance costs should be scaled by the output power of the plant.

9.2 Statistical Estimate

The amount of sources for statistical evaluation is scarce. Some were provided by Heek [1997] and Boer [2004] for land based nuclear plants, as given in the following table:

Table 11 Source data Cost

	PBMR Brian Boer	Incogen	LPI
€/MWh | year ->	2004	1997	1996
Capital	14,31	59,81	84,29
O&M	5	10,21	30,02
Fuel	4,17	12,11	12,60
Decommisioning	0,4	0,25	1,07

From these different sources the average cost percentage was calculated and corrected for a steady inflation of 2% per year, producing the following statistical figures:

Table 12 Average Cost percentages

	Average	min	max	stdev
Capital	66,13%	59,9%	72,6%	6,3%
O&M	18,93%	12,4%	23,5%	5,8%
Fuel	14,00%	9,8%	17,5%	3,9%
Decommisioning	0,94%	0,30%	1,68%	0,69%
total	100,0%	82%	115%	+

These figures are based on land based installations with high base capacity factors. When the vessel is sailing in Coastal service the capacity factor will be some where around 40-70 %. This would lower fuel cost significantly.
The relative differences between the different sources are large, causing a less reliable prediction of the costs.

The Incogen pre-feasibility study (Heek, 1997) delivers the most detailed information about the different aspects of the costs, in the same thermal range, with a further subdivision into First-of-a-kind (FOAK), a Nth-of-a-kind(NOAK), and a NOAK using a pool managements system. For the nonrecurring costs the relative differences (compared to a FOAK plant) are:

Table 13 Relative capital cost differences

		Foak	Noak	Noak pool
Engineering	Construction and field engineering	3,68%	3,80%	3,80%
	Engineering home&office fee	2,82%	2,92%	2,92%
Capital costs	Land	0,48%	0,48%	0,48%
	Structures and improvements	10,75%	7,12%	7,12%
	Reactor plant equipement	30,63%	21,72%	21,72%
	Turbineplant equipement	10,43%	5,62%	5,62%
	Electricplant equipement	9,03%	7,43%	7,43%
	Miscelaneous plant equipement	2,71%	2,23%	2,23%
	Owners Cost	3,11%	2,35%	2,35%
	Contingency	15,84%	10,85%	10,85%
Decommissioning		10,52%	10,52%	10,52%
	total	100,00%	75,03%	75,03%

Land and structures will not be necessary when building into a ship. The rest can stay approximately the same; this will give a reduction of approximately 11 % in capital costs for the FOAK. When multiple reactors would be build the Capital costs could drop with approximately 32,5 %. The relative differences (compared to a FOAK plant) for the annual costs results in the following:

Table 14 Relative operational cost differences

Operations & Maintenance	Annual	Foak	Noak	Noak pool
	nr. of personnel	25	25	10
	Cost personel	31,21%	31,21%	12,46%
	Fixed maintenance	2,62%	1,97%	1,97%
	Variable maintenance	0,92%	0,79%	0,79%
	Fixed suplies and expenses	3,15%	3,15%	3,15%
	Variable control rod en reflector	2,62%	2,62%	2,62%
	Varianle Supplies & Expenses	0,26%	0,26%	0,26%
	Offsite technical support	2,49%	1,31%	1,31%
	Nuclear regulatory fees	11,15%	6,82%	6,82%
	Property insurrance	4,07%	2,89%	2,89%
	Other administrative and general	7,48%	6,30%	6,30%
	total O&M	65,97%	57,31%	38,56%
Fuel	total Fuel	34,03%	34,03%	34,03%
Total Annual costs		100,00%	91,34%	72,59%

The first noticeable change would be the amount of personnel. There is no need to keep 25 people working around the reactor in the ship, the reactor room and engine compartments should run unmanned and rely on maintenance based on condition monitoring. Changing filters and oils will still be necessary but this is not labour intensive. The Offsite technical support and maintenance would be probably higher because of the smaller confined spaces and the time schedule of the ship. The Cost of fuel should be related to the amount of energy and not as fixed post.

To get a feeling for the cost, the non-recurring costs should be scaled and averaged per amount of output power. This leads to the following figure:

Table 15 Price per kW

€/kW	Average	min	max	stdev
Capital	€ 19.567,20	€ 2.660,57	€ 33.049,43	€ 15.481,14
O&M	€ 5.540,81	€ 929,62	€ 11.769,59	€ 5.598,10
Fuel	€ 3.456,74	€ 775,30	€ 4.939,02	€ 2.326,50
Decommisioning	€ 196,89	€ 74,37	€ 420,34	€ 193,82

Fuel costs should not be scaled to the output power, but is displayed for the sake of completeness. The high deviation of the figures shows small prediction reliability. Still these numbers need to be used because they are the only ones available for now.

Capital + Decommissioning, scaled to electrical output, would result in the following figures:

Table 16 Statistical capital cost estimation

	Average	min	max
Initial investment €/kW	€ 19.764,09	€ 2.734,94	€ 33.469,77
Delivered Power [kW]			
8400	€ 166.018.315,59	€ 22.973.468,85	€ 281.146.067,39

These figures are without correction for the land and the structures as given by the estimation of the Incogen pre-feasibility study (between 11,23 % and 32,57 %).

Operations and Maintenance are scaled per output power and corrected for a design lifetime of 40 years as assumed for the land based reactors resulting in the following annual costs:

Table 17 Anual O&M statistical cost estimate

	Average	min	max	stdev
Annual Cost O&M	€ 1.163.570	€ 195.220	€ 2.471.614	€ 1.175.600

The amount of fuel and with that the cost for the fuel will be largely dependent on the efficiency of the process, assuming that the land based reactors operate at an efficiency of 40 % the fuel costs for the marine reactor, compared to the efficiency, results in:

Table 18 statistically determined fuel costs

system efficiency	Average	min	max
10%	€ 1.780.965,03	€ 678.428,65	€ 2.401.055,25
15%	€ 1.187.310,02	€ 452.285,77	€ 1.600.703,50
20%	€ 890.482,52	€ 339.214,33	€ 1.200.527,62
25%	€ 712.386,01	€ 271.371,46	€ 960.422,10
30%	€ 593.655,01	€ 226.142,88	€ 800.351,75
40%	€ 445.241,26	€ 169.607,16	€ 600.263,81
50%	€ 356.193,01	€ 135.685,73	€ 480.211,05

9.3 Cost divided in parts

Giving a more definitive answer would be breaking the cost down to the parts used instead of relying on statistical information. The problem here is that the costs the different parts are hard to predict and mostly unavailable.

9.3.1 Gas turbine

For the gas turbines an overview on the internet of the total costs was used delivering the following figure 65 (corrected for exchange rate):

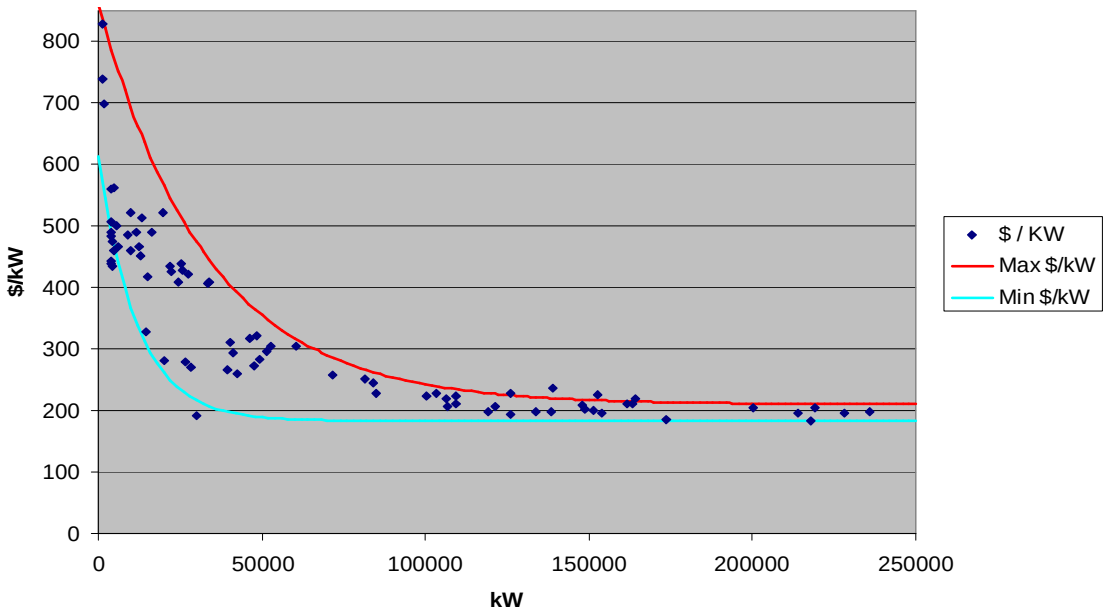

Figure 65 Cost estimation Gas turbines [€/kW]

Where the minimum line is given by:

$$Cost_{\min} = 430 \cdot e^{-8,5 \cdot 10^5 \cdot p} + 183$$

And the maximum line by:

$$Cost_{\max} = 650 \cdot e^{-3,0 \cdot 10^5 \cdot p} + 210$$

Where p is the output power in kW.

Recalculating the power from the gas turbine taking an efficiency for the electromotor of 95 %, and 95 % for the generator and taking an efficiency drop of 25 % in comparison to gas turbines with a combustion chamber delivers a necessary (conventional) turbine of 6205 kW. This would cost maximal 750 €/kW and minimal 437 €/kW resulting in a total cost for 2 gas turbines of minimal € 4.044.852 and maximal € 6.942.162.

Using a single turbine would result in a turbine of 12410 kW with a minimal cost of € 3.081.618, or a maximum of € 6.093.364, slightly lowering the capital costs, but decreasing redundancy.

9.3.2 Heat exchanger

The material of the heat exchanger would be of a special kind: S30815 or also designated as Sirius S15, 253 MA® and 2111HTR, this material is able to cope with temperatures up to 1150 °C. This material is according to the sales department from Bronswerk the driving factor behind the cost; the material can mount up to 60 €/kg. This stresses the fact that a heat exchanger should be as light as possible. The total weight of 75 tons for the heat exchangers results in a material cost price of 4,5 M€ including production cost will lead to approximately 5 M€. For minimum and maximum a variation of 25 % is applied

The pressure used inside the system is the decisive factor for the stress and so for the thickness of the materials used, largely responsible for the costs.

9.3.3 Fuel price

The fuel price is estimated by a calculator found on the internet: http://www.wise-uranium.org/nfcc.html resulting in a divided cost estimate as also is given by Boer [2004]. Caution should be taken here; WISE is a known antagonist of nuclear power, still the figures seem to be fair. Another argument to be cautious is the fact that these figures are based on cost estimates for water cooled reactors.

Still using this online calculator following figures are found:

Natural Uranium $ 28,73 per lb U_3O_8 and 10,00 $ per lb U_3O_8 future waste management.
Conversion $ 8,58 per kg.
Enrichment $ 89,55 per SWU and 110 $ per kg UF_6 tails.
Fuel Fabrication $ 205,22 per kg Uranium.
Spent fuel costs $ 626,87 per kg in spent fuel.
Resulting in the following relative amounts:

Table 19 Relative costs Uranium

Natural Uranium	26%
Conversion	2%
Enrichment	43%
Fuel Fabrication	7%
Spent Fuel	21%

Using a fuel burn up of 100 GWd/t and an efficiency ranging from 10 % to 60 % delivers:

Table 20 Uranium costs varied by efficiency

System efficiency	10%	15%	20%	25%
Amount Uranium [kg]	798,4843035	532,322869	399,2421518	319,3937214
Total Cost [5 year fill]	€ 2.351.834,22	€ 1.567.889,48	€ 1.175.917,11	€ 940.733,69
Anual Cost	€ 470.366,84	€ 313.577,90	€ 235.183,42	€ 188.146,74
System efficiency	30%	40%	50%	60%
Amount Uranium [kg]	266,1614345	199,6210759	159,6968607	133,0807173
Total Cost [5 year fill]	€ 783.944,74	€ 587.958,55	€ 470.366,84	€ 391.972,37
Anual Cost	€ 156.788,95	€ 117.591,71	€ 94.073,37	€ 78.394,47

These fuel prices are actually lower then obtained from the statistical data and may not be reasonable for the small amounts as required for the small reactor. In this case the statistical figures are chosen, because these seem the most reliable.

9.3.4 Propulsion train

The electromotor for propulsion would cost approximately € 500.000 (rough estimate by ABB) in combination with a gear of approximately € 200.000 delivering only a small part of the total costs. There can be some additional costs here for the high voltage management equipment and education of personnel due to the high voltage applications, because these engines run at 6.6 kV.

9.3.5 Reactor

The Incogen study estimates the relative costs for the reactor as 52 % of the total initial capital investments for a FOAk and 37 % for a NOAK, this is included the additional owner costs, contingency costs and miscellaneous plant equipment costs. The total initial capital investment of a 40 MWth reactor was estimated as 382 M€, corrected for 2 % annual inflation.
This would result in a cost price for a NOAK of 142 M€, for the estimation of Boer this would result into 27 M€ and for the estimation of LPI this would result into 204 M€.

These figures seem very high; taking the weight of the reactor and combining it with the material price (60 €/kg as suggested by Bronswerk) leads to approximately 15 M€. The graphite estimated at 50 €/kg and 20 €/kg for fabrication would lead to 1,8 M€. This excludes the costs for the necessary pumps, piping, shielding, control rods/equipment, the surrounding electronic components and the necessary work. The costs for these last mentioned are rough to estimate. If the costs of the vessel and graphite are in the order of one third of the total amount the total reactor costs would be in the order of 50 M€, but this is a big if. For now the costs will be estimated from the statistical data.

The costs reported by Boer are in all cases the lowest costs compared to the others all though in this thesis the costs were also derived from INCOGEN and LPI, the given costs by Boer are so extreme low that they will not be used in the comparison.
The estimation of INCOGEN will be taken with a variation of 25 % for the minimum and maximum.

9.3.6 Total parts

Summing the different parts from the previous paragraphs above into one table results in:

Table 21 Summation total Initial capital costs

			Average	Min	Max
Elongation Hull €	8,69	m	€ 406.483	€ 270.988	€ 541.963
Gasturbines	2	units	€ 5.774.104	€ 4.221.977	€ 7.326.231
Electromotor	8400	kW	€ 500.000	€ 400.000	€ 600.000
Gear 1500 -> 124 tpm			€ 250.000	€ 200.000	€ 350.000
Heat exchanger €	4	units	€ 5.772.664	€ 4.220.924	€ 7.324.404
Nuclear reactor			€ 141.793.595	€ 106.345.196	€ 177.241.994
Total			€ 154.496.845	€ 115.659.085	€ 193.384.592

9.4 Development

The economical viability also depends on the path way to production, this would be according to Vergara [2002]:

Over a period of 1 year: Market potential Confirmation, candidate ship design study, Fuel Micro particle Analysis and optimization, Preliminary public studies and flow simulations. Estimate cost corrected for historical valuta and an annual inflation of 2% results into a correction factor of 99,3 % on the original costs mentioned in the article. The article mentions a cost of $ 500.000, corrected this leads to € 496.400.

Over a period for the next 2 years: Candidate ship design, Fuel element and Core design, Power conversor preliminary design, Preliminary power plant design, Nuclear related port infrastructure design. Costs are mentioned of $ 2.000.000.

Over a period of the following 3 years: Nuclear reactor detailed design, Nuclear ship detailed design, Ship-Reactor integration design, Power Conversor detailed design, Power Conversor prototype testing, public acceptance final study. Costs are mentioned of $ 20.000.000.

Over the last period of 4 years: Prototype reactor construction, Nuclear reactor commissioning, Nuclear fuel manufacturing, Port infrastructure completion, Ship and Power plant building plus integration, start sailing. Costs are mentioned of $ 800.000.000.

These costs, corrected to be € 816.600.000, were based on the production of 1 fast nuclear container vessel. These mentioned costs are very rough estimations, but can be used for initial figures for the calculation of an economic pathway. These initial investments should be overcome with partly subsidization and the additional profit obtained from the better fuel economy (not higher efficiency but lower fuel costs!).

The development cost will be very large in the order of some hundreds of M€. Comparing the figure from Vergara with the initial estimate for the infrastructure (350-500 M€) can be seen as an affirmation of this estimate.

9.5 The future of the fossil fuel prices

The economic viability of the nuclear alternative off course is depending on the oil price. A nuclear reactor is expensive in capital costs and a diesel engine is expensive in fuel costs depending on the oil market.

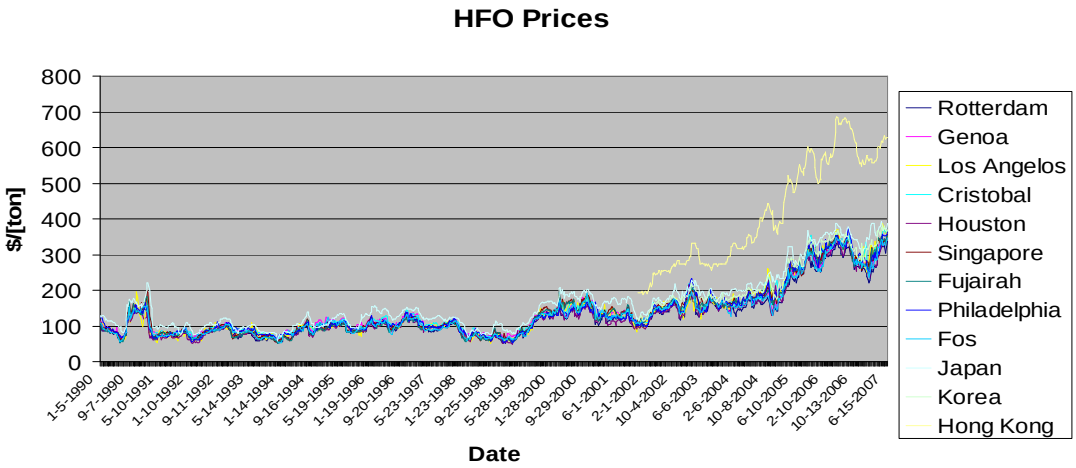

Figure 66 HFO prices over the past 17 years

The HFO prices (here 380 Cst) are hard to predict as can be seen from figure 66, although a steady grow in the last years can be seen in the graph above. The extreme fuel prices in Hong Kong are almost twice as high as in the rest of the world, this might also be a good place for nuclear propelled coasters.

There is an incentive to ban fuel containing sulfur in the coastal regions, to lower SO_x emissions. Sulphur free fuels would at least double and maybe triple the price of the fuel due to the necessary extra refinements. Additional costs can be foreseen in special taxes on CO_2 emissions and in a

possible obligation for a NO_x particulate matter filter. Taxes on CO_2 emissions will further increase the direct fuel price, while the filter system will increase the initial investment costs.

9.6 Cost Comparison

Making the bald assumption that O&M costs are the same for the nuclear system as well as the conventional system; a diesel engine of 8,4 MW will costs about 2,8 M€, assuming a fuel consumption of 178 g/kWh and a fuel bunker price of 251 €/ton, will lead to annual fuel costs of € 1.713.990.

The factor that is the most negative for a nuclear installation is the interest rate. Because of the large initial investments this is significantly higher then the annual fuel costs. Annual fraction for rent and return is defined as:

$$Z = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Where r is the rent, and n the period over which it should be recovered. A life period and low interest rate will have positive effect on the costs for a nuclear installation.
For a design period of 25 year this leads to figure 67.

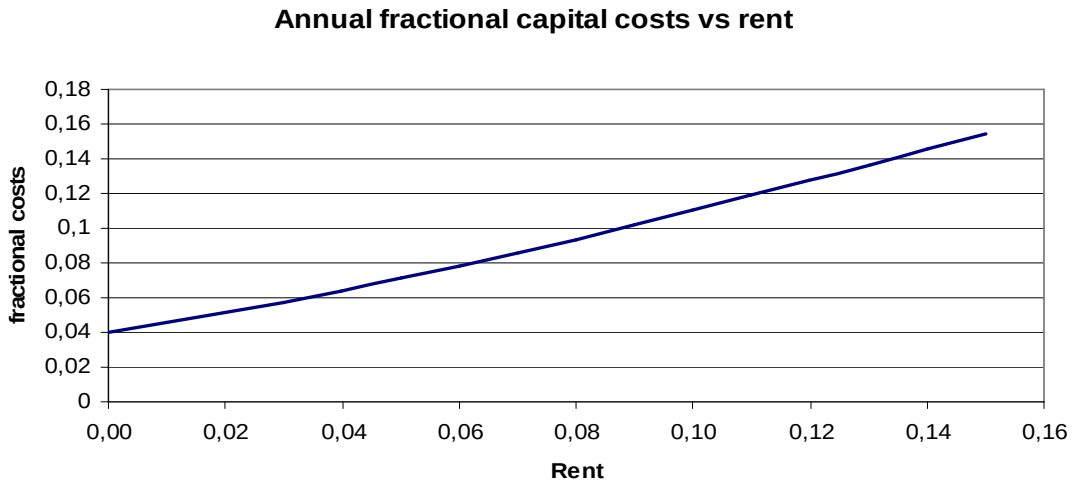

Figure 67 Annual fractional capital costs

Nuclear fuel costs are small in comparison to the capital costs. This is also the advantage of nuclear installations: the influence of fuel costs on the total costs is low ensuring a stable cost price for different inflation rates.

Varying the amount of sailing years, varying the inflation for 0%, 2%, 5% and varying the HFO costs by doubling and tripling will result in a table as given by appendix S.
The same is done for the nuclear alternative using the different cost parameters obtained from the previous paragraphs. Fueling costs are in "jumps" of 5 years were the fuel costs are also corrected for inflation over 5 years, fuel cost is estimated from the statistical data.

Comparing these figures in the appendix S results into the disappointing conclusion that it is not economical to run a nuclear short sea ship, only in a few extreme cases the total lifetime costs are lower for the nuclear installation.

Anther possibility is to review the profile of the ship increasing its sailing time by choosing for harbours with larger distances between away increase fuel usage. If the period of sailing is doubled the amount of fuel used will rise with 57,5%, still this will lead to a more economical nuclear ship when the price of HFO will at least double and with a high inflation rate.

9.7 Economic Viable?

As can be concluded from the previous paragraphs the only way a nuclear coaster can be financially attractive is if the fuel prices at least triple. The highest costs are still in the nuclear reactor itself, the parts surrounding the reactor are of minor importance.

Varying the initial capital costs to find an economical nuclear competitor for the diesel engine, with as boundaries: 5% interest rate, a design life of 25 years 2 % inflation and a doubling of the diesel fuel price compared to minimal nuclear fuel costs (Statistical minimum), results into a maximal total initial capital cost of 59 M€. The additional costs of infrastructure are not taken into account for this calculation.

Concluding: If the costs of a small nuclear reactor with its shielding and pumps will drop below approximately 60 M€ it will become economically attractive to start building nuclear short sea ships, pending on the rise in fuel costs due to the desulphurisation of the fuel. If the sailing time is doubled the nuclear ship would already be economically at initial investments of 91 M€. With the current fuel price the maximal initial investment should be below 43 M€. This is not taking into account the additional costs for the infrastructure, for personnel and maintenance. These were not evaluated in this case and are assumed to be in the same order of that of a diesel powered ship.
In short the initial investments should be kept to a minimum to make a nuclear reactor commercially attractive. Production in series will be necessary to meet such low prices.

Subsidization for the low environmental impact would also be a possibility to make the system more economically viable, as is done with wind turbines. This could compensate the initial investment costs depending on the height and form of the subsidization.

10 Conclusions

Nuclear shipping with a high temperature gas cooled reactor will be technically possible in the near future, but a lot of effort to accomplish this still has to be made. The financial risks for the start up of such an enterprise will be large, but could be worthwhile to preserve the climate due to the lower emissions. A HTR is at the moment too expensive in initial capital investments to sail a nuclear short sea ship economically, the HFO price should at least triple before it will be economically viable.

10.1 From history

The technical feasibility of a nuclear merchant ship has been proven a long time ago, with the NS Savannah, the Otto Hahn, the Mutsu and the Sevmorput. Despite this nuclear ships have never found their way commercial trade because of the high manning costs and the need for unique infrastructure. The costs of producing, maintaining and operating a unique ship with unique components are simply too high.

10.2 Concepts

Choosing a container feeder as the platform for which to design a nuclear reactor has some advantages: The market for such a ship is large; the design could be produced in series lowering capital costs. With current automation it will no longer be necessary to have large crews aboard. All the disadvantages from the past can be evaded using this concept.

The Prismatic-Block Gas Cooled Reactor seems the most promising reactor for marine application, because of its self regulating possibilities. But short sea shipping optimizes for short loading periods which results into problems with the Xenon poisoning of the reactor, a passive reactor operated on the laws of physics is out of the question in this case. A higher reactivity will be necessary to handle this problem, but will create the need for active control. Longer loading periods will not lead to this exception and will provide the possible application of a passive reactor, although the dynamic interaction with a gas turbine can lead to the necessity of active control.

10.3 System design

The primary system pressure is an important factor in the design of the reactor and surrounding components. The material thickness needed for a larger inner diameter in the reactor can go to extreme sizes due to the pressure and the high temperature, resulting in extreme high weights. Another important factor on the weight of the whole is the ratio between the height and the diameter.

The influence of the heat exchanger on the total system is very large: great volume, high weight and high costs or high pressure drop resulting in low efficiency. A shell and tube heat exchanger is too large for application in a ship of this size. Lower size and weight can be achieved if a plate heat exchanger is possible, but this is at this moment not state of the art and should be developed, problems with creep at high temperature in combination with high pressure render the current high temperature resistant steels unsuitable.

The obtained efficiency from the static model, applying 2 heat exchangers with a simple cycle gas turbine is not as high as reported in different sources. The in literature stated efficiency mounts up to 40%, while using the static model only shows a total system efficiency of 21 %. The main losses are caused by the relative high resistance in the heat exchangers in combination with the losses from the generator, electromotor, extra resistance due to the hull elongation and some additional power needs for the pumps. This could be lowered by enlarging the size of the heat exchangers, but this is costly due to the extremely high material price and would have an enormous impact on the total weight.

Small size reactors in small ships will be more voluminous than the conventional diesel plant. Enlarging the ship to maintain the same cargo carrying capabilities will be necessary. The impact of additional resistance of the slightly larger ship, is relative low due to the low impact of the fuel costs on the total costs.

10.4 Safety

Safety can be ensured by taking all precautions which are possible, the cost of safety measures in comparison to the total price for a reactor are low. A large part of the safety can be ensured by designing an extra rigid construction capable of handling possible extreme situations. The chance that the primary loop has a breach in combination with the flooding of the reactor compartment could result in a steam explosion; this effect should be investigated for acceptance in all conditions. Retrievability is an important design factor, extracting the reactor from the ship should be easily possible because of the necessity to change the reactor for refueling purposes.

10.5 Infrastructure

Building necessary infrastructure to maintain multiple ships will have high costs. The Royal Schelde Oost is a shipyard in the eastern harbor of Vlissingen, located near the Borselle Nuclear plant and radioactive waste storage facility, so familiarity with the nuclear industry is already established in that region. A building and system for the refueling of a reactor between two docking periods will be necessary. Additional crane capacity will be necessary to hoist the reactor from the ship onto a heavy load transporter, to transport the reactor to the refueling installation.

10.6 Financial viability

Based on the current available statistical data, the concept can be economically viable if the HFO price increases to approximately 3 times the current level. This scenario is also possible if taxes on emissions and a ban on sulfur containing fuels are instituted, creating the same effect. The initial investment cost for a nuclear installation, in specific the nuclear reactor itself, including interest rate give the highest overall costs. The nuclear fuel costs do not have a high impact on the total costs. This is in contradiction with a diesel plant, where this is the other way around.

Political acceptance of nuclear power as a safe and environmental friendly method of producing energy is essential. The operational costs in the form of permits and compliance to regulation can become a problem when unreasonable demands are formed. The industry needs stable regulation and cost reliability before it will agree to invest. Acceptance of the Sevmorput for example in the harbors would be a start.

10.7 Recommended additional research

For this concept:
The Creep strength in combination with the high temperature for the different exposed parts was insufficient with the values stated in literature for high temperature resistant steel. Further investigation into other materials like titanium alloys or ceramics like Silicum Carbide (SiC) will be necessary for the chosen concept in this report.

Burnable poison distribution within HTR should be investigated for long endurance and minimization of necessary control.

It is important for the overall performance and the necessary fuel load to investigate the impact of temperature and flow variation on gas turbine performance in off design condition.

Reactor load following behavior and availability due to Xenon poisoning needs to be investigated to determine the state of the reactor in off design conditions and to see what shutdown(during loading) periods are possible.

The passive decay heat removal should be investigated for a chosen small sized reactor to ensure safe operation in all cases. For example research into methods that are feasible and impact on losses.

Accident evaluation for water flow into the reactor, due to extreme damage, will be necessary to ensure safety. All possible conditions should be checked for possible steam explosions.

Optimization for shield costs, volume and mass should be investigated by further varying materials and thicknesses using Monte Carlo method. There is a possibility to split the shield into two pieces, due to the lower radiation of an inactive reactor, to lower the weight during transport.

Further optimization for heat exchanger costs, volume, mass and pressure drop will be necessary to come to the most optimum design.

Finite element analysis of the ships construction for damage assessments on IMO prescribed situations, to comply with the regulations.

Originally it was planned to investigate the impact of different fleet sizes on the total costs. The additional costs of infrastructure were not taken into account, which would make the case worse for the nuclear alternative. The additional costs for educated personnel was not taken into account. This needs to be further investigated to obtain a complete financial model.

Alternative concepts:
Further variation in reactor designs for example: Liquid salt/metal cooling. These reactors can also be smaller, but more complicated during operation.

Further system variation with the heat conversion, for example a direct cycle with nitrogen as coolant as advocated by Adams [1996], this option eludes the problems with high temperature heat exchangers.

Impact of PWR on same size ship, because of probable (Knief [1992]) lower cost, easier refueling and possible smaller size, although historical ships point out otherwise. After evaluating the refueling procedure the advantages of refueling a PWR over refueling a reactor filled with fuel containing HTR fuel compacts or pebbles seem large; the PWR can be refueled onsite by flooding the reactor and space, this is not possible with the reactor chosen for this design. Further research of the possibilities of a small PWR could lead to a more commercial model; the used materials do not have to withstand extreme temperatures, refueling is easier as stated above, lower reactor building and fuel costs are reported in Knief [1992] and the technology is already in use in numerous occasions resulting in more directly available knowledge. The only disadvantage would be the assumed higher maintenance.

Nomen Clature

Units

s	second	time
h	hour, 3600 s	time
d	day, 24 h	time
y	year, 365 d	time
cm	centimeter 0,01 m	length
m	meter	length
g	gram	weight
kg	1 kilo gram 1000 gram weight	weight
ton	1000 kg	weight
J	Joule, N·m	energy
eV	electron Volt	energy
MeV	Mega electron Volt	energy
Bar	Bar 10^5 Pa	Pressure
Pa	N/m^2	Pressure
°C	Degrees Celcius (K+273,15)	Temperature
K	Degrees Kelvin	Temperature
W	Watt, or Joule/second	Power
kW	kilo Watt, 10^3 Watt	Power
MW	Mega Watt, 10^6 Watt	Power
Wth	Watt thermal	Thermal Power
kWh	kilo Watt hour	energy
MWd	Mega Watt day	energy
Tons	1 ton-force 9806,65 N	Force
N	Newton	Force
Ci	Curie 3,7 10^{11} Bq	Decays
Bq	Becquerel, decays/second	Decays
Gy	1 joule radiation / kg tissue	Radiation Dose
R	1 Röntgen ≈ 9.330 mGy	Radiation Dose
REM	Röntgen Equivalent in Man	Radiation Dose
Sv	Sievert 0,01 REM	Radiation Dose

Symbols

α	proportional factor between H and R, or scaling factor
ε	Fast Fission Factor
ρ	reactivity or density
η	Reproduction factor
Φ	Dose rate
χ	Concentration ratio
A	Area
B	Beam
COG	Centre of Gravity
D	Diameter
$\dot{D}$	Dose rate
d_i	Inner diameter
d_o	Outer diameter
E	Energy
g	Gibbs enery
ΔG	Difference in Gibbs energy
f	Thermal Utilization Factor, or fanning factor
H	Core Height
h	Enthalpy
k	Reaction rate
k_{eff}	Effective Multiplication Factor
k_∞	Infinite Multiplication Factor
K_p	Equilibrium constant
L	Length

M	Mass
$\dot{m}$	Mass flow
n	Neutron, or years
P_f	Fast Non-Leakage Probability
P_{th}	Thermal Non-Leakage Probability
P	Power
P^o	Atmospheric pressure
Δp	Pressure drop
Q	quality factor
R	Core Radius
R_u	Gasconstant
r	radius or rent
t	Shield thickness, or time elapse
U_m	Flow velocity
T	reactor period or Temperature
V_{core}	Core Volume
V_{shield}	Shield Volume
x, y	Used variables, defined as integers
Z	Annual fraction for rent and capital cost

Shorts

AES	All Electric Ship
AGR	Advanced Gas cooled Reactor
AMvB	Algemene Maatregel van Bestuur (Form of temporary legislation in the Netherlands)
BWR	Boiling Water Reactor
CANDU	CANadian DeUterium PWR
CF	Container Feeder
COG	Centre of Gravity
CORA	Commissie opslag radioactief afval (Commission Storage Radioactive Wastes)
COVRA	Centrale Opslag Voor Radioactief Afval (Central Storage for Radioactive Waste)
EZ	Economische Zaken (Economic Affairs)
FEU	Forty foot Equivalent Unit (Container size)
FOAK	First Of A Kind
GNEP	Global Nuclear Energy Partnership
HABOG	Hoogradioactief Afval Behandelings en Opslag Gebouw, High radioactive waste treatment and storage building
HBR	Haven Bedrijf Rotterdam (Rotterdam Port Authorities)
HFO	Heavy Fuel Oil
HTR	High Temperature Reactor or also High Temperature Resistant
HTTR	High Temperature Thermal Reactor
KISS	Keep it Simple Stupid
IAEA	International Atomic Energy Agency
IBM	International Business Machines Corporation
IMCO	Inter-Governemental Consultative Organization (Renamed to IMO)
IMO	International Maritime Organization
INCOGEN	INherently safe COGENeration (pointing towards a HTR filled with TRISO elements)
JAERI	Japanese Atomic Energy Reactor Institute
KEW	KernEnergie Wet “Nuclear Energy Legislation”
IP	Idiot Proof
LASH	Lighter Aboard SHip
LMR	Liquid Metal cooled Reactor
Magnox	Magnesium Non-oxidising
MSC	Mediterranean Shipping Company
NATO	North Atlantic Treaty Organisation
NIMBY	Not In My BackYard (referring to the attitude of some people)
NOAK	N^{th} Of A Kind
NS	Nuclear Ship
PBR	Pebblebed Gas Cooled Reactor
PR	Prismatic-block gas cooled Reactor
PWR	Pressurized Water Reactor
RBMK	*reaktor bolshoy moshchnosti kanalniy* "reactor (of) high power (of the) channel (type)"

SCRAM	Safety Control Rod Axe Man, old acronym still used for a complete shutdown of the reactor.
SZW	Sociale Zaken en Werkgelegenheid (Social affairs and employment)
TEU	Twenty foot Equivalent Unit (Container size)
TL	Tube Light
TRISO	Tri Isotropic
VLCC	Very Large Crude Carrier
VROM	Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (Housing, Area planning and Environmental affairs)
vs	versus
V&W	Verkeer en Waterstaat (Transport and Public Works)
WISE	World Information Service on Energy

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http://www.insc.anl.gov/matprop/graphite/ent_hc/assessment.php
Searchdate: 06-08-07
Contents: formula for graphite enthalpy

http://www.NRG.nl
Searchdate: 08-08-07
Contents: Newspapers and articles on different subjects

http://www.intertanko.com/upload/WeeklyNews/ISO14000spreadsheetguidelines.doc
Searchdate: 05-09-07
Contents: Greenhouse gases produced by fuel

http://www.pntl.co.uk/
Searchdate: 09-11-07
Contents: Shipping company for nuclear fuel/waste

For historical nuclear ships:

Sources	Date
Mutsu	
http://inisjp.tokai-sc.jaea.go.jp/ACT95E/06/0601.htm	20-11-06
http://en.wikipedia.org/wiki/Mutsu_(ship)	20-11-06
NS Savannah	
http://files.asme.org/ASMEORG/Communities/History/Landmarks/5642.pdf	20-11-06
http://en.wikipedia.org/wiki/NS_Savannah	10-07-06
http://www.radiationworks.com/NSSavannah.htm	15-07-06
http://sandia.gov/LabNews/LN03-26-99/savannah_story.htm	15-07-06
Otto Hahn	
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Appendices

A. Nuclear physics

Atomic Model

To understand nuclear physics, a begin has to be made with an atomic model. The atomic model devised by Rutherford is most commonly accepted and can describe the discovered phenomena when reviewing fission.

The model describes the atom as a central nucleus with electrons turning in ellipse shaped orbits around the nucleus like the planetary system although the distance between the electron and the nucleus is much larger. This means that the space in an atom is mostly empty. The nucleus consists of nucleons; protons and neutrons having the most significant mass of the atom. The nucleus is filled with positively charged protons, so together with the electrons the atom can be neutral.

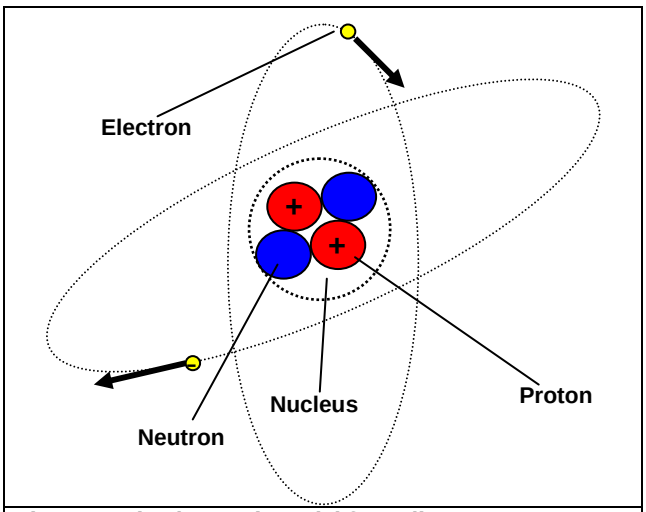


Figure 68 Simple atomic Model for Helium

All protons have an electrical charge of +e, and all electrons have an electrical charge of –e.
The amount of protons in the nucleus determines the material. The amount of Protons plus the amount of neutrons (mass number) gives the relative mass of the nucleus and is used to determine which Isotope is used; ^{235}U is short for Uranium with a mass number of 235.

Bohr extended the model by restricting electrons to only exist along certain orbits instead of arbitrary orbits around the nucleus. This quantification explains why only certain amounts of energy (in the form of electromagnetic radiation) can be received and transmitted. X-rays are an example of this kind of radiation. By absorbing or transmitting energy the electrons can change orbit, however they do not cross the space between the orbits, they simply appear and disappear in the allowed states; a phenomenon referred to as a quantum leap or a quantum jump.

The mass of an electron is 9.10939×10^{-28} g where the mass of a proton is 1.67262×10^{-24} g and the mass of a neutron is 1.67493×10^{-24} g.
Scaling approximately; electron : proton = 1 : 1836.

For example the diameter of a Boron atom is approximately $1,7 \times 10^{-10}$, the diameter of the nucleus of Boron is approximately $4,9 \times 10^{-15}$, the diameter of a Proton or a Neutron is approximately $1,5 \times 10^{-15}$, where an electron would be $1/1000^{th}$ of a proton in classical theory. From this can be seen that an atom is almost "empty".

Smaller particles like electrons, protons, etc. also can display wavelike behavior, like interference. With this in mind size of a particle becomes relative.

The nucleus is held together through the nuclear force one of the four fundamental forces; Gravitational, Electrostatic, nuclear and weak force. The gravitational force of the nucleus is too small to overcome the electrostatic force of the protons repelling each other.
The measured mass of an atom is lower then the total of protons, neutrons and electrons the rest of the mass is changed into energy for the binding energy the nucleus. The binding energy per nucleon is given below in the graph for the natural occurring elements taken from http://www.alaskajohn.com. The elements with the highest binding energy are stable. From right to left fission and from left to right fusion can deliver energy forming the more stable elements.

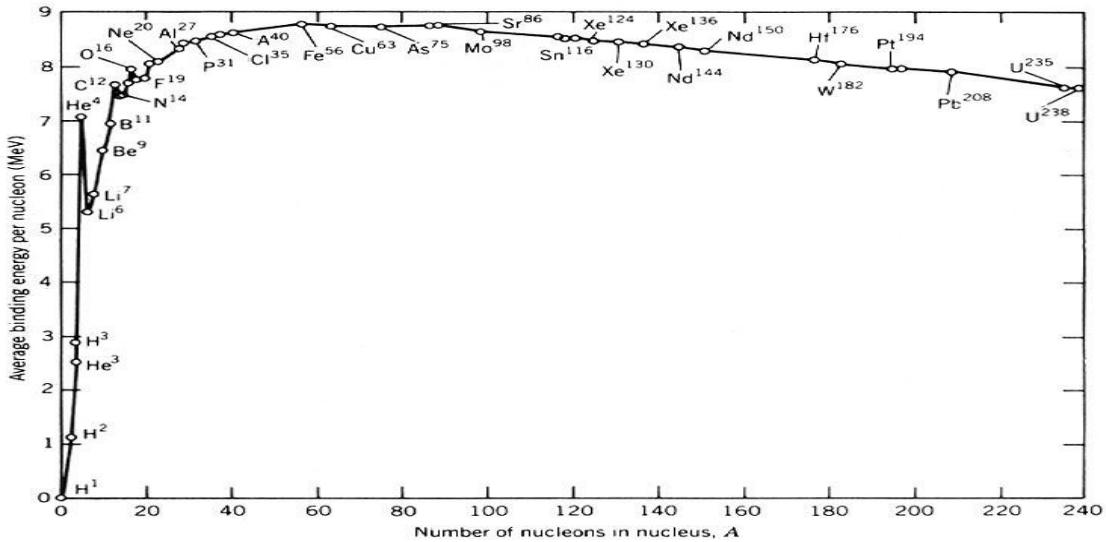


Figure 69 Binding energy per nucleon

Radioactivity

When talking about radioactivity people usually mean the property of a material to radiate harmful ionizing particles or photons. The harmless light formed by a TL is also radiation although this is never mentioned in this way.

An electron can be ejected when subjected to energy from a photon or a charged particle (electron, proton or an α-particle) this is called ionization.
When an electron is brought to a higher orbit because of such energy the atom is excitated.
When excitated the electron will, in a certain amount of time, return to the ground state radiating the excess energy through photons.

The nucleus can also be unstable, by radiating the excess energy it can become stable again. This can take multiple steps to become stable again, this is called radioactive decay. There are 3 kinds of ionizing radioactive decay; α-decay, β-decay and γ-decay.

α-decay

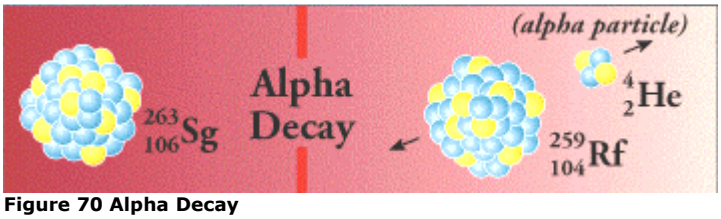


Figure 70 Alpha Decay

An alpha particle is a highly energetic helium nucleus, so containing only 2 protons and 2 neutrons. When a nucleus has too many protons, causing excessive repulsion through the electrostatic force, it is called unstable and is likely to decay by emitting an α-particle. The energy of an emitted alpha particle is somewhere between 4 and 7 MeV, cause of a minimum energy needed to escape from the nucleus. Most α-emitters are heavy nuclides.

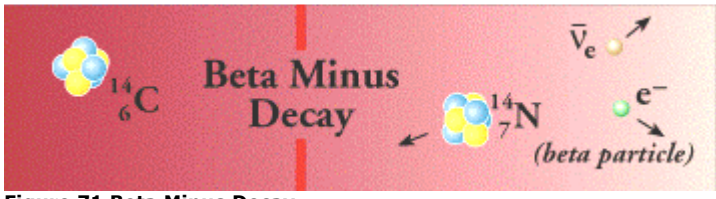


Figure 71 Beta Minus Decay

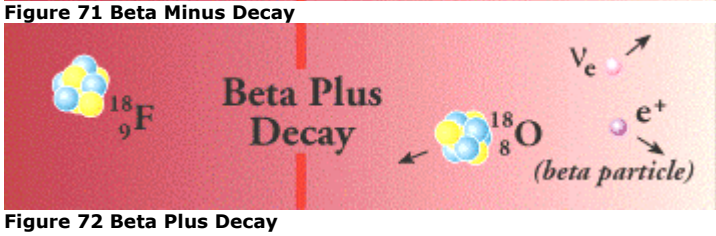


Figure 72 Beta Plus Decay

β-decay

Beta decay consists of 3 different modes β^-, β^+ and orbital electron capture.
β^- decay turns a neutron inside a nucleus over into a proton, an electron and anti-electron-type neutrino. The proton remains inside the nucleus changing the element, and the other particles move away from the nucleus as radiation.
β^+ decay turns a proton inside a nucleus over into a neutron, a

positron and a neutrino. The neutron remains inside the nucleus changing the element, and the other particles move away from the nucleus as radiation.

The nucleus can capture one of the lowest orbiting electrons, and combine this with one of its protons creating a neutron and a neutrino, where the neutron is kept inside the nucleus and the neutrino moves away as radiation. The change of orbit of the electron causes radiation in the form of X-rays.

γ-decay

The nucleus will rearrange itself to its ground state after alpha or beta decay, excess energy will be radiated in the form of gamma radiation, these are photons which are 10.000 times more energetic then visible light photons.

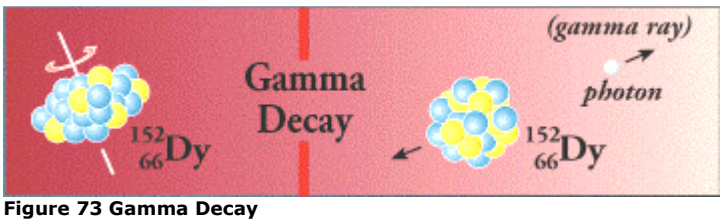


Figure 73 Gamma Decay

Fission

As can be seen from the figure with the binding energy per nucleon above the binding energy per nuclide is lower for the larger nuclei, this is the basis for the energy delivered by a fission reaction.

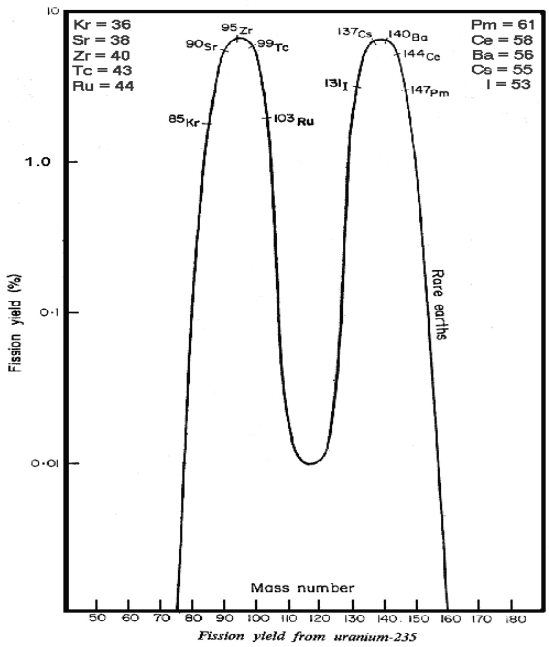


Figure 74 Fission product Yield

Not all large nuclei are suitable for fission in a reactor. For example ^{233}U, ^{235}U, ^{239}Pu and ^{252}Cf are fissile nuclei, but only ^{235}U is found in natural resources. Fissile has a different meaning then fissionable, being fissile means being able to fission through a neutron with almost zero kinetic energy. While fissionable means that the material is capable of fission in some way.

Where the fission reaction for ^{235}U is as follows:
$^{235}U + n \rightarrow {}^{236}U^{*} \rightarrow {}^{x}(\text{Element A}) + {}^{235-x-y}(\text{Element B}) + y\,n$

n means neutron and y is the amount of free neutrons formed after the fission reaction.
Element A is one of the fission products with x nucleons in its nucleus. Element B is the second fission product with 235-x-y nucleons in its nucleus. The distribution of the elements is not linear as can be seen in the graph (http://www.geocities.com/longhairedbastard/figures/fission.gif) below, illustrating the fission product yield in logarithmic scale.

To allow for stable operation neutrons are necessary. In the fission reaction 2 or 3 neutrons are produced. Neutrons contain a certain amount of energy given by the reaction in which they were produced, this energy is in the form of kinetic energy. The reaction of ^{235}U is only possible with so called thermal neutrons. Thermal is a term for the kinetic energy being 0,025 eV. Neutrons produced in a fission reaction are called fast with kinetic energy of 1-20 MeV. This surplus amount of energy should be disposed of to create another fission reaction with ^{235}U.
The kinetic energy is lowered by collisions with other elements in a reactor. The material which is meant to decelerate the neutrons is the moderator in a fission reactor.
Neutrons can also be absorbed by elements forming new nuclei. The idea off a nuclear fission reactor is to create a balance between the absorption of neutrons, the moderation of neutrons and the fission reaction.

The products from the reaction also form new situations: some of the products like ^{135}Xe or ^{149}Sm are neutron absorbers and can stop the chain reaction from proceeding or even after shutdown form restarting.
^{238}U can absorb fast neutrons forming ^{240}Pu which is fissile.

Nuclear Fission Reactor

A Fission Reactor contains a fissile material; the fuel (for example ^{235}U), means of moderating the fast neutrons: a moderator, means of controlling the chain reaction by neutron absorption control rods or chemical shim, a coolant to export the thermal energy from the core. All practically applied reactors are heterogeneous which means that the reactor has the moderator, fuel and other equivalent material as separate and discrete bodies. Some test reactors were homogeneous which means that they had the moderator and the fuel combined in a homogeneous mixture. This is not applied because of the difficulties maintaining a homogeneous installation with regard to radioactivity of the fuel.

Nuclear Fuel

Nuclear fuel consists of fissile material, fertile material and structural material. The fissile material is the actual material used to maintain the fission where ^{235}U is the only one naturally occurring. Fertile material can absorb neutrons and form by various nuclear reactions a new fissile material. ^{232}Th is an example of a fertile material, which converts into ^{233}U after capture of a neutron. ^{238}U is another example of a fertile material which can convert into ^{239}Pu after neutron capture. Structural material is the material used to keep the different fuel parts together, this can be done with all kinds of methods. The pebblebed reactor uses graphite as structural material, the Magnox reactor uses a Magnesium Non-Oxidising alloy.

Moderators

The ideal moderator for neutrons would be particles of similar size (think of snooker) and a small absorption cross section. The absorption cross section is a term for the probability in which a neutron can be absorbed by the element.
The first demand would result in a neutron, this is not stable on itself and has a halftime of 15 minutes. Next in line is 1 proton which is hydrogen, neglecting the electron. The problem with hydrogen is that it can capture the neutron and that it has another dangerous property: it's highly reactive with oxygen. If water is used instead of hydrogen part of the particles are hydrogen atoms 'polluted' with oxygen atoms. Next in line is Helium, which has a relative small nuclei is very stable and has a small neutron absorption cross section.
Currently used for moderators is: light water, heavy water, Beryllium, and Carbon.
Because the moderator is distributed through the reactor it is very practical to also use it as a coolant when possible.

Control of reactivity

Nuclear reactors often contain control rods with materials which have a very large neutron absorption cross section. Extending these rods into the reactor will slow down, or stop the reaction process. Materials used in control rods are: Boron, Cobalt, Hafnium, Gadolinium, Europium, Silver, Indium and Cadmium.
Chemical Shim is also used to control the absorption of neutrons by injecting a neutron absorber in the moderator (e.g. Boric acid)
Burnable poison is a material used through the reactor, that has a large neutron absorption cross section and which is used to control the continuity of the reaction process, the material used compensates, by absorption of neutrons and lowering its absorption cross section by that reaction, for the loss in reactivity by the "burning" of the fuel.

Reactor Control

The reactor is controlled by controlling the amount of neutrons and controlling the kinetic energy of the neutrons. There are many factors influencing these properties. Through these factors the state of the reactor core can be determined.

Fast Fission Factor ε

Some fast neutrons will cause fission of ^{238}U and ^{235}U before they slow down, most of these fissions are in ^{238}U because of the large proportion of it in the fuel. These fast fissions will produce extra neutrons, this is accounted for in the Fast Fission Factor. The thermal fissions k_1 and the fast fissions k_2 together form the total amount of fissions. The Fast Fission Factor is defined as:
$\varepsilon = (k_1 + k_2)/ k_1$

Fast Non-Leakage Probability P_f

Part of the fast neutrons will leak out of the reactor core, the rest will start to slowdown in the moderator material. The ratio of the number of fast neutrons which begin to slow down to the number of fast neutrons from all fissions is called the Fast Non-Leakage Probability

Resonance Escape Probability P_{esc}

During the moderating process, before being thermalized, neutrons can escape or can be captured in elements. The ratio of neutrons which become thermalized to the neutrons which started the moderating process is the Resonance Escape Probability.

Thermal Non-Leakage Probability P_{th}

Part of the thermalized neutrons will also leak out of the core. The ratio of the neutrons absorbed in the core to the number of the neutrons that are thermalized is called the Thermal Non-Leakage Probability. P_f and P_{th} strongly depend on the size of the reactor the smaller the reactor the larger the chance is that a neutron will escape from it.

Thermal Utilization Factor f

This factor takes the absorption of thermal neutrons in materials other than the fissile fuel into account; the absorption of neutrons in the control rods, chemical shim and thermal neutron poisons (e.g. ^{135}Xe). The Thermal Utilization Factor is defined as the ratio of thermal neutrons absorbed in a fuel to the thermal neutrons absorbed in the entire core.

Reproduction factor η

The reproduction factor is the mean amount of neutrons formed by the reaction of a neutron with the fissile fuel.

Multiplication factor k_{eff}

The multiplication factor is the ratio of the amount of neutrons between 2 subsequent generations of neutrons. The multiplication factor can be formed by multiplying all the parameters above.

$k_{eff} = \eta \cdot \varepsilon \cdot P_f \cdot P_{esc} \cdot P_{th} \cdot f$

When $k_{eff} = 1$ the reactor is critical, when $k_{eff} > 1$ the reactor is supercritical and when $k_{eff} > 1$ the reactor is subcritical.
The multiplication factor also exists in another form as the infinite multiplication factor, meaning a multiplication factor for a reactor of infinite size. In an infinite reactor there is no leakage allowing for simple modeling.

Reactivity is another way of describing the percent change of the reactors multiplication factor and is defined as:
$\rho = \Delta k_{eff} / k_{eff}$

Temperature and Pressure dependent coefficients

There is a coefficient to describe the reactivity of the fuel by varying temperatures also known as the prompt temperature coefficient or the nuclear Doppler coefficient. This coefficient is largely influenced by the amount of ^{238}U and ^{240}Pu which absorb more or less neutrons by varying temperature.

The void coefficient is only applicable for water moderated reactors and describes the reactivity of the reactor compared to the voids created by the coolant in the reactor.
The moderator temperature coefficient determines the reactivity to coolant temperature change. In thermal reactors the physical density of the moderator is changed due to thermal expansion. The thermal cross section of the moderator is also changed with a change in temperature.

The moderator pressure coefficient is defined as the reactivity caused by a change in system pressure. The pressure in the reactor vessel is highly responsible for the moderator to fuel ratio which is an important factor for the sort, speed and amount of nuclear reactions.

Transient behavior

Analysis of the size of the neutron population varies with time and is described as the transient behavior of the reactor. The following issues influence this size:

- Startup (supercritical) or shutdown (sub critical) of the reactor.
- Insertion or withdrawal of control rod, or injection of chemical shim.
- Change of amount of power drawn from reactor by cooling
- Temperature effect on several factors forming the multiplication factor.
- Fission product poisoning (during operation and after shutdown)
- Fuel burn up and fission product formation

The average lifetime of the neutrons in combination with the multiplication factor will give the amount of neutrons extra or less.
According to Jevremovic [2005] the reactor period is defined as the time needed for the neutron flux (neutrons per area per unit time) to change by a factor e.
$T=l_{\infty}/\Delta k_{eff}$

If this period is too short the reactor is dangerously unstable.

Some of the neutrons in the order of less then 1 % are delayed. It takes much longer for these neutrons to appear out of the fission products then the other 99% so called prompt neutrons. The prompt neutrons are so fast that in the startup the reactor acts exponentially if the multiplication factor is kept $k_{eff} = 1$, after a few seconds when delayed neutrons start to appear the rate of neutron flux and reactor power starts to level (if k_{eff} is kept constant!). Because of this delayed neutrons the reactor is controllable, without these delayed neutrons the reactor would react too fast for safe control.

B. Radiation Doses

Radiation is measured in several units, which include time or even relative danger for living creatures.

The amount of decays per second is given by the SI derived unit Becquerel [Bq]. This used to be curie [Ci] after the pioneers of radiology, Marie and Pierre Curie. The Curie was defined as the activity of 1 gram of radium isotope ^{226}Ra 1 Ci = 3.7 x 10^{11} Bq. The Becquerel is named for Henri Becquerel, who shared a Nobel Prize with Pierre and Marie Curie for their work in discovering radioactivity.

Röntgen [R] is a unit measurement of the ionizing capability of radiation in air named after Wilhelm Röntgen. It is defined as the amount of radiation required to neutralize one unit of electrical charge in 1 cm3 of air at standard temperature and standard pressure. In SI units; 1 R = 2.58×10−4 C/kg. In a standard atmosphere (air density ~1.293 kg/m³) and using an air ionization energy of 36.16 J/C, we have 1 R ≈ 9.330 mGy, or 1 Gy ≈ 107.2 R.

Gray [Gy] is the unit in which the absorption of radiation is defined; one gray is the absorption of one joule by one kilogram of matter. As can be seen this is derived of SI units. The United States is the only country which still uses Rad as unit. 1 rad = 0.01 [Gy] = 0.01 joule of energy absorbed per kilogram of tissue.

Rem, Röntgen Equivalent in Man, is the product between the absorbed dose in röntgen and the biological impact of the radiation. This biological impact of the radiation can be transformed in a weighting factor combining the dangers for all different kinds of tissue, also known as the equivalent dose.

Sievert [Sv] is the SI unit version of rem, named after Professor Rolf Maximilian Sievert, a medical physicist who made great contributions to knowledge of the biological effects of radiation. Sievert is defined as the amount of absorbed dose in grays multiplied by a dimensionless Quality Factor "Q", dependent on radiation type, and multiplied by another Dimensionless factor N. N depends upon the part of the body irradiated, the time and volume over which the dose was spread, even the species of the subject. Thus sievert has the same unit as gray: J/kg.

Here are some quality factor values [Q]:
Photons, all energies: Q = 1
Electrons and muons, all energies: Q = 1

Neutrons;
-energy < 10 keV: Q = 5
-10 keV < energy < 100 keV: Q = 10
-100 keV < energy < 2 MeV: Q = 20
-2 MeV < energy < 20 MeV: Q = 10
-energy > 20 MeV: Q = 5
Protons, energy > 2 MeV: Q = 5
Alpha particles and other atomic nuclei: Q = 20

Here are some N values for organs and tissues:
Gonads: N = 0.20
Bone marrow, colon, lung, stomach: N = 0.12
Bladder, brain, breast, kidney, liver, muscles, esophagus, pancreas, small intestine, spleen, thyroid, uterus: N = 0.05
Bone surface, skin: N = 0.01
And for other organisms, relative to humans:
Viruses, bacteria, protozoan's: N ≈ 0.03 – 0.0003
Insects: N ≈ 0.1 – 0.002
Mollusks: N ≈ 0.06 – 0.006
Plants: N ≈ 2 – 0.02
Fish: N ≈ 0.75 – 0.03
Amphibians: N ≈ 0.4 – 0.14
Reptiles: N ≈ 1 – 0.075
Birds: N ≈ 0.6 – 0.15
Humans: N = 1

According to the Nuclear Regulatory Commission the limits for maximum radiation dose are for adults normally working with radioactive material a cumulative maximum of 50 mSv per year and 100 mSv in 5 years.
Individual members of the public should not receive more then 1 mSv per year from any nuclear installation.
The exposure for an average person is about 3.6 mSv per year. Natural background radiation comes from two primary sources: cosmic radiation and terrestrial sources, the natural background radiation is 2.4 mSv per year on average, and so accounts for 2/3 of the average received radiation.
A quote from the World Health Organization from their November 2005 report:" Aircrew flying 600-800 hours per year are exposed to 2 to 5 mSv of radiation each year in addition to the usual radiation of 2-3 mSv through man-made (mostly medical) and natural radiation sources." So frequent flying will result in a higher received dose, the higher the altitude the more radiation received. The radiation is doubled with each 2 km in altitude. Radiation exposure should always be with the ALARA-principle in mind: As Low As Reasonably Achievable.

C. Nuclear reactor types

A nuclear reactor is a device in which nuclear reactions are initiated, controlled and sustained at a certain rate. There are several designs of nuclear reactors. Not all these designs are publicly available, because some of these reactors are designed to create isotopes usable for atomic weapons. In this chapter I will try to point out the known used reactor designs as well as some new designs suitable for power generation.

A nuclear reactor is in simple terms, in case of energy production, a heat source. There are different kinds of fuel assemblies and different kinds of coolants to get the energy out of the reactor. The next step is to create from the heat more usable energy as kinetic energy or electrical energy. In some cases heat itself can be seen as a usable product.

The different generations of reactor designs is dived into 4 generations;
The I Generation designs are the prototypes, the II Generation designs are derived from the prototypes and were commercially produced. The III Generation designs are the improved commercial designs based on the II Generation designs. The IV Generation designs are the latest improved innovative designs based on the III Generation designs.
As such there is no experience with IV Generation reactors. Because of this, these reactor types will not be considered for marine applications in this report.

The Magnox Reactor

The magnox reactor is named after its magnesium non-oxidizing alloy fuel cladding. The fuel is pressed in rods which are combined to form a fuel rod assembly. The reactor is cooled en moderated by CO_2. With the heated gas steam is produced, which is turned into electricity with a steam turbine. Additional product remaining in the fuel is plutonium usable for nuclear weapons. The reactor type has been operated at pressures between 6.9 and 27 bar. Because of the fuel cladding the reactor is operated at lower temperature. The magnox reactor is surpassed by the Advanced Gas Reactor which was derived from it.

The Boiling Water Reactor (BWR)

The BWR is a lightwater reactor which has been produced from 1950's. The fuel assembly consists of rods containing the fissionable material. The moderator is normal water which is directly in contact with the fuel assembly. The steam produced is fed to a turbine producing electricity. The water is cooled in a condenser and then fed to the reactor again. The reactor is controlled by control rods.

Breeder Reactor

The Breeder reactor breeds fissile isotopes and was mainly used to produce new fissile products as Plutonium. Energy is also produced as in heat. The reactor used fast neutrons to create new fissile material. These neutrons are not slowed down by the liquid natrium (or another material that doesn't absorb or slow down neutrons) as would have been in water or another moderator. There are many types of breeder reactors, it only has to produce more fissile material then it uses for its own reactions to be called a breeder. The reactors are usually controlled by control rods.

Pressurized Water Reactor (PWR)

The fuel assembly is somewhat the same as in a BWR. The water, the moderator in this system, which flows through the reactor, is pressured so it will not form steam. The pressurized water heats a second system that boils the water and runs it through a steam turbine to form usable energy. Reactor is controlled using chemical shim and control rods. The maximum temperature extracted from the reactor will be approximately 330 °C.

Pebble Bed Gas Cooled Reactor (PBR)

The PBR has a special fuel type; the uranium is pressed into tiny graphite balls with a silicon carbide layer around it called TRISO-particles or elements. These elements are combined in a larger graphite ball. The balls will also consist partly of burnable poison and regulate themselves to a stable temperature when activated, this temperature must be above 250 °C because of the hazardous Wigner effect. An inert gas is run through the reactor at approximately 550 °C inlet and 900 °C outlet temperature, to get the produced heat out of the reactor. From this heated gas a steam cycle or a gas turbine cycle can be run converting the heat to kinetic energy. The advantage of this reactor is that it regulates itself based on the maximum temperature in the reactor.

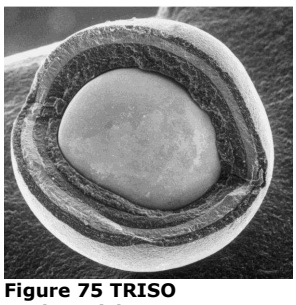


Figure 75 TRISO Fuel Particle

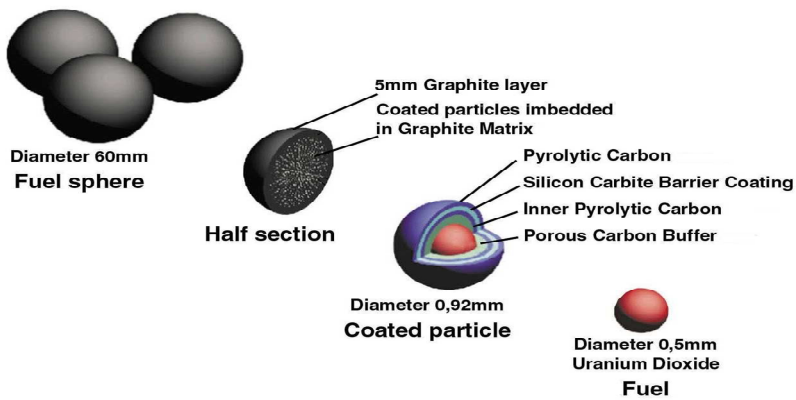


Figure 76 Fuel "Ball" with TRISO elements

Prismatic-block Gas Cooled Reactor (PR)

The prismatic-block gas cooled reactor has the same principle as the PBR but uses instead of balls, prismatic blocks as a fuel assembly. By using this block the reactor core can be made denser, smaller cooling channels, resulting in a compacter core.

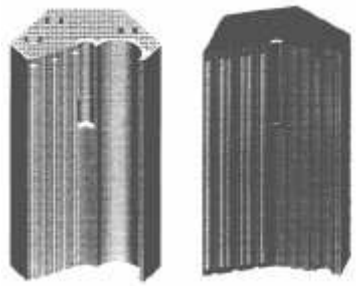


Figure 77 Prismatic Blocks

Heavy Water Reactor (CANDU)

The CANadian Nuclear power generation technology developed this reactor. It actually works the same as a PWR but instead of using normal water as a moderator it uses deuterium (heavy water) so it can run on natural uranium without enriching it.

Advanced Gas Cooled Reactor (AGR)

The AGR works with the same principles as the Magnox reactor, only on higher pressures and higher temperatures. The fuel cladding is stainless steel in stead of the magnox alloy. The higher temperatures and pressures were used to make use of the same design turbo generator plant as a conventional coal or gas fired plant.

Water Cooled Channel Reactor (RBMK)

RBMK is an acronym for the Russian *reaktor bolshoy moshchnosti kanalniy* (Russian: Реактор Большой Мощности Канальный) which means "reactor (of) high power (of the) channel (type)". This type was used in Chernobyl. The principle is almost the same as in a BWR, graphite is used as a moderator and steam is produced at 291 °C. The only difference here is that the water is moving through graphite channels in stead of a more open fuel assembly.

There are multiple variations of the reactor types mentioned above, but these cover the main working principles.

D. Naval nuclear Reactors

The Russians and Americans both developed naval nuclear reactors almost all of these reactors are PWR's, the PWR's were actually specially designed for operation on sea, later on the principle was also used ashore. A summary of the naval reactors are found below.

Russian naval reactors with one type of liquid metal cooled reactor (LMR)

KLT-40 is a PWR using enriched uranium fuel to produce 135 MWth.
KN-3 is a PWR using enriched uranium fuel to produce 300 MWth
OK-150 is a PWR using enriched uranium fuel to produce 90 MW
OK-900 is a PWR using enriched uranium fuel to produce 171 MW
OK-550 is a LMR using highly enriched uranium to produce 155 MWth
OK-650 is a PWR using highly enriched uranium fuel to produce 190 MWth
VM-4 is a PWR using highly enriched uranium fuel to produce 70-90 MWth
VM-5 is a PWR using highly enriched uranium fuel to produce 177 MWth
VM-A is a PWR using highly enriched uranium fuel to produce 90 MWth

American naval reactors

The different designs designated with letters and numbers:
A1B, A1W, A2W, A3W, A4W, C1W, D1G, D2G, S1C, S1G, S1W, S2C, S2G, S2W, S2Wa, S3G, S3W, S4G, S4W, S5G, S5W, S6G, S6W, S7G, S8G, S9G.
Where the first letter stands for the purpose; A is Aircraft Carrier, C is Cruiser, D is Destroyer and S is submarine. The number stands for the generation of the design. The last letter stands for the designer/constructor; B is Bechtel, C is Combustion Engineering, G is General Electric and W is Westinghouse. All US designs are also used for the higher power range 80-500 MWth.

So no developed naval nuclear reactor lies in the scope of propelling a small coaster with 8 MW of propulsion.

E. History of Helium cooled graphite moderated reactors

Dragon in England (1964 - 1976) was a success full demonstration reactor which used helium as a coolant and a carbide uranium fuel, also carbide thorium was tested as a fuel. The core consisted of 37 fuel elements in a hexagonal array with an effective diameter of 1,08 m. Core diameter including reflector was 1,5 m. The overall length of fuel was 2,54 m, of which 1,6 m. in the middle contained fuel.

AVR in Germany (Jüllich 1966 - 1988) was also a successfull demonstration reactor reaching an operation temperature of 850 °C, and extreme high safety due to a strong negative Doppler effect. A total loss of coolant circulation resulted in a safe shutdown all by itself.

Peach bottom in the U.S. (1967 - 1974) was a prototype helium reactor which achieved 86% availability during electricity production phase.

Fort St. Vrain in the U.S. (1979 - 1989). The coated particle fuel used in this reactor worked extremely well, but problems with the water-lubricated circulator caused large downtimes. The reactor was decommissioned after discovery of cracks in the steam ring header immediately below the reactor. Workers received extreme low doses of radiation 1% in comparison with average water reactors. 5 billion kWh of electricity was generated.

Oberhausen 2 in Germay (1975 - 1987) Helium was used in a closed cycle for electricity and heat production in a conventional steam plant. The plant incorporated large heat exchangers suitable for future helium cooled nuclear power plants.

THTR in Hamm-Uentrop, Germany (1985 - 1988). This helium cooled reactor was forced to shutdown due to political resistance caused by the Chernobyl accident.

Reactor	Power (MWe)	Power (MWth)	Tin (^oC)	Tout (^oC)	Press (bar)	Operation time	Power dens (MW/m^3)	Flow rate (kg/s)
Dragon	-	21,5	275	750	20	1964-1976	-	9,62
AVR	15	46	270	950	11	1967-1988	2,6	13
THTR	300	750	250	750	40	1984-1990	6	-
Peach Bottom	40	110	344	770	24	1967-1974	8,3	-
Fort St Vrain	330	842	400	770	50	1973-1989	6,3	-

HTTR in Japan reached first criticality in 10 November 1998. The reactor has a thermal power of 30 MW and is used as a research reactor. High temperature material irradiation research is done and nuclear heat utilisation is researched. A maximum outlet temperature of 950 °C was achieved April 2004.

A PBMR demonstration power plant in South Africa is planned to be constructed starting in 2008, using a direct closed helium gas turbine cycle. Still problems exist with a helium gas turbine, mainly in the gears; it proves not feasible to use oil to lubricate the gear. Magnetic bearings would be the solution, but this give still problems.

F. Calculations for Xenon poisoning

Jevremovic [2005] gives a calculation for the Xenon concentration:
Tellurium-135 ^{135}Te is together with Iodine-135 ^{135}I the primary source of Xenon. The fission yield of Xenon gives only 0,3 %, for ^{135}Te this is 3% and ^{135}I 3 %.

Fission → ^{135}Sb → -β(0,8s) → ^{135}Te → -β(19s) → ^{135}I → -β(6,6h) → ^{135}Xe → -β(9,1h) → ^{135}Cs → -β(2,3 x 10^6y) → ^{135}Ba (stable)

As can be seen from the decay scheme the decay times of Sb and Te are very short and for calculation ease their molar percentages can be added with the amount of Iodine I.
$y_I = y_{Sb} + y_{Te} + y_I$
The last nuclide in the decay scheme has a very long half life so the decay of this can be disregarded when looking at Xenon poisoning.
Further simplification for calculation in case of a homogeneous reactor the iodine concentration can be determined as:

$dI/dt = y_I \Sigma_f \Phi - (\lambda^I I + \sigma_a^I I \Phi)$
Where I is the concentration of ^{135}I
λ^I is the radioactive decay constant of ^{135}I
σ_a^I is the thermal neutron absorption cross section of ^{135}I
y_I is the fission yield factor of ^{135}I (=0,061 for ^{235}U fuel including Cs and Te)
Σ_f is the macroscopic cross section for the fuel material in the reactor
Φ is the thermal neutron flux
Under the same assumption the Xenon change can be determined by:

$dXe/dt = y_{Xe} \Sigma_f \Phi + \lambda^I I - (\lambda^{Xe} Xe + \sigma_a^{Xe} Xe \Phi)$

Where Xe is the concentration of ^{135}Xe
λ^{Xe} is the radioactive decay constant of ^{135}Xe
σ_a^{Xe} is the thermal neutron absorption cross section of ^{135}Xe
y_{Xe} is the fission yield factor of ^{135}Xe (=0.002 for ^{235}U fuel)
When the reactor is operating for some time the equilibrium concentrations are attained. Setting dXe/dt and dI/dt to zero the equilibrium concentrations can be obtained for a working reactor:

$I_0 = y_I \Sigma_f \Phi / (\lambda^I + \sigma_a^I \Phi) \approx y_I \Sigma_f \Phi / \lambda^I$
$Xe_0 = (y_{Xe} \Sigma_f \Phi + \lambda^I I_0) / (\lambda^{Xe} + \sigma_a^{Xe} \Phi) \approx (y_{Xe} + y_I) \Sigma_f \Phi / (\lambda^{Xe} + \sigma_a^{Xe} \Phi)$

The absorption cross section for ^{135}I is very small in the thermal energy region, so the above equation can be simplified by neglecting the absorption rate. The equilibrium concentration of ^{135}I is proportional to the fission reaction rate and the power level.
The neutron flux is for the Xenon concentration in the numerator and the denominator. When the flux exceeds 10^{12} neutrons cm^{-2} s^{-1} the term including the flux becomes dominant and at nearly 10^{15} neutrons cm^{-2} s^{-1} the ^{135}Xe concentration approaches a limiting value.

The equations are simplified after shutdown (Φ=0). The rate of change of the Xenon concentration, in case of shutdown, can then be reduced to:

$$\frac{dXe(t)}{dt} = \lambda^I I - \lambda^{Xe} Xe(t) = \lambda^I I_0 e^{-\lambda^I t} - \lambda^{Xe} Xe(t)$$

The solution to this equation gives the Xenon concentration

$$Xe(t) = \left(\frac{\lambda^I I_0 e^{\left(\lambda^{Xe} - \lambda^I\right)t}}{\lambda^{Xe} - \lambda^I} + C \right) e^{-\lambda^{Xe} t}$$

When the Xenon concentration is known the ability to restart can be evaluated.

G. Xenon Poisoning in combination with the Load Balance

Fission products can absorb neutrons, as mentioned in the appendix A. Especially Xenon and Samarian have a quite large thermal neutron absorption cross section, where Xenon has the largest effect. The fission yield for Xenon is 0.065 and for Samarian is 0.011 , with an absorption cross section of 2.800.000 barn for Xenon and 50.000 barn for Samarian, for comparison ^{235}U has a cross section of approximately 680 barn . Xenon is not directly available in the reactor but is produced through the decay of Iodine according to the following reaction:
$^{135}I \rightarrow$ β-decay (6.6 hr halftime) $\rightarrow$ $^{135}Xe \rightarrow$ β-decay (9.1 hr halftime) $\rightarrow$ ^{135}Cs
With a peak in Xenon after a reaction shutdown and a build up time of approximately 6-12 hours.
The neutron flux is the source of this Xenon-poisoning, the higher the neutron flux the higher the poisoning is after shutdown.

The negative temperature effect in a reactor using TRISO elements is not high enough to compensate for the additional neutron absorption of Xenon. From Figure 78 produced by Snoj [2005], the coefficient for temperature difference can be reviewed $\Delta k_\infty = 0.013$ with the reactivity for a infinite reactor $\rho_\infty = \Delta k_\infty / k_\infty = 0.013/1.422 = 0.00914$ over 900 K difference, where the Xenon poisoning can form factors ranging from 0.03 to 1.3 in a neutron flux range from 10^{13} to $5 \cdot 10^{14}$ /cm^{-2}s^{-1}. Clearly Xenon poisoning is stronger then the TRISO elements can overcome by their reactivity due to lower temperatures after a short shutdown period.

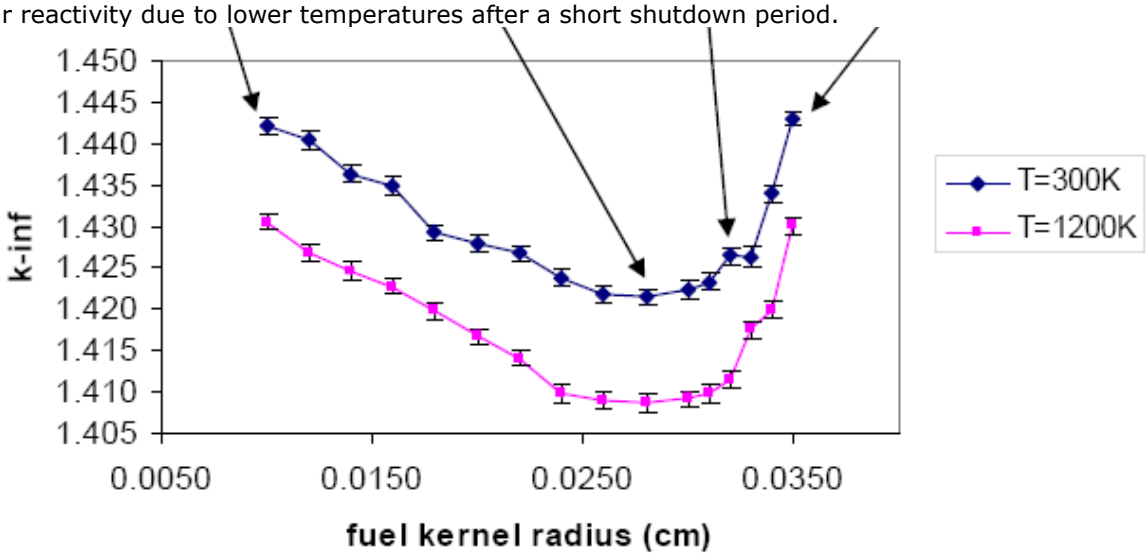


Figure 78 Kernel size in comparison with Multiplication factor

The ability of Xenon to absorb neutrons gives problems with restart. When too much Xenon is present in the reactor, the reactor will not have sufficient reactivity; approximately 0,015 change in reactivity for a ΔT of 900 °C, to restart its normal operation conditions. This amount of Xenon is present after approximately 4 hours after a shutdown for a passive reactor.

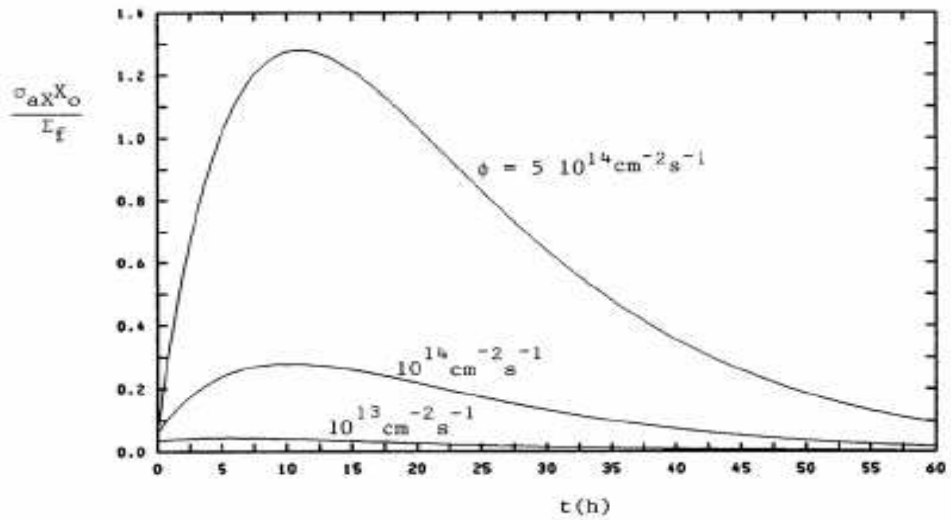


Figure 79 Xenon Buildup in reactor after shutdown

The passive reactor can commence operation after a period of approximately 20-30 hours. This largely depends on the size and the neutron flux of the nuclear reactor, see Figure 79 taken from Van Dam[2005], where $\sigma_{aX}X_o/\Sigma_f$ is the factor by which the reactivity changes according to $\rho_X = -k_\infty/v \cdot \sigma_{aX}X_o/\Sigma_f$.

Designing a reactor as such that there is a surplus reactivity, demands for active control with controlrods, or other means of neutron influencing.

Concept solutions for this problem:

- Ship profile; longer harbor time then 20 hrs
- 2 reactors in one ship; making it possible to run on 1 reactor.
- Design reactor as such that a surplus of reactivity is at present to make sure Xenon poisoning will not have a large effect. Active control rods necessary.

- Peak shaving, by use of accu's
- Peak shaving, by heat dumping

H. Major Nuclear Accidents

Windscale Fires 1957

The Windscale reactors were so called piles, reactors for the production of nuclear weapons, graphite moderated and air cooled. The Wigner effect (sudden energy release) in graphite control rods caused fire in the reactor. No immediate deaths but radioactive materials vented in the atmosphere causing a radioactive isotope distribution with effects for multiple days in the surrounding. Lack of knowledge was here the cause of the accident.

Browns Ferry March 1975

Browns Ferry reactors were BWR's. Cabling of the installation was set on fire by an engineer carrying a candle to check for air leaks in the insulation, making normal operation impossible. Reactor was kept under control by adding coolant through the controlrod drive pumps which were not designed for this purpose. No serious consequences, but a serious warning of what could have gone wrong. Human carelessness was the cause of the accident.

Three Mile Island March 1979

Three Mile Island had 2 PWR's. Problems in the secondary cooling system resulted in boiling water in the primary cooling system, eventually resulting in damage to the fuel rods and a hydrogen buildup within the containment vessel. Slight increases of radioactivity near the plant, no radioactive isotopes were released. Engineering and maintenance problems caused the failure in the system.

Chernobyl April 1986

Chernobyl had 4 RBMK's. Safety and shutdown tests lead to the depletion of the cooling water in the core, creating high steam pressures in the reactor core, which ruptured creating hydrogen and steam explosions exposing the core to the atmosphere. This caused 31 immediate deaths and severe radioactive isotope distribution across Europe. The accident was caused by a combination of lack of knowledge and design flaws.

Several more accidents happened but those above are the most serious, a list of nuclear accidents can be found on http://en.wikipedia.org/wiki/List_of_civilian_nuclear_accidents.

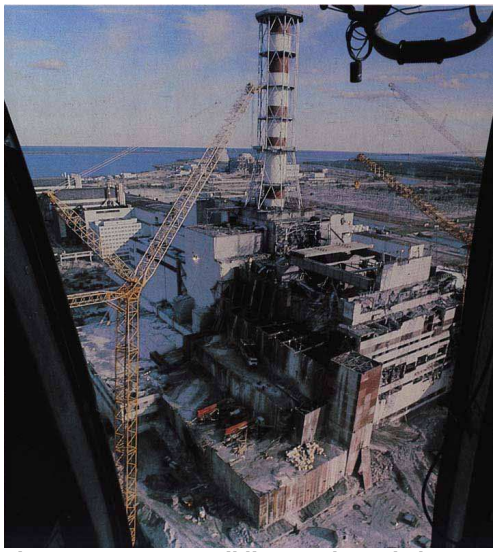


Figure 80 Reactor Building at Chernobyl

I. Nuclear Submarine Accidents

Many accidents have happened aboard nuclear submarines and because of this there are 6 Submarines lying on the ocean floor: two American vessels (USS Thresher and USS Scorpion) and four Soviet (K-8, K-219, K-278 Komsomolets and K-27). The two American submarines and three of the Soviet nuclear submarines sank as a result of accident; the fourth Soviet vessel was scuttled in the Kara Sea upon the decision of the responsible authorities when repair was deemed impossible and decommissioning too expensive. The latest accident was with the Kursk which completely sank to the bottom of the sea, but this submarine was salvaged because of national and international pressure.

The USS Scorpion (SSN-589), build in 1960, sunk on 22 May 1968, she was found at 3000 meters deep, 400 miles South West of the Azores, she was lost with all hands. The cause of the accident was never found but thought to be the vessels own test torpedo.

The USS Thresher (SSN-593), build in 1961, sunk on 10 April 1963, probably cause of saltwater piping failure, subsequent loss of power and inability to blow ballast tanks rapidly enough to avoid sinking. She was found at 1700 meters deep, 220 miles east of Boston. She was lost with all 129 crewmembers.

K-8 (Project 627 A November Class) 8 April 1970, had 2 fires on board for which she surfaced, emergency systems kicked in stopping the reactor, diesel generators wouldn't start, the aft 2 compartments flooded, 52 man died in the accident the rest was evacuated after surfacing. The ship lies in the Bay of Biscaya at a depth of 4860 meters.

K-219 (Project 667 A Yankee Class) 6 October 1986 an explosion in one of the missile tubes caused the submarine to sink, after surfacing and shutting down the reactors with loss of 4 lives the ship sunk north of Bermuda.

K-278 Komsomolets (Project 685 – Mike Class) a unique titanium and extremely fast submarine, sank in the Barents Sea off the coast of Norway, after a fire causing a leak in the compressed air system. The ship surfaced but the emergency system automatically shut down the reactors causing a lack of compressed air. There were not enough rafts for the whole crew causing 41 deaths. The vessel now rests at 1700 meters depth.

K-27 (Project 645) had a serious radiation leak, caused by a LOCA (Loss Of Cooling Accident) during a voyage and was beyond repair. The vessel was scuttled in 1981 in the Kara Sea.

The Russian submarines (except Kursk) which sank by accident had actually virtually all the same accident profile:

1. Fire while submerged on return from patrol.
2. Surfacing of the submarine. Attempts made to salvage the submarine, both in submerged and surface position. By the time of surfacing, vessel had already lost power and possibility for outside contact.
3. Penetration of outside water into the vessel.
4. Command post loss of control over submarine's essential systems.
5. Loss of buoyancy and stability of pitch.
6. Capsize and sinking.

More accidents are reported, but without the loss of the submarine. Fire is the most common cause in these submarine accidents rendering the ships powerless when the emergency system kicks in.

Only the Komsomolets is assessed for its environmental impact, because it lies in a rich fishing ground which is used by Norwegian fishermen, the dangers are thought to be in the dissolving of the plutonium warheads. There are no clear answers about the danger of the Komsomolets lying on the seabed. Raising the sub is not really an option because of the bad condition the hull is in.

The Kursk can be seen as an example of the safety of nuclear installation onboard. The reactors survived 2 explosions one with a single torpedo and one with all the rest of the torpedo's onboard equivalent to 3-7 tons of TNT.

J. Heat into energy

In order to make use of the heat produced by a nuclear reactor a heat engine is necessary. So a heat engine is an engine which converts heat, or the difference in temperature of different media, into another usable energy like kinetic or electrical energy.

Thermodynamic Cycles

The several states of which the medium is in can be described in thermodynamic cycles. For heat engines there are four classes of cycles; Phase change cycles; gas only cycles; Electron cycles.

Phase change cycles

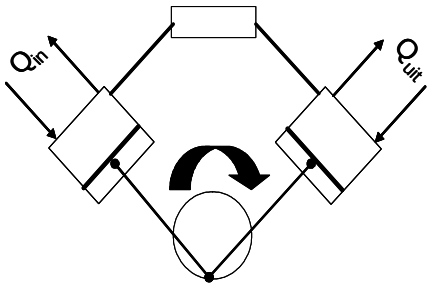


Figure 84 Aplha Model Sterling engine

In these cycles the working media change their phase. The engine converts for example the gas into a fluid producing work. The following cycle is part of these phase changing cycles: Rankine Cycle or the advanced version; the Regenerative Cycle. There are more examples like e.g. frost heaving (Ice is of greater volume then water) but these are not used in engineering.

Gas only cycles

The working media in these cycles are always gas. The following cycles are part of the gas only cycles: Carnot Cycle; Ericsson Cycle; Sterling Cycle and special for the internal combustion engine: Otto Cycle; Diesel Cycle; Atkinson Cycle; Brayton Cycle; Lenoir Cycle and the Miller Cycle.

Electron Cycles

In electron cycles the temperature difference is immediately transformed into electricity. The Peltier-Seebeck effect, the thermionic emission (Edison Effect) is part of these cycles.

Heat Engines

The following heat engines nowadays exist: Steam engine, Steamturbine, Gas turbine, Sterling engine and the peltier element.

Steam engine

The steam engine the first large power producing heat engine developed, industrial revolution was largely influenced by this invention. The heat is supplied to a closed boiler which forms the steam in a closed system. The build up pressure is used to move a piston in a cylinder, delivering kinetic energy. This power is delivered according to the Rankine Cycle.

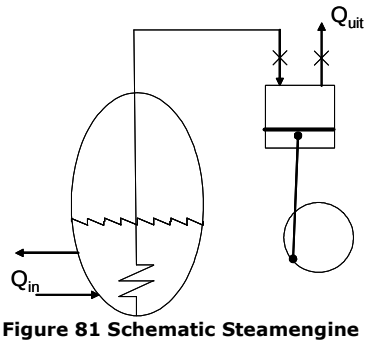


Figure 81 Schematic Steamengine

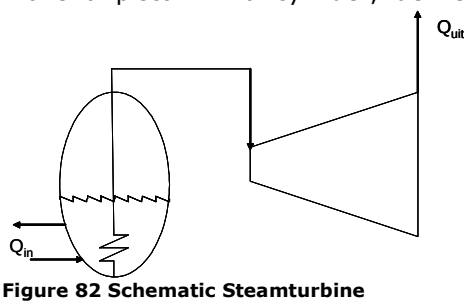


Figure 82 Schematic Steamturbine

Steamturbine

With the heat supplied to a boiler steam is formed this is run through a turbine. After the turbine the remaining steam and vapor is condensed in a condenser and is returned to the boiler. The rankine cycle is also applicable for the Steamturbine. The Steamturbine is on a larger scale more efficient then a steam engine, the steam engine however is better below 800 kW.

Gas turbine

The closed cycle Gas turbine consists of a compressor, a heater, a turbine, and a cooler. The used gas will be compressed, heat will be supplied, the gas will deliver its heat and pressure to the turbine which will deliver the kinetic energy and in the end the gas will be cooled to its original state. For an open cycle the gas is released into the environment and the environment is used as a source for the gas (air in this case). Gas turbines are readily available in

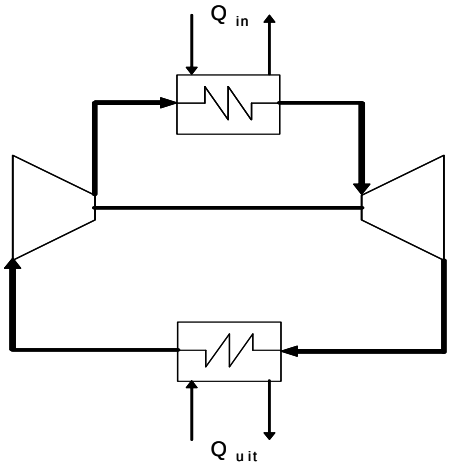


Figure 83 Schematic Gas turbine

Sterling engine

The Sterling engine is a closed system and usually consists of 2 cylinders, which off course can be put in series. The gas in the cylinder is heated and will expand pushing the piston away. A valve can be opened to another cylinder which is cooled, compressing the gas, pulling the cylinder back up. From the movement of the piston kinetic energy can be extracted. Engines for larger power outputs are still under development. Kockums has produced a larger Sterling engine for the Swedish submarines but details are hard to find.

Peltier element

Normally this element is used for cooling, but can be used in reverse way. The effect was discovered by a German physicist Thomas Johan Seebeck, who found that a potential difference existed on a bar of metal when a temperature difference existed in the bar.
The effect is that a voltage is created in the presence of a temperature difference between two different metals or semiconductors. This causes a continuous current to flow in the conductors if they form a complete loop. The voltage created is of the order of several micro volts per degree difference.
This is already used as a sort of battery on nuclear power. The decay heat of an Isotope in combination with the element provided the power. Only disadvantage is that the power delivery was rather disappointing 3-7 %.

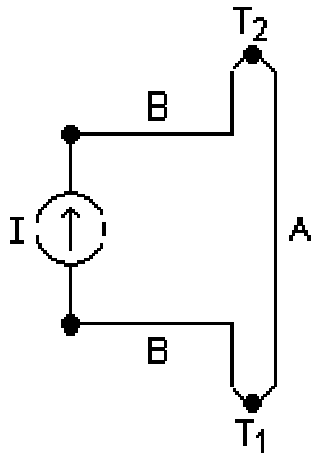


Figure 85 Peltier Element

Conclusion

The Steam engine is too large and to heavy to use in comparison with the other alternatives. The Steam turbine can be used when superheated steam is applied to maximize the results. A Gas turbine can be applied, advantages over Steam turbine: very lightweight and no phase change throughout the machine. The Sterling Engine sounds quite promising, probably high efficiency, but is likely to be heavier than a turbine just like the Steam engine, although decent engineering details are hard to find. The efficiency of a peltier element is too low for application on high output engines.
From this can be concluded that the Gas turbine has the most promising properties to process the heat into a usable energy form.

Relative INCOGEN costs

		Foak	Noak	Noak pool
year		1996	1996	1996
Plant rating	[MWe]	16,5	16,5	16,5
efficiency	%	41%	41%	41%
Base Capacity factor	%	83	90	90
Annuel power	kWh	119968200	130086000	130086000
Annuel power	MWh	119968,2	130086	130086
Thermal Power	[MWth]	40	40	40

Engineering			
Construction and field engineering	0%	-24%	-24%
Engineering home&office fee	0%	-24%	-24%
Capital costs			
Land	0%	0%	0%
Structures and improvements	0%	-34%	-34%
Reactor plant equipement	0%	-29%	-29%
Turbineplant equipement	0%	-46%	-46%
Electricplant equipement	0%	-18%	-18%
Miscelaneous plant equipement	0%	-18%	-18%
Owners Cost	0%	-24%	-24%
Contingency	0%	-31%	-31%
Decommissioning	0%	0%	0%
total	0%	-27%	-27%
Operations & Maintenance			
nr. of personnel	0%	0%	-60%
Cost personel	0%	0%	-60%
Fixed maintenance	0%	-25%	-25%
Variable maintenance	0%	-14%	-14%
Fixed suplies and expenses	0%	0%	0%
Variable control rod en reflector	0%	0%	0%
Varianle Supplies & Expenses	0%	0%	0%
Offsite technical support	0%	-47%	-47%
Nuclear regulatory fees	0%	-39%	-39%
Property insurrance	0%	-29%	-29%
Other administrative and general	0%	-16%	-16%
total O&M	0%	-13%	-42%
relative total /[Mwe]	0%	-13%	-42%
total Fuel	0%	0%	0%
relative total /MWh	0%	-8%	-8%
relative total /MW	0%	0%	0%

K. Power balance + Power profile

A minimized power balance is given below, from which the ships power profile is deducted.

Load Balance

			conditions:	At Sea		Manoeuvring		Load/Unload		Harbour	
Consumers	amount	kW	accumulati	min	max	min	max	min	max	Emerger	Still
Propulsion	1	7250	7250	4000	7250	0	4000	0	0	0	0
Bow thruster	1	700	700	0	0	0	700	0	0	0	0
Stern Thruster	1	500	500	0	0	0	500	0	0	0	0
Main Engine Support	40	293	449,72	68,12	198,22	68,12	198,22	53,07	120,57	0	43,27
Propulsion + Steering + Manoeuvring	12	196	316	30	78	34	124	0	42	12	0
Cargo handling	192	149,4	2182,9	1584	1612,5	1584	1612,5	63,5	1764,9	0	0
Emergency Handling	6	96	102	0	20	0	20	0	20	82	20
General	20	82,96	94,12	30,8	83,9	30,8	74,6	28,8	72,6	2,4	53,2
Lights	24	11,3	19,9	5	10	6	11	10	15,8	7,5	10
Air Conditioning	42	100,3	171,425	103,8	166,13	104,3	166,63	64,595	130,43	1,3	76,525
Total			**11786,07**	**5821,7**	**9418,7**	**1827,2**	**7406,9**	**219,97**	**2166,3**	**105,2**	**203**

Formula
Variable
Educated guess

	max [kW]	time %	min [kW]	time %	mean [kW]	time per trip [h]	kJ
Transit	9418,745	95%	5821,715	5%	9238,8935	20	665200332
Manoeuvring	7406,945	70%	1827,215	30%	5733,026	4	82555574
Harbor	2166,295	70%	219,965	30%	1582,396	24	136719014
Total					5118,4891	48	884474921

Energy per trip	884474920,8	kJ
Energy per trip	10,23697825	MWd
trips per week	3	
trips per year	156	
Active	85,48%	
Hours per year	7488	
Docking period	5	years
1 kWh	3600	kJ
1 MWd	86400000	kJ
Energy per year	1,37978E+11	kJ
	137978087,6	MJ
	38327246,57	kWh
	1596,968607	MWd
Burnuprate max	174	MWd/kg
usage	57%	
	100	MWd/kg
	20,76%	
Amount of fuel	384,6319731	kg

L. Gas turbine modeling for performance

For a simple cycle gas turbine:

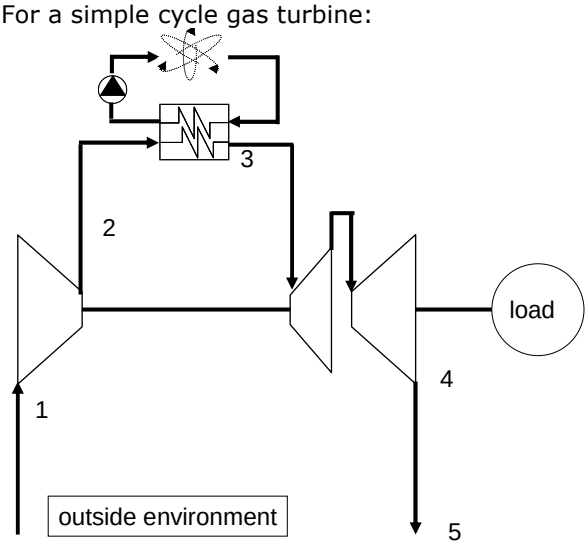


Figure 86 Schematic of simple cycle

Assuming a pressure ratio for the compressor gives the pressure after the compressor.

$$\pi_c = \frac{p_2}{p_1} \Rightarrow p_2 = \pi_c p_1$$

Assuming a polytropic efficiency (η_{pc}) for the compressor will lead to the temperature after the compressor:

$$T_2 = T_1 \left(\pi_c\right)^{\left(\frac{\gamma-1}{\eta_{pc}\cdot\gamma}\right)}$$

The temperature after the heat exchanger and pressure (drop) will follow from the assumptions made in the heat exchanger model.

At maximum power the pressure after the turbine will be ambient pressure corrected for the losses in the exhaust:

$$p_4 = \frac{p_1}{\eta_{exhaust}}$$

From this the pressure ratio from the turbine can be calculated:

$$\pi_t = \frac{p_3}{p_4}$$

Assuming polytropic efficiency for the turbine (η_{pt}) will result in the temperature after the turbine:

$$T_4 = T_3 \left(\frac{1}{\pi_t}\right)^{\left(\frac{\gamma-1}{\eta_{pt}\cdot\gamma}\right)}$$

With γ as the isentropic coefficient for air at the different temperatures.

The necessary specific power of the compressor can be calculated by:

$$\frac{P_c}{\dot{m}} = p_{\dot{m}c} = c_p \left(T_2 - T_1\right)$$

The delivered power by the turbines can be calculated by:

$$\frac{P_t}{\dot{m}} = p_{\dot{m}t} = c_p \left(T_3 - T_4\right)$$

And these equations above result in the available specific power, correcting for the losses from the shaft connecting the compressor and turbine:

$$p_{\dot{m}a} = p_{\dot{m}t} - \frac{p_{\dot{m}c}}{\eta_{shaft}}$$

Knowing the power that has to be delivered to the shaft, results in the mass flow through the turbine.

$$\dot{m} = \frac{P_{design}}{\eta_{el.gen}\eta_{el.motor}\, p_{\dot{m}a}}$$

From these calculations the ideal compressor ratio can be calculated at full power to obtain the highest efficiency. The model can also be optimized for specific power with the ability to have a smaller gas turbine with the same output, but this is not necessary the weight of the gas turbine is in comparison to the reactor very small and a lower efficiency of the gas turbine will result in a heavier reactor.

The model results into the following figures:

Gasturbine			specific heat air	1004,675	J/kg/k			temperature [˚C]	Pressure [bar]
atmospherical pressure	1,01325	bar	Specific heat hot air	1116,6	J/kg/k	environment	1	15,00	1,01
Maximum Air temperature	15	˚C	Power Compressor	335,96336	kW/kg*s	after compressor	2	349,40	9,82
Maximum Air temperature	288,15	K	Power Turbine	444,19208	kW/kg*s	After heatexchanger	3	800,00	8,94
			R	287,1		After Turbine	4	402,19	1,04
Airinlet			Efficiency shaft	0,99		After exhaust	5	395,44	1,02
Pressure ratio	0,98		Power left	104,83515	kW/kg*s				
Compressor			Design Power	4653,7396	kW				
Pressure ratio	9,89243		Mass flow	44,391022	kg/s				
gamma air	1,4								
Polytropic efficiency	0,85		Power Compressor	14913,757	kW				
			Power Turbine	19718,141	kW				
Heatexchanger									
pressure drop	0,88	bar	loss at exhaust	16967,022	kW				
Fluid temperature	800	˚C	Heat input	22334,90	kW				
Turbine			efficiency	20,84%					
Pressure after turbine	1,04								
Polytropic efficiency	0,85								
gamma heated air	1,34								
Pressure ratio	0,11679	8,6							
Exhaust									
End pressure	1,0234								
Heatloss	0,01								
Pressure ratio	0,98								

Formula
Variable
Educated guess

M. Main dimensions CF800

Main particulars	symbol	CF800		
		Design	ballast	
Length between Perpendiculars	L_{pp}	129,6	129,6	m
Length on waterline	L_{wl}	136,34	129,168	m
Length overall submerged	L_{os}	136,58	130,26	m
Breadth moulded		21,8	21,8	m
Draught moulded on Front Peak	T_f	7,3	3,75	m
Draught moulded on Aft Peak	T_a	7,3	5,75	m
Displacement mass in Seawater	Δ_1	13938	8211	t
LCB Position aft of FP	FB	67,06	69,91	m
Block Coefficient	C_B	0,654	0,592	-

Propulsion System:
Main Engine: MAK 9M43 8400 kW @ 500 rpm

Load Balance

			conditions:	At Sea		Manoeuvring		Load/Unload		Harbour	
Consumers	amount	kW	accumulation	min	max	min	max	min	max	Emerger	Still
Propulsion	1	7250	7250	4000	7250	0	4000	0	0	0	0
Bow thruster	1	700	700	0	0	0	700	0	0	0	0
Stern Thruster	1	500	500	0	0	0	500	0	0	0	0
Main Engine Support	40	293	449,72	68,12	198,22	68,12	198,22	53,07	120,57	0	43,27
Propulsion + Steering + Manoeuvring	12	196	316	30	78	34	124	0	42	12	0
Cargo handling	192	149,4	2182,9	1584	1612,5	1584	1612,5	63,5	1764,9	0	0
Emergency Handling	6	96	102	0	20	0	20	0	20	82	20
General	20	82,96	94,12	30,8	83,9	30,8	74,6	28,8	72,6	2,4	53,2
Lights	24	11,3	19,9	5	10	6	11	10	15,8	7,5	10
Air Conditioning	42	100,3	171,425	103,8	166,13	104,3	166,63	64,595	130,43	1,3	76,525
Total			**11786,065**	**5821,7**	**9418,7**	**1827,2**	**7406,9**	**219,97**	**2166,3**	**105,2**	**203**

GENERAL

YARD NUMBER	862
DELIVERY DATE	March 2007
BASIC FUNCTIONS	Transport of containers
CLASSIFICATION	GL +100 A5 E3 GL +MC E3 AUT
REGULATIONS	Equipped for dangerous goods according to SOLAS reg. 19 II-2, excl. Class VII. Sprinklers in hold 1
FLAG	Antigua and Barbuda
OWNER	MS "Jork Reliance" Bernd Becker GmbH & Co. KG

DIMENSIONS

LENGTH O.A.	140.64 m
LENGTH P.P.	130.00 m
BEAM MLD.	21.80 m
DEPTH MLD.	9.50 m
DRAUGHT	7.32 m
DEADWEIGHT	9340 ton
GROSS TONNAGE	7987 GT

TANK CAPACITIES

HFO (RMG 35)	880 m^3
MGO (DMA)	105 m^3
LUBRICATION OIL	48 m^3
DIRTY OIL	20 m^3
SLUDGE	21 m^3
SEWAGE	26 m^3
POTABLE WATER	74 m^3
BALLAST WATER	4597 m^3

CONTAINERS	TEU	TEU/FEU	30'	45'	48'/49'
IN HOLDS	206	12/97	135	97	-
ON DECK	597	69/264	376	232	40
TOTAL	803	81/361	511	329	40

PERFORMANCE

SPEED: 18 kn at 7.32 m draft with 85% MCR, 200 kW PTO and 10% sea-margin

PROPULSION SYSTEM

MAIN ENGINE	MAK 9M43
POWER	8400 kW
PROPELLER	4900 mm, 4 blades, CPP
BOW THRUSTER	700 kW, 4 blades, CPP
STERN THRUSTER	500 kW, 4 blades, CPP
RUDDER	Balance type
STEERING GEAR	Rotary vane

HOLDS AND HATCH COVERS

WEATHERDECK HATCHES	Hydraulic multi folding type
HOLD 1	Dimensions 28.44 m x 18.60/ 13.20 m
HOLD 2	Dimensions 28.44 m x 18.60 m
HOLD 3	Dimensions 28.44 m x 18.60 m

AUXILIARY EQUIPMENT

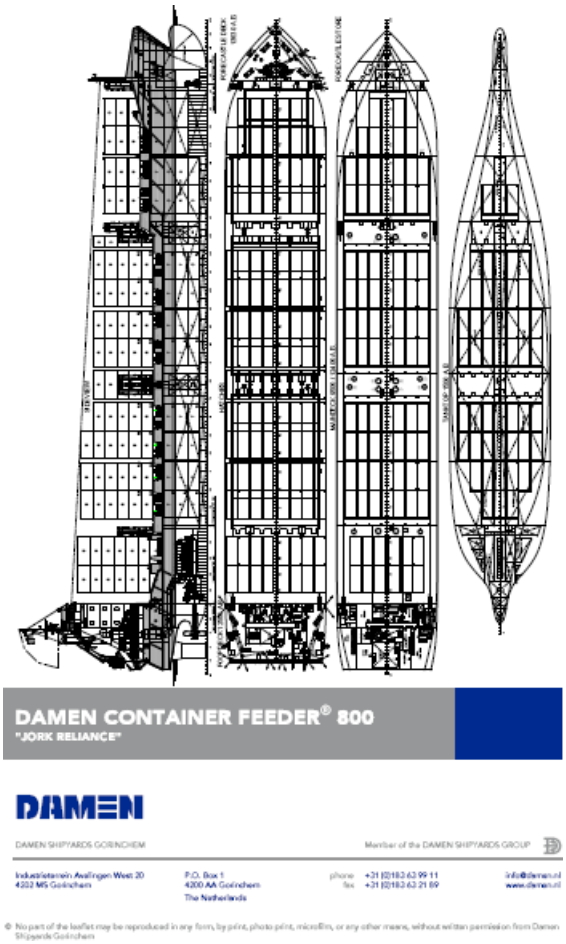
SHAFT GENERATOR	1x 2000 kVA, 60 Hz
DIESEL GENERATORSETS	2x 530 kVA, 60 Hz
EMERGENCY GEN. SET	1x 124 kVA, 60 Hz
ANTI HEELING SYSTEM	1120 m^3/hr
FIRE FIGHTING	CO_2 system for engine room and cargo holds
SPRINKLERS	In hold 1

DECK LAY-OUT

ANCHOR/MOORING WINCHES	2x electric self-tensioning on forecastle deck, with a single drum and warping head
MOORING WINCHES	2x electric self-tensioning on poop deck, with a single drum and warping head
DECK CRANE	1x for free-fall boat and provisions
DECK CRANE	1x for rescue boat and life raft
CONTAINER FITTINGS	For 20', 30', 40', and 45' on tanktop and hatch covers and 48' and 49' for one layer on deck
MOVABLE CELL GUIDES	In holds for 40' and 45' containers
REEFER PLUGS	120 on main deck, 30 in hold 2, 30 in hold 3

ACCOMMODATION

For a crew of 15 persons with heating, ventilation and air-conditioning



N. Calculation Shell and Tube heat exchanger

The reactor outlet temperature is chosen as described.(T_{rout})
The temperature difference is chosen as a constant assuming a linear temperature model for each heat exchanger. (dT_1 and dT_2)
The cold inlet temperature results from the gas turbine model. ($T_{compout}$=T_{cin2})

Main dimensions of the heat exchangers are assumed for iteration later: Tube length (L_t), Outside diameter Tube (D_o), Thickness Tube (t_t) (from which the inside diameter can be calculated (D_i=D_o-t_t)), amount of baffle plates ($N_{baffles}$) and the amount of Tubes (N_t).

From these the different necessary surfaces can be calculated:

$$\text{Inner heat transfer area} = A_{iht} = L_t \pi D_i$$

$$\text{Outer heat transfer area} = A_{oht} = L_t \pi D_o$$

$$\text{Inner flow area} = A_{if} = \frac{\pi}{4} D_i^2$$

$$\text{Outer flow area} = A_{of} = \frac{\pi}{4} D_o^2$$

The mass flow of air is determined by the specific power produced by the gas turbine and the necessary power corrected with the efficiencies of the generator and the electromotor:

$$\dot{m} = \frac{P_{design}}{\eta_{e-motor}\eta_{e-generator}P_{\dot{m}}}$$

Heat transfer

From the equations above the heat transfer can be determined if the temperature from the heat exchanger to the turbine (T_{cout2}) is assumed to be the reactor outlet temperature minus the 2 assumed constant temperature differences throughout the heat exchangers:

$$T_{cout2} = T_{rout} + dT_1 + dT_2$$

$$q_{air} = c_{p-air}\dot{m}_{air}\Delta T_{air} = c_{p-air}\dot{m}_{air}\left(T_{cout2} - T_{cin2}\right)$$

The heat transfer is for all the heat exchangers the same from which the other mass flows can be calculated:

$$q_{air} = q_{nitrogen} = q_{helium}$$

$$c_{p-air}\dot{m}_{air}\left(T_{cout2} - T_{cin2}\right) = c_{p-nitrogen}\dot{m}_{nitrogen}\left(T_{hin2} - T_{hout2}\right) =$$

$$c_{p-nitrogen}\dot{m}_{nitrogen}\left(T_{cout1} - T_{cin1}\right) = c_{p-helium}\dot{m}_{helium}\left(T_{hin1} - T_{hout1}\right)$$

In order to calculate the heat transfer at the shell side it is necessary to determine Reynolds, the heat transfer formulas are empirically determined as a function of Reynolds. For this calculation some other variables are needed which will be calculated below.

The first step is to calculate an approximation for the Shell diameter according to Kakaç [2002] this is given by:

$$D_s = 0,637\sqrt{\frac{CL}{CTP}}\sqrt{\frac{\pi D_o N_{tubes} L\left(\frac{P_t}{D_o}\right)^2 D_o}{L}} = 0,637\sqrt{\frac{CL}{CTP}}\sqrt{\pi N_{tubes} P_t^2}$$

Where CL is the tube layout constant defined as 1 for a 90° and 45° layout and as 0,87 for a 30° and 60° layout. CTP is the tube count calculation constant which account for the incomplete coverage of the shell diameter by the tubes due to necessary clearances between the shell and the outer tube circle and tube omissions due to tubes pass lanes for multitube pass design, defined as: 0,93 for 1 pass; 0,9 for 2 passes and 0,85 for 3 passes.
Kakaç also gives an equivalent diameter:
For square pitch:

$$D_e = \frac{4\left(P_t^2 - \pi \frac{D_0^{\,2}}{4}\right)}{\pi D_0}$$

And for triangular pitch:

$$D_e = \frac{2\left(\frac{P_t^2\sqrt{3}}{3} - \frac{\pi D_0^{\,2}}{8}\right)}{\pi D_0}$$

Triangular pitch gives the largest heat transfer coefficient so this will be used.
The bundle cross flow area is defined as:

$$A_s = \frac{D_s CB}{P_t}$$

Where B is defined as the baffle spacing and C as the distance between the edges of the tubes.
The velocity determining Reynolds is defined as the shell side mass velocity:

$$G_s = \frac{\dot{m}}{A_s}$$

With the variables above Reynolds for the shell side flow becomes:

$$\mathrm{Re}_s = \frac{G_s D_e}{\mu}$$

If Re_s is between $2\mathrm{x}10^3$ and $1\mathrm{x}10^6$ the shell side heat transfer coefficient is suggested to be:

$$\frac{h_o D_e}{k} = 0,36\left(\mathrm{Re}_s\right)^{0,55}\left(\mathrm{Pr}_s\right)^{\frac{1}{3}}\left(\frac{\mu_b}{\mu_w}\right)^{0,14}$$

With prandtl defined as:

$$\mathrm{Pr}_s = \frac{c_p \mu}{k}$$

The heat transfer at the tube side can be calculated from the Petuhkov-Kirillov correlation as given by Kakaç.
Reynolds is defined as:

$$\mathrm{Re}_t = \frac{\rho u_m D_i}{\mu}$$

Where u_m is the flow velocity.
And the empiric formula for Nusselt is given by:

$$Nu_t = \frac{\left(f/2\right)\mathrm{Re}_t\,\mathrm{Pr}_t}{1,07 + 12,7\sqrt{f/2}\left(\sqrt{\mathrm{Pr}_t} - 1\right)}$$

with

$$f/2 = \left(1,58\ln\left(\mathrm{Re}_t\right) - 3,28\right)^{-2}/2$$

From the empirically determined Nusselt the heat transfer coefficient for the fluid inside the tube can be determined:

$$h_i = \frac{Nu_t k}{D_i}$$

From here the overall heat transfer coefficient can be determined defined as:

$$U = \frac{1}{\frac{1}{h_o} + \frac{1}{h_i}\frac{D_o}{D_i} + \frac{D_o \ln\left(D_o/D_i\right)}{2k}}$$

From here the overall the heat transfer can be calculated:

$$Q = UA_o \Delta T$$

Iteration of the variables will lead to the desired result, the only problem is that the amount of variables which can be varied are rather large.

Approximation Stresses

Stresses in the tubes and shell of the heat exchanger are limiting factors. The maximal stress is assumed to be 60 Mpa (at peak temperature of 950 °C) which holds a safety factor of approximately 2. This will prescribe the thicknesses of the tubes and shell of the heat exchanger.
Stress in longitudinal direction is calculated by:

$$\sigma_1 = \frac{p\pi r_i^2}{\pi(r_o^2 - r_i^2)}$$

Where p is the pressure difference (taken as the maximum pressure in the vessel minus the atmospheric pressure), r_i is the inner radius and r_o is the outer radius.

Stress perpendicular to longitudinal direction is calculated by:

$$\sigma_2 = \frac{p2r_i l}{(r_o - r_i)l}$$

Where l is the length of the tube which falls out and the rest is already defined above.
Stress in the final direction is the direct effect of pressure:

$$\sigma_3 = p$$

Where according to the total strain theory the maximum stress is:

$$\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3) \leq \sigma_y^2$$

or according to the distortion energy theory, also known as the Von Mises criterion:

$$\frac{1}{2}\left((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right) \leq \sigma_y^2$$

Both criteria were used in search of the thickness of the material.

From these equations an estimate can be made for the size and weight of a Shell and Tube heat exchanger.

After conversation with sales of Bronswerk the following information was retrieved: the normal used maximal tube diameter is in inches and the thickness of the tubes maximal 2,77 mm. To lower the resistance inside the heat exchanger, the amount of tubes is altered through which the flow velocity changes. The price of the needed material can mount up to 60 €/kg. Designing to achieve extreme lightweight construction for this kind of steel is a very important factor on the total price; manual labor is often not the largest cost parameter when dealing with this heavy equipment.

The statement about the diameter is not in agreement with Kakaç [2002]. Data is provided for higher thicknesses.

Pressure drop

The pressure drop over the heat exchanger is calculated using the method described by Kakaç [2002].
For the Shell Side pressure drop:

$$\Delta p_s = \frac{fG_s(N_b + 1)D_s}{2\rho D_e \phi_s}$$

Where f the friction factor, G_s the shell side mass velocity, N_b is the number of baffles, D_s the shell diameter, ρ the density, D_e the equivalent diameter of the shell and Φ_s a correction factor for the viscosity (taken as 1).

$$f = e^{(0{,}576 - 0{,}19\ln(\mathrm{Re}_s))}$$

Where Reynolds is defined as:

$$\mathrm{Re}_s = \frac{G_s D_e}{\mu}$$

Where the shell side mass velocity is defined as:

$$G_s = \frac{\dot{m}}{A_s}$$

Where the bundle cross flow area for a triangular pitch is defined as:

$$A_s = \frac{D_s CB}{P_T}$$

Where C is the clearance between the tubes, B the baffle spacing and P_T the pitch size (distance between centres of 2 tubes)

For the equivalent diameter of the shell:

$$D_e = \frac{\left(2P_T^{\,2}\sqrt{3} - \pi d_o^{\,2}\right)}{\pi d_o}$$

Where d_o is the outside diameter of a tube.

The pressure drop inside the tubes is calculated by:

$$\Delta p = \left(4f\frac{LN_p}{d_i} + 4N_p\right)\frac{\rho U_m^{\,2}}{2}$$

Where f is the friction factor, L the length of the tube, N_p the number of tube passes, d_i the inner diameter of the tube, ρ the density, U_m the tube side velocity of the medium.

The friction factor is split into multiple equations depending on the Reynolds number:

$$\mathrm{Re}_T = \frac{U_m \rho d_i}{\mu}$$

For Re < 3000, laminar flow:

$$f = \frac{16}{\mathrm{Re}_T}$$

For 3000 < Re_T < 5 x 10^4, turbulent flow:

$$f = 0{,}0791\,\mathrm{Re}^{-0{,}25}$$

For 5 x 10^4 < Re_T < 1 x 10^6:

$$f = 0{,}046\,\mathrm{Re}^{-0{,}2}$$

Weight estimation

The weight of the shell and tube heat exchanger was estimated by multiplying the cut through surface of one tube by the length and the amount of tubes adding the weight of the shell by assuming the form of the shell as a cylinder with two half spheres on each side, resulting in:

$$m_{HE} = \left(\frac{\pi}{4}\left(D_o^{\,2} - D_i^{\,2}\right)L_t N_{tubes} + \frac{1}{6}\pi\left(\left(D_s + t_{shell}\right)^3 - D_s^{\,3}\right) + \frac{\pi}{4}\left(\left(D_s + t_{shell}\right)^2 - D_s^{\,2}\right)L_t\right)\rho_{steel}$$

This will not give the exact answer, but will lead to a satisfying approximation.

Results of shell and tube heat exchanger model

Formula
Variable
Educated guess

This model for the Shell and Tube heat exchanger results in:

		helium-nitrogen		nitrogen-air	
Temperatures					
Temperature in hotside	T_{hin}	900	°C	850	°C
Temperature out hotside	T_{hout}	452,63	°C	402,6271195	°C
Temperature in coldside	T_{cin}	402,63	°C	352,63	°C
Temperature out coldside	T_{cout}	850	°C	800	°C
constant temperature difference	dT	50	K	50	K
Dimensions					
Length tube	L_t	10	m	10	m
Outer Diameter	D_o	0,0254	m	0,0254	m
Thickness tube	t_t	0,000506572	m	0,000253663	m
Inner Diameter	D_i	0,024893428	m	0,025146337	m
Nr of baffles	$N_{baffles}$	8		8	
Amount of tubes	N_{tubes}	4261	4261,19	7233	7232,92
Distance between tube centers	P_t	0,0381	m	0,04064	m
Distance between tube edges	C	0,013206572	m	0,015493663	m
Baffle spacing	B	1,111111111	m	1,111111111	m
Shell thickness	t_s	0,055202592	m	0,038291036	m
Surfaces tubes					
Inner heat transfer area	A_{iht}	0,782050107	m^2	0,789995478	m^2
Outer heat transer area	A_{oht}	0,797964534	m^2	0,797964534	m^2
Inner flow through area	A_{if}	0,000486698	m^2	0,000496637	m^2
Outer "flow through" area (not shell side!!)	A_{of}	0,000506707	m^2	0,000506707	m^2
Material Properties					
Thermal conductivity	k	25,5	W/(m·K)	25,5	W/(m·K)
Density	ρ	7,8	ton/m^3	7,8	ton/m^3
Poisson ratio	ν	0,27		0,27	
Maximum yield stress	σy	6,00E+07	Pa	6,00E+07	Pa
Tube cut through surface	$A_{cuttube}$	2,00098E-05	m^2	1,00702E-05	m^2
Total weigth tubes	m_{tubes}	6,650409412	ton	5,681325143	ton
Shell cut through surface	$A_{cutshell}$	0,237894284	m^2	0,228170678	m^2
Total weigth shell	m_{shell}	59,28326913	ton	71,80939892	ton
Total weight	m_{total}	65,93367855	ton	77,49072406	ton
Stresses					
tubes					
pressure difference	dp	2,00E+06	Pa	1,00E+06	Pa
Stress in longitudinal direction	σ1	4,86E+07	n/m^2	4,94E+07	n/m^2
Stress tangential to cylinder	σ2	4,91E+07	n/m^2	4,97E+07	n/m^2
Stress perpendicular to cylinder	σ3	-2,00E+06	n/m^2	-1,00E+06	n/m^2
Yield stress total strain theory	σy	6,00E+07	n/m^2	6,03E+07	n/m^2
Yield stress Von Mises	σy	5,09E+07	n/m^2	5,06E+07	n/m^2
Shell					
pressure difference	dp	2,00E+06	pa	9,98E+05	pa
Stress in longitudinal direction	σ1	4,87E+07	n/m^2	4,89E+07	n/m^2
Stress tangential to cylinder	σ2	4,92E+07	n/m^2	4,92E+07	n/m^2
Stress perpendicular to cylinder	σ3	-2,00E+06	n/m^2	-9,98E+05	n/m^2
Yield stress total strain theory	σy	6,01E+07	n/m^2	5,97E+07	n/m^2
Yield stress Von Mises	σy	5,10E+07	n/m^2	5,00E+07	n/m^2

		Heat exchanger 1		Heatexchanger 2		
position		Inside tube	Outside Tube	Inside tube	outside tube	
Material properties		helium	nitrogen	nitrogen	air	
Specific heat coefficient	c_p	5191	5191	5191	1109,54	J/kg/k
Mass flow	dm/ds	9,496555	9,496554964	9,496554964	44,42977884	kg/s
System pressures	p	40	20	20	9,98	bar
Heat transfer	q	22,053969	22,05396947	22,05396947	22,05396947	Mwatt
Prandtl	Pr	0,661	0,661	0,661	0,73584	
Viscosity	μ	4,51E-05	4,51E-05	4,51E-05	3,96E-05	Pa·s
density	ρ	2,005	2,005	2,005	4,299	kg/m^3
Thermal conduction	k	0,3517	0,3517	0,3517	0,0586	W/(m·K)
Tube count calculation constant	CTP	0,93	0,93	0,93	0,93	
Tube layout constant	CL	0,87	0,87	0,87	0,87	
Shell diameter	D_s	2,7158968	2,715896801	3,774378525	3,774378525	m
Equivalent diameter square pitch	D_e	0,0473656	0,04736564	0,057391128	0,057391128	m
Equivalent diameter triangulat pitch	D_e	0,0094042	0,009404223	0,011574805	0,011574805	m
Bundle cross flow area	A_s	1,0460101	1,046010104	1,598833898	1,598833898	m^2
Shell side mass velocity	G_s	9,0788367	9,078836742	5,939675772	27,78886469	$kg/m^2/s$
Shell side velocity	G_s/ρ	4,5283488	4,528348822	2,96259582	6,464029935	m/s
Reynolds shell side	Re_s	9,529E+03	1,8919E+03	7,5534E+03	8,1204E+03	
Viscosity correction	μ_b/μ_w	0,93	0,93	0,93	0,93	
Nusselt shell side according to McAdams	Nu_s	47,909631	19,68999279	42,1633839	45,47297659	
heat transfer coefficient shell side	h_o	355,73925	736,3681535	258,3824816	230,3819617	$W/(m^2 \cdot K)$
Flow velocity inside tube	u_m	2,2840464	2,284046404	1,318614786	2,877059838	m/s
Reynolds tube side	Re_t	2,53E+03	2,53E+03	1,47E+03	7,85E+03	
Correction factor nusselt inside tube	f/2	0,0060402	0,006040212	0,007352884	0,004215909	
Nusselt inside according to Petuhkov-Kirilov	Nu_t	11,389561	11,38956068	8,263625751	25,56713793	
heat transfer coefficient tube side	h_i	160,9143	160,9142976	115,576164	59,62332003	$W/(m^2 \cdot K)$
Overall heat transfer Coefficient	U	129,71851		76,42222137		$W/(m^2 \cdot K)$
Necessary surface	$A_{necessary}$	3400,2811		5771,61173		m^2
Real Surface	A_{real}	3400,1269		5771,677475		m^2
Heat transferred	Q	22,052969		22,05422068		MW
Heat difference		0,00%		0,00%		
Pressure difference in tube						
fanning factor re < 3000	f	0,0000	0,0000	0,0000	0,0000	
fanning factor re > 3000 and < 50000	f	0,0080061	0	0,008484787	0,00833262	
fanning factor re > 50000 and < 1000000	f	0	0	0	0	
Final fanning factor	f	8,0061E-03	4,9709E-06	8,4848E-03	8,3326E-03	
Pressure drop tube side	dp_t	88,195213	20,96025399	30,49659062	307,0013544	Pa
Pressure difference in shell						
fanning factor	f	0,3119883	0,424174874	0,326066821	0,321612921	
pressure drop in shell	dp_s	16839,282	22894,4522	8505,472073	85637,567	Pa
Total pressure drop			22982,64741	Pa	85668,0636	Pa
			0,229826474	bar	0,856680636	bar

O. Plate heat exchanger

The surface enlargement factor is defined as:

$$\phi = \frac{\text{Developed length}}{\text{Projected length}} = \frac{A_{aea}}{A_{ppa}}$$

Where A_{aea} is the actual effective area and A_{ppa} is the projected plate area. ϕ varies between 1,15 and 1,25 between the various designs. Where A_{ppa} is defined as:

$$A_{aea} = L_p B_p$$

With L_p the effective length of the plate and B_p the effective width of the plate.
A measure for of the space available between the plates the mean channel spacing is defined as:

$$b = p - t$$

Where p is defined as the pitch or the outside depth of the corrugated plate and t as the thickness of the material used.
The Hydraulic diameter is defined as:

$$D_h = \frac{4\,x\,channel\ \ flow\,area}{wetted\ surface} = \frac{4bB_p}{2\left(b + B_p\phi\right)}$$

The flow inside the heat exchanger is highly dependent on the flow inside the heat exchanger which is highly dependent on the angle of the flow channels in the plates β.

Reynolds is defined as:

$$\mathrm{Re}_p = \frac{G_c D_h}{\mu}$$

Where the channel mass velocity is defined as:

$$G_c = \frac{\dot{m}}{N_{cp} b B_p}$$

Where N_{cp} is the number of channels per pass and is obtained from

$$N_{cp} = \frac{N_t - 1}{2N_p}$$

Where N_p is the number of passes and N_t is the number of plates.
Then Nusselt and the fanning factor are empirically determined by Muley and Manglik (Kakaç [2002]) as:

$$for\ \mathrm{Re} \le 400$$

$$Nu = \frac{2hb}{k} = 0,44\left(\frac{\beta}{30}\right)^{0,38} \mathrm{Re}^{0,5}\,\mathrm{Pr}^{1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0,14}$$

$$f = \left(\frac{\beta}{30}\right)^{0,83}\left(\left(\frac{30,2}{\mathrm{Re}}\right)^5 + \left(\frac{6,28}{\mathrm{Re}^{0,5}}\right)^5\right)^{0,2}$$

$$for\ \mathrm{Re} \ge 800$$

$$Nu = \left(0,2668 - 0,006967\beta + 7,244\cdot 10^{-5}\beta^2\right)$$
$$\mathrm{x}\left(20,78 - 50,94\phi + 41,1\phi^2 - 10,51\phi^3\right)$$
$$\mathrm{x}\ \mathrm{Re}^{\left(0,728+0,0543\sin\left(\pi\beta/45\right)+3.7\right)}\,\mathrm{Pr}^{(1/3)}\left(\frac{\mu_b}{\mu_w}\right)^{0,14}$$

$$f = \left(2,917 - 0,1277\beta + 2,016\cdot 10^{-3}\beta^2\right)$$
$$\mathrm{x}\left(5,474 - 19,02\phi + 18,93\phi^2 - 5,341\phi^3\right)$$
$$\mathrm{x}\ \mathrm{Re}^{\left(0,2+0,0577\sin\left(\pi\beta/45\right)+2.1\right)}$$

The heat transfer coefficient can be calculated using Nusselt as stated above:

$$Q = \frac{1}{\frac{1}{h_h} + \frac{1}{hc} + \frac{t}{k}} A_{aea}\Delta T$$

Pressure drop

And using the fanning factor (f) the pressure drop can be calculated:

$$\Delta p_c = 4 f \frac{L_{eff} N_p}{D_h} \frac{G_c^{\ 2}}{2\rho} \left(\frac{\mu_b}{\mu_w} \right)^{-0,17}$$

Where L_{eff} is the effective length of the fluid flow path between inlet and outlet ports:

$$L_{eff} = L_p + D_p$$

Where D_p is the port diameter.
The pressure drop in the port ducts Δp_p can roughly be estimated as 1,4 velocity head:

$$\Delta p_p = 1,4 N_p \frac{G_p^{\ 2}}{2\rho}$$

Where the mass velocity is defined as:

$$G_p = \frac{\dot{m}}{\frac{\pi D_p}{4}}$$

An estimation for the needed pump power is given by Branan [1998] which evolves into:

$$P_{pump}[kW] = 1,67 \frac{\dot{V} \Delta p}{\eta_{pump}}$$

Where $\dot{V}$ is the volume flow in [m^3/s] and η_{pump} the efficiency of the pump.

Stresses in plate heat exchanger

The thicknesses of these plates are hard to predict, the so called "ketel" formula does not really apply here because the edges are not solidly connected. Analysing the stresses in a plate over the length of a channel half way the sides will provide some rough estimations for the stresses. Assuming 45° angle at that point will result in the following formula's:
Corrected material thickness:

$$t_{45^\circ} = \sqrt{t^2 + t^2} = \sqrt{2} t$$

$$\sigma_1 = \sigma_2 = \frac{p 2 b L_{channel}}{2\sqrt{2} t L_{channel}} = \frac{pb}{\sqrt{2} t}$$

Assuming that the channel has an almost circular form for the tension in the last direction delivers:

$$\sigma_3 = \frac{p \pi b^2}{\pi \left((b+t)^2 + b^2 \right)} = \frac{p b^2}{\left((b+t)^2 + b^2 \right)} = \frac{p}{\left(2 + \frac{2t}{b} + \frac{t^2}{b^2} \right)}$$

Values given in the table of Smeding [2000] will be used as an assumption for the thickness of the plates, setting the stress to some result value.

Weight estimation

The weight of the plate heat exchanger is estimated by:

$$m_{HE} = \rho_{steel} \left(\phi \left(L_p \left(B_p + D_p \right) - 4 \frac{\pi}{4} D_p^{\ 2} \right) t \cdot N_t + 2 t_{hp} L_p \left(B_p + D_p \right) \right)$$

This is in fact the volume of the plate corrected with the surface enlargement factor, with the port holes subtracted from the total projected area, plus the volume of the 2 head plates multiplied by the density of steel. This is not the exact weight but will give a satisfactory estimation of the weight.

Results for the plate heat exchanger

Formula					
Variable					
Educated guess					
Temperatures		helium-helium		helium-air	
Temperature in hotside	T_{hin}	900	°C	850	°C
Temperature out hotside	T_{hout}	459,9	°C	409,9	°C
Temperature in coldside	T_{cin}	409,9	°C	359,9	°C
Temperature out coldside	T_{cout}	850	°C	800	°C
constant temperature difference	dT	50	K	50	K
Material Properties					
Thermal conductivity	k	25,5	W/(m·K)	25,5	W/(m·K)
Density	ρ	7,8	ton/m³	7,8	ton/m³
Poisson ratio	ν	0,27		0,27	
Maximum yield stress	σy	6,00E+07	Pa	6,00E+07	Pa
dimensions					
Surface enlargment factor	ϕ	1,25		1,25	
Effective length of the plate	L_p	2	m	2	m
Effective width of the plate	B_p	2	m	2	m
outside depth / pitch	p	0,016	m	0,016	m
Thickness plate	t	0,0008	m	0,0008	m
Mean channel depth	b	0,0152		0,0152	
Chevron angle (angle flow channel)	β	60	°	60	°
Port diameter	D_p	0,45	m	0,45	m
Hydraulic diameter	D_h	0,024173028	m	0,024173	m
Number of plates	N_t	102		312	
Number of passes	N_p	2		2	
Number of channels per pass	N_{cp}	25,25		77,75	
overall heat transfer coefficient	U	395,5734	W/(m²·K)	129,1544	W/(m²·K)
Transferred heat	Q	10,08712235	MW	10,074043	MW
Approximate weight	m_{he}	4,61448	ton	14,11488	ton
length package (horizontal)	L_{ph}	1,632	m	4,992	m
Power cycle pressure loss				0,3152391	
difference		20	bar	9,6231895	bar
σ1		26,87005769	Mpa	12,928783	Mpa
σ2		26,87005769	Mpa	12,928783	Mpa
σ3		0,948751643	Mpa	0,4565008	Mpa
Yield stress total strain theory	σy	3,21E+01	Mpa	1,54E+01	Mpa
Yield stress Von Mises	σy	2,59E+01	Mpa	1,25E+01	Mpa
total weight	m_t	74,91744	ton		
material price		€ 4.495.046			

		Heat exchanger 1		Heatexchanger 2		
position		hot	cold	hot	cold	
Material properties		helium	nitrogen	nitrogen	air	
Specific heat coefficient	c_p	5191	5191	5191	1109,54	J/kg/k
Mass flow	dm/ds	8,8137296	8,8137296	8,81372962	41,23516996	kg/s
System pressures	p	40	20	20	10,38	bar
Heat transfer	q	20,137461	20,137461	20,1374615	20,13746149	Mwatt
Prandtl	Pr	0,661	0,661	0,661	0,73584	
Viscosity	μ	4,51E-05	4,51E-05	4,51E-05	3,96E-05	Pa·s
density	ρ	2,005	2,005	2,005	4,299	kg/m^3
Thermal conduction	k	0,3517	0,3517	0,3517	0,0586	W/(m·K)
Viscosity correction	μ_b/μ_w	0,93	0,93	0,93	0,93	
Channel mass velocity	G_c	11,482191	11,482191	3,72894298	17,44591723	$kg/m^2/s$
Reynolds	Re	6,15E+03	6,15E+03	2,00E+03	1,06E+04	
Nusselt for reynolds <= 400	Nu	0	0	0	0	
Nusselt for Reynolds >=800	Nu	69,243929	69,243929	28,7271091	110,2418193	
fanning factor reynolds <=400	f	0	0	0	0	
fanning factor reynolds >=800	f	0,3700203	0,3700203	0,46352299	0,331499235	
heat transfer coefficient	h	801,08848	801,08848	332,346194	212,65792	
pressuredrop in channels	dp_c	0,0998706	0,0998706	0,01319488	0,096328683	bar
port mass velocity	G_p	55,41723	55,41723	55,4172301	259,2703656	
Pressure drop in port ducts	dp_p	0,0214451	0,0214451	0,02144506	0,218910378	bar
total pressure drop	dp	0,1213157	0,1213157	0,03463994	0,31523906	bar
Efficiency pump	η	0,85	0,85	0,85	0,85	
Estimated power pump	P_p	6,29E+01	6,29E+01	1,80E+01	3,56E+02	kW
Extra power necessary		125,04	kW			

P. Physical Properties of the used gases

For viscosity the Chapman-Enskog solutions from the Boltzman equations are normally used in the form:

$$\mu = 2,67x10^{-6}\frac{\sqrt{M_w T}}{\sigma^2 \Omega_v}[Pa \cdot s]$$

Where M_w and T are the molar weight and absolute temperature. The parameters σ and Ω are determined by fitting the formula to viscosity data. Which are given by Reid, Prausnitz and Poling in their book:"The properties of Gases and Liquids" currently unavailable. The pressure is not directly related in the given formula strangely enough.

Density of gases is most easily estimated by using the ideal gas law:

$$\rho = \frac{P \cdot M_w}{R_G \cdot T}$$

In this formula: P is the total pressure, M_w the molar weight, R_G the gas constant and T the absolute temperature.

Material properties can also be obtained by using a program written by National Institute of Standards and Technology (NIST): REFPROP version 8.0; which can calculate: Temperature, Pressure, Density, Energy, Enthalpy, Entropy, Cv, Cp, Sound Speed, Compressibility Factor, Joule Thompson Coefficient, Quality, 2nd and 3rd Virial Coefficients, Helmholtz Energy, Gibbs Energy, Heat of Vaporization, Fugacity, Fugacity Coefficient, K value, Molar Mass, Thermal Conductivity, Viscosity, Kinematic Viscosity, Thermal Diffusivity, Prandtl Number, Surface Tension, Dielectric Constant, Isothermal Compressibility, Volume Expansivity, Isentropic Coefficient, Adiabatic Compressibility, Specific Heat Input, Exergy, dp/dr, d2p/dr2, dp/dT, dr/dT, dr/dp, and many others.

For the evaluation and modelling of a heat exchanger this program was purchased. The program has an overall maximum error margin of 10 %. It is not entirely certain that the program will deliver the necessary values over the whole range defined by the system.

The following properties were obtained from the program:

air

Temperatu (℃)	Pressure (MPa)	Density (kg/m³)	Therm. Dif (cm²/s)	Viscosity (µPa-s)	Kin. Viscos (cm²/s)	Prandtl	Enthalpy (kJ/kg)	Entropy (kJ/kg- K)	Cv (kJ/kg-K)	Cp (kJ/kg-K)	Therm. Cond. (mW/m-K)
350	1,02	5,6786	0,077676	31,722	0,055863	0,71917	631,87	6,9504	0,76999	1,0595	46,732
400	1,02	5,2569	0,08797	33,428	0,063589	0,72285	685,13	7,0326	0,78189	1,071	49,526
450	1,02	4,8937	0,098626	35,078	0,07168	0,72678	738,97	7,1097	0,7939	1,0826	52,253
500	1,02	4,5776	0,10964	36,678	0,080126	0,73078	793,4	7,1825	0,80578	1,0943	54,922
550	1,02	4,2999	0,12103	38,234	0,088918	0,73469	848,39	7,2514	0,81735	1,1056	57,539
600	1,02	4,0541	0,13278	39,75	0,098048	0,73842	903,95	7,317	0,82848	1,1166	60,108
650	1,02	3,8349	0,14491	41,23	0,10751	0,7419	960,05	7,3794	0,83909	1,1271	62,635
700	1,02	3,6383	0,15743	42,677	0,1173	0,74511	1016,7	7,4391	0,84915	1,137	65,124
750	1,02	3,4609	0,17033	44,094	0,12741	0,74802	1073,7	7,4963	0,85864	1,1464	67,579
800	1,02	3,3	0,18362	45,485	0,13783	0,75064	1131,3	7,5512	0,86757	1,1553	70,002

nitrogen

Temperatu (℃)	Pressure (MPa)	Density (kg/m³)	Therm. Dif (cm²/s)	Viscosity (µPa-s)	Kin. Viscos (cm²/s)	Prandtl	Enthalpy (kJ/kg)	Entropy (kJ/kg- K)	Cv (kJ/kg-K)	Cp (kJ/kg-K)	Therm. Cond. (mW/m-K)
400	2	9,9266	0,045175	32,072	0,032309	0,7152	706,6	6,8076	0,79568	1,0963	49,161
450	2	9,2419	0,050611	33,639	0,036398	0,71918	761,69	6,8866	0,80759	1,1076	51,805
500	2	8,6461	0,056212	35,16	0,040665	0,72343	817,36	6,961	0,81967	1,1191	54,391
550	2	8,1229	0,06198	36,639	0,045106	0,72775	873,6	7,0315	0,83166	1,1307	56,926
600	2	7,6596	0,067919	38,082	0,049717	0,73201	930,42	7,0985	0,84337	1,1421	59,416
650	2	7,2465	0,074034	39,49	0,054495	0,73609	987,81	7,1624	0,85469	1,1531	61,864
700	2	6,8759	0,080327	40,868	0,059437	0,73994	1045,7	7,2235	0,86551	1,1637	64,275
750	2	6,5414	0,086805	42,219	0,064541	0,74352	1104,2	7,2821	0,87579	1,1738	66,653
800	2	6,238	0,093471	43,544	0,069805	0,74681	1163,1	7,3383	0,88552	1,1834	69
850	2	5,9616	0,10033	44,847	0,075226	0,7498	1222,5	7,3924	0,89467	1,1924	71,32

helium

Temperatu (℃)	Pressure (MPa)	Density (kg/m³)	Therm. Dif (cm²/s)	Viscosity (µPa-s)	Kin. Viscos (cm²/s)	Prandtl	Enthalpy (kJ/kg)	Entropy (kJ/kg- K)	Cv (kJ/kg-K)	Cp (kJ/kg-K)	Therm. Cond. (mW/m-K)
500	4	2,4754	0,23617	38,546	0,15571	0,65932	4031,7	25,282	3,1176	5,1906	303,46
550	4	2,3261	0,26248	40,281	0,17317	0,65976	4291,2	25,607	3,1174	5,1908	316,92
600	4	2,1937	0,28991	41,987	0,1914	0,66018	4550,8	25,914	3,1173	5,1909	330,13
650	4	2,0756	0,31847	43,666	0,21038	0,6606	4810,3	26,203	3,1172	5,191	343,13
700	4	1,9695	0,34812	45,321	0,23011	0,66101	5069,9	26,476	3,1171	5,1911	355,92
750	4	1,8738	0,37886	46,953	0,25058	0,66141	5329,4	26,736	3,117	5,1912	368,52
800	4	1,7869	0,41066	48,563	0,27177	0,6618	5589	26,984	3,1169	5,1913	380,94
850	4	1,7077	0,44351	50,153	0,29368	0,66218	5848,6	27,221	3,1168	5,1914	393,19
900	4	1,6353	0,4774	51,723	0,3163	0,66255	6108,1	27,447	3,1168	5,1915	405,28

Q. Stability calculations PIAS

Condition : Ballast Condition, 100% Consumables

Description	Weight ton	VCG m	LCG m	TCG m	FSM tonm
TOTAL	**11123.202**	**6.344**	**66.424**	**0.061**	**154.734**

Hydrostatics for ship in upright position

Volume =10771.192 m^3 Mom. change trim = 184.027 tonm/cm
LCF = 65.907 m Ton/cm immersion = 24.039 ton/cm
Specific weight = 1.025 ton/m^3 LPP = 138.690 m

Transverse stability

KM transverse = 10.413 m
Centre of gravity VCG = 6.344 m VCG'= 6.358 m
==========
GM solid = 4.069 m
GG' correction = 154.734 / 11123.202 = 0.014 m
==========
Metacentric height G'M liquid = 4.055 m

Drafts and trim

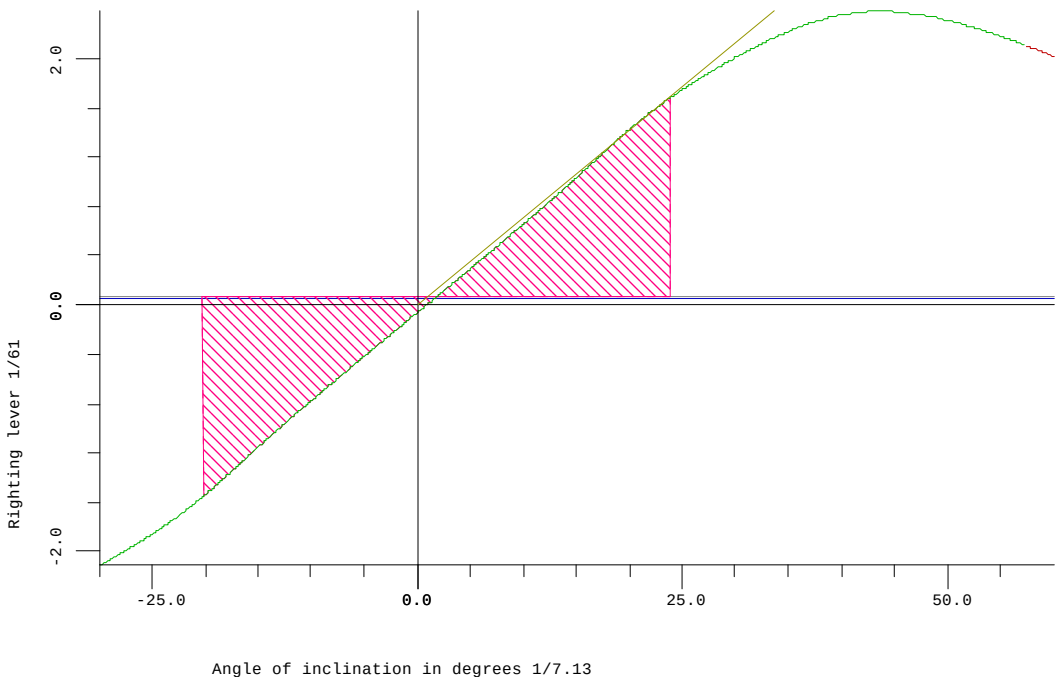
Mean draft = 5.638 m Draft aft = 5.907 m
Trim = -0.537 m Draft fore = 5.369 m

Statical angle of inclination is 0.872 degrees

Verification against the stability criteria "IMO A749 standard stability criteria"

		Criterion	Value	
Draft mld.		7.300	5.638	m
Minimum draft fore		3.600	5.403	m
Trim	= -0.537 m			
Flooding angle	= 57.32 degrees			
Minimum metacentric height G'M		0.150	4.055	meter
Maximum GZ at 30 degrees or more		0.200	2.385	meter
Top of the GZ curve at least at		25.000	43.603	degrees
Area under the GZ curve up to 30 degrees		0.055	0.536	mrad
Area under the GZ curve up to 40 degrees		0.090	0.921	mrad
Area under the GZ curve between 30 and 40 degrees		0.030	0.385	mrad
Maximum angle of inclination acc. to IMO's A.562 weathercriterion		50.000	23.859	degrees
Maximum statical angle due to wind		16.000	1.537	degrees
Maximum statical angle 80% of angle of deck immersion		15.608	1.537	degrees
VCG'	= 6.358 m			
Maximum allowable VCG'	= 9.912 m			

Loading condition complies with the stated criteria.



Condition : Ballast Condition, 10% Consumables

Description	Weight ton	VCG m	LCG m	TCG m	FSM tonm
TOTAL	**10986.144**	**6.336**	**67.090**	**0.026**	**154.734**

Hydrostatics for ship in upright position

Volume =10638.577 m^3 Mom. change trim = 180.598 tonm/cm
LCF = 66.371 m Ton/cm immersion = 23.897 ton/cm
Specific weight = 1.025 ton/m^3 LPP = 138.690 m

Transverse stability

KM transverse = 10.409 m
Centre of gravity VCG = 6.336 m VCG'= 6.350 m
==========
GM solid = 4.072 m
GG' correction = 154.734 / 10986.144 = 0.014 m
==========
Metacentric height G'M liquid = 4.058 m

Drafts and trim

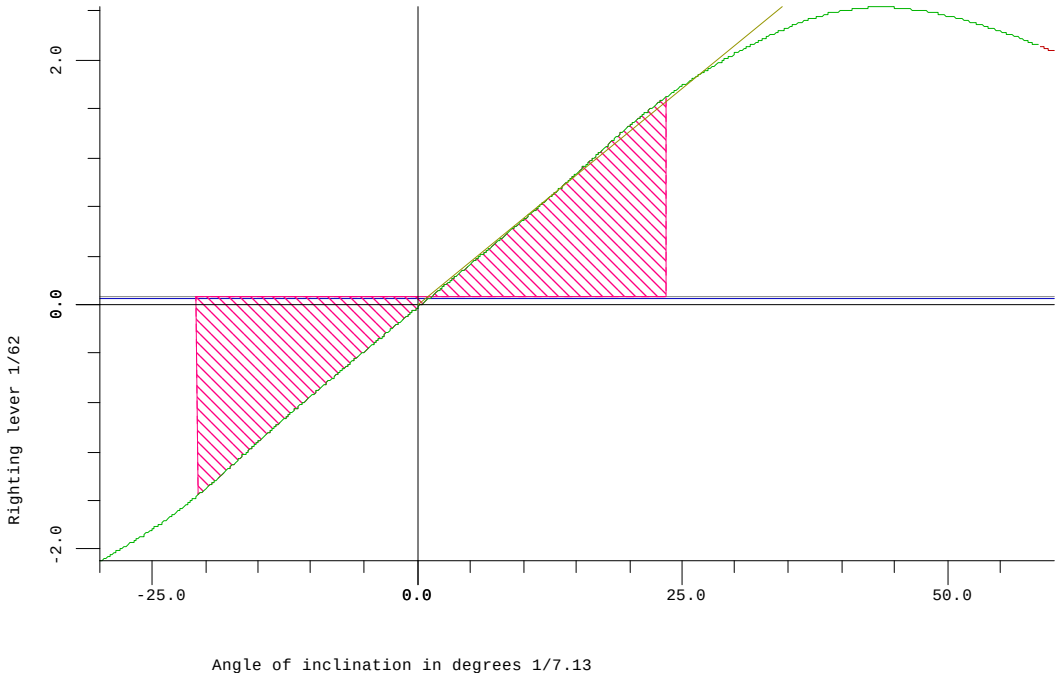
Mean draft = 5.590 m Draft aft = 5.663 m
Trim = -0.145 m Draft fore = 5.518 m

Statical angle of inclination is 0.376 degrees

Verification against the stability criteria "IMO A749 standard stability criteria"

		Criterion	Value	
Draft mld.		7.300	5.590	m
Minimum draft aft		5.300	5.663	m
Minimum draft fore		3.600	5.527	m
Trim	= -0.145 m			
Flooding angle	= 58.52 degrees			
Minimum metacentric height G'M		0.150	4.058	meter
Maximum GZ at 30 degrees or more		0.200	2.429	meter
Top of the GZ curve at least at		25.000	43.727	degrees
Area under the GZ curve up to 30 degrees		0.055	0.555	mrad
Area under the GZ curve up to 40 degrees		0.090	0.948	mrad
Area under the GZ curve between 30 and 40 degrees		0.030	0.393	mrad
Maximum angle of inclination acc. to IMO's A.562 weathercriterion		50.000	23.457	degrees
Maximum statical angle due to wind		16.000	1.053	degrees
Maximum statical angle 80% of angle of deck immersion		15.786	1.053	degrees
VCG'	= 6.350 m			
Maximum allowable VCG'	= 9.980 m			

Loading condition complies with the stated criteria.



Condition : Containers 14ton/TEU, 100% Consumables

Description	Weight ton	VCG m	LCG m	TCG m	FSM tonm
TOTAL	**15252.975**	**9.099**	**66.539**	**0.028**	**116.820**

Hydrostatics for ship in upright position

Volume =14770.267 m^3 Mom. change trim = 232.330 tonm/cm
LCF = 63.468 m Ton/cm immersion = 26.376 ton/cm
Specific weight = 1.025 ton/m^3 LPP = 138.690 m

Transverse stability

KM transverse = 10.050 m
Centre of gravity VCG = 9.099 m VCG'= 9.107 m
==========
GM solid = 0.951 m
GG' correction = 116.820 / 15252.975 = 0.008 m
==========
Metacentric height G'M liquid = 0.944 m

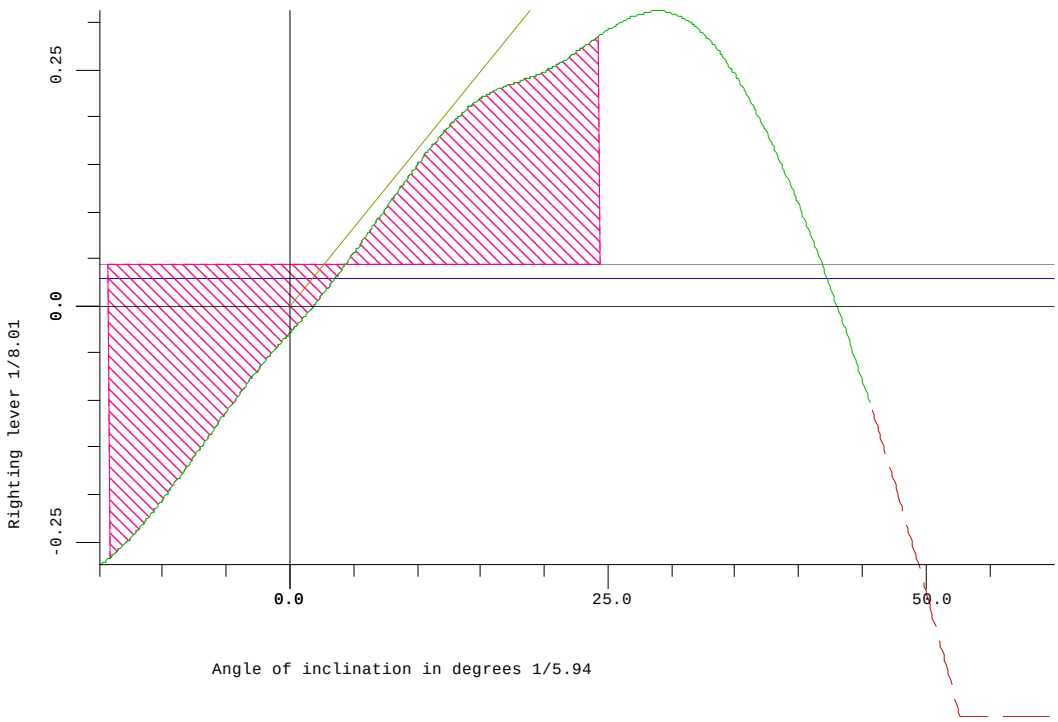
Drafts and trim

Mean draft = 7.280 m Draft aft = 7.349 m
Trim = -0.136 m Draft fore = 7.212 m

Statical angle of inclination is 1.857 degrees
Verification against the stability criteria "IMO A749 standard stability criteria"

		Criterion	Value	
User defined draft		7.300	7.280	m
Trim	= -0.136 m			
Flooding angle	= 45.58 degrees			
Minimum metacentric height G'M		0.150	0.944	meter
Maximum GZ at 30 degrees or more		0.200	0.310	meter
Top of the GZ curve at least at		25.000	28.922	degrees
Area under the GZ curve up to 30 degrees		0.055	0.098	mrad
Area under the GZ curve up to 40 degrees		0.090	0.138	mrad
Area under the GZ curve between 30 and 40 degrees		0.030	0.041	mrad
Maximum angle of inclination acc. to IMO's A.562 weathercriterion		45.570	24.263	degrees
Maximum statical angle due to wind		16.000	3.523	degrees
Maximum statical angle 80% of angle of deck immersion		9.208	3.523	degrees
VCG'	= 9.107 m			
Maximum allowable VCG'	= 9.212 m			

Loading condition complies with the stated criteria.



Condition : Containers 14ton/TEU, 10% Consumables

Description	Weight ton	VCG m	LCG m	TCG m	FSM tonm
TOTAL	**15197.271**	**9.089**	**66.761**	**-0.000**	**221.766**

Hydrostatics for ship in upright position

Volume =14716.283 m^3 Mom. change trim = 229.624 tonm/cm
LCF = 63.704 m Ton/cm immersion = 26.288 ton/cm
Specific weight = 1.025 ton/m^3 LPP = 138.690 m

Transverse stability

KM transverse = 10.043 m
Centre of gravity VCG = 9.089 m VCG'= 9.104 m
==========
GM solid = 0.954 m
GG' correction = 221.766 / 15197.271 = 0.015 m
==========
Metacentric height G'M liquid = 0.939 m

Drafts and trim

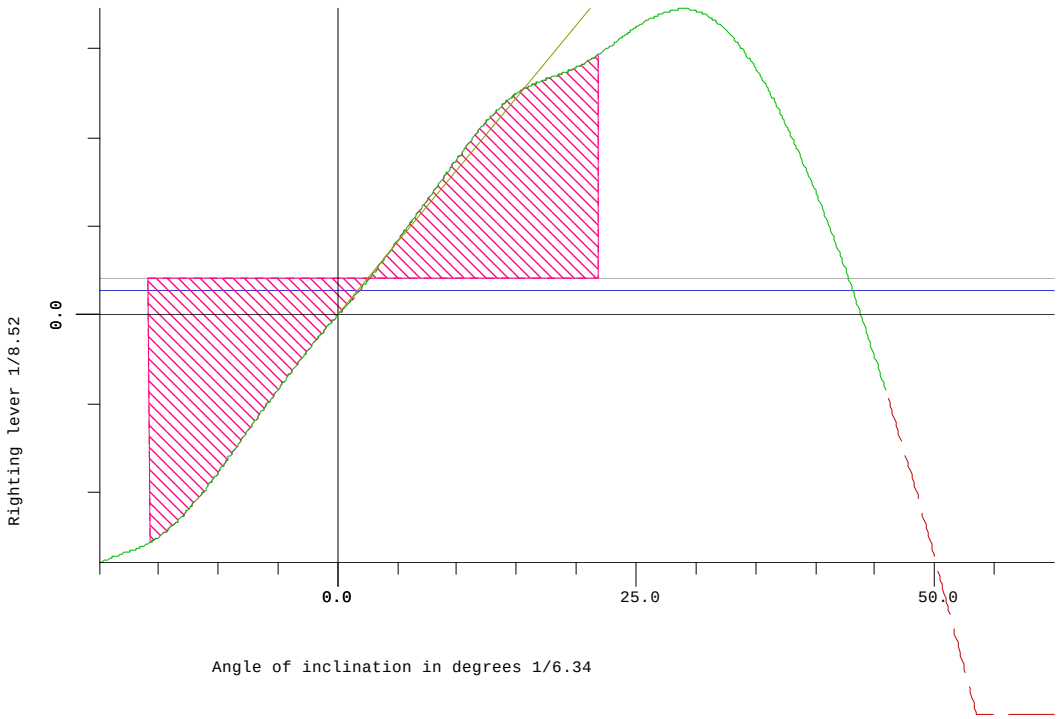
Mean draft = 7.265 m Draft aft = 7.265 m
Trim = -0.001 m Draft fore = 7.265 m

Statical angle of inclination is 0.007 degrees

Verification against the stability criteria "IMO A749 standard stability criteria"

		Criterion	Value	
Draft mld.		7.300	7.265	m
Trim	= -0.001 m			
Flooding angle	= 46.05 degrees			
Minimum metacentric height G'M		0.150	0.939	meter
Maximum GZ at 30 degrees or more		0.200	0.343	meter
Top of the GZ curve at least at		25.000	28.998	degrees
Area under the GZ curve up to 30 degrees		0.055	0.113	mrad
Area under the GZ curve up to 40 degrees		0.090	0.159	mrad
Area under the GZ curve between 30 and 40 degrees		0.030	0.047	mrad
Maximum angle of inclination acc. to IMO's A.562 weathercriterion		46.036	21.866	degrees
Maximum statical angle due to wind		16.000	1.869	degrees
Maximum statical angle 80% of angle of deck immersion		9.270	1.869	degrees
VCG'	= 9.104 m			
Maximum allowable VCG'	= 9.269 m			

Loading condition complies with the stated criteria.

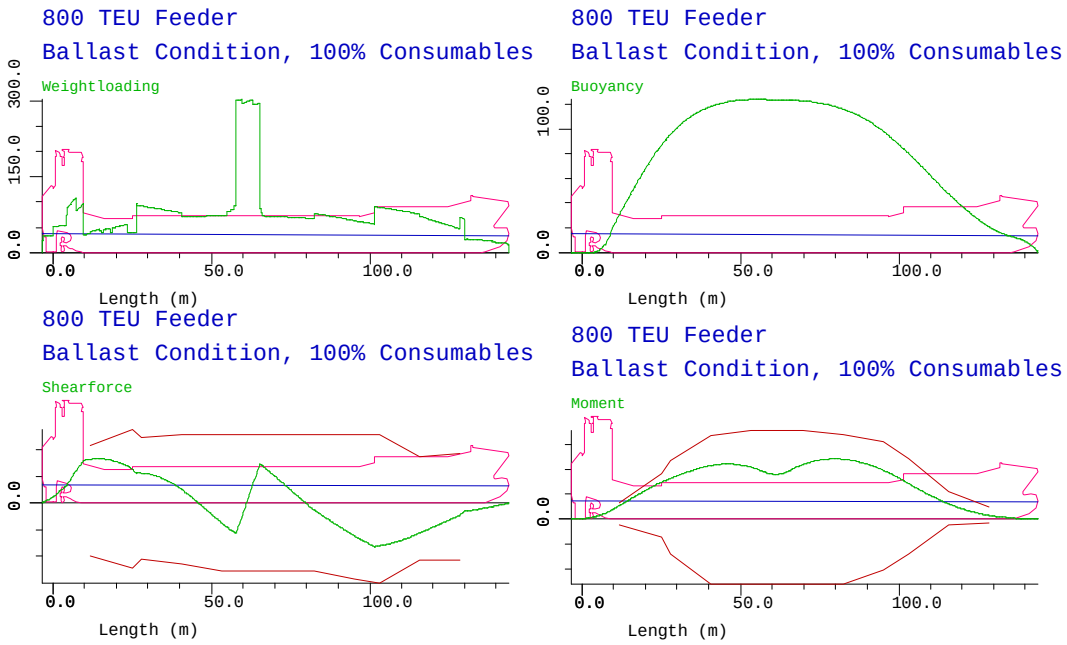


R. Strength calculations PIAS

Condition : Ballast Condition, 100% Consumables

Mean draft	5.638 m
Trim	-0.537 m
Maximum shearforce	835.236 ton
Location where maximum shearforce occurs	14.500 m
Maximum moment	26638.430 tonm
Location where maximum moment occurs	79.709 m

Loading condition complies with the stated criteria. (sea condition)

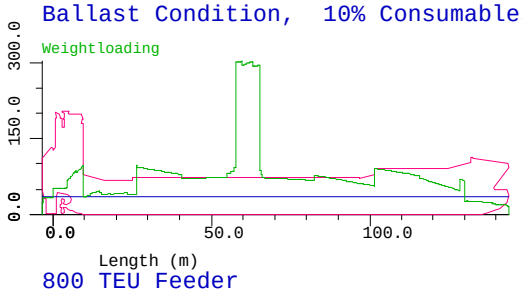


Condition : Ballast Condition, 10% Consumables

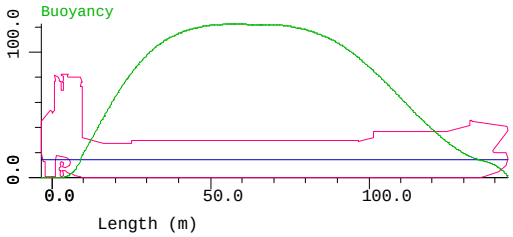
Mean draft	5.590	m
Trim	-0.145	m
Maximum shearforce	-785.890	ton
Location where maximum shearforce occurs	101.450	m
Maximum moment	25256.156	tonm
Location where maximum moment occurs	80.449	m

Loading condition complies with the stated criteria. (sea condition)

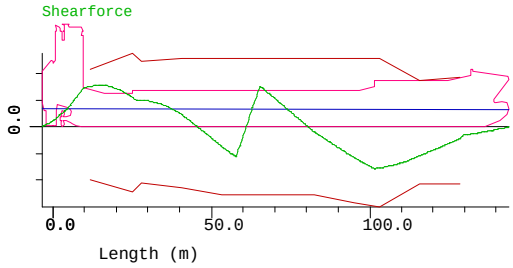
800 TEU Feeder
Ballast Condition, 10% Consumables



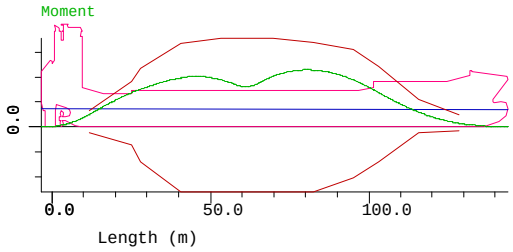
800 TEU Feeder
Ballast Condition, 10% Consumables



800 TEU Feeder
Ballast Condition, 10% Consumables



800 TEU Feeder
Ballast Condition, 10% Consumables

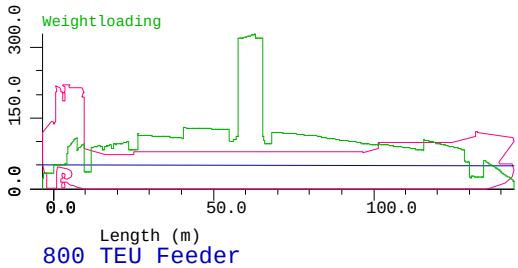


Condition : Containers 14ton/TEU, 100% Consumables

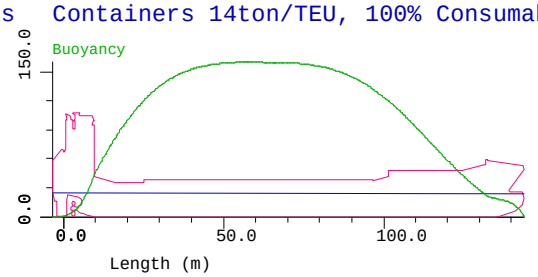
Mean draft	7.280	m
Trim	-0.136	m
Maximum shearforce	-841.289	ton
Location where maximum shearforce occurs	112.244	m
Maximum moment	28571.031	tonm
Location where maximum moment occurs	83.160	m

Loading condition complies with the stated criteria. (sea condition)

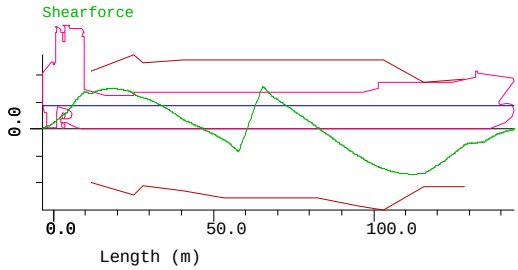
800 TEU Feeder
Containers 14ton/TEU, 100% Consumables



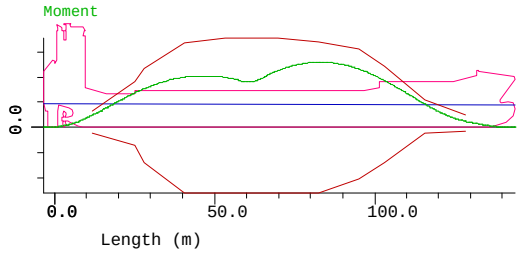
800 TEU Feeder
Containers 14ton/TEU, 100% Consumables



800 TEU Feeder
Containers 14ton/TEU, 100% Consumables



800 TEU Feeder
Containers 14ton/TEU, 100% Consumables

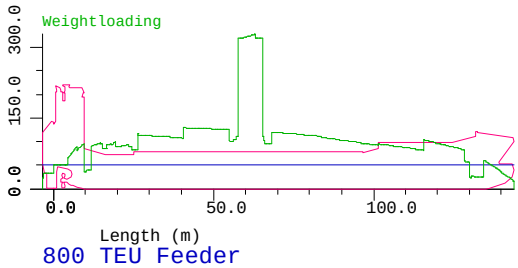


Condition : Containers 14ton/TEU, 10% Consumables

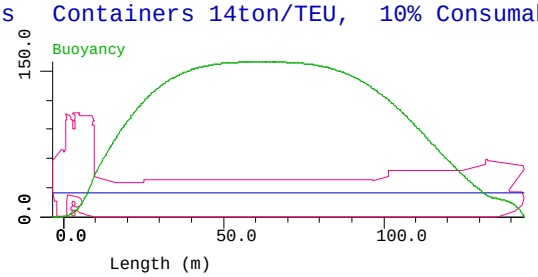
Mean draft	7.265	m
Trim	-0.001	m
Maximum shearforce	-832.248	ton
Location where maximum shearforce occurs	112.491	m
Maximum moment	28065.846	tonm
Location where maximum moment occurs	83.407	m

Loading condition complies with the stated criteria. (sea condition)

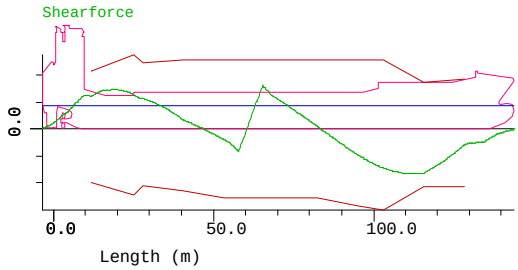
800 TEU Feeder
Containers 14ton/TEU, 10% Consumables



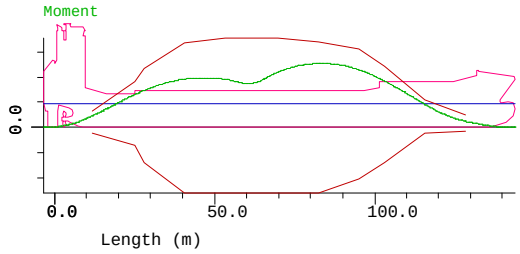
800 TEU Feeder
Containers 14ton/TEU, 10% Consumables



800 TEU Feeder
Containers 14ton/TEU, 10% Consumables



800 TEU Feeder
Containers 14ton/TEU, 10% Consumables



S. Cost estimations in time

Inflation rates are set at 0,2 and 5 %.
Variation of costs for 25 years design life and rent varied from 0-10% in steps of 2%.
For diesel:

	Current fuel price			double fuel price			Triple fuel price		
Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 124.000	€ 124.000	€ 124.000	€ 124.000	€ 124.000	€ 124.000	€ 124.000	€ 124.000	€ 124.000
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 45.929.983	€ 57.974.289	€ 84.866.035	€ 88.759.969	€ 112.848.579	€ 166.632.071	€ 131.589.955	€ 167.722.870	€ 248.398.108

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 158.783	€ 158.783	€ 158.783	€ 158.784	€ 158.784	€ 158.784	€ 158.784	€ 158.784	€ 158.784
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	2%	2%	2%	2%	2%	2%	2%	2%	2%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 46.799.567	€ 58.843.873	€ 85.735.620	€ 89.629.554	€ 113.718.164	€ 167.501.657	€ 132.459.541	€ 168.592.456	€ 249.267.694

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 198.437	€ 198.437	€ 198.437	€ 198.437	€ 198.437	€ 198.437	€ 198.437	€ 198.438	€ 198.438
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	4%	4%	4%	4%	4%	4%	4%	4%	4%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 47.790.910	€ 59.835.216	€ 86.726.964	€ 90.620.898	€ 114.709.509	€ 168.493.002	€ 133.450.886	€ 169.583.801	€ 250.259.040

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 242.503	€ 242.503	€ 242.503	€ 242.503	€ 242.503	€ 242.503	€ 242.503	€ 242.503	€ 242.503
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	6%	6%	6%	6%	6%	6%	6%	6%	6%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 48.892.554	€ 60.936.860	€ 87.828.608	€ 91.722.542	€ 115.811.154	€ 169.594.647	€ 134.552.531	€ 170.685.447	€ 251.360.686

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 290.404	€ 290.404	€ 290.404	€ 290.404	€ 290.405	€ 290.405	€ 290.405	€ 290.405	€ 290.405
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	8%	8%	8%	8%	8%	8%	8%	8%	8%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 50.090.088	€ 62.134.395	€ 89.026.143	€ 92.920.078	€ 117.008.690	€ 170.792.183	€ 135.750.068	€ 171.882.985	€ 252.558.224

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 341.521	€ 341.521	€ 341.521	€ 341.521	€ 341.521	€ 341.522	€ 341.522	€ 341.522	€ 341.522
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	10%	10%	10%	10%	10%	10%	10%	10%	10%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 51.368.009	€ 63.412.316	€ 90.304.064	€ 94.198.000	€ 118.286.612	€ 172.070.106	€ 137.027.991	€ 173.160.908	€ 253.836.147

For nuclear minimal capital investments with a refuelling period of 5 years:

	minimal fuel price			Average fuel price			Maximal fuel price		
Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 4.607.526	€ 4.607.526	€ 4.607.526	€ 4.607.526	€ 4.607.526	€ 4.607.526	€ 4.607.526	€ 4.607.526	€ 4.607.526
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 123.358.183	€ 125.245.279	€ 129.301.713	€ 136.635.549	€ 141.589.428	€ 152.238.103	€ 144.103.026	€ 150.781.729	€ 165.138.023

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 5.899.988	€ 5.899.988	€ 5.899.988	€ 5.899.988	€ 5.899.988	€ 5.899.988	€ 5.899.988	€ 5.899.988	€ 5.899.988
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	2%	2%	2%	2%	2%	2%	2%	2%	2%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 155.669.724	€ 157.556.821	€ 161.613.255	€ 168.947.091	€ 173.900.970	€ 184.549.645	€ 176.414.568	€ 183.093.271	€ 197.449.565

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 7.373.420	€ 7.373.420	€ 7.373.420	€ 7.373.420	€ 7.373.420	€ 7.373.420	€ 7.373.420	€ 7.373.420	€ 7.373.420
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	4%	4%	4%	4%	4%	4%	4%	4%	4%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 192.505.529	€ 194.392.625	€ 198.449.059	€ 205.782.895	€ 210.736.774	€ 221.385.449	€ 213.250.372	€ 219.929.075	€ 234.285.370

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 9.010.792	€ 9.010.792	€ 9.010.792	€ 9.010.792	€ 9.010.792	€ 9.010.792	€ 9.010.792	€ 9.010.792	€ 9.010.792
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	6%	6%	6%	6%	6%	6%	6%	6%	6%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 233.439.817	€ 235.326.914	€ 239.383.348	€ 246.717.184	€ 251.671.062	€ 262.319.738	€ 254.184.660	€ 260.863.364	€ 275.219.658

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 10.790.686	€ 10.790.686	€ 10.790.686	€ 10.790.686	€ 10.790.686	€ 10.790.686	€ 10.790.686	€ 10.790.686	€ 10.790.686
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	8%	8%	8%	8%	8%	8%	8%	8%	8%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 277.937.179	€ 279.824.276	€ 283.880.710	€ 291.214.545	€ 296.168.424	€ 306.817.100	€ 298.682.022	€ 305.360.725	€ 319.717.020

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 12.690.058	€ 12.690.058	€ 12.690.058	€ 12.690.058	€ 12.690.058	€ 12.690.058	€ 12.690.058	€ 12.690.058	€ 12.690.058
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	10%	10%	10%	10%	10%	10%	10%	10%	10%
design life	25	25	25	25	25	25	25	25	25
total accumulated cost	€ 325.421.463	€ 327.308.560	€ 331.364.994	€ 338.698.829	€ 343.652.708	€ 354.301.384	€ 346.166.306	€ 352.845.009	€ 367.201.304

Variation of design life (10-15-20-30-40 years) without interest rate (rent = 0%)
For Diesel:

	Current fuel price			double fuel price			Triple fuel price		
Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 310.000	€ 310.000	€ 310.000	€ 310.000	€ 310.000	€ 310.001	€ 310.001	€ 310.001	€ 310.001
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	10	10	10	10	10	10	10	10	10
total accumulated cost	€ 20.231.993	€ 21.859.056	€ 24.648.439	€ 37.363.989	€ 40.618.113	€ 46.196.879	€ 54.495.986	€ 59.377.171	€ 67.745.319

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 206.667	€ 206.667	€ 206.667	€ 206.667	€ 206.667	€ 206.667	€ 206.667	€ 206.667	€ 206.667
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	15	15	15	15	15	15	15	15	15
total accumulated cost	€ 28.797.990	€ 32.727.071	€ 40.068.382	€ 54.495.983	€ 62.354.144	€ 77.036.766	€ 80.193.975	€ 91.981.217	€ 114.005.149

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 155.000	€ 155.000	€ 155.000	€ 155.000	€ 155.000	€ 155.000	€ 155.000	€ 155.000	€ 155.000
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	20	20	20	20	20	20	20	20	20
total accumulated cost	€ 37.363.986	€ 44.726.238	€ 59.748.572	€ 71.627.976	€ 86.352.479	€ 116.397.145	€ 105.891.965	€ 127.978.719	€ 173.045.718

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 103.333	€ 103.333	€ 103.333	€ 103.333	€ 103.333	€ 103.334	€ 103.334	€ 103.334	€ 103.334
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	30	30	30	30	30	30	30	30	30
total accumulated cost	€ 54.495.980	€ 72.601.207	€ 116.922.990	€ 105.891.962	€ 142.102.415	€ 230.745.982	€ 157.287.945	€ 211.603.624	€ 344.568.973

Capital costs	€ 3.100.000	€ 3.100.001	€ 3.100.002	€ 3.100.003	€ 3.100.004	€ 3.100.005	€ 3.100.006	€ 3.100.007	€ 3.100.008
Average Capital costs	€ 77.500	€ 77.500	€ 77.500	€ 77.500	€ 77.500	€ 77.500	€ 77.500	€ 77.500	€ 77.500
Annual fuel costs	€ 1.713.199	€ 1.713.199	€ 1.713.199	€ 3.426.399	€ 3.426.399	€ 3.426.399	€ 5.139.598	€ 5.139.598	€ 5.139.598
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	40	40	40	40	40	40	40	40	40
total accumulated cost	€ 71.627.973	€ 106.580.637	€ 210.054.093	€ 140.155.949	€ 210.061.277	€ 417.008.187	€ 208.683.924	€ 313.541.916	€ 623.962.281

For nuclear minimal capital investments with a refuelling period of 5 years:

	minimal fuel price			Average fuel price			Maximal fuel price		
Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 11.518.816	€ 11.518.816	€ 11.518.816	€ 11.518.816	€ 11.518.816	€ 11.518.816	€ 11.518.816	€ 11.518.816	€ 11.518.816
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	10	10	10	10	10	10	10	10	10
total accumulated cost	€ 118.456.170	€ 118.626.238	€ 118.907.615	€ 123.767.116	€ 124.213.569	€ 124.952.220	€ 126.754.107	€ 127.356.004	€ 128.351.836

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 7.679.211	€ 7.679.211	€ 7.679.211	€ 7.679.211	€ 7.679.211	€ 7.679.211	€ 7.679.211	€ 7.679.211	€ 7.679.211
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	15	15	15	15	15	15	15	15	15
total accumulated cost	€ 120.090.174	€ 120.618.080	€ 121.569.236	€ 128.056.594	€ 129.442.418	€ 131.939.327	€ 132.537.080	€ 134.405.415	€ 137.771.689

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 5.759.408	€ 5.759.408	€ 5.759.408	€ 5.759.408	€ 5.759.408	€ 5.759.408	€ 5.759.408	€ 5.759.408	€ 5.759.408
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	20	20	20	20	20	20	20	20	20
total accumulated cost	€ 121.724.178	€ 122.817.235	€ 124.966.213	€ 132.346.071	€ 135.215.490	€ 140.856.843	€ 138.320.053	€ 142.188.535	€ 149.794.075

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 3.839.605	€ 3.839.605	€ 3.839.605	€ 3.839.605	€ 3.839.605	€ 3.839.605	€ 3.839.605	€ 3.839.605	€ 3.839.605
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	30	30	30	30	30	30	30	30	30
total accumulated cost	€ 124.992.187	€ 127.926.037	€ 134.835.032	€ 140.925.026	€ 148.626.770	€ 166.763.797	€ 149.885.999	€ 160.269.309	€ 184.721.222

Capital costs	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161	€ 115.188.161
Average Capital costs	€ 2.879.704	€ 2.879.704	€ 2.879.704	€ 2.879.704	€ 2.879.704	€ 2.879.704	€ 2.879.704	€ 2.879.704	€ 2.879.704
Annual fuel costs	€ 326.801	€ 326.801	€ 326.801	€ 857.896	€ 857.896	€ 857.896	€ 1.156.595	€ 1.156.595	€ 1.156.595
inflation	0%	2%	5%	0%	2%	5%	0%	2%	5%
rent	0%	0%	0%	0%	0%	0%	0%	0%	0%
design life	40	40	40	40	40	40	40	40	40
total accumulated cost	€ 128.260.195	€ 134.153.637	€ 150.910.296	€ 149.503.982	€ 164.975.046	€ 208.963.496	€ 161.451.945	€ 182.309.671	€ 241.613.865