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Nuclear power in marine propulsion

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Introduction

Nowadays there is much attention for environmental protection. There are cars developed without any combustion and without any emission of greenhouse gas. Also modern factories try to get emissions as low as possible. Partly this is due to the increasing focus on environmental protection.

But there is also an economical cause. More combustion mostly means more fuel used. The fuel-price is rising so it is also on economical grounds useful to rethink your process to lower the fuel-consumption of your machines. When you lower your fuel-consumption you automatically get a reduction of the gasses and a lowering of your fuel costs.

The rising of the fuel price is caused by a lack of the oil reserves around the world. We are slowly running out of oil. So we have to provide new ways of energy on board. There are many different ways to provide so called “green energy”. A few examples are: Solar power, wind energy and nuclear power. This last subject is something interesting. There has been an increasing focus on nuclear power. It seems to be a promising method to produce energy.

There are several nuclear power plants around the world. There are two nuclear plants in the Netherlands. One of them is not in use at the moment. Since 1997 the nuclear plant in Dodewaard has been closed. In Borssele is another plant, this one is still in use. This nuclear plant produces about 512MW. So the power plant in Borssele provides about 3% of the Dutch demand of energy.[1] Other countries do have more nuclear plants which provide a lot of energy. Worldwide, approximately 14% of the total amount of energy is produced in a nuclear power plant. Belgium for example is one of the leaders in nuclear energy. Belgium has 7 nuclear power plants in use. They provide about half of the total energy production. In France, the amount of nuclear energy is even bigger, about 80% of the energy in France is produced in a nuclear power plant.[2]

Maybe nuclear energy could be a way to produce energy on board of a vessel. In this report the result is elaborated of an investigation around the possible applications of a nuclear power plant on board of vessels.

To get a clear view of this subject the following question is posed.
In which way will nuclear energy be suitable for ship propulsion?

To answer this question there are a few sub-questions:

1). How does the system work?

2). How can we make a nuclear system on board of a vessel?

3). How will the ships construction be effected by the nuclear power plant?

To answer this questions we will do desk research. Also we will interview mister Crommelin. He has been working as an Officer Engineering at the Royal Netherlands Navy. Also he is very deeply involved in a project called “NEREUS.” (Naturally safe, Efficient, Reactor, Easy to operate, Ultimately

[1] See reference 11

[2] See reference 12

simple and Small) Later in this report we will explain more about it. We also want to interview mister Luteijn, he has worked for the GKN (Gemeenschappelijke Kernenergiecentrale Nederland) for about 8 years.
Our goal is to make up an advice, whether nuclear energy is a possibility for ship propulsion or not.

These questions are a guideline to guide us through the investigation. Which also guides us are the borders of our project. These project borders will keep us from taking steps into the wrong direction, and investigate in subjects which are not relevant to our project.
The end-product of our project will be an advice for other people whether nuclear energy will be a solution for marine propulsion, so we should not design a ship which will use this as propulsion but just give an advice. We also won’t make a nuclear installation.
Another subject we should not dig into is a way to get rid of the nuclear waste that will be produced by these vessels. It’s an important subject but it’s not what the question is about.

First we start with a chapter about the nuclear system. In this chapter the working of a nuclear system will be explained. This report will continue with the realization of a nuclear system onboard a vessel. Then there will be a chapter about the effect that a nuclear reactor will have on the vessels construction. After that we will have a look at the costs of a nuclear system onboard a vessel. We will end our report with a recommendation.

The system

Introduction

Nuclear marine propulsion is a ship propulsion using a nuclear reactor; it has been used on battle ships for several years now. But only a few nuclear merchant ships were built as an experiment. The nuclear system that is used on vessels is called a high pressure reactor. In this type of reactor the reactor delivers heat to make the water boil and this water drives the steam turbine. The biggest of these installations are placed on aircraft carriers such as the US-Enterprise. This warship has 8 nuclear reactors which generate a total power of 200,000 kw. With one reactor load, this means a reactor fully filled with fuel bundles of enriched uranium. This vessel is able to sail about 650,000 km. The only nuclear powered civil ship which is still sailing is the Russian ice-breaker and container vessel Sevmorput.   In this chapter a description is given of how this system works and which system is used on vessels. To gain more knowledge we will answer the following question: How does the system work?

High pressure reactor

The nuclear system that is used on vessels and submarines is the pressurized water reactor (pwr) as you can see in the picture below. In this kind of nuclear reactor heat is produced by a nuclear fission and steam is produced in several steps.

Pressurized water reactors use normal water as moderator for the neutrons. A moderator is a matter which slows the neutrons down, this is done to make sure that the fission is carried out. If the neutrons go to fast there will be less fission. This water is also used to deliver the heat from the reactor to the turbine. In other reactors the heat is delivered by different medium than water. Examples of this medium are deuteriumoxide (under pressure), a gas or another cooling fluid.

First circle

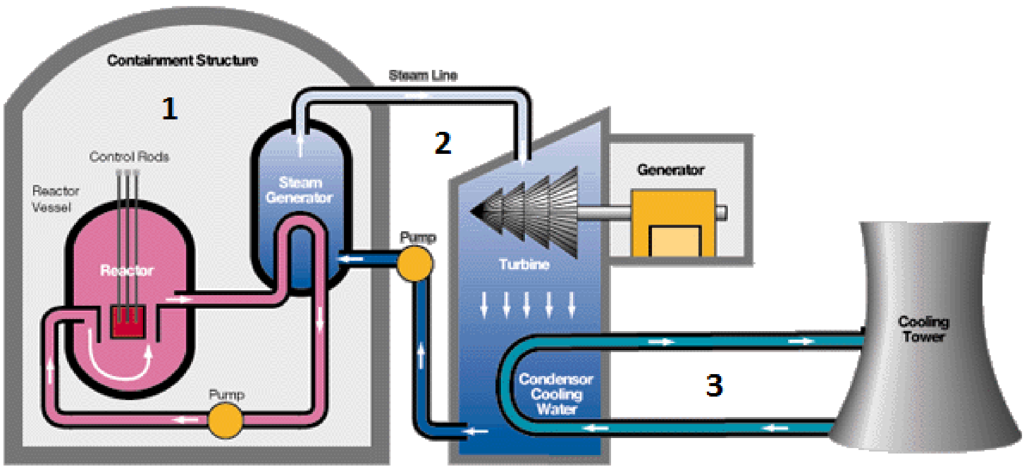
The fuel rods in the reactor deliver their heat to the primary circle which is filled with water; the water gets heated up by the nuclear fission until a temperature of 300 degrees. Because the pressure in this primary circle is around 155 bar, the water will not boil. This explains the name pressurized water reactor.

Second circle

The heat is delivered to a heat exchanger(steam turbine), in this secondary circle the pressure is lower so the water will be converted into steam. The result is steam under high pressure (around 60 bar) which drives an electric generator trough the steam turbine, as you can see in the picture. The heat is converted into electric energy by this generator.

Third circle

The steam coming out of the turbine is cooled and condensed to water. The condenser uses water from an external source to cool the steam. This part of the installation is called the tertiary circle, this is the part you see on the right side of the picture which involves the cooling tower.



picture 1

Combustion engine vs. nuclear power plant

The engine which is used in vessels nowadays is a combustion engine, an engine in which fuel is combusted in a combustion chamber with an oxidizer (usually air). In this engine high-temperature and high-pressure gases are combusted. This combustion drives the piston up and down and causes vertical movement. This movement is converted by the crankshaft into a rotating movement and this movement makes the propeller of the ship rotate.

In a nuclear power plant the steam drives a turbine and this turbine converts the steam into electric energy, The energy from the turbine is driving the main shaft and the propeller.

These systems differ a lot but eventually have the same result: movement of the vessel. Both of the systems have advantages and disadvantages but in the end the normal combustion engine still wins from the nuclear system because of the high purchase costs of the installation. There are no ship owners taking this big risk of losing money because of the high prices for the ships installation. But in long term the costs will be reduced. The costs will be lowered because a nuclear vessel is able to use one nuclear load for several years, which will reduce your fuel costs.

Also a nuclear installation is able to reach higher speeds, which decreases your travel time. Just to give an example, a fast container vessel like the Emma Maersk is able to sail with a speed of 25.5 knots. A nuclear powered vessel like the USS Enterprise is able to sail with a speed of 33.6 knots. This is a discrepancy of 8 knots, and this is when you compare the nuclear powered vessel to a fast vessel.

The nuclear fission

Nuclear fission is a process where a neutron collides with a uranium-235(235U) atom(143 neutrons and 92 protons). When this occurs the uranium atom will split into lighter elements and creates a lot of heat, which is used to gain the energy out of nuclear fission. Unfortunately this really isn’t that easy.

What is uranium?

Uranium is a silvery metallic chemical element on number 92 of the periodic table. This means that it has 92 protons and 92 electrons. Uranium has a variating number of neutrons between 141 and 146. This is coupled with the number of the isotopes U-233 trough U-238. These isotopes are very unstable but have a very high atomic weight. Another advantage of uranium is the high density. This density is 65%. The half time of U-238 is about 4.47 billion years and the half time of U-236 is 704 million years. This means that the radiation will decrease by half in the amount of time mentioned above.

Uranium is a naturally occurring element that can be found in the low levels of rock, soil and water. The worldwide production in 2009 was 50,572 tons and was mined in several ways. Used for several purposes such as: marine propulsion, generating electric energy and in hospitals.

This element Uranium named after the planet Uranus (discovered 8 years before uranium) was first discovered by Martin Heinrich Klaproth. The radioactive properties were discovered in 1896 Antoine Becquerel, the first appearance of the power of Uranium was Little Boy, this bomb was dropped on Hiroshima(1945). The first time it was used for electrical energy was 20 December 1951. Initially it lighted 4 150watt light bulbs but in the years technology improved.

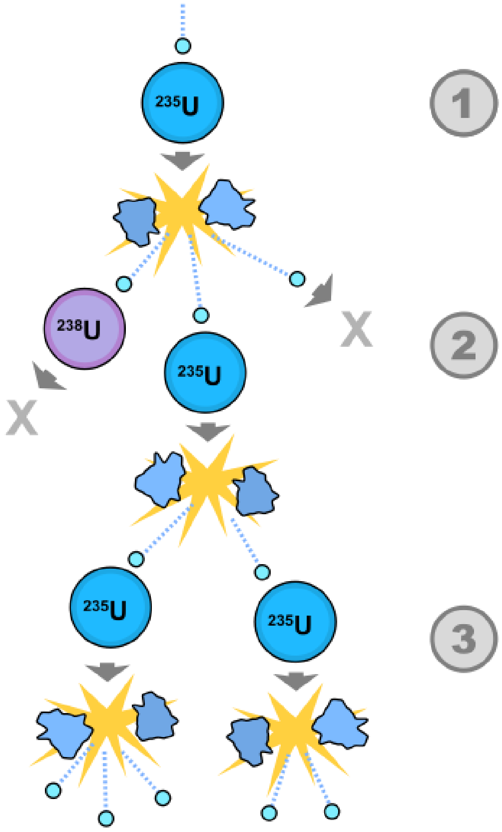
Uranium preparation

As mentioned above, the 235U is needed for the nuclear fission process. In naturally occurring uranium deposits, less than one percent of the uranium is 235U. The majority of the uranium is 238U. The 238U is not a fissile isotope of uranium. When 238U is struck by a loose neutron, it absorbs the neutron into its core and does not fission. Thus, by absorbing loose neutrons, 238U can prevent a nuclear chain reaction from occurring. This would be a bad thing because if a chain reaction doesn't occur, the nuclear reactions can't sustain themselves, the reactor shuts down, and the ship will be without electrical power and propulsion. In order for a chain reaction to occur, the pure uranium ore must be refined to raise the concentration of 235U. This is called enrichment and is primarily accomplished through a technique called gaseous diffusion. In this process, the uranium ore is combined with fluorine to create a chemical compound called uranium hexafluoride. The uranium hexafluoride is heated and vaporizes. The heated gas is then pushed through a series of filters. Because some of the uranium hexafluoride contains 238U and some contains 235U, there is a slight difference in the weights of the individual molecules. The molecules of uranium hexafluoride containing 235U are slightly lighter and will pass more easily through the filters. This creates a quantity of uranium hexafluoride with a higher proportion of 235U. This is collected, the uranium is stripped from it, and the result is an enriched supply of fuel. Usually, nuclear power plants use uranium fuel that is about 4% 235U.

The parts of the reactor

The high pressured reactor which is used for ships has merely critical parts. Inside the "core" where the nuclear reactions take place are the fuel rods, the control rods, the moderator, and the coolant. Outside the core are the turbines, the heat exchanger, and part of the cooling system.

These fuel rods are each about 10,5 feet long and about a centimeter in diameter. These are grouped into large bundles of a couple hundred rods called fuel assemblies, which are then placed in the reactor core. Inside each fuel rod are hundreds of pellets of uranium fuel stacked end to end. When a neutron hits the 235U atom, it will separate into two lighter elements, free neutrons and a lot of heat. These free neutrons will collide with other 235U atoms and they will also split etc. This is called nuclear chain reaction. (see picture)



picture 2

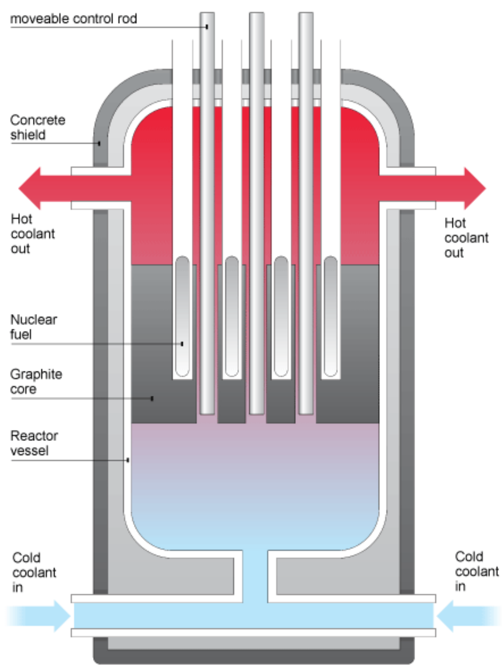
Also in the core are control rods. These rods have pellets inside that are made of very efficient neutron capturers. The rods will allow the reactor to stop at any given time. Because nuclear fission requires free neutrons that collide with the 235U. So when these rods are fully lowered into the core, the fission cannot start. When they are pulled out of the reactor fission will start again as soon as a neutron strikes a 235U atom. The atom will release more neutrons and the chain reaction will start all over again.

Another component of the reactor is the moderator. The moderator is there to slow down the high speed neutrons "flying" all around the reactor core. This is called downsizing. These neutrons are in the core because if a neutron is moving too fast, and is at a high-energy state, it passes right through the 235U core without creating nuclear fission. So it must be slowed down to be captured by the uranium core. The most common moderator is water, but sometimes it can be another material.

From fission to electricity

The job of the coolant is to absorb the heat from the reaction. The most common coolant used in nuclear power plants today is water. The coolant water is heated by the nuclear reactions going on inside the core. However, this heated water does not boil because it is kept at an extremely intense pressure, increasing its boiling point above the normal 100° Celsius.

The heated water rises up and passes through another part of the reactor, the heat exchanger. The moderator/coolant water is radioactive, so obviously cannot leave the inner reactor containment. Its heat must be transferred to non-radioactive water, which can then be sent out of the reactor shielding. This is done through the heat exchanger, which works by moving the radioactive water through a series of pipes that are wrapped around other pipes. The



picture 3

metallic pipes conduct the heat from the moderator to the normal water. Then, the normal water (now in steam form and intensely hot) moves to the turbine, where electricity is produced.

After the hot water has passed through the turbine, some of its energy is changed into electricity. However, the water is still very hot. It must be cooled somehow. Many nuclear power plants use steam towers to cool this water with air. These are generally the buildings that people associate with nuclear power plants. This will be impossible on a ship because the towers are too large. So the clean water is purified and dumped into the water, and cool new water is pumped in to replace it.

The nuclear system on board of a vessel

Introduction

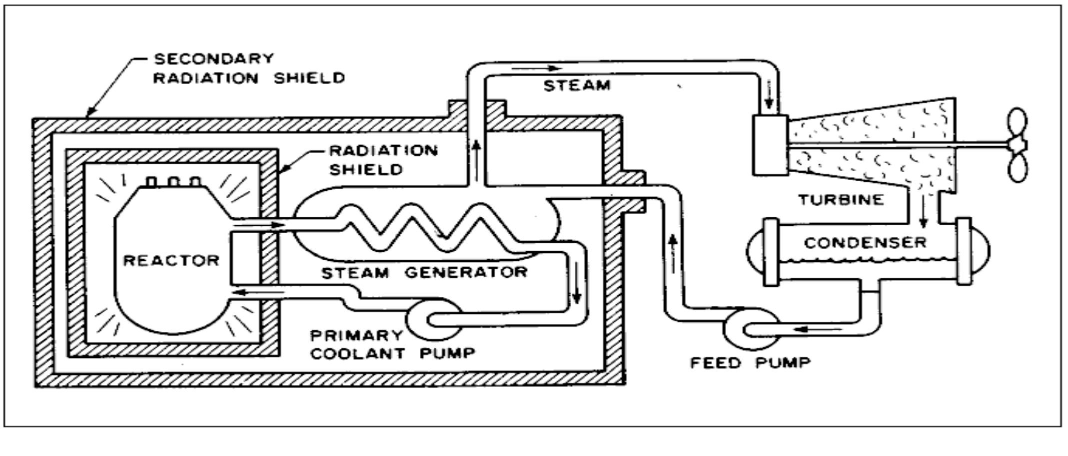
In the world of maritime propulsion are many ways to get the ship going. Nuclear power is one of these ways. It has been used by the Navy since the 1950's but only for the government, with the purpose to make war. Nowadays the nuclear energy is improved and ready to be used, but how can we use this technology to make nuclear energy work on merchant vessels?
In this sub-question the answer to how we can make a nuclear system onboard a vessel will be explained.

Nuclear power onboard a vessel

Since the first ship with nuclear propulsion was built (Savannah) there has been a slow development in the nuclear ship building. Another ship that was built in the early years of the Nuclear energy was the Otto Hahn. The ship was built in Germany and named after the German nuclear scientist Otto Hahn (8 March 1879-28 July 1968). It was built for 16870 GT, speed 16 knots and 11000 HP. The Nuclear propulsion was built up of pressurized water reactors with 38 MWth (megawatt for thermal energy, total energy of a nuclear reactor). The first voyage of this ship was on 11-10-1968. Until 1979 when she put to a hold. He had travelled 64200 Miles in 126 voyages. After that the nuclear energy based ship was put to a hold. She was rebuilt to a combustion based ship. All of the radioactive parts were dismantled and removed. After the installation of the new engine the ship was taken back into service.

The nuclear energy (fusion propulsion or nuclear power) of a vessel using a nuclear energy reactor makes ships peak in performance possibilities. This because of the enormous energy that is created by the nuclear process, which takes place in this reactor.
In a project called Nereus, there is a new design for a nuclear power plant. This system is not controlled by humans, or controlled by computers that are controlled by humans. But this system is controlled by the laws of physics. This means that the heat source will follow the required output and not the other way around as we are so familiar with. This system is designed for the markets of shipping and resembles the 8-10 MWe diesel in numbers. If more power is required, more units will be added. This makes it cheaper (because of standardization, like a diesel) and gives a better redundancy, flexible maintenance, flexible logistic support[1].

In a nuclear powered vessel, vessel's propulsion is similar to the propulsion in a conventional steam propulsion vessel. Replace the burning ovens for coal with a nuclear reactor and it will work like a steam propulsion vessel with a few improvements. With this replacement of the burning ovens with nuclear energy that works on steam, the energy that is released with the nuclear fusion of uranium will be transferred to a heat exchanger and here in the process it will be converted into steam. This steam drives the turbine or generator of the ship.



picture 4

[1] see reference 10

When the nuclear power system of the ship is running it transfers energy to the crankshaft that begins to rotate. This transfer is based on the conventional steam system transfer. The rotation drives the propeller that makes a rotary motion in the water that provides the propulsion of the ship.

Since this year the attention regarding nuclear energy has renewed, because of the pollution in nature by the maritime sector. And the facts that fossil fuels are getting expensive and are not infinite nuclear energy is becoming interesting again. The development in nuclear based propulsion has resulted in the improvement of the reactors. These reactors have to follow a stricter law in regard to emission. In this worldwide law emission of all natural fuels must be reduced by 20% Because of all of these new laws and new technology the modern nuclear reactors are smaller; they need less maintenance and are easier to operate. This makes the nuclear propulsion interesting again.

These new and smaller reactors create 70 MWth. This is enough for 20,000 households. This new reactor on the ship is named the Hyperion Power Module (HPM). This Small modular reactor is made by the factory and owned by the company Hyperion Power generation. This reactor is super small and can be used on shore and on ships. Because of the small size (1.5 meters across and 2.5 meters high) this power module has a constant temperature of 500 degrees Celsius. This power module is very efficient with the fuel(uranium). This reactor has a fast relinquish of heat with the liquid lead which is used as heat extractor. This heat is passed on to the water that is converted into steam. Which drives the steam turbine and turns back into water and returns to be heated again.

This Hyperion battery can easily be taken out of the ship and put back in. And with intensive use it is in need of docking once every 5 years. This is because the fissile product is very efficient and does not need very much maintenance.

In the existing Hyperion power module there is a problem with the “downsizing” of the power of the module. Downsizing is the decreasing of the power produced by the generator. When the HPM is downsized in the heat exchanger that exchanges the heat between the gas turbines and the Hyperion power module occurs a problem. In this heat exchanger the pressure and temperature that are developing are rising too high too quick.

The other option for reducing the power of the Hyperion power module is to scavenge a few neutrons. These neutrons ensure the generation of heat and so energy. If you take these neutrons away the power of the system will decrease. This taking away of neutrons is controlled by the control rods (as described in the paragraph “parts of the reactor” on page 9). But when this process takes place it can take a long time before the reactor can deliver full power once again.

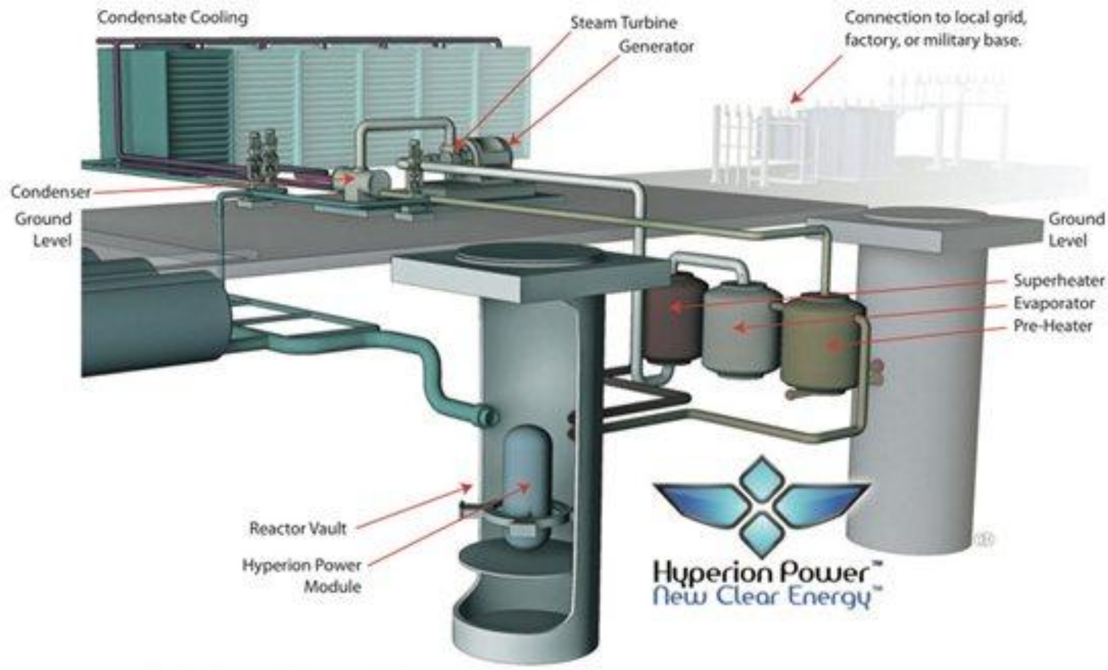
The influence of the nuclear reactor on the vessels construction

Introduction

A normal nuclear power plant is a very complicated construction. There is much attention given to the protection against the nuclear radiation as already has been noticed. Therefore the ships safety measurements have to comply with the safety rules in a nuclear power plant. In nuclear power plants there are several parts that protect the environment against the radiation. When a nuclear plant will be fit into a vessel the crew and the carried goods must also be well protected against the radiation. There is also space needed for the power plant itself. Realizing a nuclear power plant on board will cause impact on the vessels construction. To discover how the vessels construction will be effected by placing a nuclear power plant on board we will answer the following question: "How will the ships construction be effected by the nuclear power plant?"

Radiation

Most important on board is safety. A nuclear installation gains a whole new perspective on safety on board a vessel. Everything and everybody on board of a vessel must be well protected against the nuclear radiation. Exposure to nuclear radiation will cause damage to a person's DNA. Through this the chance that uncontrolled cell division will be increased and thus the chance that they get cancer will increase. That is (partly) why it is very important to provide a good protection against the nuclear radiation. In the Hyperion Power Module (HPM), this protection is provided by a lead sheath. This sheath of liquid lead is also passing the produced energy to the water. This lead sheath gives extra protection against the radiation. As you can read in the chapter "Collatorel risks" lead will transform the radiation into heat. The nuclear installation is not same shaped as a combustion based engine. Therefore the construction must be changed so the HPM will fit. The HPM will be 1.5 meters in diameter and will have a height of 2.5 meters. As you can see in the picture below the HPM is just a part of the total installation. Onboard this should not be a problem. Most of the other components are already in use at nowadays combustion based vessels. This picture gives the application of the Hyperion Power Module on land. There the nuclear reactor will be fit in a so called reactor vault. This is placed under the ground. Onboard a vessel this is impossible of course. When applied on a vessel it won't be exactly as this picture shows but it gives a good short overview of the system which is necessary for propulsion on board. As you can see the reactor is just a part of the whole installation.



Hyperion Power Module-based 25MWe Electric Power Plant

picture 5

In the Hyperion Power Module heat is produced. This heat is used to heat up water so it becomes steam. This steam is transported to a generator where the energy is converted into electric energy. Very often on a normal vessel such a steam system is already in use. For the most persons working onboard it wouldn’t be difficult to work with that part of the system.

For safety reasons this unit can be lifted out of the vessel. So when the reactor must be repaired, controlled or refilled this happens in a safe conditions. The vessel goes in dock and the nuclear reactor will be lifted out of the vessel. So the reactor is not in the vessel when maintenance is carried to the reactor. It’s also possible to transport the HPM in a standard fuel transport container. So when it needs maintenance it’s also possible to replace the HPM by another one.
The reactor also has to be resistant against all the movement of the vessel. When the vessel is rolling and pitching, the reactor must at all times stay intact to avoid any release of radiation. According to Vince Jenkins, Global Marine Risk Advisor at Lloyd’s register, the reactor is strong enough to resist collisions. The reactor is very safe, hidden deep in the vessel. The HPM is made with a very small amount of moving mechanical parts. This gives the HPM a good operational reliability.
The bedplates will take all the forces of the installation, the bedplates will be welded to another construction, to divide the forces all over the vessel, so this will give no harm to the vessel.
Inside the construction there will also be the water supply for the installation, this is needed for the cooling.

Advantages and Disadvantages:

Advantages :

- Higher speeds, compact system
- No bunkering time
- More space (no fuel spaces)
- Lower costs (no fuel consumption)
- No carbon dioxide emission

Disadvantages:

- Risk of nuclear disaster
- High installation costs
- Personal training

Advantages

A nuclear reactor has a very large radius and a high power[3]. This reactor is also very compact.
A normal combustion engine could also deliver the same power but that would cost so much fuel that there is almost no more space left for freight.
Because a nuclear driven vessel has enough fuel in its reactor to sail for a period of 5-10 years, there is no time necessary for bunkering. These fuel rods can be replaced during the normal docking period.
Nuclear engines don't have the emission of CO_2, SO_2, NO_x

Disadvantages

Because of the disasters that happened on land with nuclear power plants in the past, people are afraid that this could also happen at sea. And that it will be a danger when ships collide or hit a reef, in that case the sea water will get exposed to radioactive material. According to mister Crommelin[4], the only problem at this moment is the notion that people have about nuclear reactors, and the human factor on board of the vessel. The system is working and is safe enough to apply, the only risk would be a human factor.

According to Vince Jenkins, Global Marine Risk Advisor at Loyd's register[5], the reactor is strong enough to resist collisions, very safe and hidden deep in the ship.

[3] See references 2

[4] See references 10

[5] See references 8

Nuclear waste

When the reactor has lost its power the core must be renewed. The old core is still sending out nuclear radiation, so the core is still dangerous. All material with radioactivity are called nuclear waste when it can’t be used anymore. Nuclear waste still is dangerous. It takes years before the nuclear waste has lost its strength and won’t send out dangerous radiation anymore. These years the nuclear waste must be stored in a safe place under safe circumstances. Then it slowly loses its strength till it won’t be a threat for the environment.

There are several companies specialized in processing nuclear waste. In the Netherlands COVRA is the Central Organization For Radioactive Waste. This company gathers all the Dutch nuclear waste. The nuclear waste is processed to smaller pieces and some parts will be burnt to as. Other material will be pressed together. Thereafter the processed materials will be packed. The packed nuclear materials are fairly safe. When stored in a safe place the nuclear waste will be harmless. After a very long time the material has lost its radioactivity and can be disposed as normal waste. It can take more than thousands of years before the nuclear waste is really harmless.

Collateral Risks

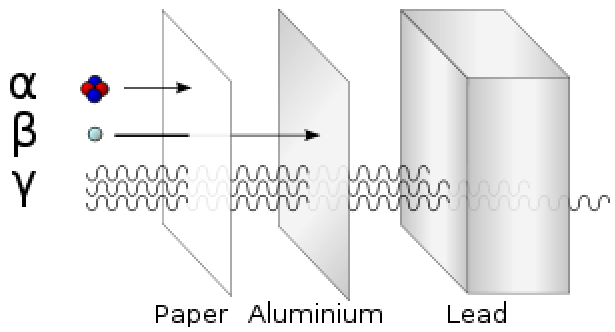
Radiation

Radiation is a process in which energetic waves and particles are travelling through a space or a medium. There are two types of radiation; ionizing and non-ionizing radiation.
Ionizing radiation is harmful. This radiation even at low radiation powers has the potential to cause cell and DNA damage, because of the high energy and a positive charge. DNA damage of a few cells has no consequences, but a longer exposure to this radiation can result in damaged DNA which can cause an increased chance of cancer. The effect of the radiation depends on the absorbed dose, the type of radiation and the sensitivity of the organ or tissue. These types of radiation which are released during the fission of uranium-235 are Alfa-radiation, Béta-radiation and Gamma-radiation.

Ionizing radiation

This is the radiation which is harmful to people, the types of this radiation are.

- Alfa particles, the cores of the helium atoms (are stopped by a piece of paper)
- Beta particles, fast moving electrons (are stopped by an aluminum plate)
- Gamma rays, electromagnetic waves with high energy (can only be stopped by a thick layer of lead ore concrete)
- X-rays (electromagnetic radiation)



picture 6

Non ionizing radiation

By non-ionizing radiation is mend, radiation which is harmless at low powers with no significant temperature rise. These waves are everywhere around us and are present in a lot of household products. These particles do not carry the amount of energy to cause ionization, examples of this radiation are:

- Radio waves
- Microwave
- Visible light

Consequences

The consequences of this radiation would be that on board of a vessel, there has to be a thick layer of lead ore another material around the reactor. To make sure that there is no danger for the people working in the engine-room. When they will enter the reactor they would have to wear special suits, to make sure that they will not get irradiated.

Nuclear meltdown

A nuclear meltdown is an accident with a nuclear reactor in which the core of the reactor overheats and melts its fuel resources. When this occurs, many radioactive materials will be released, the reactor will be destroyed until the core is fixed again. In a very severe meltdown, the nuclear chain reactor will get out of hand and will drill its way out of the reactor and eventually out of the ship. This will have catastrophic consequences if this happens. Not only life’s will be lost, but also the environmental damage will be catastrophic.

A core melt accident occurs when the heat generated by a nuclear reactor exceeds the heat removed by the cooling systems to the point where at least one nuclear fuel element exceeds its melting point. This differs from a fuel element failure, which is not caused by high temperatures. A meltdown may be caused by a loss of coolant, loss of coolant pressure, or low coolant flow rate or be the result of a criticality excursion in which the reactor is operated at a power level that exceeds its design limits. Alternately, in a reactor plant an external fire may endanger the core, leading to a meltdown.

Nuclear powered vessels

There are several nuclear powered vessels in service at this very moment. Most of them are naval vessels, especially submarines. Also the American navy uses nuclear propulsion for their aircraftcarriers. These vessels can sail for a maximum time of ten years before refuelling. That is why nuclear propulsion is so attractive for naval vessels. The Russians also have several nuclear powered ships. All of them are ice-breakers, which are needed in order to sail merchant routes.

This very day there is only one nuclear powered merchant vessel in service, the NS Sevmorput[6]. It sails under the flag of Russia and started its service time already in 1988. This vessel is a combination of a ice-breaker and container vessel.

This is the only merchant ship this very day because it all is just very expensive. In order to provide nuclear energy on board of a vessel you have to change the whole structure and get a custom build nuclear reactor inside your ship. To make this profitable, only the big merchant vessels can sail with nuclear propulsion. For smaller vessels this will be impossible due to the lack of space on board and the earning of the vessel itself.

It is a sure possibility that nuclear power is the future for marine propulsion. It is just a matter of time before the fossil fuels run out. So it is really necessary to look for alternative power sources. This is why nuclear power becomes so interesting for the upcoming years to research.

Also the use of nuclear power is not really culturally accepted. This has the effect that it is difficult to get the authorities support any investigation concerning this subject. It might be helpful when the authorities will be more informative about nuclear energy. It is difficult because when there happens a accident with nuclear energy as happened in Japan everybody gets informed about it. Meanwhile there are more than 430 nuclear power plants around the world, all working as they should. As happened in Japan, the situations are far from the average situation. According to mr. Crommelin the reactor acted as it was ment to do. The problem was that the wall wasn't calculated to withstand the sea. Another issue still is the human factor. That's wat makes the NEREUS project that interesting. The system isn't controlled by human but through the laws of physics. That decreases the change on failure and will increase the systems safety.

[6] See references 1

Conclusions

For a long time now, nuclear propulsion has been applied in several naval and merchant vessels. And after years of research the outcomes of all investigations seem to be practically the same. The materials and knowledge to make such systems are available, also it is proven that they work and even for a long time they continue to work.

Also when you will discuss the matter of safety, you will find out that the nuclear reactors used on board of vessels are very safe and the change of a nuclear meltdown is very small.

This leads us to the point which would make us not build these nuclear propelled vessels, because of the costs. After we did some research we kept running into articles and reports which told us that the installation costs are very high. And that fuel prices should triple to make a nuclear installation profitable. This would not be true when you would build a reactor for a very large vessel like the Emma Maersk, in that case the installation would be profitable after a few years.

The reason these installations are so expensive is that there is no company willing to take the risk, of producing these installations on a larger scale. If this would happen costs of the installation would decrease and the ship owners would start using them. Because of the accidents that happened in the past with nuclear reactors, most people are afraid. This is also a reason that no-one believes that this could be a good alternative for combustion engines. When these ships would start sailing there will be a lot of people trying to stop it from entering harbours, because their afraid of their own safety.

Eventually our opinion is that nuclear energy is a great replacer of the combustion engine, because of the low fuel costs and the fact that there is no emission at all. This development is obstructed by the fear of the people and the purchase costs of the installation. When it would be proven by the researchers that everything is safe enough, and there would be a company starting to produce them, these problems would fade away.

Recommendations

Our recommendations regarding the research are as following;

- Companies will soon start searching for alternative sources of energy, this is why we think it's best to do more research about the costs of a nuclear system on board. By doing this, companies might consider to trade their combustion engine for a nuclear one. This will save a lot of environmental damage and a lot of fuel costs.

-One big company has to take the lead in building such nuclear propulsion engines. Others will eventually follow which makes it cheaper for shipping companies.

- We recommend that ship builders not only look to the possibility to rebuild ships. But also look to the in our view cheaper way, to make a whole new vessel that has been built around the fact that there is a nuclear power plant inside. This new vessel will have a better match with the nuclear power plant then a rebuild combustion based ship. A nuclear powered vessel needs a smaller engine room, this provides the vessel with extra cargo space.

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Interview Mister Crommelin

We would really appreciate it when you will tell us something about your experience with nuclear energy in response to the following questions.

1. **What was/is your profession ?**

My profession was Officer Engineering Royal Netherlands Navy. From 1964 to 1978 on steam driven ships. From 1978 to 1993 on gas turbine driven ships and some jobs ashore, like head of the gas turbine office and my latest job was Head of the Engineering and ship building office of the Royal Netherlands Navy. I retired end of 1993. My wife and I, with the help of Hugo van Dam (see para 3)and a few friends, worked on the design, doing lectures, visiting exhibitions and congresses up to 2008.

2. **How did you get in touch with nuclear energy?**

Up to 1994 never. I did not attend an university, only three years at the Royal Institute for the Royal Netherlands Navy (Koninklijk Instituut voor de Marine te Den Helder). In 1978 I was, with the Netherlands gas turbine industry (Vereniging Gasturbine) at the congress and exhibition of the American Society of Mechanical Engineers – Internationl Gas Turine Association (IGTI). I did some lectures on financing, maintenance and the management system called the pooling system. During the last evening (everybody very tired) a discussion took place on what the next logical step would be in the gas turbine development. So subjects like electromagnetic bearings, water injection, biogas, etc. passed by. When they asked my opinion I said a gas turbine with a nuclear heat source! A big silence fell and we went to bed. After I retired my wife and I decided that we would take up this challenge.

3. **You were involved in NEREUS, what was your business within NEREUS?**

I took the initiative and we did most of the work ourselves. The advisor on the nuclear aspects was and still is Professor Dr.Ir. Hugo van Dam. At that time director of the Reactor Institute of the TU-Delft. He was involved in the design of the NERO, Nederlands Eerste Reactor Ontwerp, a nuclear reactor plant for shipping. He is also a great supporter of the Royal Netherlands Navy and so has a good view on the possible dangers of a NEREUS plant at sea, in case of collision and in the harbours.

4. **What does NEREUS mean? What was the intention when this project started?**

As you can see in the brochure, it stands for "A Naturally safe, Efficient, Reactor, Easy to operate, Ultimately simple and Small". And that she is indeed!

5. **Is in your opinion the production of nuclear energy safe enough to apply it on a larger scale ? (why/ why not)**

It is not clear to me what you mean with larger scale. The nuclear units at the moment (there were or still are about 450 units ashore and there were or still are about 750 units at sea) are safe. By the way, the oldest nuclear reactor are the 8 units, fabricated by Westinghouse in the second half of the fifties, on board the USS aircraft carrier Enterprise and the ship and so the reactors are still doing fine. Do not confuse the nuclear aspects with the aspects related to the tsunami in Japan. The nuclear technology did what it was supposed to do, unfortunately the calculations for the wall to protect the plant from the sea were outdated. The other two disasters Harrisburg and Tsjernobyl were human errors. As maritime designers of the TU-Delft said the past weeks about the stranding of the Costa Concordia, we can design everything but not to human mistakes.

In fact even that is covered with the NEREUS design, because it is not designed for human control systems or human control by computers, but control by the laws of physics. I will always be very impressed by this aspect. It took me a couple of times and a number of visits and so hours for Hugo van Dam before I really understood this: a heat source which follows the required output and not the other way around as we are so familiar with.

We designed the engine for the markets of shipping and the, most popular engine, in numbers, is the 8 – 10 MWe diesel. If more is required please use more units, it makes life cheaper (because of standardisation and pool management, like a diesel) and gives a better redundancy, flexible maintenance, flexible logistic support, etc

6. **Do you think that the current technologies are safe enough to apply nuclear energy on board of a vessel?**

I do not bother about the mechanical part, such as the gas turbine, heat exchangers, etc. I only bother about the nuclear part. And Hugo can explain exactly that there is no danger.

7. **Would it be attractive for terrorists to use a nuclear vessel for fabrication of weapons?**

The heat source is the High Temperature Reactor, the fuel is bedded in balls. This is called the pebble-bed reactor. I would like to see a terrorist trying to strip the balls in order to get to the fuel and the radioactive waste. His life will be extremely short! So, not attractive at all!!!

8. **Are there during your research, any extraordinary outcomes that were not expected?**

Good question. To our surprise all components are available and well-proven, the gas turbines are turbo expanders, very popular in the gas transport industry. The heat exchangers are used in oil refineries, AND the pebble-bed reactor was tested for 20 years in Jülich, Germany, about an hour from Venlo. And as the controls are done by the laws of physics, these are well-proven as well. The pebble-bed reactor is now being tested at the University of Beijing.

Interview Mr Luteijn

1. **For what company did you work?**

For the Gemeenschappelijk Kernergiecentrale Nederland (GKN), that used to be a part of KEMA (Keuring van Elektrotechnische Materialen).

2. **How long did you work there?**

For a period of 8 years

3. **What was your function?**

My function was reactor engineer, my job mostly consisted of (approx. 80%) the monitoring and controlling of the entire plant. The other part of my job was to fill in checklists and walk my everyday route to look for suspicious signs. And we tested the all the systems that where necessary to keep the nuclear power plant running (approx. 20%).

4. **How was safety being watched over during the time of your employment?**

There was a very heavy access control, because the nuclear power plant was not socially accepted. There were two gates one after the other with guards and in between the fences there where guard dogs.

The security situation in the power plant itself was such that the shoes you whore inside had to stay there, and that you had to wear a jab coat. On entering and leaving you had to pass a radiation control area (a kind of lock) with people that had to check you.

5. **Is the production of nuclear energy safe enough to apply frequently?**

It seems to me that it is possible, provided that you have a well-trained crew. In my view it is in terms of technological and safety aspects certainly possible. But there is still much psychological resistance of people, especially in view of the problems in Japan. I think it is something that will not happen in the near future.

6. **What is your opinion about Nuclear energy?**

I am still very positive about it, but i do not think it will become profitable yet on vessels.

7. **Do you think that the current technologies are safe enough to apply nuclear energy onboard of a vessel?**

In my view, yes I do think that. But something is as safe as the weakest point and that will always be the humans. There has to be a good team of well-trained people to keep the reactor up and running.

8. **Do you have any idea what a nuclear power plant on a vessel would cost?**

No, that is information which is difficult to obtain.

“I think for your project, it is not a good idea to spend a lot of time on that. Because the information is hard to get and your knowledge is not sufficient”.

9. Would it be interesting for terrorist to manufacture nuclear weapons out of this nuclear vessel?

No, a terrorist cannot use this uranium because they lack the knowledge and equipment to get the plutonium from the reactor.

It can only be used for blackmail or as threat, but it cannot be used as a bomb or for any other purpose.