A WELL-PROVEN INHERENTLY SAFE NUCLEAR PRIME MOVER FOR SHIPS
THE NEREUS INSTALLATION

BY

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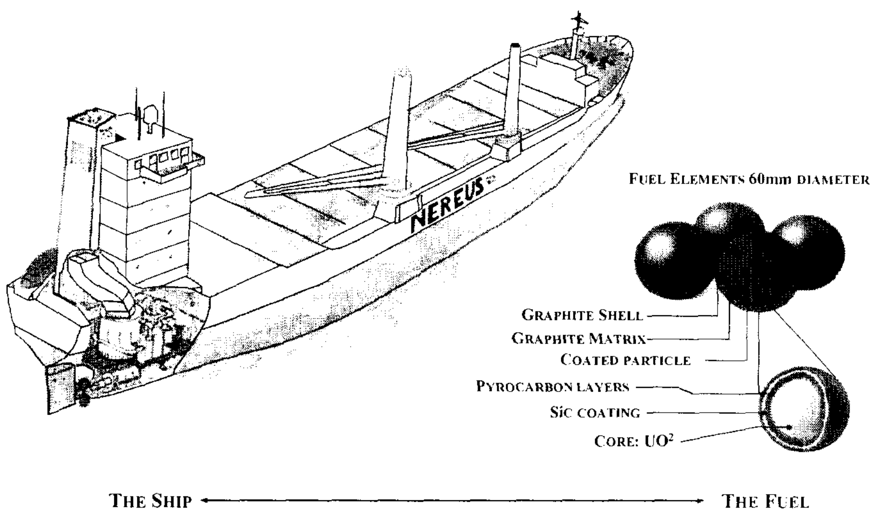
ABSTRACT

Several international publications and studies point out, that as far as can be predicted at the moment, the world population and energy consumption will be doubled by mid 21st century. In addition we all wish our fellow world citizens a better life and a better health, more prosperity and well being. Without any doubt this will lead to an enormous increase in the consumption of fossil fuels, a further increase in the shortage of fresh water and in the transport of goods and so in shipping.

The increase in demand for fossil fuel will lead to a higher CO_2 pollution, which will lead to even higher costs and penalties, and thus to higher fuel costs. Many industrial processes are based upon fossil fuels. Some processes cannot, some processes can (partly) be modified to other fuels and some processes will switch to other sources as soon as possible. But what about ship propulsion? If the fuel price increases, are we changing back to sails or even to galleys? Not very likely, humanity often tried but rarely succeeded successfully in going back in history.

So the time has come to look for innovative solutions and in this case history will help. This article will discuss a well-proven inherently safe nuclear propulsion installation and in particular the safety features.



Introduction

The World Energy Council indicate a doubling of the world population over the next 30 - 50 years. This will go in step with an estimated doubling of the energy consumption per head of that same population, due to the desired further improvement of well being and prosperity. This means that future generations will have to employ every possible means to produce this required amount of energy in the most cost-effective and environmentally friendly way. So this is a plea to use a not commonly known, but thoroughly tested, nuclear energy production technology for the markets of, among others, ship propulsion. This article will discuss such an installation. It will discuss the possibilities of an energy production unit consisting of a recuperative gas turbine directly coupled with a well-proven inherently safe nuclear heat source through a closed cycle helium system. The international abbreviation is High Temperature Reactor with Gas Turbine or HTR-GT. The basic system is shown in (FIG.2). Studies show that this so-called NEREUS installation is smaller than existing prime movers, is suitable as prime mover in an All-Electric Ship propulsion configuration and is very much comparable in price per produced kWh to existing energy production installations, when calculations are based upon through life costing. The waste heat and surplus of electricity can be used for cargo heating or to produce fresh water through desalinisation and reverse osmosis, as is the existing practice.

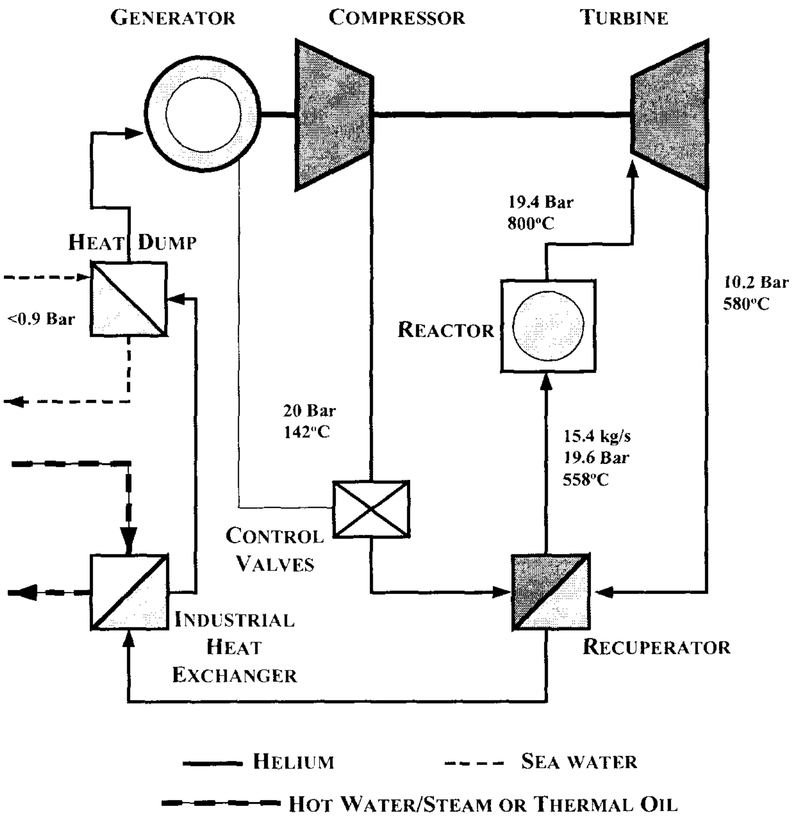


FIG.2 – THE BASIC SCHEME OF AN HTR-GT

The on-going study on which this article is based, is called **NEREUS**, which stands for:

a **N**aturally safe, **E**fficient, **R**eactor, **E**asy to operate, **U**ltimately simple and **S**mall.

It consists of an inherently safe helium cooled nuclear heat source of 20 MW thermal power, directly coupled to a recuperative gas turbine and with an output of 8 MW electric.

Due to the limitations as dictated, several important aspects such as the nuclear waste, control of criticality and energy production, costing, market potential, etc. can only be mentioned very briefly.

As the title states this article will discuss a nuclear option for ship propulsion. Any energy source consists of a heat source and the energy conversion unit or in this case a nuclear heat source and a recuperative gas turbine driving a generator. So the installation can be divided into a nuclear part and a non-nuclear part. For all kinds of reasons it is logical that the nuclear part will get the most attention.

The non-nuclear part

This part consists of a:

- Helium gas turbine
- Helium cooled generator
- Recuperator
- Heat dump
- Mass flow power control system
- Industrial heat exchanger if required for cargo heating etc.

According to the gas turbine technology, the gas turbine is a 'cool one'. Temperatures at the inlet of the turbine are low (see FIG.2), so no expensive coatings or cooled blades are needed. Lubrication oil in any closed cycle gas turbine system will lead to pollution of the heat exchangers and in this case of the nuclear heat source. So all bearings are helium cooled magnetic bearings. The generator also is helium cooled.

The nuclear part

The nuclear heat source has been extensively tested in Jülich, Germany for 20 years. Some of the tests, which will be discussed later, prove the reliability of the nuclear heat source.

The fuel

The basic fuel element is the so-called coated particle, consisting of a uraniumoxide fuel kernel surrounded by four layers (see FIG.3 – lower half). From inside to outside a:

- Porous pyrolytic graphite
- High density graphite layer
- Silicon carbide layer
- Outer pyrolytic high density graphite layer.

The diameter of the kernel is about 1 mm. The whole fuel element construction is called TRISO. The silicon carbide layer forms a confinement of the fission products inside the fuel kernel and the porous layer. The porous layer allows storage of fission products that are partly gaseous. It has in practice been proven that these particles can withstand temperatures of up to 1600°C during an indefinitely long period of time without decrease of integrity and consequently without any release of fission products

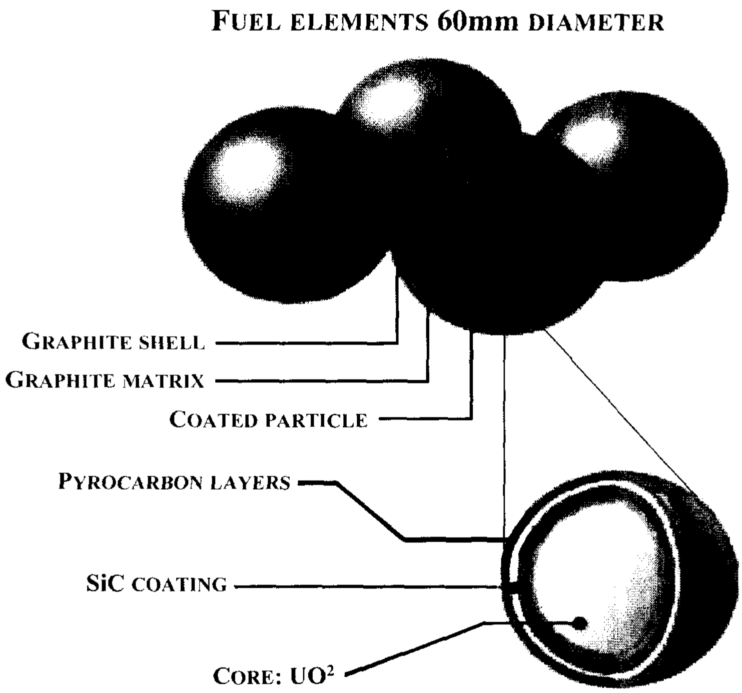


FIG.3 – THE NUCLEAR FUEL

The Fuel Element

From the outside the fuel elements look like graphite balls of 6cm or pebbles, which refers to the name of the reactor: 'Pebble-bed reactor'. About 10,000 of such TRISO have been put in a graphite matrix of the fuel element. The fuel elements can be made oxidation-resistant by coating them with silicon. As a consequence they are fireproof as well as corrosion proof (e.g. steam ingress). In fact the graphite matrix and graphite outer layer form the second containment, which is impenetrable for most of the fission products even at a long exposure at a high temperature. The build-up of highly mobile fission products in the helium coolant will be low as was also observed at the AVR test reactor in Jülich (see FIG.6)

Control of the reactor criticality

In the reactor core, during its fuel cycle, a chain of fission reactions has to be maintained. Because of the fission reactions the amount of fuel as well as the reactivity decreases after some time. Refuelling has to take place. Most studies on the Pebble-bed HTR use a so-called on-line refuelling. Consequently there is no excess reactivity in the core of an HTR and an accident like the one in Chernobyl cannot occur. But on-line refuelling means a constant adding of fresh fuel and removal of spent fuel. Especially the fuel removal implies a complicated installation, which may be prone to breakdowns. This refuelling system was applied in the AVR/Jülich. The South African ESKOM HTR will use such a refuelling systeml.

However, the NEREUS installation is based upon the principle to Keep It Simple and Stupid (KISS). The intention is to use 'burnable poison'. Some materials have such high neutron absorbing characteristics, that when placed in the reactor core their concentration decreases because of transmutation as a function of time. Such materials are called 'burnable neutron poisons'. They facilitate higher fuel concentration in the reactor core and consequently a lesser pace in the decrease of the reactivity. The burnable poison also simplifies the control rod requirements, only stop/start rods are needed.

At the moment the system works on a three year refuelling period (this operation is foreseen during the docking period). So the combination of the fuel enrichment and the burnable poison will be designed to produce 20 MW power in the reactor, resulting in about 8 MWe at the generator, over a period of three years with a usage pattern of 90% load and 80% usage, which is about 50,000 MWh electric per year. For a further flattening of the criticality curve, burnable poison will also be added to the inner part of the reflector. Recent studies indicate that a flat curve of criticality control using burnable poison in the fuel element is possible.

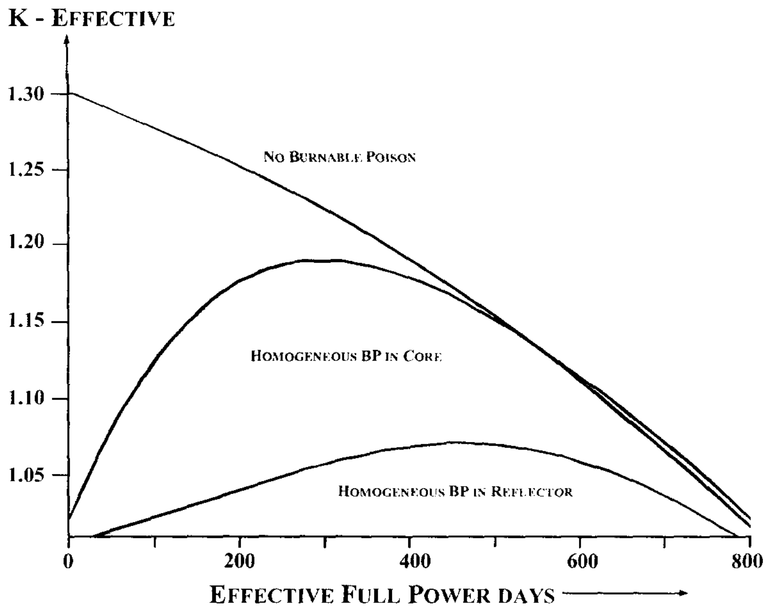


FIG.4 – CRITICALITY CONTROL THROUGH BURNABLE POISON

The control of the energy production

The reactivity is strongly dependent upon the temperature of the fuel. HTR's fuel possesses a negative temperature reactivity coefficient. This implies that when the temperature of the reactor temporarily decreases to some extent, its reactivity increases, its power generation increases and the original temperature level is restored. This was extensively tested at the AVR in Jülich. This phenomenon is being used for power control in the NEREUS reactor concept. This 'self-regulating power control' is the basis for the inherently safe character of the nuclear heat source and so for the affordability of this type of energy plant. This applies especially to two markets the project is aiming for:

- The stand-alone electricity production market
- The market for prime movers on board ships.

Both markets work, so to speak, with 'unmanned engine rooms'.

The power control output of the installation is delivered by the generator and is achieved by controlling the mass flow in the closed cycle system. This is not the optimal solution, but the one with the lesser number of parts. It is simple and well understood. After all if the fuel is cheap, the necessity of maximum efficiency at partial load is less important in comparison than when fossil fuels are used.

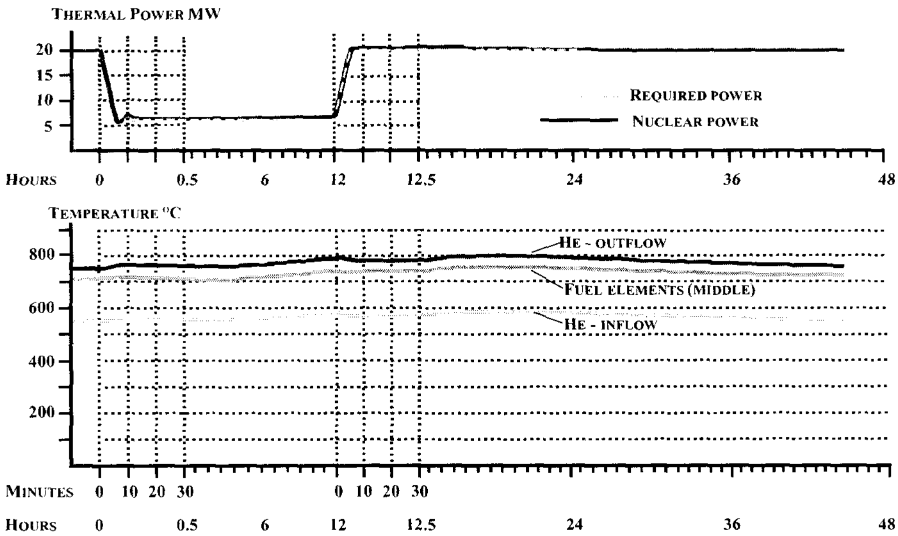


FIG.5 – TEMPERATURES AT A STEP-CHANGE IN POWER DEMAND CONTROLLED BY THE NEGATIVE TEMPERATURE COEFFICIENT, NO ACTIVE CONTROL BY CONTROL RODS ETC. OF THE THERMAL POWER.

This self-regulating thermal power control is an absolutely unique feature in 'combustion.'

The nuclear waste

Any discussion on 'Nuclear' starts with and puts a lot of attention on the matter of the nuclear waste. After three years of operation about 7 m^3 of fuel elements are removed from the core. This nuclear waste can be transported in shielded containers. A possible design has a diameter of <3m and a height of 5m. After about 10 years the radio-activity and heat production have decayed to such an extent that the waste can be classified under the category 'Middle Active Nuclear Waste'. After about 10 – 50 years of interim storage, the waste can be sent to final storage in relatively simple 0.4 m^3 drums. It must be stressed that this is mainly due to the high mechanical and chemical integrity of the fuel elements, which simplifies their final confinement from the biosphere.

Handling the Nuclear Fuel and the Nuclear Waste

The fuel load is placed in a special, walled, container, which, during refuelling, is placed in the centre of the reflector. The walls of this container are made from the same material as the reflector itself and are an actual part of the reflector construction. The walls of this fuel container contain burnable poison and the stop/start rods. Periodically this fuel container, often called the shopping basket, is replaced during the refuelling period. A standard 40ft container can be used, which brings in the fresh fuel and takes away the nuclear waste for further treatment. Specialized personnel, managed by a pool-system should deliver the equipment and the knowledge for this operation. The storage of middle active nuclear waste requires smaller investments, is easier to manage and needs less space per kg as high level nuclear waste.

Another option is to remove the fission products from the elements and to apply the well developed process of vitrification, which reduces the volume of the waste by almost a factor of 100. In this case the non-fissional part can be re-used in a reactor.

Finally it should be mentioned that the form and isotopic content of the nuclear waste are such, that there is no threat for misuse as weapons material. Several studies have even indicated that this type of reactor is very well suited for burning weapons grade plutonium.

Inherently safe means that a repetition of Harrisburg (near meltdown) and Chernobyl (over-criticality) cannot occur under any circumstances.

Decay heat

The completely passive removal of the decay heat is also a necessity. The decay heat is the heat, which is still generated after shut down. For this purpose there is a space between the outside of the reactor drum and the inside of the biological shielding, through which air is circulated, driven by natural draft. This is a very important point. This cooling will be there all the time and is established without any ventilators etc. in a natural way. For this purpose a normal ship's funnel construction is very suitable. This construction can also be used as a transport route for refuelling, maintenance and repair by replacement by the pool-management system. The cooling air must be supplied through air filter units at the open decks. This passive heat removal system is always in operation and removes about 0.5% of the heat during normal operations (100 kW).

The price of nuclear fuel

The calculated price for Marine Diesel Fuel per kWh, based upon prices of March 1999 (Rotterdam) is about 25 US$ per MWh. The price for nuclear fuel in the form of pebbles and including waste handling is less than 4 US$ per MWh.

Energy density

The energy density of the fuel in the core is 3 MW per m^3. In comparison the energy density of the Pressurized Water Reactor is 50 – 100 MW per m^3.

Safety aspects of the HTR-GT

This is the most important part of the plan. After all, the importance of subjects regarding (nuclear) energy production is:

Priority one	–	Safety.
Priority two	–	Costs.
Priority three	–	Licensing.

The engineering itself will follow if these aspects are properly covered.

Nuclear hazards to the environment: Yes or No and in what way?

The most important and incorporated safety features of the HTR-GT in relation to the environment are:

- The inherently safe character of the pebble bed reactor, which is established by:
  - The four coatings of the TRISO (first containment).
  - The coatings of the 6 cm fuel balls containing the TRISO (second containment).
  - The burnable poison in the fuel itself and the inner-cylinder of the reflector.
  - The incorporated negative temperature coefficient of the nuclear fuel.
  - The controllability of the energy production in the nuclear core.
  - The decay heat after an incident such as 'loss of coolant' or 'loss of flow', is removed from the reactor construction in a natural way through natural draft.
  - The low energy density in the core of 3 MW per m^3.

The result of this construction, proven by actual tests is, that the fission products remain under all circumstances in the double containment of the TRISO and the 6cm balls, which are not damaged by high temperatures.

Many calculations exist regarding the behaviour of the HTR heat source in case of loss of flow (the helium flow stops due to the failure of the gas turbine or ventilator) or loss of coolant (the helium leaks away through a leak). However, actual tests are much more convincing for the interested person or the potential user.

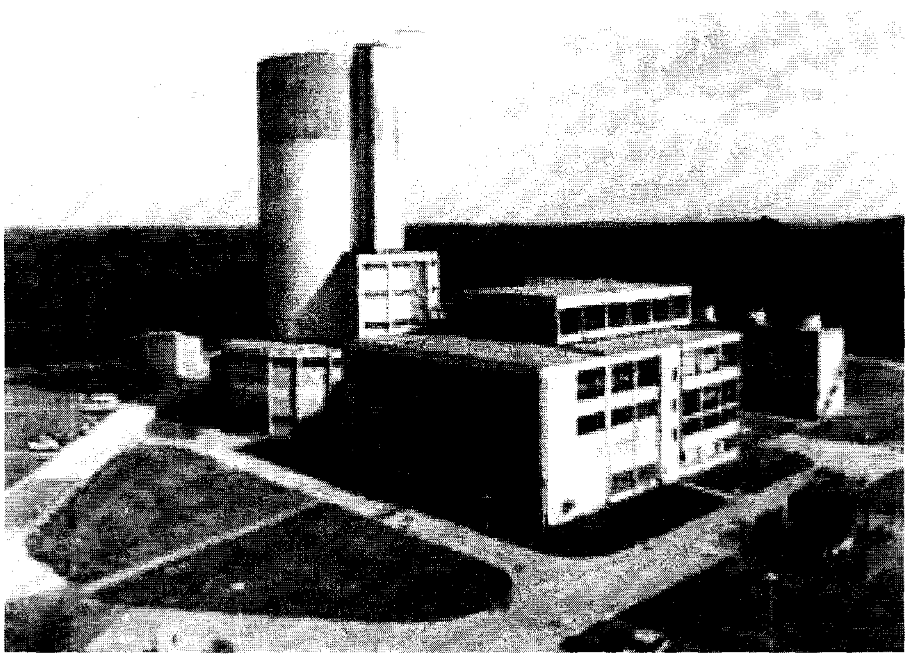


FIG.6 – THE AVR/JÜLICH TEST REACTOR

The actual (safety) test of the HTR

The AVR test reactor in Jülich, Germany (FIG.6), was a test reactor with a 13 MWe output. It was used for testing purposes over 20 years. A steam turbine was used as the energy conversion unit. The core was cooled by helium in a closed cycle system pumped around by two electrical ventilators (primary circuit). The energy was used to raise steam in a heat exchanger and the steam was used to drive the steam plant in a closed-cycle Rankine cycle, like any other conventional steam plant (secondary circuit).

In 1970 the following test was done in Jülich: the two ventilators were stopped, so the cooling of the core was abruptly stopped and the valves in the primary circuit were closed to reduce any natural ventilation to a minimum i.e. a loss of flow incident. The system that controlled the control or stopping rods had been deactivated first, so the control rods could not be and were not activated. The power of the reactor and the temperature of the reflector were measured in several places. The power decreased sharply due to the negative temperature coefficient; after 23 hours as a result of the Xenon effect the power increased again to 2 MW; however, it went down again and stabilized on 300 kW, (FIG.7).

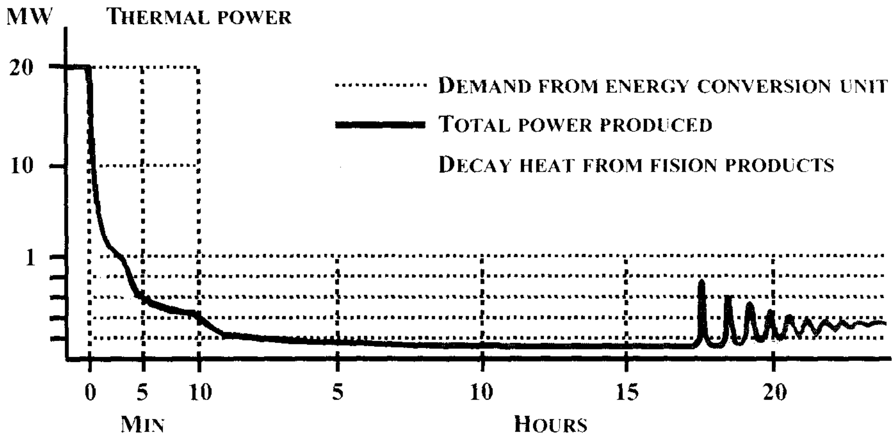


FIG.7 – THERMAL POWER AT A 'LOSS OF COOLANT' ACTUAL TEST

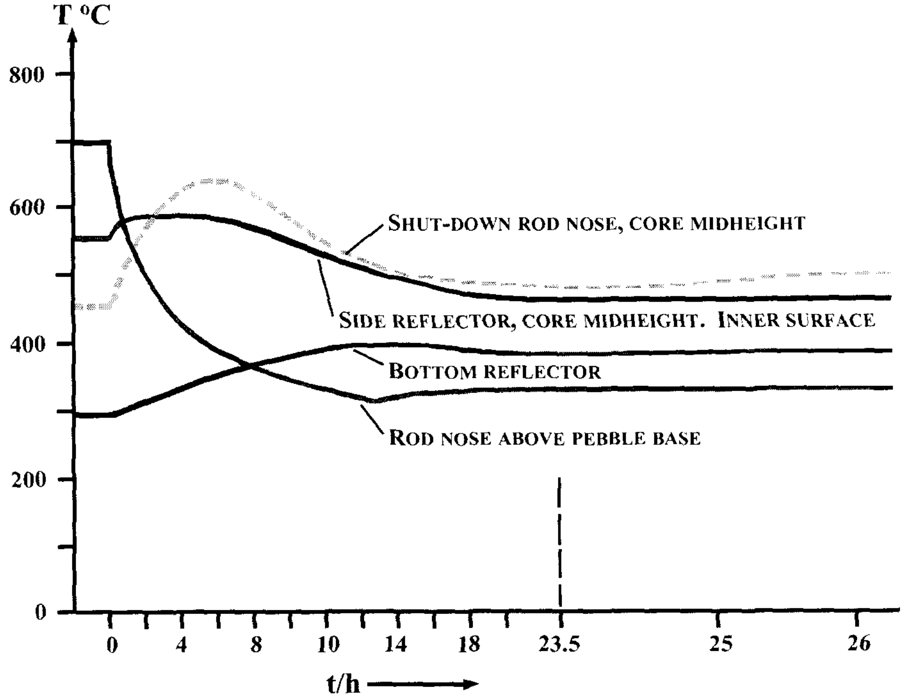


FIG.8– TEMPERATURE IN THE REACTOR AT THE SAME TEST

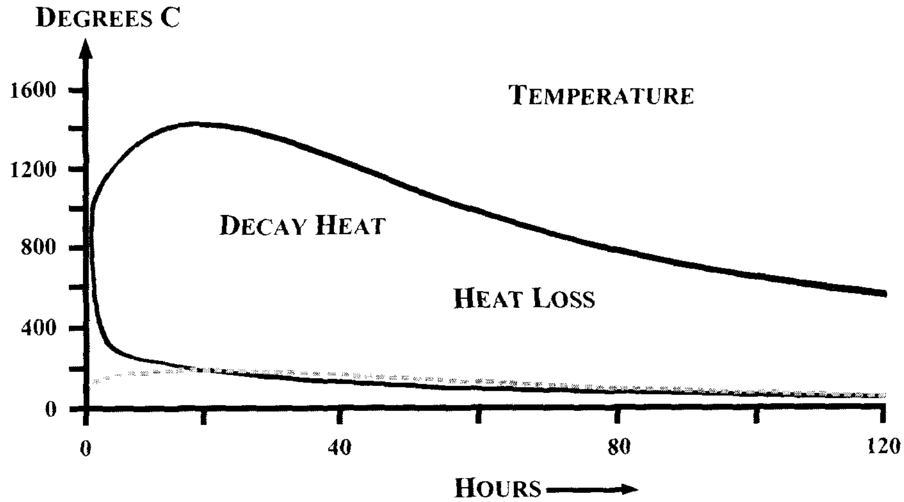


FIG.9 – DYNAMIC REACTOR TEMPERATURE BEHAVIOUR AFTER A LOSS OF COOLANT.
FUEL RETENTION, WHICH HAS BEEN DEMONSTRATED TO 1650°C, IS NEVER THREATENED

The results of the loss of coolant experiments were compared to theory. Calculations show a minimum of differences. It proves that the inherently safe character of the HTR is not only a paper exercise, but has been understood, tested and can be relied upon. This makes this type of heat source very suitable for remote controlled nuclear reactors and unmanned engine rooms on board ships.

The Summary report of the Inherently safe Nuclear COGENeration study (INCOGEN report on a 40 MWth HTR-GT installation – financed by the Ministry of Economic Affairs of the Netherlands) describes it as follows:

> 'As a consequence of the inherent and passive safety characteristics of the (HTR-GT) INCOGEN design, the individual and social risks in relation to incidents and accidents are negligible.'

Safety aspects of the sea-going NEREUS installation

The basic safety characteristics of the HTR-GT have been explained in the previous paragraphs. But what happens if the installation is flooded or even lost at sea?

Harbour circumstances

- The ship is in harbour, the main engine has been closed down, the engine room gets flooded (collision, fire main break down, etc.)

  It is assumed that the biological shielding is not watertight, so the space for the natural draft gets partly flooded. In case of a nuclear installation there is still decay heat, which has to be removed by natural draft. The flooded part will start heating up the water in the space between the reactor drum and the biological shielding. The produced steam will cool the non-flooded part. In other words - a safe condition.

- The ship is in harbour, the main engine is not closed down, the engine room gets flooded and the generator and other electrical equipment stay dry and stay on line.

  Again it is assumed that the biological shielding is not watertight. In fact this situation can also happen at sea, for example in case of a collision with damage to the engine room. The reactor will heat the water in the partly flooded space for natural draft, which is on line. The fuel temperature in the fuel core will drop due to the extra load and the reactor will slightly increase power due to the negative temperature coefficient.

  The cooling of the non-flooded part of the space for natural cooling will take place through the steam produced by the lower half. So instead of cooling by air, cooling is created by a mixture of water and steam. The reactor will increase power until a new balance is achieved between produced steam and water leaking through the biological shielding. Again an inherently safe and controllable condition.

These two situations are only about flooding of the space for the natural draft. The installation stays operational and can be controlled.

Shipping incidents at sea

In the following situations the reactor itself gets flooded. Although there will be automatic and hand control devices to control the reactor in any kind of situation, it is assumed that there is no time or no opportunity to do so, or that the automatic system fails. At the moment the design is such that when the ship sinks or the engine room gets completely flooded the (sea) water will enter the helium circuit through fast corroding plugs. The helium will disappear (helium is a noble gas and does not get radioactive) and seawater will enter the closed-cycle system and so the nuclear core. It is also assumed that the generator and other electrical equipment break down as well.

The reactor can be designed in such a way that upon flooding of the core, the nuclear chain reaction will stop inherently (i.e. as a consequence of the physical properties of the process) and immediately. It should be remarked that the design requirement for such behaviour is unique; present ship propulsion reactors do not comply with this requirement and must be stopped by active means ('reactor scram' by insertion of control rods) in the case of being lost at sea.

The HTR propulsion unit can be and will be designed in such a way that inherent shutdown upon flooding is achieved as a consequence of the nuclear design

For this purpose, the moderator-to-fuel ratio in the core is an important design parameter. So is the inclusion of cooling channels in the inner parts of the graphite reflector (i.e. close to the core), which are flooded in the case of ingress of water, thereby decreasing the neutronic coupling between the core and the reflector.

The likelihood of an implosion of the nuclear part, should the total energy production installation sink to great depths, does not exist due to the fact that the fuel is ball shaped and neatly packed in the fuel chamber.

Some discussion has taken place about what happens if the working hot reactor sinks. Will there be an explosion as with the boilers on steam ships when the boiler room gets flooded? The answer is No. A steam boiler explodes when seawater enters the (internal) furnace, because the hot firebricks, lining the furnace, explode. With NEREUS, when seawater floods the core there will be no steam explosion, because the core is too hot, the seawater will evaporate and this is a gradual process. The fuel balls will not be damaged, because they are silicon coated as mentioned before. The reactor will stop immediately.

Conclusions

The NEREUS installation is suitable as prime mover in an All-Electric Ship propulsion system (unmanned engine rooms) due to the Inherently Safety characteristics:

- Passive removal of the decay heat by natural draft.
- Negative temperature coefficient.
- Coated particle fuel (TRISO).
- Spherical fuel elements (AVR plant Jülich, Germany).
- Low power density.[7]
- Fuel integrity maintained under all conditions including depressurisation and loss of cooling, so that no 'safety procedures' and no 'defence in depth design' are needed.
- The gas turbine cycle (Brayton-cycle) has a higher efficiency, so produces less thermal pollution than the existing nuclear power plants, which use the steam cycle (Rankine- cycle)
- The inherently safe character of the nuclear heat source, the use of helium for the transport of energy between the heat source, the energy conversion unit and the low pressures in the system, allow for a simple construction, the use of cheaper materials and thus for the construction of an affordable energy production unit.

Although under study as prime mover in the All-Electric Ship propulsion configuration, the installation is also suitable for the markets of:[10]

- Stand-alone heat production (tertiary oil recovery).
- Combined Heat and Power production (breweries, paper mills, fresh water production, dairies).
- Stand-alone electricity generation on islands and in remote areas

The NEREUS study on new applications of the HTR-GT technology does not stand alone. A test reactor is operational in Japan. A second test reactor using the German invented pebble type elements, is under construction in China. But the most important and challenging project is on its way in South Africa, where the national electricity utility ESKOM has fully designed a nuclear (pebble-bed reactor) power plant, consisting of 10 modular units of 100 MWe each, to become operational near Cape Town in 2005. This project fully exploits the inherent-safety characteristics of the nuclear reactor and its German designed fuel to achieve the low electricity production costs of 1.4 US$ cents per kWh. (One has to realize that ESKOM is a utility company with management and financial operation characteristics as is used by utilities and which are quite different from the rules applied by ship owners, paper mill operators and other operators of small scale energy plants).

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