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

Captain G.A.K. Crommelin,

THERE WILL COME A TIME WHEN PEOPLE
WILL BE AMAZED THAT WE DID NOT KNOW
THE THINGS WHICH ARE SO SIMPLE

Abstract

This article will discuss the progress on studies and thoughts on small-scale nuclear power. Nuclear power conversion systems aiming for the non-utility markets, such as the stand-alone heat generation, Combined Heat & Power production, stand-alone electricity conversion and ship propulsion. The design of these installations must fully comply with the philosophies as are common in these markets, where the expression "the engine is a means to an end" applies. So design to cost, design to be operated by non professional energy producers, to be managed by a pool-management system, maintained, repaired and overhauled by replacement, etc. The paper will discuss such a design.

So far most studies have discussed the gas turbine directly coupled to the heat source.

However the helium turbine is considered quite a (technical and financial) challenge for the gas turbine industry, so alternatives had to be found. At the moment the possibilities of gas turbines with an indirect heat source (to burn refuse, wood, refinery waste, etc.) are getting much more attention. The paper therefore will discuss how an inherently safe, well proven, nuclear heat source can be coupled by an Intermediate Heat Exchanger to a recuperative, existing but adapted gas turbine.

INTRODUCTION

Many widely published studies of world leading organizations show three trends with cannot be ignored and which will be upon us and the next generation in the foreseeable future. These trends are:

- an increase of the world population.
  In 1960 there were about 1.5 billion people, in 2000 there were 6 billion people and the prediction is that in 2040 - 2050 there will be 10 billion people.

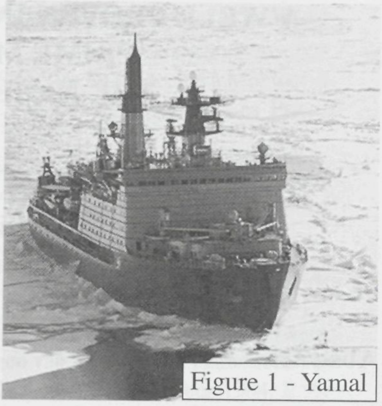
Figure 1 - Yamal

- an increase in the energy consumption per capita in the world.
  Most people think about electricity when the word energy is used, however we are not only talking about electricity but also about heat. In the Netherlands only 30% of the primary energy is converted into electricity, about 40% is used for the heating of offices, workshops, homes, etc. and industrial heat applied to produce steel, aluminum, paper, milk, beer, etc. And about 30% is used for transport.
- a further increase in the shortage of fresh water (both potable water and water for agricultural purposes) which is essentially an energy problem.

So far the latter aspect is rarely mentioned in relation to energy. But recently articles appeared about Israel starting desalination of seawater, areas in China with an immense shortage of fresh water, Singapore starting a recycling plant of wastewater, etc.

We all are aware that energy and fresh water are the building bricks for our welfare and prosperity. So if we take these warnings seriously we must search for more means to convert energy and at the same time to affect the environment as little as possible. 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. And cheap and available energy is essential for this!

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.

It is undeniable that the opinions of the attendancees of conferences on energy conversion do not differ very much. At a conference in 1999 in London commented a panel of 5 directors of British shipping companies, in response to a question at a conference commented: “We agree with the technical and non-technical arguments for nuclear power on board ships. For the near future we foresee problems with nuclear ships entering certain harbours or passengers taking a cruise on board a nuclear powered ship. However shipping is not going back to sailing or even rowing. Solar power is no solution either. There is no alternative, we have to take nuclear on board”. [1]

Nuclear power plays a very important role in keeping the peace. Sometimes it seems that only the military are aware of the logistical arguments in favour of nuclear.

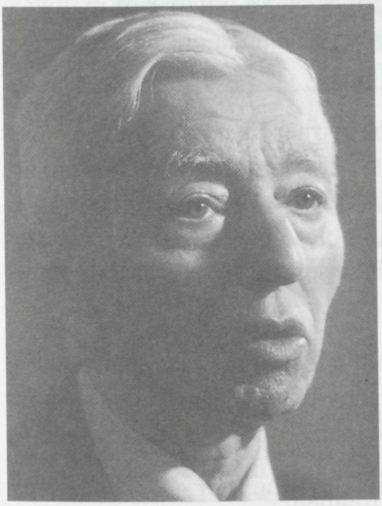

Figure 2 -
Admiral Hyman G. Rickover (USN)

The possibilities of a nuclear powered ship in comparison with a fossil fuel powered ship are almost unlimited. The first military man who realized the potential of nuclear was the father of all nuclear power plants at sea and ashore, Admiral Hyman G. Rickover (USN). And the parties in the Cold War were quick to follow. Submarines run deep and silent and must be able to stay on station for a long time without any chance of discovery. Nuclear power does just that! In 1955 Admiral Rickover sent the famous signal to his masters in Washington from the USS Nautilus: ***“on our way on nuclear power”***

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

The nuclear reactor of the USS Nautilus became the “mother of all nuclear power plants ashore”, because the power plants of all these ships and power plants ashore are very much comparable.

[1] What they and we did know at that time was that you can make a cruise on a nuclear driven ship. The Russian icebreaker Yamal makes cruises to the North Pole.

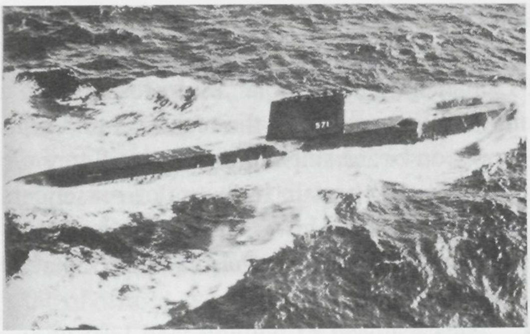

Figure 3 -
U.S.S. Nautilus on the surface in heavy weather, during her acceptance

The heat of the water-cooled reactor produces steam through an intermediate heat exchanger, called the steam generator, which drives steam turbines. So this technology can be considered as well-proven. About 700 nuclear power plants have served or serve at sea and about 400 nuclear power plants have been or are in operation ashore. The USS Nautilus was followed by many nuclear driven warships and submarines and a number of merchant ships: the German Otto Hahn, the American ship Savannah, the Japanese ship Mushie and several icebreakers such as the Yamal.

However no technology can be allowed to stop further Research and Development and so innovative actions. What we consider as being innovations are not the modifications and adjustments to new legislation, which are called innovative actions nowadays but results of actions so clearly described by Captain Kirk of the USS Enterprise in the STAR TREK series: "Its five year mission, to boldly go where no one has gone before".

Or in other words: "Because innovative technologies are the pushing forces in our search for better products and industrial activities and are a condition for competition. If we pay attention tot innovation our economy will grow and so will employment and as result the dynamic will return in our society".
Mirs. Voûte-Droste, Member of the Dutch Parliament.

Another diction for any company is: "Timely innovation is a necessity for a company in order to survive".

A fact proven by history is: that new technologies have never waited until the old version was worn out, or the fuel had run out, etc. Also known as the law: "the Stone Age did not finish because humanity could not find stones anymore, but because new technologies and tooling became available".

The solutions? There is a well-proven, demonstrated, documented, inherently safe nuclear technology in the cupboard of several scientific institutions and organisations waiting to be used. It is called the "HTR-GT", which stands for High Temperature Reactor with a Gas Turbine as energy conversion unit.

THE NEREUS PROJECT

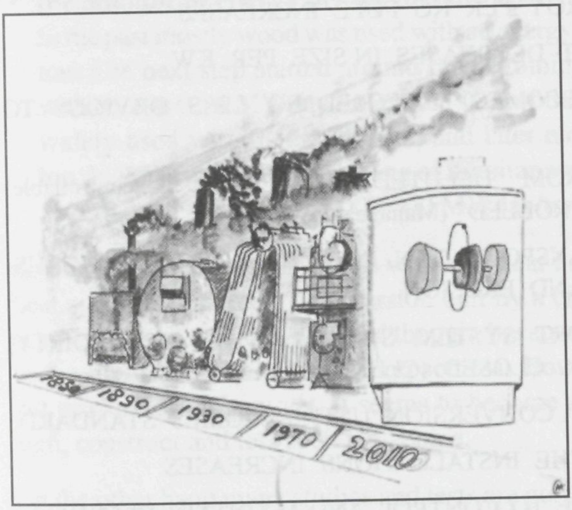

Figure 4 -
"combustion" over the centuries.

The project, mentioned in the abstract, is called "The NEREUS-project". In this case "NEREUS" stands for: a Naturally safe, Efficient, Reactor, Easy to operate, Ultimately simple and Small. This describes very well the aims of the design team and the only way in which a nuclear plant will be technically acceptable in the markets of stand-alone heat generation, Combined Heat and Power production, stand-alone electricity conversion and as prime mover on board ships with an All-Electric propulsion system. In other words the markets of the non-professional energy producers. (Haverkate et al, 1997)

HISTORY

The step towards nuclear power conversion is a logical one in the history of mankind. Figure 3 shows, in an artistic way, the history of the way in which the human race has produced energy. The way this energy was converted into useful energy can also be analysed. It is beyond discussion that the attainments related to the availability to mankind of cheap energy will never be given up.

Human beings are somewhat reluctant to accept new developments, but when they have learned the advantages they will only give it up when further improvements are available. Only in difficult times, as during a war, will achievements and goods considered as luxuries (temporarily) be set aside.

As far as the subject of "energy" is concerned, the availability of cheap and reliable energy, good medical care and clean potable water within a manageable environment are the building stones of our prosperity and welfare. The human race has sometimes tried to turn back history, even at great costs, but it has always been in vain.

TRENDS IN THE HISTORY OF ENERGY PRODUCTION

- THE AMOUNT OF ENERGY PER KG FUEL INCREASES
- THE COMBUSTION UNIT DECREASES IN SIZE PER KW
- OPEN COMBUSTION BECOMES ENCLOSED, SO LESS OBVIOUS TO THE USERS[2]
- EMISSIONS CHANGE FROM "DELUTED & DISPERSED" (Uncontrollable) TO "CONFINED & CONTROLLED" (Manageable)
- THE MEDIUM FOR TRANSPORTATION INCREASES IN PURITY, CAUSING LESS CORROSION AND EROSION
- THE ENERGY TRANSPORT SYSTEM STARTS AS AN OPEN (DIRTY) CYCLE, BUT BECOMES A CLOSED (CLEAN) CYCLE
- THE ROTATING ENERGY CONVERSION UNIT BECOMES STANDARD
- THE COMPLEXITY OF THE INSTALLATIONS INCREASES
- THE NUMBER OF PEOPLE TO CONTROL AND MAINTAIN DECREASES
- THE WEIGHT AND VOLUME PER PRODUCED KW DECREASES
- THE TOTAL PROCESS EFFICIENCY INCREASES CONSTANTLY
- NEW SYSTEMS NEVER APPEARED AS A RESULT OF A SHORTAGE OF A TYPE OF FUEL, BUT BECAUSE BETTER SYSTEMS BECAME AVAILABLE
- THE END IS ALWAYS A VERY COMPLEX ENGINE TO FIGHT OFF (IN VAIN) THE NEW SYSTEM COMING ALLONG

CONCLUSION 1:

RESULTING IN ENERGY PRODUCTION SYSTEMS WITH LOWER THROUGH LIFE COSTING PER KWH

CONCLUSION 2:

NUCLEAR POWER PRODUCTION IS THE LOGICAL NEXT STEP IN THE WAYS HUMANITY PRODUCES ENERGY

CONCLUSION 3:

THE (CLOSED-CYCLE) GAS TURBINE WITH AN INHERENTLY SAFE NUCLEAR HEAT SOURCE SEEMS TO BE THE NEXT LOGICAL STEP IN HISTORY

[2] Professor Dr.Ir. H. van Dam - September 2003

For example:

- **the amount of energy per kg fuel increases**

  In the past mostly wood was used with an energy content of only 0.18 MWday/ton. The next step started around the beginning of the industrial revolution with coal at 0.34 MWday/ton, at the start of the 20th century oil began to be widely used with 0.46 MWd/ton and later natural gas with 0.55 MWday/ton. In the last century fissioning of uranium was discovered with a potential energy content of about 1,000,000 MWday/ton (if all uranium is fissioned).

So far all studies on gas turbines with a nuclear heat source have connected the heat source to the energy conversion unit by a closed-cycle system consisting of a helium gas turbine. A logical thought because it seems undoubtedly to lead to the highest efficiency and compactness. However helium gas turbines are not proven technology yet. It seems to become an expensive operation to design, construct and test such a machine.

On the other hand many studies and tests are going on to design different external heat sources for gas turbines. Heat sources which are able to burn, in a controllable and effective way, waste of refineries, biomass, industrial waste gases, pulverized coal, etc. So it seems logical to investigate whether uranium could be added to this list of fuels.

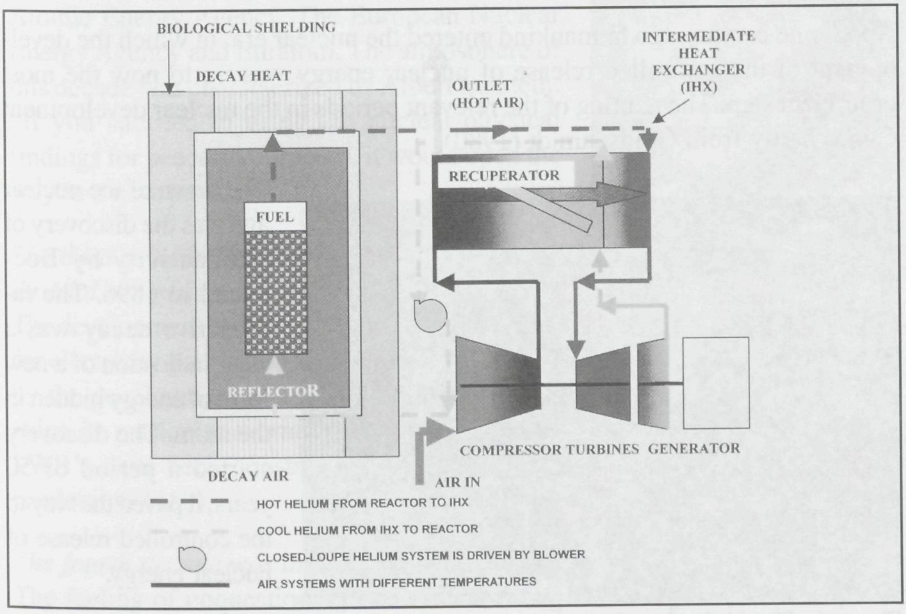

Figure 5 - BASIC SCHEMATIC OF STANDARD OPEN-CYCLE GAS TURBINE WITH AN INHERENTLY SAFE AND WELL-PROVEN NUCLEAR HEAT SOURCE

From the publications on the closed-cycle nuclear gas turbine (HTR-GT) one learns that the nuclear fuel is cooled by helium, pumped around by a recuperative gas turbine. However, the test reactor in Jülich worked with a two loupe system. The reactor was cooled by helium pumped around by a so-called helium ventilator. The heat was transported to a steam cycle via an Intermediate Heat Exchanger. So this test bed was actually a standard (Rankine) pressurized water reactor power plant, with a new nuclear heat source.

The logical next thought is why not change, in the Jülich concept the Rankine-type secondary water-steam closed cycle into a Brayton-type open cycle and see how these systems compare with the Brayton-type open cycle for small (circa 20 MWth) plants. Afterall the advantages of gas turbines over steam plants have been discussed many times in publications and at conferences.

THE HISTORY OF NUCLEAR ENERGY

About one million years ago there was a dramatic step in evolution, the birth of humankind, its separation from the animal world. Two factors were decisive for this step change: the development and the use of tools and the control and use of fire. The latter has led to industrial development and a tremendous increase in well-being.

About one century ago humankind entered the nuclear era, in which the development of the controlled release of nuclear energy was up to now the most prominent step. The naming of the relevant periods in the nuclear development comes partly from Goldschmidt (1980).

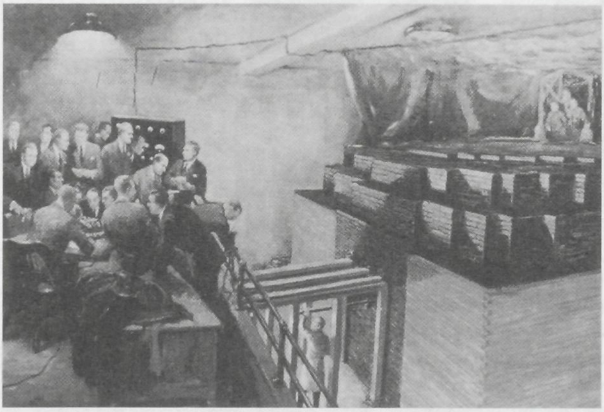

Figure 6 - The birth of nuclear power, December 2, 1942, Chicago, USA.

The dawn of the nuclear age was the discovery of radioactivity by Becquerel in 1896. The radioactive decay was a clear indication of a new form of energy hidden in the atom. The discovery started a period of 50 years, it paved the way to the controlled release of nuclear energy.

These discoveries resulted, under the pressure of World War 2, in the actual birth of the controlled release of nuclear power. The birth took place in secrecy in the basement of a baseball stadium in Chicago (USA); the leader was the brilliant Italian physicist Enrico Fermi, the date was December 2, 1942. As we all know the first application were the two atomic bombs on Japan, which ended World War 2 about one year earlier than foreseen. This fact has had a considerable effect on the further development of this new technology and the problems surrounding its social acceptance.

The first decade after World War 2 can be described as the period of hope.
This period was characterized by the first deployment of nuclear energy for ship propulsion, the production of electricity and the great secrecy. In 1951 the first "nuclear" electricity was produced by a nuclear reactor in the Idaho dessert. The world's first civilian nuclear power station was built in the Soviet Union (1954 - 5 MWe).

The second decade was one of euphoria.
Decisive was the "Atoms for Peace" program, started by President Eisenhouwer of the United States in 1953. It led to a more relaxed form of secrecy, and the establishment of important international organizations such as the International Atomic Energy Agency, The European Nuclear Energy Agency and Euratom. The atmosphere of this decade was characterized by Albert Einstein: "If you succeed in using the nuclear-physical findings for peaceful purposes, it would open the way to a new paradise".

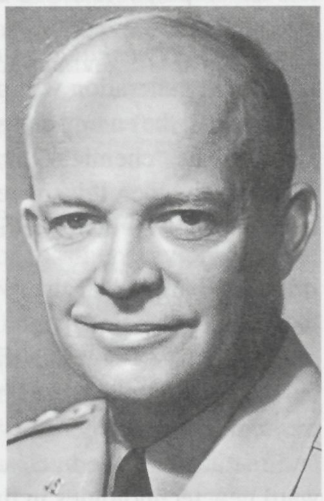
Figure 7 - General Dwight W. Eisenhower, President of the United States (1953-1961)

The third period (1965 - 1975) witnessed the industrial expansion.
The development of the light water reactor (LWR) for electricity generation was strongly stimulated by the development of compact LWR's to drive ships, in particular submarines. It is not generally known that up to now more LWR's have been constructed for ship propulsion (700) than for electricity production (450).

The fourth decade was the decade of confusion.
The feeling of unquestioning enthusiasm changed to skepticism as the public refused to accept nuclear technology uncritically. The main issues were the safety of nuclear energy, the disposal of radioactive waste, the supposed role of

power generation in nuclear arms proliferation, economic aspects and the supposed threat to our society, namely the creation of a "nuclear state". It is clear that safety is the most relevant issue in the nuclear debate. In the historical process, human failure and short-sightedness played a role, highlighted by accidents as Three Mile Island and Chernobyl (March 28, 1979 and April 26, 1986, respectively).

The fifth decade we would like to name "Shock and New Perspectives".
The shock was the Chernobyl accident, which had a tremendous impact on the general public and on the nuclear specialists. It led to a thorough reconsideration of all safety issues for nuclear power. The new perspectives are important developments in safety. Modern safety philosophies increasingly emphasize systems with inherent safety characteristics, based on a well-considered application of physical laws to provide safety in a "natural" way. One example of this development is the so-called High Temperature Reactor (HTR).

The sixth period should be the revival of the "Atoms for Peace" program.
If the next generation will peacefully take up the challenges as described they will need all the energy conversion systems available. In other words the "green" systems, the "chemical" systems and the "nuclear" systems, applied in addition to each other. It is the responsibility of this generation to leave them all the tools we know; which one fits best where, when and how is their responsibility.

It is abundantly clear that we cannot achieve a "sustainable" world, in view of the challenges pointed out, if we rely too heavily on chemical energy. After one million years of chemical fires, we have merely crossed the threshold of harnessing the "nuclear fire" and important developments are still ahead. There may come a time when people laugh about the laborious and troublesome birth and maturing of the nuclear technology, as we laugh about the resistance toward new technologies in the past, without which life today would impossible to imagine. As is worded on top of a Japanese nuclear reactor: "There will come a time when people will be amazed that we did not know the things, which are so simple".

URANIUM

An argument often heard against nuclear power is : "there is only enough uranium for 40 years".

- the recoverable amount of uranium on earth depends, as with all minerals, on the price one is willing to pay. A well-known law in Mining Engineering states: "if you multiply the price that you are willing to pay for a raw material by a factor x, then the resources will multiply by x squared". The amount of uranium on earth is more than that of silver, gold, wolfram and molybdenum. For example, the recoverable amounts of uranium at a price (present) of 80 USD per kg U is about 3 million tons. At a price between 80 and 260 USD per kg U, it is about 9 million tons and speculative resources are about 20 million tons.

- The nuclear reactors at present use less than 1% of the energy content of the uranium ore. This is a wasteful use in the history of fuel consumption. In half a century of nuclear energy we have been wasting uranium and we have stockpiled an amount of depleted uranium (1.4 million tons), that has an energy content equivalent to more than 10 times the present recoverable amounts of oil reserves in the world. The newer type of so-called fast nuclear reactors is able to burn uranium almost completely and so increases the effective use of uranium a hundred times. This will even make uranium extracted from sea water (total amount 4 billion tons), with present technology for a price of 450 USD per kg U, economically attractive.
- Fast nuclear reactors can also burn thorium. There is about four times more recoverable thorium than the uranium reserves on land.

All kinds of waste are a form of emission during the energy conversion process. However, due to the large amounts of waste of fossil energy production, the only way it could be handled up to today was by "uncontrollable dilution and dispersion". In fact not at all conform the mostly used definition of sustainability: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Nuclear is a step further in the history of energy conversion. Thanks to its extremely limited amount, the waste can be properly confined and stored in a controllable way.

THE NUCLEAR FUEL

We will only focus on the most important nuclear aspects.

Handling the Nuclear Fuel

The fuel load is contained in a 'cartridge' consisting of a graphite (nuclear grade) vessel filled with fuel elements to be described further on. This cartridge is placed in a thick walled graphite vessel that is a fixed part of the reactor system; this vessel acts as a neutron reflector enabling to sustain the chain reaction. Periodically, once every 3 to 4 years, the cartridge is replaced. A standard 40-ft container can be used, which brings in the fresh fuel and takes away the used cartridge for further treatment. Specialized personnel, managed by a pool-system, should deliver the equipment and the knowledge for this operation. This new approach for nuclear energy production aims for the markets of the non-professional energy producers. So the installation will be designed in such a way that construction, maintenance, refueling, overhaul, repair and general logistic support will be done through the well-proven pool-management system. Non-specialized personnel can perform routine operation.

The Type of Fuel[3]

The heart of the installation is the so-called pebble-bed reactor. This type of nuclear heat source was invented in Germany. The AVR (Arbeitsgemeinschaft Versuchsreaktor) test reactor (15 MWe) was successfully operated and extensively tested during 20 years in Jülich, Germany. The nuclear fuel is based upon the proven high quality German moulded graphite spheres and TRISO (Tristructural ISOtropic) coated particles (Kugeler and Schulten, 1989). One of the most important safety features is that radioactive fission products produced during the energy conversion process are confined within the fuel during all operating and accident conditions. Consequently, there will be no release of radioactivity from the fuel particles to the outside world.

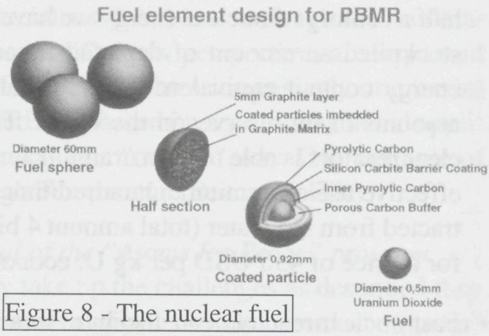

Figure 8 - The nuclear fuel

This ultimately safe confinement of radioactivity is assured by the design of the fuel elements themselves. The fuel elements consist of graphite balls (also called 'pebbles'), with a diameter of 6 cm, in which fuel is placed. The fuel particles (Figure 5, bottom right) consist of a uranium-oxide fuel kernel surrounded by four coatings: from inside to outside a porous pyrolytic graphite coating, a high density graphite coating, a silicon carbide coating and an outer pyrolytic high density graphite coating. The diameter of the uranium-oxide kernel is about 1 mm.

The silicon carbide coating acts as an impenetrable containment for the radioactive fission products inside the fuel kernel and the porous coating.

[3] PBMR stands for Pebble-Bed Modular Reactor. This is a type of nuclear reactor in the design phase. The project is financed by a consortium under chairmanship of ESKOM, the national South African electricity production company.

The porous coating allows a build-up inside the fuel kernel of fission products, which 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 any release of integrity and consequently without any release of fission products.

Every pebble contains approximately 10,000 coated particles (the TRISO), the equivalent of 10 g uranium. The large heat transfer surface of these particles and the high thermal conductivity of graphite ensure good heat transfer from fuel to the embedding graphite matrix. This prevents hot spots in the core.

The core, with a volume of approximately 7 m3, produces a thermal power of 20 MW. This low power density (~3 MW/m^3), coupled to small particles of fuel, and the good thermal conductivity of graphite fission product release due to the failure of fuel particles, occurs at much higher temperatures. Each coated particle can be seen as a miniature pressure vessel that can retain fission products. This ensures, that the fuel element temperature does not exceed 1600°C, even in the event of direct cooling failure. This construction forms the **first containment** of the radioactive material from the biosphere.

Fuel particles allow some freedom in the uranium enrichment: the enrichment can be chosen in correspondence with the energy production required per fuel cycle; we have assumed 8.6% enrichment in the present study. In our present design the attainable thermal energy extraction per pebble amounts to 0.6 MWdays, which is equivalent to the burning of 1.2 tons of crude oil.

The pebbles can be made oxidation-resistant by coating them with silicon. As a consequence they are fireproof as well as corrosion proof. 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 AVR/Jülich (Schulten et al., 1990).

Use of a gaseous coolant, helium, in a graphite environment is another safety feature. Helium is both chemically and nuclear inert; it does not react with graphite or the metallic core components. Helium cannot become radioactive. In helium no abrupt changes brought about by phase transition are experienced, thus ensuring continuous thermal evacuation throughout operation.

The use of graphite (a solid) instead of a liquid (water) as a moderator has the advantage that the moderating behavior is very constant.

Control of Reactor Reactivity

In the reactor core, during its fuel cycle, a chain of fission reactions has to be maintained. Because of the fissions, the amount of fuel decreases gradually and so does the reactivity (ability to sustain the chain reaction). Refueling has to take place. Most studies on the pebble bed HTR assume on-line refueling. Consequently there is no excess reactivity in the core of an HTR and an accident alike the one in Chernobyl cannot occur. But on-line refueling 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.

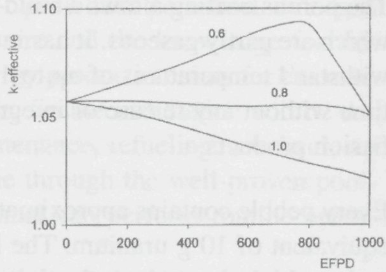

Figure 9 - Reactivity control by burnable neutron poisons (EFPD = effective full power days)

However, the NEREUS installation is based upon the principle to Keep It as Simple as possible (KISS), our intention is to use burnable poison. Some materials have such a high neutron absorbing property, that when placed in the reactor core their concentration diminishes because of transmutation as a function of time. Such materials are called burnable neutron poisons. They facilitate higher fuel contents in the core, while keeping the reactivity constant during burn up.

The burnable poison also simplifies the "control rod" requirements, only stop/start rods are needed.

On indications from the small-scale energy production branch, intensive studies were performed recently to improve the working of the burnable poison even further. A recent development is to introduce the burnable poison in the pebbles in the form of 'burnable particles'. In this way, as you see in Figure 6, it is possible to deliver a nearly flat line of reactivity over the whole usage period.

The figures at the curves denote the diameter (in mm) of the very small cylinders ('needles') of burnable poison, embedded in the fuel pebbles. With a diameter of 0.8 mm the reactivity (in cold state, without xenon poisoning) of the reactor as a function of time (expressed in effective full power days, EFPD) is almost constant which eliminates long-term reactivity control by control rods (Van Dam, H., 2000).

At the moment we are working on a three-year refueling 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.

Control of Energy Production

The reactivity is strongly dependent upon the temperature of the fuel. HTR's fuel possesses a negative temperature reactivity coefficient, which can be even improved by the use of burnable particles as mentioned in the last section. 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. So the reactor functions like a thermostatic device. It 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" makes this fuel very suitable for unmanned power plants, such as on board ships. This applies especially to two markets the project is aiming for: the stand-alone electricity production market and the market for prime movers on board ships. Both markets prefer to work with "unmanned power plants" and "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 a maximum of efficiency at partial load is less important than when fossil fuels are used.

Decay Heat

After shut down of a nuclear reactor, the radioactivity of the fission products gives rise to production of some decay heat, which gradually decreases. The completely passive removal of this decay heat is an essential part of the inherently safe nuclear installation. For this purpose there is a space between the outside of the reactor drum and the inside of the biological shielding, through which air flows, driven by natural draft. 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 (100 kW)can be used during normal operation.

The funnel can also be used as transport route for refueling, 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.

The Nuclear Waste

It should be realized that the amount of waste produced by a nuclear heat source is much and much smaller than the amount of waste resulting from fossil fueled engines, simply because the fission process liberates the energy that keeps a nucleus together (which is typically in the order of hundreds of millions of eV's), instead of a chemical reaction, that makes use of the binding energy of electrons (which is only several eV's). The presently proposed nuclear heat source uses its fuel very economically, thus resulting in even smaller amounts of waste (and in lower fuel costs!). The fuel elements themselves are ideal waste containers: after some three years of operation the core can be replaced by a fresh one and the old core serves as a waste container. The high burn-up of the fuel makes reprocessing unnecessary.

After three years of operation about 7 m3 of fuel pebbles are removed from the core. This nuclear waste can be transported in shielded containers. A possible design has a diameter of <3 m and a height of 5 m. After about 10 years the radioactivity and heat production have decayed to such an extent that the waste can be classified under the category "Medium-active waste of the upper category". After 10 - 50 years of interim storage, the waste can be sent to final storage in relatively simple 0.4 m3 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.

SAFETY ASPECTS OF THE HTR-GT

This is the most important part of the concept. After all, the importance of subjects regarding (nuclear) energy production are: priority 1: safety, priority 2: costs, priority 3: licensing. The engineering itself will follow if these aspects are properly covered.

The most important and incorporated safety feature of the HTR-GT in relation to the environment is the inherently safe character of the pebble bed reactor, which is established by:

- three coatings of the TRISO fuel particles (first containment);
- coatings of the 6 cm fuel pebbles containing the TRISO (second containment);
- burnable poison in the fuel;
- negative temperature coefficient of the nuclear fuel;
- controllability of energy production in the nuclear core;

- removal of decay heat after an incident such as "loss of coolant" or "loss of flow", in a natural way through natural draft
- low energy density in the core of 3 MW per m3.

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

The Actual Safety Test of the HTR (see figure 10)

Many calculations were performed on the behavior 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 to the interested persons or the potential users.

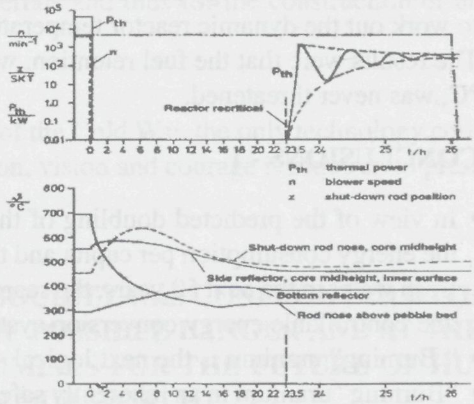

Figure 10 - Demonstration of the inherently safe shutdown of the AVR reactor in 1970. The upper part shows the course of the reactor power after stopping the blowers with the control rods remaining withdrawn. The lower part shows the developement of temperature at several locations of measurement. No dangerous situations ever occurred.

The AVR test reactor in Jülich, Germany, was a test reactor with a 13 MWe output. It was used for testing purposes during 20 years. A steam turbine was used as energy conversion unit. The core was cooled by helium in a closed cycle system; the gas was pumped around by two electrical ventilators. 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 with the reactor (Schulten et al., 1990): the two ventilators were stopped, so the cooling of the core was abruptly stopped and the valves in the primary circuit were closed in order to reduce any natural ventilation to a minimum. In fact 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 and the decreasing temperature the power increased again to 1.8 MW; however, it went down again and stabilized at 300 kW.

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 energy production installations. Calculations were also used to work out the dynamic reactor temperature behaviour after a loss of coolant. The results were that the fuel retention, which has been demonstrated to 1650 °C, was never threatened.

CONCLUSIONS - 1

- In view of the predicted doubling of the world population, the doubling of the energy consumption per capita and the further increase in the shortage of fresh water in the next 50 years, the search for more environmentally friendly and controllable energy conversion systems is a necessity.
- " Burning" uranium is the next logical step in combustion.
- "Burning" uranium in an inherently safe way and, indirectly in an open-cycle adapted gas turbine, is possible.
- Timely innovation is a necessity for a company or industrial branches to survive.
- All technologies required are available. However study and engineering by all parties involved are needed to find the optimal solutions.

The next logical step for small-scale inherently safe nuclear energy conversion can be taken!

CONCLUSIONS - 2

The High Temperature Reactor is suitable as a heat source for energy conversion units for the markets of small-scale energy production because of its inherent safety characteristics, such as:

- Passive removal of the decay heat by natural draft
- Negative temperature coefficient
- Coated particle fuel (TRISO)
- Spherical fuel elements
- Low power density

- Fuel integrity is maintained under all conditions including depressurization and loss of cooling, so 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 and the energy conversion unit, as well as 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.

Finally.
The nuclear technology is, as result of the Cold War, the only technology controlled by Politicians. So their opinion, vision and courage is required to press on with innovations in this field.

As did their colleagues in the past!
NEVER BEFORE IN HISTORY, SOCIETY WAS CONFRONTED WITH A POWER THAT IS SO FULL OF POSSIBLE DANGER AND AT THE SAME TIME SO FULL OF PROMISES FOR THE FUTURE OF HUMANKIND AND FOR PEACE IN OUR WORLD.....".

Although it looks like a statement about nuclear energy generation, it is actually a statement from a meeting of the Congress of the United States in 1875. It shows the hopes and the worries about the invention of the internal combustion engine. These Politicians had the courage and the vision to press on, otherwise we would not have the achievement of freedom of transport as we know today.

REFERENCES

General information:

World population (2050) - www.worldenergy.org
Availability of potable water (2025) - www.worldwatercouncil.org

These websites give further information about studies and projects regarding small-scale nuclear power:

IAEA	- http://www.iaea.org/inis/aws/htgr/
South-Africa	- http://www.pbmr.co.za and http://id.inel.gov/Pebble_Bed/mpbr.htm
Japan	- http://www.jeari.go.jp/english/temp.html
China	- http://www.inet.tsinghua.edu.cn/English/project/htr10.htm
United States	- http://www.ga.com/gtmhr.html, http://atomicinsights.com and
	- http://atomicengines.com

These theses and papers discuss aspects of the inherently safe High Temperature Reactor:

- Wallerbos E.J.M. (1998) Reactivity Effects in a pebble-bed Type Nuclear Reactor. An Experimental and Calculational Study (Ph.D. thesis, Delft University of Technology, The Netherlands)
- Bende E.E. van (2000), Plutonium Burning in a Pebble-Bed Type High Temperature Nuclear Reactor (Ph.D. thesis, Delft University of Technology, The Netherlands)
- Verkerk, E.C. (2000), Dynamics of the pebble-bed Nuclear Reactor in the Direct Brayton Cycle (Ph.D. thesis, Delft University of Technology, The Netherlands)
- Kikstra J.F. (2001) Modelling, Design and Control of a Cogenerating Nuclear Gas Turbine Plant (Ph.D. thesis, Delft University of Technology, The Netherlands)
- Op het Veld, R. and Buijtenen J.P. van, An Empirical Approach to the Preliminary Design of a Closed Cycle Gas Turbine. American Society for Mechanical Engineers (ASME) paper 98-GT-393
- Crommelin G.A.K., The NEREUS Installation - the Nuclear Part, ASME Gas Turbines 99-GT-88
- Crommelin G.A.K. The NEREUS Installation - The non-nuclear Part, ASME 99-GT-87
- Crommelin G.A.K., Hagen T.H.J.J. van der and Buijtenen J.P. van, The Next Logical Step in Prime Movers on Board Ships, ASME International Joint Power Generation Conference (IJPGC) 2001
- Hagen T.H.J.J. van der, Buijtenen J.P. van and Crommelin G.A.K. The Next logical Step in Prime movers on Board Ships - the Nuclear Part. ASME IJPGC 2001
- Buijtenen J.P. van, Crommelin G.A.K. and Crommelin W.F.- The Design of Closed Cycle Gas Turbines for HTR and other Heat Sources. ASME IJPGC 2001

Author's Biography

The author retired as Captain Engineering from the Royal Netherlands Navy at the end of 1993. During his naval career he sailed for more than 19 years as Marine Engineering Officer. He sailed from 1964 to 1978 on board steam driven ships. In 1978 he changed to gas turbine driven ships, starting with an appointment at MOD(UK) to set up a Memorandum of Understanding for the logistic support of the Rolls Royce gas turbines in service with the navies of the United Kingdom, The Netherlands, Belgium and France. He retired as Head of the Engineering Bureau of the Admiralty of the Royal Netherlands Navy. At the end of 1993 he took the initiative and became the co-ordinator for the NEREUS project, also called the "sea-going HTR-GT".