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A Feasibility Study of Nuclear Powered Freight Carriers.

일반상선에 적용 가능한 핵 추진에 대한 연구

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지도교수 이 귀 주

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Graduate School of Chosun University

Department of Naval Architecture and Ocean Engineering

Bibhupriya Acharya

Bibhupriya Acharya의 석사학위논문을 인준함

위원장 조선대학교 교수 박 제 웅 印

위 원 조선대학교 교수 이 귀 주 印

위 원 조선대학교 교수 권 영 섭 印

2008년 5월

Graduate School of Chosun University

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조선대학교 일반대학원
선박해양공학과

핵추진상선의 개념은 지난 40년 동안 조선분야에서 이야기만 되어왔다. 그러나 최근 상선은 보다 크고, 빠르며, 보다 효율적인 배에 초점을 맞추어 개발하고 있다. 이러한 시점에 핵 추진은 고려할만한 가치가 있다고 사료된다. 고속 해상운송수단으로서 핵 추진을 동반한 선박 설계의 개발은 새로운 시장의 개척과 항공 운송수단으로만 운송이 가능했던 소량의 고가 운송물자의 확보를 가능하게 할 것이다. 오래전부터, 운송 수단 발전 방향은 고속화, 정기선의 증가, 가능성 있는 다른 시장과의 도조하려는 추세를 보여 왔다. 이러한 발전은 새로운 선형 설계, 고 사양의 추진기와 고 사양의 발전시설의 출현을 가능하게 하였다. 위험하다는 인식 속에서도, 핵 추진 기관은 가장 새로운 기술의 사용하는 차세대 선박을 설계하는데 이용할 수 있다. 현재 복합되어 사용되고 있는 추진기와 에너지변환을 위한 가스터빈과 열 교환기를 포함하는 핵 기술은 기존의 추진기관을 대체할 수 있는 추진기관이다. 핵 추진은 1회 항해에 5000톤 정도의 연료를 절약할 수 있고, 안정된 가동과 비교적 낮은 핵연료의 핵연료가 그 장점이라고 할 수 있다. 본 논문은 기존에 상선에서 사용하던 전형적인 추진을 넘어선 핵추진의 장점을 알리는데 그 목적이 있다.

Abstract

A Feasibility Study of Nuclear Powered Freight Carriers.

Bibhupriya Acharya
Advisor : Prof. Lee, Kwi-joo, Ph.D.
Department of Naval Architecture
& Ocean Engineering,
Graduate School of Chosun University

The concept of nuclear-powered merchant ships has been blooming in the naval architecture community for more than four decades now. But the recent developments in commercial shipping include bigger, faster and more powerful ships, where nuclear propulsion may prove an option worth considering. The development of advanced ship designs along with the nuclear power opens an opportunity for high-speed maritime transportation that could create new markets and recover a fraction of the high value goods currently shipped only by air. Over the past years, marine transportation has shown an evolutionary trend in the high-speed transport segment, with a mark consolidation in fast ferries, and an encouraging innovation potential in other markets. This evolution has been possible evolution has been possible due to the joint emergence of new hull designs, high performance propulsors and highly compact power plant package. Despite perceived hazards, inherently safe nuclear propulsion plants can be designed for next generation merchant ships employing the newest technology. Combining an existing and well proven gas turbine plus heat

exchangers with inherently safe nuclear technology for energy conversion promises a viable alternative propulsion solution for various tonnage typed vessels. Nuclear power would save, per trip, almost 5000 tons of exposure to fuel price fluctuation, not to forget the advantage of a more stable operation due to the relatively constant low price of nuclear fuel. This thesisis an effort to reveal the advantageous position of nuclear propulsion over conventional propulsion methods for merchant vessels.

1. INTRODUCTION

Over the past years, marine transportation has shown an evolutionary trend in the high-speed transport segment, with a mark consolidation in fast ferries, and an encouraging innovation potential in other markets. This evolution has been possible evolution has been possible due to the joint emergence of new hull designs, high performance propulsors and highly compact power plant packages. Atomic engines offer capabilities that cannot be achieved with fossil fuel engines. Nuclear fission requires no oxygen and produces no exhaust gases, and nuclear reactors are reliable, compact sources of continuous heat that can last for years without new fuel. These beyond competition capabilities have encouraged the development of certain types of nuclear systems without much regard for cost. Economic concerns are low on the priority list if the desired product is a high endurance submarine or a speedy aircraft carrier capable of independent operations. Of course, contractors love to work for a customer who has a "cost is no object" mentality.

Conventional wisdom states that the high cost of military nuclear ships proves that nuclear power cannot compete in less specialized markets. Advanced nuclear technologies and a careful focus on cost conscious design can result in nuclear propulsion systems that are economically superior to conventional systems for a wide variety of commercial applications. The nuclear gas turbine, for example, offers the simplicity and low capital investment of combustion gas turbines combined with the high endurance, low fuel cost and zero emission characteristic of nuclear powered systems. This concept should attract the attention of commercial shipping industry decision makers in their unending quest for a competitive advantage.

In October of 1999, an interest developed within the Society of Naval Architects and Marine Engineers (SNAME) to examine power plants for the next classes of large, high-speed, ocean-going ships. These ships will attain higher speeds (over 40 knots) and contain more installed power (over 325,000 hp) than the most powerful merchant ship ever built previously, the SS United States. It was projected that as these new ships prove themselves in transatlantic service, ship owners will be drawn to Pacific Ocean trade-routes, requiring larger ships with even higher speeds and power levels. Million-horsepower ships could possibly be on the CAD screens of ship designers by the end of the decade. The ships now perceived in this category, a precursor of which might be those designed by FastShip, Inc., will use gas-turbine engines similar to the jet engines of the largest airliners. However, with five engines in each ship running on diesel fuel, the Society is concerned about the environmental impact of these ships, even though it will still be much lower, per unit of cargo carried, than typically attributed to airfreight. In January of 2000, a meeting was held at SNAME headquarters to discuss the feasibility of commercial ship nuclear applications. While it was decided that this topic could prove promising, it was also decided that the scope of study should be broadened to include other alternatives such as fuel cell power.

Accordingly, an "Ad Hoc Panel" was formed. SNAME Ad Hoc Panels are the mechanisms used by the Society to investigate and address matters of urgent concern to the marine community that justify more timely technical evaluation. The resulting Mission of the Panel is to determine the State of the Art in selected marine propulsion and related systems technology:

- Emphasis will be on commercial marine applications.
- It will include national and international initiatives and programs.
- It will consider both a current and near-term range of development.
- It will include a literature and technology search as can best be accomplished by the Panel participants.

In addition to low environmental impact, criteria to be considered include the technical and economic feasibility, safety, and social and political acceptability (as time and resources allow).

2. HISTORY OF NUCLEAR POWERED SHIPS

On January 17, 1955, the Nautilus reported "Underway on nuclear power." Her success clearly demonstrated that nuclear reactors could be used as the heat source for marine engines. In the forty years since that first nuclear propelled voyage, however, nuclear power has had essentially no impact on commercial shipping. The only ones still in operation are Russian ice-breakers. This situation was not what was predicted by 1950s vintage visionaries. Large passenger liners like the United States and the Queen Mary were prodigious oil burners, consuming 50 tons per hour at high speed. Fast cargo ships, like those used to transport perishable items were not as large or powerful, but they could consume 10-20 tons per hour. Even with oil priced at $320.00 per ton, fuel represents a significant operating cost, but even more critical is the fact that the fuel storage space needs for long-range, high speed travel limiting the operating range of the ship. Many ships such as N S Savannah and N S Ottohan, proved to be economically inefficient consequently pertaining to the fact that there was less advancement in nuclear technology during their life time.

- Nuclear power is particularly suitable for vessels which need to be at sea for long periods without refueling, or for powerful submarine propulsion.
- Over 150 ships are powered by more than 220 small nuclear reactors and more than 12,000 reactor years of marine operation has been accumulated.
- Most are submarines, but they range from ice-breakers to aircraft carriers.
- In future, constraints on fossil fuel use in transport may bring marine nuclear propulsion into more widespread use.

Work on nuclear marine propulsion started in the1940s, and the first test reactor started up in USA in 1953. The first nuclear-powered submarine, USS

Nautilus, put to sea in 1955.

This marked the transition of submarines from slow underwater vessels to warships capable of sustaining 20-25 knots submerged for weeks on end. The submarine had come into its own. Nautilus led to the parallel development of further (Skate-class) submarines, powered by single pressurised water reactors, and an aircraft carrier, USS Enterprise, powered by eight reactor units in 1960. A cruiser, USS Long Beach, followed in 1961 and was powered by two of these early units. Remarkably, the Enterprise remains in service. By 1962 the US Navy had 26 nuclear submarines operational and 30 under construction. Nuclear power had revolutionized the Navy.

The technology was shared with Britain, while French, Russian and Chinese developments proceeded separately. After the Skate-class vessels, reactor development proceeded and in the USA a single series of standardized designs was built by both Westinghouse and GE, one reactor powering each vessel. Rolls Royce built similar units for Royal Navy submarines and then developed the design further to the PWR-2. Russia developed both PWR and lead-bismuth cooled reactor designs, the latter not persisting. Eventually four generations of submarine PWRs were utilized, the last entering service in 1995 in the Severodvinsk class. The largest submarines are the 26,500 tonne Russian Typhoon-class, powered by twin 190 MWt PWR reactors, though these were superseded by the 24,000 t Oscar-II class (eg Kursk) with the same power plant. Compared with the excellent safety record of the US nuclear navy, early

Soviet endeavors resulted in a number of serious accidents - five where the reactor was irreparably damaged, and more resulting in radiation leaks. However, by the third generation of marine PWRs in the late 1970s safety had become paramount.

2.1 Nuclear Naval Fleets

Russia built 248 nuclear submarines and five naval surface vessels powered by 468 reactors between 1950 and 2003, and were then operating about 60. At the end of the Cold War, in 1989, there were over 400 nuclear-powered submarines operational or being built. Some 250 of these submarines have now been scrapped and some on order cancelled, due to weapons reduction programs. Russia and USA had over one hundred each in service, with UK and France less than twenty each and China six. The total today is about 160. The USA has the main navy with nuclear-powered aircraft carriers (11), while both it and Russia have had nuclear-powered cruisers (USA: 9, Russia 4). Russia has eight nuclear icebreakers in service. The US Navy has accumulated over 5500 reactor years of accident-free experience, and operates more than 80 nuclear-powered ships (with 105 reactors as of Aug 2004). Russia has logged 6000 nautical reactor years.

2.2 Civil Vessels

Nuclear propulsion has proven technically and economically essential in the Russian Arctic where operating conditions are beyond the capability of conventional ice-breakers. The power levels required for breaking ice up to 3 meters thick, coupled with refueling difficulties for other types of vessels, are significant factors. The nuclear fleet has increased Arctic navigation from 2 to 10 months per year, and in the Western Arctic, year-round. The icebreaker Leninwas the world's first nuclear-powered surface vessel (20,000 dwt) and remained in service for 30 years, though new reactors were fitted in 1970. It led to a series of larger ice-breakers, the six 23,500 dwt Arktika-class, launched from 1975. These powerful vessels have two reactors delivering 56 MW at the propellers and are used in deep Arctic waters. The Arktika was the first surface vessel to reach the North Pole, in 1977. For use in shallow waters such as estuaries and rivers, two shallow-draft Taymyr-class icebreakers of 18,260 dwt with one reactor delivering 38 MW were built in Finland and then fitted with their nuclear steam supply system in Russia. They are built to conform to international safety standards for nuclear vessels and were launched from 1989. Development of nuclear merchant ships began in the 1950s but on the whole has not been commercially successful. The 22,000 tonne US-built NS Savannah, was commissioned in 1962 and decommissioned eight years later. It was a technical success, but not economically viable. It had a 74 MWt reactor delivering 16.4 MW to the propeller. The German-built 15,000 tonne Otto Hahn cargo ship and research facility sailed some 650,000 nautical miles on 126 voyages in 10 years withoutany technical problems. It had a 36 MWt reactor delivering 8 MW to the propeller. However, it proved too expensive to operate and in 1982 it was converted to diesel.

The 8000 tonne Japanese Mutsu was the third civil vessel, put into service in 1970. It had a 36 MWt reactor delivering 8 MW to the propeller. It was dogged by technical and political problems and was an embarrassing failure. These three vessels used reactors with low-enriched uranium fuel (3.7 - 4.4% U-235).

In 1988 the NS Sevmorput was commissioned in Russia, mainly to serve northern Siberian ports. It is a 61,900 tonne lash-carrier (taking lighters to ports with shallow water) and container ship with ice-breaking bow. It is powered by the same KLT-40 reactor as used in larger icebreakers, delivering 30 propeller MW from the 135 MWt reactor and it needed refuelling only once to 2003. Russian experience with nuclear powered Arctic ships totalled 250 reactor-years in 2003. A more powerful icebreaker of 110 MW net and 55,600 dwt is planned, with further dual-draught ones of 32,400 dwt and 60 MW power at propellers.

2.3. NS Savannah Experience - Purpose of the Savannah The First Nuclear-Powered Merchant Vessel

A technological success, the N.S. SAVANNAH was never intended to be commercially competitive, and was not. The N.S. SAVANNAH served as the trail blazer for future generations of nuclear-powered merchant vessels. It demonstrated to the world the interest of the United States in the peaceful application of nuclear power and provided a vehicle which would establish the procedures and precedents for the future operation of commercial nuclear ships.

Figure 1. NS Savannah

2.4 History of the Savannah

On April 25 1955, in a speech before the Associated Press in New York, President Dwight D. Eisenhower announced plans for a nuclear powered merchant ship. The ship would be based on specifications developed by the Atomic Energy Commission and the Maritime Administration that he would submit to Congress. Authorization to build the ship was given by Congresson July 30, 1956 through public law 848 Chapter 792. The ship was designed by George G. Sharp, Inc. of New York and was built by the New York Shipbuilding Corporation of Camden, New Jersey. The Babcock and Wilcox Company as prime contractor for the power plant designed and built the 74 maximum power thermal megawatt pressurized water reactor. In a ceremony on July 21, 1959, Mrs. Dwight D. Eisenhower christened the N.S. SAVANNAH which then slipped down the building ways into the Delaware River. It was fitting that this ship, to usher in the Atomic Age of merchant ships, be christened "SAVANNAH", for in May of 1819 a 320-ton ship started an epoch-making voyage from Savannah, Georgia to Liverpool, England. She was the S.S. SAVANNAH, the first vessel to use steam on a transatlantic voyage. Her 29-day, 11-hour voyage had ushered in the Steam Age in ocean travel.

Construction took longer than planned, but was essentially completed in the spring of 1961. After public hearings on the safety of the ship's nuclear system and following extensive tests of the reactor and propulsion plant, the reactor was loaded with uranium oxide fuel in the fall of 1961. It took less than thirty hours to insert all thirty-two fuel bundles which would supply 3½ years' power for the historic ship. During her sea trials, the captain showed that the SAVANNAH'S reactor could actually surpass its original operating objectives. Instead of delivering 20,000 shaft horsepower to a single propeller, the plant easily produced more than 22,300. Instead of being limited to about 20 knots, SAVANNAH surged along at 24. Considered by some marine engineers the most beautiful ship ever built, the sleek white SAVANNAH was shown off to the crowds at the 1962 Seattle World's Fair. Then, suddenly, in Galveston, Texas, the triumphant cruises were interrupted by an argument over salaries. The engineering officers on the SAVANNAH had been granted extra pay from the outset because of the needed nuclear training in addition to their other qualifications. However, the deck officers insisted that they should be paid more than the engineering officers because a deck officer's duties were traditionally more demanding. An arbitrator agreed with the deck officers, but the engineers refused to accept the ruling. In May 1963, the engineers shut down the ship's reactor in protest. No one could persuade the engineers to return to work so long as they were being paid less than the deck officers. Finally, the Federal Maritime Administration cancelled its contract with States Marine Lines and picked American Export Isbrandtsen Lines to operate the ship. This meant that an entirely new crew (from a different union) would have to be trained. So, for almost a year, the world's first nuclear powered merchant ship sat at the dock in perfect condition but going nowhere. When the crew was ready, the SAVANNAH steamed back into the spotlight. More than 150,000 visitors boarded her at the first four European ports she visited. In mid-1965, the luxurious cabins were stripped out and the passenger spaces sealed off and 1,800 tons of solid ballast was removed in preparation for the ship to carry nothing but cargo. In September, 1965, the SAVANNAH left New York for the first time with a capacity load of 10,000 tons of general cargo. Even in her new role, the SAVANNAH continued to serve as a goodwill ambassador and a cruising exhibit for the peaceful use of nuclear power in visits to Africa, the Far East, the Mediterranean, and Northern Europe. In the fall of 1968, the SAVANNAH spent two months at a Galveston shipyard for refueling and maintenance. The actual refueling took only two weeks. After nearly 350,000 miles, only four of the original thirty-two fuel bundles had to be replaced. A second complete core was built for the SAVANNAH, but never installed. Since there were no plans for future ships, the Maritime Administration decided that little more research and development information could be gained from the $90 million-plus which had been invested in the entire SAVANNAH project. In the fall of 1971, the historic ship was retired. In January of 1972, the deactivated ship was presented to the city of Savannah, Georgia as part of a proposed Eisenhower peace memorial located there. The city was unable to raise the $2 million required to develop the center and, after four years, the SAVANNAH was again retired. On August 28, 1980, through public law 96-331, Congress authorized the Secretary of Commerce to charter the SAVANNAH to Patriots Point Development Authority, an agency of the State of South Carolina. At Christmas time 1981, the SAVANNAH became a permanent exhibit at the Patriots Point Naval and Maritime Museum in Mt. Pleasant, South Carolina.

Figure 2. NS Savannah in 1968

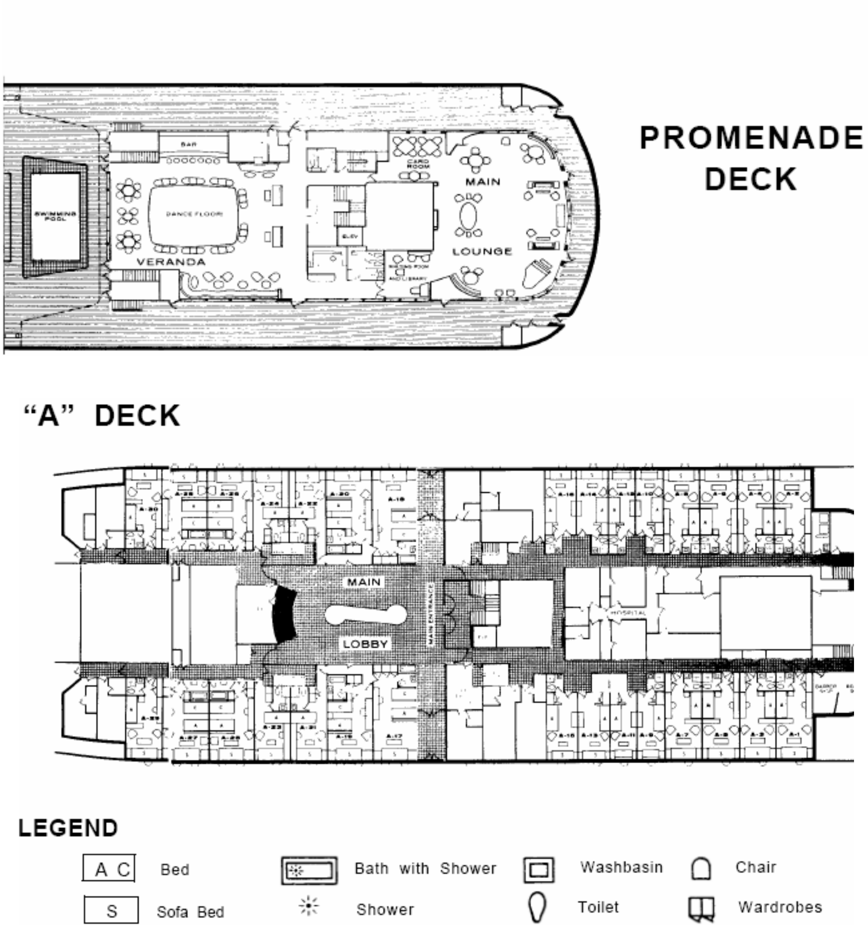

Figure 3. Deck plan of NS Savannah

These Deck Plans show the attractive and ample spaces allocated to SAVANNAH's passengers. The public rooms, modern and colorful in design, are conveniently located on the Promenade Deck. "A" Deck provides air-conditioned accommodations for 60 passengers, with a private bath for each stateroom. The Dining Room is located on "B" Deck.

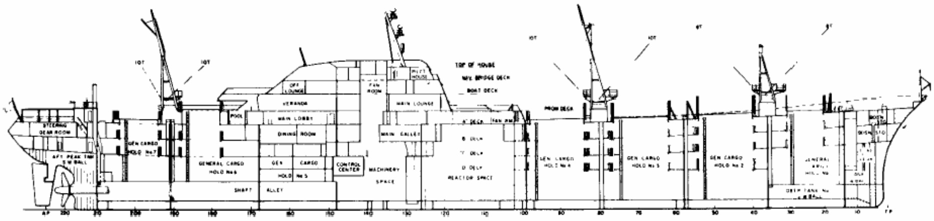

Figure 4. Profile view

PRINCIPAL CHARACTERISTICS OF THE SHIP

LENGTH, OVERALL APPROXIMATE	595'-6"
BEAM	78'-0"
DEPTH TO PROMENADE DECK	59'-0"
DISPLACEMENT AND TONNAGE	
Full Load Displacement	21,850 L.T.
Light Ship	11,850 L.T.
Total Deadweight	10,000 L.T.
Cargo Deadweight	9,250 L.T.
CAPACITIES	
General Cargo, Bale Cubic @ 80.6 Cu Ft/Ton	746,000 Cu Ft
Refrigerated Cargo	None
Cargo Oil	None
COMPLEMENT	
Passengers (One Class)	60
Officers	25
Crew	84
Other	15
Total	184
SPEED AND POWER	
Trial Speed at Normal Power	21 Knots
Normal Power to Shaft	20,000 SHP
Maximum Continuous Power to Shaft	22,000 SHP
Emergency Take-Home Speed	6.8 Knots
Emergency Take-Home Power	640 SHP
MACHINERY	
Main Power Plant:	Nuclear Steam Generator with Geared Steam Turbine
Emergency Propulsion Motor, Electric	750 HP
Number Propellers	1
Generators, Steam Turbine	2-1500 kw
Generators, Aux Diesel	2- 750 kw
Generators, Emergency Diesel	1- 300 kw
Evaporators	2-16,000 Gal/Day
Boiler, Aux Oil-Fired Package Type	1-7500 Lb/Hr
COMPARTMENTATION	
Nine Watertight Compartments, of Which Any Two May Be Flooded without Loss of the Ship	

PRINCIPAL PLANT PERFORMANCE DATA

OPERATING CONDITION	NORMAL POWER	MAXIMUM POWER
Shaft Power - SHP	20,000	22,000
Propeller Speed - RPM	107	110
Turbine Inlet Pressure - psia	460	445
Main Condenser Pressure - "Hg abs.	1.5	1.5
Boiler Drum Pressure - psia	485	472
Feedwater Temperature - °F	348	340
Total Electrical Load - kw	2,169	2,408
STEAM CONSUMPTION - LB/HR		
a. Main Turbines	187,400	204,500
b. Feed Pump Turbine	21,200	21,500
c. Turbogenerators	32,320	34,540
d. Low Press. Steam Generator	700	700
e. Air Ejectors, Sep'rs and Losses	4,300	4,610
f. Total Generation Required	245,920	265,850
HEAT TRANSPORT - MW		
a. Steam Generators	64.1	69.4
b. Purification System	1.2	1.2
c. Primary Pumps	-0.8	-0.8
d. Heat Losses	0.2	0.2
e. Reactor	64.7	70.0
Primary Loop Pressure - psia	1750	1750
Primary Loop Pressure Drop - psi	61.4	61.4
Primary Loop Flow - lb/hr	8,640,000	8,640,000
Primary Loop Temperature Rise -°F	21.6	23.4
Primary Loop Mean Temperature-°F	508	508
Blowdown - lb/hr	2,400	2,600

Figure 5. Dimensional Characteristics of NS Savannah

3. POWER PLANTS

Naval reactors (with one exception) have been pressurised water types, which differ from commercial reactors producing electricity in that:

- they deliver a lot of power from a very small volume and therefore run on highly-enriched uranium (>20% U-235, originally c 97% but apparently now 93% in latest US submarines, c 20-25% in some western vessels, and up to 45% in later Russian ones),
- the fuel is not UO_2 but a uranium-zirconium or uranium-aluminium alloy (c15%U with 93% enrichment, or more U with less - eg 20% - U-235) or a metal-ceramic (Kursk: U-Al zoned 20-45% enriched clad in zircaloy, with c 200 kg U-235 in each 200 mW core),
- they have long core lives, so that refueling is needed only after 10 or more years, and new cores are designed to last 50 years in carriers and 30-40 years in submarines (US Virginia class: lifetime),
- The design enables a compact pressure vessel while maintaining safety. The Sevmorput pressure vessel for a relatively large marine reactor is 4.6 m high and 1.8 m diameter, enclosing a core 1 m high and 1.2 m diameter.
- Thermal efficiency is less than in civil nuclear power plants due to the need for flexible power output, and space constraints for the steam system.

The long core life is enabled by the relatively high enrichment of the uranium and by incorporating a "burnable poison" such as gadolinium in the cores which is progressively depleted as fission products and actinides accumulate, leading to reduced fuel efficiency. The two effects cancel one another out. Long-term integrity of the compact reactor pressure vessel is maintained by providing an internal neutron shield. (This is incontrast to early Soviet civil PWR designs where embrittlement occurs due to neutron bombardment of a very narrow pressure vessel.) The Russian Alfa-class submarines had a single liquid metal cooled reactor (LMR) of 155 MWt and using very highly enriched uranium. These were very fast, but had operational problems in ensuring that the lead-bismuth coolant did not freeze when the reactor was shut down. The design was unsuccessful and used in only eight trouble-plagued vessels. Reactor power ranges from 10 MWt (in a prototype) up to 200 MW (thermal) in the larger submarines and 300 MWt in surface ships such as the Kirov-class battle cruisers. The French Rubis-class submarines have a 48 MW reactor which needs no refueling for 30 years. Russia's Oscar-II class has two 190 MWt reactors. The Russian, US and British navies rely on steam turbine propulsion, the French and Chinese use the turbine to generate electricity for propulsion. Russian ballistic missile submarines as well as all surface ships since the Enterprise are powered by two reactors. Other submarines (except some Russian attack subs) are powered by one.

The larger Russian ice-breakers use two KLT-40 nuclear reactors each with 241 or 274 fuel assemblies of 30-40% enriched fuel and 3-4 year refueling interval. They drive steam turbines and each produce up to 33 MW (44,000 hp) at the propellers. Sevmorput uses one of the same units, though it is said to use 90% enriched fuel. For the next generation of Russian ice-breakers, integrated light water reactor designs are being investigated possibly to replace the conventional PWR.

Decommissioning nuclear-powered submarines has become a major task for US and Russian navies. After defuelling, normal practice is to cut the reactor section from the vessel for disposal in shallow land burial as low-level waste. In Russia the whole vessels, or the sealed reactor sections, sometimes remain stored afloat indefinitely. A marine reactor was used to supply power (1.5 MWe) to a US Antarctic base for ten years to 1972, testing the feasibility of such air-portable units for remote locations. Russia is well advanced with plans to build a floating power plant for their far eastern territories.

3.1 Future prospects

With increasing attention being given to greenhouse gas emissions arising from burning fossil fuels for international air and marine transport and the excellent safety record of nuclear powered ships, it is quite conceivable that renewed attention will be given to marine nuclear propulsion.

3.2 Aspects of High Speed Ship Design

In recent years, there has been a steady increase in the levels of installed propulsion power for commercial ships as well as an increase in the level of environmental awareness. The need for ships that can compete successfully with airfreight in certain niche markets as well as ships that can provide a credible fast-sealift capability have been the primary drivers in high speed ship design. The need, in both cases, to compete economically with existing technology, or, to provide at least an order of magnitude reduction in cost of transport is essential for the successful transition of ideas to reality. The highest power levels are typically achieved, currently, with very large marinized gas turbines and to a limited extent with large medium speed diesels. The increasing price of fossil fuel as well as the environmental impact of fossil fuel based powering options has brought the use of nuclear power as a potential solution for ships with high power requirements. Fuel cells are proving to be a viable option for vessels with lower power requirements designed for coastal operations, where emissions from marine engines have been coming under increasing scrutiny. In the past, the use of nuclear power for commercial ships has been limited to technology demonstrators and has not been actively considered as a viable source of commercial ship propulsion power due to issues like risk, international politics and the unwillingness to transfer successful naval applications of nuclear power to commercial operators. Several new high-speed ship concepts have emerged in recent years and have received tremendous press in recent times. Most of these concepts involve naval architectural advances and highlight innovative solutions to improving the efficiency of moving an object on the air-water interface. The motion of a body at the interface of two fluids, like air and water, results in the formation of a wave train that requires energy to overcome, in addition to the drag experienced by the body due to its translation in the medium. Brief descriptions of high-speed ship concepts currently receiving attention are presented to provide a flavor of the technologies.

3.3 Fast-Ship

The essence of Fast-Ship is reliability, of which speed is an important adjunct. The vessel, 860-foot long and carrying a 10,000-ton payload, is designed to make the passage from Philadelphia to Cherbourg in less than four days, and to sustain speeds of up to 40 knots, maintaining reliability to within one hour of schedule over 97 percent of operations. The vessel, 860-foot long and carrying a 10,000-ton payload is designed to make the passage from Philadelphia to Cherbourg in less than four days, and to sustain speeds of up to 40 knots. This is roughly twicethe rate of conventional freighters and cuts the transatlantic crossing from seven or eight days to three and a half. The key to this improvement is the ship's "semi-planing" hull. While the stern of an ordinary ship drives deeper into the water as speed increases, the FastShip's stern is wide and shallow, with a hydrodynamic curve that lifts it partway out of the sea at high speeds. Five Rolls-Royce Marine Trent gas turbines driving large water jets powers FastShip. The revolutionary system delivers a total of 250 megawatts, or 335,000 horsepower. The hull form, coupled with the propulsion package, will enable the ship to maintain those speeds even under adverse weather conditions. Once in port, the ships will be loaded and unloaded in six hours using a rail-based roll-on roll-off system.

3.4. KMM Trimaran

One promising area for commercial ship system engineering application is very high-speed trimaran technology with speeds up to 70 knots. Kvaerner Masa Marine (KMM) is leading a technology team which includes Band Lavis & Associates and SAIC to develop computational fluid dynamics (CFD), high-powered/high speed ship waterjet design, structural analysis and other design engineering analytical methods and tools. This set of computational tools will be applicable to the design and engineering of all types of high-speed ships. KMM's very high speed trimaran development has included two sets of large scale hydrodynamic tests including fluid flow and wake analysis to allow future validation, and validation of CFD codes. It also includes waterjet technology development for propulsion powers up to 100 megawatts per unit and speeds up to 70-knot ship operation.

3.5. Surface-Effect Ships

Salient results of the 1997 workshop hosted by Naval Surface Warfare Center - Carderock, Maryland (NSWC-CD) on High-Speed Sealift and the post workshop brief-out indicate that with both near-term and far-term propulsion technology, Surface Effect Ships are the least power options for speeds greater than approximately 45 knots. The availability of marinized gas turbines in the 60,000 hp range and the commercial development of large waterjet units that can be matched to these gas turbines have, thus, led to the desirability to re-examine the potential of SES for fast sealift applications.

3.6. Evaluation Methodology of High Speed Ship Concepts

The ability to design, constructs, and operate ships that achieve high speed in dynamic ocean environments is a continuing challenge to the international marine community. Fast ships offer important advantages in both commercial and military applications, in many deployments, and missions throughout the maritime world. While each such vessel must be uniquely designed to meet its specific mission requirements, there are some general methodologies available that allow for the exploration of the key enabling technologies for high-speed ships. There are three principal ship performance parameters relative to mission effectiveness:

- Payload the more the better
- Speed the higher the better
- Range the greater the better

Of course, there are technical and economic prices to be paid for each of these performance parameters. Clearly, the object is to maximize them relative to a total ownership life cycle cost for the ship, or better yet, for the ship system. Costs should include research, development, design, construction, acquisition, deployment, operation, support, and disposal over the economic life of the ship, in the context of the ship system, or the "business" environment within which the ship performs its mission. The relative effectiveness of different platforms in performing the same mission can be quantified parametrically. The ship technical effectiveness parameter and the transport factor are two such parameters and are briefly described below. Ship technical effectiveness is a type of "transfer function" which describes the "effectiveness" of a ship in "converting" installed power into payload delivery rate. Ship technical effectiveness is a function of lift/drag ratio, overall propulsive coefficient, deadweight/displacement ratio, specific fuel consumption, fuel margin and range. The Transport Factor also compares competing designs to relate the utility of each design when performing its transport task, and assumes that there is a unique non-dimensional characteristiccalled TF for each design that relates the full load weight of the ship to the total installed power on the ship and the average voyage speed.

While the ship's technical effectiveness and transport factor describe the performance of a ship in a particular mission or deployment, cost must be considered in any overall measure of effectiveness (MOE). Furthermore, cost considerations must include those components related to acquisition or capital cost as well as operation and support costs in a total ownership cost (TOC) context on a life cycle cost (LCC) basis. This brings into focus design methodologies and tools that can objectively design and compare several designs for a given mission, like whole-ship design synthesis models.

3.7. Assessment of Whole-Ship Impact of Propulsion System Choice

Whole-Ship Design Synthesis Models have been developed and employed for many years. Additionally, the recent growth in computing power has resulted in rendering these very powerful tools readily available to the naval architect to perform rapid ship design and assessment studies. Whole-ship design synthesis models are designed to simulate the typical naval architecture design spiral in a rapid, automated, and consistently repeatable manner. This is accomplished in order to quickly produce and visualize a balanced design and provides the capability of running systematic parametric variations in order to evaluate the key drivers of the design being developed. In the past, design synthesis models have often been finely tuned to represent, with good accuracy, the type of design primarily performed by naval architects. Models were designed to handle specific hull forms such as monohulls, catamarans, SWATHs, surface effect ships, air cushion vehicles etc. As a result, these models are built on algorithms that reflect accepteddesign practice and tend to be primarily empirical in nature. This limits the user from utilizing these models to investigate the impact of new and emerging technologies without undue bias from built-in empirical algorithms that represent the paradigm of existing trends. The incorporation of capabilities to include emerging technologies in synthesis models will result in their use with greater reliability to help shape investment strategies for future research and development. This requirement is a challenge and calls for the use of physics-based algorithms that will allow us to depart from our existing or prior technology base and incorporates new technology trends as and when they occur. This has led to the development of a new generationof design synthesis models. PASS, for "Parametric Analysis of Ship Systems" is a physics-based design synthesis model that satisfies this emerging requirement. The parametric nature of PASS is ideal for quick exploration of the design space or for examining the sensitivity of ship characteristics to changing requirements or subsystem choices. PASS was developed by Band, Lavis & Associates, Inc. (BLA), under a Small Business Innovation Research (SBIR) effort lead by the U.S. Office of Naval Research (ONR) and monitored by the Carderock Division of the Naval Surface Warfare Center. PASS, with its emphasis on the use of physics-based algorithms, is the first of a new generation of concept exploration models that allows rapid and reliable exploration of the available design space beyond that which can be explored reliably with normal empirically based tools. Intrinsic capability for technology innovation characterized in terms of its mass properties, energy-needs, geometry and cost to develop, build and operate is included in PASS as illustrated in Figure 6. Including this information along with the other inputs required to describe the type and operational needs of the ship(s) being examined will allow the user of PASS to determine the whole-ship costand performance impact of the innovation. Comparing this with the investment cost to develop the innovation will then allow the user to judge whether the investment would be worthwhile. In addition, with PASS, the designer or technologist can:

- Compare vessel types designed to common requirements.
- Optimize vessel and fleet size for minimum cost.
- Compare subsystem innovation options.
- Provide rapid response to "What If?" questions.

All of these can be done with a high level of accuracy and analytic rigor.

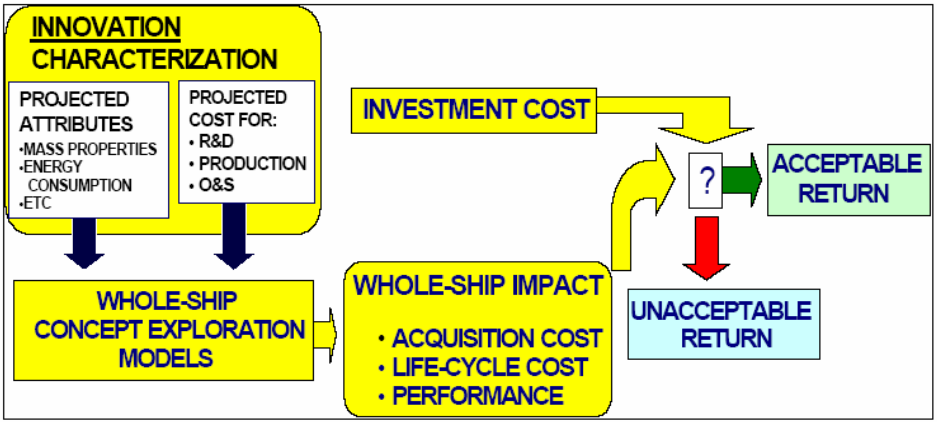

Figure 6. The Approach to Answering: What R&D is Worth Pursuing? Or, What Return Will We Get On Our Investment?

The use of such design-synthesis models and the use of measures of effectiveness described earlier can quite easily help in providing direction in focusing research and development into areas that are more promising than others. The impact of alternative propulsion for high- speed ships, especially with nuclear and fuel cell based power, can be investigated to determine limiting levels of power that are economically viable and hence pursuing in the near future, while providing direction for far-term research.

4. NUCLEAR POWER RESEARCH

The emergence of candidate commercial High Speed Ship systems designed to attract selected segments of the international High Value/Time Sensitive cargo market suggests a radical change in both ship design and ship propulsion systems in order to meet market requirements.

The issue is no longer the movement of cargo from dock to dock as a prescribed service but rather one of movement from cargo origin to destination with advances in ships speed, dockside cargo transfer and subsequent intermodal movements. Candidate High Speed Ship systems are considering speeds of 40 knots, container terminal transfer in the 6-8 hour range and commensurate intermodal transfer times. High Speed Ship systems are weight and displacement sensitive, and require high horsepower propulsion systems (with their attendant fuel weight for the power and speeds required) to assure the critical requirement of dependability to meet the scheduled movements of cargo. The required fuel weight (several thousands of tons) represents a deadweight that could have significant impact on available revenue and system profitability. It has been 25 years since the United States has considered nuclear powering as an alternative for commercial ship systems. The state of the art in nuclear power has since seen many significant advances; the economics associated with international movement of containers has been the precursor to larger ships, collaborative management and the formation of countless alliances.

World-wide trends indicate a doubling of marine trade within the next 20 years, possible threats of Global Warming, the indirect economic implications which may be incurred by fossil fuel powering systems (with their attendant increasing oil costs), growing requirements for the rapid ocean transport of time sensitive freight, and finally, continued technological advancements which have been made in the area of nuclear reactor design. These, collectively, all lead to conclusions that justify support for a more in-depth analysis of both the technology and the prospective economics associated with a commercial nuclear power system for the commercial High-Speed ship systems being considered for the Twenty-first Century. Nuclear power could offer speed, power, environmentally safe burning, and clear economic feasibility for high speed and high power vessels. The effects from today's high oil prices are destined to remain, regardless of OPEC, as additional cost will probably be accrued to oil burning facilities for the reduction of sulfur dioxide and greenhouse gas emissions likely mandated by future legislation and levies. In addition, there are a number of emerging nuclear power technologies and reactor concepts, which might form a basis for rebirth of commercial nuclear power as well as nuclear merchant ships. Some of these concepts are briefly described here.

4.1. Nuclear Ship Criteria for the Era After 1990

The shipping business has changed dramatically since 1955. Ships have grown, the container revolution has cut in port turn-around times for general cargo ships, and international trade in high value cargos like automobiles and construction equipment has steadily increased. Many ships in busy port cities are now required to install expensive equipment and/or restrict their operations to meet anti-pollution laws that limit discharges of oil, stack gases, and ballast water. In order to decide if nuclear power is now right for a particular ship, the following additional factors should be considered:

- Speed requirements
- Volume limits
- Emissions limits
- Oil handling limits
- Ballast water limits
- Deck space limits
- Need for flexible operation
- Local cost, availability, and quality of fuel

The following types of ships may benefit from nuclear power. Operators of these ships would be well advised to learn more about what uranium fuel can do. As usual, a detailed economic analysis will be required to reach a correct propulsion plant decision.

- Large container ships
- Automobile carriers

- Refrigerated cargo ships
- Long distance passenger ships
- Logistics support ships
- Commercial submarines
- Bulk cargo carriers

5. ADVANTAGES OVER CONVENTIONAL FUELS

5.1. The Need for Speed

An example calculation might help explain the characteristics of nuclear propulsion that allow it to claim a speed advantage over oil burning ships. If a ship needs 26,000 shaft horsepower to travel at 17 knots, it will burn about 1700 gallons (6.4 tons) of bunker fuel every hour. If the same ship wished to increase speed to 25 knots to make a delivery schedule, the fuel rate would increase to 8500 gallons (32 tons) per hour while the power needs would increase to 130,000 SHP. It is obvious why fast ships are not generally considered to be an economical way to transport bulk cargo. Even if oil is cheap, the space required for storagefor a long trade route becomes a major concern. A ship like the above carrying goods from New York to Cape Town, South Africa would need at least 2.3 million gallons of fuel (6900 tons) to make the trip at 25 knots versus 673,000 gallons (2019 tons) at 17 knots. Even though the trip takes five days longer, space and fuel costs favor the slower journey. With nuclear ships, fuel expenditures are minor, both in terms of weight and cost. At current nuclear fuel prices an SHP hour produced by fissioning slightly enriched uranium fuel costs less than one sixth as much as an SHP hour produced by burning residual oil. The advantage is even more dramatic when compared to distillate fuels. There is virtually no change in weight on a nuclear powered ship because of fuel consumption.

There are obvious advantages to increased speed if fuel consumption is less constraining. More cargo can be moved with the same number of ships. Cargo will spend less time at sea and more time where it is needed. Shippers will pay higher rates for certain types of cargo since they will save on financial carrying costs. Since a faster ship requires the same crew size as a slow one, productivity can increase be improved without painful lay-offs.

5.2. Reliability

Nuclear ships have demonstrated a high degree of reliability. They have operated for decades in some of the world's harshest climates including the Persian Gulf and the Arctic Ocean. They are not subject to clogged fuel filters, burst fuel lines, loss of compressed starting air, contaminatedfuel from substandard suppliers, bent rods, failed gaskets, or a whole host of other problems common to combustion engines. Even single reactor plant submarines comfortably operate under the Arctic ice cap where a loss of propulsion power can be deadly. The engines rarely fail. Since a substantial portion of the marine accidents can be blamed on propulsion casualties, this characteristic is an important advantage for nuclear power.

5.3. Power Density Comparisons

Savannah's propulsion plant weighed about 2500 tons including the shielding. Her specific power ratio was 238 lbs/hp (151 kg/kw), which is obviously not very competitive with today's medium speed diesels or gas turbines. However, Savannah's propulsion plant weight included enough fuel for 340,000 miles of operation. In contrast, a diesel engine system with a specific weight of 36 lbs/SHP (23 kg/kw) and a specific fuel consumption of .3 lbs/hp-hr (.2 kg/kw-hr) would match Savannah's characteristics if its required voyage lasted 28 days (13,000 miles at 20 knots), ignoring the weight of tanks, and piping and reserve fuel requirements. Actually, the comparison between a modern diesel and a 1950s first generation nuclear plant with a low pressure saturated steam plant does not provide a realistic picture of what a nuclear plant can achieve. The below table, which includes ducts and foundations, provides better information:

Engine type	Specific weight
combustion gas turbine	2.9 kg/kw
medium speed diesel	10 kg/kw
nuclear gas turbine (including shielding)	15 kg/kw
nuclear steam plant (including shielding)	54 kg/kw

Table 1. Power density of typical engine types

5.4. Total system power density comparisons

Engine power density is not the only consideration for vehicles like ships that must carry their fuel. One of the main reasons for converting ships from coal to oil rested on the fact that oil has more energy per unit weight. Therefore, we need to compare the power density of various types of engines including stored fuel. When fuel for a 10 day voyage is taken into consideration, nuclear plants can have a decided advantage over combustion plants. This advantage allows a greater portion of the ship to be dedicated to carrying revenue generating cargo.

Engine type	Specific weight
nuclear gas turbine	15 kg/kw
nuclear steam plant	54 kg/kw
diesel engine (.2 kg/kw-hr)	58 kg/kw
combustion gas turbine (.24 kg/kw-hr)	60 kg/kw

Table 2. Power density for various engines with 10 day fuel supplies

5.5. Specific volume comparisons

Many of today's ships are more limited by space than by displacement. Nuclear propulsion plants, with high density materials making up a large portion of their weight, have an advantage over fossil fueled ships. A nuclear gas turbine plant would require approximately 60% of the volume of an equivalent combustion gas turbine for a nominal 10 day voyage; the advantage increases for longer ranges. Container ships, like aircraft carriers, need as much free deck space as possible. This requirement is one thing that has inhibited the use of marine gas turbines, which require a high air flow and subsequently require large intakes and exhausts. Nuclear gas turbines, however, have no need for intakes and exhausts. The space saved on deck can increase operating efficiencies and revenues for the life of the ship.

5.6. Environmental considerations

In most ports, it is illegal to discharge oil contaminated water. This has led to the development of segregated ballasting systems to ensure that compensating water is not contaminated. There are also limits associated with biological hazards that prevent the discharge of ballast water taken in at a different port. Nuclear ships have no need to compensate for changes in fuel weight during a voyage so they can have simpler ballasting systems.

Governments have implemented air emission limits in certain busy ports that require costly modifications to existing propulsion systems. Simple,but somewhat costly, solutions include separate bunkers with low sulfur (but more expensive) oil, and ship speed (power) limits when within certain boundaries. There is increasing pressure for the installation precipitators, selective catalytic reformers and scrubbers. Aside from the expense, these technologies can be difficult to adapt to ships because of space limitations. Nuclear ships do not emit any exhaust gases, a fact that is clearly demonstrated by the success of nuclear powered submarines.

Finally, rules on liability for oil spills are increasing the cost of bunkering. Provisions must be made for containment booms and stand-by response teams. Separate fueling piers are becoming common, requiring extra time in port and extra expense for tugs and pilots. Bottom tanks now need double hull protection, increasing the cost of both construction and operations. Nuclear ships will be refueled during scheduled maintenance periods; it is easily possible to design cores that can last for six to ten years of normal ship operation.

5.7. Availability & Energy Production Rates

Considering the availability of fuels, fossil fuel would last for, keeping in mind the usage rate, would last for not more than 50 years from now. Whereas the nuclear fuels, keeping in mind theusage rate, would last for more than 200 years from now. Uranium-235 is the isotope of uranium that is used in nuclear reactors. Uranium-235 can produce 3.7 million times as much energy as the same amount of coal. As an example, 7 trucks, each carrying 6 cases of 2-12 foot high fuel assemblies (refer Fig), can fuel a 1000 Megawatt-electrical (Mwe) reactor for 1.5 years.

Figure 7. Truck loaded with 6 cases of 2-12 foot fuel assemblies

During this period, 2 metric tons of Uranium-235 (of the 100 metric tons of fuel - uranium dioxide) would be consumed. To operate a coal plant of the same output would require 1 train of 89-100 ton coal cars each every day. Over 350,000tons of ash would be produced AND over 4 million tons of carbon dioxide, carbon monoxide, nitrogen oxides and sulfur oxides would be released to the environment.

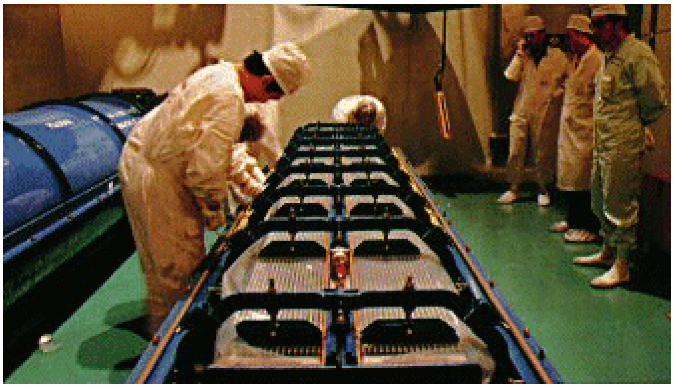

Figure 8. Typical Container with 2 Fuel Assemblies

5.8. Energy Production Costs

The best example of cost comparison is shown by this graph provided by the Nuclear Energy Institute that compares average nuclear and coal production costs over recent years. Nuclear fuel costs are considerably less than coal. However, various capital, operating and maintenance costs for coal may be lower than nuclear. Thus, the 2 costs are comparable.

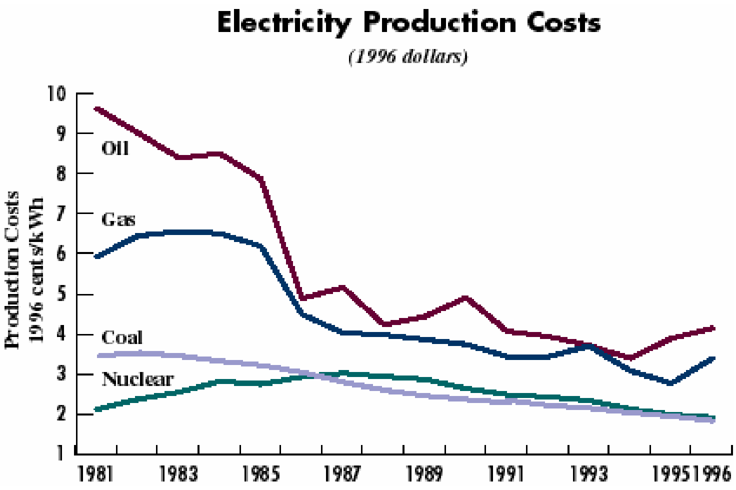

Figure 9. Power Production Costs

The various components of energy generation account for the following:

- Capital costs to build the plant and modifications after the plant is built
- Ongoing operation and maintenance costs
- Fuel costs
- US Department of Energy (US DOE) charges for ultimate spent fuel disposal

- US Nuclear Regulatory Commission (US NRC) charges for regulation

Typically, the plant capital expenses are depreciated over 30 to 40 years. Modifications are depreciated over the remaining life of the plant (usually taken as the end of the current license). The operating and maintenance costs and US DOE and US NRC charges are accounted for as an annual expense. Fuel costs are usually treated separately as a capital expense depreciated over a number of years.

6. SUITABILITY OF REACTOR TYPES FOR MARINE USE

6.1. Pressurized Water Reactors (PWRs)

The Pressurized Water Reactor (PWR) has been in use in navy ships for 50 years. The navy PWRs are fully developed, but much of the data is classified. The technology of civil applications is representative for early applications. Except for some of the Russian ice-breakers nuclear power has ceased to exist in civil shipping. Size and weight and safety and control systems of the plants of the Savannah, Mutsu and Otto Hahn need to be improved. Power plants of Russian ice-breakers saw an evolution in safety and reliability on their ships (Khlopin et al [1]), although they may not be fully optimized for weight and volume. Furthermore, they do not meet the high power requirements of high-speed cargo ships. The Japanese Atomic Energy Research Institute (JAERI) has recently designed a state-of-the-art PWR for marine use in Japan called Marine Reactor X (MRX) (Kusunoki et al [2]). The 100 MWth PWR of the integral type shows enhanced safety, reliability, compact and lightweight construction with the adoption of new technologies. A 210 MWth design is also available, although less data is provided (Fujino [3]. Westinghouse Electric Company designed a land-based reactor that addresses the high US DOE Generation IV requirements Paramanov [4]). The Integral Reactor Innovative and Secure (IRIS) is a candidate marine power plant because of the low to medium power range (100-350MWe) and the simplicity in design, while maintaining all advantages of the latest reactor technology. Unfortunately the containment of this reactor is not suited for marine application yet. To conclude, there is no existing marine PWR that provides the high power for high-speed transatlantic cargo vessels. The reactors that are availableare either too small, land-based or have not yet been presented in literature. There is no reference PWR in the required power range. The solution provided here is to scale up the most modern PWR design suited for marine application. The up scaled PWRs can be compared with the competing HTGR reactor types, and the optimum power plant size can be selected. The unavailability of an 'off-the-shelf'PWR marine reactor unfortunately reduces the chances of near future applications.

6.1.1. PWR DESIGN

The MRX serves asa reference reactor for scaling. The Russian KLT-series could also be used, but little is published on weight and volumes of the reactor installations. The MRX design is more state-of-the-art. Low power density of the MRX is not favorable for small size, but ensures passive safety. The designers have however optimized the power plant for small size while maintaining low power density. Land based reactors can have a core density of up to 130 MWth/m3, while the MRX has about 40 MWth/m3. The reactor will therefore not provide the smallest available. The core volume could be about three times as small, leading to considerable smaller power plants. The safety is paramount however for application on board ships, as the MRX designers recognize. Figure 10 shows the scaling procedure that is used to dimension the reactor plant. The outcome of the dimensions-scaling is presented in Figure 5. The associated weight analysis is based on a weight breakdown of the MRX. Kusunoki [2] shows a breakdown of the weights of the MRX reactor plant components. Using these data and the scaling methodology presented above four weight-scaling factors are applied to the components:

- Core volume
- Reactor vessel-volume
- Reactor vessel-outer surface
- Containment volume

The results are presented in Figure 10.1. The small bend in the curve results from a change in the shape of the core; between 100 to 200 MWth the height increases with power, beyond that point only the core diameter increases.

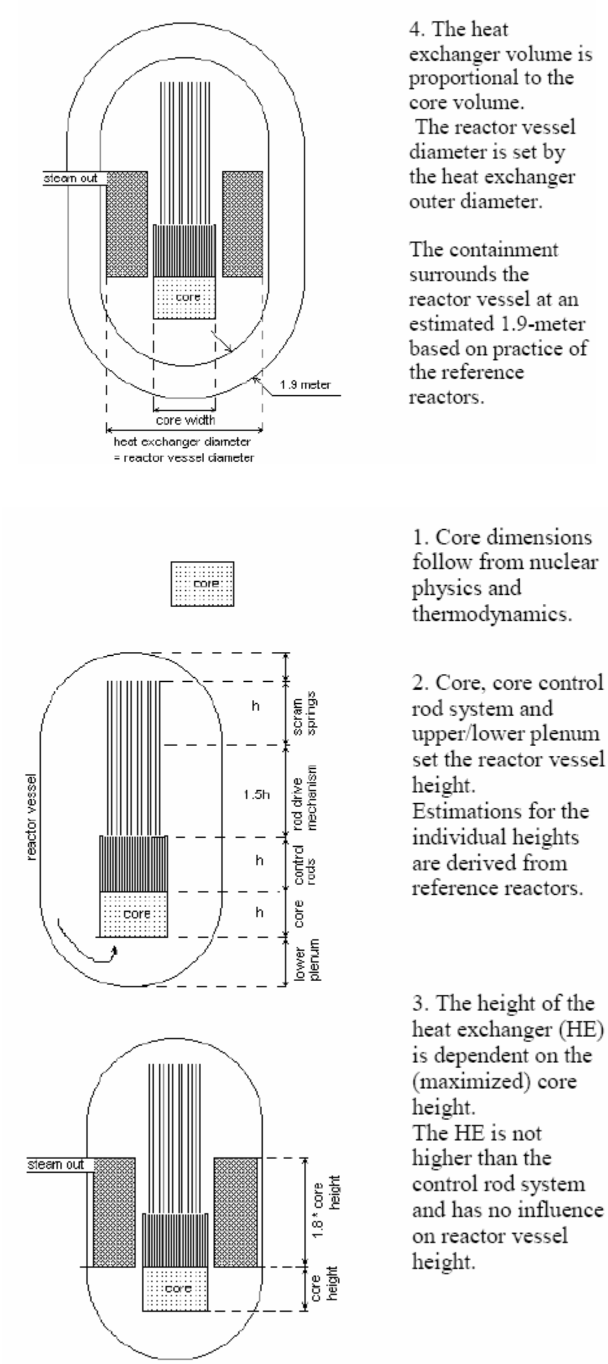

Figure 10. Model of the PWR for Parametric Conceptual Design.

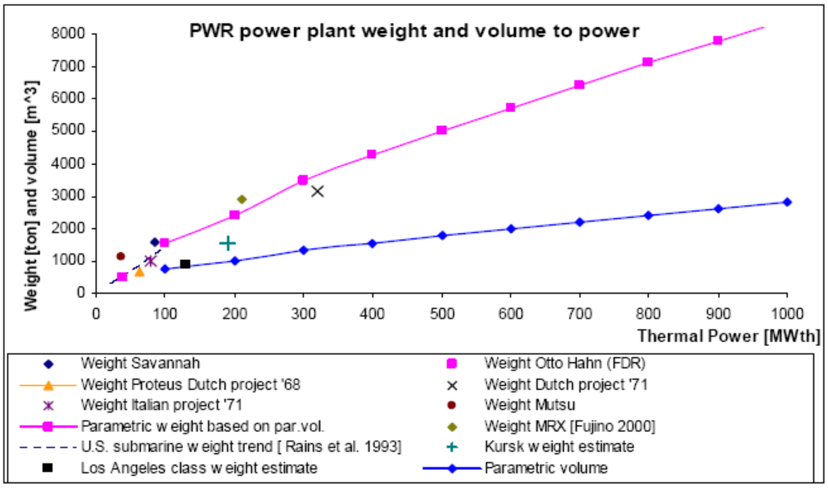

Figure 10.1. PWR Scaling Results.

For obvious reasons only the low power end of the curve can be validated, but two designs of intermediate power are worth mentioning. A weight of 5800ton is reported by Fujino for two MRX plants together of 210 MWth each. This weight is slightly under predicted by the model. Dutch design from '71 by Muysken also shows satisfactory comparison. Estimates for two submarine-classes show lower weights, this could be contributed to the higher power densities of the core.

PWRs are robust and proven reactors for aircraft carrier and submarine propulsion; however, specific volume and weight seems to be prohibitive for merchant ship propulsion. This emerges from the choice of the coolant, which demands massive high-pressure vessels and components for a satisfactory thermal efficiency in liquid phase, and which are subjected to in-service degradation. Also, unless these reactors become radically simplified, they would remain relatively expensive under for a high efficiency i.e. 500 MWe (electric) per unit. A schematic diagram is shown in the figure below.

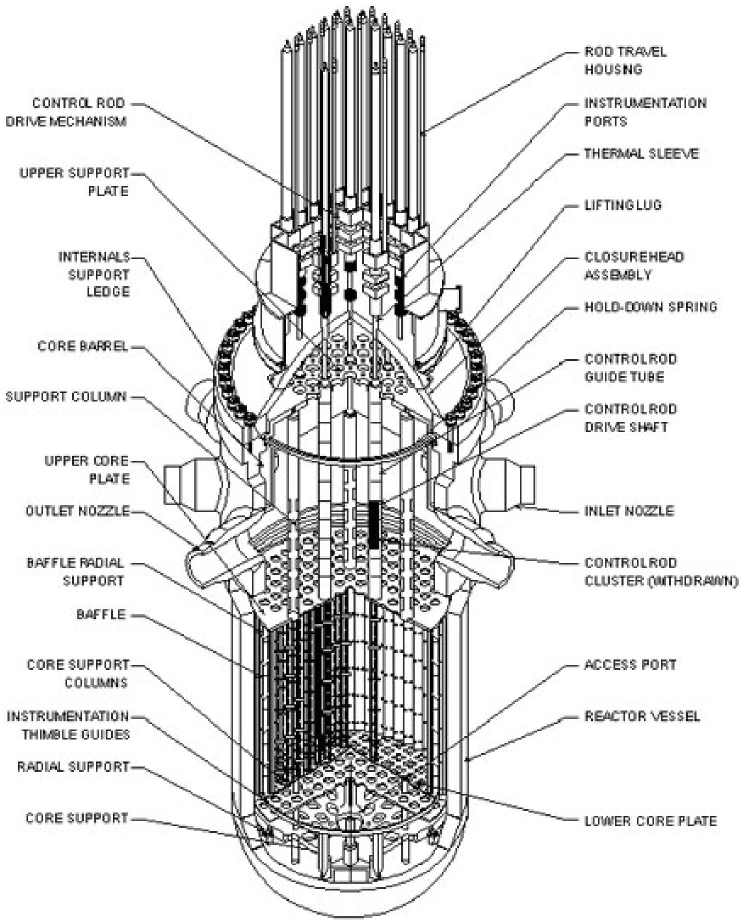

Fig. 11 Schematic diagram of a PWR

6.2. Boiling Water Reactor

BWR is the abbreviation for the Boiling Water Reactor. These reactors were originally designed by Allis-Chalmers and General Electric (GE). Other suppliers of the BWR design world-wide have included ASEA-Atom, Kraftwerk Union, Hitachi. Commercial BWR reactors may be found in Finland, Germany, India, Japan, Mexico, Netherlands, Spain, Sweden, Switzerland, and Taiwan. Japan and Taiwan have the newest BWR units.

The BWR reactor typically allows bulk boiling of the water in the reactor. The operating temperature of the reactor is approximately 570F producing steam at a pressure of about 1000 pounds per square inch. Current BWR reactors have electrical outputs of 570 to 1300 Mwe. As this the PWR designs, the units are about 33% efficient. In the figure below, water is circulated through the Reactor Corepicking up heat as the water moves past the fuel assemblies. The water eventually is heated enough to convert to steam. Steam separators in the upper part of the reactor remove water from the steam.

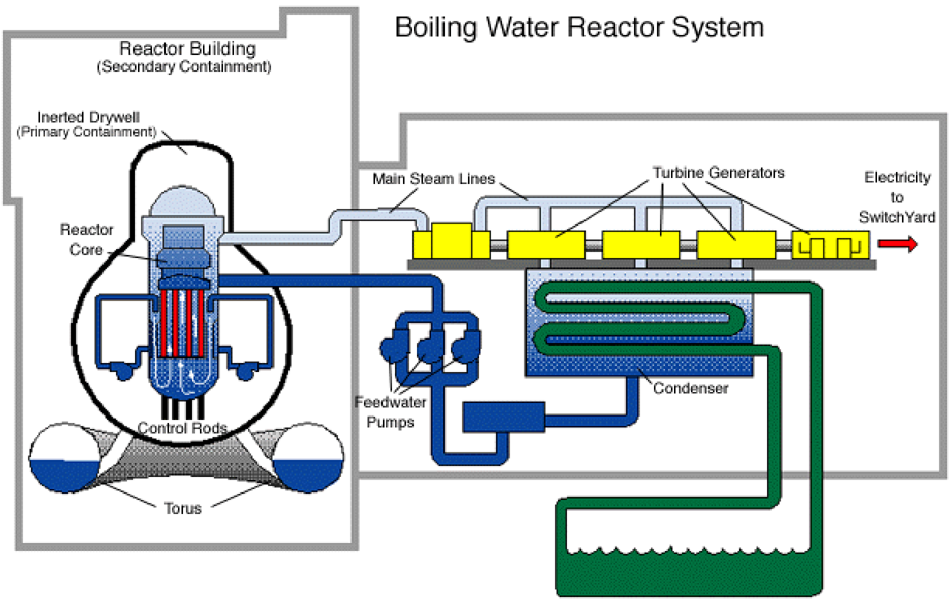

Figure 12. Boiling Water Reactor System

The steam then passes through the Main Steam Lines to the Turbine-Generators. The steam typically goes first to a smaller High Pressure (HP) Turbine, then passes to Moisture Separators (not shown), then to the 2 or 3 larger Low Pressure (LP) Turbines. In the sketch above there are 3 low pressure turbines, as is common for 1000 MWe plant. The turbines are connected to each other and to the Generator by a long shaft (not one piece).

The Generator produces the electricity, typically at about 20,000 volts AC. This electrical power is then distributed to a Generator Transformer, which steps up the voltage to either 230,000 or 345,000 volts. Then the power is distributed to a switchyard or substation where the power is then sent offsite. The steam, after passing through the turbines, then condenses in the Condenser, which is at a vacuum and is cooled by ocean, sea, lake, or river water. The condensed steam then is pumped to Low Pressure Feedwater Heaters (shown but not identified). The water then passes to the Feedwater Pumps which in turn, pump the water to the reactor and start the cycle all over again.

The BWR is unique in that the Control Rods, used to shutdown the reactor and maintain an uniform power distribution across the reactor, are inserted fromthe bottom by a high pressure hydraulically operated system. The BWR also has a Torus (shown above) or a Suppression Pool. The torus or suppression pool is used to remove heat released if an event occurs in which large quantities of steam are released from the reactor or the Reactor Recirculation System, used to circulate water through the reactor. In the boiling water reactor (BWR), the water which passes over the reactor core to act as moderator and coolant is also the steam source for the turbine. The disadvantage of this is that any fuel leak might make the water radioactive and that radioactivity would reach the turbine and the rest of the loop. A typical operating pressure for such reactors is about 70 atmospheresat which pressure the water boils at about 285. This operating temperature gives a Carnot efficiencyof only 42% with a practical operating efficiency of around 32%, somewhat less than the PWR. BWRs are supposed to offer slight investment reductions, but this design has not found justification in Marine propulsion, because of phase differences and heaving accelerations that would impair reactor power control. Moreover heaving accelerations would in turn result in heavy vibrations that are totally unacceptable in marine applications. Another disadvantage of these types of reactors is that it requires heavy and extensive shielding, due to radiochemical carryover increasing radioactive radiation hazards. A schematic diagram of a BWR is shown in the figure below [Fig. 13].

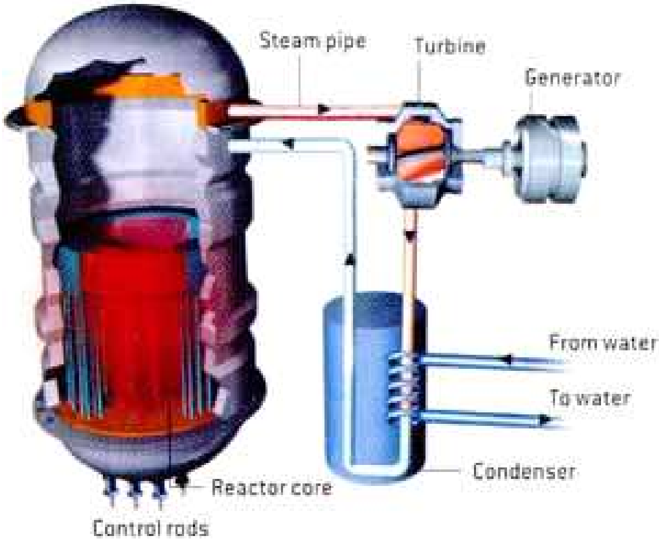

Figure 13. Schematic diagram of a BWR

6.3. Gas-Cooled Reactors (GCR)

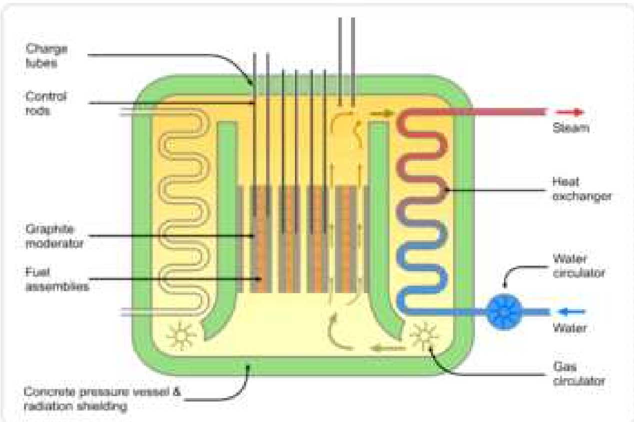

Figure 14. Schematic diagram of the Advanced Gas-cooled Reactor.

Note that the heat exchanger is contained within the steel-reinforced concrete combined pressure vessel and radiation shield. An Advanced Gas Cooled Reactor (AGR) is a type of nuclear reactor. These are the second generation of British gas-cooled reactors, using graphite as the neutron moderator and carbon dioxide as coolant. The fuel is uranium oxide pellets, enriched to 2.5-3.5%, in stainless steel tubes. The carbon dioxide circulates through the core, reaching 640°C and then passes through boiler (steam generator) assemblies outside the core but still within the steel lined, reinforced concrete pressure vessel. Control rods penetrate the moderator and a secondary shutdown system involves injecting nitrogen into the coolant or releasing boron ball shutdown devices. The design of the AGR was such that the final steam conditions at the boiler stop valve were identical to that of conventional power stations. Thus the same design of turbo-generator plant could be used. In order to obtain high temperatures, yet ensure useful graphite core life (graphite oxidises readily in CO2 at high temperature) re-entrant flow is utilised, ensuring that the graphite core temperatures do not vary too much from those seen in a Magnox station. The AGR has a good thermal efficiency (electricity generated/heat generated ratio) of about 41%, which is better than modern pressurized water reactors which have a typical thermal efficiency of 32%. This is largely due to the higher coolant outlet temperature of about 640°C practical with gas cooling, compared to about 325°C for PWRs. However the reactor core has to be larger for the same power output, and the fuel burnup ratio at discharge is lower so the fuel is used less efficiently, countering the thermal efficiency advantage.

The AGR was developed from the Magnox reactor, also graphite moderated and CO2cooled, a number of which are still operating in UK. The Magnox used natural uranium fuel in metal form and magnesium based cladding. The original design concept of the AGR was to use a beryllium based cladding. When this proved unsuitable, the enrichment level of the fuel was raised to allow for the higher neutron capture losses of stainless steel cladding. This significantly increased the cost of the power produced by an AGR. Like the Magnox, CANDU and RBMK reactors, and in contrast to the light water reactors, AGRs are designed to be refueled without being shut down first, though a number of nuclear safety issues were identified in relation to this and so all AGRs either refuel at part load or when shut down. The prototype AGR at the Sellafield (Windscale) site is in the process of being decommissioned. This project is also a study of what is required to decommission a nuclear reactor safely. Currently there are seven nuclear generating stations each with two operating AGRs in the United Kingdom. They are all owned and operated by British Energy. These are located at Dungeness B, Hartlepool, Heysham 1, Heysham 2, Hinkley Point B, Hunterston B and Torness.

Of the various kinds of GCRs, the most common ones are GT-MHR (Gas Turbine Modular helium reactor), PBMR (Pebble Bed Modular Reactor) and HTGR (High Temperature Gas Reactor).

6.3.1. GT-MHR

This reactor is an aero-derivative gas turbine, except for the existence of a nuclear reactor instead of fuel burners, and the choice of a closed helium cycle, resulting in a decrease in the compression ratio. Helium is heated by the nuclear fission reaction and expands across the blades of the turbine. The helium is recompressed and redelivered to the hot side of the engine. The turning turbine produces torque, and in some cases is directly coupled to a generator (within the containment shell) for direct delivery of electrical power. GTMHRs are lighter, simpler, have high thermal efficiency have chemical fuel-coolant affinity, and fuel burn up. These are less sensitive to ship motion unlike PWRs and BWRs. The Gas Turbine Modular Helium Reactor (GT-MHR) is an advanced nuclear power system that is well suited to shipboard application by virtue of its compact size, high thermal efficiency, inherent safety features and environmental advantages. The concept was originally developed by General Atomics under U.S. Department of Energy funding for stationary power production. However, its high degree of safety and flexible design arrangement make it adaptable to many applications. The GT-MHR couples a helium-cooled modular helium reactor, contained in one vessel, with a high efficiency Brayton cycle gas turbine Power Conversion System (PCS), contained in an adjacent vessel. The stationary GT-MHR module, as shown in Figure 3 is designed to be located below ground in a concrete silo with both vessels in a vertical arrangement. However, the vessel dimensions and orientation of the PCS vessel can be altered to fit the specific application. The GT-MHR power conversion system employs an optional intercooler and seawater cooling. Helium coolant is heated in the reactor. The heated coolant flows through the cross-vessel to the PCS, where it is expanded through a gas turbine to drive the electric generators and compressors. Helium re-compression is accomplished using precooling and optional intercooling. Energy is transferred back into the helium in a recuperator prior to the helium being returned to the reactor. An intermediate cooling loop is used as a safety buffer between the primary cooling helium and the external heat sink (e.g., seawater). This provides a double barrier (precooler and intermediate heat exchanger) against possible release of any radioactive material to the environment. The intermediate cooling loop also provides essential cooling to the generator. One of the most important features of the GT-MHR for shipboard application is safety. The GTMHR

is melt-down proof and passively safe. This safety is achieved through a combination of inherent safety characteristics and design selections that take maximum advantage of the inherent characteristics. These characteristics include:

- Helium coolant: which is single phase, inert, and has no reactivity effects
- Graphite Core: which provides high heat capacity and slow thermal response, and structural stability at very high temperatures
- Refractory coated particle fuel: which retains fission products at temperatures much higher that normal operations
- Negative temperature coefficient of reactivity: which inherently shuts down the core above normal operating temperatures

- A low power density core in an un-insulated steel reactor vessel surrounded by a reactor cavity cooling system (RCCS).

The RCCS is an independent means provided for the removal of core decay heat from the reactor vessel in a passive manner in the event the two active, diverse heat removal systems, the power conversion system and a shutdown cooling system, are not available. For passive removal of decay heat, the core power density and the core configuration are designed such that the decay heat can be removed by heat conduction, thermal radiation and natural convection without exceeding the fuel particle accident temperature design limit. Core decay heat is conducted to the pressure vessel and transferred by radiation from the vessel to the normally operating RCCS. As a result, radio-0nuclides are retained with the refractory coated fuel particles without the need for safety system actuation or operator action. These safety characteristics and design features result in a reactor that can withstand loss of coolant circulation or even loss of coolant inventory and maintain fuel temperatures below damage limits (i.e., the system is meltdown proof). The large heat capacity of graphite core structure is an important inherent characteristic that significantly contributes to maintaining fuel temperatures below damage limits during loss of cooling, or coolant, events. The core graphite heat capacity is sufficiently large to cause any heatup, or cooldown, to take place slowly. A substantial time (on the order of days versus minutes for other reactors) is available to take corrective actions to mitigate abnormal events and to restore the reactor to normal operations. The high negative temperature coefficient of reactivity provides protection against control malfunctions and/or failure of normal reactivity control mechanisms. This feature, which is an inherent property of the uranium fuel and graphite moderator, adds a large amount of negative reactivity in the event that the core temperature rises above the normal operating temperature, thus causing the power to reduce to the shutdown level. Thus, a core heat-up will inherently shut the reactor down.

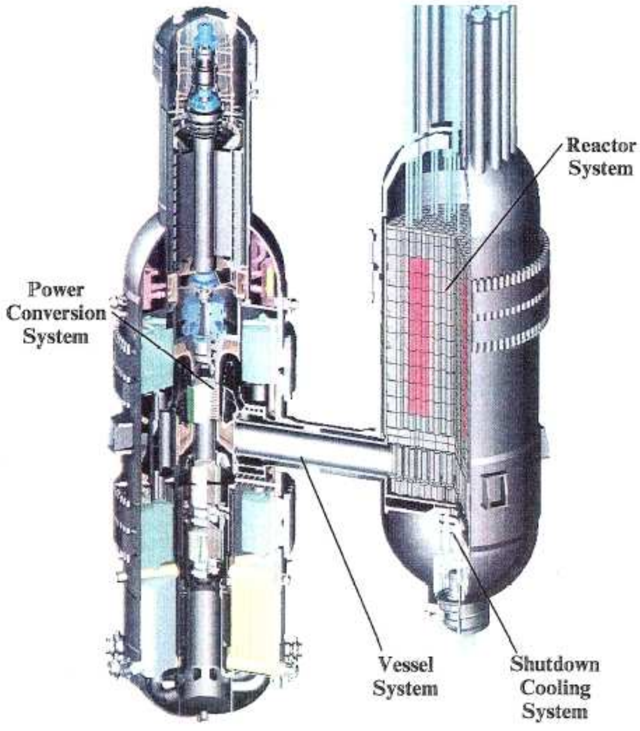

Figure 15. GT-MHR Cross Section

A schematic diagram is shown in figure [Fig. 16] below.

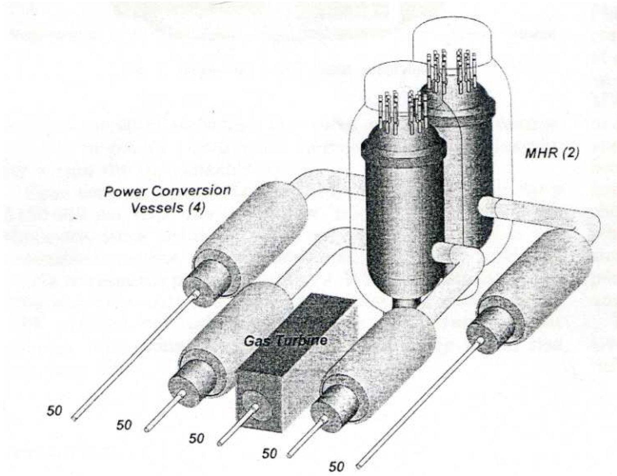

Fig. 16 Schematic diagram of a GT-MHR

The simplicity of a GT-MHR is shown in the figure [Fig. 17].

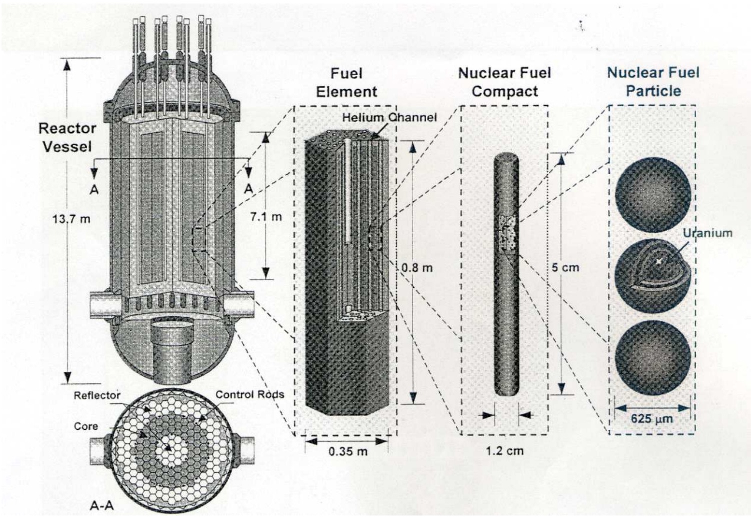

Fig. 17 Simple construction of a GT-MHR

This type of reactor has been chosen an option for the conceptual idea of a fast container ship that was conceived by Thornycroft, Giles & Co. for fast ship Atlantic Inc. of Virginia with the assistance of MIT (Dept of Ocean Engineering for Hull Design and Sea Keeping Simulation) [Fig. 18].

Fig. 18 SPMH (Semi-Planning Mono Hull) Concept

6.3.2. PBMR

The PBMR is an advanced nuclear reactor design. Instead of water, it uses an inert or semi-inert gas such as helium, nitrogen or carbon dioxide as the coolant, at very high temperature, to drive a turbine directly. This eliminates the complex steam management system from the design, and increases the transfer efficiency to about 50%. Safety Features: The reactor is cooled by an inert, fireproof gas, so it cannot have a steam explosion as a light-water reactor can and the reactor will not crack, melt, explode or spew hazardous wastes. The primary advantage of pebble bed reactors is that they can be designed to be inherently safe. In particular, most of the fuel containment resides in the pebbles [Fig. 7], and the pebbles are designed so that a containment failure releases at most a 0.5 mm sphere of radioactive material. A significant technical advantage is that some designs are throttled by temperature, not by control rods.

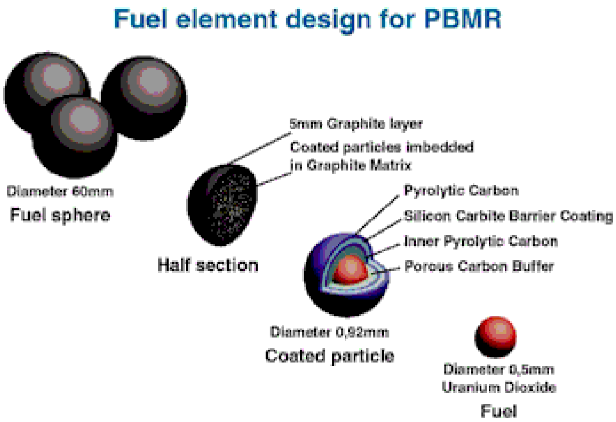

Figure 19. Fuel Element Design for PBMR

6.4. The High Temperature Reactor - Gas Turbine (HTR-GT)

The HTR-GT is an inherently safe, helium cooled, graphite moderated, high temperature reactor directly coupled to a closed-cycle gas turbine. The NEREUS installation is the 20 MWth or 8 MWe version of the HTR-GT with a pebble-bed nuclear reactor as heat source. The HTR-GT is not a competitor for existing Pressurized Water Reactor (PWR) installations, which are designed for direct drive in commercial shipping applications. The HTR-GT is not suitable for direct drive and only suitable for low power range and as a prime mover in ships with an all-electric propulsion system. The heart of the installation is a so-called pebble-bed reactor.

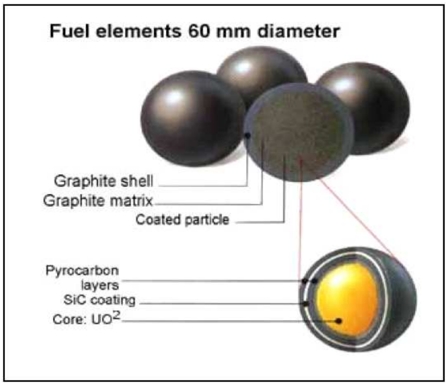

Figure 20. The nuclear fuel

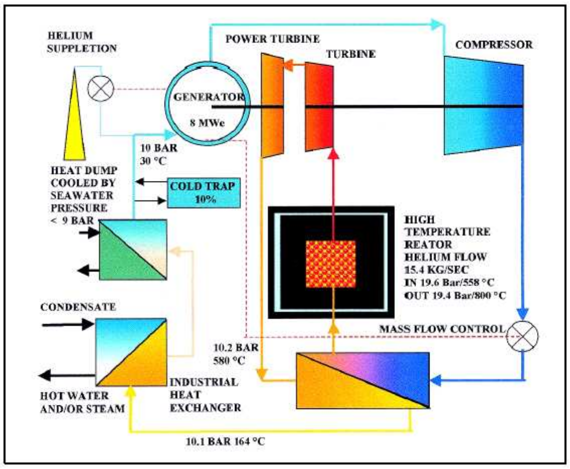

Figure 21. The NEREUS cycle

The basic fuel element is the so-called coated particle, consisting of a uraniumoxide fuel kernel surrounded by four coatings (see figure 20): 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 uraniumoxide kernel is about 1 mm. The whole fuel element construction is called a triso coated particle. The silicon carbide coating acts as an impenetrable containment for the radioactive fission products inside the fuel kernel and the porous coating. 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. The enrichment of the uranium depends upon the amount of energy required for the fuel cycle (8 19.75%). For the LWR the enrichment is 3 - 5%. This construction forms the first containment of the radioactive material from the biosphere. From the outside the fuel elements look like graphite balls of 6 cm or pebbles, hence the name of the reactor. About 10,000 of such triso coated particles have been put in the 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. ingress of steam). In fact the graphite matrix and graphite outer layer form the second containment, which is impenetrable for most of the fission products even at prolonged exposure to high temperatures. The built-up of highly mobile fission products in the helium coolant will be low as was also observed at AVR/Jülich. In fact the graphite matrix and graphite outer layer form the second containment, which proved in tests to be impenetrable for the fission products. The numerical figures for the curves shown in Figure 22 denote the diameter (in mm) of very small cylinders ('needles') of burnable poison, embedded in the fuel elements. With a diameter of 0.8 mm the reactivity 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. 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 as well as the reactivity decreases after some time. Refueling has to take place. Most studies on the pebble bed HTR assume on-line refueling.

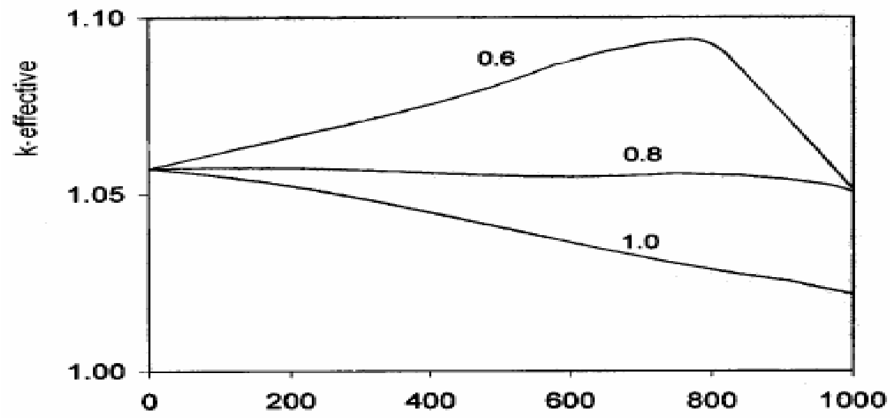

Figure 22. Criticality control through burnable poison

Consequently there is no excess reactivity in the core of an HTR. 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. However, the NEREUS installation is based upon the principle of simplicity. The 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 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. "Burnable poison" is a very basic feature for this type of small scale energy production units. 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 phenomenon is being used for power control in the NEREUS reactor concept. When more power is needed the coolant flow is increased, the temperature of the fuel will decrease, the number of fissions will increase and as a result the power produced by the core will increase as well, and reversibly. This feature of the HTR has been fully demonstrated, even to the extreme, with a sudden power change from maximum power to zero power, during the operation of the AVR/Jülich. It is also an important feature of the inherently safe character of the HTR.

Decay Heat: The decay heat is the heat, which is still generated by the nuclear fuel after shut down. The completely passive removal of the decay heat is a necessity to prevent a meltdown. 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. This flow is driven by natural draft. This cooling will be there all the time and is established without any ventilators, blowers or other mechanical means but in a natural way. For this purpose a normal ship's funnel construction is very suitable. This construction can also be used as transport route for refueling, maintenance and repair by replacement. The cooling air must be supplied from the open decks. This passive heat removal system is always in operation and removes about 0.5% of the energy produced in the reactor during normal operations (100 kW). Due to the low energy density in the core and the small construction, the outside surface of the reactor drum is enough to allow the decay heat to be taken away by natural draft. If the ship sinks, 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 seawater will enter the helium circuit through fast corroding plugs. The helium will disappear and seawater will enter the closed-cycle system and so the nuclear core.

7. OVERVIEW OF NUCLEAR PROPULSION

Once, naval propulsion gave birth to the dominant commercial nuclear power reactors. Now, the advances in innovative reactor designs may pay back. Even though most of the reactors discussed above, would incur an economic viability averagely of 200 million $ for only the plant installation, there is an advantage of considerable reduced weight for each type of reactors which is evident from the table [Table 2] below.

Components	Added Wts (tons)	Removed Wts (tons)
Reactor vessel	270	
Reactor Core	380	
Shields and Structures	1050	
Power converters	290	
Helium converters	40	
Cooling systems	15	
Spare He Compartment	5	
Auxiliary Equipments	150	
Decontamination chamber	40	
Gas Turbines & Auxiliaries	50	250
Air ducts & Exhaust	20	150
Fuel Oil	300	4800
Total	2610	5200
Net Wt. advantage	2590	

Table 3 Relative power plant weight estimation

This reduced weight also grabs in it the advantage of a simpler construction of the vessel. Considering these points, and other service factors, the vessels which can have nuclear propulsion are container carriers. The net benefits per ship, considering revenues at a preferential rate of 38 cents/ kg with a service factor of 87%, and a load factor of 70% with 7.25 tons/TEU, would be $65 millions per year. This proves that the only economic barrier, other than the not specific and flexible rules for nuclear merchant vessels, is only for a short-term basis and is profitable on a long-term basis.

7.1 Conclusion

The economic viability of nuclear propulsion is anticipated for fast container ships. There is currently little interest in the world on the part of either the government or major corporations to consider the possibility of uranium fueled ships. There are obvious hurdles that must be overcome, but the benefits of nuclear propulsion make the effort worthwhile. The benefits are enough to encourage countries to continue to support nuclear ship research. The future is bright, the benefits are apparent, and the technology is available. The impact of nuclear power on ocean shipping can be as great as that of containerization. Because of the increased speed and flexibility of operation, atomic energy can allow ships to compete more effectively with aircraft in the market for international deliveries.