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POTENTIAL ADVANTAGES OF MOLTEN SALT REACTOR FOR MERCHANT SHIP PROPULSION

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ABSTRACT

Operating costs of merchant ships, related to fuel costs, has led the naval industry to search alternatives to the current technologies of propulsion power. A possibility is to employ nuclear reactors like the Russian KLT-40S, which is a pressurized water reactor (PWR) and has experience on civilian surface vessels. However, space and weight are critical factors in a nuclear propulsion project, in addition to operational safety and costs. This work aims at comparing molten salt reactors (MSR) with PWR for merchant ship propulsion. The present study develops a qualitative analysis on weight, volume, overnight costs, fuel costs and nuclear safety. This work compares the architecture and operational conditions of these two types of reactors. The result is that MSR may produce lower amounts of high-activity nuclear tailings and, if it adopts the 233U-thorium cycle, it may have lower risks of proliferating nuclear weapons. Besides proliferation issues, this 4th generation reactor may have lower weight, occupy less space, and achieve the same levels of safety with less investment. Thus, molten salt regenerative reactors using the 233U-thorium cycle are potential candidates for use in ship propulsion.

1. INTRODUCTION

Operating costs of merchant ships, related to fuel costs, has led the naval industry to search alternatives to the current technologies of propulsion power. A possibility is to employ nuclear reactors like the Russian KLT-40S, which is a pressurized water reactor (PWR) and has experience on civilian surface vessels. However, space and weight are critical factors in a nuclear propulsion project, in addition to operational safety and costs. This work aims at comparing molten salt reactors (MSR) with PWR for merchant ship propulsion.
During the last century, propulsion of merchant ships has undergone a significant transformation. Now diesel-powered engines dominate this market, where fuel costs are proportionately high compared to the ship's operating costs. Due to this fact, recent developments have instigated the naval industry to question whether the current model of naval merchant propulsion is sustainable, mainly due to three factors [1].

- Rising fuel costs because of rising oil prices;
- Environmental regulations introduced to mitigate the effects of climate change; and
- Potential introduction of carbon taxes.

The three above factors can be circumvented using nuclear power, and that is why naval nuclear propulsion is not new, being first introduced in the USN Nautilus submarine (United States), which sailed from 1954 to 1980. Since then, approximately 700 nuclear reactors have been developed for applications at sea and today around 200 reactors provide propulsion to ships and submarines [1]. NS Savannah was the first merchant vessel to have PWR-based nuclear propulsion, running from 1962 to 1972.

Russia also has accumulated considerable experience in using nuclear power for propulsion of surface vessels and submarines. High performance characteristics of reactor plants developed by JSC "Afrikantov OKB Mechanical Engineering" (OKBM) have been validated during long-term operation of nuclear icebreakers and one nuclear ice reinforced vessel on northern sea routes [2]. The latest version of Russian maritime reactor plants is the KLT-40, a pressurized water reactor, which it has been installed in the icebreaking freighter Sevmorput (135 MWt) and in two icebreakers, Taimyr and Vaigatch (171 MWt, each one) [3].

Nuclear reactors employed in naval propulsion throughout the world use PWR-type reactors, where the fuel is enriched uranium. Nonetheless, according to [4] [5] [6], the world reserves of ^{235}U are not adequate to provide indefinitely the needs of industrial nuclear power based only on converting or burners reactors. With the introduction of breeder reactors, however, ^{235}U-based fuels are exchanged for ^{238}U or thorium, both being considerably more abundant than ^{235}U, and the amount of thorium is approximately three to four times greater than that of uranium [7] [8] [9]. Molten salt breeder reactor (MSBR), which makes part of the 4th Generation Reactors, is a thermal regenerative reactor that uses the ^{233}U-thorium cycle, being ^{233}U the only isotope capable of regenerating in thermal reactors.

As there is a likely future shortage of uranium, with the consequent progressive price increase, a potential source of uranium fission fuel is thorium, which is more abundant than uranium. Thorium-based reactors, depending on their configurations, can produce low amounts of high-activity nuclear waste (around 3%) and have a lower risk of proliferation of weapons (in view of the production of ^{233}U contaminated with ^{232}U, which produces intense emitters of gamma radiation, from their decay products, making their handling difficult).

From the foregoing, a qualitative analysis regarding dimensions, weight, costs, fuel, and safety between a PWR and a MSBR is performed, in order to evaluate whether the referred 4th Generation Reactor can be a candidate to replace PWRs used for merchant ship propulsion.

2. METHOD

The present study develops a qualitative analysis on weight, volume, overnight costs, fuel costs and nuclear safety. This work compares the architecture and operational conditions of these two types of reactors, PWR and MSR.

This work adopts the following steps:

- Find the main systems in current PWR architecture;
- Check if molten salt reactor architecture should have an equivalent system, for each PWR system;
- Check if MSR architecture needs any other system;
- MSR safety performance and lifetime;
- For each MSR system, compare the life cycle cost, weight, volume with equivalent PWR system;

- Compare the life cycle costs, weight, and volume for the overall plant (MSR and PWR); and
- Assess if MSR may compete with diesel engines.

3. DEVELOPMENT AND RESULTS

3.1. Main Systems in Current PWR Architecture

The reactor coolant system of the PWR consists of:

- reactor vessel;
- steam generators;
- reactor coolant pumps;
- pressurizer;
- reactor cooling system;
- reactor internals;
- core; and
- fuel.

These principal components are interconnected by the reactor coolant piping to form a loop configuration, as Figure 1 shows.

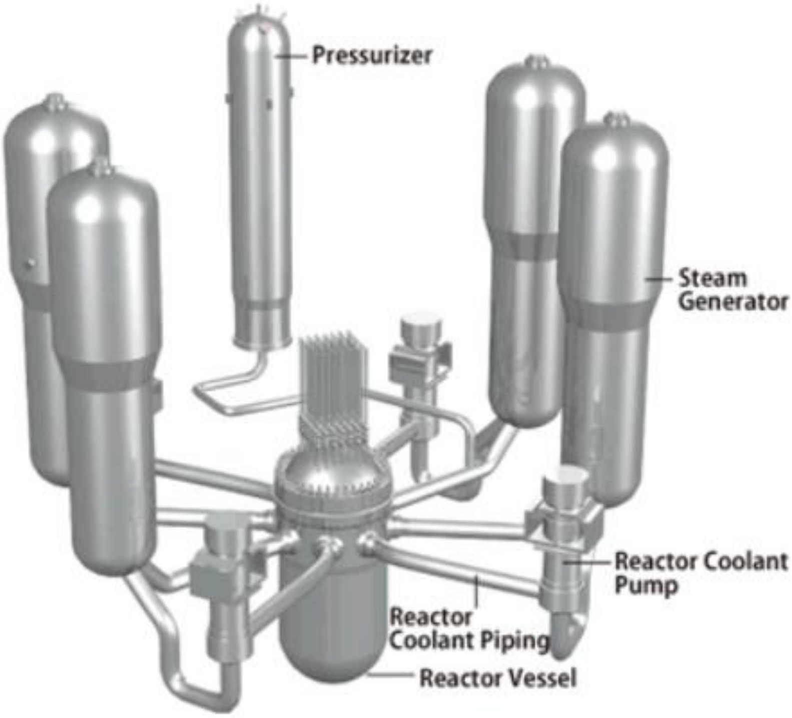

Figure 1 – Typical PWR reactor architecture

3.2. MSR Architecture

As presented in [10], the research into the MSR started at Oak Ridge National Laboratory (ORNL) in the 1950's with the Aircraft Reactor Experiment (ARE), which ran successfully for 100 hours at a power up to 2.5 MWth and an outlet temperature up to 860°C. ARE showed that the UF_4 was chemically stable in the salt and that the gaseous fission products were removed automatically by the circulation pumps. The fuel salt had a strong negative temperature coefficient, and the reactor power could be manipulated from zero to full power without control rods by changing the power demand.

Afterwards the ORNL focused on graphite moderated reactors working with the thorium-uranium fuel cycle. Neutrons leaking from the primary salt were captured in the blanket salt to produce ^{233}U. This uranium could easily be recovered by fluorination of the UF_4 in the salt to the volatile UF_6. This process is nowadays used to produce UF_6 for uranium enrichment.

The research at ORNL culminated in the Molten Salt Reactor Experiment (MSRE), shown in Figure 2, which ran successfully for five years until December 1969. The MSRE had a thermal power of 8 MW and operated either with ^{233}U, ^{235}U or ^{239}Pu. However, the fuel salt did not hold any thorium. During operation, uranium was removed from the fuel salt through fluorination.

The experience gained was used in the design of the Molten Salt Breeder Reactor (MSBR), sketched in Figure 3, which had a large core to reduce neutron leakage and a low power density to reduce irradiation damage to the graphite moderator. To achieve net breeding, the produced ^{233}U was removed by fluorination, and a process flow sheet was designed to separate the thorium from the lanthanides. Both salt loops were connected to drain tanks via freeze plugs made of solid salt cooled by air. This plug could thaw in the events of overheating or operator intervention. Unfortunately, the MSBR was never built and the freeze plug and chemical fuel salt processing were never applied.

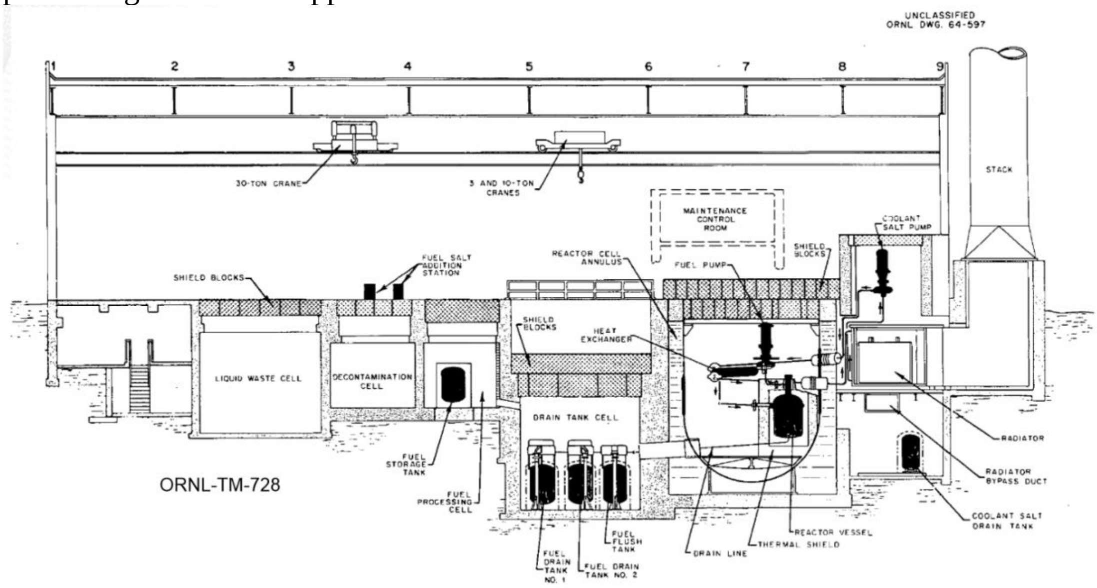

Figure 2 – Elevation Building 7503[1]

[1] The MSRE was installed in an existing building in the 7503 area at ORNL that was constructed specifically for the Aircraft Reactor Experiment (ARE) and Aircraft Reactor Test (ART).

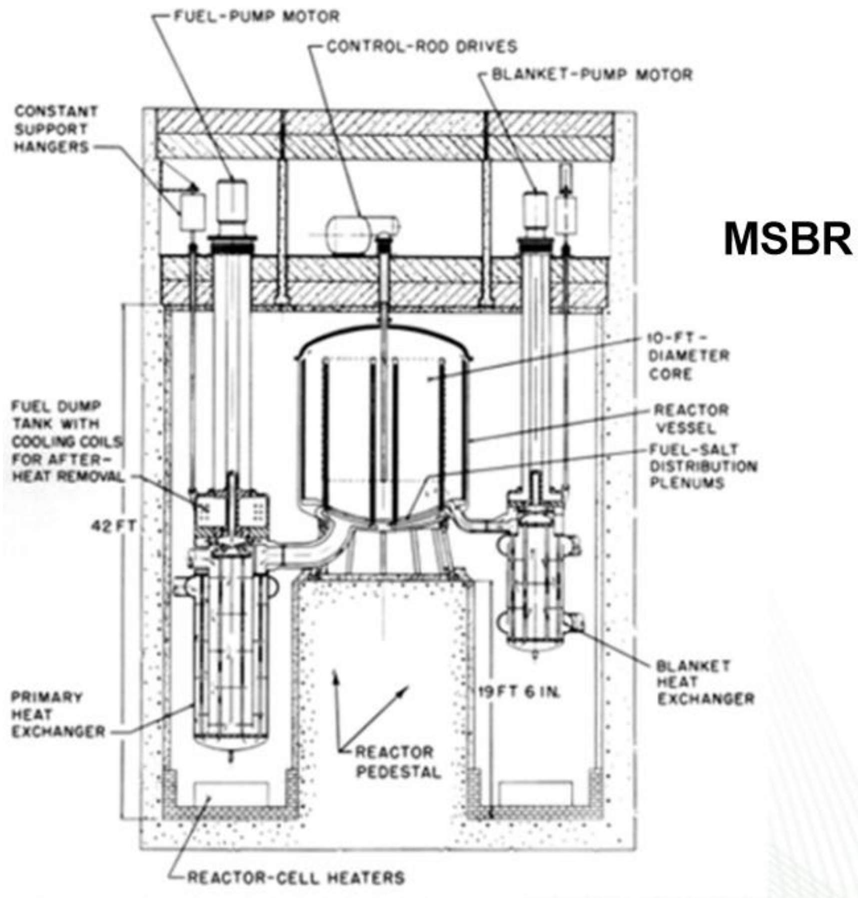

Figure 3 – Molten Salt Breeder Reactor Experiment (150 MWt, 65 MWe)

3.3. MSR Safety Performance and Lifetime

The most important safety performances are coming from the following factors [11]:

- The primary and secondary systems have pressure lower than 5 bar, and do not have the danger of accidents due to high pressure such a system destruction or salt leakage;
- The fuel and coolant salts are chemically inert, and without risks of fire or explosions with air or water (as occurred in the Fukushima accident);
- The boiling point of fuel salt is about 1670 K or more, much higher than the operation temperature 973 K. Therefore, the pressure of primary system cannot increase;
- The fuel salt will be able to become just critical when it coexists with the graphite moderator. Therefore, leaked fuel salt will not induce any criticality accident (Epithermal-type MSR is not the same);
- MSR has a large prompt negative temperature coefficient of fuel salt. The temperature coefficient of graphite is slightly positive, but controllable due to the slow temperature increase depending on its high heat capacity;
- The delayed-neutron fraction in ^{233}U fission is smaller than that in ^{235}U, and half of the delayed neutrons is generated outside the core. However, it is controllable owing to the longer neutron life, and large negative prompt temperature coefficient of fuel salt;

- As the fuel composition can be made up anytime if necessary, the excess reactivity and required control rod reactivity are sufficiently small, and the reactivity shift by control rods is small; and
- Gaseous fission products such as Kr, Xe and T are continuously removed from fuel salt, minimizing their leakage in accidents and in the chemical processing.

Regarding the MSR lifetime, it can operate for about 30 years (per original design; modern design would be a minimum of 40 years) [12]. Many references can supply the lifetime for PWR about 30 to 40 years of operation, depending on maintenance and design.

3.4 Comparison between PWR and MSR

Instead of presenting two complete concepts of architecture and operation for PWR and MSR, this work focuses in analyzing the general subsystems of both technologies. This way, it is possible to understand about their differences and the need to have a determined system, for instance, MSRs do not need pressurizers and boron systems, see Table 1.

Table 1 – Architectural comparison between PWR and MSR

PWR system	MSR system	Comment
Reactivity control (rods)	Reactivity control (flow rate of the primary pump and rod)	Whilst reactivity control in a PWR is performed by the insertion or withdrawing of control rods, in an MSR, the reactivity control is done from the variation of the flow rate of the fuel pump. The higher the flow rate, the higher the reactivity and vice versa. For MSR, control rods function as redundant and diverse control system to assure shutdown. As MSR net core excess reactivity is smaller than PWR, control rod worth and number of control rods is also smaller.
Reactor core	Fuel circuit	Moderator, in a PWR, is water, while nuclear fuel is settled in fuel rods. In an MSR, the moderator is graphite rods and the fuel is a viscose fluid, containing nuclear material.
Reactor coolant	Primary circuit Secondary circuit	PWR: water MSR: viscose fluid
Reactor pressure vessel	Primary Tank	Pressure in a primary circuit of a PWR is higher than 100 bar, while in an MSR is lower than 5 bar.
Coolant pumps	Primary salt pump	Coolant pumps of both types of reactors must be robust to comply the standards requirements.
Pressurizer	*Not applicable*	MSR does not need pressure.
Steam generator	Steam generator	They are similar, however instead of water in the tubes of the steam generator in a MSR, the fluid is a molten salt.
Boron injection	*Not applicable*	Boron concentration in coolant and control rods are two diverse and redundant reactivity control systems in PWRs. MSRs use coolant and fuel pump speed and control rods to control reactivity.

<table>
<tr><th>PWR system</th><th>MSR system</th><th>Comment</th></tr>
<tr><td>Residual heat removal</td><td>Passive heat removal</td><td>After shutdown the reactor core of a PWR must the cooled. In an MSR, the fluid is transferred to another tank.</td></tr>
<tr><td>Auxiliary feedwater</td><td>Passive secondary heat removal</td><td>Secondary circuit needs residual heat removal as a redundancy.</td></tr>
<tr><td>Reactor coolant purification</td><td>Salt degassing</td><td>The purification system treats the water coolant to avoid activation of corrosion products (mainly). The salt degassing is an operation aimed to remove hydrogen dissolved in the melt along with poisoning fission products.</td></tr>
<tr><td>Radiological shielding</td><td>Radiological shielding</td><td>Installed around the containment, both have the function to avoid elevated level of radiation outside the reactor.</td></tr>
<tr><td>Reactor protection</td><td>Reactor protection</td><td>It provides the shutdown of the reactor in case of malfunctioning. In PWR, the safety and control rods are released to drop down; in an MSR, a valve is opened to drain the liquid.</td></tr>
<tr><td>Reactor control</td><td>Reactor control</td><td>Depending on the operation demand, the concentration of boron acid in the primary circuit of a PWR is changed. In a MSR, the flow rate of the primary pumps is altered.</td></tr>
<tr><td>Radioactive waste</td><td>Radioactive waste</td><td>In an MSR, fission products are released to the liquid salt fuel solution and contained by the fuel barrier. Tritium needs treatment or storage. However, in a PWR, activated corrosion products and tritiated water needs storage and disposal.</td></tr>
<tr><td>Nuclear fuel (rods)</td><td>Nuclear fuel (viscose fluid; coolant and nuclear material)</td><td>PWR: 3%-5% of enriched uranium (^{235}U)
MSBR: Mol composition (%) of a molten salt reactor fuel
<table>
<tr><th>Sal</th><th>Mol (%)</th></tr>
<tr><td>^{7}LiF</td><td>73</td></tr>
<tr><td>BeF_2</td><td>16</td></tr>
<tr><td>ThF_4</td><td>10,7</td></tr>
<tr><td>$^{233}UF_4$</td><td>0,3</td></tr>
</table>
</td></tr>
</table>

As number and worth of control rods is smaller and they are not subjected to pressure, both costs, weight and volume of control rods for MSR, including their electronic control cabinets, should be one order of size smaller than for PWR.

MSR core should be heavier because of higher density of graphite compared to water and it should be bigger because of the lesser moderation power of graphite. The core costs should be about the same as PWR because graphite costs more than water, but fuel fabrication is cheaper.

The reactor coolant pressure barrier (part of reactor coolant system) for MSR should be one or two orders of size lighter than PWR because of operating pressure (atmospheric pressure). Volume should be similar, as it is proportional to the heat exchange area, which is proportional to nominal power. Assuming cost is proportional to materials weight, MSR reactor coolant system should be one or two orders of size cheaper than the equivalent on PWR.

MSR should spend more money on purification system than PWR, as the blanket (salt holding thorium) needs treatment to supply the ^{233}U that feeds the fuel circuit. ^{232}Th gains a neutron to form ^{232}Th, which soon beta decays (half-life 22 minutes) to Protactinium (^{233}Pa). The ^{233}Pa (half-life of 27 days) decays into ^{233}U. The issue is the 400 ppm ^{232}U that comes along because this isotope produces gamma rays. Such process need fluorination to remove the ^{232}U from the ^{233}Pa by fluorination to UF_6 before reducing it to UF_4 for adding to the primary fuel salt circuit. The use of the Th-U fuel cycle is of interest to the MSR, because this reactor is the only one in which the ^{233}Pa can be stored in a hold-up tank to let it decay to ^{233}U.

MSR control and protection systems should be cheaper because MSR process is simpler and risks are smaller. For instance, MSR excess reactivity may be so low that a prompt criticality accident could be impossible by design. On the other hand, waste treatment should be more expensive because the tritium production is two orders of size larger on MSR, generating radioactive waste needing storage and control.

Because MSR may easily breed fissile fuel from fertile isotopes, it may extract more energy from the same amount of mined uranium or even use thorium. The result is that MSR may produce lower amounts of high-activity nuclear tailings and, if it adopts the ^{233}U-thorium cycle, it may have lower risks of proliferating nuclear weapons. Besides proliferation issues, this 4th Generation Reactor may have lower weight, occupy less space, and achieve the same levels of safety with less investment.

From the safety point of view, MSR avoids the design basis accidents of PWR by using tanks at atmospheric pressure. In its turn, the architecture of MSRE does not follow the concentric and independent barriers like PWR, meaning a leakage in fuel circuit liberates radioactivity in nuclear containment.

Using the cost model of [13], due the lack of need of fuel fabrication and breeding, use of MSR make fuel costs (including mining, conversion, enrichment, fabrication, and waste management) about half of PWR fuel costs. The underlying assumptions are that enrichment costs are equal (although MSR may be cheaper) and waste management of MSR fuel is 10 times cheaper because of breeding and reprocessing. This means authors assumed that MSR exploits economically 10 times more fissile and fertile material than PWR, which is conservative.

Table 2 presents a rough order of size comparison between PWR and MSR weight, volume and overnight costs.

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Table 2 – Weight, volume, and overnight cost comparison

PWR systems	MSR systems	Weight	Volume	Cost
Reactivity control (rods)	Reactivity control (rods)	Smaller (10 times less)	Smaller (10 times less)	Smaller (10 times less)
Reactor core	Fuel circuit	Greater (about 3 times greater)	Similar volume	Same
Reactor coolant	Primary circuit Secondary circuit	Smaller (10 times less)	About 3 times smaller	About 3 times smaller
Reactor pressure vessel	Primary Tank	Less than ten times smaller (no pressure)	Similar volume	Less than ten times smaller (no pressure)
Coolant pumps	Primary salt pump	Similar weight	Similar volume	Greater (pump for high temperatures)
Pressurizer	*Not applicable*	Not applicable	Not applicable	Not applicable
Steam generator	Steam generator	Similar weight	Similar volume	Same cost
Boron injection	*Not applicable*	Not applicable	Not applicable	Not applicable
Residual heat removal	Passive heat removal	Less than ten times smaller (no pressure, no pumps)	Similar volume	Smaller (10 times less, no pumps)
Auxiliary feedwater	Passive secondary heat removal	Less than ten times smaller (no pressure, no pumps)	Similar volume	Smaller (10 times less, no pumps)
Reactor coolant purification	Salt degassing	Less than ten times smaller (no pressure, no pumps)	Similar volume	Smaller (10 times less, no pumps)
Radiological shielding	Radiological shielding	Similar weight	Similar volume	Similar cost
Reactor protection	Reactor protection	Smaller weight (less process variables)	Smaller volume (less cabinets)	Smaller cost (simpler process)
Reactor control	Reactor control	Smaller weight (less process variables)	Smaller volume (less cabinets)	Smaller cost (simpler process)
Radioactive waste	Radioactive waste	Similar weight	Similar volume	Greater cost because tritium production is larger
Overall installation		About 60% of PWR	About 80% of PWR	About 30% of PWR

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4. DISCUSSION

As this work had not a detailed architecture for both MSR and PWR for mobile nuclear power plants (MNPP), authors worked with size orders, meaning that there is imprecision in figures of Table 2 results. However, physics are immutable, and these results should not change over time and technological advances may give minor changes, but the overall order of size should remain.

Such analysis uses physical concepts known by the authors, which means there may be phenomena that are still unknown and may prevent or at least make MSR more expensive than expected. However, given the knowledge gained with the MSRE, including the long-term storage of fuel and waste, the risks are small, and construction of a floating prototype can check the feasibility.

Energy and transport are permanent needs and any gain on costs have a large potential for society, as cheaper transport may enable new businesses and wealth generation. Although it is uncertain if a given technology will be successful, one thing is certain: countries procrastinating on development of innovative technologies are going to lag. The same reasoning applies to policy: countries adopting uneven policies, privileging one type of energy over another are going to lag behind those adopting a single health and safety policy as United Kingdom [14].

Nuclear power plants may have long lives, requiring planning to perfect life cycle costs and, considering policy controls economic activity, policy must be stable to allow nuclear development. If a MNPP may last 60 years, policy should not change in an equal or longer period, otherwise, financial risks to utilities are too high.

In conclusion, MSR is only a technical solution to make Nuclear Power Plants cheaper and do not change the fact that nuclear power needs to take advantage of scale economy to be competitive. Indeed, it may reduce the minimal effective power to be competitive. Thus, if a PWR based MNPP needs to supply at least 50MW to be competitive, an MSR based one could compete at 15MW and above range. This way, container ships above 2000 TEU (Twenty-foot Equivalent Unit) could adopt this type of propulsion, which means a market of about 2927 ships in 2017 [15].

Currently, without a detailed architecture, it is impossible to make a probabilistic safety analysis on MSR, therefore authors only did qualitative analysis on MSR safety. Even if MSRE architecture does not follow concentric barriers requirement, the lack of high-pressure vessels eases the adoption of cheap risk management measures.

A preliminary analysis showed the fuel costs could reduce by half making conservative assumptions (same enrichment costs and 10% of waste management costs). A better cost estimate would need a complete fuel cycle definition and to take thorium ore and processing costs into account. However, fuel is not as dominant in lifecycle costs as the capital costs, so in terms of competitivity against other power sources, there is little to gain on fuel cycle optimization.

5. CONCLUSIONS

Because of the low operating pressure, both weight and costs of MSR should be smaller than PWR. Costs reduce more than weight because MSR uses far less nuclear safety material. Radiological shielding should be similar for both technologies and, being the main weight driver, makes MSR almost as heavy as PWR.

Due the liquid nature of nuclear fuel, MSR may be safer and simpler and improve waste generation, except for tritium. MSBR can be cheaper and lighter than a PWR, taking into

consideration an equivalent thermal power, that type of reactor, using the ^{233}U-thorium cycle, is potential candidate to be used in ship propulsion. It also can overcome a future shortage of uranium, produce low amounts of high-activity nuclear waste (approximately 3%) and have a lower risk of proliferation of weapons.
In a rough estimation, authors concluded that MSR overnight costs could be about 30% of PWR, allowing nuclear power to be competitive even for container ships of 2000 TEU or larger. However, such economic advantages depend on fair policy to have effect, as nuclear power is always depending on scale economy and long lives to achieve competitiveness.

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