POTENTIAL ADVANTAGES OF MOLTEN SALT REACTOR FOR MERCHANT SHIP PROPULSION

Luiz Gonzaga de Freitas Neto, Luciano Ondir Freire, Adimir dos Santos and Delvonei Alves de Andrade

VI ENIN

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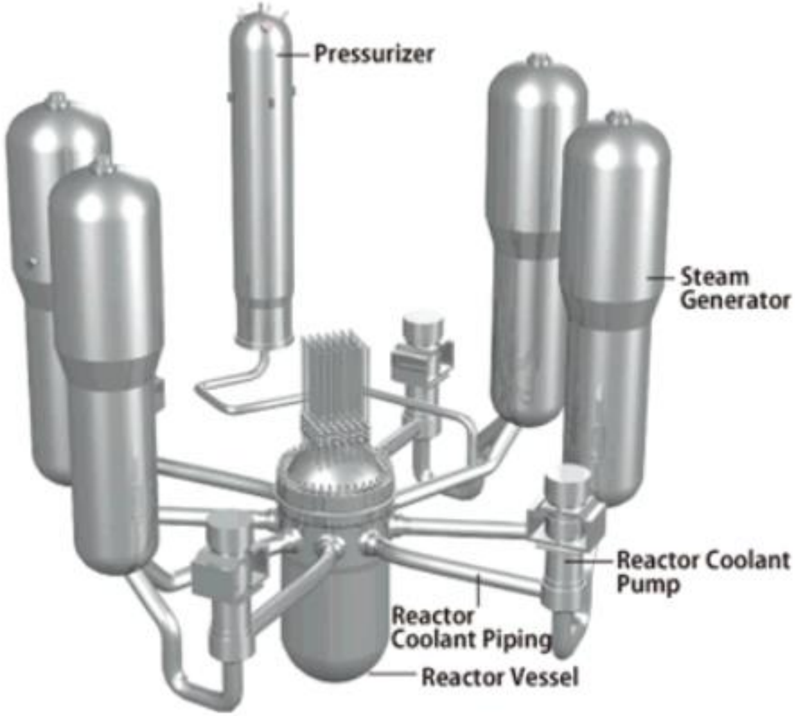
1. INTRODUCTION

- This work aims at comparing MSR with PWR for merchant ship propulsion
- The major part of operating costs of merchant ships is related to fuel
  - Rising fuel costs because of rising oil prices;
  - Environmental regulations introduced to mitigate the effects of climate change; and
  - Potential introduction of carbon taxes
- A possibility is to employ nuclear reactors like the Russian KLT-40S (PWR)
- Space and weight are critical factors in a nuclear propulsion project
- Since 1954, approximately 700 nuclear reactors have been developed for applications at sea and today around 200 reactors provide propulsion to ships and submarines
- Nuclear power may be competitive for merchant ships propulsion, for large container ships with shaft power in range of 60 to 80MW
- PWR reactors use enriched uranium
- MSR may breed fissile isotopes from ^{238}U or thorium, increasing fuel availability

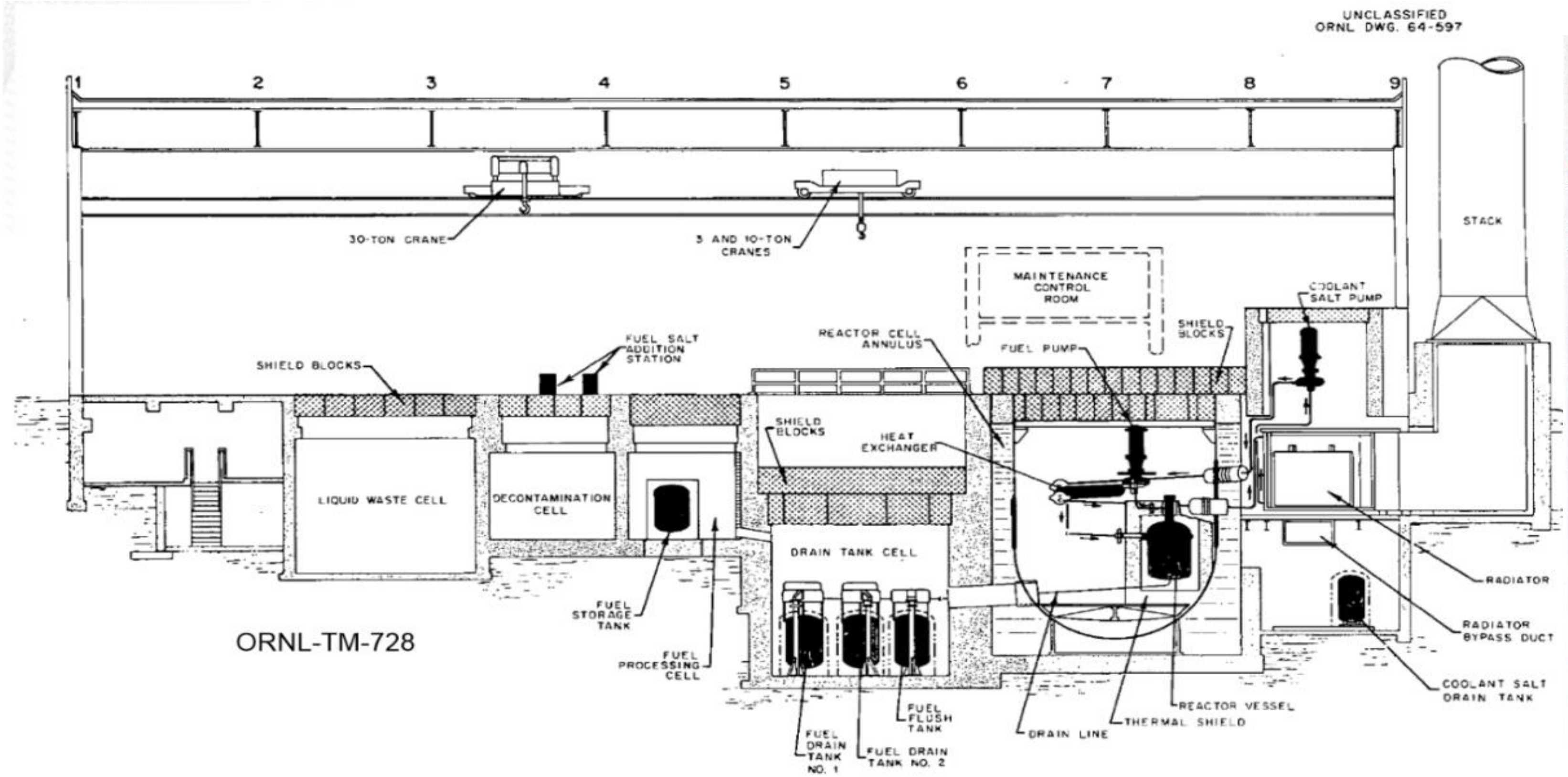
1. INTRODUCTION

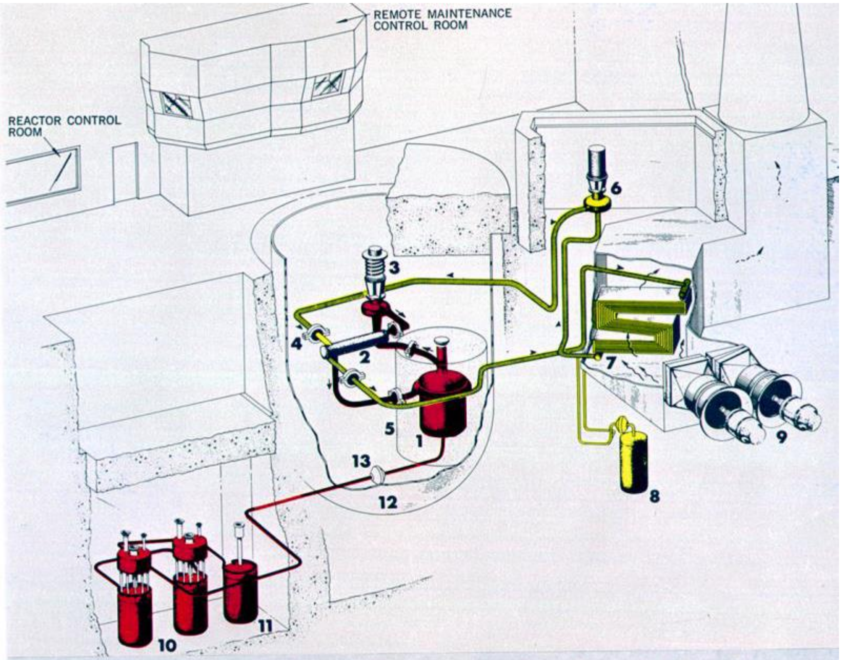
- The reactor coolant system of the PWR consists of:
  - reactor vessel;
  - steam generators;
  - reactor coolant pumps;
  - pressurizer;
  - reactor cooling system;
  - reactor internals;
  - core; and
  - fuel.



1. INTRODUCTION

- the research into the MSR started at Oak Ridge National Laboratory (ORNL) in the 1950’s with the Aircraft Reactor Experiment (ARE)
- After, in 1960’s, they made the MSRE (5 years of operation, 8 MW)

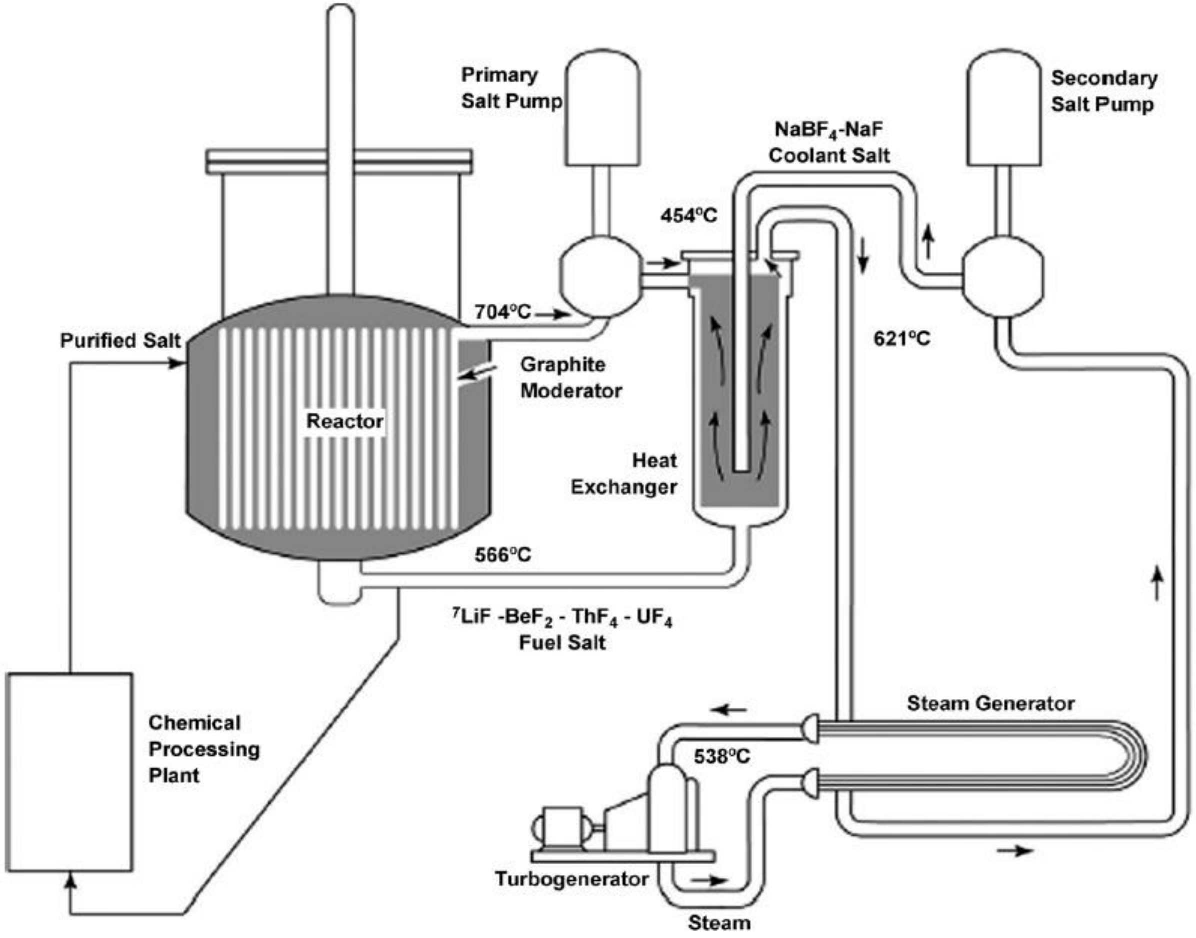




1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

1. INTRODUCTION

- ORNL studied (from 1964 to 1964) the use of two fluid (separate blanket and fuel), but returned to single fluid (simplify design)
- Based on the successful MSRE, ORNL proposed the single fluid Molten Salt Breeder Reactor (MSBR)
- Electricity is produced from supercritical steam with an overall efficiency of 44%



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2. METHOD

- This work compares the architecture and operational conditions of these two types of reactors, PWR and MSR
- This work adopted the following steps:
  - Find the main systems in current PWR architecture;
  - Check if MSR architecture has 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 PWR system;
  - Compare the life cycle costs, weight, and volume (MSR and PWR); and
  - Assess if MSR may compete with diesel engines.

3. DEVELOPMENT AND RESULTS

PWR system	MSR system	Comment
Reactivity control (rods)	Reactivity control (fl ow rate of the prim ary pump and rod)	Whilst reactivity control in a PWR is performed by the insertion or withdrawing of control rod s, in an MSR, the reactivity control is done from the variation of the flow rate of the fuel pum p. The higher the flow rate, the higher the reactivity and vice versa. For MSR, control rods fun ction as redundant and diverse control system to assure shutdown. As MSR net core excess re activity 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 moder ator 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 requiremen ts.
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 f luid is a molten salt.
Boron injection	Not applicable	Boron concentration in coolant and control rods are two diverse and redundant reactivity con trol systems in PWRs. MSRs use coolant and fuel pump speed and control rods to control reac tivity.

3. DEVELOPMENT AND RESULTS

PWR system	MSR system	Comment
Residual heat removal	Passive heat removal	After shutdown the reactor core of a PWR must the cooled. In an MSR, the fluid is transferred to another tank.
Auxiliary feedwater	Passive secondary heat removal	Secondary circuit needs residual heat removal as a redundancy.
Reactor coolant purification	Salt degassing	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.
Radiological shielding	Radiological shielding	Installed around the containment, both have the function to avoid elevated level of radiation outside the reactor.
Reactor protection	Reactor protection	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.
Reactor control	Reactor control	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.
Radioactive waste	Radioactive waste	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.
Nuclear fuel (rods)	Nuclear fuel (viscose fluid; coolant and nuclear material)	PWR: 3%-5% of enriched uranium (^{235}U) MSBR: Mol composition of fuel ^{7}LiF **(73%),** BeF_2 (16%), ThF_4 (10,7%), $^{233}UF_4$ (0,3%)

3. DEVELOPMENT AND RESULTS

- The most important MSR safety performances come from the following factors :
  - The primary and secondary systems have pressure lower than 5 bar
  - The fuel and coolant salts are chemically inert
  - The boiling point of fuel salt is about 1670 K or more, much higher than the operatio n temperature 973 K
  - The fuel salt will be able to become just critical when it coexists with the moderator
  - MSR has a large prompt negative temperature coefficient of fuel salt
  - The excess reactivity and required control rod reactivity are small
  - Gaseous fission products (such as Kr, Xe and T) inventory is small (continuous remoti on)
- Regarding the MSR lifetime, it can operate for about 30 years (per original design; modern design would be a minimum of 40 years)

3. DEVELOPMENT AND RESULTS

- Costs, weight and volume of control rods for MSR should be one order of size smaller than for PWR
- MSR core should be heavier and bigger. The core costs should be about the same as PWR
- The reactor coolant pressure barrier (part of reactor coolant system) for MSR should be one or two ord ers of size lighter than PWR. Volume should be similar. MSR reactor coolant system should be one or tw o orders of size cheaper than the equivalent on PWR.
- MSR should spend more money on purification system than PWR
- MSR control and protection systems should be cheaper because MSR process is simpler and risks are s maller.
- Waste treatment should be more expensive because the tritium production is two orders of size larger on MSR
- MSR may produce lower amounts of high-activity nuclear tailings and, if it adopts the ^{233}U-thorium cycl e, it may have lower risks of proliferating nuclear weapons
- MSR avoids the design basis accidents of PWR by using tanks at atmospheric pressure
- MSR fuel costs are about half of PWR fuel costs
    - enrichment costs are equal (although MSR may be cheaper)
    - waste management of MSR fuel is 10 times cheaper (conservative)
    - including mining, conversion, enrichment, fabrication, and waste management

3. DEVELOPMENT AND RESULTS

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)

3. DEVELOPMENT AND RESULTS

PWR systems	MSR systems	Weight	Volume	Cost
Auxiliary feedwater	Passive secondary heat re moval	Less than ten times smaller (no pressure, no pumps)	Similar volume	Smaller (10 times less, no pumps)
Reactor coolant purificatio n	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 proces s variables)	Smaller volume (less c abinets)	Smaller cost (simpler p rocess)
Reactor control	Reactor control	Smaller weight (less proces s variables)	Smaller volume (less c abinets)	Smaller cost (simpler p rocess)
Radioactive waste	Radioactive waste	Similar weight	Similar volume	Greater cost because t ritium production is lar ger
Overall installation		About 60% of PWR	About 80% of PWR	About 30% of PWR

3. DEVELOPMENT AND RESULTS

- Nuclear power needs scale economy to be competitive
- It seems Mobile Nuclear Power Plants (MNPP) need to supply at least 50MWe to compete with diesel generators
  - Russian nuclear barge produces 70MWe
  - Chinese ACPR50S project means to produce 50MWe
- 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

4. DISCUSSION

- Authors worked with size orders, meaning that there is imprecision in figures
- Physics are immutable: 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
- It is uncertain if a given technology will be successful, it is sure countries procrastinating on development of innovative technologies are going to lag
- Policy must be stable to allow nuclear development
- MSR does 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
- The lack of high-pressure vessels eases the adoption of cheap risk management measures
- A better fuel cost estimate would need a complete fuel cycle definition and to take thorium ore and processing costs into account
- 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
- 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 233U-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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