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A Comprehensive Review of Molten Salt Reactors and Related Technological Innovations over the Years

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Abstract: This paper intends to describe the concept of molten-salt reactor (MSR) briefly and explain the major technological innovations for it between the 1960s and 2000s. The origin of the molten salt reactor concept and how its potential for commercial electricity generation was recognised by the results of aircraft reactor program. The objective of the MSR experiment was to show the practicality of high-temperature fluid fuel concept based on information regarding the compatibility of materials and calculated costs of the fuel cycle.This paper also briefly explains the reactors that include the fuel composition, moderators, diagram structures, cost, efficiency, cost and layout. It also evaluates the safety hazards resolved in advanced molten state reactors a result of improvements in technology. Along with that, the major technological innovations in Trans-atomics Power's (TAP) advanced MSR followed by design pathways selected in place of a thorium-fuelled reactor area also reviewed. Finally, a comparative analysis proving that MSRs used by TAP proves to be more advanced to other light water reactors (LWR) by considerably reducing wastage.
Keywords: Thorium Fuelled Reactor, Molten-Salt Reactor (MSR), Trans-atomics Power's (TAP), Zirconium Hydride Moderator (ZHM) & Uranium Fuel.

I. INTRODUCTION

MSRs have been in presence since the 1960s, however, it is as yet not used to its maximum capacity and the research with respect to the enormous scope of utilization of these reactors has been constrained. Yet, since the 1960s there has been a ton of progress to make the reactor protected, dependable, and maintainable. MSRs have numerous safety benefits over customary LWRs and other conventional reactors, for example, the low-pressure piping, negative void, passive shutdown capacity, and chemically stable coolant. Most of the early work on these plans focused on part lifetime, explicitly, making composites prepared to keep up their mechanical and material honesty in corrosive radioactive salts. Notwithstanding this development, the world remained focused on LWRs or Heavy Water Reactors (HWR) for business use, basically as a result of wide past working involvement in maritime water-cooled reactors and early conventional reactors [1]. The advanced structures have incredibly improved molten salt idea while fundamentally holding its safety advantages. In Molten Salt Reactor Experiment (MSRE) the fuel in the salt is principally uranium. Cutting edge reactors utilize low-enriched uranium (LEU) at the industrially accessible fuel enrichment of 5% which is far lower than other reactor structures. Past MSRs, for example, the Oak Ridge National Laboratory (ORNL) depended on high-enriched uranium fuel, that was enriched up to 93% U-235 [2]. Enrichments of that extent would raise proliferation risk if implemented in current commercial nuclear power plants.

A. Diagram Structure

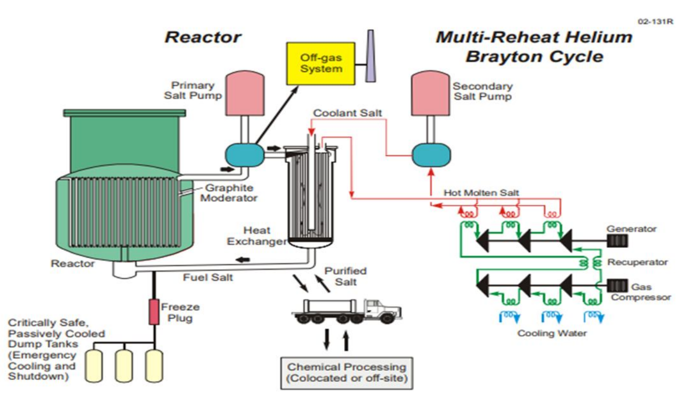

Figure 1: Molten Salt Reactor Experiment, Oak Ridge National Laboratory (1960) [3]

Figure 1 shows the schematic layout of the MSRE. It hosts a smaller core-reactor to have the most neutron leakage along with no cover of fertile material. The fuel salt was explicitly made without thorium as the reactor was designed to be a 2-liquid breeder. The MSRE had the typical working conditions at 8 MW, the most extreme limit at which the air-cooled secondary heat exchanger can work. The structure lodging the reactor is the one where the Aircraft Reactor Experiment was carried out in 1954. The cylindrical-shaped reactor cell was added to the Aircraft Reactor Test (later decommissioned) and was later adjusted for MSRE utilization.
The core is made up of graphite bars with fuel exposition. The control rods are versatile, including an empty cylindrical chamber of Gd2Os-Al2Os clay, canned inside Inconel and hung on a tempered steel hose which fills additionally in as a cooling-air channel. The rods are lifted and brought down at the same time. A filtration bed having pipes with charcoal is lowered in a water-filled tank. Every salt vessel is electrically warmed with the goal of having the salt in a molten state, even if no nuclear energy is created. The reactor vessel furnace is covered with thick radiator shield made of hardened steel and steel balls and water for cooling. The shield assimilates the greater part of the energy of neutrons and gammas getting away from the reactor vessel. All the parts in the reactor and drain tank cells are planned and spread out in such a manner that they can be expelled by the utilization of tools with long handles from above. Also, in the structure, near the channel tank cell, there is a quite simple facility for preparing the fuel for flush salt [4]. As shown in Figure 2.

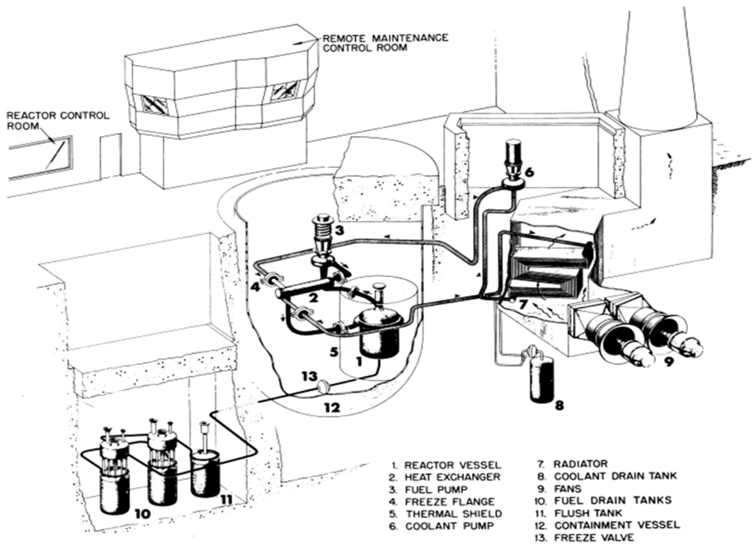

Figure 2: Layout of MSRE [4]

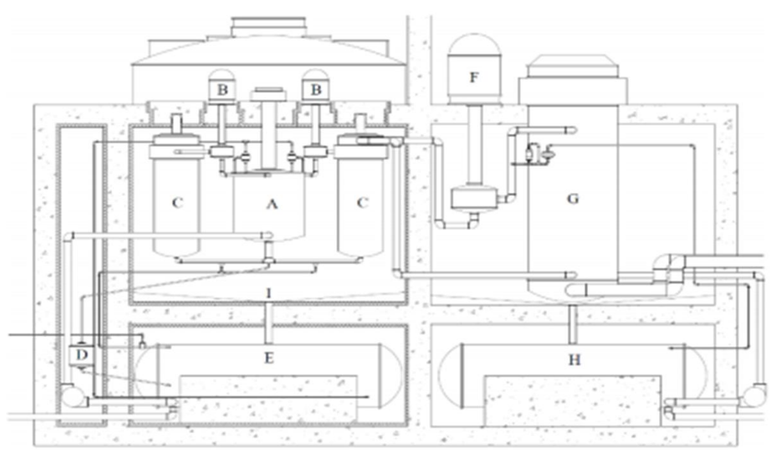

Figure 3: TAP's Design for Advanced Molten Salt Reactors [1]: A) Reactor Vessel, B) Fuel Salt Pumps, C) Primary Heat Exchanger, D) Freeze Valve, E) Primary Loop Drain Tank, F) Intermediate Loop Salt Pump G) Steam Generator, H) Intermediate Loop Drain Tank, and I) Fuel Catch Basin.

Figure 3 shows a reactor's main loop that consists of the reactor vessel, main heat exchanger, pumps, and moderators. Pump's objective is to pump the salt fuel throughout the loop. The heat produced during this step in the primary stage is moved to employ heat exchangers into a transitional loop containing liquid salt. This loop further transfers the heat to the steam generators, including an additional layer of security against radioactive discharge. The heat is then utilized by generators to make steam by boiling water, which is then transferred into a building that has the turbine.

B. Different Reactor Fuels

Commercial nuclear power plants utilize pellets of solid uranium oxide covered by metal cladding (behaves like a barrier and provides shielding) as fuel. The above-described form of plant utilizes liquid fuel instead, that is uranium dissolved inside a molten fluoride salt. The salt goes about as both fuel and coolant, leading to high thermal efficiency instead [1].

C. Higher Outlet Temperatures

As shown in figure 4, the utilization of liquid fuels permits considerably better heat transfer which in-turn leads to more reactor outlet temperatures leading to increased thermal efficiency.

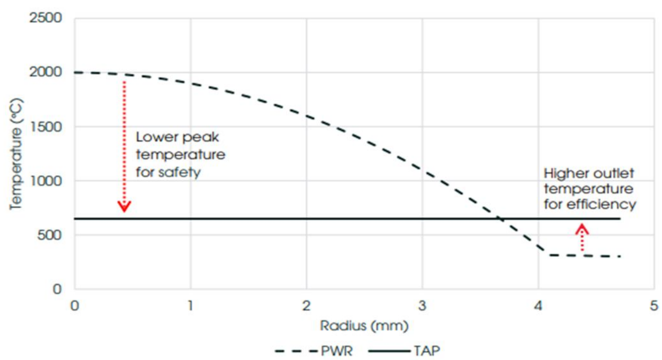

Figure 4: Temperature Profile of LWR Solid Fuel Pin, from Centre to Edge, Compared to the Temperature Profile of a TAP MSR Fuel-Salt [1]

D. Zirconium Hydride Moderator:

A characterizing contrast in this specific reactor and other MSR is its utilization of zirconium hydride moderator rather than a normal graphite moderator. The graphite moderator therapists and swells after some time because of irradiation, these dimensional changes decrease mechanical integrity [2]. This leads to the requirement of substitution of the moderator at regular intervals.

The Zirconium Hydride Moderator rods show noticeable changes under irradiation [5]. Namely considerably high resistance against radiation damage and possessing a lower degree of neutron absorption

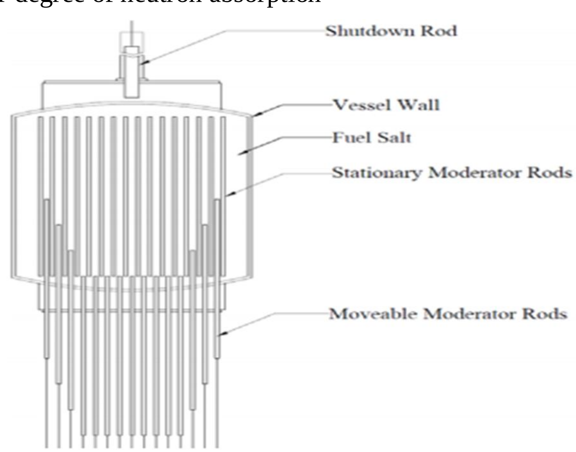

Figure 5: Moderator Design [1]

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II. SAFETY MEASURES

Generally, Nuclear power plants suffer from two major issues: the production of radioactive nuclear waste and the vulnerability to cause nuclear disasters like nuclear meltdowns. The reason for Nuclear meltdowns is that the water utilized for cooling the radioactive rods bars can't be siphoned in, for the most part, because of failure of backup power. This heats the fuel very quickly and leads to explosions.

Be that as it may, safety isn't just about halting calamities. The fuel itself is harmful and needs to be stored underground for a large span of time. Such solid fuels can just remain in the reactor for a constrained measure of time before they begin to breakdown and requires to be physically expelled. We can just use about 4% of the net possible energy that could be possibly extracted from uranium and the rest is deserted as waste.

The crucial safety and authorized issues are one of the most significant components to be thought of while contrasting power plants. MSRs are nuclear fission reactors of Generation IV with conceivably predominant safety measures. The central point considered are neutrons, Source Term, and Decay Heat Removal. MSRs have an alternate Decay Heat Approach as they dump fuel salt to tanks. Also, the actinides and products of fission in the solution assume a key job in the security of the reactor.

Low pressure (boiling pint of molten salt is about 1400^{o}C), Low accident source, Low chemical reactivity, with passive cooling and nonstop evacuation of fission products by dumping fuel into cooled tanks which incorporates facilities for emergency cooling and emergency shutdown has prompted an exponential increment in safety. Decreased radionuclide source, the restricted release of radionuclides because of low iodine and caesium discharge potential under reactor conditions have contributed colossally to the expanding overall safety over the recent decades.

Regardless of having little accident sources in the reactor, there has been an ascent in the likelihood of an accident because of the Off-Gas system, explicitly the security issues of spent atomic fuel (SNF) handling plants. It was presumed that while the reactor can accomplish criticality on SNF fuel load and SNF fuel feed, it can't keep up criticality for adequate periods to deliver a practical net-negative waste profile.

Trans-atomic's reactor configuration will utilize the fuel in a fluid form with the goal that it can remain in the reactor for a more extended timeframe straightforwardly leaving altogether less waste. Utilization of fuel pebble rather than traditional uranium rods has been assimilated. This new structure incorporates uranium in a golf-sized sphere. It's made of an extremely solid ceramic material that can withstand a lot higher temperatures, so it can't dissolve and is more secure to utilize. The points coming up next are the main reason for the better safety of Trans-atomic's MSR [1].

A. Self-Stabilizing Core:

Similar to LWRs, MSRs also have a strong negative temperature coefficient and void. These negative coefficients incredibly help reactor control and go about as solid support against temperature excursion. The salt expands simultaneously with the rise of core temperature. At the point when the salt expands the thickness of the fissile material is diminished, reducing the fission rate without intervention by the operator. Furthermore, neutron capturing cross-section area of U-238 additionally increments with temperature because of the Doppler Effect.

B. Radio Nuclide's Smaller Inventory:

The fissile material required is less for the reactors, as TAP's design generates more thermal efficiency. The reduction of lanthanides, noble gases and noble metals reduces the maximum size of possible discharge

C. Reduced Driving Force:

The need for fuel salt to be held under high pressure does not exist due to its chemical properties. Furthermore, to ensure against upstream pressure transients rupture disk technology is utilized. Thus, there is no prerequisite of a huge driving force. The TAP's MSR is further developed than LWRs in light of the fact that it is walkways safe and can latently cool its depleted core employing cooling stacks associated with its auxiliary tank. If the freeze valve fails, an electromagnetic fail-safe or an operator inserts a shutdown rod, preventing an explosion. On the off chance that these measures can't be utilized the salt temperature increments. The salt then expands due to this excessive heat. In case the temperature continues increasing melting of zirconium hydride moderator takes place (Releasing not sufficient enough amount of hydrogen to create an explosion. The absence of adequate neutron moderation due to decreased moderator area carries the reactor to a sub-critical state. Shown in figure 6 are the key temperatures for an LWR and a TAP's MSR.

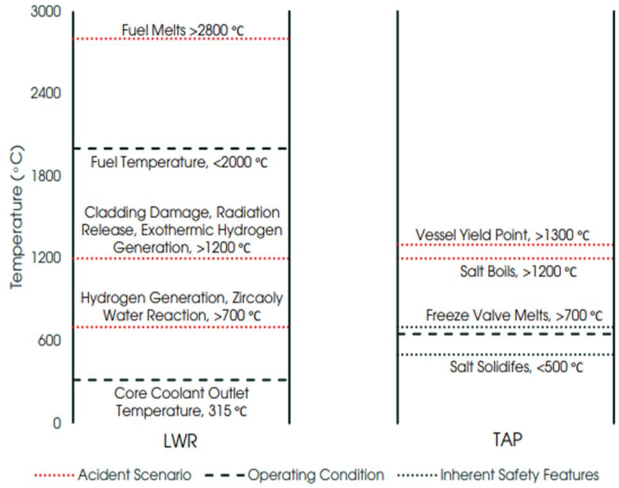

Figure 6: Key Temperatures for an LWR and a TAP MSR [1]

III. THORIUM AS FUEL

Thorium fuel cycle possesses theoretical advantages in the long run over uranium but we still use uranium due to several constraints. Safety is one of the major concerns as thorium reactors also contain plutonium; leading to possible proliferation vulnerabilities as a result of the protactinium present in their fuel salt. Protactinium has a high neutron capturing cross-section area and, as such, in most liquid thorium reactor plans, it must be removed periodically from the reactor. This process yields commonly unadulterated protactinium, which by then decays into U-233. By plan, the unadulterated U-233 is sent over into the reactor where it is marked as its primary fuel. The drawback, in any case, is that U-233 is a weapons-grade isotope that triggers much easily as compared to plutonium [1].

The second concern is the possibility of chemical reprocessing as certain procedures are too hard to be in any way actualized. This can have a few causes: “the processes considered are not well understood or mastered, the flow of materials to be processed is too large, the reprocessing implies direct coupling to the reactor core " [6].

It is essential to keep up the reactor’s breeding ratio equivalent to 1 for fuel regeneration to be consistent. “The breeding ratio expresses the balance between the creation of ^{233}U through neutron capture on ^{232}Th and the destruction of ^{233}U through fission or neutron capture”. The more fissile matter is fed continuously to reactor core if the breeding ratio comes less than 1. In case it gets higher than 1, the reactor core gets damaged by the excessive fissile matter. Therefore, it is necessary to maintain the ratio or else extra money is required in both extremes. [6]

Materials life expectancy is another issue. This is in regard to how the graphite responds to irradiation. Past a specific level of harm, it turns into the seat of swelling. Thus, the core graphite is not replaced too frequently [7].

Some may abstain from contemplating the risk of proliferation of the thorium fuel cycle on the grounds that the U-233 in the reactor would be blended in with U-232, making it a not so good means to proliferation purposes. In any case, it is U-232’s decay products that generate high-energy gamma radiation making it hard to deal with it. Handling the products in a reactor containing weapon-grade uranium is not possible.

IV. CONCLUSIONS

Significant improvements have been made by Transatomic Power’s design to the current plans and have utilized the fundamental technology behind the idea. The critical contrasts between the prior reactors and Tran's power reactors are expressed above and it accomplishes high actinide burn up and financially feasible design. The TAP MSR has a thermal/epithermal range unlike other industrial reactors, which decreases damage caused by neutron to the moderator and other components of the plant, considerably bringing down the expenses related with component substitution consequently leaving no requirement for continually changing the zirconium hydride moderator. This reactor is additionally safe form proliferation since thorium and the risks accompanying it are kept away. Furthermore, plant’s safety is radically improved as expressed previously. The TAP’s MSR addresses the biggest issues confronting the nuclear industry, for example, safety, proliferation, waste, and cost. This plainly shows the MSR is better than LWRs in all regards

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