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The Integral Molten Salt Reactor (IMSR)

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ABSTRACT – The Integral Molten Salt Reactor is a simple burner or converter design that seeks to maximize passive and inherent safety features in order to minimize development time and achieve true cost innovation. Its integration of all primary systems into a unit sealed for the design life of the reactor will be reviewed with focus on the unique design aspects that make this a pragmatic approach. The IMSR is being developed by Terrestrial Energy in a range of power outputs with initial focus on an 80 MWth (32.5 MWe) unit primarily for remote energy needs. Similar units of modestly larger dimension and up to 600 MWth (291 MWe) are planned that remain truck transportable and able to compete in base load electricity markets worldwide.

1. Introduction

Molten Salt Reactors (MSRs) were originally developed as potential aircraft reactors with a successful test reactor built in 1954 which ran at up to 860°C. This work led to a major breeder power reactor program from the late 1950s to mid 1970s at Oak Ridge National Laboratories, highlighted by the 8 MWth Molten Salt Reactor Experiment (MSRE) that ran from 1965 to 1969. Design work evolved to a Single Fluid, graphite moderated Molten Salt Breeder Reactor (MSBR) in competition with the sodium cooled, fast breeder reactor. Given the belief at the time of very limited uranium resources, a breeder design with as short a doubling time as possible was the ultimate goal - doubling time being that needed to breed the startup fissile of the next breeder reactor. This led to an aggressive proposed salt processing procedure, removing most fission products from the MSBR salt on a 10 day cycle giving an impressive 20 year doubling time. Ultimately though, in the mid 1970s the U.S. decided, for reasons beyond the scientific case for the MSR, to focus solely on the fast breeder option and the ORNL program was canceled.

The MSR's fundamental advantage lays in its most novel feature, that of being a liquid fueled reactor. To the uninitiated, the utilizion of a fluid fuel may appear to be a daunting task. However, molten salt provides the foundation for an enhanced safety profile for the MSR based on its low pressure operation, devoid of any chemical or mechanical driving forces and having many layers of very secure containment. As a fluid, the fuel's mobility can be used to transport decay heat either using a traditional fuse plug and drain tank, or in fact by in situ methods that rely on the liquid fuel's ability to establish natural circulation. Being able to rely upon truly passive safety features is also key to cost innovation which must be in place for any advanced nuclear system to reach commercialization. Fluid fuel also adds numerous advantages including unlimited burn-up potential, no fuel fabrication, no structural material needed within the core and no concern for local hot spots.

The re-emergence of interest in Molten Salt Reactors was affirmed when the MSR was chosen as one of six GEN IV reactor types in 2002. An objective review shows MSR's many unique attributes, leading to clear potential advantages ranging through overall costs, safety, resource sustainability and long lived waste reductions [1]. Much of this revival of interest has continued to focus on breeder options or MSR-Breeders, including revived interest in the fast spectrum approach such as the Molten Salt Fast Reactor program in Europe [2]. A fast spectrum does offer some advantages but also many unique and significant challenges leading to an expected lengthy development period. In general for MSR-Breeders, while liquid fuel does simplify processing technology, the degree of difficulty and costs are often underestimated, especially in terms of needed R&D before commercialization. Furthermore, MSR-Breeders require the use of highly enriched uranium which would call for treaty revisions worldwide. Finally, to attain breeder status, even break-even level, requires numerous sacrifices to conserve neutron losses.

2. MSR-Burner Approach

A potentially superior approach involves simplified convertor designs or MSR-Burners that forego complex on-site salt processing at the modest expense of needing a small annual makeup of low enriched uranium (LEU). This work is based on the final funded efforts of ORNL in the late 1970s on a design termed a Denatured Molten Salt Reactor (DMSR) [3] proposed to run a 30 year lifetime on a single batch of salt started on LEU and thorium but supplemented by an annual makeup of LEU. This greatly simplified plant design and also increased proliferation resistance by denaturing any ^{233}U with ^{238}U. In fact this approach has been singled out as having maximum proliferation resistance [4]. Even without salt processing, uranium utilization was determined to be excellent, roughly 1/6th that of LWR. Moreover, a single batch process after many years of use to recycle transuranic elements, in particular Pu, would give a waste profile virtually free of troublesome transuranic wastes.

Another major factor that favors the MSR-Burner approach is flexibility in carrier salt choice. MSR-Breeders are forced to utilize expensive and currently unavailable 99.995% Li-7 and/or beryllium, as a mixture often termed FLiBe. Beyond high cost, both of these produce copious amounts of tritium (roughly equal to CANDU rates). Tritium is of great concern, at least from a regulatory standpoint, as it can pass directly through the hot metallic walls of heat exchangers. Binding tritium before it could potentially reach building containment or the final working fluid such as steam is a challenging and important duty. Tritium capture techniques have been at the foundation of all MSR-Breeder work since the concept's inception. With MSR-Burners however, alternate salts that avoid tritium production are possible at the minor penalty of a fractionally larger annual uranium consumption [5]. As example, 46%NaF-33%RbF-21%UF_4 with a melting point of 470°C, which is an even lower melting point than traditional FLiBe fuel salt but with somewhat inferior heat transfer properties.

Many of the advantages of MSRs come from the superior nature of the fluoride salts as coolants, operating at ambient pressure with very high boiling points and high volumetric heat capacity. This has led to a recent concept to use fluoride salts as coolants of TRISO solid fuels in the form of pebble beds or solid fuel blocks [6,7]. While these “salt cooled” cousins of “salt fueled” MSR-Burners do not have as strong a case on resource sustainability and long lived waste profile, many view these new options, termed FHRs (Fluoride salt cooled High temperature Reactors) as potentially a less encumbered step, in particular due to the U.S. NRC’s prescriptive focus on solid fuels. Many innovations have been made in the FHR field that may see use for liquid fuel MSRs as well.

3. Remaining Challenges of the MSR-Burner Approach

The fundamental challenge of even a simplified MSR-Burner approach is that of materials lifetime. Any proposed facility needs, at minimum, a 30 year design life and assuring this full lifetime out of primary reactor components and/or the ability to service or replace is a daunting task. While a fluid fuel can be drained to storage tanks during maintenance outages, there will inevitably remain residual fission products associated with any component in contact with the fuel salt. The three main areas of concern are the reactor vessel itself, the primary heat exchangers and graphite moderator if employed.

Reactor vessel walls are subject to potential neutron induced helium embrittlement by both thermal and fast neutron flux as well as potential corrosion mechanisms particularly due to fission products such as tellurium. Extensive salt loop and the in-service experience of the MSRE gained in the 1960 and 1970s, clarified corrosion issues and mechanisms. Modified Hastelloy N, the commonly proposed wall material, would be expected to perform very well in terms of corrosion and there are numerous, somewhat less well substantiated alternatives including some common stainless steels. The issue of potential neutron damage is greatly aided by a graphite moderated approach as this allows for methods to substantialy reduce neutron flux reaching the outer vessel. This is achieved through a method termed an under-moderated outer zone where a higher salt to graphite ratio gives a localized harder spectrum and encourages fertile absorptions over fissile. This effectively curtails neutron leakage out of the core and limits flux at the vessel wall. In general, it can be said that assuring multiple decades of use is likely an achievable goal but one that would require far more experimental verification and would add to the regulatory challenge.

Heat exchangers (HX) could employ a similar material as the reactor vessel, but in this case a 30+ year lifetime without service or replacement is unlikely. In traditional ORNL MSR development, the concept has been to put the utmost care into HX tube in shell fabrication as it was deemed impractical to undertake repair operations. This is due to the inevitable build up of noble metal fission products on metal surfaces. ORNL design thus called for multiple (typically 4) independent external primary heat exchangers. If any fault was discovered during operation, salts could be drained from the HX, the shell opened and the entire tube bundle removed and replaced with a new one. Only after many years would the bundle possibly be repaired for reuse. This replacement operation would be very challenging from a regulatory perspective due to the possibility of a release of fission products upon opening the HX shell and tube bundle transport. Furthermore, it had been a concern of ORNL that if the HX was drained shortly after shutdown for whatever reason, noble metal fission product heat generation in the now dry HX could be damaging.

Of greatest importance in regard to reactor material lifetime is the graphite moderator. The use of graphite imparts many advantages in MSR design but its usable lifetime is directly related to the power density employed. This is due to fast neutrons causing vacancies and interstitials that cause graphite to at first shrink modestly but then to expand, eventually beyond its original dimension, leading to physical cracking. In most non-MSR graphite reactor use, for example Magnox or AGR, power density is limited by the thermal hydraulic limitations of removing heat from the solid fuels, so as a consequence, very large dimension cores are common. While this lower power density (and low fast flux) is detrimental in an economic sense, it does allow many decades of use of the graphite. In the MSR case, there are no such thermal hydraulic limitations and it is very advantageous to attain higher power densities. Thus a simple choice has long faced developers. That choice is to to design with low power density to achieve a full plant lifetime out of graphite (the "Sealed" approach) or, alternatively, to employ a far more compact, high power density core but to provide provisions for graphite replacement (the "Swap" approach).

All ORNL work on MSBR designs in the 1960s and early 1970s assumed the swap-out route with a power density, giving a typical graphite lifetime of 4 years.. The proposed replacement operations were, however, a massive undertaking and would be considered perhaps even more daunting today. Any opening of the reactor vessel risks some level of volatile fission product release even though fuel salts would of course be drained well in advance. The bigger challenge is that the graphite to be moved would be substantially radioactive (both by activation and some fission product deposition primarily from Xenon and Krypton precursors). In the traditional MSBR Single Fluid 1970s design, it was planned that the core would be moved as a unit, employing a 250 tonne hoist and a two inch thick steel shielding cask to encase the core and upper vessel head during transit to a nearby storage cell. As the reactor could not be out of service for a long duration, these operations would be only 10 days after shutdown and would require the building to have a 90 cm thick domed concrete shell simply as shielding to assure radiation exposure outside the building did not exceed regulations during the brief transit.

The great challenges of graphite replacement or swap-out led many later MSR proposals to choose the sealed approach and employ a low power density. Examples of these include the 1978-1980 DMSR designs of ORNL and later FUJI [8] work from Japan on a similar but non-denatured Th-^{233}U burner. In the DMSR design, the 1000 MWe unit would have required a graphite core of 8.6 m by 8.6 m within a roughly 10 m by 10 m reactor vessel. As well, capacity factors of the period were expected to be lower (75%) and as such the DMSR's 30 year lifetime was only 22.5 full power years. A modern version would likely need to raise this lifetime by going to even lower power density. Although this sealed approach solves the enormous challenges of graphite replacement while keeping the great advantages of graphite, it does sacrifice significantly in terms of potential cost innovation.

4. The IMSR: A New Design Philosophy

The concerns listed above for a practical graphite MSR burner have been addressed through a simple but major change in basic reactor design. The basic design philosophy of the Integral Molten Salt Reactor (IMSR) is to maximize the simplicity and advantages of the graphite-moderated MSR-Burner approach, while also offering a novel solution to the material lifetime challenges of graphite, vessel and heat exchangers. This patent pending solution [9], is the integration of all components with lifetime challenges into a permanently sealed core-unit and, central to the concept, to design for periodic replacement of the core-unit itself in order to allow far higher and more economically viable power densities. With replaceable core-units and the ability to refurbish other components such as steam generators or turbines, a many decades long plant lifetime is possible. The overall advantages including the easing of regulatory compliance, minimizing of R&D and providing operational lifetime confidence are most significant in this 'Sealed *and* Swapped' approach.

The IMSR, while taking much from the DMSR, also owes much of its design philosophy to the more recent work on fluoride-salt cooled, high temperature reactors (FHR), specifically the SmAHTR. In the 2010 SmAHTR 125 MWth ORNL design [7], heat exchangers, both primary and those for passive decay heat removal, are integrated into a modestly sized reactor vessel. This salt cooled design is limited on power density related to thermal hydraulic and solid fuel burn issues to allow a 4.2 year core life between full fuel core replacements. Heat exchangers employ a 2 of 3 philosophy such that if a fault develops, the unit can continue its 4.2 year fuel cycle while running on the remaining two heat exchangers, which can later be swapped out during fuel core swap out.

The IMSR, like the SmAHTR, will have multiple, independent heat exchangers that can be isolated and taken out of service if a fault occurs within the operational lifetime of the core-unit, with power production continued in its absence with the remaining heat exchangers. As a default, the IMSR plan calls for six independent primary heat exchangers, each with its own dedicated pump and inlet and outlet secondary coolant lines. The IMSR is designed with a high power density - chosen to give an upper limit approaching 10 years of graphite lifetime, which however, for planning purposes will be assumed to be a more conservative 7 year unit lifetime. Optimization at the conceptual design level will determine the most pragmatic core-unit lifetime. Various aspects are shown in the basic figures below, such as the use of in-situ decay heat removal through the vessel wall aided by a surrounding buffer salt.

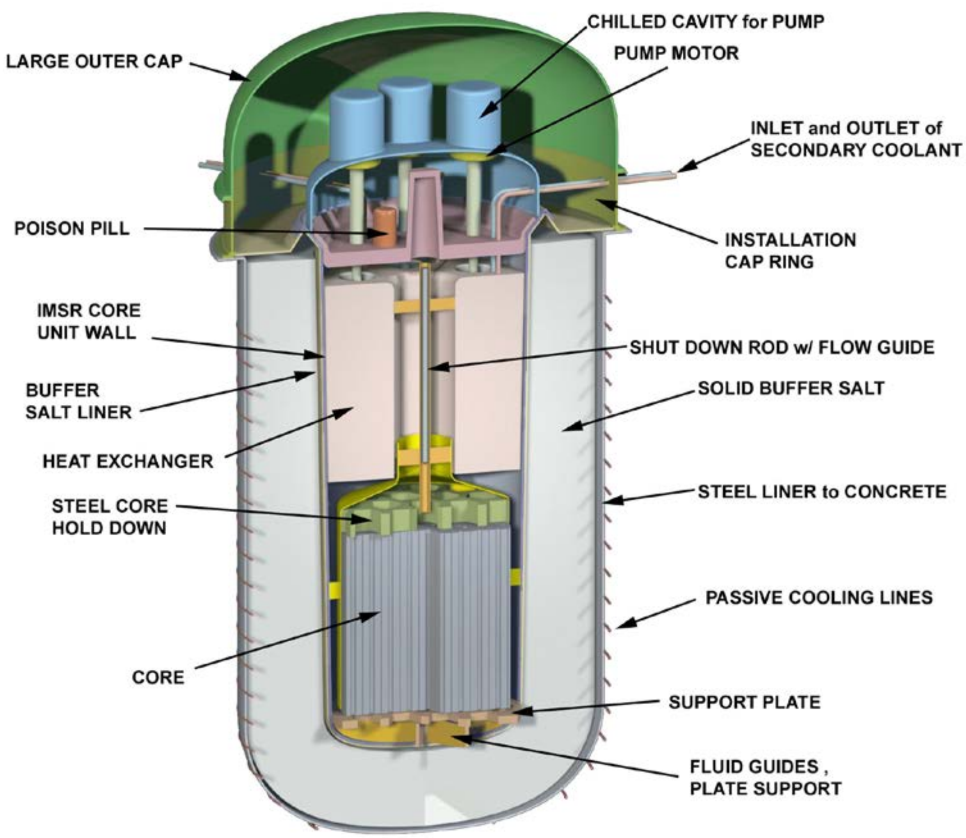

Figure 1 The IMSR Core-unit nested within a buffer salt liner

	INTEGRAL MOLTEN SALT REACTOR
Thermal Capacity	Three sizes: • IMSR80: 80 MWth • IMSR300: 300 MWth • IMSR600: 600 MWth
Electrical Capacity	Three sizes: • IMSR80: 32.5 MWe • IMSR300: 141 MWe • IMSR600: 291 MWe
Primary Fuel/Coolant Salt	Liquid Fluoride Fuel Salt such as LiF-BeF_2-UF_4 or NaF-RbF-UF_4
Secondary Coolant	Liquid Fluoride salt such as; NaF-BeF_2 or KF-ZrF_4
Moderator	Hexagonal Graphite Elements
Primary Circulation	Low pressure pumped
System Pressure	Near Atmospheric
Core Outlet Temperature	700 $^{\circ}$C
Thermodynamic cycle	Superheat Rankine
Cycle Efficiency	48.5% for IMSR600
Fuel Material	LEU as UF_4 Within Liquid Carrier Salt. Thorium use optional
Fuel Enrichment – Initial Loading	< 5%
Fuel Enrichment – Makeup Fuel	5% to 19.9%
Fuel Cycle	>84 months
Reactivity Control	Long Term Reactivity Changes by Periodic Liquid Makeup Fuel Additions
Shutdown Mechanism	Primary: Passive Buoyancy Driven Rod Insertion Secondary: Passive, Temperature Induced Poison Injection
Emergency Safety Systems	Passive
Residual Heat Removal Systems	Passive
Design life	Plant >50 years Sealed primary unit >7 years
Design Status	Pre-Conceptual Design Completed
Planned development	Early 2020s
Distinguishing Features	MSR-Burner system with integrated primary heat exchangers. High power density core and 7 year operating life from a sealed and replaceable low maintenance core-unit.

Table 1. General Features and Parameters of the IMSR

Following in the footsteps of the 125 MWth SmAHTR FHR design of ORNL, the IMSR is planned with a limit on its outer diameter of 3.6 meters to allow flatbed truck transport. Separate shipping of core graphite and/or heat exchanger sections may prove warranted. The first goal of Terrestrial Energy's development of the IMSR is a small IMSR80 unit of 80 MWth and 32.5 MWe, with first instalment meant as a commercial demonstration for rapid further deployment.

As the IMSR in many aspects is very similar to the proven 8 MWth MSRE design run by ORNL in the 1960s, a smaller pilot stage is not deemed warranted. The IMSR80, while significantly larger than the MSRE, will be substantially reduced in dimension from SmAHTR's 3.6 wide by 9 m high unit. Two subsequently larger versions, but still flatbed deliverable, are planned at the 300 MWth and 600 MWth size to supply larger industrial users and baseload electrical production.

In summary, the design philosophy of the IMSR is that the primary reactor vessel is sealed for its design life, currently planned for 7 years. Any heat exchanger failure is dealt with by isolating the affected HX and operation continues with the remaining heat exchangers somewhat uprated to maintain power levels. Pump failure may be handled in a similar fashion but it remains to be determined what level of pump motor and/or bearing/shaft maintenance will be planned for (pump failure is considered of higher frequency than HX failure). Once the design life of the unit is complete, it is shutdown and an identical core-unit takes over operation in an adjacent containment silo by connecting coolant lines to the new unit. The spent core-unit can remain in place for the next 7 years and at any later point, fuel salt can be removed for re-use, recycle or conversion to waste form. The drained unit will be devoid of any actinides, however both graphite and heat exchangers represent a low to intermediate level waste due to neutron activation, noble metal plate out and noble gas daughter products within a surface layer of the graphite. After this 7 year cool down period the first spent core-unit is then lifted out and transferred to long term storage, making way for the third core-unit, and the cycle continues. The IMSR core-unit thus also serves a secondary duty as a medium to long term waste sequestration vessel, without the need to unseal the core-unit for decades - if ever.

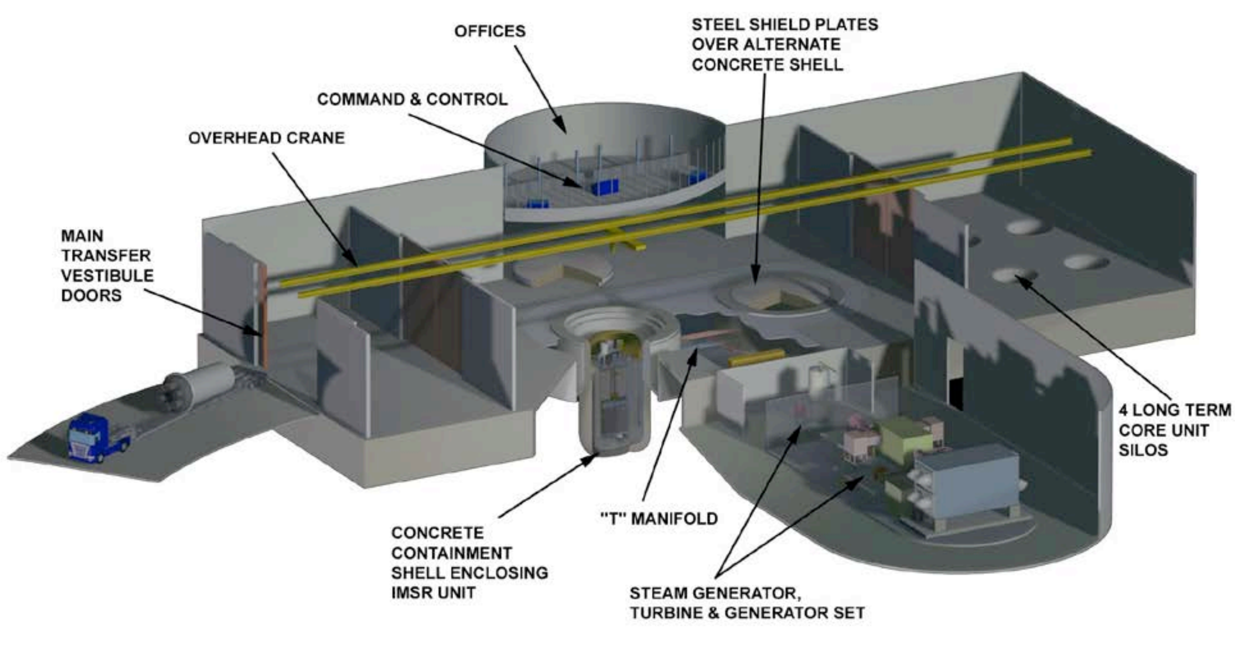

Figure 2 Generalized facility layout showing the IMSR Core-unit within its containment cavity

5. Safety Case Basics: Decay Heat, Shut Down Systems and Reactivity Coefficients

The IMSR approach also differs significantly from other major MSR efforts in terms of decay heat management, passive shutdown systems and all important temperature reactivity coefficients.

Removal of decay heat by passive means has long been an advantage of MSR design. Traditionally this has been in the form of a fuse plug and emergency dump tank in which a frozen plug of salt melts if electrically powered cooling of the plug ceases. Fuel salt then passively drains by gravity to tanks built specifically for decay heat removal. While this option remains for the IMSR, there do exist potential failure modes (drain blockage) and as such in-situ decay heat removal would be advantageous and would add to system simplification. The new innovation developed is to rely again on the fluid nature of the fuel but in this case for it to naturally circulate within the core unit and have heat removed from the vessel walls. By removing heat through the metallic vessel wall, cooler and denser fuel salt in the outer annulus will drive natural circulation. Only very slow flow rates are needed as the fuel salt has a very large thermal inertia. For example the IMSR80, is currently planned with 3.5 m^3 of fuel salt giving a total heat capacity of 16 MJ/$^{\circ}$C. At the instant of shutdown, with a decay heat of at most 7% of 80 MWth, the salt temperature would only be rising at 21°C per minute. Decay heat drops to 3% within a few minutes and to 1% within two hours, and by this time it would only be 3°C per minute. This ignores any other heat removal pathways and the very large heat capacity of graphite, along with the fact that some short lived fission products leave as off gas. Adding in roughly 15 tonnes of graphite in core and its heat capacity of 27 MJ/°K drops the temperature rate change to about two thirds. Thus even natural circulation with a cycle time of an hour or more within the core-unit is adequate to avoid excessively high temperatures of the salt in any location.

The large thermal inertia of graphite moderated designs with substantial salt volumes was recognized early on to be a desirable trait. By comparison the graphite-free 3000 MWth MSFR [2] must minimize salt volume for economic reasons as the fast spectrum calls for a fissile loading per unit volume approximately 10 times that of thermal spectrum MSRs. The MSFR projects just 18 m^3 of fuel salt and thus has 37.5 times the power but only about 2.4 times the heat capacity of an IMSR80

As seen in Figure 1, the IMSR vessel wall is surrounded by a liner that contains a solid buffer salt, chosen to have a melting point just slightly above the normal vessel wall temperature. During normal operation this thick layer is both a thermal insulator and neutron and gamma shield. During a failure of all secondary cooling however, this buffer salt begins to melt and pull away decay heat. As it melts, the liquid form will move heat to the remaining frozen buffer salt through highly effective convective heat transfer. Even a modest thickness can absorb many hours or even days of decay heat. When the buffer salt is nearly completely melted, a surrounding water jacket embedded in the outer concrete silo transitions to be the main heat sink while keeping the concrete at modest temperatures. A surface tank supplies several weeks of coolant water by which point normal radiative losses assure the overall system remains secure if for any reason power or makeup water has not returned.

A full description of reactor control, operation and fuel utilization is beyond the scope of this introduction to basic IMSR principles but it should be mentioned that two independent and passive shutdown systems are currently planned. Both systems originate from salt cooled or FHR work. The primary shutdown mechanism consists of a buoyancy-driven control rod [10], of slightly higher density than the fuel salt at normal temperature. Pump induced flow keeps the rod out of the core until a pump failure or a salt density decrease due to a rise in temperature passively initiates rod drop. As independent backup, a thermally activated neutron poison injection [11] is planned, wherein a eutectic salt mix of GdF or EuF will melt and mix into the fuel salt if a threshold core temperature is exceeded.

Basic supporting reactor physics modeling to date has been through sponsored efforts at the University of Tennessee (UTK) under direction of Dr. Ondrej Chvala [5]. This work has studied the previously largely unexplored set of alternate carrier salts that avoid enriched lithium and beryllium to avoid their cost and tritium production. An obvious drop in conversion ratio was found as expected, typically between 0.1 and 0.2 compared to a FLiBe carrier salt. The resulting increase in annual uranium usage is very modest however, especially in terms of cost per kwh. For example, an MSR-Burner dropping from conversion ratio of 0.8 down to as low as 0.6, only means makeup fuel costs increasing from about 0.1 cents/kwh to 0.2 cents/kwh.

More importantly, recent modelling work at UTK has been confirming the expectation of superior temperature reactivity coefficients. It is vital to attain an overall negative temperature coefficient and some previous MSR-Breeder efforts only predicted a very weakly negative term, for example -2 pcm/K for the early 1970s MSBR. There are three contributing factors in the overall temperature reactivity coefficient;

> Fuel-salt density. A decrease in density removes fuel salt from the core, changing the fuel-to-moderator ratio and increasing neutron leakage. Fast acting.
>
> Doppler broadening of resonance-absorption peaks. Higher temperature produce broader peaks increasing neutron absorption in ^{238}U or ^{232}Th. Prompt response.
>
> Graphite temperature. Higher temperature shifts the Maxwellian thermal neutron peak to higher energy, and into (or out of) fission-resonance peaks. Slow acting.

While the Doppler term is consistently strongly negative, in graphite moderated MSR-Breeders, the density term can sometimes be positive and the graphite term is consistently positive. In fact there is debate whether the global reactivity term for the 1970s MSBR design might actually be slightly positive.

The IMSR already benefits from having a smaller dimensioned core as this typically leads to a negative density factor (increased neutron leakage with lowered fuel density). The major difference however is that, as an MSR-Burner, the IMSR will have either reduced or non existent levels of ^{233}U (depending if LEU is used on its own or with thorium). The positive graphite term results from the shift of the Maxwellian peak of thermalized neutrons moving to higher energy as graphite heats up. In this region of interest, the drop in absorption cross section of thorium is much steeper than the drop in fission cross section for ^{233}U. As well, the leading edge of the Maxwell peak begins to enter a strong ^{233}U fission peak. As the ratio of fissile to fertile absorption rises, this drives up reactivity. For other fissile isotopes, especially ^{235}U, this is not the case, and in fact a negative graphite term typically dominates.

While modeling efforts are ongoing, results to date are showing all three terms to be separately negative, with a strongly negative total. Many core size and fuel salt combinations have been investigated at beginning of cycle conditions. For these scoping exercises a global total reactivity coefficient ranging from -5 to -11 pcm/°K has been observed. This strong term greatly aids in transient response as even hard to imagine reactivity insertions are merely countered with a modest shift upwards in fuel temperature.

6. Conclusions

While Molten Salt Reactors have long held great promise, there appears no reason to complicate initial commercial development by attempting a breeder approach. The MSR-Burner approach is the pragmatic approach and one that is able to lead to more rapid and widespread commercialization. The IMSR concept is predicated on further reducing all of the developmental challenges of bringing these much needed systems to market. Development is a major undertaking that will call upon many international partners, but Terrestrial Energy plans to continue to focus development within Canada with the objective of demonstrating its IMSR80 early in the next decade. A growing interest from industry and academia and the more performance-based regulatory body in the CNSC bodes well for the future. The Canadian market also holds great promise, ranging from remote communities to mining interest [12], as well as the western oil sands where the high temperature output (700°C) and scalability of the IMSR appears ideal for replacement of natural gas use in Steam Assisted Gravity Drainage (SAGD) [13,14] bitumen production.

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