Molten Salt Converter Reactors: From DMSR to SmAHTR

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ABSTRACT – Molten salt reactors were developed extensively from the 1950s to 1970s as a thermal breeder alternative on the Thorium-U233 cycle. Simplified designs running as fluid fuel converters without salt processing as well as TRISO fueled, salt cooled reactors both hold much promise as potential small modular reactors and as larger base load producers. A background will be presented along with the most likely routes forward for a Canadian development program.

1. Introduction

Molten Salt Reactors were original developed as a potential military aircraft reactor 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 that ran from 1965 to 1969. Design work resulted in a Single Fluid, graphite moderated Molten Salt Breeder Reactor running off the Thorium-U233 cycle 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. This led to an aggressive proposed salt processing regime of removing most fission products from the salt on a 10 day cycle giving a modest breeding ratio of 1.06 but an impressive 20 year doubling time. Ultimately in the mid 1970s the U.S. decided to focus solely on the sodium cooled fast breeder option and the ORNL program was canceled.

Molten Salt Reactors saw a reemergence of interest when chosen as one of six GEN IV reactors in 2002. An objective review shows MSRs have unique attributes that lead to clear potential advantages ranging from overall costs, safety, resource sustainability and long lived waste issues [1]. Much of this revival of interest has continued to focus on breeder options and while fluid fuel does simplify fuel processing technology, the degree of difficulty and costs can be underestimated by many, especially in terms of needed R&D. Recently however there is increasing interest in removing this aspect of MSR design by going to simplified converter designs that skip salt processing at the modest expense of needing a small annual makeup of low enriched uranium (only a small fraction needed for LWR or CANDU). This work is based on the final funded efforts of ORNL in the late 1970s on a design termed a Denatured Molten Salt Reactor running on thorium and low enriched uranium that both greatly simplified plant design and also increased proliferation resistance by denaturing the U233 with U238[2].

Much 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 [3,4]. While not having as strong a case on resource sustainability and long lived waste profile as true molten salt fueled MSR options, many view this new work, termed Fluoride Salt Cooled High Temperature Reactors (FHR), as potentially being faster to develop and gain acceptance while having cost and safety advantages similar to MSRs. Many innovations have been made in the FHR field that may see use for MSRs as well.

2. Breeder Versus Converter Reactors

While the allure of a breeder making its own fuel after startup is obvious, one must be pragmatic and examine the resulting costs and benefits. The main cost of operating MSRs as breeders is the development and operating costs of online processing of the salts to remove fission products. In terms of development costs, while techniques have been developed which range in level of difficulty, none have been advanced to anywhere near a commercial stage and would appear to require a great deal of expenditures to do so. In terms of operating costs it is widely accepted that processing of liquid fuels should be less of a challenge than solid fuel processing such as PUREX. However, taking the example of the historic MSBR of ORNL circa 1970 [5], this design called for processing the entire fuel salt every 10 days (even faster for Protactinium removal) using liquid bismuth reductive extraction. With roughly 150 tonnes of fuel salt this equates to 5500 tonnes per GWe-year. In order to simply match the fuel cycle cost of a LWR (50M$ or 0.6cents/kwh) this processing would need to be under 10$ per kg, highly unlikely. PUREX in comparison is accepted as being 1000$ to 2000$/kg to process solid fuels.

There are other salt processing options, such going to two fluid designs which ORNL pursued through much of the 1960s [6]. This calls for separate salts, a fertile thorium blanket salt and a fissile U233 fuel salt, which allows simpler processing as thorium is no longer present in the fuel salt (thorium is chemically similar to rare earth fission products). Processing is by fluorination to remove U233 from the fuel salt followed by vacuum distillation to recover the expensive carrier salt with most fission products left behind. ORNL abandoned this approach in 1968 due to the complexity of graphite plumbing required to both separate and interlace the two fluids within the core. A solution to those plumbing issues has recently been proposed [1,7] but while vacuum distillation should be a less expensive method than liquid bismuth reductive extraction, its challenge should not be underestimated.

Another approach has been undertaken by researchers in Europe with the Molten Salt Fast Reactor (MSFR) [8] whose proposed design would still require the complex reductive extraction techniques but a combination of high power density and better neutronic budget of the faster spectrum results in a large reduction in the annual salt processing. It may still though be difficult to match existing LWR fuel cycle costs and the adoption of this particular fast spectrum design has introduced new challenges such as higher salt operating temperatures and metallic barriers and reflectors needing to function in a strong neutron flux.

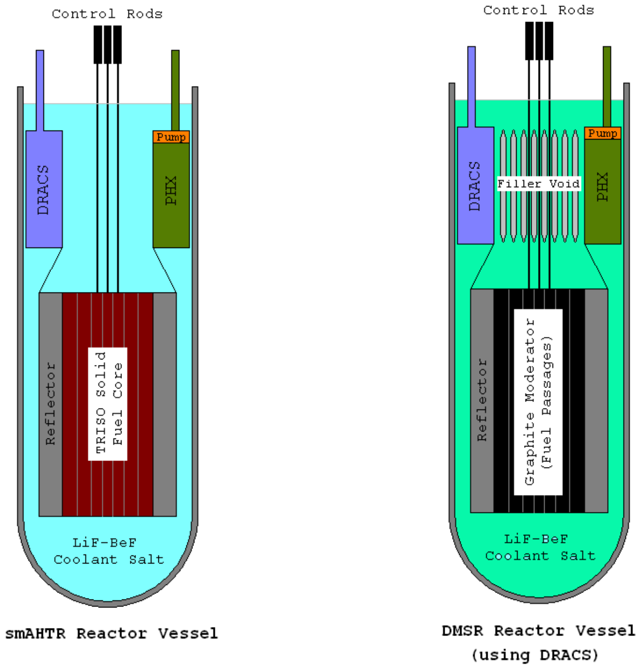
Operating MSRs as breeders is thus not likely warranted on economic grounds alone. Some may view other potential benefits of resource sustainability and long lived waste as being the true benefits of the breeder case but in fact a closer look at the converter option, namely the DMSR, reveals an excellent prognosis for these designs as well.

3. Denatured Molten Salt Reactors

Work at ORNL in the late 1970s focused on greatly simplifying their breeder work to a converter design where both fuel salt and graphite would attain a full 30 year cycle [2]. A rational for this work was also to maximize proliferation resistance as any uranium in the salt would always be in a denatured state due the presence of substantial U238. This fact differentiates the DMSR approach to other MSR converter options such as the FUJI [9] approach of Japan whose premise has similar reactor simplification but having only thorium as fertile and employing a makeup fissile material of accelerator produced U233. The DMSR startup and annual makeup is by readily available Low Enriched Uranium (up to 20% U235 depending upon design). Even though salt processing is not employed, resource utilization is still excellent, needing roughly 1/6th that of LWR or about 35 tonnes uranium per GWe-year versus 200 to 250 tonnes for LWR. Design optimization could likely bring that figure down to at least 20 tonnes U per GWe year [1]. Low uranium and enrichment needs combined with no solid fuel fabrication result in well defined fuel cycle costs of only around 0.1 cents/kwh. The low uranium needs means that even a massive build out of DMSR reactors worldwide would have little impact on the long term availability of uranium since even a tenfold or more increase in uranium prices would have little effect on the DMSR and mean massive amounts of low grade ores would be profitable or even from seawater extraction. Thus on resource sustainability the DMSR achieves high marks as does a breeder.

In terms of long lived wastes, as is well known it is mainly transuranic wastes that are the true issue as the vast majority of fission products have become stable after a few hundred years. With the DMSR approach there is indeed a greater annual production of transuranics due to the presence of U238 in the salt. However, the produced Pu stays within the salt where it mostly consumed during the batch lifetime of the salt (30 years in ORNL work). Long lived waste reduction was not a priority at the time of development but a simple modification to practice would be to remove and recycle all transuranics into the next batch of salt. All uranium can similarly be recycled but perhaps eventually requiring re-enrichment to avoid a buildup of U238. This does represent salt processing but many years of operation are possible before it is needed and can be practically done at a large central facility or perhaps by equipment brought on site as there is no rush to complete the recycling task. If this is done and even assuming a standard chemical loss of 0.1% during processing, the DMSR can obtain a waste profile equal to the pure Th-U233 breeder designs. Th-U233 breeders have less transuranics in the salt but need to process more frequently. Thus a 10,000 fold improvement over TRU waste versus LWR Once Through is possible. It will be a nation’s choice however whether such actinide recycling is employed.

The simple DMSR design lends itself well to scaling to small modular reactor size of anything from a few tens to a few hundreds of MWe. This is a likely starting point for development with larger units coming later. As well, while the original DMSR proposed using 20% enriched LEU to allow as much thorium as possible (a superior fertile isotope than U238) there are actual a number of advantages with forgoing thorium use at the modest expensive of a slightly lower conversion ratio. Another obvious change is to reduce the batch lifetime of the salt from 30 years down to perhaps 5 to 10 with a great improvement in uranium utilization. While work by the author on many other design simplifications and improvements are not ready for full disclosure, several innovations made under the ORNL FHR program, specifically the SmAHTR design has overlap to the DMSR and can be reviewed.



smAHTR Reactor Vessel

DMSR Reactor Vessel (using DRACS)

Figure 1 The ORNL SmAHTR.design on left and a simple DMSR counterpart on the right

4. Small Advanced High Temperature Reactor SmAHTR

Salt cooled designs or FHRs have been under development in the U.S. for roughly a decade [3,4]. Led by MIT, UC Berkeley and ORNL the basic principle is that fluoride salt are in general excellent coolants so using fuel free clean salts to cool TRISO fuel particles instead of high pressure helium has much potential. MIT and Berkeley have focused on pebble beds while ORNL work is on various fuel block forms. The relative advantages of each are reviewed in Table 1 and also compared to the DMSR approach. Of particular interest is the SmAHTR design which has introduced many innovations including integrating both primary heat exchangers and decay heat removal DRACs within the primary vessel. This arrangement also relieves the vessel head of significant neutron flux. Details are available elsewhere [4] but this 125 MWth, 50 MWe design has many advantages and obvious direct overlap into fluid fueled MSR design as depicted in Figure 1 in which the solid TRISO fuel core is replaced by simple graphite and fuel is relocated to the salt. A simple filler void helps lower overall salt volume and should be depicted in the bottom plenum as well.

As outlined in Table 1 there are many potential advantages a DMSR version would have over the TRISO fueled FHRs while all three designs offer significant improvement over current reactor offerings. In addition if the same power density is employed, a DMSR version following the SmAHTR design could go close to 20 years before core graphite would need replacing whereas the SmAHTR only achieves a 2 to 4 year lifetime between core replacements. Alternatively a DMSR unit could go to higher power output and change graphite more frequently. Furthermore, a DMSR design has the option to switch carrier salts to remove costly enriched lithium and/or beryllium which can also eliminate tritium production from the salt and its management issues whereas the FHR designs appear forced to use the standard Flibe (2LiF-BeF2) carrier salt for safety reasons (to obtain negative void coefficients).

Table 1 Comparing options to LWRs, all also have clear cost and safety advantages

	DMSR Converter	**FHR Pebble Bed**	**FHR Fuel Blocks**
Uranium Utilization	Far Superior to LWRs, roughly 1/6th the Uranium	Slight Reduction to LWR (roughly CANDU levels)	Burnable poisons needed and up to twice LWR U needs
Fuel Cycle Costs	About 1/10th LWR, low U and no fabrication costs	Roughly the same as LWR, less U, high fabrication	Higher than LWRs and any FHR require new fuel factories
Waste Profile	With batch processing after salt use, almost zero TRU waste. Transmutes more long lived elements than it produces	Reprocessing harder than LWRs so Once Through likely and significant TRUs. Larger waste volume but well contained in fuel form	Same issues as Pebble FHR
Major Challenges	Periodic graphite replacements, Off Gas systems, servicing of Heat Exchangers	Pebble handling equipment, high pumping power needing cross flow, tritium management	Fuel block replacement (whole core or batch), tritium management

5. Conclusions

Both molten salt “fueled” (MSRs) and molten salt “cooled” (FHRs) show great potential as both base load power generators and more specifically as ideal Small Modular Reactors. While China has announced a major MSR and FHR program and a modest MSR development program continues in Europe, interest within Canada in particular is new and growing. This is partly due to the halt of almost all advanced CANDU studies and thus underutilized talent. Along with growing academic and corporate interest is the fact that an ideal proving ground exists in the western Canadian Oil Sands where the high temperature output (700 ^{o}C) of these reactors appears ideal for replacement of natural gas use for SAGD oil production [10,11] in which the reactors simply need produce high temperature steam. While MSRs in particular do offer the potential of functioning as breeder reactors, it appears at least a first generation will be far simpler converter reactors with the option to later upgrade to breeders with the addition of fission product removal systems.

5. References

1. D. LeBlanc, Nuclear Engineering and Design Vol 240, pages 1644-1656, (2010)
2. J.R. Engel et al., Oak Ridge National Laboratory Report ORNL TM 7207, (1980)
3. P. Peterson et al., Proceedings of the ICAPP 08, paper 8211 (2008)
4. S. Greene et al., Oak Ridge National Laboratory Report ORNL TM 2010/199 , (2010)
5. R.C. Robertson, Oak Ridge National Laboratory Report ORNL 4541 (1971)
6. R.C. Robertson., Oak Ridge National Laboratory Report ORNL 4528 (1970)
7. D. LeBlanc, U.S. Patent Application, Ser 12/118,118, May 2008
8. Elsa Merle-Lucotte., Proceedings of the ICAPP 2007
9. K. Furukawa. Japan-US Seminar on Th Fuel Reactors, Nara (1992)
10. D. LeBlanc and C. Popoff,, WHOC12-314 World Heavy Oil Congress, Aberdeen Sept 2012
11. R.B. Dunbar and T.W. Sloan, Canadian International Petroleum Conference paper 096, 2003