Denatured Molten Salt Reactors (DMSR): An Idea Whose Time Has Finally Come?

D. LeBlanc[1,2]
[1]Physics Dept, Carleton University, Ottawa, Canada
[2]Ottawa Valley Research Associates Ltd.

Abstract

Molten Salt Reactors are one of six next generation designs chosen by the Gen IV program. Traditionally these reactors are thought of as thermal breeder reactors running on the thorium to ^{233}U cycle and the historical competitor to fast breeder reactors. However, simplified versions running as converter reactors without any fuel processing and consuming low enriched uranium are perhaps a more attractive option. Uranium consumption levels are less than 1/6th that of LWR or a 1/4th of CANDU while at the same time offering clear advantages in safety, capital cost and long lived waste production along with increased proliferation resistance. A review of previous work and potential improvements proposed by the author will be presented.

1. Introduction

Molten Salt Reactors, now often termed Liquid Fluoride Reactors, come in many potential forms. All involve fluorides of fissile and fertile elements mixed within carrier salts that act as both fuel and coolant to transfers fission heat from a critical core to an intermediate heat exchanger. There exists a broad range of design choices such as whether graphite is used as moderator or not, whether fuel processing for fission product removal is employed, whether the system runs in a denatured (LEU) state by the inclusion of ^{238}U and also whether one operates as a Single Fluid or a Two Fluid system (a Two Fluid system has separate salts for fissile ^{233}U and fertile Th). These choices also dictate whether a system has a Breeding Ratio > 1.0 (to produce excess fissile for future startups) or a B.R.=1.0 to break even on fissile production or if B.R.< 1.0 making it a converter reactor requiring annual additions of fissile fuel of some kind.

The development of Molten Salt Reactors at Oak Ridge National Laboratories (ORNL) took place from the early 1950s until the 1970s at which time the funding was cut. A more complete historical review is available elsewhere[1-4] but an important point to realize was that development was mandated to be for a breeder reactor with as short a doubling time as possible (the time needed to breed enough fissile to start another such reactor). This mandate was not surprising given the belief at the time that worldwide uranium resources were extremely limited and also given the tremendous head start that PWR converter reactors had due to their high military priority for use in nuclear submarines.

Breeding excess fissile for future start-ups is no longer a priority given the large and increasing world reserves of uranium and that hundreds of tonnes of spent fuel plutonium exist and would be an ideal start up source of fissile material for any sort of molten salt design. Furthermore, due to proliferation concerns (or the mere perception thereof) even the phrase breeder reactor is now rarely used. Break even conversion ratios in which no fissile material need enter or leave the nuclear plant after start up is still a very attractive goal but simple converter reactors using Low

Enriched Uranium (LEU) as makeup fuel can be shown to have unique and major advantages over other molten salt designs and arguably over all existing or proposed reactor designs.

While optimizing resource utilization is surely an important issue and the focus of much work, it is only one aspect of the overall attractiveness in comparing one reactor design to another. Safety, Capital and O&M costs, Long Lived Waste Production and Proliferation Resistance must be included as overall benchmarks. The case will be presented that Denatured Molten Salt Reactors (DMSR) can attain a high level of resource optimization and very low fuel cycle cost while surpassing other molten salt concepts and existing or next generation reactors in the four later categories. It will also be shown that while of course substantial, the R&D required to commercially develop a DMSR is much lower than many would imagine. Finally, potential improvements to further increase their attractiveness will be presented

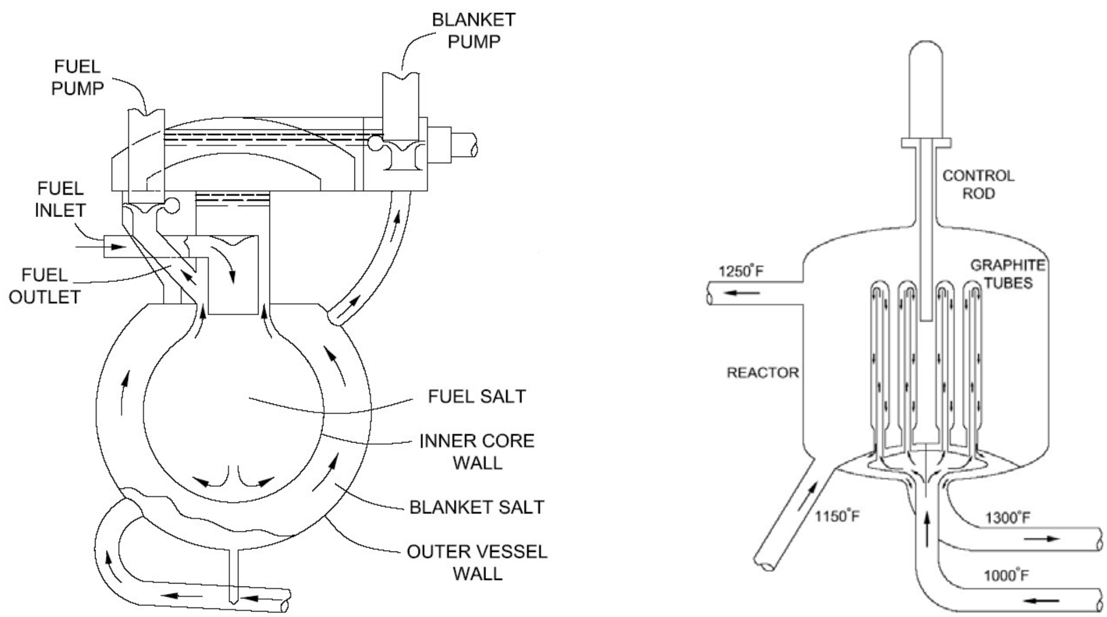

Figure 1. (Left) Depicts the 1950s graphite free, two-region concept. Reproduced from ORNL 2474. (Right) Depicts the 1960s intermixed Two Fluid MSBR design using internal graphite plumbing. Reproduced from ORNL 4528.

2. Molten Salt Design Evolution

As mentioned a more complete review can be found elsewhere but it is important to briefly review the major development period at ORNL and subsequent efforts. The very first work was in support of the Aircraft Reactor Program for the U.S. Air Force. The concept being an onboard MSR to replace combustion heat for the jet engines of bombers. While this project did not lead to an operational bomber, it did lead to a large knowledge base being developed and to a successful test reactor, the Aircraft Reactor Experiment built and run in the mid 1950s. The ARE was a high temperature reactor with a peak temperature of 860 ^{o}C employing a $NaF\text{-}ZrF_4$ carrier salt and fuelled with highly enriched ^{235}U. Clad blocks of BeO provided moderation.

A program directed to power reactors was begun in the late 1950s and first focused on simple sphere within sphere designs of a fuel salt (containing both fertile and fissile elements) surrounded by a blanket salt containing fertile thorium. This mode of operation was called 1 and ½ Fluid since the core salt had both fertile and fissile. By about 1960 it was proven that graphite had excellent behaviour in conjunction with the salts and the program changed focus to graphite moderated designs. To simplify fuel processing for fission product removal, they chose a Two-Fluid design with no thorium in the fuel salt (thorium is chemically almost identical to the rare earth fission products). At the time they thought it necessary to interweave both fuel and blanket salts within the inner core by complex graphite plumbing but a recent proposal by the author [1,5] has shown there is a much simpler route to obtain the benefits of the Two Fluid design.

Also during the 1960s, the highly successful test reactor, the Molten Salt Reactor Experiment (MSRE) was constructed and operated. It was an 8 MW(th) design chosen to be a Single Fluid for simplicity (it was designed during the Two-Fluid era). It operated for 5 years with great success. Two unknown issues with the Hastelloy N alloy used for the vessel and heat exchangers did surface. One was corrosion induced by the fission product tellurium and the other was irradiation damage caused by (n,alpha) reactions in nickel and boron contaminants. In subsequent years of the program, these issues were largely addressed by modifying the alloy makeup of the Hastelloy and the reduction potential of the salt accomplished simply by the occasional additions of metallic beryllium.

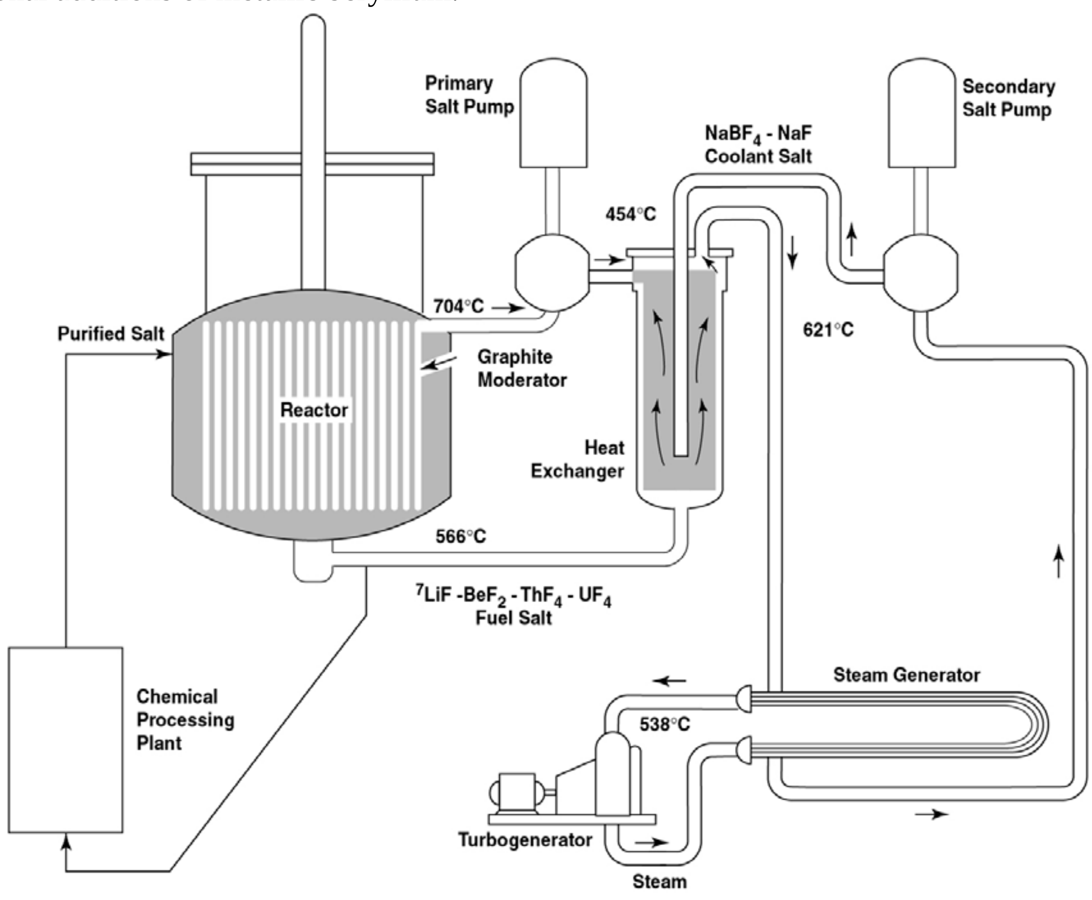

Figure 2 The 1970s Single Fluid, graphite moderated Molten Salt Breeder Reactor. 1000 MWe with a specific fissile inventory of 1500 kg. Reproduced from ORNL 4812.

ORNL abandoned their complex Two Fluid design in 1968 and adopted a Single Fluid design with a much simpler core but needing more complicated fuel processing. This became the graphite moderated, Single Fluid Molten Salt Breeder Reactor (MSBR) and was the focus of efforts for the remaining years of funding before the very controversial cancellation of the program in the mid 1970s.

Work did not completely stop at ORNL though. Due to an increase in sensitivity in regards to proliferation issues, they examined [6,7] running the same basic Single Fluid system in a denatured state after start up on LEU and thorium. They showed that with similar fission product removal processes they could break even and not require fissile after start up while remaining denatured (denatured uranium has less than a weighted combination of 20% ^{235}U and 12% ^{233}U). More importantly they later discovered how attractive the basic Single Fluid design was if run without any fuel processing as a simple converter reactor. Both studies were called DMSR with the converter design having the added label of "30 Year Once Through". It is this system, along with simple modifications that form the heart of the proposed new reactor offering.

3. ORNL`s DMSR "30 Year Once Through Design"

The 1000 MWe DMSR is a simple graphite core design with flow channel sized optimized for minimizing ^{238}U resonant absorptions. It would start from a mix of LEU (20% ^{235}U) containing 3450 kg ^{235}U along with 110 tonnes of thorium to improve neutron production. Annual makeup fissile is by LEU with all uranium remaining in the denatured state. It would involve no processing of the fuel salt beyond simple chemistry control. This meant no removal of fission products beyond the usual fact that noble gases like Xenon and noble metals come out continuously. The gases bubble out and are drawn away from the reactor and the noble metals plate out, ideally on added metal sponges but also on heat exchanger walls (not expected to effect HX viability). Most other fission products form stable fluorides that simply stay in solution. iodine is an exception as it does not form a fluoride but was found to stay in solution. Thus its airborne release is not a safety issue as it with solid fuels due to its volatility inside solid fuel elements. No fuel processing also means no removal and hold up of ^{233}Pa as proposed for the MSBR design (^{233}Pa being the 27 day half life intermediate between Th and ^{233}U).

The DMSR was to have a larger 8.3m diameter, lower power density core to allow a full 30 year lifetime of the core graphite. Graphite has a limited lifetime under neutron fluence and in most previous ORNL designs they assumed that they would simply change out graphite periodically (every 4 to 8 years) to allow smaller cores. This change also brings about two other advantages. The lower power density results in less neutron losses to ^{233}Pa and secondly the lower fluid velocity meant less worry about Xenon gas infiltrating the graphite. Thus, less expensive, unsealed graphite can be used. It should be noted though that this design choice is not intimately tied to the other main advantages of the DMSR such that higher power density cores with shorter graphite lifetimes might be a possible attractive option.

The end result of this design study was a system that dramatically lowered the needed R&D to reach commercialization, specifically due to lack of need to develop fuel processing methods to a commercial stage. The core design is little more than a larger version of the 1960s MSRE test reactor. At the same time, proliferation resistance was brought to an extremely high level while maintaining the numerous cost, safety and long lived waste advantages found in all molten salt designs.

TABLE 1 Resource Utilization for LWR, CANDU and DMSR 1000 MW(e) Converter Designs[a]

	Lifetime Uranium Ore (tonnes)	Annual Ore (tonnes)	Annual Ore Costs **100$**/kgU 10^6\$	Annual Ore Costs **1000$**/kg U 10^6\$	Annual Ore Costs[b] **5000$**/kg U 10^6\$
LWR Once Through	**6400**	200	17	170	850 *(0.13$/kWh)*
LWR Pu recycle	**4080**	125	10.6	106	530
CANDU Once Through	**4910**	150	12.7	127	635
CANDU Pu Recycle	**2420**	85	7.2	72	360
DMSR Once Through	**1810**	35	3	30	150 *(0.02$/kWh)*
DMSR With single U recycle	**1000**	35	3	30	150

(a) Based on 30 Year Lifetime, 75% capacity factor and 0.2% uranium tails. LWR and CANDU data from "A Guidebook to Nuclear Reactors" A. Nero 1979 (U of Cal Press)
(b) At $5000/kg, uranium recovery from sea water is likely feasible, giving a virtually inexhaustible resource

The only minor penalty paid is that of resource utilization since the system can no longer run solely on abundant thorium after start up as the MSBR could. While needing annual LEU additions to function, its superior neutronics and the fact that all fissile and fertile material stays within core (i.e. unlimited burnup) results in far superior resource utilization than LWR or CANDU (see Table 1). On the simple Once Through cycle it requires less than 1/3 the lifetime uranium than an LWR and if a single simple fluorination process is performed on the carrier salt after 30 years to recycle the contained uranium, the lifetime uranium needs drop to less than 1/6th that of LWR. Either way, the annual needs are only 35 tonnes of uranium versus 200 tonnes for LWR which means the system can afford uranium prices of upwards of 5000$ per kg without undue effect on electricity prices. This virtually assures an unlimited world supply of uranium. Viewed another way, about six times the GW(e) of DMSRs could run with the current uranium consumption levels and without adding a single new enrichment facility.

4. Safety, Capital Costs, Long Lived Wastes and Proliferation

With a general understanding of what is meant by a molten salt converter reactor and the DMSR it is best to review just why it is proposed as an alternate route to a nuclear renaissance. The DMSR minimizes needed R&D but will of course be a massive undertaking ORNL`s dedication to document every aspect of their work will help in this respect as just about every component needed by the plant was well thought out and meticulously described. This information is open to all to review online at www.ornl.gov/info/library, or www.energyfromthorium.com .

4.1 Safety

The inherent safety of molten salt reactors is evident when trying to imagine any possible scenario for the release of radioactive material. As reviewed, within the salt itself there are virtually no volatile fission products as these are continuously removed during operation and stored well away from the reactor. Thus, while a salt spill is possible, fission products will remain within the salt. As well there are a full three levels of containment as with solid fueled reactors. In the molten salt case the first barrier is the primary loop itself which is entirely contained within the second layer, a tight containment zone with only penetrations for pump drive shafts, intermediate coolant lines and possibly a shutdown rod. This containment zone which contains the primary heat exchangers is also made to collect and redirect any salt spills into decay heat dump tanks set up to deal with decay heat removal. This containment zone is also housed within an overall building containment to further assure no pathways for release.

The decay heat drain tanks also act in conjunction with passive freeze plugs to drain the salt to the safety of these tanks in any situation. If for any reason the core salt begins to rise in temperature, for example the failure of all pumps, this temperature increase melts a plug of frozen salt which then drains the core salt to the dump tanks. After any use of the dump tanks, the salts can be pumped back up into the core for a restart of the reactor.

There is also absolutely no chemical or other driving potential for any major release. The system is not pressurized as the salts have very high (1400 ^oC) boiling points at ambient pressure. In fact the primary salt loop is kept at the lowest pressure of the system so any leaks are inwards, the opposite of LWRs. There is no water used within containment that could lead to steam explosions or hydrogen production and subsequent detonation. No sodium or highly reactive substance that will react violently with water.

In terms of possible reactivity excursions molten salt reactors are also superior. There is no excess reactivity needed during operation and no control rods that can be accidentally removed (some designs included low worth rods for minor temperature control). The salts have negative temperature reactivity coefficients dominated by Doppler shifting that act instantly. In transient studies even sudden (and difficult to imagine) reactivity insertions giving prompt criticality, the salts merely jump up in temperature until they are sub critical again. As with LWRs the reverse situation of sudden cooling must be planned for but this is as simple as assuring pumps are such that a cold slug of salt can not be moved into the core too quickly. As well, since the minimum salt temperature is already close to its freezing point, such an event is virtually impossible. In general, the high heat capacity of roughly 300 tonnes of salt also help in smoothing any transient and make any temperature rise from decay heating very gradual.

It should be mentioned that recent studies in France [9] on updated versions of the standard MSBR design showed a potential temperature reactivity problem which meant the original design might have actually had a slightly positive global temperature coefficient (the fast acting term is indeed negative but a positive contribution occurring 10s of seconds later from the graphite heating leads to a net global positive coefficient). While there are many solutions for this for the pure Th to ^{233}U cycle, a DMSR converter reactor has no such issue due to an enhancement of the negative terms from the presence of ^{238}U.

Any recriticality events with the salts out of core are virtually impossible as they are only critical within the heterogeneous core graphite. Any external sabotage or explosions would render the core geometry and heterogeneity useless to reach criticality.

4.2 Capital Cost

Several previous cost estimates of power production for MSBR type reactors have always been very favorable in comparison to LWR or coal. With the far simpler DMSR which needs no capital and O&M costs for fuel processing the advantage should be even greater. As no fabrication of fuel elements is required and only minor chemical control are needed, fuel cycle cost at present uranium and SWU prices would be only 5 to 6 million per GWe year or under 1 mill/kwh (0.1 cent/kwh), compared to approximately 50 million for LWR. The startup fissile capital costs are far lower as well (3.5 t ^{235}U for DMSR and no fabrication versus 5 t for PWR plus fabrication or roughly 100 million versus almost 200 million)

While a molten salt reactor does require the expense of an intermediate loop (like a sodium cooled fast reactor) there are numerous areas for major savings. Most come down to the fact that the reactor is so inherently safe. Something like a pump failure is an inconvenience, not a safety issue so components do not require multiple backups and the highly engineered "defense in depth" approach of solid fueled reactors.

The superior nature of the molten salt as coolants also results in great benefit. The salts have 25% higher volumetric heat capacity than pressurized water (and 5 times that of sodium). This combined with large temperature differences across its heat exchangers mean all components are much smaller. The total volume of DMSR heat exchangers, steam generators and steam reheaters comes in at only 150 m^3 per GWe while a PWR is about 500 m^3 per GWe for its steam generators and a sodium fast reactor like PRISM 1350 m^3 per GWe for its heat exchangers and steam generators. Smaller volume and weight also translates into building and construction schedule savings along with assembly line type fabrication. It is true that the nickel alloy Hastelloy N is more expensive than stainless steel but its total effect on the budget is not substantial and there are possibilities in regards to replacing Hastelloy with common stainless steels (if the operating temperature is lowered somewhat).

The overall thermal efficiency of the plant is also much higher. 1970s versions expected 44.4% with supercritical steam of 540 ^{o}C based on the highly successful Bull Run coal plant in Tennessee. With salt inlet/outlets of 565^{o}C/705^{o}C the latest ultra supercritical steam cycles closer to 50% would be possible which would be far more economically attractive than the low efficiency, saturated steam of LWR and CANDU turbines. As well, molten salt reactors are an ideal match to gas brayton cycles, such as multi reheat helium or supercritical carbon dioxide also reaching close to 50%. Gas turbine options offer large cost and rapid production advantages but as seen in recent South African [9] efforts, establishing a "first of kind" turbine is a large hurdle even when the advantages of the "nth" turbine are so attractive. Thus the ability to match well to both steam or gas is a large advantage.

The reactor building itself offers significant savings. An overall containment building would likely be called for but it does not need the huge volume and ability to deal with steam pressure buildup as do LWRs or CANDUs. Simply an air tight structure along with ability to deal with aircraft incidents (overhanging wire mesh, earthen berm etc).

While up to date cost estimates are not available it is quite simple to see the potential overall advantages. It is not unreasonable to assume that capital costs could be 25% to 50% less for a simple DMSR converter design than for modern LWRs and even better in comparison to fast breeders such as the Integral Fast Reactor (IFR). As with any reactor, satisfying regulators concerns correlates to costs. Molten Salt reactors might be seen to suffer in this respect given how fundamentally different their operating principles are and thus how difficult to fit within existing regulations formed for solid fueled reactors. However, given the robust, inherent and simple to understand safety of these reactors one could also argue that if given a rational overview by a regulatory body they may in fact prove far simpler to license. .

4.3 Long Lived Wastes

Long lived spent fuel radiotoxicity is dominated by the effect of the higher actinides such as Np, Pu, Am and Cm. After 300 years or so the vast majority of fission products have decayed away and it is only the actinides that dictate the need for safe storage for numerous millennia. Added to that is the need to safeguard against the proliferation concerns of any Pu content (unless ^{238}Pu is over 80% by IAEA standards).

Molten salt reactors like the MSBR on the pure Th-^{233}U cycle have always touted the large advantage that after a few hundred years the radiotoxicity would be about 10,000 lower than LWR Once Through and quite similar to natural ore levels. LWRs or CANDUs with Pu recycle do not actually do all that much better since the Pu can not be recycled indefinitely in these reactors and the minor actinides (Np, Am, Cm) are not recycled. The MSBR has the advantage of producing about 10 times less higher actinides to begin with and that they can be recycled back into the reactor to be consumed. As well, in comparison to a fast reactor like the IFR, the MSBR is also at least an order of magnitude better since they need only reprocess a small fraction the higher actinides that the IFR does (a small fraction of actinides is typically expected to be lost during reprocessing, 0.1% is often assumed).

At first glance the DMSR with its higher production of transuranic actinides and with its “Once Through” label would seem incapable of matching the great reduction in long lived waste that the MSBR does. However at the minor expense of a one time only reprocessing of the salts at the end of their 30 year lifetime, the DMSR can in fact do even better than the MSBR. As mentioned earlier, removing uranium from the salt is fairly simple and the minor actinide Np comes out with it. Fluorination of Pu from the salts is possible but far more difficult. There are though, established processes to remove the Pu along with all transplutonium elements by what is known as Liquid Bismuth Reductive Extraction. The fission product zirconium would accompany Pu, Am and Cm as they are simply recycled, along with any Np to a subsequent batch of salt to be consumed. If this one time only operation is done and the traditional 0.1% loss is expected this equates to only about 1 kg of transuranics to waste in 30 years. Thus equivalent to 30 grams per GWe year compared to over 200 kg per GWe year in LWR and over 400 kg in CANDU. One also conveniently has 30 years worth of income to help pay for this one time batch process. For comparison, in 30 years the MSBR would need an even more complex processing done 1000 times since a 10 day fission product removal cycle was called for.

4.4 Proliferation Resistance

The proliferation resistance of a DMSR is likely higher than any other current or proposed reactor design. The reasons for this statement are numerous. For one, it is not possible to have isolated sources of fertile material within the core that can be removed after short irradiation times since anything added to the fuel salt is instantly homogenised with all other elements. One can not cycle in and out ^{238}U producing ^{239}Pu as is possible with any solid fuel design (albeit with much difficulty if it is to also function as a power reactor). The DMSR is fed low enriched uranium and the uranium content in the fuel salt always remains denatured. While the DMSR does have Pu present in the salt it is of much poorer isotopic quality than LWR or CANDU reactor grade Pu and is very difficult to remove from the salt. As well the salt itself need never leave the reactor inner containment zone which is kept near the operating temperature of 700 ^{o}C. The Pu content of the salt is very low (less than 0.1% molar) such that a great deal of highly radioactive salt would need to be collected to obtain a significant quantity of Pu.

The DMSR was likely the first reactor designed specifically to be as proliferation resistant as possible and a recent major study [10] singled out the DMSR as a reactor option worth developing for increasing resistance. There were only two credible scenarios that the ORNL developers foresaw. First is that in the first year of operation the isotopic quality of contained plutonium would be higher (true of any LEU burning reactor). If thought necessary, this is easily countered by simply adding a small amount of LWR spent fuel plutonium to the starting load of LEU and thorium such that from start up onwards, the Pu content is virtually useless for weapons use (and as mentioned near impossible to get to).

The second potential issue is the fact that protactinium is possible to chemically isolate from the salt and can be allowed to decay to relatively pure ^{233}U. However, there exists only small amounts of Pa in the entire 100 m^3 of salt (about 60 kg at a max) and the equipment and level of sophistication required to remove Pa would be high, especially as the processing must be done quickly. Attempting to add such equipment to an existing reactor would be a major effort, easily detected by inspectors. In a breakout scenario in which inspectors are removed it would be extremely difficult to bring in the equipment necessary and process the salt quickly enough before the Pa safely decayed within the fuel salt. In addition, this Pa route can be removed altogether simply by running a DMSR without any thorium, just on LEU (start up would then require 4.6% enrichment). The drawback to this is more uranium resource is required as it is missing the neutron rich thorium component. It is likely a LEU only [4] DMSR would require perhaps 50 tonnes natural U per GWe year as opposed to 35 tonnes for the LEU+Th DMSR but still far less than the upwards of 200 tonnes required for LWR or 150 for CANDU.

If the continued existence of enrichment facilities is of concern, there is even an interesting option to run off natural uranium. That would be through a synergistic relation with traditional CANDU plants. One drawback of CANDU is the large production of Pu in the spent fuel of about 550 kg per GWe year (85% capacity factor, 31% net efficiency by IAEA Nuclear Fuel Cycle Simulation System). Of this over 400 kg is fissile ^{239}Pu and ^{241}Pu. Thus 1 GWe CANDU plant running off 143 tonnes of natural uranium per year could provide the fissile makeup for roughly 3 GWe of DMSR simply by employing fluoride volatility processing of the CANDU spent fuel and direct use of the PuF_3 this produces.

5. Potential Improvements for a New DMSR

The fine work done on the DMSR at ORNL was done with little funding after the main program was cancelled. As such it was not subjected to a high level of optimization or review of alternate designs. It is thus fertile ground for examining many possible improvements. Such possibilities are reviewed more fully by the author elsewhere [3,4] but a brief review should suffice here to elicit interest.

There are numerous simple changes to the DMSR design that may prove optimal. The first is in regards to the 30 year lifetime of both salt and graphite and there is no reason these need be the same. For example, if we run the salt only 10 years and at least recover the uranium by fluorination then three 10 year cycles would require far less lifetime uranium as the fission products do not build up to as high a level. Likely only about 25 tonnes ore per GWe year and 750 tonnes lifetime could be obtained. This also improves the source term in any remote accident scenario.

ORNL never felt it unreasonable to change graphite so it may be best to design for higher power density, smaller cores. This would have an advantage for initial capital costs as fissile, carrier salt and graphite needs are lowered. Higher power density means slightly poorer neutronics due to increase neutron losses to Pa but if one only doubles or triples power density there is but a small effect on uranium utilization.

Another fairly simple change with large potential gains would be to change carrier salts. The traditional ^{7}LiF-BeF_2 "flibe" carrier salt is ideal neutronically but is expensive and both lithium and beryllium lead to tritium production (about the same as CANDU levels). Managing tritium was always a major portion of ORNL design efforts and lead to the specific choice of intermediate coolant salt. There are numerous potential carrier salts that would not produce tritium and also be very inexpensive. Examples include RbF-NaF and the carrier salt used in the ARE, NaF-ZrF_4. In various studies with the Th to ^{233}U cycle, the neutron economy does not suffer greatly from these alternate salts and would lead to only minor increases in uranium needs in a DMSR design.

A more major change under investigation by the author would be to employ a simple pebble bed of graphite balls as the moderator. These pebbles would be extremely simple to manufacture and capable of higher graphite quality than large log or hexagon elements normally used. The pebbles might actually have a much longer lifetime and replacing pebbles is much simpler than a fixed core. This could potentially be done online or using a brief shutdown period and batch replacement. A random pebble bed has a higher salt fraction than is ideal but one simply lowers the fissile concentration in the salt to compensate (again at the expense of a minor increase in uranium needs). Figure 4 shows such an embodiment also including the conventional undermoderated outer layer that diminishes neutron leakage (part of all fixed core Single Fluid MSBR designs). Various pebble bed concepts for the MSBR program were often considered and modelled but the high mandate placed on maximizing the breeding ratio kept pebble beds always as a backup design.

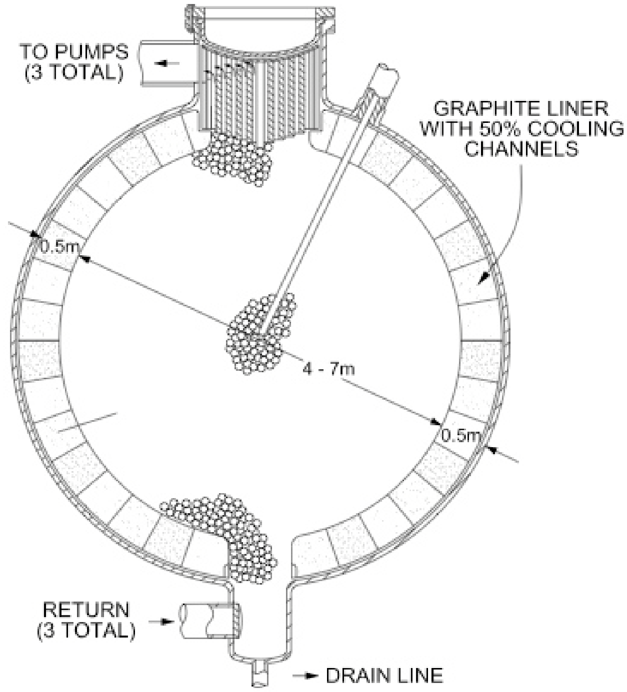

Figure 4 A newly proposed embodiment of a Pebble Bed DMSR Converter based on a modification of design work from ORNL 4344.

6. Conclusions

An emergence of molten salt reactors as commercial power producers is of course a huge undertaking. However, the simple DMSR concept removes some of the largest unknowns of the more commonly promoted thorium breeder MSR designs. Namely no need to bring salt processing to a commercial scale and not employing highly enriched uranium. It will take a different mind set as the traditional vendors all have much in stake with their solid fuelled designs, including lucrative fuel fabrication contracts. Government funding has been equally absent, especially in the U.S. but perhaps the renaissance currently underway in the space industry led by numerous entrepreneurial endeavours can provide a road map and even involve some of the same players. Traces of this are already evident looking at the work on the travelling wave reactor[11] put forward by Terrapower LLC with a large Microsoft connection. They have hired many of the top nuclear engineers in the U.S. and their design core is likely bigger than most traditional nuclear vendors. The DMSR will also take a large effort but every indication points to a power reactor that will excel in cost, safety, long term waste, resource utilization and proliferation resistance. With the enormous potential gains ranging from financial, environmental to general political stability in the face of peak oil, there are surely others out there interested.

7. References

[1] A.M Weinberg et al.,. Entire Volume on Molten Salt Breeder Reactor. Nuc App and Tech, Feb 1970 Vol 8

[2] D. LeBlanc "Molten Salt Reactors: A New Vision for a Generation IV Reactor" Canadian Nuclear Society Conference, Toronto May 2008

[3] D. LeBlanc "Molten Salt Reactors: A New Beginning for and Old Idea" ICONE 17 Brussels July 2009

[4] D. LeBlanc "Molten Salt Reactors: A New Beginning for and Old Idea" Article in Press, Nuclear Engineering and Design, Accepted Dec 18th 2009 (expanded version of the above conference paper)

[5] D. LeBlanc, "Molten Salt Nuclear Reactor" U.S. Patent Application, Ser 12/118,118, May 2008

[6] J.R. Engel et al., "Molten Salt Reactor for Efficient Nuclear Fuel Utilization Without Plutonium Separation." ORNL-TM-6413 August 1978

[7] J.R. Engel et al., "Conceptual Design of a Denatured Molten Salt Reactor with Once-Through Fueling". ORNL-TM-7207 July 1980

[8] A. Nuttin, "Potentialités du concept de réacteur à sels fondues pour une production durable d'energie nucleaire basee sur le cycle thorium en spectre epithermique" Ph.D Thesis, L'Universite Joseph Fourier-Gernoble I, 2002

[9] S. Thomas "The demise of the pebble bed modular reactor" Bulletin of the Atomic Scientists, June 22, 2009

[10] H. Feiveson, A. Glaser, M. Miller & L. Scheinman, "Can Future Nuclear Power Be Made Proliferation Resistant", Report issued by joint effort of University of Maryland`s Center for International and Security Studies and Princeton`s Program on Science and Global Security, July 2008

[11] Nuclear News interview "Terry Gilleland: On the Travelling Wave Reactor" Nuclear News, Sept 2009