# The Molten Salt Reactor Option for Beneficial Use of Fissile Material from Dismantled Weapons

Uri Gat and J.R. Engel
Oak Ridge National Laboratory

The Molten Salt Reactor (MSR) option for burning fissile fuel from dismantled weapons is examined and is found very suitable for the beneficial use of this fuel. MSRs can utilize any fissile fuel in continuous operation with no special modifications, as demonstrated in the Molten Salt Reactor Experiment. Thus, MSRs are flexible while maintaining their economy. Furthermore, MSRs require only a minimum of special fuel preparation. They can tolerate denaturing and dilution of their fuel. The size of fuel shipments can be determined to optimize safety and security—all of which supports nonproliferation and resists diversion. In addition, MSRs have inherent safety features that make them acceptable and attractive. They can burn fissile material completely or can convert it to other fuels. MSRs also have the potential for burning the actinides and delivering the waste in an optimal form, thus contributing to the solution of one of the major remaining problems in the deployment of nuclear power.

## Introduction

There are expectations that fissile material from nuclear arms reduction will become available and will require disposition.[1] Proposals for this disposition vary widely from disposing of it as waste (with all the associated issues of monitoring, safeguards, and verification, and the need to control it for long time periods) to its utilization as a nuclear fuel for beneficial energy production. The concerns are to retain control of the fissile material over its lifetime, to avoid any recycle into weapons, and to maximize the economic benefits and minimize any risks. The use of the dismantled fissile material in light water reactors is discussed elsewhere.[2]

The emphasis here is on the use of this fissile material from dismantled weapons as a fuel for the beneficial generation of power in molten-salt nuclear reactors (MSRs). Specifically, we discuss the potential advantages of MSRs as versatile, flexible fuel utilizers. Some safety features of MSRs—proliferation-inhibiting properties and possibilities for advantageous handling of waste—are pointed out. MSRs utilize the fuel in the form of fluid fissile material. Fluid fuel reactors have some unique possibilities associated with their ability to circulate the fuel.[3]

The molten-salt programs of the US Department of Energy (DOE) and its predecessor agencies had their manifestation in two very successful reactor experiments. The Aircraft Reactor Experiment (ARE)[4] and the Molten Salt Reactor Experiment (MSRE)[5]. Both of these reactors were designed, built, and operated by the Oak Ridge National Laboratory (ORNL). ORNL also conducted many extensive studies of various molten salt reactor concepts. The ARE was a product of the Aircraft Nuclear Propulsion Program[6] and it was operated successfully in 1954. That program was subsequently discontinued, but a civilian-oriented Molten Salt Reactor Program (MSRP)[5] that began in 1956 continued developing this general technology. The primary goal of the early MSRP and the goal during most of this program was to develop molten salt breeder reactors[7] (MSBR) using the Th-$^{233}$U fuel cycle that could compete with other concepts using the $^{238}$U-Pu fuel cycle. Consequently, the effort was focused on a system with integral, on-line chemical processing. The MSBR effort was discontinued in 1972, resumed as a technology-development program in 1974, and finally closed out in 1976. A small design study was undertaken in 1978 as part of DOE's Nonproliferating Alternative Systems Assessment Program (NASAP).[8] This study examined additional MSR concepts that might offer greater resistance to nuclear proliferation than light-water reactors operating on a once-through fuel cycle. This study led, ultimately, to two similar conceptual MSRs—one, a break-even breeder[8,9] using a complex, on-line fuel processing plant and the other a simplified converter[10] with a once-through 30-year fuel cycle.

Molten salt reactor studies have been undertaken in many places. One of the larger programs was conducted in Germany with the Molten Salt Epithermal-MOSEL reactor.[11,12] The MOSEL reactor foregoes the graphite in the core, which is used as a moderator in other MSR concepts, to achieve an epithermal spectrum that enhances breeding in the thorium cycle. More recently some concepts in Japan[13] and at ORNL[14] addressed simplicity of design and enhanced safety as their primary goals.

This paper is based on the earlier studies and previous work. No specific calculations have been performed to confirm the potential capabilities of the molten salt reactors suggested here. Many of the ideas proposed are conceptual. Several of the past concepts have been combined into new concepts. Not all of the possible resulting interactions have been explored. Thus, further studies are necessary to fully understand all of the implications of the ideas suggested herein.

## Fuels for Molten Salt Reactors

Molten salt reactors are usually geared toward the thorium-uranium-233 fuel cycle. They were developed initially when breeder reactor designs were being emphasized. The MSRs were conceived as near thermal reactors with a graphite moderator. The preferred salts were fluorides, including beryllium and lithium fluorides, because of their desired nuclear and thermodynamic properties. Both the beryllium and the fluorine cause significant neutron moderation. To achieve breeding with the soft neutron spectrum, it is necessary to select the thorium cycle.[15] To enhance breeding, the MOSEL concept removed the graphite moderator of the thermal design in order to harden the spectrum and reach into the peak region of the uranium-233 neutron yield in the epithermal spectrum.[11]

The MSRE was operated initially with $^{235}$U as the fissile fuel at about 35% enrichment. That operation spanned 34 months (beginning in 1965) and included a sustained run of 188 days (partly at low power to accommodate the experimental program). All aspects of operation, including the addition of fissile fuel with the reactor operating at power, were demonstrated. Subsequently, the mixture of $^{235}$U and $^{238}$U was removed from the salts by fluorination on-site, and $^{233}$U was added to the fuel salt for the next phase of the operation. Plutonium produced during the $^{235}$U-$^{238}$U operation remained in the salt during the $^{233}$U operation. Several fissile additions consisting of $PuF_3$ were made[15] for fuel makeup to demonstrate that capability. The plutonium additions were made by adding capsules of the $PuF_3$ in the solid form to the reactor salt and by allowing the plutonium salt to dissolve. Thus, plutonium from two sources was burned in the MSRE: the added plutonium and the plutonium that was bred from the uranium-238 in the initial operations. Therefore, the same reactor, without changes in design, operated successfully on all of the major fissile fuels: uranium-235 and 233, and plutonium mixed with uranium; this property provides the ultimate flexibility in the utilization of fissile fuel.

Conversion to either plutonium or uranium-233 is possible by mixing the fuel with adequate proportions of fertile material. Calculations have indicated promising conversion ratios (near 0.9) for a variety of conditions, and values above 1.0 may be achievable under carefully controlled conditions with on-line processing to remove fission-product poisons. With an appropriate fuel cycle, one fissile material can be burned off almost completely or burned and “converted” into another. As an example, plutonium could be burned to produce uranium-233. Such a conversion would transform a fuel, plutonium, particularly suitable for weapons, into a fuel, uranium-233, that may be less suitable for weapons but more neutron productive in non-fast spectra. Furthermore, while plutonium could be separated from the salt (or other additives) by chemical means, uranium would contain substantial amounts of uranium-232, which is considered a strong deterrent to proliferation. The very strong radioactivity emanating from the uranium-232 decay products makes any direct handling prohibitive only a short time after chemical purification.

The choice of fissile material in MSR fuel salt does not seriously affect the salt properties. Hence, a given reactor plant would be capable of using fissile materials in arbitrary combinations for high-temperature, high-efficiency power operation.

The fuel supply from the dismantled nuclear devices could be augmented at any time or could be totally displaced by fuel from other sources. By adjusting other components of the fuel, the conversion ratio could be controlled within rather wide limits. This further assures uninterrupted operation of molten-salt reactors for support of the overall energy economy. The fact that no substantial design changes are required to accommodate fissile supply changes acts as a damper on the propagation of interruptions and on changes in schedule or plans. This flexibility reduces any costs that might result from changes and interruptions.

## Dismantled Weapons Fuel

Fissile fuel from dismantled weapons is either highly enriched uranium (HEU) or plutonium. Although only rough guesstimates are available, it is assumed that quantities becoming available in the foreseeable future are sufficient to fuel one to a few reactor lifetimes.[1] It is further reasonable to assume that the fuel will become available on a continuous, rather than batch, basis. It is desirable to degrade the fuel to non-weapon grade immediately by such means as denaturing, diluting, or spiking. This will reduce the concern about diversion, the need for control and accounting, and the extent of security provisions. To reduce cost, the fuel must be degraded only one time, preferably at the location of and immediately upon dismantling. There should be no need to reverse any of these steps later, as for example in the manufacture of fuel elements. As discussed above, the MSRs are particularly well-suited to accommodate these needs.

For ordinary reactors, the quantity and supply rate of fuel from dismantled weapons poses a dilemma. If minimum numbers of reactors are dedicated to using this fuel, then the fuel must be accumulated, protected, stored, and monitored for very long periods of time. If large numbers of reactors are utilized, then the probability of operation disruptions becomes very high. Furthermore, relatively large facilities and large numbers of reactors need to be modified to accommodate a short spurt of fuel supply. Such an effort can be expensive and would require much detailed advanced planning and an intense commitment to a detailed schedule. MSRs, as discussed above, require no design changes and can readily switch between fuels on an ad hoc basis.

Also, solid fuel reactors with no reprocessing and no fuel recycling leave a large percentage of the original fissile material in the spent fuel. This constitutes an indefinite commitment to guarding and storing the spent fuel. Eventually it adds a burden to the solution for the disposal of the waste.

## Fluid Fuel Reactors

The MSRs are fluid fuel reactors and, as such, they differ from all the present, common, solid-fuel reactors. Fluid fuel can be transferred remotely by pumping it through pipes connecting the storage or reaction vessels (e.g., a reactor core). The relatively simple remote handling allows even the fresh fuel to be highly radioactive, which provides a strong diversion inhibitor. Also, highly radioactive fuel can be detected easily. If the temperature of the fuel is allowed to drop, the fuel solidifies and again is difficult to manipulate, providing additional diversion protection. The fluid fissile fuel at operating reactor concentrations provides inherent protection against criticality accidents during handling. In thermal designs, the graphite moderator is required for criticality so that criticality can occur only in the core. For other concepts, the design would have to exclude vessels that are not criticality-safe for credible fuel mixtures.

Fuel prepared for an MSR can be conveniently shipped as a cold solid and remelted just before it is added to the reactor system. For small additions, the reactor can be designed to accept the fuel in the frozen state, as in the MSRE. With a fluid fuel, the entire fuel element fabrication process is avoided. This saves a significant part of the head-end effort and cost. The absence of a solid fuel manufacturing phase provides enormous flexibility. The fuel can be blended into the reactor exactly as needed at any time. The amount of fuel added depends on the type of fuel, its isotopic makeup, and concentration. There is no need for exact long-range planning that might be upset by variations on either the supply or the demand side. There is no need for long lead times and interim storage. These advantages are particularly important for fuel derived from weapons. The rate and exact kind of fuel that becomes available can be accommodated by the reactor. The fine tuning of the composition can be done on an ad hoc basis at the site.

One possibility for the process of converting weapons fissile material to fluid fuel for a reactor is to do it at a dismantling facility. At that facility, the fissile material could be converted into a salt, denatured, spiked, diluted, or whatever else may be deemed desirable for safety, security, economy, or practicality. The denaturing and spiking can render the fuel unattractive for proliferation or diversion. Being designated for MSRs allows shipment in quantities and form that are optimized for safety and security, again inhibiting diversion but also reducing potential public objection. Safety and security will be maximized or at least optimized.

## Molten Salt Reactors

Molten salt reactors are unique in many ways. One of the major advantages of the fluoride-based MSRs is the potential for an integrated fuel recovery capability. The processing is based on the high volatility of $UF_6$. By sparging the salt with fluorine, uranium can be removed as $UF_6$, which can then be converted back to $UF_4$ and recycled into a fresh batch of fuel salt. The residual salt, now free of uranium, can be subjected to any of a number of processes to remove fission products and concentrate them. The carrier salt components (Li, Be, F) could also be isolated and recycled if that were economically desirable. All of these steps can be made independent of reactor operation.

The feasibility of the various steps for online processing has been calculated and individually demonstrated at ORNL.[16,17] In addition, the uranium recovery step was demonstrated in the MSRE when the fissile material was changed from uranium-235 to uranium-233. This process involved 47 hours of fluorine sparging over a six-day periods to produce a uranium product pure enough for cascade re-enrichment.

Molten salts can operate at high temperatures and low pressures, and they possess favorable heat transfer properties. These properties result in high thermal efficiencies for the reactor and in an absence of the safety hazards associated with high pressures, such as explosions or depressurizations. The salts are chemically stable and nonflammable, averting fire hazards, and there are no energetic chemical interactions between the salts and water.

## Safety of Molten Salt Reactors

MSRs can potentially achieve almost any degree of safety desirable at a cost. Some extreme degrees of safety were summarized in the proposal for the Ultimate Safe Reactor (USR).[18] MSRs possess many inherent safety properties. For instance, because their fuel is molten, a “meltdown” does not imply an accident. The fuel is critical in the molten state in some optimal configuration. If the fuel escapes this environment or configuration because of relocation, it will become subcritical—thus recriticality in any reasonable design cannot occur.

Fluid fuel inherently has a strong negative temperature coefficient of reactivity due to the expansion of the fluid, which results in the removal of the fuel from the core. This property is in addition to any other spectral contribution to the negative reactivity coefficient. At the very extreme, the fuel would cause the failure of the primary coolant boundary (without a serious pressure rise) in which case the fuel would be returned to a critically safe configuration. Furthermore, the ability to add fuel with the reactor on-line strongly limits the amount of excess nuclear reactivity that must be available in the system.

On-line processing reduces the amount of fission products retained in the system. This reduces both the risk of dispersal of radioactivity and the amount of decay heat that must be contended with during shutdown In an earlier configuration of the Molten Salt Breeder Reactor (MSBR), the fission product inventory was planned to be a 10-day accumulation.[7] A more recent proposal (the USR)[18] suggests reducing the fission products to a level at which the entire afterheat can be contained in the salt without reaching boiling.

In practically all MSR concepts, the fission gases and volatiles are removed continuously, significantly reducing the radioactive source term.

Fluid fuel also allows shutdown of the reactor by draining the core into subcritical containers from which any decay heat can be readily removed by conduction and natural convection. Proliferation resistance and other safety attributes are described elsewhere in this paper. MSRs can be designed in an extremely safe manner with inherently safe properties that cannot be altered or tampered with. These safety attributes make the MSRs very attractive and may contribute to their economy by reducing the need for elaborate safety measures.

## Waste

Nuclear waste is an important issue affecting the acceptability of any nuclear-related system and nuclear reactors in particular. Although there is no way that a reactor utilizing the fission process can eliminate the fission products, MSRs can significantly alleviate concerns regarding nuclear waste.

The on-line processing can significantly reduce the quantities of radioactive shipments because there is no shipping required between the reactor and the processing facility. Storage requirements are also reduced because there is no interim storage for either cool-down or preparation for shipment.

The actinides can be recycled into the fuel for burning. Although further work is required to fully analyze this possibility, several proposals to burn actinides have been made. MSRs with on-line processing lend themselves readily to recycling the actinides into the fuel. Eliminating the actinides from shipments and from the waste reduces the very long, controlled, storage time to more acceptable and reasonable periods of time.[18]

The fission products, already in a processing facility and in a fluid matrix, can be processed to the optimal form desired. That is, they can be reduced in volume by concentration to the most desirable condition. They can be further transformed into the most desirable chemical state, shape, size, or configuration to meet shipping and/or storage requirements. The continuous processing also allows making the shipments to the final disposal site as large or as small as desired or practical, and therefore reducing the associated risk to a minimum.

## Summary

MSRs are very suitable for the beneficial utilization of fissile material from dismantled weapons for efficient and economical energy production. MSRs can utilize all three major fissile fuels: uranium-233, -235, and plutonium, as demonstrated in the MSRE. This flexibility is achieved without: reactor-core design modifications. MSR fuels can be fed continuously on-line with a variety of fuel combinations. The fuels can be made proliferation and diversion resistant during preparation at the head end. The resistance to misuse can be accomplished by dilution, denaturing, spiking, and/or controlling the size of shipments.

MSRs are expected to be generally attractive because they have inherent safety attributes that reduce the risks to low levels. These safety attributes include reduced probability for an accidental criticality or for recriticality possibilities and freedom from core meltdowns. The online processing potential can reduce the fission product inventory, and with it, any risks of radioactive dispersal and can reduce the risks associated with the inability to remove the afterheat. On-line processing may also enable treatment of the waste by recycling and burning the actinides so that controlled storage is not required over a long period of time. The bulk of the waste can be reduced in volume and brought into a shape, form, chemical combination, and shipment and disposal size that are the most acceptable. Power production need not be interrupted by fissile supply fluctuations from the dismantled weapons. A particular fissile type can be burned completely and, if desired, converted into another fissile isotope. Fuel recycling and fabrication are not necessary. Fissile materials can be treated completely at the head-end dismantling facility. Fuel shipment sizes are arbitrary and thus optimally safe, and fuel transportation is reduced to a minimum.

All of the above considerations make the MSRs very attractive for the utilization of dismantled weapons fuels, and they enhance, encourage, and support the MSR option for beneficial utilization of fissile material from dismantled weapons.

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Discussion following Uri Gat’s talk:

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**Question:** The international implications of what you say are very important, and I have two related questions: one, are you familiar with the work in France by Lequoc and others? Second, what do you know about Soviet capabilities to be able to invoke a system like this?

**Gat:** “Lequoc”—I guess the easiest thing is to say that it's due to Lequoc that I'm here, so while I've never met him personally—we always pass one another—we know about one another. I must add that he's more active on the political scene than on the development scene. There is a program in Russia, and they have been pushing for a cooperative agreement with us. They offered to come to the US to talk about molten salt reactors. They apparently have an in-pile loop. A person by the name of Novikoff at the Kurchatov Institute has made a presentation. They have a program, but it seems to be mostly in the academic regimes, similar to what we have here. There are few people here who are enthusiastic about it, and I like to think they know about it. There's a lot of hesitation. The problem, of course, is that the climate is not right to introduce another kind of reactor right now unless there is a compelling reason. And it seems to be similar in Russia, but there are few of us here who would like to cooperate with the Russians. The Oak Ridge National Laboratory (ORNL) has the most knowledge about molten salt reactors. There's some interest in Japan, France (you mentioned Lequoc), and Germany did work. (I, by the way, didn't work on molten salt reactors at ORNL; I worked on them in Germany—on the Molten Salt Epithermal—MOSEL Reactor.)

**Question:** You've laid out the advantages for the molten salt reactor. Are there any disadvantages?

**Gat:** I'm glad you asked!

**Question:** For example, you've got liquid everywhere and liquids leak. There's a lot of radioactivity associated with this system. You're always going to have a minimal level, because you can't burn it all up. You'll make some technicium-99; you'll make some iodine-129. Are there any disadvantages to this? We have had the concept now for twenty years or more—why hasn't it ever gone anywhere?

**Gat:** To answer you specifically, yes, a fission reactor has fission products. The molten-salt reactor in its processing can bring those fission products to the most advantageous form that you can think of. You cannot avoid the fission products. You can burn some of the actinides—recycle them. You can form, shape, stabilize, and fix them; whatever you want; whatever is most acceptable. Another thing is that they are separate from the fuel, so you don't have to compromise—you optimize. With the fuel located elsewhere, we need to do some rethinking, and that would be my answer also to your other question: people haven't done their rethinking sufficiently. When the molten salt reactor was discontinued, the emphasis was on breeding. That was at the time when EBR-1 came out, and we needed a breeder a week. One gigawatt a week for the next twenty years. There are some common stories about problems in the molten salt reactors—there were questions about materials, corrosion, which are considered resolved. This is, however, not well known, because that was one of the ultimate results after the program was finished. There is a, problem with the graphite swelling—that limits the power density—however, the fuel in the molten salt reactor is relatively low in terms of kilograms per megawatt. One kilogram per megawatt, roughly. Production of tritium is an issue that you can talk about for a long time, but it's really an issue only if you insist on breeding, and it could become an issue for proliferation. Remote technology—there has been so much development that this is probably not an issue anymore. There was an issue of toxicity, but that's really not a very severe problem, because if you add that on top of the radioactivity, it's a non-issue. Processing is an issue, which needs development no question about that. The leaks, again, are not a big issue. You put down a pan, and you catch the liquid. The biggest problem is if it freezes, then you need to chisel it off, or heat it up. You need to keep those pipes and pots heated with trace heaters, so you can pump it. You don't need to have any mechanical dealings with those things.