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THE MOLTEN SALT REACTOR OPTION FOR BENEFICIAL USE OF FISSILE MATERIAL FROM DISMANTLED WEAPONS

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ABSTRACT

The Molten Salt Reactor (MSR) option for burning fissile fuel from dismantled weapons is examined. It is concluded that MSRs are very suitable for beneficial utilization of the dismantled fuel. The 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. MSRs further require a minimum of special fuel preparation and can tolerate denaturing and dilution of the fuel. Fuel shipments can be arbitrarily small, all of which supports nonproliferation and averts diversion. MSRs have inherent safety features which make them acceptable and attractive. They can burn a fuel type completely and 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 for deployment of nuclear power.

INTRODUCTION

There are expectations that fissile material from nuclear arms reduction will become available and require disposition [1]. Proposals for this disposition vary widely from disposal as waste, with all the associated issues of monitoring, safeguards, verification, and long time periods of needed control, to 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 the fissile material as a fuel for the beneficial generation of power in molten salt nuclear reactors. Specifically the potential advantages of MSRs as versatile, flexible fuel utilizers are discussed. 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 the ability to circulate the fuel [3].

The molten salt programs of the U.S. Department of Energy and its predecessor agencies had their manifestation in two actual, 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 possible molten-salt reactor concepts. The ARE was a product of the Aircraft Nuclear Propulsion Program, and operated successfully in 1954 [6]. That program was subsequently discontinued, but a civilian-oriented Molten Salt Reactor Program (MSRP) that began in 1956 [5] continued development of this general technology. The primary goal of the early MSRP and for most of this program was the development of 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 Non-proliferating Alternative Systems Assessment Program (NASAP)[8]. This study examined additional MSR concepts that might offer greater resistance to nuclear proliferation than the light-water reactors operating on a once-through fuel cycle. The 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 forgoes the graphite in the core, that is used as a moderator in other MSR concepts, to achieve an epithermal spectrum for enhanced breeding in the thorium cycle. More recently some concepts in Japan [13] and at ORNL [14] addressed simplicity of design and enhanced safety as the 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 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 there was high emphasis on breeding. The MSRs were conceived as near thermal reactors with a graphite moderator. The preferred salts are fluorides, including beryllium and lithium fluorides, for 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 concept, 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 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.

Thus, 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.

By mixing the fuel with adequate proportions of fertile material, conversion to either plutonium or uranium-233 is possible. 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, one could burn plutonium and produce uranium-233. Such a conversion will 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 will 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 totally displaced by fuel from other sources. By adjusting other components of the fuel, the conversion ratio can be controlled within rather wide limits. This further assures uninterrupted continued 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, changes in schedule, or plans. This flexibility also moderates 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. While there are only rough guesstimates available, it is assumed that quantities that would become 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-weapons grade immediately by such means as denaturing, diluting, or spiking. This will reduce the concern of diversion, the need for control and accounting, and the extent of security provisions. To reduce cost, it is required to degrade the fuel 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 for the manufacture of fuel elements. As discussed above, the MSRs are particularly well suited to accommodate these needs.

The quantity and supply rate of dismantled weapons fuel poses a dilemma. If a minimum number of reactors is dedicated to using this fuel, then the fuel must be accumulated, protected, stored, and monitored for very long periods of time. If a large number of reactors is utilized then the probability of operations disruption becomes very high. Furthermore, relatively large facilities and a large number 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.

Solid fuel reactors with no reprocessing and fuel recycling leave a large percentage of the original fuel in the spent fuel. This constitutes an indefinite commitment for guarding and storing the spent fuel. Eventually it adds a burden on 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 through pipes connecting 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 fuel at operating reactor fissile 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 for enormous flexibility. The fuel can be blended into the reactor exactly as needed at any time. The amount of fuel added will depend on the type of fuel, its isotopic makeup, and concentration. There is no need for exact long-range planning that may 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 as 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 (MSRs) 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 essentially quantitatively 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, could 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 could be made independent of the reactor operation.

The feasibility of the various steps for on-line 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. The process involved 47 hours of fluorine sparging over a six-day period [5] 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 absence of 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 (U.S.R)[18]. MSRs possess many inherent safety properties. Being a molten fuel, a "meltdown" is of no particular consequence. The fuel is critical in the molten state in some optimal configuration. If the fuel escapes this environment or configuration due to relocation, it will become subcritical – thus recriticality in any reasonable design cannot occur.

Fluid fuel has inherently a strong negative temperature coefficient of reactivity due to expansion of the fluid results in removal of 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 failure of the primary coolant boundary (without a serious pressure rise) in which case the fuel would be returned to a critically safe configuration. Further, 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 an accident. The fission product inventory, in an earlier concept the Molten Salt Breeder Reactor (MSBR), was planned to be a 10-day accumulation [7]. A more recent proposal, the U.S.R [18] suggests reducing the fission products to a level where 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, reducing significantly 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 reactors in particular. While there is no way that a reactor that utilizes the fission process can eliminate the fission products, MSRs can significantly alleviate concerns regarding nuclear waste.

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

The actinides can be recycled into the fuel for burning. While 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 [19].

The fission products, already being 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, reducing the associated risk to a minimum, as desired and practical.

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 and can come in a variety of 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 on-line processing potential can reduce the fission product inventory, and with it, any risks of radioactive dispersal and 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 the long time controlled storage is not required. The bulk of the waste can be reduced in volume and brought into shape, size, 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. Fissiles 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 these make the MSRs very attractive for the utilization of dismantled weapons fuels and enhance and encourage and support the MSR option for beneficial utilization of fissile material from dismantled weapons.

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A Question of Disposition

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Reactor Disposal of Fissile Material From Weapons Requires Special Capability (All Costly)

- Fuel recycle for solid fuel reactors
- Fluid fuel (molten-salt) reactors
- Other possibilities

Disposing Fissile Material from Weapons – The Molten Salt Reactor Advantage

- Requires no dedicated reactor – can be used indefinitely with non-weapon fuel
- Produce beneficial energy
- Does not require fuel recycling nor associated facilities
- No fuel manufacture – only a simplified "head end"
- Significantly reduced fuel shipping
- Inhibits diversion
- Enhanced safety – simpler licensing, acceptability and siting

The Molten Salt Reactor Dismantled Fissile Fuel Burner – Optional Advantages

- Can be used to burn actinides – reduced waste storage concerns
- Can leave little weapons fissile residue by end feed with regular fuel

MSRs Have Inherent Benefits

- Safety of fluid fuel reactors
  - No "melt down"
  - On-line (continuous) fissile material feed
  - Little excess reactivity
  - Can choose burner or converter

Diversion Resistant MSR Has a Simple Fuel Cycle for Burning Weapons Fissile Materials

- Dismantle
- Dissolve (can: denature, spike, dilute) into fluoride
- Feed (burn, produce power)

MSR Has Options That Can Enhance Its Usefulness and Acceptance

- On-line processing
  - Reduce fission product inventory
    - Enhance safety
    - Improve waste handling
  - Develop actinide recycle
  - Increase conversion (breeding possible)

Experience With MSRs

- ARE and MSRE – successful operations
- Operated on ^{235}U and ^{233}U
- Processed some fuel
- Burned some Pu
- Conceptual design of MSBR

Attractive MSR Features

- Fuel cycle flexibility
  - Can operate with any fissile isotope, without design changes or dedicated fuel cycle facilities
  - Can shift from one fissile fuel to another on line
- Actinide recycle
  - Actinides can be separated from fission products and returned to the reactor
  - Without actinides, the waste disposal problem is reduced from 10^5 years to hundreds of years. This should make repository siting and operation much simpler.

Attractive MSR Features (cont.)

- Safety
  - Negative temperature coefficient
  - Small excess reactivity required (due to on-line fissile fuel feed)
  - Small fission product inventory (on-line processing)
  - Easy decay heat removal
    - External cooling
    - Simple fuel dump to safe configuration
  - No possible meltdown (fluid fuel reactor)
  - Low-pressure system

Attractive MSR Features (cont.)

- Safeguards of fissile material
  - Simple, on-site treatment
  - Fissile material remains or recycled into same reactor
  - Only fission products shipped for disposal
  - Mass balances easy to track (minimal processing losses due to simplified fuel cycle)

Molten Salt Reactors Introduction Requires

- Familiarization and education of NSSS operators
- Licensing and familiarization and education of regulators
- Time for demonstration and commercialization
- For processing
  - Development
  - Operation of chemical plant

MSRs Can Burn Weapons Fissile Material Beneficially

- Can burn all fissile fuels while producing power
- On-line feed can accept all fissiles in the same design
- Have choice of burner or converter (breeder)
- Safety enhances acceptability
- Simplified waste handling and actinide burning contributes to acceptability
- Experience shows feasibility of basic concept
- Can reduce Pu and ^{235}U residue to small level
- Diversion resistant

Back-up only

MSRs Major Issues

- Materials – corrosion, considered resolved
- Graphite – swelling
- Tritium – getter developed, considered resolved
- Pa – fast separation for breeding needed
- Remote technology – much developed but application to MSR to be demonstrated
- Toxicity – beryllium, fluorine
- Processing – brittle molybdenum

MSR Waste Handling – Optimized (to be developed)

- The actinides can be recycled for burning (development required)
- Continuous removal of fission products in liquid processing
- Reduce waste to optimal concentration
  - chemical combination (fix or set)
  - shape and form
  - size and quantity
- Prompt shipment to final disposal in small (optimal) shipments – low risk
- Relatively short cool-off periods without the actinides