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MOLTEN SALT REACTORS - SAFETY OPTIONS GALORE[a]

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ABSTRACT

Safety features and attributes of molten salt reactors (MSR) are described. The unique features of fluid fuel reactors of on-line continuous processing and the ability for so-called external cooling result in simple and safe designs with low excess reactivity, low fission product inventory, and small source term. These, in turn, make a criticality accident unlikely and reduce the severity of a loss of coolant to where they are no longer severe accidents. A melt down is not an accident for a reactor that uses molten fuel. The molten salts are stable, non-reactive and efficient heat transfer media that operate at high temperatures at low pressures and are highly compatible with selected structural materials. All these features reduce the accident plethora. Freeze valves can be used for added safety. An ultimate safe reactor (U.S.R) is described with safety features that are passive, inherent and non-tamperable (PINT).

I. INTRODUCTION

The Molten Salt Reactors (MSR) that are the subject of this paper, are fluid fuel reactors (FFR)that utilize primarily fluoride salts as their working fluid . These reactors have the fissile material, as a salt, homogeneously mixed in the carrier salt. Fluid fuel reactors differ fundamentally from solid fuel reactors. Some of the more important differences are that the fuel can be readily processed on line to remove, or add, selective components. This processing differs from solid fuel reprocessing where the entire fuel (elements) must be removed, treated, remanufactured into elements, and reinserted in the reactor. In contrast, the processing of fluid fuel can consist of continuous removal of gases and volatiles in an on-site processing of a selected side stream. Another important difference is the fact that the fuel itself can be the coolant and circulated to a heat exchanger that is external to the core. This cooling method is referred to as external cooling. External cooling and on-line processing are contributors to unique safety features of FFRs.

II. FLUID FUEL REACTORS

It was recognized from their inception that FFRs possess unique and desirable safety features.[1] Some of these features are: Simple structure – this is particularly applicable for external cooling. The core can be optimized for nuclear and safety, and there is no need for compromise to accommodate coolant and heat exchanger surfaces. FFRs can have continuous removal of fission products. This feature dispenses with the need for excess reactivity to compensate for burnup and poisoning, removing the source of reactivity excursions, and reducing the source term and driving force (after heat) for an accident. They also possess, "Inherent safety and ease of control."[b] The inherent safety refers to the high negative reactivity temperature coefficient associated with the expansion of the fluid upon heating and

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[a]Based on work performed at the Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corporation for the U. S. Department of Energy under contract number DE-AC05-96OR22464.

[b]Attention is drawn to the terminology used in 1958![1] Just shows that there is nothing new under the sun, which is also an old saying.

DISCLAIMER

resulting in the expelling of fuel from the core to reduce the reactivity. This response is limited by the speed of sound propagation (shock wave). Combined with low excess reactivity the FFRs can be self controlling. They can operate with no externally operated controls, thus the safety can be passive, inherent and non tamperable (PINT). Control rods may be used in FFRs to control the operation temperature. Ultimate shut-down is accomplished by draining the fuel, by gravity, from the critical configuration in the core to guaranteed subcritical configurations in train tanks. These features have been demonstrated in the operation of the Molten Salt Reactor Experiment (MSRE).[2]

There are safety concerns associated with FFR[1]: "Possible fluctuations of reactivity caused by density or concentration changes in the fuel, e.g., bubbling." For MSRs this concern is primarily the coalescence of dissolved gas into large bubbles and their collapse, or in some concepts, such as the MSBR, the expansion of bubbles. To assure that this does not occur, continuous removal of gaseous (fission products) must be employed, usually through sparging. Early concerns of loss of delayed neutrons, which are carried out of the core in external cooling, turned out to be of no significance.

III. MOLTEN SALT REACTORS

The molten salts considered for MSRs are chemically stable. They do not react rapidly with moisture or air. Their chemical inertness precludes accidents that are due to chemical interaction. There is no fire hazard or explosion hazard. They are also compatible and are non-corrosive with respect to suitable structural materials. The experience with the MSRE has shown that high-nickel alloys, combined with adequate oxidation potential balancing of the salt, can result in low corrosion of the structural materials.[3]

The molten salts considered for the MSR are stable to high temperatures at low pressures. This feature allows for high efficiency with no extreme safety demands from the structure materials. Being a liquid system at low pressure eliminates the storage of potential energy or other risk of an energetic burst or explosion. Molten salts are often used in industry as heat transfer media for their inertness and safety. There is ample experience in handling molten salts.

Small spills are not a source of a major accident as there are no violent reactions that can accompany a spill. As a spill occurs, the salt is spread out and cools more efficiently than in the insulated pipes. The salt freezes in place without spreading and is available for recovery operation. The freezing process is inherent and passive. Should there be some residual heat sources in the salt, it will stay molten until it reaches a configuration in which the thermodynamic equilibrium brings it to a freeze.

IV. FREEZE VALVES

The MSR can utilize freeze valves in critical locations or where desired, . Freeze valves can be ordinary sections of pipe which are exposed to a cooling stream of environmental gas to the extent that it creates a frozen plug that blocks the flow and acts as a valve. Where such a valve has a safety function, as in draining the fuel to the storage tanks, it is prudent to design it such that the required flow is gravity driven. The frozen valve itself can be designed such that when the salt rises above a certain, predetermined, temperature the heat overrides the cooling, melts the frozen plug and opens the valve. Such an arrangement is passive, inherent and non-tamperable (PINT-safe). Furthermore, the properly sized external cooling of the freeze valve cooling drive, such as an electric driven fan, will cease with any failure of the power and release the valve to melt and perform its safety function. This mode of operation is again PINT-safe.

V. SEVERE ACCIDENTS

For nuclear reactors it is common to consider three types of severe accidents: criticality accident, failure to remove after heat and a melt down. The melt down is not an accident by itself but rather a description of a consequence of an accident. The concern with a melt down is the possibility of breach of containment and release of the source term, and also a rearrangement of the fuel into a re-critical configuration. For the MSR the fuel melting is, of course, a moot issue since the fuel is in a molten state in its normal operating configuration. A possible advantage of the MSR is that the fuel is subject to freezing, upon breach of a vessel or pipe, and its dispersement. The fuel will disperse, and thus increase its cooling geometry, until it reaches a freezing configuration and thus will be confined to that location and configuration. The design of the MSR must account for such a situation so that recovery, by collecting the fuel and correcting the failure that led to the dispersal, is simple and readily possible. The issues of the source term, recriticality, and after-heat removal are discussed in the respective following paragraphs.

VI. THE SOURCE TERM

The source term, which is the inventory of radioisotopes in the reactor available for dispersion to the environment, contributes two-fold to an accident. The source term is the measure of the radiation which needs to be contained from reaching any sensitive location or target. The energy contained in the source term also provides the driving force for the dispersion of the source term as it is also a measure of the after heat, or the energy, to damage a reactor in the event of heat-removal failure or loss-of-coolant accident (LOCA). For an MSR, as for any fluid fuel reactor, on-line fuel processing can be applied. The on-line processing, at the least, removes the gaseous and volatile part of the source term. This part is the most likely to be dispersed when there is a breach of containment. Fuel processing also reduces the inventory of longer and long-lived isotopes as their accumulation is time dependent. The MSRs processing can be adjusted to have a small source term.[4] The safety advantages of this small source term are many fold: The driving force for dispersion is reduced; the gaseous and volatile components, which are the most likely to disperse, are essentially all but eliminated; the long half-life isotopes (elements) are reduced such that the long-term effect of even the most unlikely accident is not severe; and, the short-lived isotopes require a proportionately short-term protection time till they decay. Thus, even a hypothetical severe accident is ameliorated a priori.

A properly designed processing facility quickly removes the separated radioisotopes from the purview of the reactor. This makes them totally unavailable to the reactor source term even under the most extreme hypothesized circumstances.

VII. CRITICALITY ACCIDENT

In MSRs with processing, the criticality accident is essentially eliminated (See concerns section for exceptions.). There are two factors that make an excess reactivity incident unlikely, temperature control and optimized geometry. The MSR can be temperature controlled. The large negative temperature coefficient allows for control without control rods or other mechanically operated control mechanism. The operability of the reactor under temperature control has been demonstrated on FFR(HRT).[5] The control rods can be used for temperature regulation. Continuous fuel processing, with the ability to externally add fissile material when needed, reduces the need for excess reactivity inventory. There is no need to compensate for burnup as the poisoning fission products are kept at (low) equilibrium. The simple design, particularly when utilizing external cooling, eliminates the possibility of shifting or rearranging materials to result in an increased reactivity. The absence of coolant per se does not provide room that could be filled with shifting fuel to increase reactivity. The MSR can be designed so that bred fuel, at a breeding ratio of 1.0, keeps the reactor at equilibrium with fertile-material feed and with no need to add fissile material. Since the fuel is also the coolant, the reactor is largely temperature controlled regardless of the power.

The adequately designed MSR has an optimum geometrical design for criticality in the core. The externally cooled reactor has neither coolant nor structural materials in the core that may require design compromises and thus can truly be optimized for safety. This core optimization also assures that no criticality, or recriticality, outside the core can occur.

VIII. AFTER HEAT ACCIDENT

The MSR can be designed, with sufficiently rapid processing, that it can contain adiabatically the entire inventory after-heat without reaching boiling.[6] Furthermore, since the fuel is the coolant, in external cooling, a LOCA has no meaning. As a rule, natural convection cooling could be designed but may not be desirable as the temperature controlled reactor will maintain its design temperature regardless of the power. The reaction needed is to drain the fuel, by gravity, into dump tanks that are assured to retain subcriticality and have sufficient natural cooling to assure cooling of the fuel. The activation of the draining can be done by means of freeze valves that assure PINT safety for after heat removal.

IX. CONCERNS

There are two safety concerns for the MSR that can lead to a power excursion. The first of these concerns is the accumulation of gases and volatile materials in the fluid fuel that would coalesce into bubbles that could then collapse at once in the core, resulting in a reactivity excursion. A careful design will ensure that such an event is avoided. The dispersed gases must accumulate over an extended period of time, which allows for removal by sparging, and recognizing and noticing the failure of the gas and volatile removal system. By removing the gases early in the cycle of the fuel from the core to the heat exchanger, the likelihood of the collapse of a bubble in the core can be minimized. The geometrical design of the core can also assure that the added volume has a small reactivity contribution.

The second concern is the cold slug accident. A core with little or no fuel circulation will remain at criticality, while the external fuel can cool down to low temperatures. A sudden reestablishment of the circulation will introduce a slug of cold fuel to the core. Due to the large negative temperature coefficient, this cold fuel represents a reactivity excursion that will result in a power burst. The primary pump, or absence thereof, must be carefully sized to assure that such an excursion does not exceed the design margins of the reactor.

X. THE ULTIMATE SAFE REACTOR (U.S.R)

The Ultimate Safe Reactor (U.S.R) is a special concept of a molten salt reactor with prime and complete emphasis on safety.[7] The U.S.R uses a processing frequency, yet to be developed, that is about an order of magnitude higher from that contemplated for the molten salt breeder reactor (MSBR).[8] The MSBR had a ten day inventory turn around in the fuel processing. The U.S.R uses a one day or less of turn around of the fuel inventory. This rather fast turn around reduces the build up of all fission products with half-lives of a few days or longer. The reactor is an epithermal spectrum reactor and uses no moderator per se in the core. The clean core consists solely of a low-pressure vessel. Freeze valves are used throughout. The prime circulating pump is sized to assure no critical cold slug accident can occur. Furthermore, the U.S.R uses the Th-U fuel cycle with a breeding ratio of exactly one. Thus, the U.S.R has all the safety benefits that are passive, inherent and non-tamperable and, in addition, has proliferation resistant attributes and simplified waste that is free of fissile material, which can be transported in any arbitrary size or quantity from the processing part of the plant.

The U.S.R has no control rods and is temperature controlled by elevation of fuel in the core. The start-up procedure is the pumping of the fuel from its storage or dump tanks into the core. The small pump that accomplishes this transfer is sized such that at maximum capacity the temperature rise rate of the core is within the design limits.

XI. THE ABSOLUTE AND ULTIMATE SAFE REACTOR (A+U.S.R)

The absolute and ultimate safe reactor (A+U.S.R) is a special concept of the U.S.R which utilizes natural convection to transfer the heat from the core to the heat exchanger. The A+U.S.R has no safety related mechanical operating parts nor any externally actuated controls, it becomes the ultimate in PINT safety. The reactor responds internally and inherently to a change in power demand via its temperature response.

Frequent processing of the fuel increases the fuel inventory in the processing part and puts high demand on the performance of the processing units. The removal of the fission products from the fuel stream occurs at low concentrations, which requires precision and sophistication. In an actual plant, an optimization between performance, inventory and safety is needed.

XII. SUMMARY

The molten salt reactor with fuel processing can be designed to be almost as safe as desirable. The basic features of fluoride based molten salts allow for a high temperature, and thus efficient, operation at low pressures. The molten salts are inert and well compatible with selected structural materials. The MSR is not subject to safety concerns from chemical or mechanical violent reactions or explosions. External cooling results in a simple design with few structural requirements that permits optimization of the design for safety eliminating compromises. The on-line processing results in an equilibrium fuel that requires no excess reactivity for burn-up or poison compensation. The fission product inventory, and therefore the source term, is held low. The severe accidents of uncontrolled super-criticality or loss of cooling that fails to remove the after heat can become a hypothetical accident. The dreaded melt down looses all its meaning in a fluid fuel reactor. In an MSR, a spill may be self containing by the freezing of the fuel upon cooling. Freeze valves are one more feature that can make an MSR PINT (passive, inherent, non-tamperable) safe.

The U.S.R and the A+U.S.R are concepts that bring together the safety features of an MSR and result in a reactor with safety features that are beyond current requirements and expectations.

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