LIQUID METAL REACTORS POSTULATED ACCIDENTS

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INTRODUCTION

Liquid metal cooled reactors are characterized with a fast neutron spectrum which allows for fissile fuel breeding in the fast region. Liquid metals such as sodium, lead, lead-bismuth and sodium-potassium eutectic, do not appreciably moderate the neutrons to thermal energy and hence provide the hard spectrum suitable for breeding in the U^{235}-Pu^{239} fuel cycle.

Liquid metals also offer the advantage of high heat transport rates and can operate at atmospheric pressures. Hence upon depressurization in a loss of coolant situation, the coolant does not flash into steam land could be lost like in the case of pressurized water, and hence remains available for core cooling.

Liquid coolants are chemically reactive in air and must be covered with an inert gas. They are also chemically reactive with water mandating the use of double-walled heat exchanger to avoid interaction with water in case of a leakage, causing a fire.

If sodium is used as a coolant, since irradiated sodium in the reactor core forms the isotope Na^{24}; a strong gamma emitter, an extra layer of safety is added by using intermediate activated sodium to inactivated sodium heat exchanger followed by an inactivated sodium to water heat exchanger to produce steam.

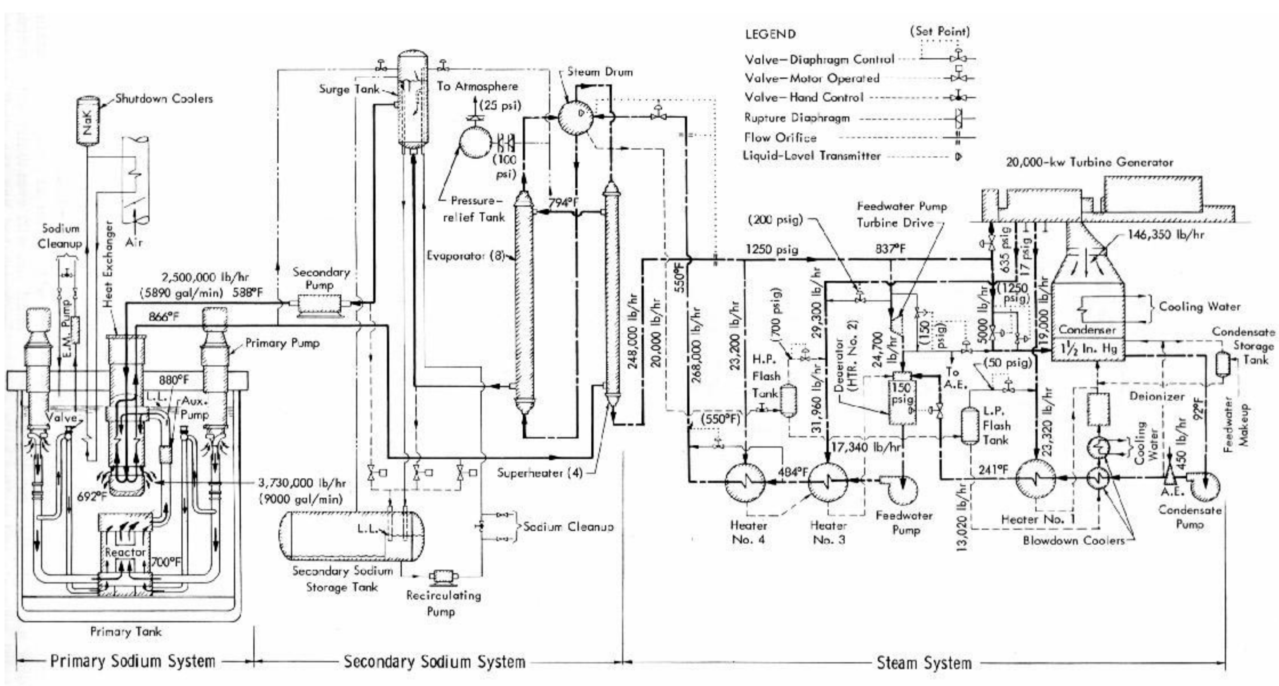

Figure 1. Experimental Breeder Reactor , EBR-II flow chart showing intermediate sodium cooling circuit.

In some liquid metal reactor designs, electromagnetic pumps without moving parts are substituted for impeller pumps.

POSTULATED CORE MELTDOWN ACCIDENT

Liquid metal cooled reactors are characterized by very high fuel ratings resulting in high heat transfer rates and compact cores.

This creates concerns about the consequences of postulated core meltdowns. One particular postulated accident scenario is related to the failure of all the primary Na coolant pumps associated with a complete failure of the reactor shutdown system.

The accident scenario proceeds as follows:

1. Failure of primary coolant pumps and reactor shutdown mechanism.
2. Sodium reaches its boiling point, resulting in voiding.
3. As Na acts as a neutron poison, a positive void coefficient of reactivity ensues.
4. Heating accelerates with an increase in temperature.
5. Within 1 second of the sodium voiding, melting of the fuel and the cladding occurs within a particular assembly.
6. Within the assembly a mixture of molten fuel Na vapor, liquid steel, fuel fragments, fission gases, and steel vapor occurs.
7. As the fuel channel wall melts away, the damage cascades to the adjacent channels.

Simulating these events is difficult since it involves complex interactions the computational fluid dynamics, heat transfer processes and the nuclear interactions. Depending on the particular reactor design and the initial conditions two outcomes have been identified:

a) Power Excursion

If a large portion of the molten core materials remained initially within the active core region, a large reactivity increase occurs resulting in the fuel being blown apart and dispersed by the fission product gases trapped in the interstitials of the fuel pellet. The dispersal increases the surface area and hence increases the leakage, terminating the criticality environment, shutting the fission reaction. In the process, a shock wave may be formed damaging the core region as well as the reactor's containment structure.

b) Core meltdown

If half the fuel inventory gets removed from the active core region through gradual leakage, or molten blanket material dilutes the fuel in the central region, a severe power excursion could not occur.

The molten mixture or "corium material" would fall to the bottom of the reactor vessel. A possible interaction between the corium material and any remaining sodium could lead to a vapor explosion similar to a steam explosion in the case of light water reactors. The corium material could melt through the reactor vessel and gets embedded in the concrete base mat below the reactor vessel.

OPERATIONAL STATES OF LIQUID METAL REACTORS

NORMAL OPERATION AND OPERATIONAL TRANSIENTS

Sodium and lead are not liquid at room temperatures and must be heated. Steam was used to continually heat the lead coolant in the Russian class of alpha submarines and lead to serious operational problems resulting in their eventual decommissioning.

Alternatively, a eutectic of Na-K can be liquid at room temperature and was used as a coolant in the Experimental Breeder Reactor, EBR-I.

In the case of sodium cooled reactors, electrical resistance heating must be continuously maintained after shutdown to maintain the Na whose melting point is 98 ^oC, at a molten state. The resistance heaters are wound around the pipe work to maintain the temperature at 100 ^oC since there exists a time delay in the response to temperature changes.

UPSET CONDITIONS

Several upset conditions are postulated for liquid metal reactors including: loss of electrical load, turbine trip, loss of feedwater cooling, and the loss of a single main coolant pump.

EMERGENCY STATES

1. Loss of electric power, station blackout

An emergency state involves a possible loss of electric power and a resultant coast down of the coolant pumps. However the pool design, rather than the loop design, for a liquid metal cooled reactor adds a substantial layer of safety since it would take 24 hours for the pool of Na to reach its boiling point.

2. Increased reactivity from fuel element bowing or local boiling

Another emergency state would result from the inadvertent increase in the neutron population in the core. This could result from the removal of a control rod, fuel elements bowing or local Na boiling.

To avoid fuel elements bowing as happened in an early EBR-I reactor core, the fuel elements in the core must be allowed to expand upon heating both radially and axially. An expanding core as a result of a temperature transient results in a larger surface area increasing the neutron leakage, decreasing the reactivity, hence the power level and provides a valuable stabilizing negative feedback mechanism.

It must be noticed that local Na boiling results in an increase in the reactivity, and hence a positive temperature feedback mechanism, since the Na acts there as a neutron poison.

On the other hand, if the local boiling occurs in the outer region of the core, this leads to a negative temperature feedback effect since it causes dilation of the core, increasing its surface are and leading to increased neutron leakage, hence decreased reactivity and power level.

3. Fuel channel blockage

Local damage within a fuel subassembly can result from blockage caused by debris blocking the channel. This caused a core meltdown accident at the Fermi-I reactor among the 300, 6 mm diameter fuel pins.

4. Loss of heat removal from secondary systems

These include the Na or steam systems. In this situation is tripped and natural circulation cooling is set up.

The decay heat is removed by the decay heat removal heat exchangers.

PASSIVE, FAIL-SAFE, INHERENT-SAFETY FEATURES

To maintain a high level of safety, liquid metal cooled reactors are designed to maintain two concurring cooling circuits:

1. Forced circulation in the primary circuit cooling through the intermediate Na circuit to the steam generators.
2. Natural circulation of the primary circuit using a separate liquid metal cooling circuit to an air-cooled heat exchanger outside the containment walls. This provides a "walkaway" safety capability of the liquid metal reactor core that is not available in other reactor concepts that depend on active safety systems requiring the intervention of human operators as well as the availability of onsite and offsite power supplies under natural disasters or accident conditions.

The possibility, but not probability, of the criticality and core meltdown postulated accidents, has called for careful consideration of the reliability and redundancy of the shutdown systems in liquid metal cooled fast reactors.

A suggested approach is the design approach of arranging the core structures so that an excessive increase in core temperature would cause thermal expansion of the core leading to increased leakage and a subsequent shutdown of the fission reaction.

Another recommended feature is the configuration of the core as a flat pancake shaped cylinder, or even better, an annular core. Such configuration would constitute a "fail-safe" passive safe design of the liquid metal cooled fast reactor core.