Molten-salt reactor MSR

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Note
In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

Molten salt reactors

A molten salt reactor (MSR) is a class of nuclear fission reactor in which the primary nuclear reactor coolant, or even the fuel itself, is a molten salt mixture. MSRs run at higher temperatures than water-cooled reactors for higher thermodynamic efficiency, while staying at low vapor pressure. The nuclear fuel may be solid or dissolved in the coolant itself. In many designs the nuclear fuel is dissolved in the molten fluoride salt coolant, e.g. uranium tetrafluoride (UF_4). An MSR is not typical for thorium-based systems, for it can be fuelled by enriched uranium-235, plutonium and uranium-233. The fluid becomes critical in a graphite core which serves as the moderator. Solid fuel designs rely on ceramic fuel dispersed in a graphite matrix, with the molten salt providing low pressure, high temperature cooling.

The Aircraft Reactor Experiment ARE (1954, 2.5 MW(th)) was primarily motivated by the small size that the design could provide. The Molten-Salt Reactor Experiment MSRE (1965–1969, 7.4 MW(th)) was a prototype for a thorium fuel cycle breeder reactor nuclear power plant. The reactor was fuelled by a mixture of LiF-BeF_2-ZrF_4-UF_4; the breeding blanket of thorium salt was omitted.
As of 2011, the ARE and the MSRE remained the only molten-salt reactors ever operated, according to [MSRwiki 2016] Q693.

Although the concept is not new there is a renewed interest in thorium-fuelled MSR technology in China, Japan, Russia, France and USA, along with other Generation IV reactor technologies. One of the Generation IV reactor designs is a molten-salt-cooled, molten-salt-fuelled reactor; the initial reference design is 1000 MWe.

Seaborg Wasteburner/ Copenhagen Atomics Wasteburner

The Seaborg Wasteburner [Seaborg 2015] Q695 and Copenhagen Atomics Wasteburner [Copenhagen Atomics 2014] Q694 are similar in design.
Without discussing both concepts in detail, some remarks may be appropiate.

Molten Salt Reactor MSR

As far as known only two small experimental molten salt reactors have ever been operated in the world, both in the USA and both based on enriched uranium-235 as fissile material:

- ARE, Aircarft Reactor Experiment, in 1954, power 2.5 MWth
- MSRE, Molten Salt Reactor experiment, during 1965-1969, power 7.4 MWth

The MSRE was intended to explore the possibilities of an MSR with thorium, but the experiments were finished without thorium in the reactor.
The MSR technology is far from proved, not even a pilot plant has been constructed, let alone a full-scale installation (1000-3000 MWth).

Integrated Fast Reactor IFR

The IFR concept comprises a fast reactor with an integrated reprocessing facility to remove fission products, so the the reactor could operate without removal of spent fuel and loading with fresh fuel.
This concept has never been tested. Some partial laboratory experiments have been conducted to explore some chemical implications of the separation processes.

Th-232/U233 breeding cycle

Thorium (consisting of nearly 100% Th-232) is not fissile and has to be converted into fissile uranium-233 by irradiation with neutrons. This would imply a breeding cycle (see text above). A crucial part of that cycle is the reprocessing of the irradiated fuel, to separate the newly formed U-233 from the remaining thorium-232 and to remove fission products. Reprocessing is a very complicated process. The separation processes comprise chemical and physical equilibria which are governed by the Second Law of thermodynamics. It is principally impossible to achieve 100% perfect separation and to produce 100% pure materials. In practice this means that all fractions after a separation process are impure and that a part of the wanted and unwanted materials will be lost into the waste streams.

Unavoidable contamination

The recovered U-233 would unavoidably be contaminated with highly radioactive non-fissionable isotopes of uranium (U-232, U-234 and U-236). Reprocessing of fuel from a thorium reactor would become more difficult after each cycle, because of the increasing radioactivity. The materials could only be handled by remote control, for reason of the high radioactivity.
Because all uranium isotopes have identical chemical properties, the unwanted isotopes cannot be removed from uranium-233 by chemical separation processes (reprocessing).

Thorium reactor

As far as known there exists only one experimental U-233 reactor in the world: the 0.03 MWth Kamini in India.

Containers

The concept of the Copenhagen Atomics Wasteburner with the reactor and associated installations packed in containers may be derived from the early concepts investigated in the USA during the 1950s of military power units to be used in remote locations. This container concept has been abandoned after the first experiments in the 1950s.

Prototype

The prototype of the Copenhagen Atomics Wasteburner would have a nominal power of 50 MWth. For comparison: the present world operating nuclear capacity is some 370 GWe, or roughly 1 000 000 MWth.

Hybrid reactor

A genuine Th-232/U-233 reactor cannot sustain the fission process: the rate of forming new U-233 nuclides from Th-232 would be lower than the rate of fissioning U-233 nuclides. This implies that a thorium reactor always needs an extra neutron source either by fissioning added U-235 or plutonium, or from an external accelerator-driven neutron source.

Burning actinides

Both Wasteburner concepts claim that transuranic actinides from conventional nuclear fuel, from the existing nuclear power plants, can be burned. This would imply that conventional nuclear fuel has to be reprocessed first, to remove the fission products and unused uranium. Reprocessing of spent nuclear fuel is an extremely contaminating and extremely expensive process.
The transuranic actinides are highly radioactive and very difficult to handle. Moreover spontaneous fission of these radionuclides may make the fission process in a reactor difficult to control.

Reprocessing waste

In both Wasteburner concepts handling of the removed fission products is unclear. Are the gaseous fission products discharged into the air? What happens with the other wastes? How are the removed from the sustem?

Timescale

It would take decades to generate sufficient U-233 in special (non-power) reactors to start up the first thorium reactor. Even if the Th-232/U233 cycle would work as advertised, it would take many doubling times of the breeder to come at the present nuclear capacity. The timescale would have to be measured in centuries.

Energy balance

The energy investments required to construct a given thorium system, to operate, maintain and refurbish it during its operational lifetime and to decommission the installations after their useful life ended might be prohibitive: most likely the system would work as an energy sink instead of an energy source.

Second Law

Examining the crucial components of the Wasteburner concepts, it can be concluded that these systems are inherently infeasible, because they are implictely based on the assumptions of 100% perfect separation processes, 100% pure materials and the absence of ageing processes. These assumptions are in conflict with the Second Law of thermodynamics.

Some other alleged advantages of thorium reactors are disproved by [PSR-IEER 2009] Q617 and [Lovins 2016] Q696.

Epilogue

A quote from Amory Lovins in The Ecologist [Lovins 2016] Q696 seems to apply to publications such as [Copenhagen Atomics 2014] Q694, [Seaborg 2015] Q695 and [SAMOFAR 2015] Q697:
"The nuclear industry is forever reinventing itself with one brilliant 'new' idea after another, Amory Lovins wrote in this classic 2009 essay. But whether it's touting the wonders of future SMRs, IFRs or LFTRs, the reality never changes: the reactors they are building right now are over time, over budget and beset by serious, entirely unforeseen technical problems."

A quote from Admiral Rickover, quoted by Amory Lovins, seems also to apply to above optimistic publications, and many other, on this subject:
"No new kind of reactor is likely to be much, if at all, cheaper than today's LWRs, which remain grossly uncompetitive and are getting more so despite five decades of maturation. 'New reactors' are precisely the 'paper reactors' Admiral Rickover (mastermind of the US Navy's development of the Pressurized Water Reactor, the PWR) described in 1953:
"An academic reactor or reactor plant almost always has the following basic characteristics:

It is simple.
It is small.
It is cheap.
It is light.
It can be built very quickly.
It is very flexible in purpose.
Very little development will be required. It will use off-the-shelf components.
The reactor is in the study phase. It is not being built now.

On the other hand a practical reactor can be distinguished by the following characteristics:

It is being built now.
It is behind schedule.
It requires an immense amount of development on apparently trivial items.
It is very expensive.
It takes a long time to build because of its engineering development problems.
It is large.
It is heavy.
It is complicated."

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