Liquid Fluoride Thorium Reactors

Devin Battice

Thermodynamics ENGR-312

Abstract

As the world continually increases its energy consumption, power generation must continually be advanced to become more efficient, safer, and to seek new sources in order to maintain our standard of living. Although nuclear energy has been used as a power source since the 1950's, there is an increasing interest in using thorium for nuclear reactors due to its abundance and increased safety over uranium. This paper will examine thorium as a fuel source in liquid fluoride thorium reactors.

Background

Nuclear reactors work based on a few principles. The first is that when radioactive atoms collide with neutrons the atoms break apart into smaller atoms and releases a massive amount of energy. This process of atoms breaking apart is called fission. Fission is the same process that nuclear bombs go through when they are detonated. The energy released by fission in a nuclear reactor is mainly heat which goes through a heat exchanger (Bahri, Majid, Al-Areqi, 2015). The energy from the heat exchanger then increases the temperature of the water that flows through a turbine; the turbine spins a magnet which induces an electric current as explained by Faraday's Law. The current is the source of the electrical power produced by a nuclear power plant (Chiang et al., 2014).

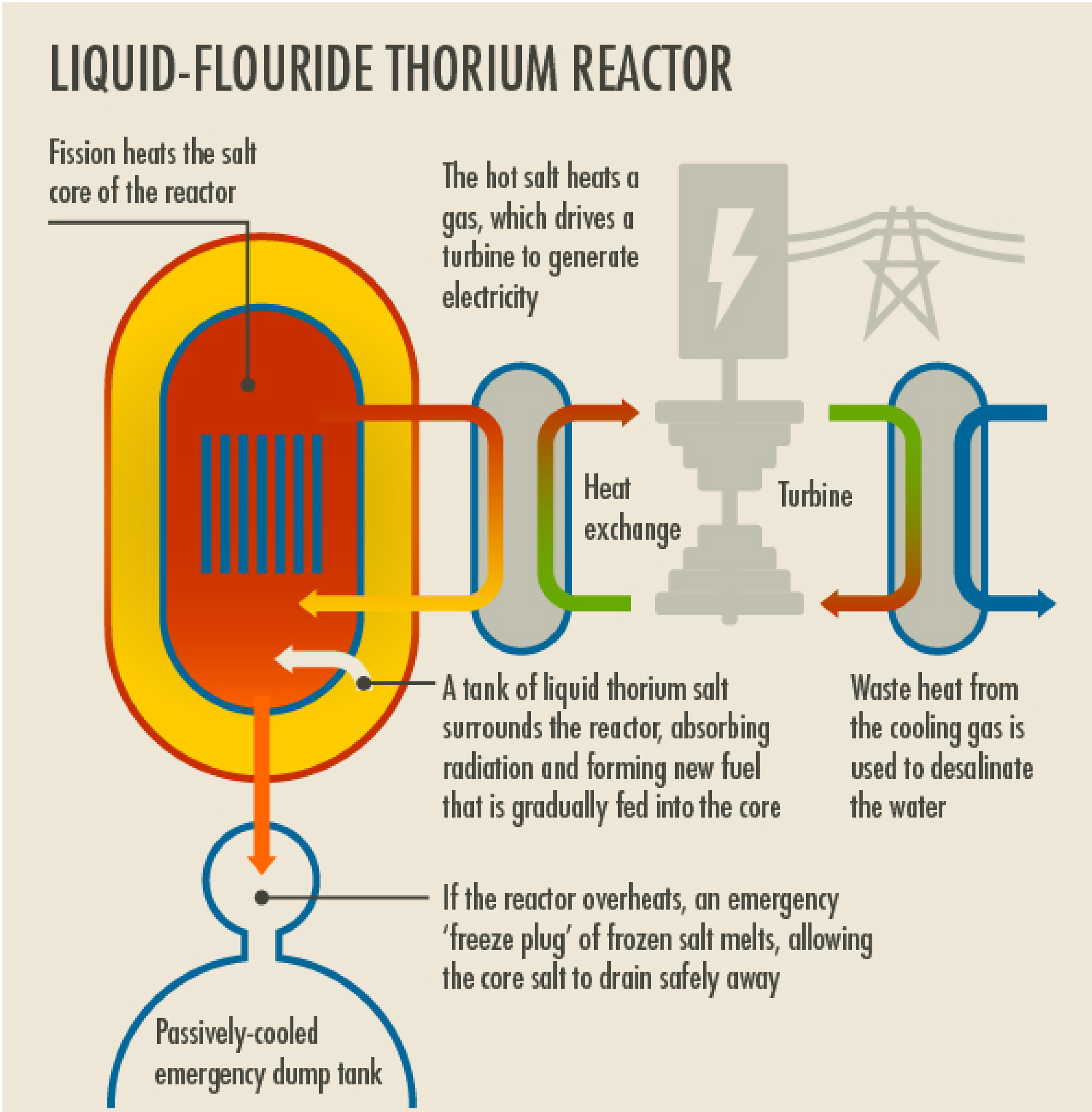
In the past few years, there has been an increase in the interest for using thorium in nuclear reactors. One nuclear reactor design that uses thorium as a nuclear fuel is called the liquid fluoride thorium reactor (LFTR). which is also called molten salt reactor, fluoride salt high-temperature reactor, or molten salt fast reactor. This means that thorium is the main fuel, and a liquid salt mixture containing fluoride is used as a coolant to prevent the nuclear core from becoming too hot. A LFTR still involves a nuclear reaction generating heat which increases the temperature of steam that turns a turbine. LFTRs are an attractive option because of its natural safety features, fuel sources, radioactivity, efficiency, and for the potential of other industrial uses.

Details of LFTR

The LFTR involves putting uranium-233 in a reactor and surrounding it with thorium dissolved in a fluoride salt that also contains lithium fluoride and beryllium fluoride called FLiBe (Bahri et al., 2015). The uranium-233 decays and releases neutrons, and those neutrons fuse with thorium-232 atoms to become thorium-233 and releases energy (Bahri et al., 2015). The thorium-233 decays into protactinium which then decays into uranium-233 which started the process (Bahri et al., 2015). When using thorium as a fuel source, the thorium is bonded to fluorine, which not only contains the neutrons from the decaying atoms, but also cools the reactor, containing the reaction. The inner core carries heat to a heat exchanger that heats helium (Hargraves, Moir, 2015). The helium then turns a turbine producing energy (Bahri et al., 2015). The image below gives a nice representation of a LFTR (see pg.4).

Controlling the reaction

In the reaction when the heat is released, the fluoride mixture has what is called a negative temperature reactivity coefficient (Juhasz, 2014). As the salt heats up, it expands and at the same time slows down the nuclear reactions. This means that the hotter and faster the nuclear reactions happen, the more the salt will expand to slow down the reactions and thus the reactor regulates itself. The negative temperature reactivity coefficient is a huge safety feature that no other energy source has. Even in an emergency, and even if the salt mixture becomes too hot or too dangerous, there is a backup in place that can stop the reaction. This backup system is a freeze plug located below the reactor, which when heated, melts, and then the fuel drains to another tank (Jaradat, 2015). The tank slowly lets the heat transfer away from the salt mixture. Since the heat plug works by gravity and heat, the drainage of the reactor will happen even if there is no external power being supplied to the reactor (Lam, 2013). Additionally, there is almost no chance of a LFTR exploding. LFTRs only need 500 kilopascals of pressure to operate properly, which is thirty times less than pressurized water reactors, another type of nuclear reactor (Greaves, Furukawa, Sajo-Bohus, Barros, 2012). The reason other reactors are so highly pressurized is so the water can be a liquid at a higher temperature and still act as the coolant (Bahri et al., 2015). Also, the fluoride salt has a boiling point that is 700K higher than operating temperature (Greaves et al., 2012). The high boiling point of FliBe further reduces the chance of an explosion in the core (Bahri et al., 2015). The LFTR does not require fuel rods to regulate the reaction because the reactor is self-regulating as discussed previously (Bahri et al., 2015).



http://illumin.usc.edu/assets/media/1067/thorium_reactor04.jpg

Abundance

LFTRs also have a greater abundance of available fuel compared to traditional reactors. LFTRs can take the excess fuel from uranium reactors and use that as fuel, meaning there is more available fuel than just using thorium (Serp et al., 2014). Additionally, the total radioactivity can be reduced further using the stockpiles of nuclear waste that currently do not have another use (Serp et al., 2014). LFTRs can take other highly radioactive materials and use them as fuel, in addition to the thorium and uranium LFTRs are designed for, with only slight modification to the salt coolant (Heuer et al., 2014). This reduces radioactive waste from other nuclear reactors. LFTRs can also take old nuclear material from nuclear weapons and spent fuel from other reactors and use that as fuel (Greaves et al., 2012). Using different sources for nuclear fuel is good because not only does it increase the available fuel, but also reduces the potential of making more nuclear weapons and gets rid of nuclear weapons in the best way possible. Additionally thorium is three to four times more abundant on earth (Ade et al., 2014).

Radioactivity

In addition to using other radioactive sources as fuel, LFTRs can be used to reduce overall radioactivity because it produces less plutonium than uranium-fueled reactors (Ade et al., 2014). Having less plutonium is important because the radioactivity of a nuclear reactor is over 100 times greater if the reactor contains plutonium-239 (Li et al., 2015). Plutonium-239 is also the best material that has been found to make a nuclear weapon (Greaves et al., 2012). LFTRs themselves are safer than traditional nuclear reactors because of the higher amount of uranium-232 and uranium-233 (Basak, 2016). Uranium-233 is considered safer because it is extremely radioactive, and thus very dangerous to try assemble a weapon out of it (Greaves et al., 2012). Since uranium-233 is the preferred material for the core of LFTRs, it is beneficial that uranium-233 is being used in LFTRs because then all of the energy from the radioactive atoms being produced is exactly what makes the reactor run well. Thorium is added to reactors to increase the amount of uranium-233 (Ade et al., 2014).

Efficiency

LFTRs do not need to be shut down frequently like uranium reactors do, because more fuel can be added to the reactor core to keep the reaction going instead of having to replace the fuel rods (Chiang et al., 2014). In LFTRs, fuel rods are not needed, which makes the energy cheaper because the plant can run for longer periods of time without shutting down for maintenance and because there is less processing of the fuel (Greaves et al., 2012). Because the thorium that is added is converted into the uranium, the fuel is completely burnt up in the nuclear reactions (Bahri et al., 2015). Also, uranium reactors only convert three percent of uranium fuel into electrical energy before the fuel rods are changed to prevent damage to the fuel rods (Bahri et al., 2015). Fission byproducts can remain in the reactor until they decay even further, so the reactor does not have to be shut down to remove waste (Bahri et al., 2015). In LFTRs less fuel needs to be added because the fuel added is completely burnt up (Basak, 2016). Since LFTRs operate at higher temperatures, they can run more efficiently (Shriver, Blyth, Lowery, Thesling, Smith). Thorium reactors also have 300 times the energy density compared to current nuclear power plants, which means that LFTRs will take up much less space to produce the same amount of energy (Juhasz, 2014). The thermal to electrical power is roughly 45-50% in LFTRs instead of 30-35% in traditional reactors (Bahri et al., 2015). One ton of thorium is equivalent to the energy of thirty five tons of enriched uranium, meaning there is less mining needed to obtain thorium for LFTRs (Bahri).

Other Applications

Although LFTRs are efficient, they can also be used for other purposes than electricity generation by using some of the heat that is produced by the nuclear reactions. There have been a few ideas on how to use the excess heat in order to increase the total efficiency and utility of LFTRs. One such application of heat is cogeneration (Plehanov, 2015). Cogeneration can be useful to get an even higher efficiency and allow the electricity to be used for other purposes while still providing heat to several homes. Another potential use of LFTRs is to desalinate water (Juhasz, 2014). The excess heat from LFTRs could also be used to grow food in greenhouses in cold climates, decreasing reliance on warmer places to produce food (Plehanov, 2015). LFTRs could also produce isotopes for medical uses and hydrogen for use in hydrogen fuel cells (Plehanov, 2015).

Lack of Experience with LFTRs

One major challenge for LFTRs integration in mainstream use is that not as much research has been conducted on them as has been conducted on uranium reactors. A major cause of lack of research is that the United States government stopped research in thorium because uranium was considered more efficient in the past and uranium could be turned into a nuclear weapon (Bahri et al., 2015). Suspending the research into LFTRs set back research into alternative fuels for nuclear reactors by decades. Only recently have countries started to consider a nuclear fuel besides uranium. There currently is not enough information available about LFTRs to make a very efficient and cheap reactor (Basak, 2016). There is also a question of how to separate the various compounds from the FliBe mixture.

The other challenge LFTRs face is the cost. However, the costs for LFTRs are mainly due to the initial construction and the decommissioning (Chiang et al., 2014). The actual power generation of the plant is a very good investment with very cheap maintenance and operation costs (Chiang et al., 2014). The construction costs will go down as more research will determine the most efficient way to build a reactor and as more reactors are built (Hargraves, Moir, 2011).

Bibliography

Ade, B., Worrall, A., Powers, J., Bowman, S., Flanagan, G., & Gehin, J (2014). *Safety and Regulatory Issues of the Thorium Fuel Cycle* (No. ORNL/TM-2013/543; NUREG/CR-7176). Oak Ridge National Laboratory (ORNL). Oak Ridge, TN (United States).

Bahri, C. N. A. C. Z., Majid, A. A., & Al-Areqi, W. M (2015, April). Advantages of liquid fluoride thorium reactor in comparison with light water reactor. In A. A. Mohamed, F. M. Idris, K. Hamzah, & A. B. Hasan (Eds.). *AIP Conference Proceedings* (Vol. 1659, No. 1, p. 040001). AIP Publishing.

Basak, U (2016). Thorium Fuel Cycle Activities in IAEA. *Thorium Energy for the World, ISBN 978-3-319-26540-7. Springer International Publishing Switzerland, 2016, p. 51*, 51.

Chiang, H., Jiang, Y., Levine, S., Pittard, K., Qian, K., & Yu, P (2014). Liquid Fluoride Thorium Reactors: Traditional Nuclear Plant Comparison Analysis and Feasibility Study.

Greaves, E. D., Furukawa, K., Sajo-Bohus, L., & Barros, H (2012, February). The case for the thorium molten salt reactor. In R. Alarcon, E. Ayala, C. Granja, & N. Medina (Eds.)., *AIP Conference Proceedings* (Vol. 1423, No. 1, pp. 453-460). AIP.

Hargraves, R., & Moir, R (2011). Liquid fuel nuclear reactors. *Physics and Society 40 (1)., 6-10 (January, 2011). http://www.aps.org/units/fps/newsletters/201101/hargraves.cfm*.

Heuer, D., Merle-Lucotte, E., Allibert, M., Brovchenko, M., Ghetta, V., & Rubiolo, P (2014). Towards the thorium fuel cycle with molten salt fast reactors. *Annals of Nuclear Energy*, *64*, 421-429.

Jaradat, S. Q. M (2015). Impact of thorium based molten salt reactor on the closure of the nuclear fuel cycle.

Juhasz, A. J (2014). Gas Turbine Energy Conversion Systems for Nuclear Power Plants Applicable to LiFTR Liquid Fluoride Thorium Reactor Technology.

Lam, S (2013). Economics of Thorium and Uranium Reactors. *Economics*.

Li, X. X., Cai, X. Z., Jiang, D. Z., Ma, Y. W., Huang, J. F., Zou, C. Y., .. & Chen, J. G (2015). Analysis of thorium and uranium based nuclear fuel options in Fluoride salt-cooled High-temperature Reactor. *Progress in Nuclear Energy*, *78*, 285-290.

Plehanov, A. V (2015). *On the possibility of a small nuclear reactor application for energy supply of isolated communities in Northern Canada* (Doctoral dissertation, University of British Columbia).

Serp, J., Allibert, M., Beneš, O., Delpech, S., Feynberg, O., Ghetta, V., & Luzzi, L (2014). The molten salt reactor (MSR). in generation IV: overview and perspectives. *Progress in Nuclear Energy*, *77*, 308-319.

Shriver, M., Blyth, G., Lowery, A. D., Thesling, W., & Smith, J. E. THE FEASIBILITY AND PRACTICALITY OF INTRODUCING THORIUM INTO THE CURRENT ENERGY MARKET.