COMMENTS ON LIQUID FLUORIDE THORIUM REACTOR (LFTR) TECHNOLOGY PROVIDED TO THE DEPARTMENT OF ENERGY AND CLIMATE CHANGE

FUEL UTILIZATION

LFTR utilizes a LiF-BeF2-UF4 fuel salt and a LiF-BeF2-ThF4 blanket salt and is designed for a conversion ratio of 1.0 or better. This has an excellent chance of being met or achieved based on the analyses done by ORNL in the late 1960s on the two-fluid Molten-Salt Breeder Reactor concept. In that design, they projected a breeding ratio of 1.07 using straightforward processing techniques such as fluorination, distillation, and reduction.

The modern LFTR concept strives to achieve a breeding ratio of 1.0 or better. With fission gas removal of xenon poisons, batch distillation and steady removal of U-233 from the blanket salt, this should be readily achievable. With this strategy, the reactor will not require any continued uranium input to sustain its nuclear power generation and will require only roughly one metric tonne of thorium per gigawatt-year of energy generation.

This performance is substantially in excess of the fuel cycle performance of any of the fast breeder options, which must depend on pyroprocessing or PUREX to move bred fissile material from solid blanket elements to solid fuel elements. Furthermore, the pyroprocessing or PUREX processing techniques suffer inevitably from losses in the dissolution and reconstitution of fuel elements. This step is entirely missing from the LFTR fuel processing sequence, leading to improved performance.

HIGH-LEVEL WASTE VOLUME

The volume of high-level waste produced by a reactor is a key factor in its long-term storage. MSRs as a class of reactors can have a variety of different fuel cycles and waste forms. LFTR technology being developed by Flibe Energy Inc. has a simple and well-defined fuel cycle that dates back to the 1960s. The fuel salt (and LiF-BeF2-UF4-fission product fluorides) is fluorinated, leading to the removal of uranium and volatile hexafluorides from the fuel salt. The volatile fission products will be recovered and many can be applied in commercial industry instead of disposed of as waste. The uranium is returned immediately to reconstituted fuel salt. The remaining salt mixture (LiF-BeF2-nonvolatile fission product fluorides) is then distilled at high temperature. LiF and BeF2 boil off and are recovered and purified, leaving only stable nonvolatile fission product fluorides. These processes were actually demonstrated in the Molten-Salt Reactor Experiment (MSRE).

After the extraction of valuable materials such as neodymium and other radiologically stable rare-earths, the amount of nonvolatile fission product fluorides will have been reduced in mass and volume considerably. After a suitable cooling period, these can then be formed into iron fluorophosphate glass which is a stable disposal form suitable for geologic disposal without additional conditioning. This final form represents nearly a theoretical minimum for high-level waste volume, having been stripped of the carrier salt (LiF-BeF2) and actinides, as well as all gaseous and volatile hexafluoride fission products. Graphite used for moderator is removed from the reactor and oxidized to CO2 and vented. The fluoride chemical form is more stable than the oxide form and chemical conversion of fission products is not expected.

LONG-TERM HEAT-OUTPUT AND RADIOTOXICITY
Long-term heat output and radiotoxicity are absolutely minimized in the LFTR waste stream by the exclusion of transuranics that have long-term decay heat output and radiotoxicity, important considerations for repository management. LFTR does substantially better in this respect than the fast-reactor options for which aqueous processing or pyroprocessing techniques lead to actinide loss and inclusion in the waste stream.

ENVIRONMENTAL IMPACT
LFTR minimizes environmental impact relative to other reactor options. The physical footprint of the LFTR plant is much smaller (for a given power rating) than other existing reactor options. The physical footprint of the nuclear plant can be minimized relative to other reactors by the use of a high-core-power-density reactor with dense heat transfer fluid in a close-fitting containment driving compact power conversion equipment. All of these factors also offer a dramatically reduced cost of construction of a LFTR relative to solid-fueled reactor concepts.

Thorium is already obtained as a rare-earth mining byproduct so thorium use does not constitute an additional environmental burden from the mining perspective. The high temperature operational characteristics of the LFTR mean that air-cooling can be productively utilized, freeing up the reactor to be sited in a variety of locations, unlike the steam-cycle-based fast reactor options which still depend on a water supply for the condensing of low-pressure steam. Siting flexibility also allows long-distance power transmission to be minimized, further reducing environmental impact.

The fuel and blanket processing techniques used in the LFTR (fluorination in the blanket, fluorination/reduction/distillation in the core salt) are conceptually simple, radiation-hard, and do not pose criticality-safety concerns like the aqueous processing techniques used in some fast reactor processing options. They occupy little physical space and are built to operate in a continuous-flow manner with the reactor inside the containment structure. This maximizes their capacity factor and minimizes the flow rate needed through the processing steps, which minimizes the environmental impact.

DIVERSION OF MATERIALS OR SABOTAGE
A LFTR is designed to retain fissile material in the system, from the blanket to the core and throughout the recycling system. To alter the passage of fissile material after the reactor is operating would be exceptionally difficult. The entire primary loop would be inside a stout containment structure that is not designed to be opened—quite unlike a solid-fueled reactor whose containment is designed to be opened and whose reactor vessel much be opened for refueling operations. The entire primary loop is also protected by high temperatures and strong radiation fields.

The uranium-233 fuel in a LFTR is strongly contaminated by uranium-232 and is thus a very poor candidate for diversion. Indeed, there are 70,000 nuclear weapons in the world and none are based on uranium-233 or the thorium fuel cycle. All of them are based on uranium-235 and plutonium-239. The LFTR, with its high temperatures, strong radiation fields, and inherently unattractive fuel for diversion, is very proliferation resistant.
Also, the reactor operates at low pressure, so there is no high-pressure stored energy to release through a compromised pressure vessel. The fuel is fluid and freezes at temperatures below 400°C, so even an intentional breach of the reactor vessel, depending on its size, could range from a situation where the frozen salt “plugs” the breach to a situation where the liquid salt runs down the side of the reactor, drips into the catch basin, and drains into the drain tank, as it would under a standard shutdown.

The fluoride reactor has no chemical stored energy since it uses a chemically-stable fuel form that will not react vigorously with air and water. This is a significant advantage relative to metal-cooled reactors that must contend with the potential chemical energy release of liquid-sodium and metal fuel when exposed to air or water, which could lead to the mobilization and release of radioactivity.

PROLIFERATION RESISTANCE
It is difficult to create uranium-233 without forming uranium-232. Uranium-232 has a half-life of 69 years and follows the same decay chain as thorium-232. The thorium-232 decay chain includes thallium-208 and bismuth-212, both of which emit strong gamma radiation.

U-232 as a contaminant in U-233 can play a role in nonproliferation of nuclear weapons and still allow U-233 to be used in the nuclear fuel cycle. A recent work by Dr. Ralph Moir, commissioned by Lawrence Livermore Laboratory, describes the two features of U-232, its gamma radiation and its heat release, both of which causes problems for use in nuclear weapons. The gamma radiation at low levels causes health problems and even death for people nearby after prolonged exposures. At high levels it causes degradation of the high explosives of the weapons after a sufficiently long exposure. The heat causes problems in weapons design, for example, thermal degradation of high explosives. These properties of U-232 are quantified in his note. The role of U-232 as a potential nuclear weapon contaminant is similar to that of Pu238 in that both give off troublesome heat, U-232 much more than Pu-238, but the strong radiation from U-232 makes its role unique as Pu-238 has little radiation associated with it.

Dr. Moir's examinations of gamma doses and heat generation indicated that the high explosives used in weapons would be degraded sufficiently to render them unsuitable for stockpile use by a nation-state.

References:
LLNL-TR-438648, "U232 Nonproliferation Features", Ralph Moir, June 2010

RELIABILITY
A LFTR can be continuously refueled with uranium-233, which is generated in the blanket and extracted through fluorination and then reduced to UF4 in the core salt. In contrast, a typical reactors must be shut down for solid fuel removal, addition, and reshuffling. LFTRs use a fuel form that is impervious to radiation and they maintain their reactivity through the continuous addition of new fissile material generated in their blankets. They effortlessly reject the most significant of the fission product poisons, xenon-135, through the natural off-gassing of fission product gases in the primary salt pump. This effect was conclusively demonstrated in the successful five-year operation of the Molten-Salt Reactor Experiment from 1965 to 1969.
Despite being simply an experiment, that reactor showed very high reliability in operational modes.

SAFETY AND RADIOLOGICAL EXPOSURE
Radiological exposures are minimized with the LFTR because, unlike solid-fueled reactors, there is never the need to shut down, depressurize the reactor, remove, reshuffle, and replace solid fuel. The entire core fuel inventory is homogeneous in composition and the reactor is continuously refueling itself through the operation of the blanket and the fluorination/reduction processing system. There is no need to add fuel or remove fuel. Since refueling of a solid-fueled reactor is the primary pathway to radiological exposure of workers, this is a very important feature.

MSRs and LFTRs in particular have a compelling safety case relative to solid-fueled reactors.

There are several bases for this argument:
1. Absence of stored energy sources (pressure, chemical reactivity, etc.)
2. No excess reactivity
3. Strongly-negative temperature coefficients of reactivity
4. Totally passive decay heat removal
5. Fuel form that does not undergo structural or chemical changes
6. Chemically stable environment for fission products (in particular strontium, cesium) and continuous removal of volatile fission products (e.g., xenon, krypton).

Primary safety concerns for any reactor type are decay heat management and reactivity control. These have been the bases for the major nuclear accidents that have taken place in the world. Three Mile Island-2, Windscale, and Fukushima were all related to decay heat management, and Chernobyl and SL-1 were accidents related to reactivity control.

Decay heat removal in nearly all MSRs and certainly in LFTR is benefitted tremendously by the low operating pressures of the reactor. There is no "driving" term seeking to move radioactivity out of the reactor. No depressurization issue to contend with like in a light-water reactor or a gas-cooled reactor.

Furthermore, if primary heat removal is lost, only fluid-fueled reactors like MSRs and LFTRs can "downshift" into a completely different core cooling configuration.
REACTIVITY CONTROL
The conclusion to ORNL-2997 states:

"At high powers, the MSRE is a highly damped system. It returns to its original power level rapidly with no undershoot or wallowing. At low power levels, the uncontrolled reactor tends to be sluggish and slow in returning to its original power level. With the reactor at 1 MW, it was observed that over 400 sec was required for the flux level to stabilize after a step change in reactivity. In summary, the MSRE was stable at all power levels and the stability increased with power as predicted."

References:


ORNL-TM-2571, "Theoretical Dynamic Analysis of the MSRE with 233U Fuel", July 1969

ORNL-TM-1647, "Experimental Dynamic Analysis of the MSRE", October 1966
FUEL THERMAL RESPONSE
Fuel thermal response is another area of tremendous strength for a LFTR. The fuel has a high heat capacity, is chemically stable, is impervious to radiation damage, and inherently generates a strongly stabilizing response to thermal transients. Fluoride salt is nearly as close to the perfect form of nuclear fuel as any devised by man. It has low neutron absorption; it readily accepts a large variety of different fissile materials; it is impervious to radiation damage; it is easily separated from gaseous fission products; it has attractive thermal expansion characteristics that yield a strongly negative temperature coefficient of reactivity; and its chemistry is ideal for the thorium-uranium fuel cycle.

Because of the good self-regulating characteristics of the MSRE, the system is quite simple to control. In more than 15,000 hours of critical operation, not once did the MSRE have the nuclear power, period, or fuel temperature go out of limits so as to cause a control-rod scram.

Reference:

FUEL CYCLE
Inside a liquid fluoride thorium reactor, or LFTR (pronounced LIF-ter), the processes of the thorium fuel cycle are manifested in the equipment of the reactor. Thorium in the outer region of the reactor, called the “blanket”, absorb about half of the neutrons produced in fission. As uranium-233 is formed in the thorium blanket, it is removed by fluorination from uranium tetrafluoride (UF4) which is its stable chemical form in the salt, to uranium hexafluoride (UF6) which is a gas and will come out of solution from the blanket salt. Thorium exists only as a tetrafluoride (ThF4) and has no gaseous hexafluoride state, so uranium is removed while thorium is left behind in this straightforward chemical process. Uranium fluorination is done every day on tonnage scale as part of today’s preparation of uranium fuel for enrichment and is a well-understood chemical process.

Once the uranium hexafluoride gas is removed, it is reduced back from UF6 to UF4 in the presence of the “core salt” of the LFTR using hydrogen gas. Thus the core salt is constantly refueled by new uranium-233 produced in the blanket and the uranium-233 consumed in fission is replaced. In a similar manner the blanket is continually creating new uranium-233 from thorium using the neutrons from fission in the core salt. Thorium tetrafluoride is fed into the blanket to make up for the consumption of thorium in the blanket.

After reduction in the core salt, hydrogen fluoride (HF) gas is produced and recovered from the reduction column. It is then electrolyzed to produce fluorine (F2) gas for the fluorinator and hydrogen (H2) gas for the reduction column. HF electrolysis units are common industrial equipment and allow the HF to be recycled indefinitely.
Periodically or continuously, depending on the economics, the core salt is fluorinated and distilled to remove fission products from the core salt. The regenerated core salt is then returned to the core. The chemical form of the salts renders them impervious to radiation damage, allowing them to function as a medium for nuclear reactions essentially forever.

**SUSTAINABILITY**
Continued operation of LFTRs uses only natural thorium at a rate of one metric tonne per gigawatt-year after initial startup on fissile material. They have a sustainability rating that is vastly superior to any other thermal reactor, and is significantly in excess of the fast-breeder reactors (SFR, GFR, and LFR). The fast-breeder reactors do not extract as much energy from a unit of nuclear material (in their case uranium) as a LFTR does from a unit of nuclear material (thorium). In addition, the LFTR fuel cycle is far simpler and less prone to fissile material losses from reprocessing.

**DECOMMISSIONING COSTS**
Decommissioning aspects in a LFTR are greatly simplified over a comparable solid-fueled reactor, primarily because of the ease of recycling the primary and secondary fluids that make up the fuel and blanket of the reactor. Fluoride salts are impervious to radiation damage due to the ionic nature of their chemical bonding. This is a strong contrast to the covalently-bonded solid fuels, where neutron and gamma bombardment cause lattice dislocations, swelling, and cracking. Fluid fuels give up fission product gases effortlessly during operation; solid fuels retain fission product gases which enhance swelling and cracking. The fluoride salt combination used in the fuel of the LFTR is LiF-BeF2-UF4, along with the fission product fluorides that will accumulate. When it is time for decommissioning, the UF4 can be easily recovered from the fuel salt by fluorination to UF6 gas. The valuable LiF-BeF2 carrier salt can be removed from the fission product fluorides by high-temperature distillation, a technique actually demonstrated in May 1969 with 12 liters of fuel salt during the operation of the Molten-Salt Reactor Experiment. The LiF-BeF2 recovered from distillation and the UF6 recovered from fluorination can then be recombined into LiF-BeF2-UF4 fuel salt and recycled into the next generation of LFTR. The remaining fission product fluorides can be further separated and distilled to remove both radioactive and non-radioactive components. Remaining byproducts that do not have independent commercial value can be immobilized in iron phosphate glass and sent to a burial site.

The blanket salt of the reactor (LiF-BeF2-ThF4) should have a low fission product inventory, particularly if protactinium isolation has been employed in reactor operation. If the fission product inventory is sufficiently low, the blanket salt can be readily recycled to the next LFTR reactor. If there is a more significant fission product inventory then additional purification steps will be necessary.

References: