

Thorium: Not ‘green’, not ‘viable’, and not likely

1. Introduction

"With uranium-based nuclear power continuing its decades-long economic collapse, it's awfully late to be thinking of developing a whole new fuel cycle whose problems differ only in detail from current versions."

Amory Lovins, Rocky Mountain Institute, March 2009.

A number of commentators have argued that most of the problems associated with nuclear power could be avoided by both:

- using thorium fuel in place of uranium or plutonium fuels
- using ‘molten salt reactors’ (MSRs) in place of conventional solid fuel reactor designs.

The combination of these two technologies is known as the Liquid Fluoride Thorium Reactor or LFTR, because the fuel is in form of a molten fluoride salt of thorium and other elements.

In this Briefing, we examine the validity of the optimistic claims made for thorium fuel, MSRs and the LFTR in particular. We find that the claims do not stand up to critical scrutiny, and that these technologies have significant drawbacks including:

- the very high costs of technology development, construction and operation.
- marginal benefits for a thorium fuel cycle over the currently utilised uranium / plutonium fuel cycles
- serious nuclear weapons proliferation hazards
- the danger of both routine and accidental releases of radiation, mainly from continuous ‘live’ fuel reprocessing in MSRs
- the very long lead time for significant deployment of LFTRs of the order of half a century – rendering it irrelevant in terms of addressing current or medium term energy supply needs

1. Background

1.1 What is thorium?

Thorium is a heavy metal named after Thor, the Nordic God of thunder. The naturally occurring isotope, ^{232}Th , is mildly radioactive with a very long half life of 14 billion years. Thorium presents a health hazard mainly from inhalation of dust, and from emissions of the powerfully radioactive gas radon (^{220}Rn).

It occurs mainly in deposits of rare earth metals. . As it has few uses requiring more than minimal volumes of material it is considered as radioactive waste – and requires careful and expensive handling to prevent contamination. It is three to four times

more abundant in the Earth's crust than uranium, and is especially plentiful in Australia, Norway, India, the USA and China.

Although thorium can be used to make nuclear fuel, it is not fissile. But it is 'fertile' - that is, it can be transformed into fissile material. Under neutron irradiation, typically provided by the fission of uranium or plutonium, it breeds the fissile uranium isotope ^{233}U . Thus any thorium fuel cycle needs to be initiated by a supply of existing fissile material.

The thorium-uranium fuel cycle has some advantages over the dominant uranium-plutonium cycle, in terms for example, of the reduced production of long-lived actinides and somewhat diminished radio-toxicity overall. However, it also creates new hazards of its own. As far as radioactive fission products are concerned, there is little to choose between the two.

(see Appendix 1 for further details)

1.2 What are molten salt reactors?

Unlike conventional nuclear reactors which use solid fuel in the form of rods or pellets, molten salt reactors (MSRs) use fuel in the form of a complex mixture of fluoride salts in a molten state. The salt mixture includes the fissile material (fissile isotopes of plutonium and/or uranium), together with any fertile material (such as thorium or ^{238}U) together with other elements.

The molten fluoride salt serves as the primary coolant, carrying heat away from the reactor, and delivering it to a secondary cooling circuit and ultimately to the steam turbines that generate electricity.

In principle, MSR's offer several potential advantages over conventional reactor designs:

- the reactor and its cooling circuits operate at near atmospheric pressure, reducing the chance of any explosion
- In the event of a reactor overheating, the fuel can simply drain out into a secondary container and the fission chain reaction will halt, reducing the risk of reactor meltdowns such as those experienced at Chernobyl and Fukushima

But before 'production' MSRs can be built, there are significant technical problems to be overcome, among them:

- the development of corrosion-resistant materials capable of surviving for decades in a uniquely hostile environment – highly corrosive and subject to intense radiation including neutron bombardment
- and, the continuous fuel reprocessing that MSRs demand, requiring the development of hazardous, complex and currently experimental pyro-processing and electro-refining technologies on a production scale.

If these technologies are successfully developed - and it cannot be taken for granted that they ever will – they are likely to be very expensive. Moreover, reprocessing will always represent a weak link from a safety and proliferation perspective.

(See Appendix 2 for further details)

2. Current State of Play

2.1 Actual thorium reactors

Thorium fuel has so far been used in about 30 operational reactors in conjunction with fissile uranium (^{235}U / ^{233}U) or plutonium (^{239}Pu) to initiate the fuel cycle. Most of these were located in the USA, Germany, Netherlands and India. A single example operated in the UK, from 1965 to 1976: the Dragon Reactor at Winfrith, a helium-cooled test reactor evaluating fuel and materials for the European high-temperature reactor programme. It is currently partially decommissioned.

Most thorium reactors have been of conventional designs originally intended for uranium fuel, such as pressurised water reactors, boiling water reactors and pressurised heavy water reactors. But thorium has also been included in more exotic designs, notably the molten salt breeder experiment (MRSE) reactor (see 2.3, below), the thermal breeder reactor (USA), and the liquid metal fast reactor (India).

The only operational thorium reactors today are in India, which possesses abundant thorium reserves but little uranium. These are all solid fuel reactors. As of 2010, India had used only a small amount of thorium - approximately one tonne - in its reactors.

2.2 Planned thorium reactors

In December 2011, India announced its plans for a new generation of Advanced Heavy Water Reactors using a plutonium / uranium / thorium MOX (mixed oxide) fuel. The programme would begin with an initial test reactor whose construction could commence in 2013. Again, this would not be a molten salt reactor but would use conventional solid fuel.

Norway's Thor Energy is also intending to develop a thorium-plutonium MOX nuclear fuel, aimed at replacing conventional fuels in light water reactors (LWRs). It is currently seeking investment to irradiate thorium-plutonium oxide fuel pins in simulated LWR conditions in the Halden fuel-testing reactor. A separate project is to optimise thorium-plutonium fuels for boiling water reactors, while maximising the breeding of ^{233}U . Thor Energy anticipates that 25-30% of power output could arise from the thorium.

Proposals have been made to construct LFTR reactors in China, Japan and the US (see 2.3). Initially these would be research reactors and the first 'production' LFTR would appear to be 20-30 years away (see 2.4).

2.3 Actual molten salt reactors

The molten salt reactor was originated in the 1950s as a potential power source for the USAF's fleet of high altitude nuclear bomber aircraft. A working reactor was produced (under the Airborne Reactor Experiment) programme, but never commissioned.

The technology was further developed at Oak Ridge National Laboratory in the 1960s under its MSRE (Molten Salt Reactor Experiment). The 7MW reactor employed fluoride salts of uranium and plutonium as fuel. In the 1970s, Oak Ridge built its Molten Salt Breeder Reactor (MSBR), which used as fuel fluoride salts of uranium, thorium and plutonium as its fuel.

2.4 Planned molten salt reactors

There are a number of proposals to build MSRs:

- In January 2011, the Chinese Academy of Sciences announced plans to develop the LFTR technology into commercial reactors. But it warned that 20 to 30 years of research and development would probably be needed before an LFTR was operational.
- Flibe Energy was set up in 2011 to develop LFTR technology in the USA and worldwide. Its initial intention is to build a small test reactor. Ultimately, it aims to bring about a world with many thousands of LFTRs.
- The FUJI LFTR project in Japan is attempting to raise £300 million to build a 10 MW 'MiniFUJI' research reactor. Following the 2011 Fukushima catastrophe, the project has a low chance of attracting the necessary finance.
- the UK's Weinberg Foundation was established in September 2011 to act as a communications, debate and lobbying hub to promote thorium energy and the LFTR in particular. There are currently no plans in the UK to build an actual LFTR.

Despite the resurgence of interest in the MSR / LFTR technology, there are no concrete plans to build even a single such reactor. China currently appears most likely to provide the funding necessary to develop LFTR technology due to that country's relatively large nuclear programme and the government's willingness to invest in new energy generation technologies. But even there any production-scale LFTR is unlikely to materialise for 20-30 years.

2.5 New-found interests – why?

Several factors underlie the current vogue of interest in thorium reactors. Perhaps the most important is the desire for energy and nuclear independence in countries with large thorium reserves and little uranium, or which have concerns about long-term price of uranium and its availability. This would appear to apply to India, China, the USA and Norway.

Noting the large volumes of surplus thorium produced as waste in the mining of valuable rare earth metals, there is also a clear commercial interest among the mining companies concerned to give value to this waste. However, we have no evidence of any efforts by mining companies to drive forward the thorium project.

A more significant factor is perhaps a deeply-rooted techno-optimism in human psychology – the desire to believe that one or other technology provides ‘the answer’ to deep-rooted problems. Faced with the prospect of ‘peak oil’ and accelerating climate change from the burning of fossil fuels, those who are sceptical about the potential of renewable energy sources will naturally incline towards some other answer. For some, it would seem that thorium fills that particular ‘desire gap’.

The established nuclear industry in the UK has little interest in thorium as such, since any use of thorium would create far more cost than it ever saved. However, the mere idea that there exists a notionally ‘green’ version of nuclear power could be seen by the nuclear industry as positive in public relations terms, and useful in promoting the persistence of nuclear power in the UK’s electricity mix.

3. Thorium claims – and the reality

Numerous advantages for thorium as a nuclear fuel and for the LFTR design over conventional solid fuel reactors have been claimed. In this section we consider each of these claims in turn.

3.1 Abundance of thorium relative to uranium

Claim: Thorium is several times more abundant in the Earth's crust than uranium.

Response: Thorium (^{232}Th) is indeed more abundant than uranium, by a factor of three to four. But whereas 0.7% of uranium occurs as fissile ^{235}U , none of the thorium is fissile. The world already possesses an estimated 1.2 million tonnes of depleted uranium (mainly ^{238}U), like thorium a fertile but non-fissile material. So the greater abundance of thorium than uranium confers no advantage, other than a very marginal advantage in energy security to those countries in which it is abundant.

3.2 Relative utility of thorium and uranium as fuel

Claim: 100% of the thorium is usable as fuel, in contrast to the low (~0.7%) proportion of fissile ^{235}U in natural uranium.

Response: Thorium must be subjected to neutron irradiation to be transformed into a fissile material suitable for nuclear fuel (uranium, ^{233}U). The same applies to the ^{238}U that makes up depleted uranium, which as already observed, is plentiful. In theory, 100% of either metal could be bred into nuclear fuel. However, uranium has a strong head start, as 0.7% of it is fissile (^{235}U) in its naturally-occurring form.

3.3 Nuclear weapons proliferation

Claim: thorium reactors do not produce plutonium, and so create little or no proliferation hazard.

Response: thorium reactors do not produce plutonium. But an LFTR could (by including ^{238}U in the fuel) be adapted to produce plutonium of a high purity well above normal weapons-grade, presenting a major proliferation hazard. Beyond that, the main proliferation hazards arise from:

- the need for fissile material (plutonium or uranium) to initiate the thorium fuel cycle, which could be diverted, and
- the production of fissile uranium ^{233}U .

Claim: the fissile uranium (^{233}U) produced by thorium reactors is not “weaponisable” owing to the presence of highly radiotoxic ^{232}U as a contaminant.

Response: ^{233}U was successfully used in a 1955 bomb test in the Nevada Desert under the USA's Operation Teapot and so is clearly weaponisable notwithstanding

any ^{232}U present. Moreover, the continuous pyro-processing / electro-refining technologies intrinsic to MSRs / LFTRs could generate streams of ^{233}U very low in ^{232}U at a purity well above weapons grade as currently defined.

3.4 Safety

Claim: LFTRs are intrinsically safe, because the reactor operates at low pressure and is and incapable of melting down.

Response: the design of molten salt reactors does indeed mitigate against reactor meltdown and explosion. However, in an LFTR the main danger has been shifted from the reactor to the on-site continuous fuel reprocessing operation – a high temperature process involving highly hazardous, explosive and intensely radioactive materials. A further serious hazard lies in the potential failure of the materials used for reactor and fuel containment in a highly corrosive chemical environment, under intense neutron and other radiation.

3.5 State of technology

Claim: the technology is already proven.

Response: important elements of the LFTR technology were proven during the 1970s Molten Salt Breeder Reactor (MSBR) at Oak Ridge National Laboratory. However, this was a small research reactor rated at just 7MW and there are huge technical and engineering challenges in scaling up this experimental design to make a 'production' reactor. Specific challenges include:

- developing materials that can both resist corrosion by liquid fluoride salts including diverse fission products, and withstand decades of intense neutron radiation;
- scaling up fuel reprocessing techniques to deal safely and reliably with large volumes of highly radioactive material at very high temperature;
- keeping radioactive releases from the reprocessing operation to an acceptably low level;
- achieving a full understanding of the thorium fuel cycle.

3.6 Nuclear waste

Claim: LFTRs produce far less nuclear waste than conventional solid fuel reactors.

Response: LFTRs are theoretically capable of a high fuel burn-up rate, but while this may indeed reduce the volume of waste, the waste is more radioactive due to the higher volume of radioactive fission products. The continuous fuel reprocessing that is characteristic of LFTRs will also produce hazardous chemical and radioactive waste streams, and releases to the environment will be unavoidable.

Claim: Liquid fluoride thorium reactors generate no high-level waste material.

Response: This claim, although made in the report from the House of Lords, has no basis in fact. High-level waste is an unavoidable product of nuclear fission. Spent fuel from any LFTR will be intensely radioactive and constitute high level waste. The reactor itself, at the end of its lifetime, will constitute high level waste.

Claim: the waste from LFTRs contains very few long-lived isotopes, in particular transuranic actinides such as plutonium.

Response: the thorium fuel cycle does indeed produce very low volumes of plutonium and other long-lived actinides so long as only thorium and ^{233}U are used as fuel. However, the waste contains many radioactive fission products and will remain dangerous for many hundreds of years. A particular hazard is the production of ^{232}U , with its highly radio-toxic decay chain.

Claim: LFTRs can 'burn up' high level waste from conventional nuclear reactors, and stockpiles of plutonium.

Response: if LFTRs are used to 'burn up' waste from conventional reactors, their fuel now comprises ^{238}U , ^{235}U , ^{239}Pu , ^{240}Pu and other actinides. Operated in this way, what is now a mixed-fuel molten salt reactor will breed plutonium (from ^{238}U) and other long lived actinides, perpetuating the plutonium cycle.

3.7 Cost of electricity

Claim: the design of LFTRs tends towards low construction cost and very cheap electricity.

Response: while some elements of LFTR design may cut costs compared to conventional reactors, other elements will add cost, notably the continuous fuel reprocessing using high-temperature 'pyro-processing' technologies. Moreover, a costly experimental phase of ~20-40 years duration will be required before any 'production' LFTR reactors can be built.

It is very hard to predict the cost of the technology that finally emerges, but the economics of nuclear fuel reprocessing to date suggests that the nuclear fuel produced from breeder reactors is about 50 times more expensive than 'virgin' fuel. It therefore appears probable that any electricity produced from LFTRs will be expensive.

We must also consider the prospect that relatively novel or immature energy sources, such as photovoltaic electricity and photo-evolved hydrogen, will have become well established as low-cost technologies long before LFTRs are in the market.

3.8 Timescale

Claim: Thorium and the LFTR offer a solution to current and medium-term energy supply deficits.

Response: The thorium fuel cycle is immature. Estimates from the UK's National Nuclear Laboratory and the Chinese Academy of Sciences (see 4.2 below) suggest that 10-15 years of research will be needed before thorium fuels are ready to be deployed in existing reactor designs. Production LFTRs will not be deployable on any significant scale for 40-70 years.

4. Thorium / LFTR prospects

4.1 Timescales for thorium fuel

The thorium fuel cycle is immature and unready for production-scale deployment. Although thorium fuels have been used in approximately 30 reactors, their nuclear dynamics and operational performance remain poorly characterised.

India is already deploying thorium in its reactors as a component of mixed oxide (MOX) fuels comprising plutonium / uranium, and plans more of the same in its forthcoming Advanced Heavy Water Reactors. However, Norway's Thor Energy and the UK's National Nuclear Laboratory (NNL) both believe that considerable research, development and testing lies ahead before thorium fuels will be ready for operational use.

As the NNL states, *"Thorium reprocessing and waste management are poorly understood. The thorium fuel cycle cannot be considered to be mature in any area."* It estimates that 10-15 years work is required before thorium fuels will be ready for use in current reactor designs, and that their use in new types of reactor is at least 40 years away. [*The Thorium Fuel Cycle - An independent assessment*, NNL, August 2010]

4.2 LFTR lead time: half a century

The assessment of the Chinese Academy of Sciences as it embarks on its LFTR programme is that a production LFTR is 20-30 years in the future – rather shorter than the NNL's estimate of 40 years (see 4.1).

Given the hazards, such as the potential failure of reactor materials under intense neutron irradiation and chemical corrosion, risk-averse utilities and investors would want to observe the performance of any such full-scale LFTR for at least a decade and probably more, before embarking on any substantial LFTR programme. The lead time for nuclear construction is of the order of a decade, so this could add a further 20-30 years before production LFTRs were deployed at full scale.

The total lead time for LFTRs would therefore be a minimum of 40 years on the shortest estimates, or 70 years based on more conservative figures.

4.3 Thorium and LFTRs – investment outlook

The development of thorium / LFTR technologies represents a poor investment for national governments, utilities and private investors given:

- the marginal benefits to be derived from using thorium fuels in existing reactor designs;
- the very long-term nature of any benefit that may be realised from LFTRs, of the order of half a century;
- the uncertainty as to whether the very significant technical challenges of the LFTR will ever be overcome;
- the possibility that the materials used for reactor construction may degrade more rapidly than anticipated, causing early shut-down;
- the likely very high cost of LFTR electricity – especially when compared against the anticipated low future cost of electricity from renewable sources, solar in particular, over the applicable time frame.

As NNL states: *“thorium is competing with the uranium/plutonium fuel cycle which is already very mature. To progress to commercial deployment would demand major investments from fuel vendors and utilities ... LWR and PHWR utilities would be unlikely to invest in thorium fuels to the levels required under current market conditions. The potential savings that thorium fuels offer and other claimed benefits are insufficiently demonstrated and too marginal to justify the technical risk that the utility would be exposed to.”*

We therefore see little prospect that LFTRs will present an economic solution if and when they are ever ready for large scale deployment. Any money invested in LFTRs, whether by governments, utilities or other investors, is likely to be wasted.

Far better to invest in the renewable technologies that are already shaping our national and global future, and whose cost is rapidly falling - in the process developing valuable UK-based expertise and technologies, and accelerating the renewables revolution.

Oliver Tickell, April / May 2012.

Appendix 1 - The thorium fuel cycle

Thorium is not itself fissile, however it is 'fertile'. That is to say that, under neutron irradiation, it can be used to breed fissile material. In any thorium reactor, the naturally occurring ^{232}Th is irradiated with neutrons from fissile material (for example, ^{235}U , ^{233}U or ^{239}Pu). Some of the thorium nuclei capture a neutron and become ^{233}Th . This isotope then undergoes beta decay to ^{233}Pa (protactinium 233) which in turn beta decays to ^{233}U , a fissile isotope of uranium.

So in a thorium reactor, the fissile material is in fact uranium. The ^{233}U behaves like the more familiar naturally occurring ^{235}U . It has a fairly long half life of 160,000 years, and like ^{235}U , ^{233}U is fissionable and can create and sustain a nuclear fission chain reaction, in which the neutrons emitted by one fission event trigger further fission events in other ^{233}U nuclei. When ^{233}U undergoes fission, it produces similar fission products as ^{235}U , but in different proportions.

Thorium fuel does possess some advantages over conventional uranium / plutonium fuels:

- the ^{232}Th is more likely than the ^{238}U to capture thermal neutrons;
- the resulting ^{233}U is more likely to fission following neutron capture than is ^{239}Pu ;
- fissioning ^{233}U produces more neutrons to sustain the nuclear chain reaction.

These factors combine to create a more efficient 'neutron economy' for thorium than for conventional nuclear fuels, making smaller reactors more viable. They also mitigate against the formation of long-lived transuranic isotopes such as plutonium.

There is also one important disadvantage: the breeding of ^{232}U , a non-fissile but strongly radioactive uranium isotope. This arises when the ^{233}Pa absorbs a neutron before it decays to ^{233}U . The resulting ^{234}Pa may then expel a pair of neutrons to make ^{232}Pa , which then undergoes beta decay to ^{232}U .

This isotope is typically present in small quantities with a ^{232}U : ^{233}U ratio of well under 1%. But it presents a considerable hazard due to its short half life of under 70 years and the rapid decay chain which follows, culminating in an ultra-hard 2.6 MeV gamma ray - capable of passing through a metre of lead. This powerful gamma irradiation creates a hazard to personnel and to unshielded electronic control systems. Consequently, thorium fuel requires far more shielding, and more stringent remote handling techniques than conventional nuclear fuels.

But the greatest problem with the thorium fuel cycle is our relative inexperience of it, compared to the conventional uranium / plutonium fuel cycle. According to the UK's National Nuclear Laboratory, "*Thorium reprocessing and waste management are poorly understood. The thorium fuel cycle cannot be considered to be mature in any area.*" The NNL estimates that 10-15 years of research and development will be required before thorium fuels are ready for production deployment in conventional reactors:

"Starting from fabrication of a commercially-relevant mass of ThO_2 fuel, which might take 1 or 2 years, the subsequent irradiation to full burnup would likely take 4 to 5 years. Subsequent post-irradiation examination might take

another 1 to 2 years, so the overall timescale will be of the order of ~10 years. In practice, a gradual ramp-up to commercial scale loading might be necessary, leading to a more realistic timescale of about 15 years for commercial demonstration. This is comparable to the timescale that was required to commercialise MOX in LWRs."

Appendix 2 – Molten salt reactors

A2.1 History of the molten salt reactor

MSRs were first developed in the early 1950s as the US Airforce sought a novel power source for its fleet of high altitude nuclear bombers. Although a working reactor was developed under the ARE (Airborne Reactor Experiment) programme, it was never deployed.

In the 1960s, the ARE technology was taken up by the Oak Ridge National Laboratory which conducted its own MSRE (molten salt reactor experiment) from 1965 to 1969. This was based on a graphite-moderated reactor using fluoride salts of uranium and plutonium as fuel. Subsequently Oak Ridge built a Molten Salt Breeder Reactor (MSBR), which operated from 1970 to 1976. In its initial phase the MSBR used as fuel fluoride salts of ²³⁵U and thorium, later followed by using the ²³³U it had bred in the first phase, also with thorium. It was also tested using plutonium fuel (mostly ²³⁹Pu).

The experiment demonstrated that the reactor design was viable. Particular successes included the breeding of ²³³U from the initial thorium; the subsequent use of the ²³³U to re-initiate the a thorium fuel cycle; and the de-gasification of the molten salt fuel, extracting unwanted gases such as xenon (¹³⁵Xe), an important neutron sink that would otherwise slow down or indeed halt the fission chain reaction.

The MSBR also highlighted some unexpected hazards. For example, the nickel-molybdenum alloy used to build the reactor became brittle under thermal neutron irradiation, and suffered extensive surface cracking due to the presence of the fission product tellurium. This highlights the importance of developing materials capable of surviving the highly corrosive environment of an LFTR environment, and to withstand the intense neutron bombardment, over a multi-decadal timescale. It also raises the prospect that any material used may degrade well before its anticipated end of life and cause premature reactor closedown.

It should also be pointed out that the power output of the MSBR was limited to just 7 MW. Any production MSR built for power generation would be expected to have a thermal output closer to 500 MW, two orders of magnitude greater, with correspondingly greater fluxes of neutrons. This would create of host of challenges in engineering design, materials science and fuel reprocessing.

A2.2 Molten salt processing

A key benefit of MSRs is that they provide the ability to clean the fuel of unwanted fission products on a continuous basis. In conventional solid fuel reactors, fission

products build up in the fuel rods or pellets, and some of these are powerful neutron absorbers, like the Xenon isotope ^{135}Xe . It is the accumulation of these neutron-absorbing fission products that ultimately limits the lifetime of solid fuels by reducing the efficiency of the reactor's 'neutron economy' until the nuclear fission chain reaction slows down or halts.

In the course of molten salt reactor operation, other undesirable fission products also build up in the fuel. These include oxygen, which gives rise to particulate deposits of solid metal oxides, and highly corrosive sulphur and metals. These also require removal.

Techniques for extracting these various contaminants from the molten salt fuel were originally developed at Oak Ridge. Typical processing temperatures are in the region of 400C to 600C and involve the use of highly reactive chemicals such as hydrogen, hydrogen fluoride and hydrofluoric acid. This creates a highly hazardous environment.

Further 'pyro-processing' techniques that are highly applicable to MSR's were developed at the Argonne National Laboratory in the context of its Integral Fast Reactor (IFR) programme. These involve high temperature 'pyrometallurgy' and electro-refining.

Note that these technologies could be used to produce very high purity streams of fissile uranium and plutonium well above weapons grade as currently defined (see A3.2 and A3.3 below).

The continuous purification of the molten salt inevitably creates a waste stream of fission products in various combinations and in mixtures of reagents and waste chemicals arising from the process. The safe handling and disposal of these wastes, while minimising radioactive releases to the environment, presents further serious challenges in radio-chemical engineering.

A2.3 Safety in operation

Proponents of the LFTR claim important safety advantages for the technology:

- LFTRs are unable to suffer reactor core meltdown, as occurred at Chernobyl and Fukushima. If the core temperature rises too high, the liquid fuel expands and the fission chain reaction slows down. Also the removal of the 'neutron sink' isotope ^{135}Xe can be halted so as to slow down the fission chain reaction. As a fail-safe, a salt plug is included in the bottom of the reactor which will melt at a set temperature and allow the fuel to drain into a holding tank where fission will halt.
- the LFTR operates at near-atmospheric temperature is therefore less susceptible to explosive pressure release venting fuel and fission products to secondary containment or the atmosphere.

These claims are broadly accurate. But while LFTRs do indeed reduce certain risks, other new risks appear. There is the risk of materials failure in the reactor / liquid fuel containment as the alloys become brittle under neutron irradiation, or suffer cracking and surface damage in the high-temperature, intensely corrosive reactor environment.

Any accidental release of the hot fluoride salt fuel could be highly damaging owing to the fuel's highly corrosive chemistry, and cause radioactive releases to the environment. Similar accidents could also take place in the continuous fuel reprocessing system, which will use highly reactive and potentially explosive chemicals such as hydrogen, fluorine and hydrofluoric acid, all at very high temperatures.

Due to the intensely radioactive nature of some the isotopes that need to be handled during reprocessing, there is no scope for direct human intervention in the fuel reprocessing system or the reactor itself in the case of failure. All personnel will need to be shielded and will only be able to intervene via remote handling systems or robots, themselves subject to potential failure. In the event of an accident, there might be little alternative but to abandon the reactor, possibly for an extended period of time, until radioactivity declined to sub-lethal levels permitting human access.

It is therefore hard to sustain with any certainty the idea that LFTRs are intrinsically safe. Indeed considerable dangers appear to be attached to LFTRs and their routine operation.

Appendix 3 - Nuclear weapons proliferation

A3.1 General considerations

As already noted, thorium reactors work by breeding ^{233}U , a fissile isotope of uranium. It has been stated that thorium reactors present no nuclear weapons proliferation hazard because they do not breed plutonium like conventional uranium reactors. However, there are a number of stages of the thorium fuel cycle in which fissile material for weapons could be diverted.

First, the thorium fuel cycle needs to be initiated by externally supplied fissile material, whether uranium (^{235}U or ^{233}U) or plutonium (^{239}Pu). Accordingly there is the risk that some of this externally-supplied fissile material could be diverted into weapons.

Second, the ^{233}U that is bred in thorium reactors is highly weaponisable. Such a bomb was exploded in the Nevada desert in 1955 as part of Operation Teapot, a series of 14 nuclear bomb tests conducted by the US government. In one of these tests, the Military Equipment Test or 'MET shot', engineers replaced the ^{235}U core of the uranium / plutonium bomb with ^{233}U . The bomb successfully detonated and the principle that ^{233}U can be used to make nuclear bombs, with fearsome destructive potential, was firmly established.

It has been suggested that the inevitable presence of ^{232}U as a contaminant of ^{233}U - as we have noted, a powerful gamma emitter though its decay products - renders ^{233}U unusable as a bomb-making material, due to health damage to handlers and machinists, and disruption to electronics. Given that a ^{233}U bomb has already been assembled and detonated using 1950's technology, this is clearly not an insuperable problem. Pyroprocessing technologies could also be used to produce highly

concentrated ^{233}U untainted by ^{232}U or any other uranium isotope from thorium fuel (see A3.2 below).

One means that has been proposed to prevent the generation of sufficiently pure ^{233}U to build a nuclear bomb is to add to the thorium fuel a significant percentage of natural or depleted uranium, rich in non-fissile ^{238}U . It is impossible to chemically separate ^{233}U from ^{238}U since they are both the same element.

However as the NNL notes, "*Attempts to lower the fissile content of uranium by adding U-238 are considered to offer only weak protection, as the U-233 could be separated in a centrifuge cascade in the same way that U-235 is separated from U-238 in the standard uranium fuel cycle.*" Indeed, owing to the greater difference in atomic mass the centrifuge separation would operate more efficiently.

The presence of ^{238}U in the fuel would also create another hazard. One of the advantages of using thorium fuel is its low level of conversion to long-lived transuranics. But if the fuel contains ^{238}U as an anti-proliferation measure, then it will absorb neutrons (in the process degrading the 'neutron economy') and form plutonium. Next, 'pyroprocessing' technologies could be used to extract any plutonium from the molten salt fuel, potentially producing ^{239}Pu at very high concentrations well above ordinary weapons-grade (see A3.2, below).

A3.2 Weapons grade uranium (^{233}U)

The process whereby fissile ^{233}U is bred in the thorium fuel cycle involves an intermediary stage, with the protactinium isotope ^{233}Pa . The ^{233}Pa undergoes beta decay to ^{233}U with a half life of 27 days. But the ^{233}Pa may first absorb a second thermal neutron to make ^{234}Pa . This isotope may either decay to the undesirable uranium isotope ^{232}U , or the non-fissile uranium isotope ^{234}U .

This makes it beneficial to remove the protactinium from the molten salt fuel before it can intercept a second neutron. Left to itself, away from the neutron flux, the ^{233}Pa decays over a period of months to produce very pure ^{233}U . Furthermore the removal of the protactinium leaves more neutrons to maintain the reactor's neutron economy, maintaining both the thorium fuel cycle and the fission chain reaction.

Oak Ridge demonstrated several effective methods of protactinium removal, for example, precipitation by addition of thorium oxide to the molten salt [*Removal of protactinium from molten fluoride breeder blanket mixtures*, C. J. Barton and H. H. Stone, 1966]. This technique precipitated ^{233}Pa when present at just 0.1 parts per billion.

But the authors note that the protactinium is highly radioactive and hazardous to handle even on the milligram scale, due to its short half life of 27 days, and its high combined beta and gamma energy of 570 KeV. For this reason, Oak Ridge used a mixture of ^{233}Pa and much less radioactive ^{231}Pa for its experiments, in which the ^{231}Pa was ~100,000 times more abundant than the ^{233}Pa . This indicates that the handling of the highly radioactive ^{233}Pa extracted from molten salt fuel would need to be done entirely by remote handling with any personnel shielded from radiation.

This method of producing very pure fissile ^{233}U , while highly desirable as regards reactor operation, represents a significant weapons proliferation hazard. Purities of ^{233}U well above accepted weapons grade (85% for ^{235}U) would be achievable.

A3.3 Weapons grade plutonium (^{239}Pu)

A similar approach could also be used to produce weapons-grade plutonium from molten salt fuel rich in ^{238}U . In the normal operation of a uranium solid fuel reactor the ^{238}U captures a neutron and then undergoes two beta decays to form ^{239}Pu . However, the ^{239}Pu itself has a high probability of capturing further neutrons to make ^{240}Pu . Hence the plutonium in spent fuel typically comprises under 80% ^{239}Pu and most of the remainder is ^{240}Pu with some ^{241}Pu .

^{240}Pu is highly undesirable in a plutonium weapon since it can trigger premature fission giving rise to a low-yield explosion known as a 'fizzle'. As a result weapons grade plutonium contains a maximum of 7% ^{240}Pu . So in order to make weapons grade plutonium the fuel is only left for a short time in the reactor before reprocessing.

The same result could be served in a molten salt reactor by including a high level of ^{238}U in the fuel, and extracting the ^{239}Pu as it is formed. It would make sense to use the pyro-processing technology developed by the Argonne National Laboratory for its Integrated Fast Reactor - a high temperature (500C) electrolysis process using molten salts. This could be employed to concentrate the plutonium, together with some residual uranium and any minor actinides from the molten salt fuel [*Proliferation-Proof Uranium/Plutonium Fuel Cycles, By G. Kessler*]. Standard aqueous methods such as PUREX could then be employed to purify the plutonium. This approach should be capable of producing plutonium with a very high ^{239}Pu content well above normal weapons-grade.

END