New Nuclear

By Ian Scott, Chairman & Chief Scientist, Moltex Energy

NUCLEAR energy is in retreat globally. The International Energy Agency reports that on current trends, even with China's ambitious programs, nuclear energy will fall from 5.8% of world generating capacity to 3.7% by 2040. Nuclear energy is becoming irrelevant, which is a tragedy as it seems very unlikely that climate change goals will be achieved without it.

Ultimately, this decline in the relevance of nuclear energy is driven by its escalating costs which, without massive subsidy, simply make it uncompetitive.

Why has nuclear energy become so expensive? In the 1970s, nuclear power was highly competitive with fossil fuels, and several countries built profitable nuclear industries. The near disaster of Three Mile Island and actual disaster at Chernobyl, along with the meltdown at Fukushima highlighted that the technology was not safe enough. The industry has since doubled down on trying to make existing reactor designs safer by adding layer after layer of engineered safety systems and administrative controls around new reactor designs. Nuclear power plants are now amongst the safest facilities on Earth. However, in doing this, the industry ignored a fundamental principle of achieving safety, which is illustrated in the hazard pyramid in *Figure 1*.

When seeking to improve safety, one should first seek to eliminate or reduce the fundamental hazard. Only then should one seek to manage or contain the remaining hazards through engineered safety systems or administrative controls. The fundamental hazards of the current generation of pressurized water reactors (PWRs) are:

- making the reactor core out of a fuel in which the most hazardous radioactive fission products are trapped as gasses in the fuel pellets at pressures of about 1 t/cm^2; and

- putting the reactor core inside a pressure vessel full of water at over 300°C which will flash into steam if the vessel fails, violently driving dispersion of the radioactive materials and allowing decay heat to melt the fuel pellets and release the highly pressurized fission gasses into an already-compromised vessel.

Given these hazards, it is perhaps not surprising that the current generation of reactors requires a plethora of additional systems, containment and control in order to achieve the enviable levels of safety which are, in fact, achieved.

The Stable Salt Reactor (SSR) is a new concept in nuclear reactors, albeit one based on ideas conceived, tested but not commercialized in the 1960s and 70s. It addresses both of those fundamental hazards:

- the fuel is a molten salt in which the most hazardous fission products are not gasses but non-volatile salts; and

- the coolant is a different molten salt which operates at atmospheric pressure and cannot be made to boil by decay heat if the reactor fails in any way.

Figure 1: Hazard pyramid

SSR vs molten salt reactor

Nuclear reactors using molten salts as fuel and coolant are not in fact a new idea. Indeed, a prototype molten salt fuelled reactor was built and operated in the US in the 1960s. There is a vital difference however between that reactor, and all its successor designs, and the SSR.

Every reactor design using molten salt fuel, since that prototype in the 1960s, has followed the same paradigm. This is that the molten salt fuel is pumped between a reaction chamber where it achieves critical mass and generates heat, and a heat exchanger which transfers the heat out of the reactor to generate electricity. This has some real attractions, particularly that the fuel can be continuously chemically processed as it passes around the circulating system. But it creates a major new hazard. If the pumps, seals, valves and so on of the system leak, then highly radioactive fuel spills into the reactor space where it can be heated by decay heat to temperatures where even the salt will boil, releasing the radioactive fission products as vapours.

In the SSR, the molten salt fuel is held in conventional fuel tubes where it replaces the solid uranium oxide pellets. Those fuel tubes are cooled by a separate molten salt coolant pool which transfers the heat to turbines to generate power. The fundamental safety advantages of molten salts are still achieved but, by separating the fuel salt from the coolant salt, the reactor avoids the new leakage hazard created in pumped molten salt fuel.

Simple sealed tubes are far less likely to spring leaks than complex plumbing – indeed the integrity of nuclear fuel tubes today is such that leaks are almost unknown. Even if a fuel tube did leak, the leaked fuel will be massively diluted in the large pool of coolant salt ensuring that it can neither achieve critical mass nor heat to the point where the fission products become volatile. The reactor could continue operation despite several such leakages since the radioactivity remains securely within the containment.

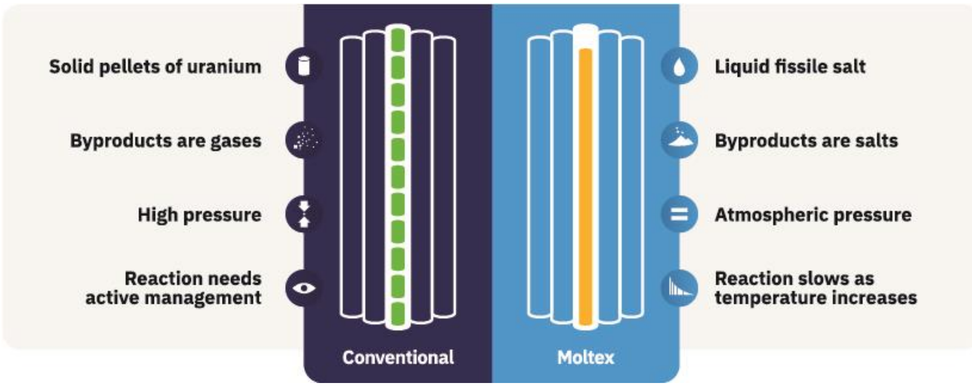

Figure 2: Conventional fuel vs Moltex fuel

The key science

The simple idea of putting molten salt fuel into conventional fuel tubes is, extraordinarily enough, novel. A broad patent covering this invention has now been granted in most major jurisdictions worldwide. The reason for the novelty is interesting – and an object lesson in the dangers of projects achieving their own momentum.

Back in the years immediately after the Manhattan Project, a team in the US sought to design a nuclear reactor to power a plane. They actually looked at exactly the idea of putting molten salt fuel into tubes – but they rejected it. Their reason was sound. Heat moves in fluids primarily by convection. Convection requires gravity. Gravity is unreliable in an aircraft since it (apparently) disappears when the aircraft goes into freefall. So rejecting fuel in tubes for an aircraft nuclear reactor was entirely rational.

But when the pipe dream (or rather nightmare) of nuclear reactors on planes was abandoned, the decision to reject fuel in tubes was never revisited. All the world remembered was that fuel in tubes did not work. That is until the author (new to the nuclear field and ignorant that experts in the field "knew" that fuel in tubes did not work) did the fluid dynamic calculations to show that, with gravity at 1g, fuel in tubes works perfectly well.

That simple discovery, coupled with the courage and vision of many investors, led to the formation of Moltex Energy.

The stable salt reactor today

Moltex found a very positive attitude to new thinking in nuclear energy in Canada. In 2016, it established Moltex Energy Canada and transferred some of its intellectual property rights to that company.

Moltex has also found, in NB Power, a hugely supportive nuclear operator with a nuclear licensed site perfectly suited to advanced reactors. New Brunswick has invested financially in Moltex and the Canadian federal government has a clear strategy to support advanced nuclear and New Brunswick. Financial support has also been given by the US Department of Energy through its ARPA-E program. Moltex launched its first ever crowdfunding campaign, which was extremely successful. In 2021, Moltex will complete the first stage of the nuclear regulatory process with the Canadian Nuclear Safety Commission.

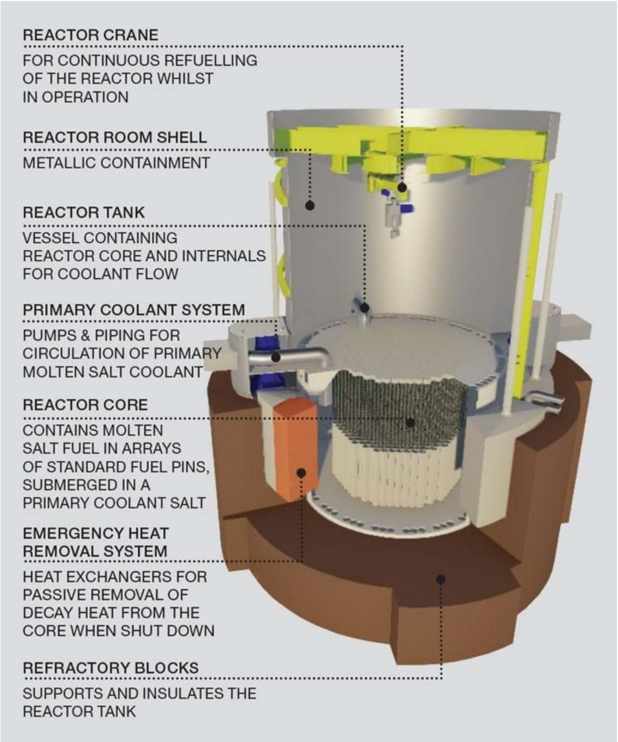

Figure 3: Core of the Stable Salt Reactor – Wasteburner

Why is the SSR a 'wasteburner'?

There are actually many possible variants of the SSR. The Stable Salt Reactor – Wasteburner (SSR-W) is merely the first of what may become a family of reactors. It is what is known as a fast spectrum reactor. This is a reactor with no moderator to slow down the neutrons produced by fission. The lack of moderator means that more fissile material is needed to achieve critical mass but that the reactor will burn up all the higher actinides produced in conventional moderated reactors.

This is important because spent nuclear fuel contains two distinct classes of radioactive waste products. The fission products are highly radioactive but rather short lived. After 300 years they have decayed to a radioactivity similar to that of mined uranium. But not all nuclei that absorb neutrons fission. Some just absorb the neutron and become new, heavier, atoms. This is how the "higher actinides" of plutonium, americium and curium are formed. These new species are both highly radioactive and long lived. Between 300 years and one million years they dominate the radioactivity of the spent fuel and largely create the need for enormously expensive "deep geological repositories" to keep the fuel safe for millennia.

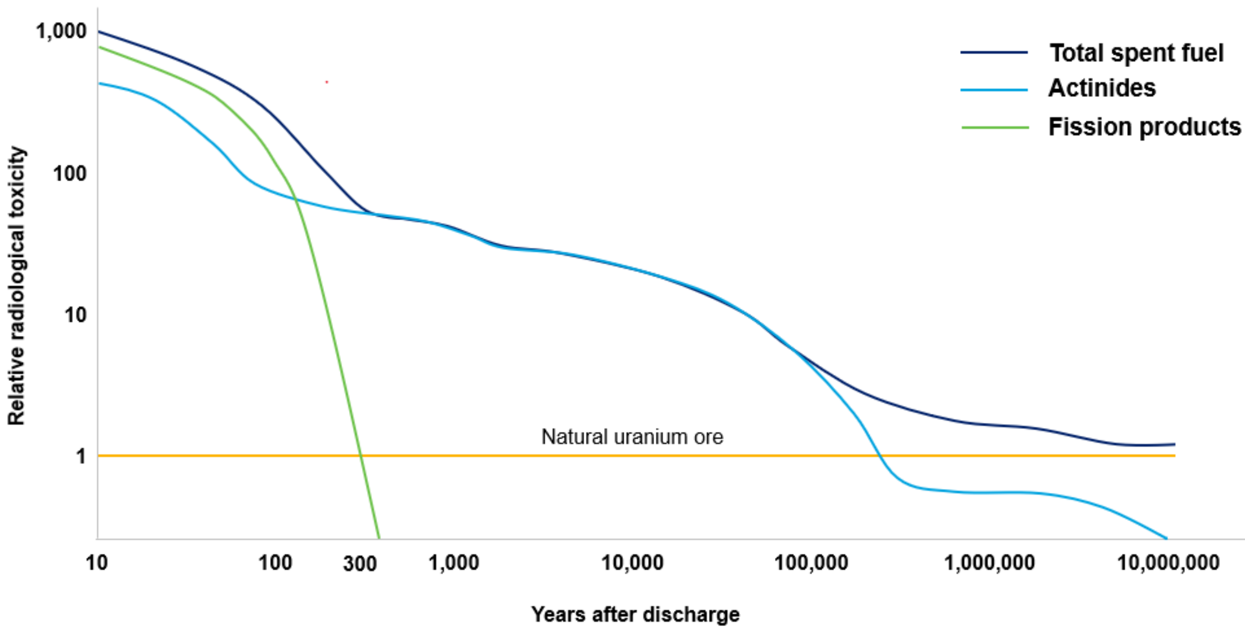

Figure 4: Decay of spent fuel waste products.

Because it burns these higher actinides, and not just plutonium, the result is that the SSR-W can radically clean up the nuclear waste left by today's generation of nuclear reactors. This is vitally important to giving nuclear energy the "social licence" to expand beyond its current limits.

But first, it is necessary to extract those higher actinides from the spent fuel. In Canada, the dominant nuclear reactor is the CANDU reactor, a Canadian-invented and developed reactor which has the unique ability to use natural, non-enriched uranium as fuel. Because it uses natural uranium, it only achieves a relatively low burnup, about 1/5 of that achieved by reactors using enriched uranium. For a given amount of energy produced, CANDU reactors therefore produce five times the mass of spent fuel, and that spent fuel contains about 1/3 of the higher actinides found in spent enriched fuel.

Extraction of higher actinides from spent fuel has, to date, been an expensive flop in the nuclear industry – though it has been very successful in producing nuclear bombs. Processing the large mass of spent CANDU fuel through the aqueous reprocessing methods conventionally used would be utterly uneconomic.

Moltex has therefore had to invent a new way to extract higher actinides from spent fuel. This is the WAste To Stable Salt (WATSS) process.

WATSS: Turning nuclear waste into fuel

The central simplifying fact that makes the WATSS process possible is that the SSR-W does not need, nor indeed does it want, high purity of its fuel. It needs the higher actinides as the fissile material but allows them to be mixed with both unused uranium and lanthanide fission products. As any chemical engineer knows, high purity costs money.

The WATSS process first electrochemically reduces the uranium, the higher actinides and some of the lanthanides in spent CANDU fuel to a molten metal alloy. This is essentially the same process used in aluminium smelters. While it is novel to nuclear, it has an extensive industrial pedigree.

The second stage is that this alloy is extracted with a clean molten salt mixture of sodium and iron chlorides. The extraction process is actually a series of chemical reactions:

$2Ln + 3FeCl_2 = 2LnCl_3 + 3Fe$ $\Delta G = -464$ kJ
(where Ln represents the lanthanides)

$2An + 3FeCl_2 = 2AnCl_3 + 3Fe$ $\Delta G = -393$ kJ
(where An represents the higher actinides)

$2U + 3FeCl_2 = 2UCl_3 + 3Fe$ $\Delta G = -304$ kJ

These reactions are listed in their order of free energies which shows they take place in the same order. First the lanthanides are extracted, then the higher actinides, and finally the uranium.

Because the SSR-W loves fuel which contains both uranium and lanthanides, it is possible to extract all the higher actinides from the alloy in a single, or double step. The low need for purity leads to a simple process. It also ensures that it is utterly impossible to use this process to produce plutonium of sufficient purity to use in nuclear weapons – an important moral imperative in a non-nuclear weapons country like Canada.

The output of this process is exceptionally simple. Highly radioactive, long-lived, CANDU waste enters the process. What comes out is:

A small volume (about 1/100 the volume of the input spent fuel) of highly radioactive but relatively short-lived electrolyte from the electroreducer. That can be disposed of down 5 km deep boreholes in geologically stable rock at a fraction of the cost of a conventional deep geological repository (which is only about 500 m deep) and with a fraction of the final surface radiation exposure to our descendants.

A residual uranium alloy with very low radioactivity and negligible heat generation that can be safely and inexpensively stored until the uranium and other noble metals in the alloy have a value worth recycling it for.

Fuel for the SSR-W which can be recycled indefinitely until all the higher actinides are consumed and clean energy produced.

The problem with molten salt reactors

What keeps molten salt reactor designers awake at night, given their huge intrinsic advantages? One word. Corrosion.

The engineering world has largely solved the problem of metal corrosion in water and air, despite the fact that iron plus oxygen or water will eventually produce rust. The solution has been to find ways to form stable oxide layers on steels which massively slow down corrosion. These are stainless steels.

That approach fails in molten salts which are excellent at dissolving such oxide layers. Many molten salt reactor designers resort to advanced alloys containing very high levels of nickel which is less easily corroded. The problem with such alloys is, however, that they have no track record of use in the nuclear industry – which conservatively adds a decade to any development timeline.

Moltex has pioneered a different approach, one which is in fact enabled by our fuel-in-tube design. Addition of small amounts of metallic zirconium to each fuel tube has the effect of scavenging any oxidizing species in the salt – and since fission produces about 1/3 of the periodic table as fission products there are many such species.

In chemical terms, the zirconium locks the redox potential of the salt to that of zirconium metal. That redox potential is so strongly reducing that the thermodynamically stable form of iron and chromium is actually as the metal. There is no driving force to extract the metal into the salt as chromium or iron chlorides. This means we can use standard, well-understood Fe/Cr ferritic steels for construction and avoid use of nickel (which has the unfortunate property of producing helium when irradiated by neutrons and rendering the alloy brittle).

The downside of this approach is that the zirconium metal will migrate through the salt to deposit in the coldest part of the system. This makes it impossible to use in pumped molten salt reactors where the deposit will undoubtedly happen where it will do the most harm (an invariable law of engineering). But with the fuel salt in tubes, we really do not care where the zirconium is – it is of no importance whatsoever.

Summary

Nuclear power is absolutely required if we are to make sufficient progress in the decarbonization of our energy use and tackle climate change in any meaningful way. But it is currently too expensive. Without a new approach to nuclear, we are destined to fail.

By removing the hazards of contained pressure and radioactive gases, Moltex has found a way of making nuclear power cost-effective. In fact, not just cost-effective, but actually less expensive than the fossil fuels which it will replace.

That raises the prospect of addressing climate change while simultaneously reducing the cost of energy for the world. There is work to do to bring the technology to market – our target date for commissioning and operation of the first Moltex reactor is 2030 – but the strength of the underlying science combined with innovative engineering gives us confidence that we will succeed.