The 'Fast Neutron' Breeder Can Be a Truly Cost-Cutting Nuclear Power Plant

by Richard Burden

This is an abridged version of a technology report on nuclear breeder reactors, which use isotopes of nuclear fuel that conventional nuclear reactors cannot use, greatly reducing nuclear waste. The full article with all source information and footnotes may be obtained upon request from the author at richard.w.burden@gmail.com.

Los Alamos National Laboratory

Molten salt, seen here in a furnace, is a good medium for heat transfer, and the nuclear fuel can actually be dissolved in it, eliminating the need for fuel rods. Here, an experiment at the Los Alamos National Laboratory.

May 1—One would think, given the tremendously low cost of nuclear fission fuel[1], and the maturity of fission power technology, that nuclear fission power would be vastly cheaper than any alternative. But the designs that are presently allowed to be built and run do not allow this. The restrictions placed upon nuclear power, which make it prohibitively expensive for most uses, are defended by claims that they are necessary for public safety, including the prevention of nuclear weapons proliferation.

Various new and repackaged old designs are being proposed to overcome the politically imposed, high cost of nuclear power. Invariably, these are promoted with obsessive genuflection to the priests of the climate-change cult, hoping that those priests will see fit to fund their idea in order to reduce carbon dioxide emissions, while advocates of nuclear power in general also obsessively genuflect in hopes of obtaining credits for reducing carbon dioxide emissions. Without such credits, they believe, nuclear power cannot compete with natural gas or coal or even wind and solar. And coal, being heavily penalized for emitting carbon dioxide, cannot compete with natural gas, wind, or solar.

But rather than reacting to popular fears, what if a nuclear power plant were designed to address legitimate safety concerns according to *known chemistry* and physics? Could we then stop genuflecting and really make electricity "too cheap to meter?" What I present here is an existing, developed design that does just that.

Thorium vs. Spent Fuel and Depleted Uranium

The cost of nuclear fuel is much higher than it should be, because the reactors presently in use, use no more than 1% of natural uranium supplied as fuel.

1. Fissile material is cheap because a tiny amount produces a huge amount of power, and is it fairly abundant and not too difficult to extract. Pure fissile material, when completely fissioned, releases approximately 80 million megajoules per kilogram via fission. Radioactive decay and some exothermic neutron captures can release up to 11% as much again during the lifetime of the fuel in the reactor, to make 10% of the total power of the reactor, bringing the total to 89 million MJ/kg. See energy density calculations of nuclear fuel posted at whatisnuclear.com. The most energy-dense naturally occurring and abundant chemical fuel, per unit mass, is methane at just 55.6 MJ/kg.

The inefficient use of the fuel results in 100 times as much waste per unit of power produced, and that waste presents a much greater long-term storage problem than it should, because it also contains slightly more than 1% plutonium and other transuranic elements.

The popular solution to this problem is to build a reactor that uses thorium. Thorium, we are told, is safer because it can never be used to make a bomb.

Thorium is not fissile, but "fertile," i.e., when bombarded with neutrons, it captures some and becomes a highly fissile (prone to splitting) isotope. The isotope produced when thorium captures neutrons is uranium-233 (U-233), which, although it is highly fissile, is said to be of no use to nuclear bomb-makers because, when produced in a reactor which uses thorium, uranium-232 (U-232) is also produced. U-232 is hard to separate from U-233, and emits so much gamma radiation that heavy shielding is required to handle it, and by implication, to hide the bomb, and active cooling is required to prevent it from overheating from the decay energy. Besides being poor bomb material, U-233 will rarely capture enough additional neutrons, before undergoing fission, to become one of those scary transuranic elements such as plutonium or americium featured in nuclear accident horror movies.

There is nothing wrong with using thorium, which is about three times as abundant as uranium in the earth's crust. But why should we not use spent nuclear fuel or depleted uranium,[2] which can likewise be made fissile by capturing neutrons, and of which we have a huge store which could supply the world with power for centuries without any mining? Can we do no better than to bury it in a deep geological repository (assuming the litigation on this matter ever ends)?

Conserving Neutron Energy

The key to unlocking the full potential of uranium's extraordinarily high energy density, is to prevent neutrons from leaving the mass of fuel *without* massively slowing them down.

Given that most existing reactors use moderators (water, heavy water or graphite) to slow down the neutrons, in order to make more of them cause fission before leaving the mass of fuel, this would seem counter-intuitive. Slowing down the neutrons has an effect analogous to slowing a rocket that is passing a moon; it allows the rocket to be captured by that moon's gravitational field, causing it to orbit the moon, and to collide with the moon if the orbit is low enough and elliptical enough.

But if our aim is to explode the moon, then we need our rocket to be massive enough, but also to strike the moon at the highest possible velocity. We also need the moon to be fragile and full of energy, like a fissile atomic nucleus. The slower the speed of impact, the more fragile the moon must be for our rocket to be able to explode it.

Thus, the moderators in standard nuclear reactors, while increasing the frequency of neutron-nucleus collisions, do so at the expense of reducing the effect of those collisions, producing fewer new neutrons on average from each fission, and failing to fission any but the most fissile nuclei—those of U-235, Pu-239 (plutonium-239), and U-233. The result is a buildup of semi-fissile, or "fissionable" isotopes produced by capture of neutrons into the naturally occurring uranium nuclei. These, by a series of neutron captures and decays, become various isotopes of elements, called "transuranics," such as neptunium, plutonium and americium, which have more protons, thus higher atomic number, than uranium. Many of the slow neutrons are also captured by the moderator or other reactor core materials, such as the fuel cladding, the control rods, or the core vessel.

The build-up of semi-fissiles creates a long-term storage problem, which further increases the cost of nuclear power. The semi-fissiles are less radioactive than fission products, but have much longer half-lives and far more energy, because the potential energy of nuclear fission in them has not been released. They will emit radiation at a hazardous level for over a hundred thousand years, gradually releasing their fission potential through a long series of radioactive decays to a stable isotope, usually of lead. Natural uranium does this, too, but over so long a time (billions of years) that it is not dangerous.

In order to sustain a chain reaction without a moderator (i.e., with "fast" neutrons), the neutrons freshly released from each neutron-nucleus collision resulting

2. Natural uranium contains about 0.73% U-235, a highly fissile isotope with a half-life in the 700s of millions of years. When uranium is "enriched," U-238 is removed to increase the concentration of U-235. The removed material, mostly U-238, is called "depleted uranium," and we have tremendous stores of it.

in nuclear fission must be prevented from leaving the fuel before they do their job, despite their velocities from 4 to 6% of light speed. This is accomplished by enriching the fuel to a higher concentration of fissile nuclei, packing the fuel closer together and surrounding it with a good neutron reflector.

This, in turn, creates a problem for heat transfer: how to prevent closely packed fuel from melting or boiling. Excellent solutions to this problem have been known for 50-plus years (though not developed in industrial practice). For example, use liquid metal to transfer the heat. Or combine the fuel and the coolant into a liquid that flows through heat exchangers, transferring heat to another liquid, then returning to the reactor core.

For the latter, the liquids that have worked best are molten salts.

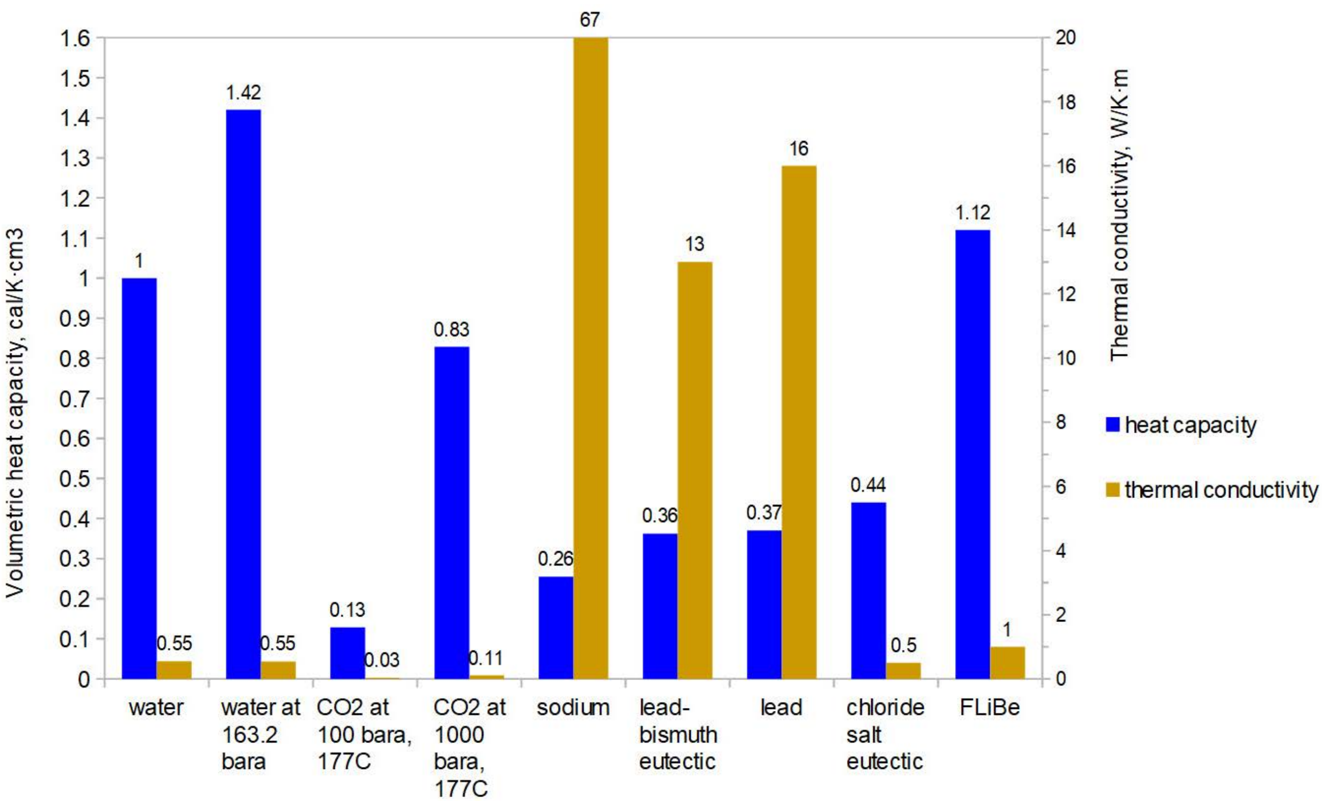
Molten Salt vs. Liquid Metal

The only *fast neutron* fission reactors thus far built and operated commercially, or to power submarines, use *liquid metal* for heat transfer. The metals used have relatively low melting points, and far higher boiling points than water (as nearly all metals do). The fuel used is in solid form, with a much higher melting point than the metal used in liquid form to transfer heat. The nuclear weapons proliferation alarmists prefer solid fuel because it is much easier to account for, being in discrete and countable pieces encased in a metal cladding designed to contain the fission products.

But this arrangement has several disadvantages compared to liquid fuel. First, there is the cost of fuel fabrication. Second, none of the fission products can be removed while the fuel is in use. The buildup of these

FIGURE 1

Heat Capacity and Thermal Conductivity of Coolants



At typical maximum reactor operating temperatures for each fluid: 100C for water; 350C for pressurized water; 177C for supercritical carbon dioxide; 550C for sodium, lead-bismuth and lead; and 700C for chloride salt and FLiBe. The thermal conductivity of sodium is off the chart at 67.

fission products interferes with the reaction long before most of the fuel is consumed. Third, if one wishes to reprocess the spent fuel, so as to remove the fission products in order to be able to use the remaining fuel, the fuel must be de-fabricated. This means chopping the fuel rods and dissolving them in acid in order to chemically separate the cladding from the fuel and everything else that is inside the cladding. This de-fabrication must be done behind a radiation shield, with remote control, because spent fuel rods are much more radioactive than fresh fuel even after decades of sitting in containers.

Using *liquid* metal coolant, on the other hand, has important advantages for a fast neutron reactor that aims at fuel "breeding," or full utilization of all the isotopes of uranium and transuranics found in conventional spent nuclear fuel, natural uranium, depleted uranium, or thorium.

First, liquid metal has high thermal conductivity. This is especially true of sodium, which is off the chart. (See **Figure 1**.)

Thermal conductivity is the *rate* at which heat travels a unit of distance through the material when the temperature difference at either end is one unit of temperature and is thus expressed in watts/degree Kelvin per meter, or how many watts conduct through a meter when the temperature difference is one Kelvin degree. (The rate at which heat is conducted in all materials is proportional to the temperature gradient, or temperature difference per unit of distance.)

In volumetric heat capacity, metal is not as good as water or molten salt, but it is still far better than gas, by virtue of its density, and is adequate. *Volumetric heat capacity* is the amount of heat that a unit volume of a material can absorb while raising its temperature by one unit and is thus expressed in calories per degree Kelvin per cubic centimeter. The calorie here is 1/1000 of the popular food calorie, which chemists and physicists call a "kilocalorie."

Finally, liquid metal has viscosity comparable to water, much better than molten salt when near its freezing point. And the freezing point of metal is lower than molten salt (especially sodium and lead-bismuth eutectic).

For fuel that must be closely packed in order to capture fast neutrons, thermal conductivity is the most important characteristic—to carry the reaction heat away from the fuel mixture—and low viscosity second. The high boiling point of metal, especially lead and lead-bismuth eutectic, is a valuable passive safety feature, also allowing operation at low pressure.

The chief *disadvantage* of liquid metal coolant is that the fuel cannot be dissolved in it; therefore it must be fabricated into solid fuel with cladding, and de-fabricated several times, to make full use of it.

The second disadvantage of liquid metal is its opacity, which prevents monitoring of the interior of the reactor core and heat exchangers without exotic equipment that can "see" through liquid metal, which not even x-rays can penetrate.

Molten salt, by contrast, is clear and transparent without fuel in it, like water, and with fuel in it, is colored but translucent, like Kool-Aid.

Elysium Industries' Molten Chloride Salt Fast Reactor Cuts Costs

The reactor designed by Elysium Industries Chief Technical Officer Ed Pheil[3] dissolves the fuel in a molten salt fluid that circulates between the reactor core and the heat exchangers. That fluid is plain table salt (sodium chloride) with magnesium chloride added to bring down the melting point, which is, of course, still very high. The fuel is in the form of chlorides of uranium, plutonium, and the trans-uranic elements. The mix may also include thorium chloride. All of these chlorides have good solubility in the chloride salt. (See **Figure 2**.)

When the fuel-molten salt solution is in the heat exchangers, the geometry stops the chain reaction because, while the fuel moves through narrow tubes, there are not enough fissile nuclei in the vicinity to sustain the chain reaction. The chain reaction resumes when that fuel-molten salt solution returns to the reactor core.

Figure 3 is a schematic of the Molten Chloride Salt Fast Reactor.

The three large structures at the top are, left to right: reactor vessel, primary heat exchanger, secondary heat exchanger; the three copper tubes to the right are heat pipes; below the reactor vessel is a thin brown drain tank for the fuel salt; its thinness prevents criticality. All

3. October 1, 2019 video, "Molten Chloride Salt Fast Reactor," a presentation by Ed Pheil of Elysium Industries USA, produced for a Thorium Energy Alliance Conference; a November 2017 video, also of Ed Pheil; and slides from earlier video, "Advanced Nuclear Technology to Close the Fuel Cycle," produced by Elysium Industries USA, January 24, 2018.

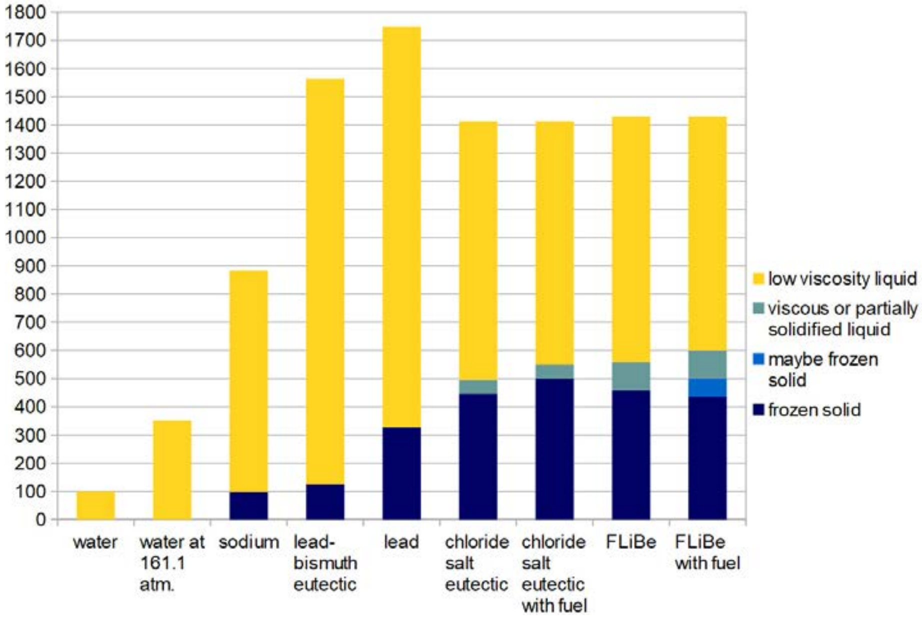
structures are immersed in the secondary molten salt; the drain tank is fully immersed, the other structures mostly. The horizontal gray pipes carry fluid between the reactor, the heat exchangers and the turbine, in both directions, concentrically. The reactor vessel has closed fittings for 5 additional pipes connecting to optional additional heat exchangers.

Unlike other molten salt-cooled designs, the molten fuel-salt drains continually from both the reactor vessel and the primary heat exchanger and is continually pumped back in from the thin drain tank (brown) through the green tubes. The secondary heat exchanger (purple) is larger because it transfers heat from liquid secondary salt to a gas, such as superheated steam, which drives the turbines or may be used for industrial process heat. The heat pipes passively transfer heat from the secondary salt in which everything is immersed to the ambient air in case of loss-of-flow of the salts or the gas.

FIGURE 2

Liquid Phase of Reactor Fluids

(At 1 atmosphere pressure, unless otherwise noted. Temperature in degrees Centigrade. Where there is uncertainty in the boiling temperature, the lowest plausible boiling point is shown.)



Note: FLiBe is a special non-eutectic mixture of lithium fluoride and beryllium fluoride which aims to minimize viscosity, and its boiling point is known to be 1430°C, about mid-way between the boiling points of its ingredients (1169°C for beryllium fluoride and 1676°C for lithium fluoride.) "Fuel" means chlorides or fluorides of fissile or fertile isotopes, whose melting and boiling points are much higher than those of the chloride salt eutectic or of FLiBe, but which dissolve in those salts without raising the melting point too much. A version of FLiBe with fuel optimized for slow-neutron breeding of U-233 from thorium was reported to melt as low as 434°C, but with excessive viscosity. At 600°C, this mixture had a dynamic viscosity of 12 cP and a density of 3.35 g/cm3, vs. 1 cP and 1 g/cm3 for water at room temperature. See Grimes, Table II, p.143, "MSBR Fuel" column.

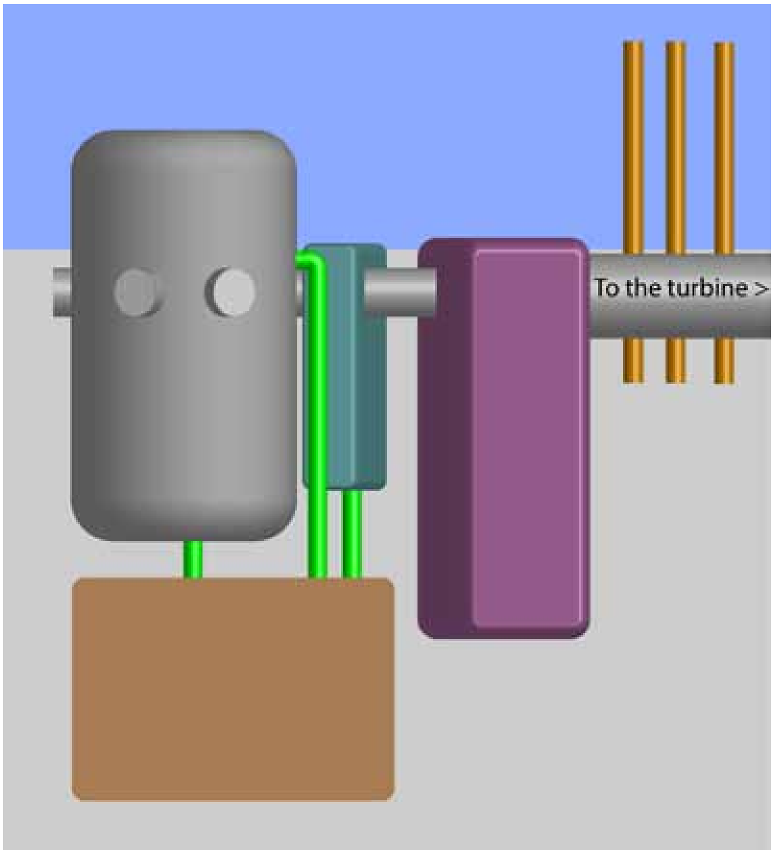
The fluid contains no beryllium, no moderator, no control rods inserted during normal operation, no structural components other than the wall of the core vessel and the openings to pipes that carry the fuel salt through the primary heat exchangers. The reaction rate is determined by the strong negative thermal coefficient of reactivity, which causes the fission rate to follow the rate of cooling.

The lack of anything solid inside the core, such as a moderator, control rods or fuel elements, assures that the geometry will not change due to production of gaseous fission products or neutron damage, assuring that the negative thermal coefficient of reactivity will be maintained.

If for any reason it gets too hot, the fuel salt will fall into tanks whose geometry will stop the chain reaction (e.g., multiple small tanks that are far from spherical) and conduct heat away. The design presented in the 2019 video does not rely on an actively frozen drain plug to melt for this to occur; instead, during normal operation, fuel salt is continually pumped from the drain tank [tan color] into the reactor core; if this pump stops, the fuel salt will simply drain into the tank through a permanent opening in the bottom of the core. Elysium's design uses one core size for all power levels from about 125 MW electric to a full gigawatt electric. The power-generating capacity is determined by the cooling capacity of the heat exchangers and pumps which are all built outside the reactor core.

The reactor is expected to run for 40 years with no maintenance other than daily addition of fertile material and continuous filtering of fission products that can

FIGURE 3
Schematic of the Molten Chloride Salt Fast Reactor



Cross-section is a measure of the probability of a sub-atomic particle interaction, usually, an interaction between a neutron and an atomic nucleus.

Elysium Industries' Ed Pheil argues that, despite the obvious disadvantages of fast neutrons—requiring more concentrated fissile fuel to achieve criticality and incurring more neutron damage to structural components—the fast neutron breeder reactor can be built more economically and will perform better overall. This is because fast neutrons cause more neutrons to be released when fission occurs. The extra neutrons will cause all neptunium, plutonium and higher atomic number isotopes to become fissile and fission, and fast neutrons will sometimes cause even U-238, the most stable and abundant isotope of uranium, to fission directly. Therefore breeding can be achieved and maintained without a moderator.

Pheil claims that chloride salts, in addition to being cheaper and less toxic than the fluoride salt with beryllium proposed for slow neutron breeders, are less corrosive and have a lower melting point, allowing the use of "fully qualified" nuclear reactor materials, rather than materials not yet having achieved such institutional approval for the proposed use and expected operating conditions.[5] The previously cited study published by Oak Ridge National Laboratory in 2011 partly confirms this claim.

be removed without chemical separation,[4] at which time, it is necessary to replace the reactor vessel due to neutron damage. How could a reactor run that long without the buildup of fission products poisoning the reaction (even if some products are continuously removed)? A study published by Oak Ridge National Laboratory in 2011 shows that:

> Fission products have relatively large neutron capture cross sections in the thermal energy range but smaller capture cross sections at higher energies. Thus much greater fission product buildup is tolerable in an FS [fast spectrum]-MSR [molten salt reactor] than in a thermal-spectrum MSR. [Holcomb, p.10].

What Are the Real Nuclear Weapons Proliferation Risks?

Ed Pheil claims that his reactor design is as proliferation resistant as any other. How can that be, given that the fuel is liquid, and contains all those scary transuranic elements, and a much higher fissile inventory than most slow neutron reactors?

First of all, what makes fissile material "weapons grade" or suitable for bomb-making is not merely that it contains a high enough concentration of fissile material, at least 85%, but that it is free of anything that would cause premature detonation or make the material

4. Ed Pheil claims that the reactor can run for 40 years before there is sufficient build-up of "pile poisons," or fission products that interfere with the reaction, that these fission products must be purged before the reaction will continue at a useful rate.

5. Explicitly approved for nuclear construction within American Society of Mechanical Engineers (ASME)'s codes and standards, Section III. See also Holcomb, pp.9-10.

too radioactive to handle and make into a bomb.

The fuel cycle in the Elysium Industries reactor offers little opportunity to extract weapons grade material, because the liquid in the reactor is never removed for chemical processing; it is only filtered to remove volatile (gaseous, or low-boiling point) materials, such as helium from alpha decays, xenon and krypton, and noble metals (e.g., palladium) that will not dissolve in the salt. All the other fission products stay in the mix, relying on the low neutron capture cross-section of fission products for high-energy neutrons. So, while someone could divert some of the liquid, that person would have to do all the processing on their own; there would be nothing at the power plant to help. The content of fission products would likely be higher than at any other kind of nuclear power plant, and being fresh, it would for sure be extremely radioactive!

The content of fissile material, around 10%, would still be far too low to make a bomb, and there is no chemical treatment that anyone could apply to the mixture of many isotopes of uranium, plutonium, transuranic, and possibly thorium chlorides that would yield only fissile isotopes suitable for a bomb.

Safer and Cheaper Power than Anything Else

We have shown that a nuclear fission reactor can be built without fuel rods, without any moderator to slow the neutrons, without control rods, really nothing more than liquid in a can, at low pressure, whose power output is controlled by the rate of cooling.

Because the fissile fuel is in the coolant, which expands when it heats, the reaction slows when it gets hotter, as the fissile nuclei become further apart. And it makes power from all isotopes of every element on the periodic table with 90 or more protons (thorium has 90), leaving only fission products, whose radioactivity declines to the level of an equal mass of natural uranium in about 300 years.

The Elysium reactor outputs heat at about 600°C, not the highest achievable with, for example, TRISO solid fuel encased in ceramics, and gas coolant, typically helium, but high enough for efficient generation of electricity and some industrial uses of heat, unlike pressurized water reactors, which deliver a maximum of only 350°C.

Without any chemical processing of spent fuel, much less de-fabrication, the Elysium molten salt reactor is designed to run for 40 years, the fuel lasting longer than the reactor core. Some filtering of the liquid is required, yielding valuable isotopes and elements, the noble metals and noble gases. If the liquid leaks, it freezes and does not ignite or react violently with anything; it is salt. Thus, it produces power from fuel we have already mined but cannot use as fuel, including what we call "high-level waste" or "spent nuclear fuel," as well as "depleted uranium." The fuel-coolant mixture is translucent, so it is relatively easy to monitor.

Fission fuel yields over 1.5 million times as much power by mass and over 20 million times by volume compared to any fossil fuel. Yet we hear that it is "obsolete," and can't compete even with solar and wind power backed by natural gas from fracking, but maybe it could compete if it were given credit for being "zero carbon." Why put up with expensive electricity and energy austerity, and the myriad hazards of intensive mining, not to mention all the pollution that creates? Or all the pollution and general misery that results from lack of power? We can do much better!

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