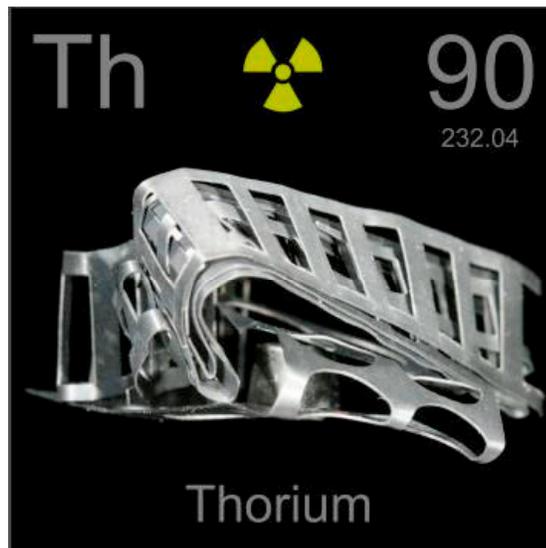


**THE SUPERIOR DESIGN ADVANTAGES
OVER ALL OTHER
NUCLEAR REACTOR DESIGNS
OF THE
LIQUID FLUORIDE THORIUM REACTOR
(LFTR)**



**WITH AN EMPHASIS
ON ITS
ANTI-PROLIFERATION FEATURES**



White Paper Prepared for The South Africa Independent LFTR Power Producer Project
By SA LFTR Energy (Pty.) Ltd.

Just before his death Edward Teller, famous for his pioneering work on the Hydrogen Bomb, collaborated with R.W. Moir on a paper extolling the way forward for nuclear energy – the **Liquid Fluoride Thorium Reactor (LFTR)**.

We propose the burning of thorium dissolved as a fluoride in molten salt in the minimum viscosity mixture of Lithium Fluoride (LiF) and Beryllium Fluoride (BeF₂) together with a small amount of uranium-235 (²³⁵U) or plutonium fluoride to initiate the process to be located at least 10 meters underground.

The fission products could be stored at the same underground location.

With graphite replacement or new cores and with the liquid fuel transferred to the new cores periodically, the power plant could operate for up to 200 years with no transport of fissile material to the reactor or of wastes from the reactor during this period.

Advantages that include utilization of an abundant fuel, inaccessibility of that fuel to terrorists or for diversion to weapons use, together with good economics and safety features such as an underground location will diminish public concerns. (Moir & Teller, September 2005)

Dr. David LeBlanc's Tube-within-Tube Two Fluid LFTR Design, 2009

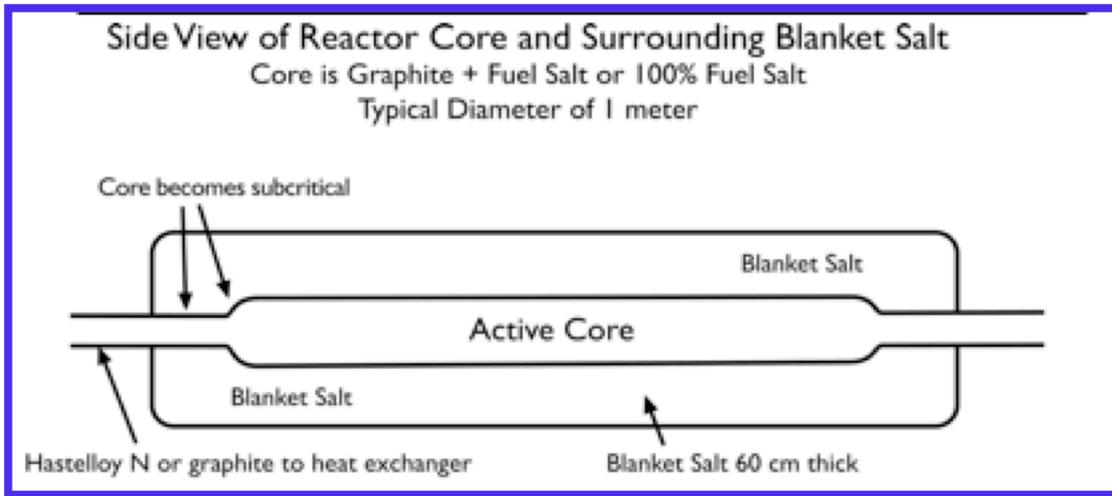
Dr. David LeBlanc, a professor of nuclear physics at Carleton University in Ottawa, Canada, has analyzed the molten salt reactor extensively. He has recently patented a new design for the LFTR. This nuclear energy solution possesses the following advantages:

Two Fluid Tube-within-Tube LFTR is

- *The Safest Nuclear Energy Design*
 - *No pressure containment vessels*
 - *No chemical driving forces such as steam build up / explosions, or production of hydrogen*
 - *All volatile fission products passively and continuously removed from molten salt*
 - *No excess reactivity required*
 - *Instantly acting negative temperature reactivity coefficients maintain high reactor stability*
 - *Freeze valve drains molten salt to tanks designed to remove decay heat*
 - *Molten salts are excellent coolants (a 25% higher volumetric heat capacity than pressurized water and nearly 5 times that of liquid sodium) – therefore, much smaller heat exchangers and pumps can be manufactured more easily*
 - *High thermal efficiency of 40% + using Gas Brayton turbines*
 - *Elaborate in-depth defense not needed –*
 - *No massive internal steam containment structures*
 - *No massive water cooling resources*
- *Much simpler removal of fission products as there's no thorium in core molten salt*
- *Strong negative temperature coefficient for core molten salt*
- *Very low fissile material content requirement in core molten salt (0.7t/GW(e))*

- Can use Two Fluid fuel processing without the Oak Ridge National Laboratories' (ORNL) Two-Fluid 'plumbing problem'
- Blanket will also have negative temperature / void coefficient, acting as a weak neutron reflector
- Simple transportable cores
- Fissile inventory of 400 kg per GW(e) or less
- Offers the best overall breeding ratio package

(LeBlanc, 29Mar10).



The Two-Fluid system greatly simplifies processing out fission products from the fuel salt because of the absence of thorium. ^{232}Th is only in the blanket salt.

Processing out fission products can be readily accomplished using Vacuum distillation, which was developed in 1964.

After removal of all UF_4 , the carrier salt can be evaporated off and recycled, leaving most fission products behind.

Furthermore, the neutron losses to ^{233}Pa can be minimized as it is effectively diluted in the much larger volume of blanket salt and experiences a lower neutron flux.

^{233}Pa is the 27-day half-life intermediate which decays to ^{233}U following its production by a neutron absorption in ^{232}Th .

Thus Two Fluid designs do not require any complex and rapid processing to remove ^{233}Pa to allow it to decay to ^{233}U as has been often portrayed as necessary.

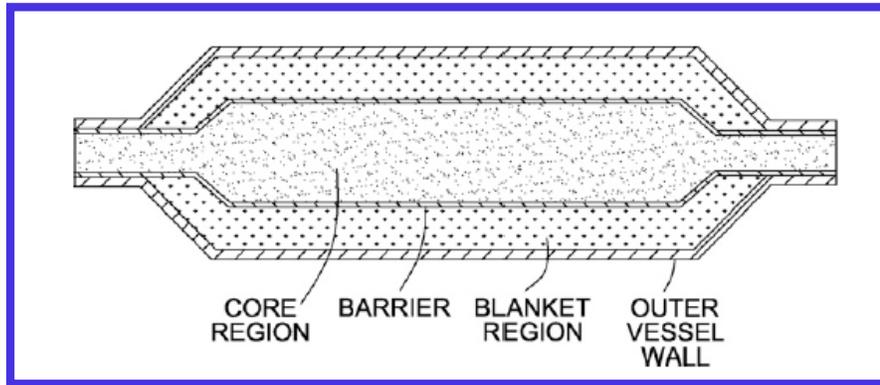


Diagram #2 of LeBlanc's LFTR Design

Traditionally reactor cores are spherical or short cylinders to minimize neutron leakage. Leakage is not an issue with the Two Fluid design's 360° molten salt blanket.

The simple solution (to the ORNL Two-Fluid size constraints and maintenance problems) is a core geometry switch to increase the power producing volume while maintaining the required small critical diameter.

For the same fuel salt, a long cylinder will have a critical diameter approximately 77% that of a sphere. If a specific combination of fissile concentrate, graphite and carrier salt gives a critical diameter of 1 meter for a sphere, then a long cylinder would have a critical diameter of 0.77 meter.

A practical total power can be obtained by simply extending the length of the core.

A single barrier between the core salt and the blanket salt is far less complex than the internal plumbing and blanket salts of Oak Ridge National Laboratory's (ORNL's) Two Fluid designs.

The cylindrical core is tapered at the ends to a sub-critical diameter (that is, too small to achieve criticality) while still surrounded by the blanket salt, virtually eliminating neutron leakage.

This tube-within-a-tube Two Fluid design will have a strong negative temperature and void coefficient for the fuel salt. This negative coefficient means that if the fuel salt temperature rises, the nuclear reaction slows. If the fuel salt temperature rises too much, the reaction stops, the freeze plug is melted, and the salt drains down and freezes in the heat sink tanks that remove decay heat.

This design improves on the ORNL Two Fluid designs because the blanket salt also has strong negative coefficients – the outer blanket acts as a weak neutron reflector.

Lowering its density decreases this reflective quality and lowers core reactivity. This is accomplished without graphite or other reflective materials in the blanket salt.

The hydrostatic pressure of the far denser blanket salt assures that any leak through the barrier between the core and blanket adds fertile to the core, lowering reactivity. (LeBlanc, D., 2010)

Initial state nuclear characteristics of spherical two fluid, homogeneous, molten fluoride salt reactor with ^{233}U from ORNL 2751 (1959)

Inner core diameter	91 cm
Thorium in fuel salt	0 %
$^{233}\text{UF}_4$ in fuel salt	0.592%
Neutrons per absorption in ^{233}U BE, Li and F in Fuel Salt	0.0639
Hastelloy N Core Wall (8.5 mm)	0.0902
Li and F in Blanket salt	0.0233
Leakage	0.0477
Neutron Yield	2.1973
Median fission energy	174 ev
Initial breeding ratio (BR)	0.9722
Projected BR thinner wall (1)	1.060
Projected BR carbon wall (2)	1.105

(1) Projected assuming a thinner Hastelloy core barrier wall of 1/6 inch (4.2 mm) and 90% leakage reduction by using a thicker blanket salt.

(2) Projected assuming a graphite or carbon-carbon composite core barrier wall and 90% leakage reduction by using a thicker blanket salt.

Taking the 3-foot (91 cm) case as example, this would equate to a 70 cm wide cylindrical core. A modest average power density of $200\text{MW}/\text{m}^3$ still gives impressive results.

Using the standard ORNL 140 Kelvin inlet/outlet temperature change and a salt speed in the core of 2 meters per second gives a 505 MW(th) [thermal] output from a 6.6m long, 0.7m wide core

At 44.4% for a steam cycle, this is 224 MW(e)[electrical] with a somewhat higher output if a gas cycle is used.

Including a meter thick blanket and outer vessel wall still results in a simple to manufacture design that can fit within a tractor-trailer for transport. (LeBlanc, D., 2010)

General Proliferation Threats

Proliferation resistance is well understood from perspective of the OECD's Nuclear Energy Agency's "Generation IV Proliferation Resistance and Physical Protection Working Groups" statement of five general proliferation threats:

1. Concealed diversion or production of nuclear material. The solution: making all records of their management public, requiring careful records be kept on all materials produced.
2. Production of material in clandestine facilities. The solution: making it a crime to divert Uranium from LFTR facilities to any weapons program.
3. Breakout. The solution: All chemical processing of LFTR salts will be conducted in a "hot cell", fission products management regulated by the Federal nuclear authority and IAEA. Offsite movement of fission material overseen by federal nuclear authority.
4. Theft of nuclear material for use in nuclear bombs. The solution: LFTR processes the thorium fuel cycle in a hot cell -- designed to retain fissionable materials under similar protection to its core.
5. Radiological sabotage. The solution: LFTR safety features are its chemical processing of the coolant / carrier / fuel salts. Underground siting will place LFTRs out of reach where radioactive materials will be safe from accidents or terrorists. (Peterson and Barton, 2009, July 19)

Beyond these elements, there are specific features of the LFTR reactor design and its management of the thorium fuel cycle in molten salts that render proliferation risks very low, unstable, impossible to hide, and very expensive, as illustrated by the following:

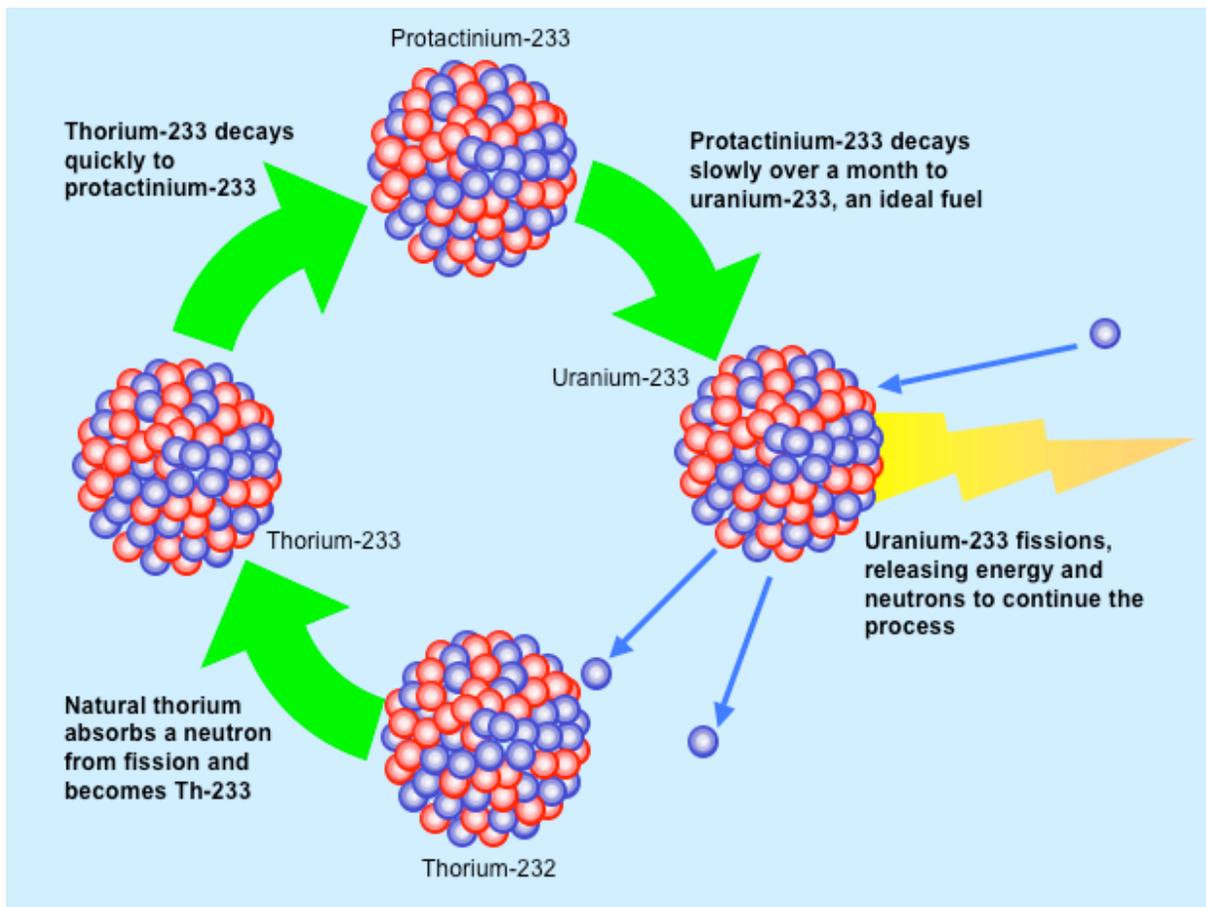


Figure 1. Illustration of the Thorium Fuel Cycle (Sorensen, 20jul09)

Domestic and international safeguards recognize that high-enriched uranium (HEU) containing ≥ 20 wt % ^{235}U can be used to build nuclear weapons, but that low-enriched uranium (LEU) — a mixture of ^{235}U and ^{238}U — can not be used practicably to build nuclear weapons. Because of this difference, the respective safeguards and security requirements for Highly Enriched Uranium (HEU) and Low Enriched Uranium (LEU) are substantially different. The different requirements imposed on HEU and LEU have a major impact on the total costs to process each. It is widely recognized within the technical community that ^{233}U which has been isotopically diluted to a sufficient degree with ^{238}U cannot be used to build nuclear weapons.

The molten salt reactor, LFTR, that is designed to consume thorium and spent nuclear fuel (SNF), and not extract Protactinium (^{233}Pa), which is produced as a by-product of neutronizing Thorium, is thus rendered non-proliferative.

Without expensive and difficult enrichment technology, any ^{233}U produced will be contaminated by ^{232}U , produced in one of three ways:

Th-230(n,gamma)->Th-231(beta)->Pa-231(n,gamma)->Pa-232(beta)->U-232

Th-232(n,gamma)->Th-233(beta)->Pa-233(n,2n)->Pa-232(beta)->U-232

Th-232(n,gamma)->Th-233(beta)->Pa-233(beta)->U-233(n,2n)->U-232

^{232}U contaminating ^{233}U in the thorium cycle provides intense gamma radiation contamination making the ^{233}U most difficult to handle. ^{232}U follows the same decay chain as thorium, only it follows it much more quickly because it has skipped all the “slow” steps at the beginning.

That decay chain contains two strong gamma-emitting decay steps — bismuth-212 and thallium-208. Those strong gamma decays make fabrication, testing, and basic survival of a nuclear weapon very doubtful.

LWR fuel cycle outputs are different: ^{238}Pu on the other hand decays to ^{234}U , which has a very long half-life, and from there follows the standard uranium-238 decay chain, which doesn't have the strong gamma-emitting isotopes. The basic weapons-deterrence feature of ^{238}Pu is simply spontaneous fission and the high heat generation of its fairly rapid decay. (Forsberg, March 1998.)

No nation or nuclear program has ever chosen ^{233}U as a weapons material because it is inevitably contaminated with the strong gamma emitter ^{232}U , from which it is difficult if not impossible to separate.

None of the thousands of nuclear weapons built and lying in wait globally use ^{233}U .

As a further anti-proliferation advantage, the molten salt LFTR renders and manages, ^{233}U in fluid form. As a fluid, it can be quickly “denatured” by mixing it with readily available ^{238}U in just a few moments, thus preventing it from being used by even a suicidal terrorist group – not for a dirty” bomb and not for an atomic bomb, either.

On the other hand, plutonium, the nuclear bombardier's fuel of choice, cannot be denatured by any means.

In his “*Introduction to Weapons of Mass Destruction: Radiological, Chemical, and Biological*”, Roland E. Langford makes the point that the U.S. tested a few ^{233}U bombs, but the presence of ^{232}U in the ^{233}U was a problem – ^{232}U is a copious alpha emitter and tended to ‘poison’ the ^{233}U bomb by knocking stray neutrons from impurities in the bomb material, leading to unwanted pre-detonation.

Separation of the ^{232}U from the ^{233}U thus proved to be very difficult and not practical.

Therefore no ^{233}U bomb was ever deployed, since ^{239}Pu , a much better nuclear bomb fuel, was becoming more plentiful and easier to get.

Could weapons be made from the fissile material?

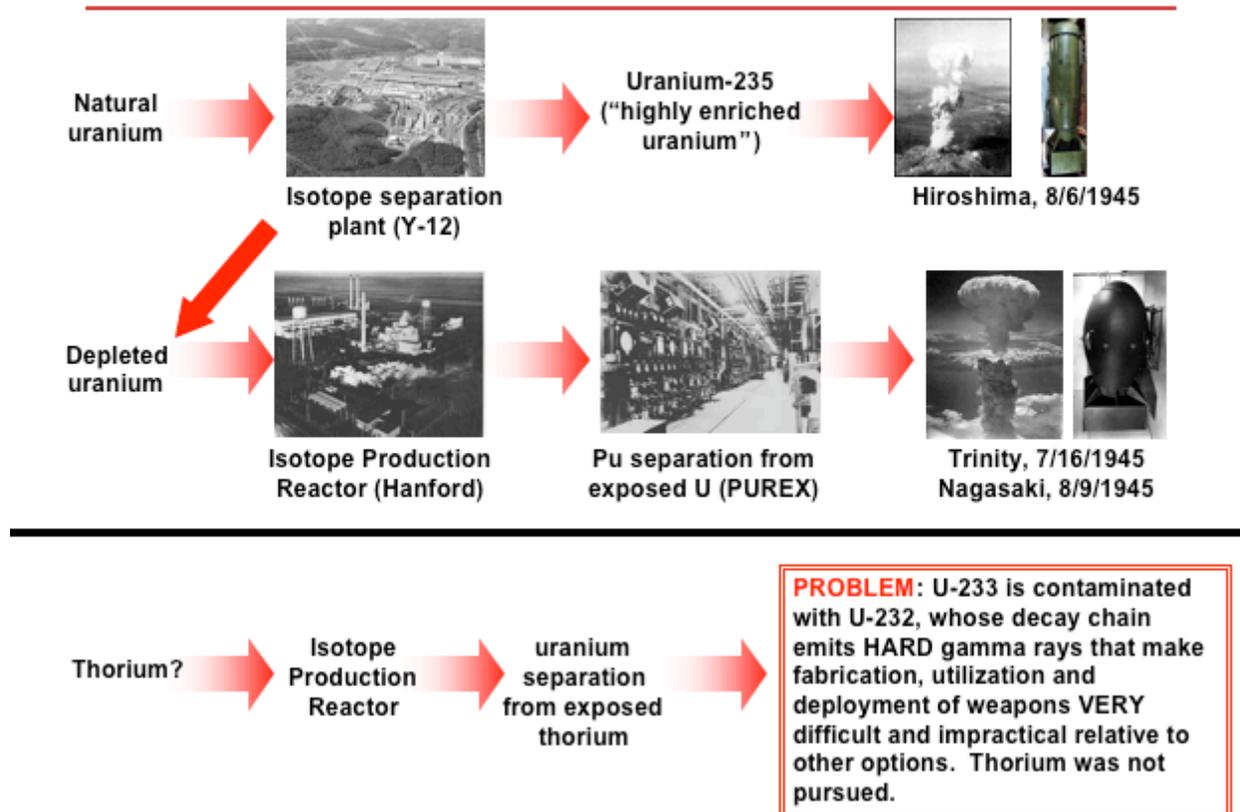


Figure 2. **Illustration of the Origination of a Nuclear Bomb** (Sorensen, 20jul09)

The IAEA reports that the enrichment boundary below which enriched uranium is not directly usable to make fission explosives is 20 percent ^{235}U . Thus dilution by ^{238}U “denatures” ^{235}U for weapons purposes. ^{238}U is available in abundance in natural and depleted uranium to denature ^{235}U . (Kang et al, 2001).

^{233}U , bred from the thorium, can be diluted with the naturally abundant isotope ^{238}U to such an extent as to make the mixture unsuitable for weapons without isotope separation – currently a technology available only to a few nations. In contrast, no comparable isotopic “denaturant” exists for plutonium. (Bulletin of Atomic Scientists, December, 1976).

Proliferation Resistance from Managing Fuels as Fluids

Producing weapons grade plutonium (^{239}Pu) requires that the ^{238}U fertile material be irradiated long enough so that there are sufficient neutron captures to create enough ^{239}Pu to make chemical extraction practical, but not so long that the newly produced ^{239}Pu captures neutrons and either fissions or transmutes into non-fissile ^{240}Pu and ^{242}Pu . (Holdren, 1995).

There are no solid fuel elements in the Molten Salt Reactor (MSR) [of which the LFTR is one design example] therefore there is no mechanical damage done by neutron irradiation, and requirements for fuel fabrication, transportation or reprocessing (tempting opportunities for nuclear theft) are bypassed. (Engel, November 1979).

Where there is no mechanical damage combined with the ability to constantly process the fuel in a fluid molten salt environment, it can be completely burnt up. As the fluid is a homogeneous fluid, there are no subunits that can be specially treated or irradiated so as to clandestinely produce undetected fissile material to later suborn for bomb-making. (Engel, 1980.)

^{233}U fuel is easily removed from LFTR molten salts via the fluoride volatility process. There need not be any fissile in any of the wastes to later be clandestinely "mined".

Plutonium is very difficult to remove from the salt. Due to its much higher neutron reaction rates plutonium suffers fission and isotopic conversion to non-fissile plutonium (non-bomb grade Pu) at a much more rapid rate than the uranium fuels; ^{233}U and ^{235}U . This makes MSRs inconvenient, and difficult candidates for producing bomb material. (Hoglund, 1995).

Proliferation Resistance from Uranium Fissile Dilution

After many years of operation, the fuel salt will contain all the long-lived isotopes of uranium. It seems that this natural denaturing of uranium has not been fully considered, as when the MSR was studied as a non-proliferation system ^{238}U was added to denature (that is, isotopically dilute) the molten fuel salt.

This has the disadvantage of slightly reducing neutron economy and producing plutonium [Pu] - although at levels far below the predominant design of most of the world's nuclear power reactors, Light Water Reactors [LWRs]. It should be emphasized that this plutonium is also very difficult to isolate and remove from the molten fuel salt.

Even if an MSR were operating on bomb grade material, there would be no need to denature the fissile within the salt. The MSR converts the Pu to ^{233}U via thorium neutron absorption. (Hoglund, 1995).

Proliferation Resistance from A Propensity For Spontaneous Fission

It is well known among nuclear bomb designers that there are two basic types of bomb designs: "The Gun Type" of bombs are generally considered simpler than the "Implosion Type" (which is required when the rate of spontaneous fission is "too" high). Plutonium isotopes exhibit high enough levels of spontaneous fission so as to require implosion type bombs. Uranium isotopes, with the possible exception of ^{232}U , do not exhibit high spontaneous fission rates, which allows the construction of either gun or implosion type weapons.

It is doubtful if spontaneous fission will require implosion type bombs for ^{233}U fissile, even with large amounts of ^{232}U are also present since the Spontaneous Fission Rate is still orders of magnitude smaller than the plutonium isotopic contaminants. (Hoglund, 1995).

Proliferation Resistance from High Energy Gamma Radiation

But “The Gun Type” of nuclear bomb design does not work very well with ^{233}U fuel either. Gun Type bomb designs require high explosive detonators that are invariably damaged by such gamma radiation associated with ^{233}U fuel that is ‘poisoned’ by ^{232}U .

The Molten Salt Reactor Experiment (MSRE) was the first reactor to operate on ^{233}U . The MSRE was fueled with 39 kilograms of ^{233}U that contained ~220 parts per million (ppm) of ^{232}U .

This made it so radioactive as to practically prohibit any other use.

Although the ^{233}U used in the MSRE came from relatively low burn-up fuel elements from various Light Water Reactors that had operated on ^{235}U (such as the Indian Point PWR) and thorium fuel elements that were subsequently reprocessed by the Thorium-Uranium Recycle Facility (TURF) and only contained 222 ppm of ^{232}U , it was sufficient to generate a gamma dose of 300 rems per hour (**röntgen** (roentgen) equivalent in man (or mammal) or rem) from a 450 gram (~1 pound) amount of the uranium oxide at a distance of 2 inches (5 cm) -- just an example of the unique proliferation resistance of the MSRE thorium based fissile fuel, ^{233}U that is irrevocably ‘poisoned’ by ^{232}U . (Hoglund, 1995).

Proliferation Resistance from Gamma Radiation Detection & Shielding

To shield the weapons maker (the object) from the full Gamma radiation dose from ^{233}U , sufficient mass has to be placed between the source and the object. In this way, the source can also be made more difficult to detect by shielding due to its obscuring effect on radiation.

To reduce radiation by 1% of the original *unscattered* (significant for detection prevention) radiation amount, the bomb-sized mass of ^{233}U (6.7 kg ^{233}U) would have to be surrounded by a 0.49 meter (~19 in.) thickness of concrete.

While this bulky shielding might be achievable, it does greatly complicate bomb design and perhaps prevent clandestine construction or movement of a weapon constructed using ^{233}U . Perhaps this is why no current nuclear weapon nation has any known ^{233}U -based weapons.

Keeping the hiding place and number of weapons a secret would be largely impossible.

In addition, the hazard to weapon handling personnel would ultimately undermine their health. Any weapon designer, clandestine or not, will always take the simplest route to create a weapon that meets his organization’s minimal requirements.

Proliferation Resistance from the LFTR’s Salt Heat & Radiation

Another hurdle for the pilferer of 700° C. molten salt is the heat that is released by the salt. Even with a 1-hour cooling period to allow the decay of the high energy releasing, short lived isotopes, the salt still releases ~350 W/liter (~10 kW/ft³), not to mention the associated radioactivity. Obviously not a material that someone would put in their pocket.

Even if terrorists seeking nuclear material attempted to steal the salt in the 200 ft³ Pa Decay Tank they could not -- the concentrations of Pa are highest there and the heat release is 1 kW/liter (28 kW/ft³), which makes it even hotter.

With just modest design effort, terrorists will never successfully steal ^{233}U from a LFTR and make a bomb, even if the LFTR uses ^{233}Pa separation and thus makes relatively pure ^{233}U . The primary reason is that the ^{233}U must be

remotely handled for personnel safety reasons, and it is pretty easy to make it very hard for insiders or outsiders to steal stuff from 'hot cells'. ²³³U has roughly the same bare-sphere critical mass as plutonium, almost no spontaneous neutron generation, and almost no heat generation. The primary disincentive for weapons use involves OSHA issues due to personnel radiation exposure from ²³²U.

The bomb maker can avoid this by instead choosing weapons-grade plutonium or Highly Enriched Uranium (HEU) instead of ²³³U. (Peterson, Per M. Web Log Comments, 28Oct09)

High explosives and detonators are invariably damaged by gamma radiation. More than just an OSHA (the U.S. Occupational Safety & Health Agency) issue to be ignored where human life is cheap – the ²³³U weapon is rendered unreliable with a short and uncertain shelf life.

One of those Non-Proliferation Treaty criteria is nuclear fuel and waste “self protection” by the means of its nuclear radiation. The uranium isotope ²³²U is a prodigious producer of lethal gamma radiation.

Table 1

Unshielded working hours required to accumulate a 5 rem dose (5 kg sphere of metal at 0.5 m one year after separation)

Metal	Dose Rate (rem/hr)	Hours
Weapon-grade plutonium	0.0013	3800
Reactor-grade plutonium	0.0082	610
U-233 containing 1ppm U-232	0.013	380
U-233 containing 5ppm U-232	0.059	80
U-233 containing 100 ppm U-232	1.27	4
U-233 containing 1 percent U-232	127	0.04

Radiation Dose Rate Table from (Kang & von Hippel, 2001)

The LFTR can achieve a U^{232}/U^{233} ratio of 0.1% to 0.2% (D.LeBlanc). “The main feature related to the proliferation resistance is the presence of a very energetic ray which prevents easy manipulation of the salt and above all of the Extracted Uranium and which may therefore help to detect the diversion of Uranium even in small quantities.” LeBrun et al, P. 13

What To Do With What Is Left

After operating for 40 years, there will be TransUranic wastes that we cannot sell or retrieve profitably. This radioactive waste must be sequestered in a safe, remote place while its decay heat cools down, and its radioactive half-life dissipates. Proliferation issues arise when such radioactive waste is packaged up and transported to some safe and remote storage location, away from the decommissioned nuclear reactor where it was originally created. The solution is a deep

borehole drilled five km (3 mi) into the earth's crust at the site of the decommissioned nuclear reactor where it was originally created.

The potential technical and cost advantages of deep borehole disposal have become more apparent over time. Drilling technology for petroleum and geothermal production has improved, resulting in lower costs and greater reliability for the construction of deep boreholes. Small radioactive waste inventories require fewer boreholes. Characterization of near-surface geology and hydrology required for deep borehole disposal should be less extensive and costly than for shallower mined repositories because of the greater isolation of waste in deep boreholes. Conditions favorable for deep borehole disposal exist at many locations, particularly on geologically stable continental cratons.

In 1957, the U.S. National Academy of Sciences Committee on Waste Disposal considered both deep borehole disposal of radioactive waste in liquid form, and mined storage of radioactive waste in a positive light. The intervening half-century has seen high-level waste and spent nuclear fuel disposal efforts in the U.S. and other nations focus primarily on mined repositories.

The deep borehole disposal concept consists of drilling a borehole into crystalline basement rock (typically granite) to a depth of about 5,000 meters, emplacing waste canisters containing spent nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2,000 meters of the borehole, and sealing the upper 3,000 meters of the borehole. The concept is illustrated in Figure 1, showing the borehole disposal depth relative to the typical depth of mined repositories of several hundred meters. Waste in the deep borehole disposal system is several times deeper than that for typical mined repositories, resulting in greater natural isolation from the surface and near surface environment.

The viability and safety of the deep borehole disposal concept are supported by several factors. Crystalline basement rocks are relatively common at depths of 2,000 to 5,000 meters in many countries, suggesting that numerous appropriate sites exist. Low permeability and high salinity in the deep continental crystalline basement at many locations suggest extremely limited interaction with shallow fresh groundwater resources, which is the most likely pathway for human exposure. The density stratification of ground water would also oppose thermally induced ground water convection from the waste to the shallow subsurface, as shown in Figure 1. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the sorption of many radionuclides in the waste, leading to limited mobility.

A relatively simple nominal design for the deep borehole disposal system has been evaluated herein. The borehole would be drilled and cased in stages with the diameter decreasing from about 122 cm at the surface to about 44 cm in the disposal interval. Emplacing intact spent fuel assemblages without pre-consolidation, is one of the simplest approaches to borehole disposal. A canister made of standard oilfield casing 5 meters tall and having an inner diameter of 32 cm and an outside diameter of 34 cm could hold one pressure water reactor (PWR) fuel assembly. End-caps would be welded on after assemblies had been inserted into the canisters. Crushing of underlying canisters during the operational period would be prevented by bridge plus in the borehole. The canisters would be surrounded by bentonite slurry and the upper 3,000 meters of the borehole would be sealed by a combination of compacted bentonite packs, asphalt, and concrete plug.

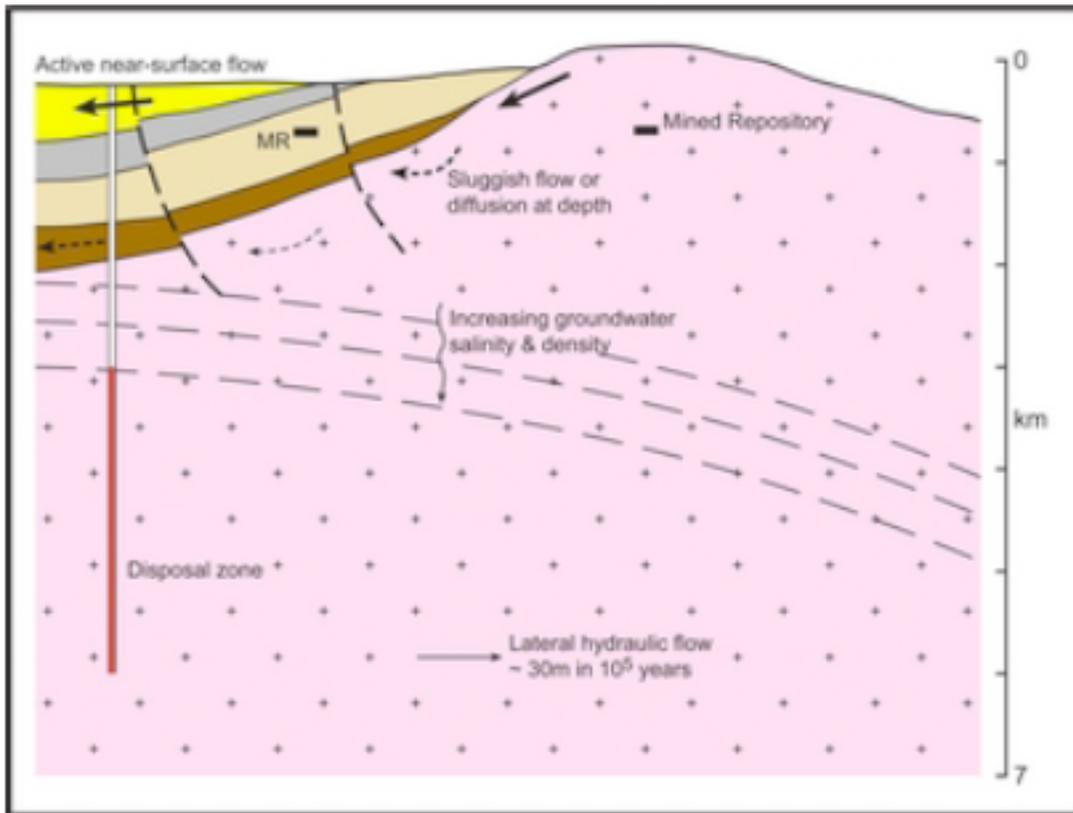


Figure 1. – The general deep borehole concept, drawn schematically as a cross section through the earth’s crust, “Into The Deep,” [Nuclear Engineering International](#), 25 March 2010.

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