Mechanical Engineering Seminar:
“Thor—The Life-Saver”

Ajay Kothari

President, Astrox Corporation

Date: Friday, July 22 at 3 pm
Location: 2164 Martin Halll or via Zoom
Zoom registration: https://go.umd.edu/kothari

Thorium Molten Salt Reactors do not need the 2-300 atmosphere pressure containment vessels required by the prevalent Light (or Heavy) Water Reactors (LWR) that have resulted in explosions such as TMI, Chernobyl and Fukushima. They work at 700-1200 C temperatures, making them more efficient for conversion to electricity. They leave only 1% waste products as opposed to about 95% for LWR. There is enough Thorium in the US to provide us electricity for 600 years, and enough in the world to provide electricity for many thousands of years.

Dr. Ajay Kothari is president and founder of Astrox Corporation, an aerospace R&D company located in suburban Washington, DC. His PhD and MS in Aerospace Engineering are from the University of Maryland and his BSc in Physics from Bombay University. He has over 45 professional publications and was awarded a National Merit Scholarship. He has been invited to speak on aerospace subjects by many entities and interviewed on television shows. His articles on space-related topics have been published by various newspapers. He is a member of the Screen Actors' Guild and also an artist.

A. JAMES CLARK
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

go.umd.edu/pandey

Introduction by:
Dr Ashwani Gupta
Distinguished University Professor
Department of Mechanical Engineering
Clark School of Engineering
University of Maryland
College Park, MD 20742

THOR – THE LIFE SAVER

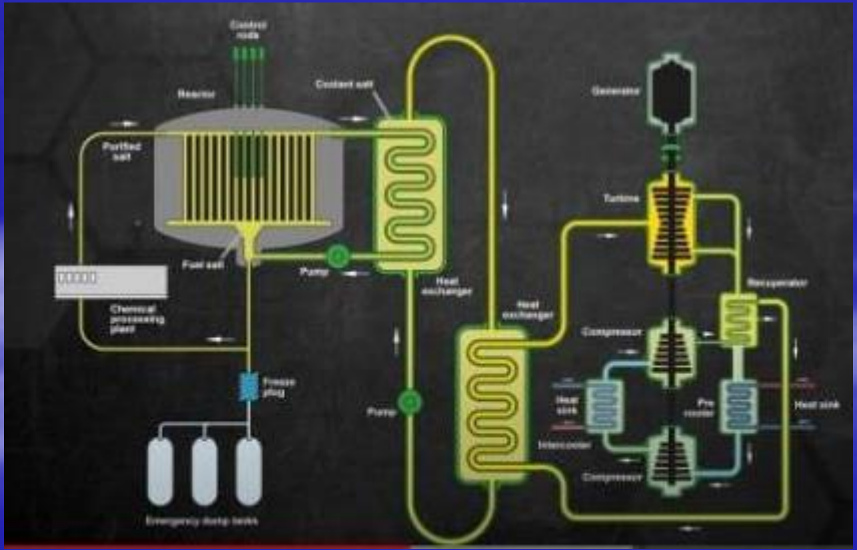
Thorium Molten Salt Reactors

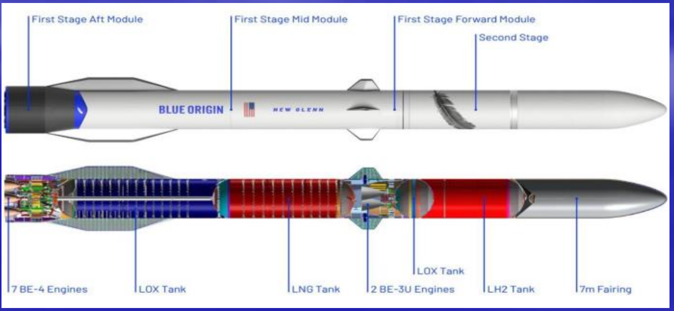
for Terrestrial, In-Space and Off-Planet Use

At:

Clark School of Engineering
University of Maryland
College Park, MD 20742
July 22, 2022

By:
Dr. Ajay P. Kothari
President
Astrox Corporation





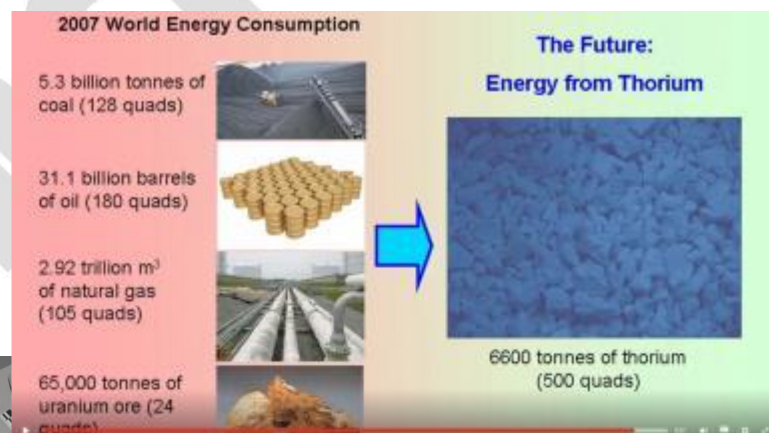
Thorium

What does it look like?

Country	Tonnes
India	846,000
Brazil	632,000
Australia	595,000
USA	595,000
Egypt	380,000
Turkey	374,000
Venezuela	300,000
Canada	172,000
Russia	155,000
South Africa	148,000
China	100,000
Norway	87,000
Greenland	86,000
Finland	60,000
Sweden	50,000
Kazakhstan	50,000
Other countries	1,725,000
World total	6,355,000

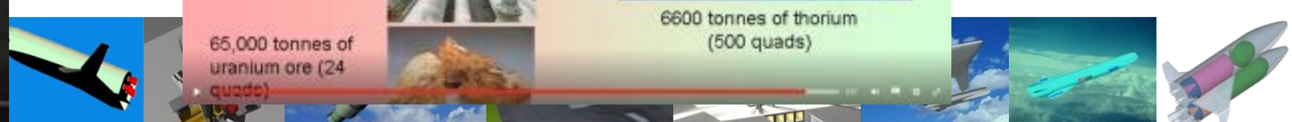
Actinide Series on PT

Comparison - NO COMPARISON!



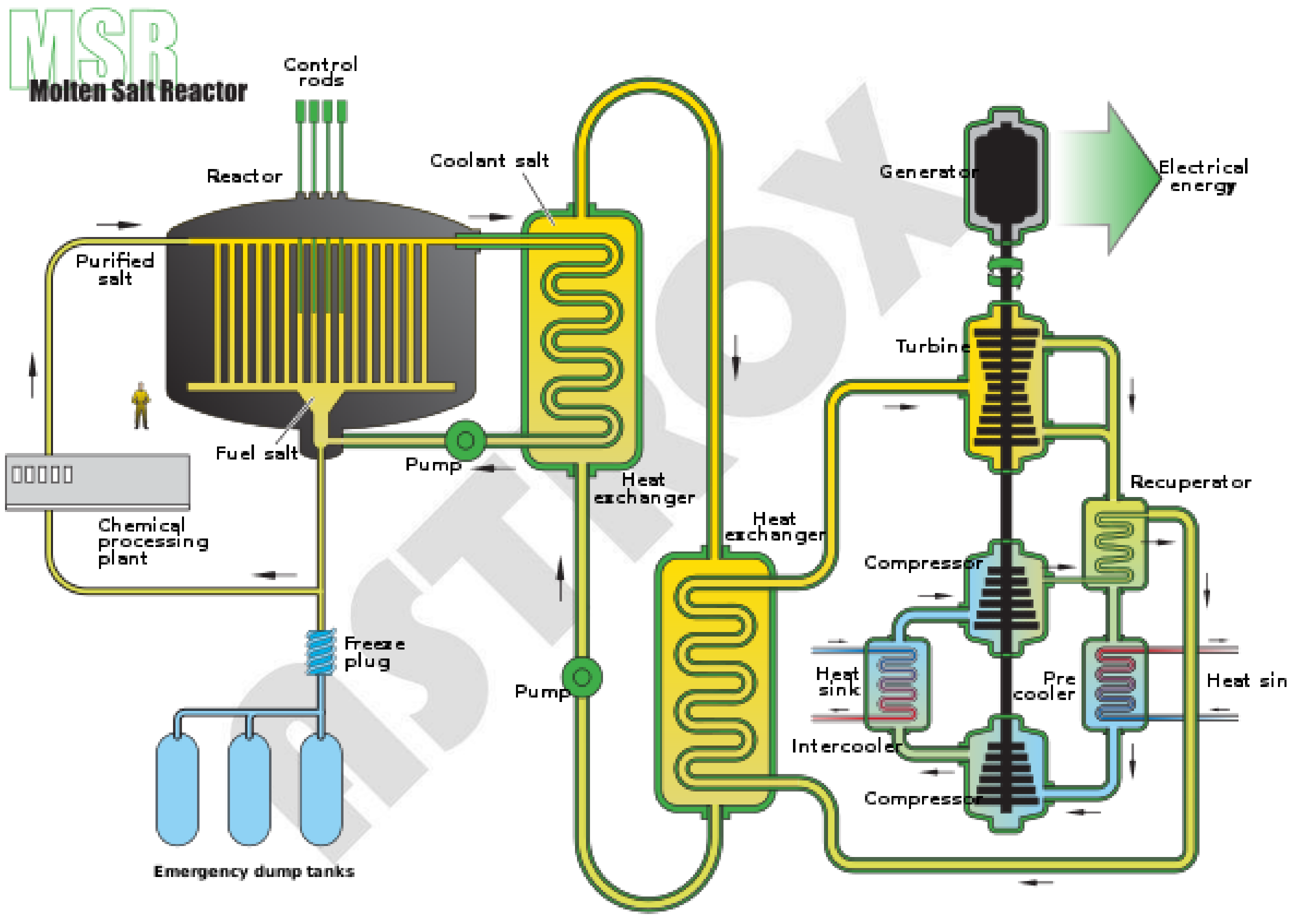
<u>ONE tonne of Th is roughly equivalent to 5 million barrels of oil.</u> So total Th reserves are equivalent to 30 million million barrels of oil reserves (or 30 trillion)!

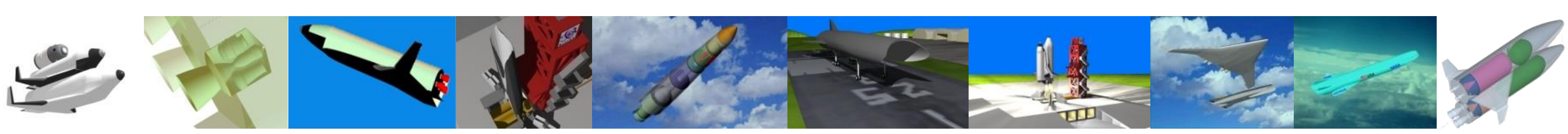
Whereas the TOTAL world reserves of oil are ~1.8 Trillion barrels



Thorium Reactor

What would it look like?





•OPINION

The Global Nuclear Power Comeback

Countries are realizing they can't meet their climate, energy and national-security goals with renewables and fossil fuels.

By Christopher Barnard

July 18, 2022 5:13 pm ET

https://www.wsj.com/articles/the-global-nuclear-comeback-green-energy-fossil-fuels-supply-climate-mandates-power-generation-11658170860

"Sen. Dianne Feinstein, a longtime nuclear-energy critic, said in June she had changed her mind about California's last nuclear plant, at Diablo Canyon. Closing it, she said, makes little sense "under these circumstances."

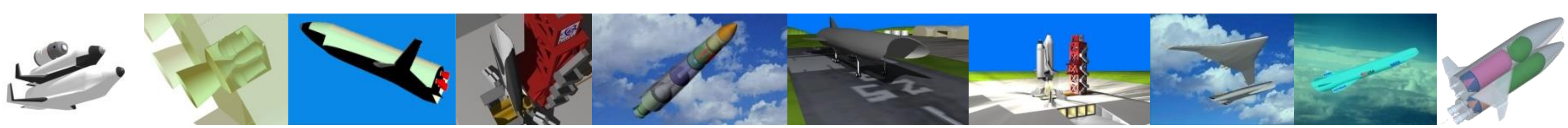
……

"Antinuclear activists have spent years fomenting fear about atomic power. Many countries took the bait and prematurely closed plants that were producing clean, reliable energy. Now, reality is forcing them to rethink. A report published by the International Energy Agency last month concludes that the "policy landscape is changing, opening up opportunities for a nuclear comeback." Countries seem to be waking up to the realization that they can't meet their climate, energy, and national security goals without nuclear energy."

In Brief: Recent Article in Seattle Journal of Technology, Environment and Innovation Law

- Nuclear power offers **more energy in less physical space** than solar and wind and yields more energy per pound than fossil fuels.
- However different nuclear fuels yield different waste profiles and create different beneficial products.
- Uranium 233 ($^{92}\mathbf{U}_{233}$ bred from $^{90}\mathbf{Th}_{232}$) **resists use in nuclear weapons**, yields beneficial daughter products, and produces dramatically less of the most problematic waste products than Uranium 235 ($^{92}\mathbf{U}_{235}$).
- $^{92}\mathbf{U}_{233}$ results from reactions with Thorium, a **plentiful**, ubiquitous element currently considered waste from rare earth mines.
- Additionally, $^{92}\mathbf{U}_{233}$ functions well in a **liquid** fuel reactor resulting in **safer**, more efficient reactors than current solid fuel $^{92}\mathbf{U}_{235}$ or Plutonium reactors.
- To capitalize on the benefits of $^{92}\mathbf{U}_{233}$ the Nuclear Regulatory Commission (NRC) should clarify its definition of reprocessing to exclude the extraction phase of liquid fuel reactors. The NRC should also resume rulemaking to allow consolidation of nuclear waste, particularly for reactors transforming that waste into liquid fuel. The Department of Energy should support U233 reactors with its grant programs.

Hanson, Maris (2022) "Uranium 233: The Nuclear Superfuel No One is Using," *Seattle Journal of Technology, Environmental & Innovation Law*: Vol. 12: Iss. 1, Article 3.
Available at: https://digitalcommons.law.seattleu.edu/sjteil/vol12/iss1/3



Possible Advantages

1. **Thorium (${}^{90}Th_{232}$) is abundant**. It is 3-4 times more abundant than mined Uranium which contains 0.7% ${}^{92}U_{235}$ and 99.3% ${}^{92}U_{238}$. Since only ${}^{92}U_{235}$ is fissionable, while all of ${}^{90}Th_{232}$ mined is fertile, the ratio then becomes much greater, almost 500 times more abundant.
2. **Thorium is fertile but not fissionable as is, so it is also not radioactive to touc**h.
3. It of course goes without saying that CO2 emissions from these energy production would be nil, a highly desirable implication politically in today's environment. But "We are not using our best weapons to fight global warming", Andrew McAfee, MIT Sloan School.
4. But unlike the CO2 threat, there is one another faced by many poorer countries – pollution. Pollution in India and China, **especially India, is already shortening a healthy life of millions – the pollution that comes from burning fossil fuels including lots of coal. It really is awful situation and it is so right now.** TMSR can go a long way to alleviate it. China just announced their intention to build 30 such reactors but India, with the largest reserve of almost a million ton, has not released any such plans which is astounding and even appalling.

Possible Advantages

(Cont.)

5. Unlike the Light Water Reactors (LWR), which the majority of reactors worldwide are, it will not require 200-300 atmospheres pressure that the LWRs require to keep the coolant water in liquid form. **Instead it will work at a couple of atmosphere pressure. So no high pressure dome needed with its associated threat of blow-ups on malfunction as we saw in Fukushima or Chernobyl. This is a huge positive**.
6. The huge positive above comes with one negative viz. the temperature of liquid salt now is much higher 6-700 C which would lead to corrosive impact on containment vessel. However it also has some advantage that the steam generation and electricity generation from turbine will be done at **higher efficiency, almost 45%,** unlike LWR where it is about half that.
7. If due to some unexpected circumstance, the temperature of the liquid goes beyond the planned, the distance between nuclei increases, decreasing the impact of these thermal neutrons, thus decreasing the fission of $^{92}U_{233}$. More on that later.
8. **If that does not occur fast enough, a freeze valve installed at the bottom melts, flooding the containment tanks below automatically cooling the fissionable fuel. Solidified TMS cannot not lead to fission. This also is a huge anti-accident insurance.**

Possible Advantages

(cont.)

9. The lack of pressure containment needed resulting in thick heavy structure for LWRs, also amounts to **much lighter and smaller plants**, thus making them portable. It may also lend itself to its use on rockets and airplanes changing the paradigm compared to 60's when nuclear applications were last looked at.
10. **MSRT will burn about 90-99% of Thorium fuel into safe and even medically useful byproducts**. This would mean even reducing the existing nuclear waste by 90+%, some of which will form the seed for starting the initial neutron source.
11. Since this reaction requires neutrons to begin the process, what better way than to use up (albeit slowly) the residues left at various reactor locations? Yes, it will also help to reduce this horrendously long half-life residues that we do not know what to do with. Now we may.
12. Pairing alkali metals with halogens results in strongly bounded compounds with no chemical energy left for rapid reactions.
13. Molten salt is an ionically bonded liquid, which does not suffer radiation damage, unlike covalently bonded solid fuel, so the fuel does not degrade over time.

Possible Advantages

(cont.)

14. The molten salt is exactly the chemical medium amenable for partitioning and extraction of valuable elements, in particular isotopes for medical and industrial application.
15. The liquid fuel is continuously mixed and homogenized as it circulates about the loop, eliminating potential hot spots.
16. The molten salts dissolve uranium, thorium, and plutonium, offering fuel flexibility. And last but not least, the liquid fuel is much easier to cool in the event of station blackout, **eliminating potential for meltdowns**.
17. **System that can be refuelled as it operates.**

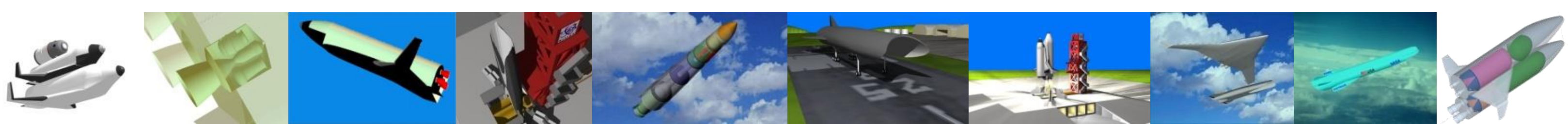
Possible Disadvantages

https://www.nuclear-power.com/nuclear-power-plant/reactor-types/thorium-reactor/advantage-and-disadvantages-of-thorium-reactors-pros-and-cons/

1. **Material Buckling.** As was written, naturally occurring thorium is effectively mononuclidic of thorium 232, which is a fertile isotope. Therefore to initial fuel load another fissile material must be added to achieve criticality. This fact must be taken into account during considerations about possible advantages. (in reactors, **material buckling** is a measure of **neutron production minus absorption).**
2. **Half-life of ^{233}Pa.** Thorium 232 is “only” a fertile material and the main problem can be directly in the breeding of fissile uranium 233. If **^{232}Th** is loaded in the nuclear reactor, the nuclei of **^{232}Th** absorbs a neutron and become nuclei of **^{233}Th**. The half-life of **^{233}Th** is approximately **21.8 minutes**. **^{233}Th** decays (negative beta decay) to **^{233}Pa** (protactinium), whose half-life is **26.97 days**. **^{233}Pa** decays (negative beta decay) to **^{233}U**. Therefore, proposed reactor designs must attempt to physically isolate the protactinium from further neutron capture before beta decay can occur. Separation of **^{233}Pa** from **^{233}U**, however, can easily be done through a chemical processing plant in the loop as Pa Tetrafluoride is liquid whereas U Hexafluoride is gaseous.

Possible Disadvantages

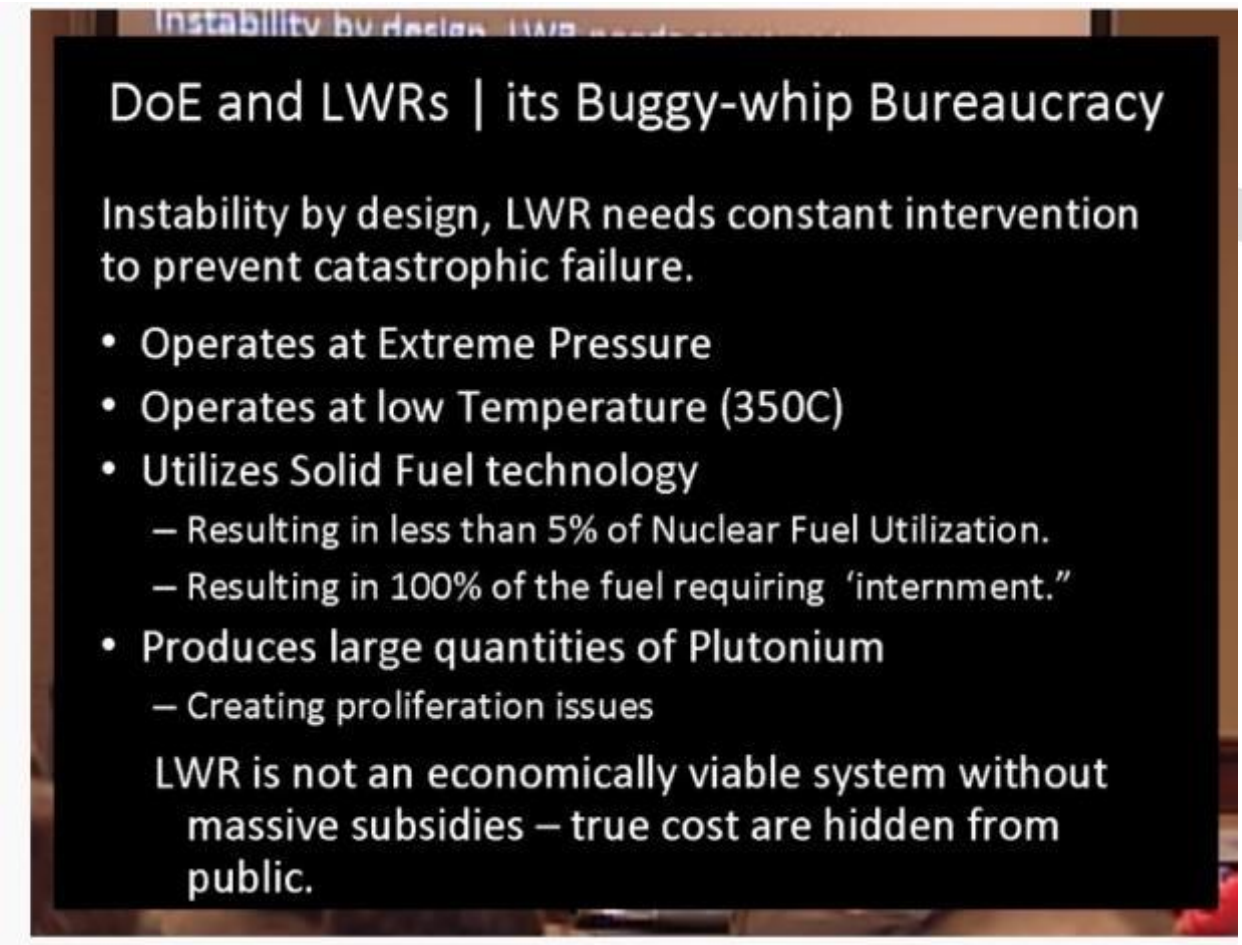
3. **Radiation Protection.** ^{232}U is produced from ^{232}Th via specific **(n,2n) reactions** in which an incoming neutron knocks two neutrons out of a target nucleus. ^{232}U has a relatively short half-life of 68.9 years, and therefore **the specific activity of ^{232}U is much higher** than specific activity of the isotope ^{238}U. **In addition the decay chain of ^{232}U produces very penetrating gamma rays.** These gamma rays are very hard to shield, requiring more expensive spent fuel handling and/or reprocessing.
4. **Delayed Neutrons.** Another important aspect for reactor safety is the **delayed neutron fraction**. Despite the fact the **number of delayed neutrons** per fission neutron **is quite small (typically below 1%)** and thus does not contribute significantly to the power generation, **they play a crucial role in the reactor control** and are essential from the point of view of reactor kinetics and **reactor safety**. The delayed neutron fraction is significantly lower for uranium 233 than for uranium 235. In result, a reactor in which uranium 233 is the predominant isotope responds more rapidly and puts increased demands on the design of control system.

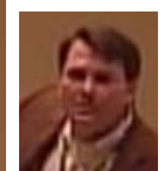


Possible Disadvantages

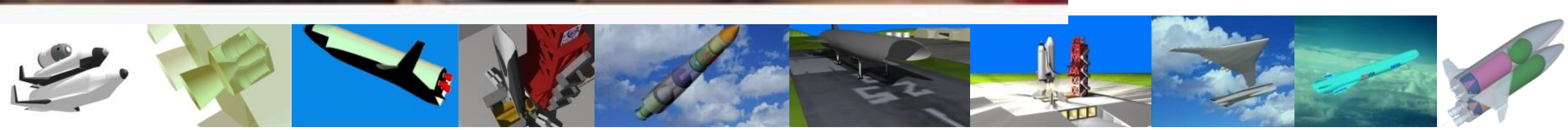
5. **Research into thorium energy is politically restricted.**
   Although thorium research has occurred in Germany, Denmark, Norway, Netherlands, the U.S., and other locations, only India and China are actively pursuing this technology with an intent to utilize it in the near future, and **only China is building MSRs**. India, for example, forecasts that they could produce up to 30% of their projected power needs with the implementation of **solid** thorium reactor technologies by 2050 – a mistake. Part of the reason for this is that traditional nuclear technologies are still functional and the resistance from them is unfortunately and shortsightedly quite strong. There is no risk of having zero payoff occur like a thorium reactor creates.

Why not LWRs





Credit: Screenshot from presentation by Jim Kennedy



Why Thorium Molten Salt Reactors

Astrox

Th-MSR/LFTR = Energy Independence

Total Thermal Energy Generation

1000 kg of thorium is 1000/0.232 = 4310.3 moles of Th232. 4310.3 moles x 6.022 exp23 atoms/mole x 200.1 MeV x 1.6022 exp-13 J/Mev = 8.322 exp16 Joules/tonne. 1 GW-Year is 1exp9x365.25x24x3600 = 3.16 exp16 Joules. Thus 2.637 GW(th)-years of thermal energy in the reactor.

One Ton of Thorium = 2.6 GW.y or 83,000,000 GJ of thermal energy.

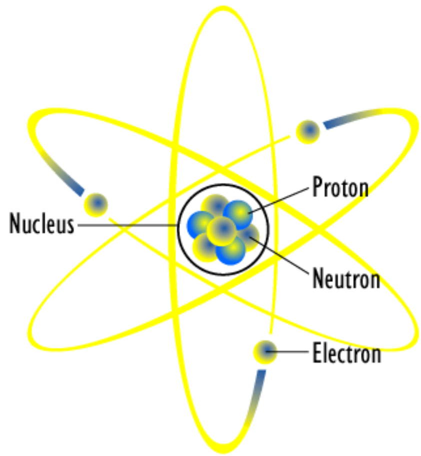
- Operational Temperature of 700 to 800 c
- Capital Cost under $2 million per 2500 Thermal / MW.y*
- Fuel cost per ton = $1000 or less**
- NEAR-ZERO EMISSIONS - Carbon Sequestration Not Required***
- U.S. Energy Independence

Credit: Screenshot from presentation by Jim Kennedy

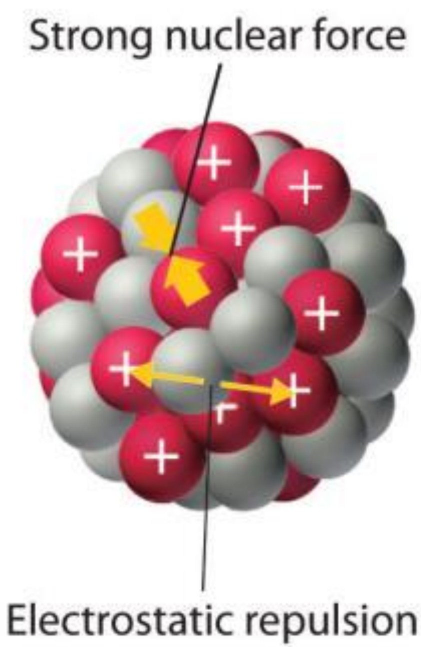
- One gm-mole of Th is 232 gm of Th
- Hence the 4310.3 mole number here is in gm-moles.
- Avogadro # quoted here is also per gm-mole
- So we are okay here
- 200.1 MeV is energy released per reaction (per atom) from U233 Binding Energy

- The WORLD electrical need is about 55 x 10^9 GigaJoules per year
- This means 667 Ton of Thorium can FULFIL this need.
- Considering efficiency of energy conversion, it may be 2-3 times this number but with 6.3 MILLION ton of reserve, we have PLENTY to last 5-6000 years! I am sure by then we will have licked the controlled fusion problem!

Nuclear Forces and Binding Energy



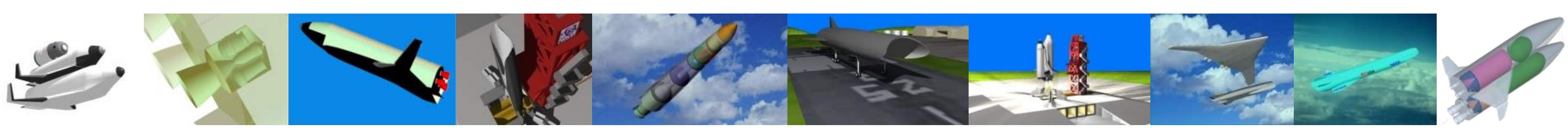
We imagine the atom as a consisting of a tiny nucleus made of discrete particles, protons and neutrons, orbited by a series of tiny electrons. The protons are positively charged, while the neutrons have no charge at all. Since particles with the same electric charge repel one another, a simple question was asked: <u>what holds the nucleus together?</u>



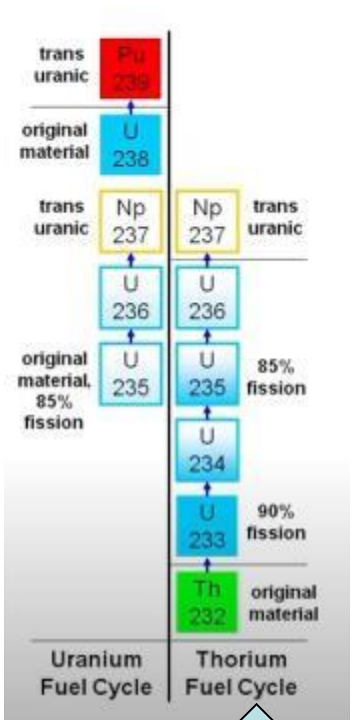
No one knew, so we surmised that there must be some incredibly strong nuclear force that bound all of these protons and neutrons into one tiny nucleus. Both protons and neutrons contributed to the nuclear force, but only protons had electric force that repelled them from one another. Neutrons acted as a sort of nuclear glue, holding the nucleus together. This realization also helped solve the puzzle of radioactivity. Radioactivity came about because there were too many or too few neutrons for a given number of protons.

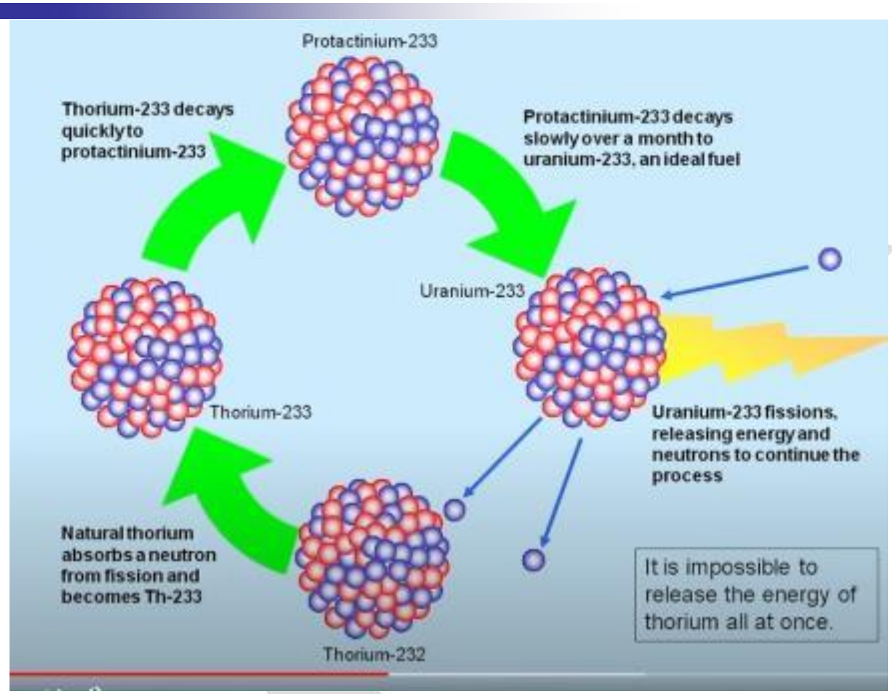
Energy Released

- One of the forces that the physicists have long been trying to amalgamate in the Unified Field Theory of course is the strong nuclear force, enough to overcome the repellant electrostatic force of protons bound in a nucleus.
- This binding energy thus residing in a nucleus is the boon of nuclear power, in this case the fission power.
- About 200.1 MeV of energy is released per atom of $^{92}\mathbf{U}_{233}$ upon fissioning.
- This is a **million** times greater per unit mass than chemical such as that produced by burning fossil fuel or coal.
- A kilogram of Uranium-235 ($^{92}\mathbf{U}_{235}$) or Thorium-232 ($^{90}\mathbf{Th}_{232}$)converted to $^{92}\mathbf{U}_{233}$ via nuclear processes releases approximately **three million times** more energy than a kilogram of coal burned conventionally (7.2×10^{13} joules per kilogram of uranium-235 or Thorium-232 versus 2.4×10^{7} joules per kilogram of coal)



Thorium Nuclear Reaction



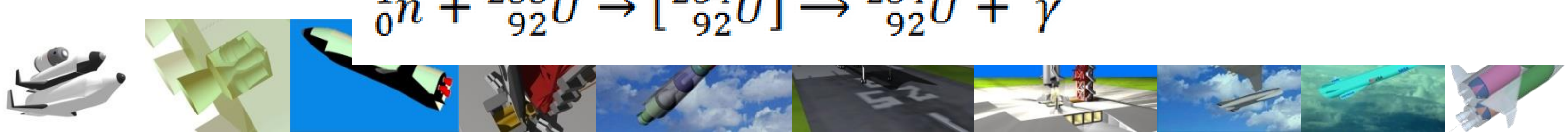


Beta Decay	**Electron or Positron (plus neutrino)**
Alpha Particle	**2 protons + 2 neutrons (He nucleus)**
Gamma Ray	**Highest frequency photons. Most damaging**

54Xe137 Beta decays to Cs137 in 4 min. 38Sr94 has half-life of ~30 years

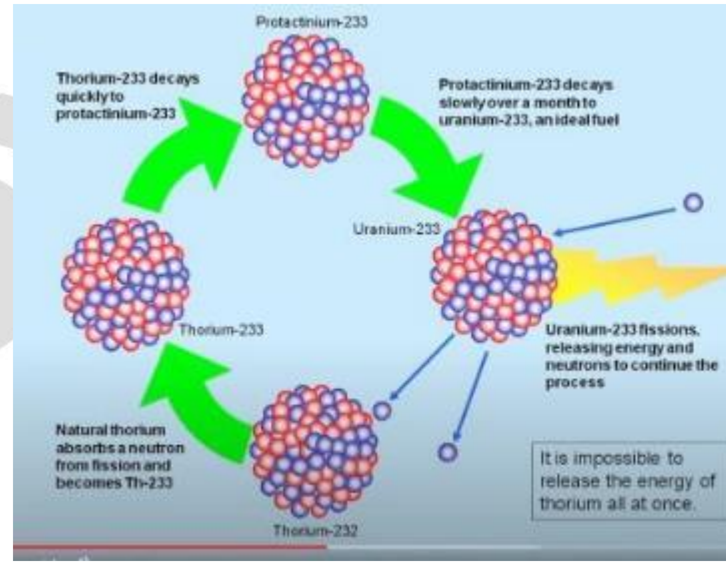
$$ {}^{1}_{0}n + {}^{233}_{92}U \rightarrow [{}^{234}_{92}U] \xrightarrow{94\%} fission\ (e.g.\ {}^{137}_{54}Xe + {}^{94}_{38}Sr + 3\ {}^{1}_{0}n) $$

$$ {}^{1}_{0}n + {}^{233}_{92}U \rightarrow [{}^{234}_{92}U] \xrightarrow{6\%} {}^{234}_{92}U + \gamma $$



How Does It Work?

1. A Thorium atom, $^{90}Th_{232}$, when bombarded by a neutron from some external source absorbs that neutron producing $^{90}Th_{233}$, thus increasing the atomic weight by one but not the atomic number.
2. It being unstable, releases one electron via a Beta decay thereby changing its atomic number to one plus viz. Protactinium $^{91}Pa_{233}$, more or less instantly, with half-life of 22 mins.
3. $^{91}Pa_{233}$ further Beta decays over 27 days to a still higher atomic number viz. $^{92}U_{233}$ which is fissionable. This atom fissions into Strontium and Xenon atoms releasing almost the same energy per atom as $^{92}U_{235}$, viz. 200.1 MeV.



Daughter Products

1. 54Xenon137: **Xenon** is a chemical element with the symbol **Xe** and atomic number 54. It is a colorless, dense, odorless noble gas found in Earth's atmosphere in trace amounts.[11] Although generally unreactive, it can undergo a few chemical reactions such as the formation of xenon hexafluoroplatinate, the first noble gas compound to be synthesized

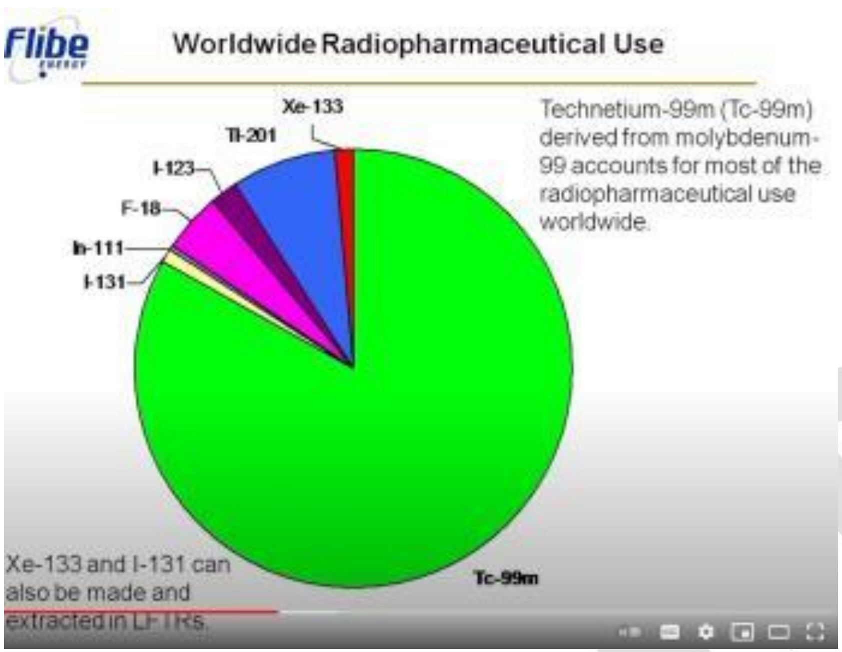
   Some radioactive isotopes of xenon (for example, ^{133}Xe and ^{135}Xe) are produced by neutron irradiation of fissionable material within nuclear reactors.[12] ^{135}Xe is of considerable significance in the operation of nuclear fission reactors. ^{135}Xe has a huge cross section for thermal neutrons, 2.6×10^{6} barns,[23] and operates as a neutron absorber or "poison" that can slow or stop the chain reaction after a period of operation.

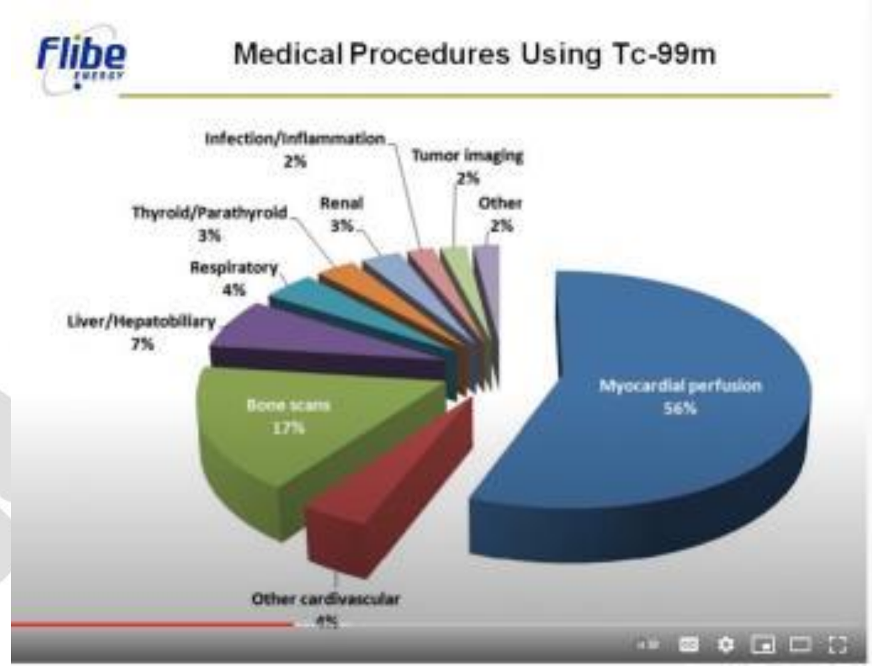
2. 38Strontium94: **Strontium** is the chemical element with the symbol **Sr** and atomic number 38. An alkaline earth metal, strontium is a soft silver-white yellowish metallic element that is highly chemically reactive. The metal forms a dark oxide layer when it is exposed to air. Strontium has physical and chemical properties similar to those of its two vertical neighbors in the periodic table, calcium and barium. It occurs naturally mainly in the minerals celestine and strontianite, and is mostly mined from these.

   The human body absorbs strontium as if it were its lighter congener calcium. Because the elements are chemically very similar, stable strontium isotopes do not pose a significant health threat. The average human has an intake of about two milligrams of strontium a day.[79]

   Strontium-90 is a radioactive fission product produced by nuclear reactors used in nuclear power. It is a major component of high level nuclear waste and spent nuclear fuel. Its 29-year half life is short enough that its decay heat has been used to power arctic lighthouses, but long enough that it can take hundreds of years to decay to safe levels. Exposure from contaminated water and food may increase the risk of leukemia, bone cancer[98] and primary hyperparathyroidism.

Side (Waste) Products from Thorium Reactor for Medical Industry





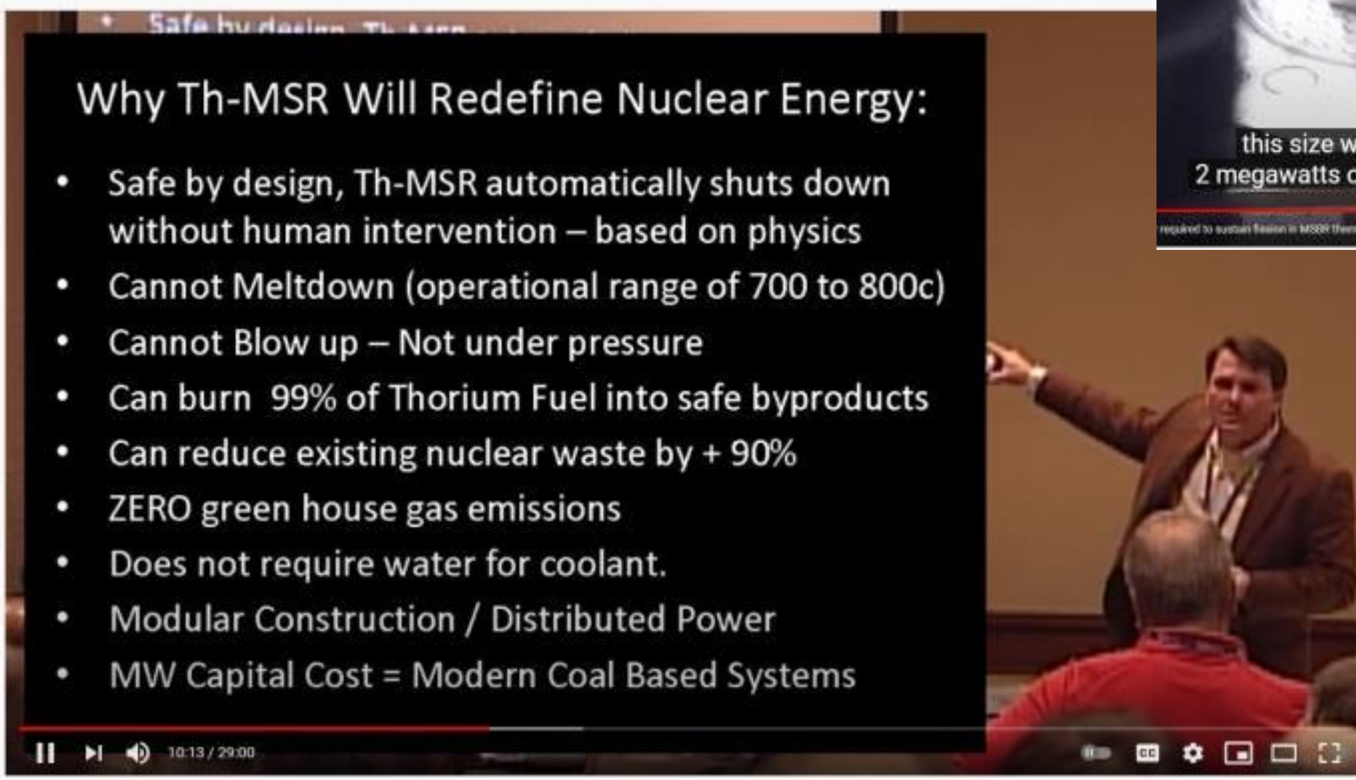
Credit: Screenshot from presentation by Kirk Sorensen

- **Most of the waste is useful for radiopharma diagnostics in medical industry**
- **That which cannot be, has half life of <u>hundreds to thousands</u> of years as opposed to U235 waste products wherein it is <u>hundreds of thousands</u>.**

Thorium-MSR Advantages

SIZE

A 1 GW reactor would be 500 times bigger or about 8 times larger in each dimension. With this 2 MW plant at ~1 m in each dimension, the 1 GW reactor may be 8x8x8 m, much smaller than the PWRs of today.



THE THORIUM PROBLEM - Manufacturing & energy sector hobbled by thorium

Built in 60's at Oakridge National Lab by Dr Weinberg. Ran for 5 years (~1965-69)

As is seen, this is just the power plant. The heat exchangers and turbines will be larger. But even then, the power generation part is MUCH smaller than at LWR.

China WuWei Thorium Experimental 2 MW Plant

China is ahead of us and will be far ahead if we do not wake up. They tested one such small (2 MW) plant in WuWei in September/October 2021 time frame, and intend to build 30 more 273 MW level plants for them and for selling to other countries on the Road Initiative. It measures ~3x3x4 m in total (including the heat exchangers and turbines) .

[China prepares to test thorium-fuelled nuclear reactor - Nature](https://www.nature.com/news)
https://www.nature.com › news

Sep 10, 2021 — Scientists are excited about an experimental **nuclear reactor** using **thorium** as fuel, which is about to begin tests in **China**. Although this radioactive element ...

Why China is developing a game-changing thorium-fuelled ...
https://www.france24.com › France 24 › Asia / Pacific

Sep 12, 2021 — **China** is poised to test a **thorium**-powered **nuclear reactor** in September, the world's first since 1969 ... such as in Taishan, pictured here on June 17, **2021**.

[China eyes thorium breakthrough in Gobi desert - Asia Times](https://asiatimes.com/2021/09/china-set-to-test-a-tho...)
https://asiatimes.com › 2021/09 › china-set-to-test-a-tho...

Sep 20, 2021 — This experimental **nuclear reactor** uses **thorium** as a fuel and experts believe that **China** will be the first country to have a chance to commercialize the ...

Norway Thorium Developments

https://www.zdnet.com/article/as-thorium-tests-begin-in-norway-the-nuclear-industry-watches-closely/

Putting its foot down. The thorium crowd is adamant that thorium trumps uranium for nuclear safety and efficiency. These engineers stand atop the test reactor in Halden, Norway, which is now burning thorium.

As thorium tests begin in Norway, the nuclear industry watches closely

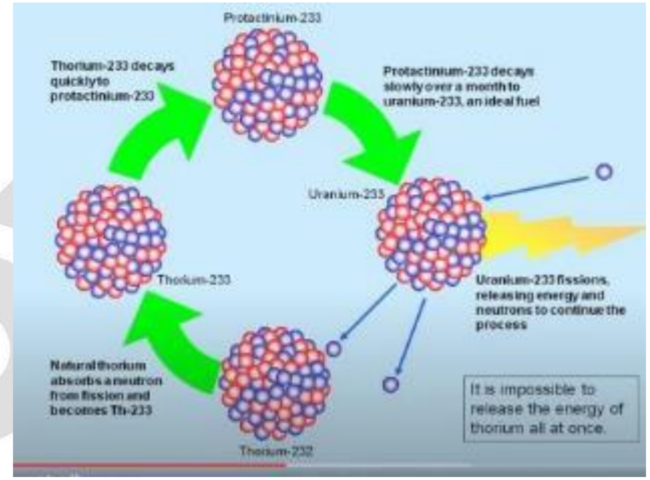
Safer and less waste than uranium, acknowledges the conventional nuclear crowd.

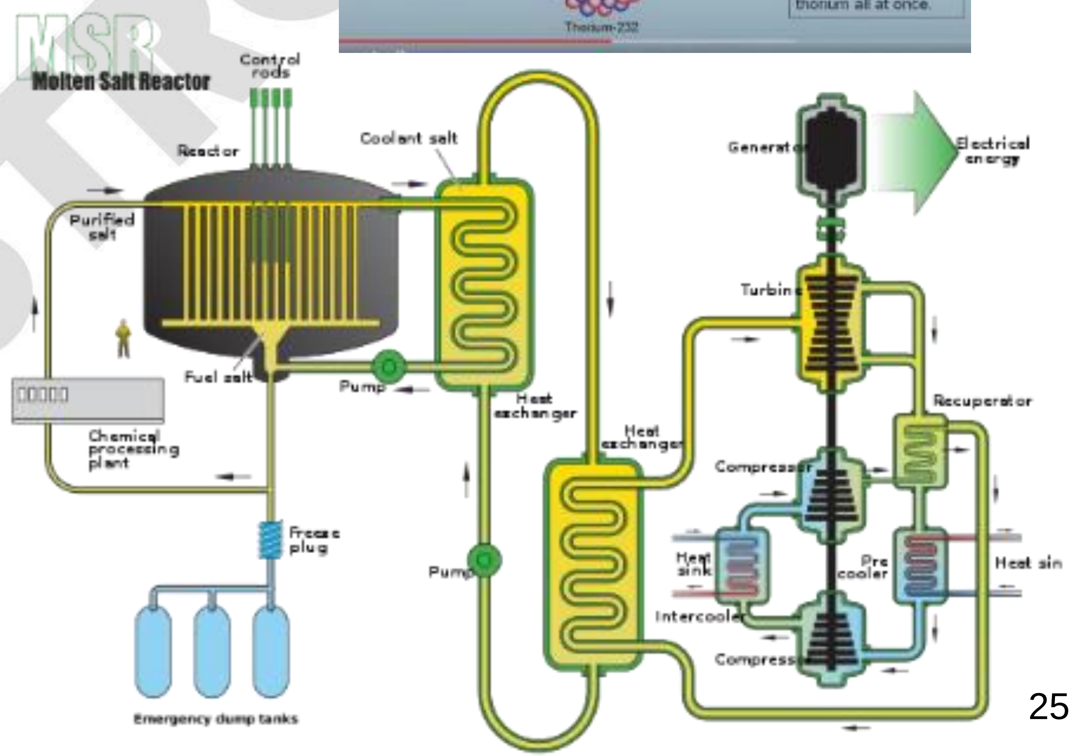
Written by **Mar Halper, Contributing Editor** on June 26, 2013

- The thorium fuel is in the form of pellets composed of a dense thorium oxide ceramic matrix containing about 10% of finely blended plutonium oxide as a 'fissile driver'.
- **SO THIS WAS NOT A MOLTEN SALT REACTOR**

For Earth: Thorium Molten Salt Reactor (TMSR)

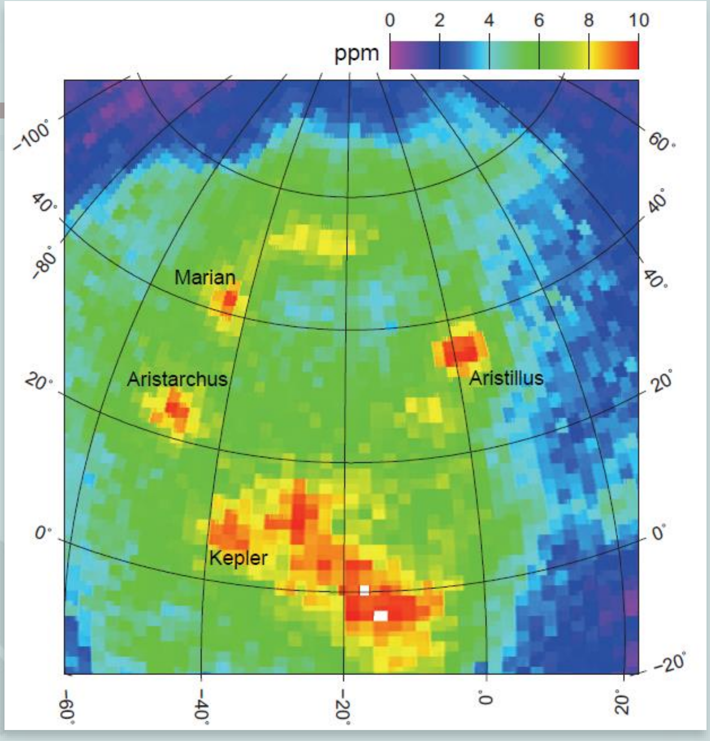
- For humanity of Earth, this solution is available today with enough supply of Thorium to last thousands of years, and with zero CO_2 emissions.
- We do not need to build tens of thousands of one GW Space Based Solar Power (SBSP) plants at GEO (GeoStationary Orbit), with their associated rectenna on Earth and ongoing maintenance calls at GEO!
- <u>This solution needs to be developed right here in America.</u>
- The time is now, for us, and for the rest of pollution ridden countries to be availed of this technological marvel.
- One hopes this administration will pay attention to it and find a reasonable path for all of us. Soon.
- <u>The same tech can be used on Moon and Mars</u> – w/o turbines for thermal and with closed loop turbines for electricity





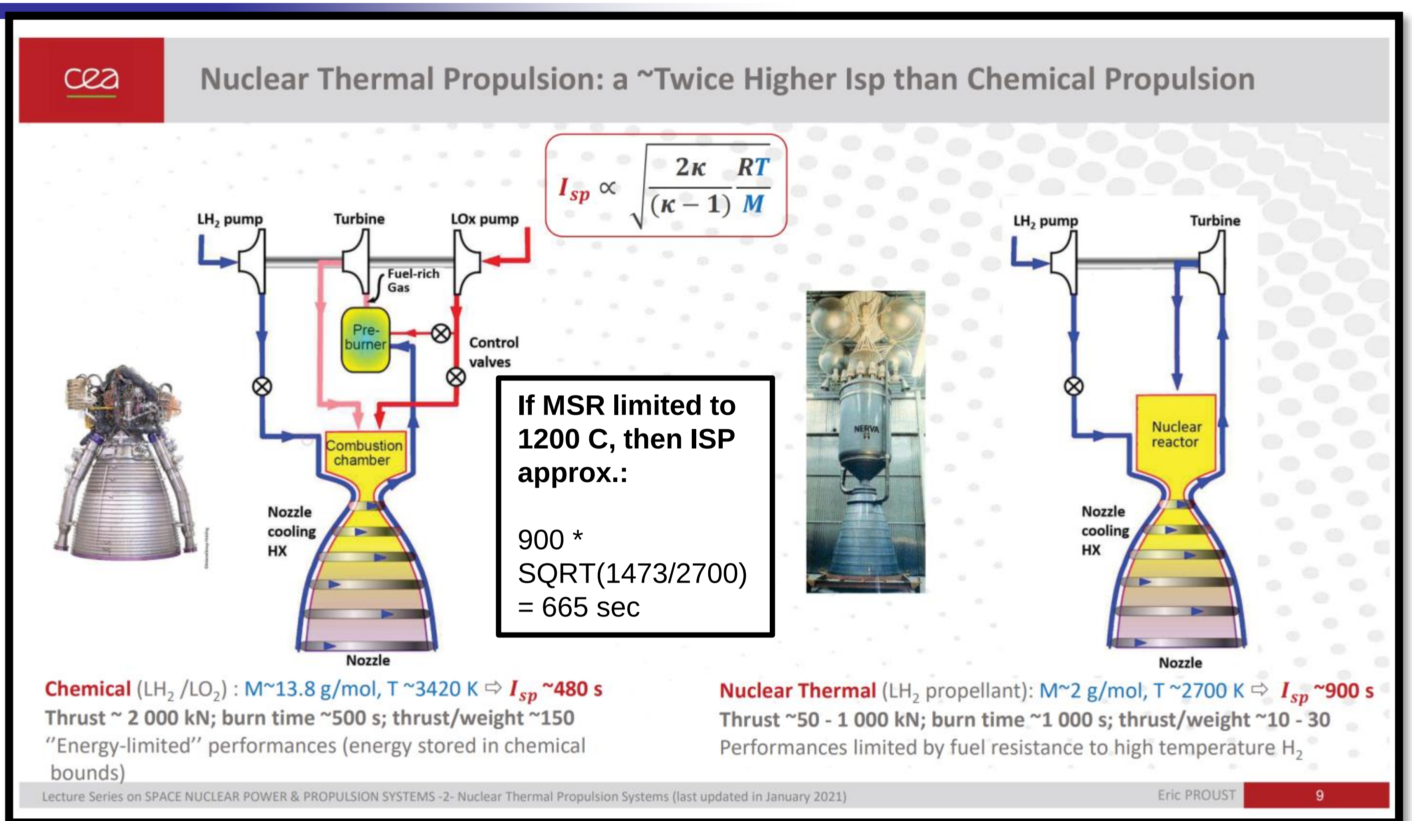
Lunar Power

- [Thorium has been detected on Moon by Chang e 2 also]().
- One kilogram of Thorium taken from Earth to begin with can provide 2.6 thermal MW plant for a year.
- Imagine ten such plants in ten different locations with ten kg of Thorium taken from Earth and the associated salt, which will eventually become self-sustaining with Lunar Thorium.



- Only the first such plant will require neutron producing radioactive material to commence the chain reaction.
- The U233 thus produced can provide any further neutrons for additional reactors, thus becoming self-sustaining.
- For power on Lunar surface however, this is only ONE of the promising options. Different location may find different solutions, such as beamed power from SBSP, or a combination there of, as whatever would be ideal for that locale.

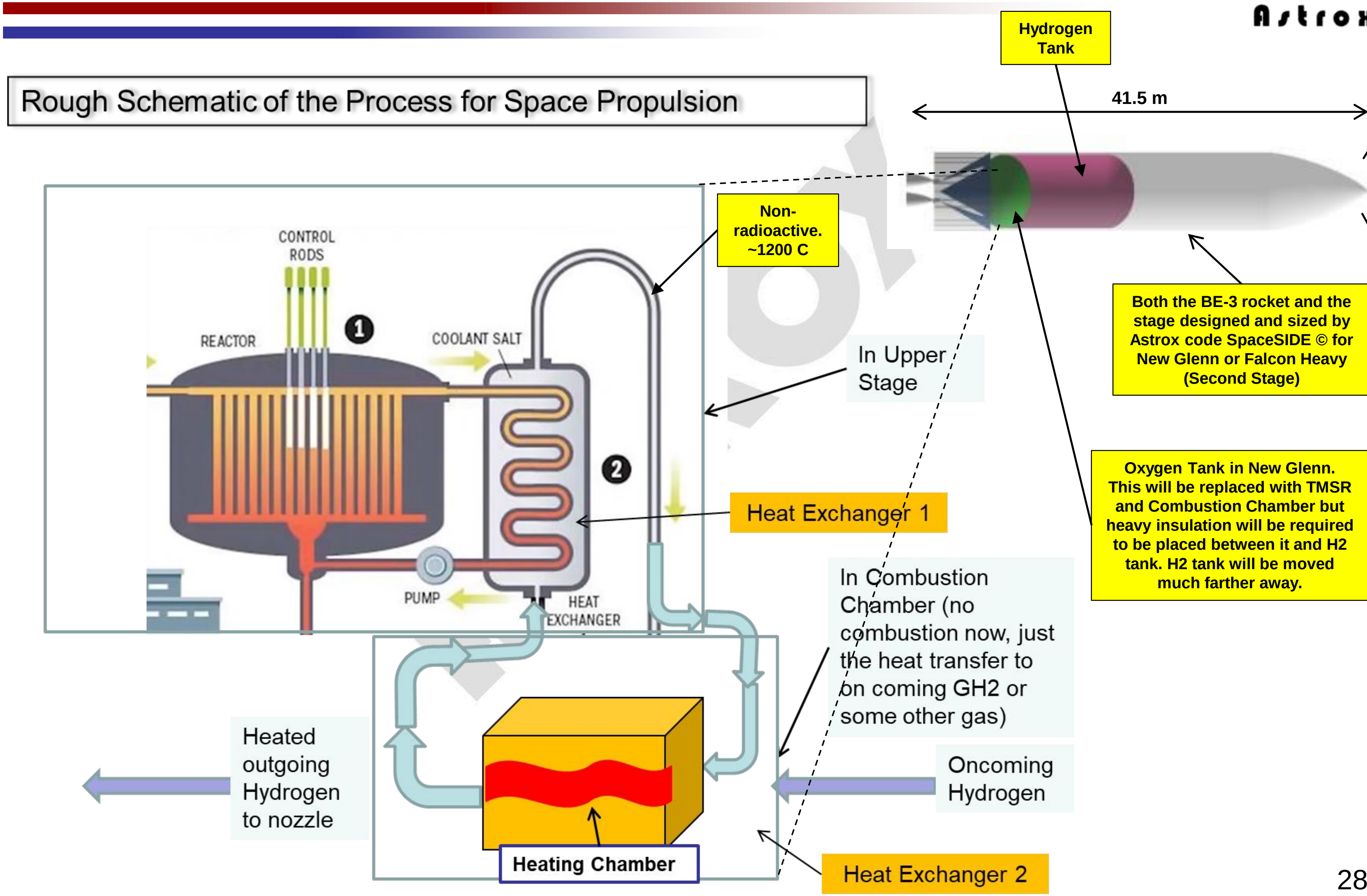
Space Propulsion



Courtesy: John Livingston

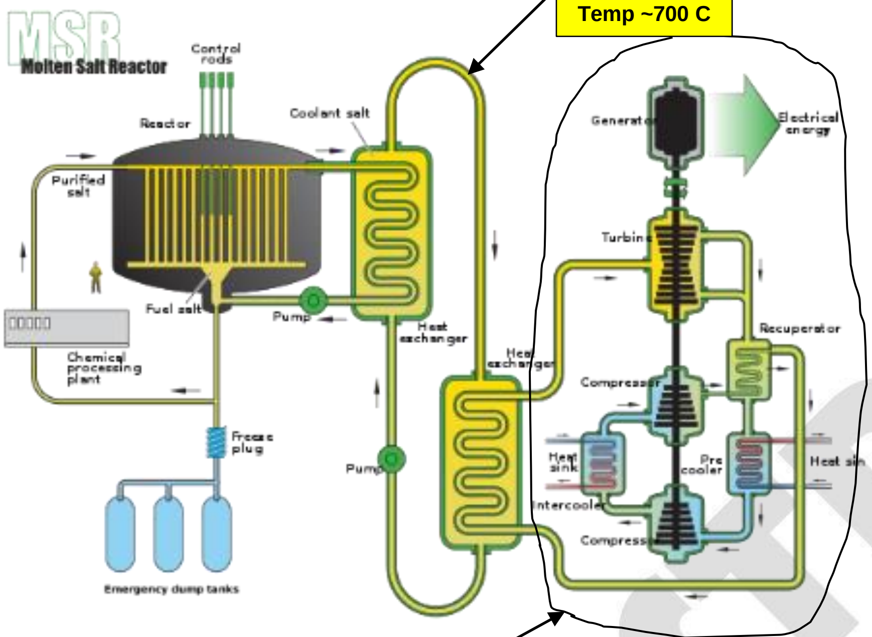
With considerable reduction in size and weight compared to NERVA type solutions, MSR maybe more attractive at system level.

Space Propulsion – for journeys within CiSLunar space and to Moon/Mars



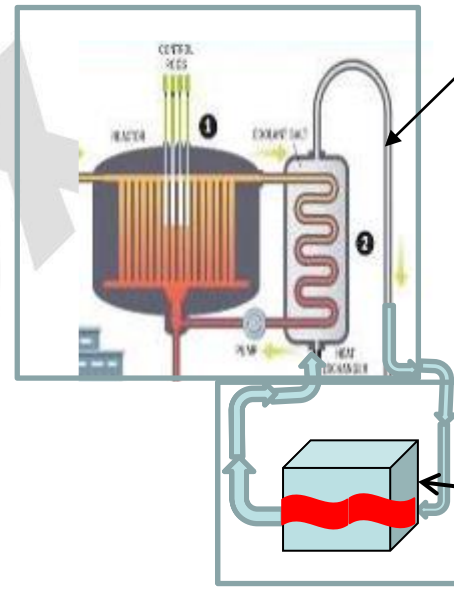
Repurposing TMSR on Moon/Mars

Non-radioactive. Temp ~700 C



Closed loop CO2 turbine cycle for electricity production for habitats. Taken separately or in the same payload bay.

Non-radioactive. Temp ~700 C



Lunar Regolith or Ice

- Repurposing allows for reuse of the reactor
- Temperature of the molten salt is reduced to ~700 C whereby the corrosion of containment/pipes would be nil to limited (as ORNL 2 MW reactor showed)

SUMMARY

For US and the World terrestrially:

- Thorium offers immense supply of energy that can last several thousand years
- No CO2 emissions or pollutants
- No high-pressure explosion possibility
- Twice the efficiency of conversion to electricity as PWR
- Natural and fail-safe (freeze valve) mechanisms
- <1% radioactive waste products compared to ~95% for PWRs of today
- No Plutonium that can be used for nuclear explosives
- Does not need to be near water supply (river/lake/ocean), so can be built even in desert (ideal for Moon/Mars)
- Can be refueled continuously with chemical processing in the loop – without having to shut down as in PWRs
- WHAT MORE DO WE WANT???
- I respectfully urge this Administration to take this idea seriously and provide funding for this RD&E

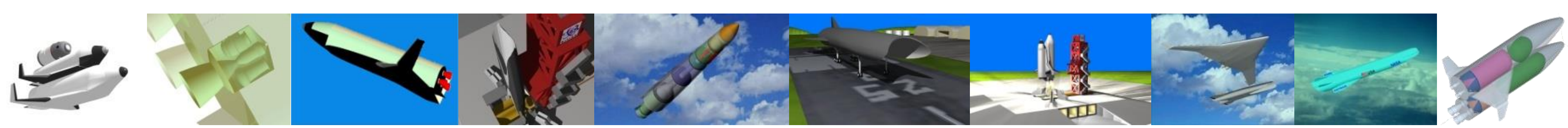
SUGGESTIONS FOR UMD

- **For ME:**
  - **Do computational analysis to assess the heat transfer in heat exchangers.**
  - **Build a ~30 cm dimension, 3D printed simulation (no reactor for now) to confirm the containment, pipes and Heat Exchangers can work efficiently and last for many months**
  - **Containment and pipes can be made from GE produced C/SiC material being suggested now for hypersonic flights**
- **For Aerospace:**
  - **The application for CiSLunar and to Moon/Mars travel are promising which can be analyzed by students through research topics for MS/PhD.**
  - **Topics based on Repurposing of nuclear TMSR rocket for energy on Moon and Mars must be explored and papers published**
  - **It is possible to fly a vehicle on Mars using the heat generated through TMSR at (turbine powered) subsonic speeds with no combustible fuel needed. This can promise immense potential for access anywhere on Mars with no chemical propellant taken from Earth. Only 10 gm of Th232 will fly the vehicle for a whole orbit around Mars!**
  - **Could be very useful for Martian colonies of future for experimentation, mapping and transport.**
- **This Thorium MSR solution is going to go ‘big’ worldwide and certainly in US. So IMHO, and respectfully, the Clark School should revive the Nuclear Engineering Department partly concentrated on TMSR**

BACKUPS

Thorium Dissolved in Molten Salt

- MSRs may operate with epithermal or fast neutron spectrums, and with a variety of fuels. Much of the interest today in reviving the MSR concept relates to using thorium (to breed fissile uranium-233), where an initial source of fissile material such as plutonium-239 needs to be provided. There are a number of different MSR design concepts, and a number of interesting challenges in the commercialization of many, especially with thorium.
- The salts concerned as primary coolant, mostly lithium-beryllium fluoride and lithium fluoride, remain liquid without pressurization from about 500°C up to about 1400°C, in marked contrast to a PWR which operates at about 315°C under 150 atmospheres pressure.
- The main MSR concept is to have the fuel dissolved in the coolant as fuel salt, and ultimately to reprocess that online. Thorium, uranium, and plutonium all form suitable fluoride salts that readily dissolve in the LiF-BeF_2 (FLiBe) mixture, and thorium and uranium can be easily separated from one another in fluoride form. Batch reprocessing is likely in the short term, and fuel life is quoted at 4-7 years, with high burn-up.



Thorium Dissolved

- MSRs have large negative temperature and void coefficients of reactivity, and are designed to shut down due to expansion of the fuel salt as temperature increases beyond design limits. The negative temperature and void reactivity coefficients passively reduce the rate of power increase in the case of an inadvertent control rod withdrawal (technically known as a ‘reactivity insertion’). When tests were made on the MSRE, a control rod was intentionally withdrawn during normal reactor operations at full power (8 MWt) to observe the dynamic response of core power. Such was the rate of fuel salt thermal expansion that reactor power levelled off at 9 MWt without any operator intervention.
- Th-232 gains a neutron to form Th-233, which soon beta decays (half-life 22 minutes) to protactinium-233. The Pa-233 (half-life of 27 days) decays into U-233. Some U-232 is also formed via Pa-232 along with Th-233, and a decay product of this is very gamma active. However, the U-233 is contaminated with up to 400 ppm U-232 which complicates processing, due to its highly gamma-active decay progeny.

China's dual programme

- Second one: The **TMSR-LF** stream claims full closed Th-U fuel cycle with breeding of U-233 and much better sustainability with thorium but greater technical difficulty. It is optimized for utilization of thorium with electrometallurgical pyroprocessing. SINAP aims for a 2 MWt pilot plant (TMSR-LF1) initially, then a 10 MWt experimental reactor (TMSR-LF2) by 2025.
- SINAP sees molten salt fuel being superior to the TRISO fuel in effectively unlimited burn-up, less waste, and lower fabricating cost, but achieving lower temperatures (600°C+) than the TRISO fuel reactors (1200°C+). Near-term goals include preparing nuclear-grade ThF_4 and ThO_2 and testing them in a MSR.

Other liquid-fuel types: two-fluid breeders

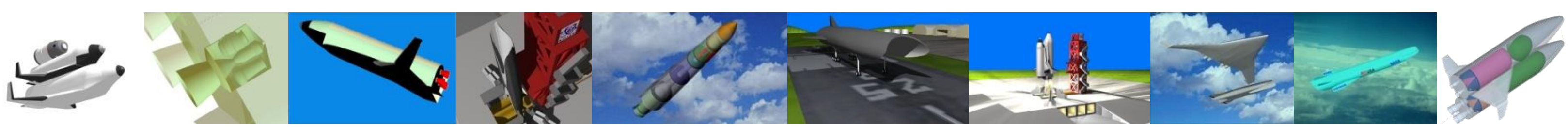
- Liquid fluoride thorium reactor

The liquid fluoride thorium reactor (LFTR) is a heterogeneous MSR design which breeds its U-233 fuel from a fertile blanket of lithium-beryllium fluoride (FLiBe) salts with thorium fluoride. The thorium-232 captures neutrons from the reactor core to become protactinium-233, which decays (27-day half-life) to U-233. It may be possible to separate Pa-233 on-line and let it decay to U-233. Otherwise, newly-formed U-233 forms soluble uranium tetrafluoride (UF_4), which is converted to gaseous uranium hexafluoride (UF_6) by bubbling fluorine gas through the salt (which does not chemically affect the less-reactive thorium tetrafluoride). The volatile uranium hexafluoride is captured, reduced back to soluble UF_4 by hydrogen gas, and finally is added to the FLiBe core to serve as fissile fuel. A complication is that traces of U-232 are formed, reporting with the U-233, and having highly gamma-active decay progeny.

LFTRs can rapidly change their power output, and hence be used for load-following. Because they are expected to be inexpensive to build and operate, 100 MWe LFTRs could be used as peak and back-up reserve power units.

- Flibe LFTR

Flibe Energy in the USA is studying a 40 MW two-fluid graphite-moderated thermal reactor concept based on the 1960s-'70s US molten-salt reactor programme. It uses lithium fluoride/beryllium fluoride (FLiBe) salt as its primary coolant in both circuits. Fuel is uranium-233 bred from thorium in FLiBe blanket salt. Fuel salt circulates through graphite logs. Secondary loop coolant salt is sodium-beryllium fluoride (BeF_2-NaF). A 2 MWt pilot plant is envisaged, and eventually 2225 MWt commercial plants.



China Thorium Developments

DW is a German public broadcast service.
https://www.youtube.com/watch?v=rEpVJ8pOS2I&ab_channel=DWNews
Did China just figure out how to make nuclear energy safe? | DW News

China's experimental thorium reactor is ready for testing
https://www.freethink.com › technology › thorium-reac...

Sep 29, 2021 — ***China's*** experimental ***thorium reactor*** is ready for testing. The device could bring ***nuclear energy*** to deserts and beyond. By Kristin Houser. September 29, ***2021***.

China Is About to Test Its Thorium-Fueled Nuclear Reactor
https://interestingengineering.com › china-to-test-thoriu...

Sep 14, 2021 — ***China*** will start tests on its first molten-salt ***nuclear reactor***! Based on ***thorium***, the new technology could serve as a major milestone for the world.
You visited this page on 9/14/21.

The World's First 'Clean' Commercial Nuclear Reactor to Be ...
http://m.stdaily.com › 2021-09 › content_1221278

Sep 23, 2021 — Source: Science and Technology Daily| ***2021***-09-23 09:48:14| Author: QI Liming ... ***China's*** molten-salt ***reactor*** program was first launched in 2011, ...

China eyes its Gobi desert for uranium alternative thorium to use
https://www.aninews.in › news › world › asia › china-e...

Sep 26, 2021 — ANI | Updated: Sep 26, ***2021*** 20:47 IST. Beijing [***China***], September 26 (ANI): ***China*** may soon test a new inexpensive ***nuclear energy*** that will not need water to ...

China Thorium Developments

[Experimental reactor could hand China the holy grail of ...](https://www.thetimes.co.uk)
https://www.thetimes.co.uk › article › experimental-reacto...

Sep 16, 2021 — ***China*** is due to fire up an experimental ***nuclear reactor*** this month that could revolutionize the ... Thursday September 16 ***2021***, 12.00am BST, The Times.
You've visited this page 3 times. Last visit: 9/14/21

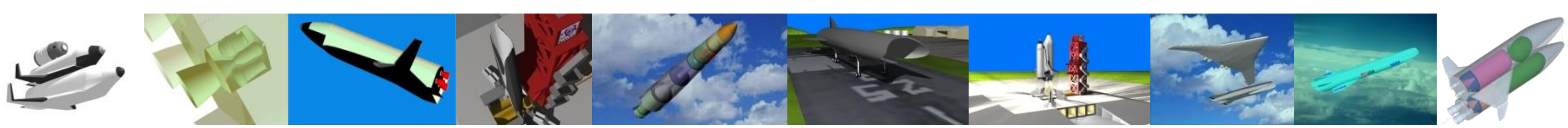
China Is About To Revolutionize Nuclear Power With A ...
https://www.technologytimes.pk › 2021/09/20 › china-i...

Sep 20, 2021 — Since ***thorium reactors*** do not need water for cooling, they could be built even in desert regions, far from big cities. ***Thorium*** is a rare earth mining waste (monazite mines)...

Why China is developing a game-changing ... - Yahoo News UK
https://uk.news.yahoo.com › why-china-developing-ga...

Sep 12, 2021 — ***China*** is poised to test a ***thorium***-powered ***nuclear reactor*** in September, the world's first since 1969. ... 12 September ***2021*** ·5-min read. ***China*** is poised to ...
China shows us the path to the nuclear future - European ...
https://www.europeanscientist.com › features › china-sh...

6 days ago — This experimental nuclear ***reactor*** will use ***thorium*** as fuel. ... financial increases of fossil fuels that will become unbearable for the citizens in ***2021***.



Nuclear vs Chemical Energy

But the nuclear force must be incredible powerful to hold nuclear particles like protons and neutrons together, and this is the reason why nuclear energy is millions of times more powerful than chemical energy. Chemical energy is the energy of the electrons orbiting the nucleus. All of our commonly understood energy-releasing processes are based on chemical energy. From the digestion of food to the burning of coal, all of it is based on a **rearrangement** of electrons in atoms.

But nuclear energy was something different, something not encountered in our daily experience. The only natural example of nuclear energy we might encounter would come from the natural decay of thorium and uranium. When humanity learned how to release nuclear energy on demand, through the marvelous process of nuclear fission of uranium, we for the first time could access an energy source millions of time more powerful than any other.

Opportunity

Astrox

What is the Opportunity?

Flibe ENERGY

- Energy generated from a liquid-fluoride thorium reactor (LFTR) has the potential to be the most inexpensive energy to produce anywhere:
  - Trivial fuel cost (thorium is surplus material) **(In Monazite mines)**
  - No carbon dioxide emissions (like wind/solar/hydro)
  - Very high availability factor (like coal/oil/gas/uranium)
  - Much simpler and safer than conventional uranium-fueled reactors
  - Scalable from small to large energy generation opportunities
- Political pressure to reduce greenhouse gas emissions
- Economic pressure to lower the cost of energy
- Public pressure to address concerns of current nuclear power
  - Waste, perceived safety risks
- Military pressure to generate power reliably in remote locations
- All of these point towards LFTR as the global energy solution

Credit: Screenshot from presentation by Kirk Sorensen

Another Estimate

Country	Total thorium resources, tonnes Th (rounded)
Others (CIS) (excluding Russia, Kazakhstan and Uzbekistan)	1,340,000
India	980,000
Brazil	632,000
Australia	595,000
United States of America	595,000
Egypt	380,000
Turkey	374,000
Venezuela	300,000
Canada	172,000
Russia	155,000
South Africa	148,000
China	100,000