FOUR GOOD BOOKS TO READ

1. The Answer: Why Only Inherently Safe Mini Nuclear Power Plants Can Save Our World
   - Reese Palley

2. Power to Save the World: The Truth About Nuclear Energy
   - Gyneth Cravens

3. Super Fuel: Thorium, the Green Energy Source for the Future
   - Richard Martin

4. Thorium: Energy Cheaper than Coal
   - Robert Hargraves
THIS IS FISSION OF A FISSION/FERTILE ATOM

Atom splits! (fission)

These two fission products are unstable and will release energy sometime between now and thousands of years in the future.

They make up **high-level nuclear waste.**
FROM WHERE DID OUR ELEMENTS COME?
THORIUM IS PLENTIFUL
FISSION PRODUCT POSSIBILITIES
WORLD’S NUCLEAR REACTORS IN 2014

• **Abbreviations Defined:**
  - PWR = Pressurized Water Reactor
  - BWR = Boiling Water Reactor
  - GCR = Gas-Cooled Reactor
  - PHWR = Pressurized Heavy WR
  - LWGR = Light Water-cooled, Graphite-moderated Reactor
  - FBR = Fast Breeder Reactor
URANIUM LIGHT WATER REACTORS
PRESSURIZED VS BOILING TYPES
LIGHT WATER REACTORS (LWRs)

- **Pressurized Water Reactor (PWR)**
  - **PROs:**
    - Inherently safe: coolant=moderator.
    - Easier maintenance; “clean” turbine.
    - Extensive operating experience.
  - **CONS:**
    - Can’t breed new fuel.
    - Requires refueling every 2 years.
    - Leaves 95% of fuel un-fissioned.

- **Boiling Water Reactor (BWR)**
  - **PROs:**
    - Simpler plumbing reduces costs
    - Load-following is easier.
    - Extensive operating experience.
  - **CONS:**
    - Can’t breed new fuel.
    - Requires refueling every 2 years.
    - Leaves 95% of fuel un-fissioned.
HOW THE FUEL RODS ARE ARRANGED

The smallest unit of the reactor is the fuel pin. These are typically uranium-oxide (UO₂), but can take on other forms, including thorium-bearing material. They are often surrounded by a metal tube (called the cladding) to keep fission products from escaping into the coolant.

Fuel assemblies are bundles of fuel pins. Fuel is put in and taken out of the reactor in assemblies. The assemblies have some structural material to keep the pins close but not touching, so that there’s room for coolant.

This is a full core, made up of several hundred assemblies. Some assemblies are control assemblies. Various fuel assemblies around the core have different fuel in them. They vary in enrichment and age, among other parameters. The assemblies may also vary with height, with different enrichments at the top of the core from those at the bottom.
REVIEW OF PELLET TO REACTOR VESSEL

Figure 5.3  Assembly of the fuel into a core. COURTESY OF THE AMERICAN NUCLEAR SOCIETY.
Table 1. Heavy metal composition of 4.2% enriched nuclear fuel before and after running for about 3 years (40,000 MWD/MT). Minor actinides include neptunium, americium, and curium. This table does not include structural material such as zirconium and stainless steel.

<table>
<thead>
<tr>
<th></th>
<th>Charge</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>100%</td>
<td>93.4%</td>
</tr>
<tr>
<td>Enrichment</td>
<td>4.20%</td>
<td>0.71%</td>
</tr>
<tr>
<td>Plutonium</td>
<td>0.00%</td>
<td>1.27%</td>
</tr>
<tr>
<td>Minor Actinides</td>
<td>0.00%</td>
<td>0.14%</td>
</tr>
<tr>
<td>Fission products</td>
<td>0.00%</td>
<td>5.15%</td>
</tr>
</tbody>
</table>
ENRICHMENT OF URANIUM

• There are 3 ways (including differential centrifugation) to enrich the tiny amount of $^{235}\text{U}$ that exists in natural uranium.

• The $^{238}\text{U}$ remaining after enrichment is known as depleted uranium (DU), and is considerably less radioactive than natural uranium, though still very dense.

• At present, 95% of the world's stocks of depleted uranium remain in secure storage.
GAS-COOLED REACTORS

• These types use graphite (instead of water) as a neutron moderator.
• Cooled by non-reactive gases, mostly CO$_2$, but can be He or N$_2$.
• Chief advantage is they can use natural (non-enriched) Uranium.
• Countries using them include UK, Italy & Japan (Magnox) as well as France and Spain (UNGG).
• There are also high and very high-temp helium-cooled reactors, such as prismatic and pebble-bed types.
CANDU (PHWR) REACTORS

- **Canada Deuterium-Uranium Reactors (CANDUs)**
- Designed in Chalk River, Ontario, they contain heavy water, in which the H in H2O (light water) is replaced by Deuterium, a heavier isotope of H.
- Deuterium absorbs many fewer neutrons than Hydrogen, allowing CANDUs to operate on non-enriched Uranium.
- **PROs:** CANDUs can be refueled while operating, since the cauldron is horizontal, and it can use many different types of fuel.
- **CONs:** Neutron absorption by Deuterium leads to Tritium production, which can leak in small quantities. Some variants have safety concerns or could be modified to produce weapons-grade plutonium more easily than LWRs.
A measure of a reactor's performance is the "conversion ratio," i.e., the ratio of: newly produced fissile atoms/consumed fissile atoms. Most reactors experience some degree of conversion. When the conversion ratio > 1, it’s called the Breeding Ratio.

- Eg., commonly used LWRs have a conversion ratio of ~ 0.6.
- Pressurized heavy water reactors have a conversion ratio of 0.8.
- Breeder reactors have a conversion ratio of > 1.
- Break-even is achieved when the conversion ratio = 1, and the reactor makes as much fissile material as it uses.
All 15 of these early Gen-II reactors were built in Russia.

Graphite moderation allows non-enriched uranium to be used as fuel.
FBR = FAST BREEDER REACTOR

• FBR=one type among 6 families of Generation IV reactors.
• China has one in Beijing.
• Experimental Breeder Reactor–1 (EBR-1) was built by O.R. in Idaho.
• The leading contender among Gen-IV reactors is the Molten Salt Reactor (MSR).
• MSR fuels are Uranium and/or Thorium, as liquid fluoride salts.
WORLD’S NUCLEAR REACTORS IN 2014

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SHORTCOMINGS OF URANIUM FUEL

• As an energy source, U has issues, long overshadowed by its advantages over coal.
• A tiny fraction (0.7%) of mined U is its fissile isotope, $^{235}$U.
• Enrichment of $^{235}$U from $^{238}$U is difficult (isotopes are very similar).
• $^{235}$U can be used to make nuclear weapons.
• Only ~4% of its energy is used for making electricity.

• In contrast: $^{238}$U is fissionable but not fissile; it will split apart only when struck by a neutron traveling very, very fast. But breeder reactors have their own problems: big changes can happen very quickly, and liquid sodium coolant explodes in air/H2O.
I don't have anything against Th fuel cycles, per se. It's just that when carefully assessed against a complete set of societal metrics, the benefits are marginal at best in most places in the world.... but many in the Th community have convinced lay audiences otherwise.
THORIUM:

LFTR = LIQUID FLUORIDE THORIUM REACTOR

- **Liquid**: its fuel is dissolved in molten salt and circulated continuously to allow complete fuel burnup.
- **Fluoride**: such salts are very stable compounds, even when hot.
- **Thorium**: a very abundant element on Earth, not requiring enrichment.
- **Reactor**: operates at high temp but normal pressure, providing safe, compact, less expensive energy.
ORIGINAL MSR AT OAK RIDGE

ORNL MSR Experiment (1965-1974)

7MW, 20,000 Hours

7MW Radiator

Reactors Salt

Drain Tanks

7MW Graphite Core

Core

Glenn Seaborg Turning It On
How a molten salt reactor works

A molten salt reactor differs from a conventional nuclear reactor in a number of ways, starting with the fact that it uses nuclear fuel that is liquid instead of solid. This has profound implications for safety. For example, meltdown would be a non-issue. The fuel is already molten. And if temperatures in the fuel mix get too high for any reason, a plug of frozen salt below the reactor will melt and allow everything to drain into an underground holding tank for safekeeping. Long-lived nuclear waste would also be a non-issue. A chemical system would continuously extract reaction-stopping fission products from the molten fuel, which would allow plutonium and all other long-half-life fission products to be completely consumed.
Molten salt reactors (MSR) use graphite as moderator, molten fluoride salt of high boiling point ($\geq 1400^\circ$C) with dissolved ‘fissile’ and ‘fertile’ materials as fuel and primary coolant and operate in an epithermal neutron spectrum. The core of MSR is usually a cylindrical graphite block that acts as moderator, through which holes are bored, in which the molten fluoride salt containing thorium uranium and plutonium circulates. The primary coolant, containing the fuel, flows to a primary heat exchanger, where the heat is transferred to a secondary molten salt coolant and then flows back to the graphite channel of the reactor core. The secondary coolant loop transfers the heat to the power cycle or hydrogen production facility. The operating temperature range of MSRs is between $450^\circ$C, the melting point of eutectic fluoride salts to around $800^\circ$C. In the secondary molten salt, the temperature is lower than the primary.
Thermal Neutron (<1eV) From Prior Fission

Th-233 has a half life of 22 minutes. A neutron undergoes beta decay and turns into a proton. The decay releases an electron and an anti neutrino. The resulting element is Pa-233.

IAEA “Self-Protective” Fuel >2.4% ²³²U

2³³Protactinium

Electron + Neutrino

2³³Thorium

Beta Decay

Electron + Neutrino

2³²Thorium

(<1eV)

U-233 captures a neutron and fissions. When the atom fissions it generates 198 MeV of energy.

Fission-Product Pairs (~20 Possible Daughters)

The nucleus splits into two new elements of unequal size, one heavy and one light. In addition, two or three neutrons are released. Many of these elements such as xenon and neodymium can be collected and sold.

Start

1²C Moderator (Graphite…)

The neutrons that come from fission are moving very fast, and are not likely to cause fission or be absorbed. By striking carbon nuclei in graphite, they give up almost all of that kinetic energy without being absorbed. The neutrons are then called “thermal neutrons” because they’re at the same temperature as the rest of the salt mixture.

Th-232 absorbs a neutron and transmutes to Th-233.
LWR (BLUE) VERSUS MSR (GREEN)

Uranium-$^{235/238}$U Cycle

>90% U Wasted

Future Waste Destruction Via MSRs

1GW Thorium MSR Brayton Cycle

~10 Acres No Fuel Wasted

Normal Solid-Fuel Pellet Damage In <5 Years, Cladding Must Hold Unused Fuel + Wastes For Millennia

1st Civilian Uranium Solid-Fuel Core LWR, 60MW

Equivalent 60MW Thorium MSR Core

Equal Scales
• **PROs:**
  - No need to shut them down for refueling.
  - Ability to breed more fuel at low neutron energies.
  - Liquid fuel avoids cladding; more efficient.

• **CONs:**
  - A containment breach might release more fission product gases than a single pin in water.
  - On-line reprocessing is a potential “proliferation” concern.
HISTORY OF THE MSR AT OAK RIDGE

• Hyman Rickover applied for duty in submarines in 1929, but his only command, in 1937, lasted 3 months, after near-mutiny. By Dec 1941 he was chief of the Navy’s electrical section. He oversaw building the largest submarine fleet in history, spurring his men to exhaustion, driving contractors into rages, but making a reputation for getting things done.

• Meanwhile at Oak Ridge, Alvin Weinberg showed that MSRs had proven advantages over LWRs. But by 1954, with the launching of the Nautilus, Rickover had gained powerful influence over the AEC, helping to remove the government from atomic research, leaving GE and Westinghouse, already committed to LWRS, to dominate.
“During my life, I have witnessed extraordinary feats of human ingenuity. I believe that this struggling ingenuity will be equal to the task of creating the Second Nuclear Era. My only regret is that I will not be here to witness its success.” - 1994
ADVANTAGES OF TH OVER U

1. Thorium is 4X more abundant than U in the earth’s crust, and is easily found near the earth’s surface.
2. Thorium does not need to be enriched, as uranium often does, before using it in a fission reactor.
3. Thorium is FERTILE, but not FISSILE, so it cannot be used by itself as a nuclear weapon.
4. Thorium’s decay product, $^{233}\text{U}$, fissions more completely, so there is much less waste.
### URANIUM vs. THORIUM in NUCLEAR REACTORS

<table>
<thead>
<tr>
<th>Qualifier</th>
<th>U-235 Light Water</th>
<th>Th-232 Liquid Fluoride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel State</td>
<td>Solid U oxide in rods is easily damaged by heat and irradiation. By-products like xenon-135 require careful reactor management.</td>
<td>Liquid fluoride salts of Th and U are not damaged, and readily yield their products for separation and recycling.</td>
</tr>
<tr>
<td>Fuel Element</td>
<td>Uranium is less common, is difficult to purify, and its by-products (Pu-239, Am, Np) are very long-lasting and highly toxic.</td>
<td>Thorium is 4X commoner in the earth and is more easily extracted. U-233 product is easily recovered after fluoridation and recycled.</td>
</tr>
<tr>
<td>Reactor Design</td>
<td>Needs large structures to contain pressurized water or steam, then a giant dome for tertiary containment.</td>
<td>Relatively simple vessels that can be mass-produced and assembled without requiring high pressures.</td>
</tr>
<tr>
<td>Operation</td>
<td>Fuel rods must be replaced every 18 months, requiring plant shutdowns. Thermal efficiency = 30% vs 45% →</td>
<td>Core of U-233 emits neutrons into a ‘blanket’ of Th-232. Latter burns to U-233, which is continuously separated and recycled into the core.</td>
</tr>
<tr>
<td>Safety</td>
<td>Spent fuel is highly radioactive and dangerous to handle, even remotely.</td>
<td>No structural stresses in liquids; less need to handle, no pressure increase.</td>
</tr>
<tr>
<td>Waste Management</td>
<td>After years of storage under water, it must be removed again, dried and stored in casks.</td>
<td>Easily removed by fluoridation or plating; less volume waste and less toxic.</td>
</tr>
<tr>
<td>Cost</td>
<td>Huge costs for infrastructure and fuel manufacturing, as well as loss of efficiency: 18-month shutdowns.</td>
<td>Less expensive to build both structure and fuel; few shutdowns and less need for shielding.</td>
</tr>
<tr>
<td>Proliferation</td>
<td>By-products remain active for many years, and require constant guarding to prevent abuse by terrorists.</td>
<td>Thorium technology is still poorly understood, less likely to be stolen; abuse is easy to detect.</td>
</tr>
<tr>
<td>Resistance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fission Choices

Thorium bred to $^{233}$U with a neutron (via Protactinium decay), or via proton-beam & spallation.

Next neutron hitting $^{235}$U has a very high probability of causing fission & releasing $\sim$180 MeV energy, but $^{238}$U bred to Plutonium is much less likely to fission, thus building up higher-mass Pu, which has bomb-making potential, plus Am & other long-lived, transuranic wastes.

Because Thorium starts at mass 232 & neutron captures rarely exceed 236 (< 20% of 10% = 2%), $^{238}$U & Pu are rarely produced, but are consumed if fissile.

Graphics Courtesy of Wikipedia
IS “WASTE” DISPOSAL ALL THAT DIFFICULT?

• We’ve been disposing more toxic wastes than nuclear for decades.

• Spent nuclear fuel from LWRs is allowed to cool for ~ 5 years before storage, where it’s not as toxic as industrial wastes (formaldehyde, benzene or cyanides) 9 billion gallons of which we store annually.

• EPA’s radiation standards for Yucca Mountain storage are too rigorous, 20X > the current “background” radiation we all receive.

• Spent nuclear fuel storage beside existing nuclear plants is sensible, and it could be used to fuel advanced reactors in future.
YUCCA MOUNTAIN IN SOUTHERN NEVADA
Used ‘Spent’ Fuel = Not Waste

>74,000 tons = 1 football field

Enrichment >500,000 tons pure U238

Used + unused Uranium = >570,000 GW-years of clean energy, when used
to breed new fuel for fast-neutron reactors (IFR, EBR, MSFR...)
“...and...make possible the exploitation of the vast energy resources latent in the
fertile materials, uranium-238 and thorium.” – Glenn Seaborg to JFK, 1962.

>95% Not Waste: ~2% unused fissile fuel, ~4% fission products, ~95%
Uranium, and <1% transuranics.
Solution to the Waste Problem

- Not a total solution, but if the original actinides are consumed, the toxicity of the remaining fission products drops by 5 logs to only 800 years.
- This is a powerful side-benefit of total “burn”.

Figure 8.13 Relative radiological toxicity of high-level waste. Courtesy of Argonne National Laboratory.
WHY DO WE KEEP PLAYING WITH LEGOS?

Figure 5.3  Assembly of the fuel into a core. COURTESY OF THE AMERICAN NUCLEAR SOCIETY.
Uranium’s Long Road to MRS (monitored retrievable storage)
**MSRs can consume existing LWR wastes**

- Typical wastes from a 1 GWe LFTR, over 30 years, is < 100 lbs (<1/2 cubic ft).
- A 1 GWe LFTR makes 1/1000th the Plutonium made by an equivalent LWR.
- LFTR wastes are < wastes of fissioning U oxide pellets, with less fission products.
- OTHER MSR advantages are:
  - Higher temps give ~30% better thermal efficiency, and no pressurization.
  - MSRs automatically throttle via thermal expansion of atoms in fluid salt.
  - There is no “runaway” or “meltdown” with liquid fluoride salt reactors.
  - Expensive containment systems are avoided by using a “frozen plug” to release the fluid salts in the event of an electrical power failure.
## Comparison with Fossils

### 1000 Mwe-yr Power Plant Emissions

<table>
<thead>
<tr>
<th></th>
<th>COAL</th>
<th>GAS</th>
<th>NUCLEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur-oxide</td>
<td>~1000 mt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrous-oxide</td>
<td>~5000 mt</td>
<td>400 mt</td>
<td></td>
</tr>
<tr>
<td>Particulates</td>
<td>~1400 mt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2</td>
<td>&gt;7 million mt</td>
<td>3.5 mill. mt</td>
<td></td>
</tr>
<tr>
<td>Trace elements</td>
<td>&lt;1 mt**</td>
<td>&lt;1 kg</td>
<td></td>
</tr>
<tr>
<td>Ash (solids)</td>
<td>~1 million mt</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Volatilized heavy metals: e.g., Mercury, Lead, Cadmium, Arsenic**

- Spent Fuel: 20-30 mt
- Fission Products: ~1 mt
<table>
<thead>
<tr>
<th>Fission Product</th>
<th>Half-Life (years)</th>
<th>Activity Discharged Annually from a 1000 MW PWR Reactor (Ci/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sr-90</td>
<td>28</td>
<td>$2.1 \times 10^6$</td>
</tr>
<tr>
<td>Cs-137</td>
<td>30</td>
<td>$2.9 \times 10^6$</td>
</tr>
<tr>
<td>Se-79</td>
<td>$6 \times 10^4$</td>
<td>11</td>
</tr>
<tr>
<td>Sn-126</td>
<td>$1 \times 10^5$</td>
<td>15</td>
</tr>
<tr>
<td>Tc-99</td>
<td>$2.1 \times 10^5$</td>
<td>390</td>
</tr>
<tr>
<td>Zr-93</td>
<td>$1.5 \times 10^6$</td>
<td>50</td>
</tr>
<tr>
<td>Cs-135</td>
<td>$3.0 \times 10^6$</td>
<td>8</td>
</tr>
<tr>
<td>Pd-107</td>
<td>$7 \times 10^6$</td>
<td>3</td>
</tr>
<tr>
<td>I-129</td>
<td>$1.7 \times 10^7$</td>
<td>1.0</td>
</tr>
</tbody>
</table>
GEOMELT = VITRIFICATION

• Geomelting: dangerous contaminated material is mixed with clean soil, industrial waste and glass “grit”, and melted to create a very hard, leach-resistant glass. This vitrification immobilizes nearly all contaminants by incorporating them into a glass matrix. Organic wastes are destroyed by pyrolysis.

• Developed in 1980 by the US-DOE, the Geomelt process is conducted in situ (in place) or by In-Container Vitrification (ICV) in a special steel-lined container.
THE FACTS ABOUT “WASTE”

• Nuclear “waste” is Compact, Contained & Curated.
• Its dangers are greatly exaggerated by the oil lobby and by fearful, poorly informed environmentalists.
• Yucca Mountain and other waste sites need to be made operational for storing fission products.
• We need to consider Thorium as well as Uranium for future reactors, rather than remain limited by our current, uranium-based infrastructure.
EVOLUTION OF MORE INNOVATIVE REACTOR DESIGNS

**Generation IV:** Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics.

- **Generation I:** Early Prototype Reactors
  - Shippingport
  - Dresden, Fermi I
  - Magnox

- **Generation II:** Commercial Power Reactors
  - LWR-PWR, BWR
  - CANDU
  - VVER/RBMK

- **Generation III:** Advanced LWRs
  - ABWR
  - System 80+
  - AP600
  - EPR

- **Near-Term Deployment:** Generation III+ Evolutionary Designs Offering Improved Economies
  - Highly Economical
  - Enhanced Safety
  - Minimal Waste
  - Proliferation Resistant

- **Generation IV**

There is an urgent need to have safer, more efficient designs available as soon as the oldest of our fleet of mostly 2nd-generation reactors are decommissioned.
AN ECONOMIC RESCUE?

- **NuScale** is a Small Modular Reactor (SMR) that might occupy the niche of III+ to save the beleaguered nuclear industry until Gen IV reactors enter the market.
TERRESTRIAL IMSR
The fight to rethink (and reinvent) nuclear power
MORE INFORMATION NEEDED?

- www.thoriumenergyalliance.com
- www.world-nuclear.org
- www.rethinkingnuclear.org