THE UNIVERSITY of TENNESSEE KNOXVILLE

Department of Nuclear Engineering

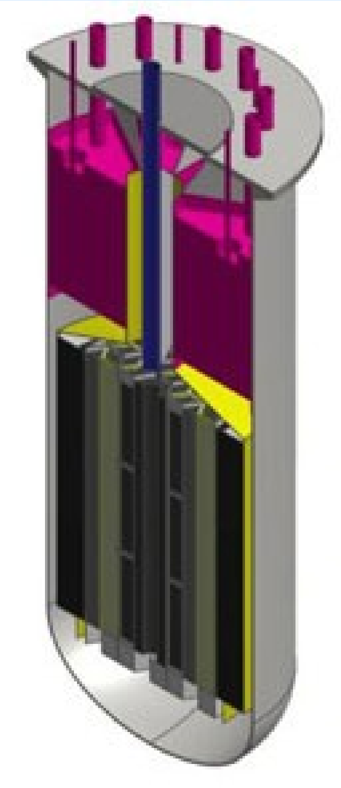
CERN seminar, May 13th 2015

Recent progress in nuclear power applications of molten salts

Ondřej Chvála <ochvala@utk.edu>

Seminar overview

- Introduction & motivation
- Why molten alkali-halide salts?
- History of Molten Salt Reactor (MSR) research
- Current developments in MSRs in the U.S. & abroad
- More information
  - my MSR research: http://web.utk.edu/~ochvala/MSR/
  - Gordon's popular videos: http://thoriumremix.com/



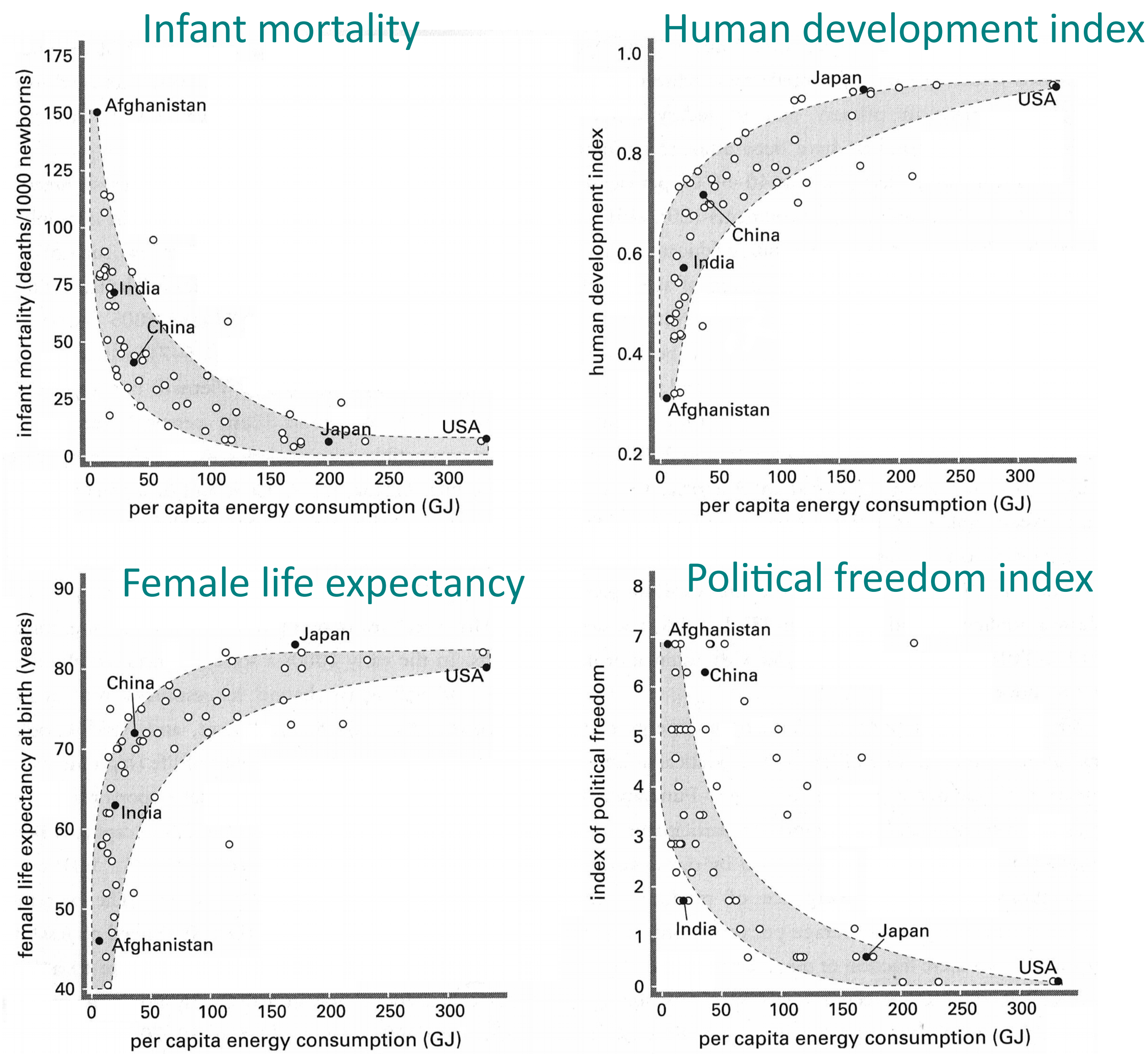
Ondřej Chvála - My background

- From Prague, Czech Republic.
- PhD in Nuclear Physics at Charles University in Prague, research at NA49 experiment at CERN – soft hadronic physics, detector R&D, data analysis.
- 2007 – moved to US as a UC Riverside postdoc working on PHENIX experiment at BNL.

- 2011 – Jumped from a high energy physicist to a nuclear engineer, motivated by magnitude and urgency of environmental issues.
- 2012 – Research assistant professor at UTK NE; teaching Reactor physics, Numerical methods and Fortran, Radiological laboratories.
- Research interests: high performance computing, physics of radiation transport in matter, next generation of nuclear power, nuclear security.
- Study abroad program – Experimental reactor physics in Prague.

Introduction – quality of life relation to energy use

Relationship of several QoL indicators with annual per capita energy consumption



from: Vaclav Smil: Energy in Nature and Society, MIT Press 2008, page 347

→ About ½ of US per capita energy consumption is required for decent standards of living.

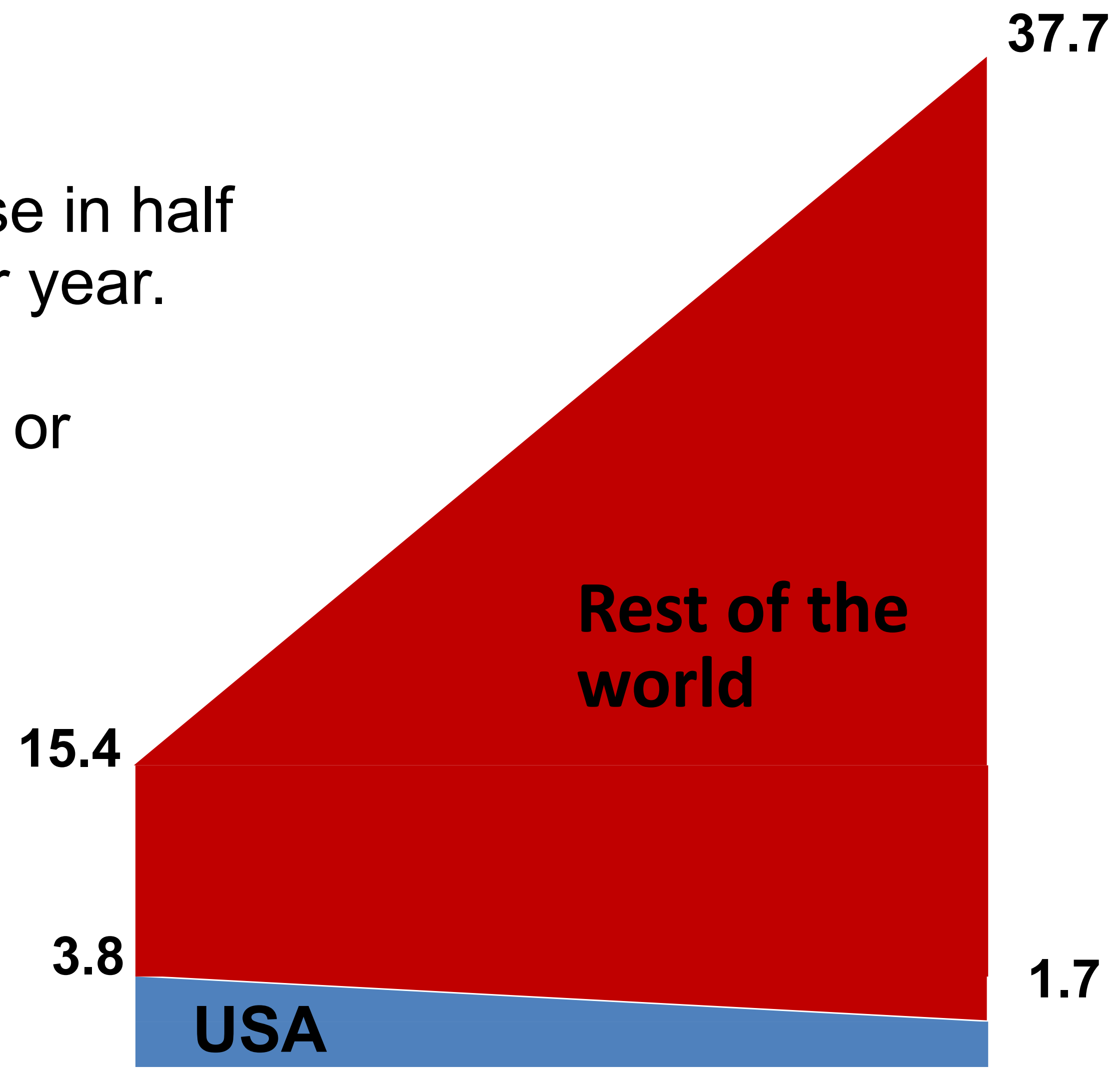
Introduction II

<u>Thought experiment</u>

US cuts per capita energy use in half to 6,000 KWh per person per year.

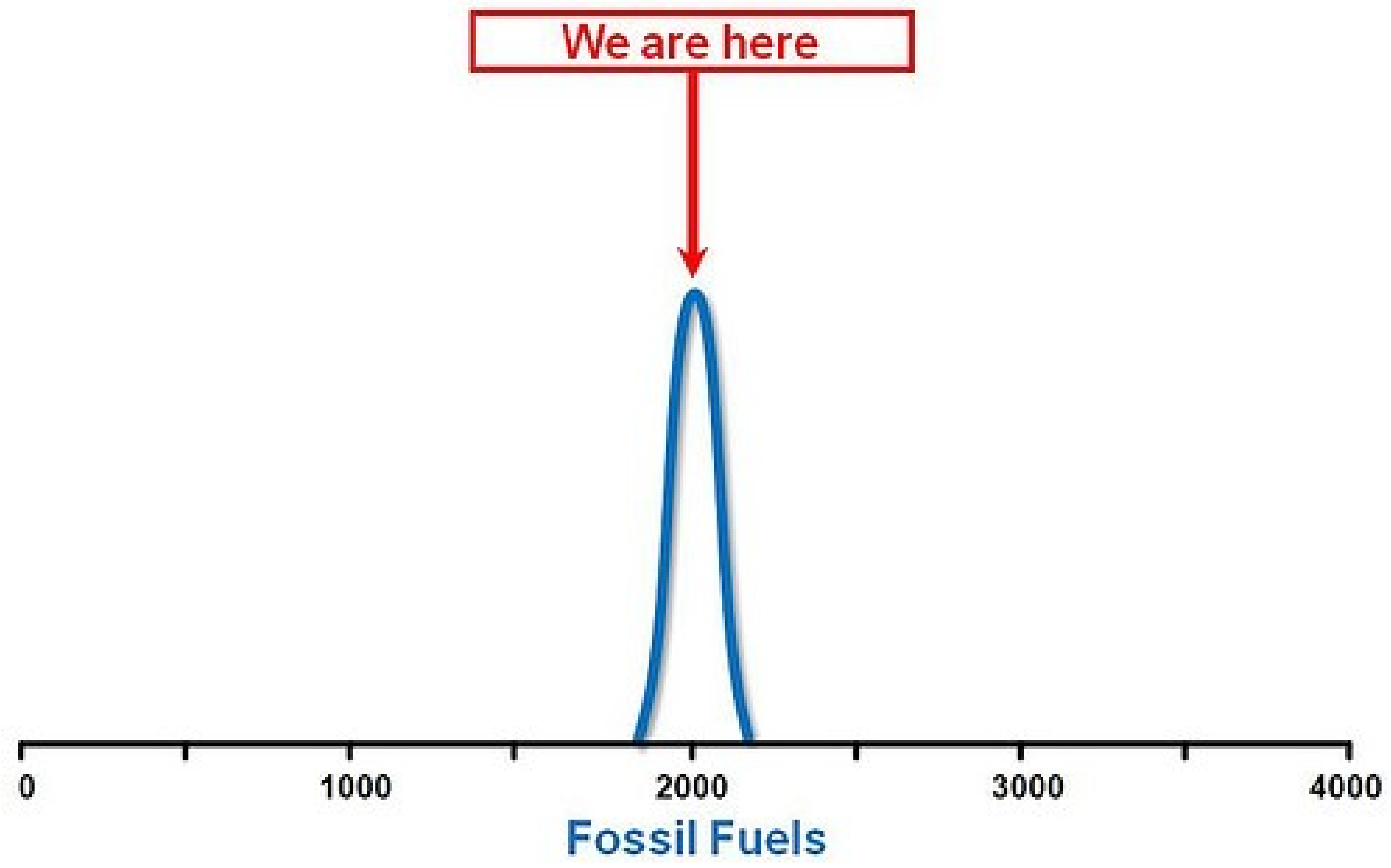
Rest of the world nations cut or grow to achieve the same.

Global energy consumption in TWh / year



NB: Age of substitutability (Goeller & Weinberg, 1975) – energy is the ultimate raw material.

Motivation



Alternatively

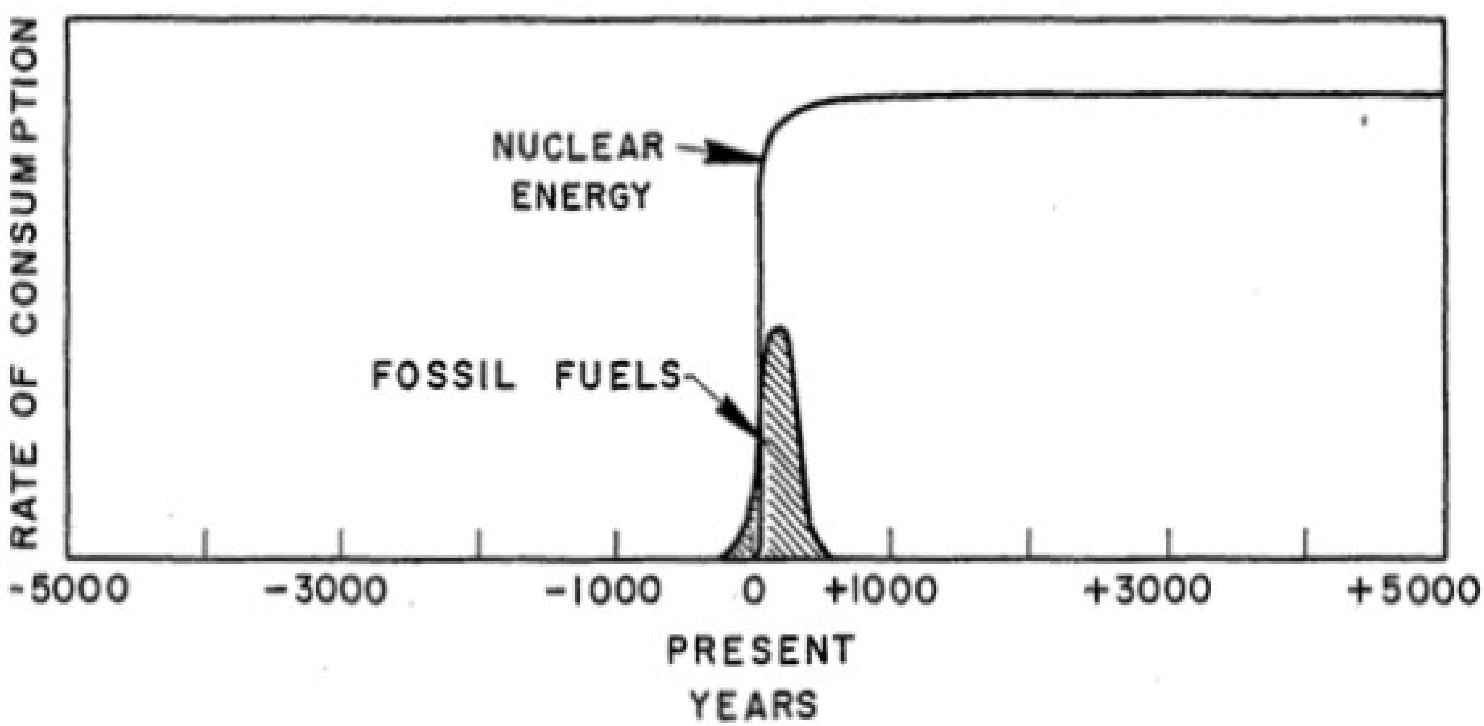
- Humankind has already cut the branch it was sitting on. Now it is falling down in joy – thinking it flies like birds.

Aside: Grave digging for future generations

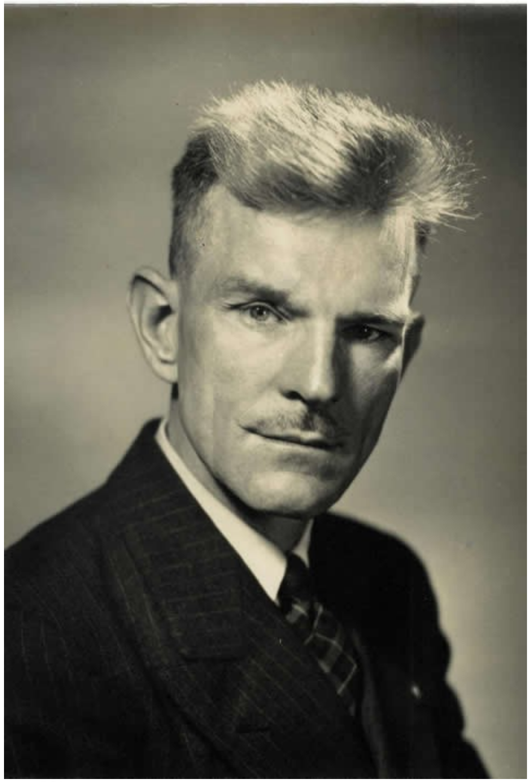
- The loss of faith in the future generation is the heaviest burden the future generations can carry.
- Shall this loss of faith remain long term, it will become literately unbearable – like a curse which one cannot come to terms with, as it is unbreakable, but only fulfill – since it will not be a burden imposed from outside, but an internal infection.
- It is particularly vile if one feels the need to proudly spread this defeatism and claim “just want and see!”.

Benjamin Kuras - http://blisty.cz/art/77681.html
Ztráta víry v budoucí generaci je to nejtěžší břímě, které si budoucí generace může nést.
Bude-li tato ztráta víry dlouhodobá, bude doslova nesnesitelná, bude jako kletba,
se kterou se nelze vyrovnat, protože ji nelze zlomit, pouze naplnit, jelikož to nebude vnější
překážka, ale vnitřní infekce. Každý, kdo nevěří v budoucnost svých dětí, prohrál. Je trestuhodné,
má-li navíc potřebu tento defétismus hrdě šířit a prohlašovat "na má slova dojde".

Motivation II



jure 30 - Relative magnitudes of possible fossil-fuel and nuclear-
ergy consumption seen in time perspective of minus to plus 5000 years.

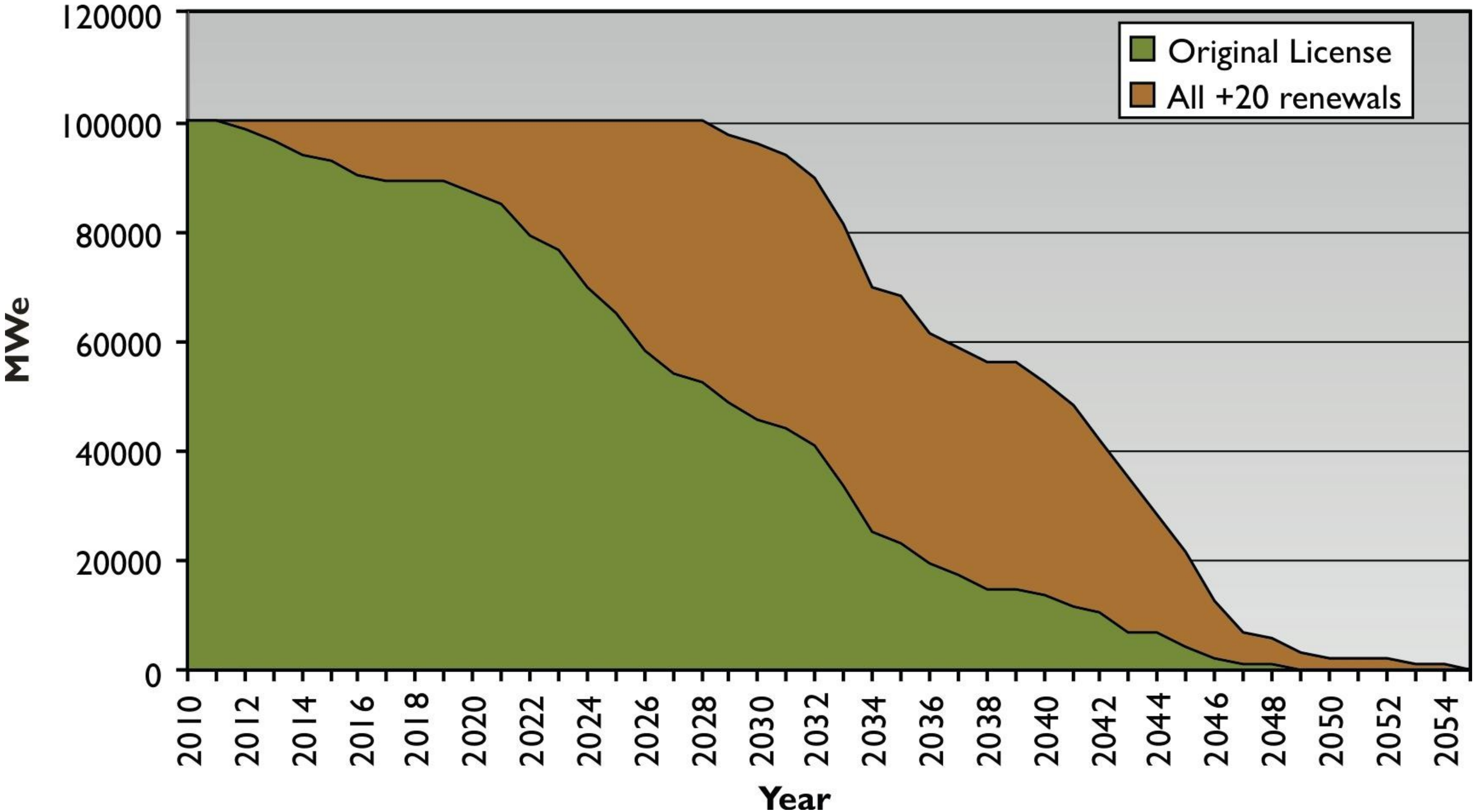


Marion King Hubbert
Nuclear Energy and the Fossil Fuels
A.P.I. journal Drilling and Production Practice (1956)

Energy, quality of life, polution quandary

- To make life on Earth bearable and stabilize population, we need to **triple** current global energy production.
- At the same time reducing global green-house gas (GHG) emissions by 80% or more.
- For this to happen, this new clean energy source must be cheaper (without subsidies, feed in tariffs, etc.) than coal or gas. Most people cannot afford to overpay for energy.
- We have about 30 years to do it.

The US Nuclear Retirement "Cliff"

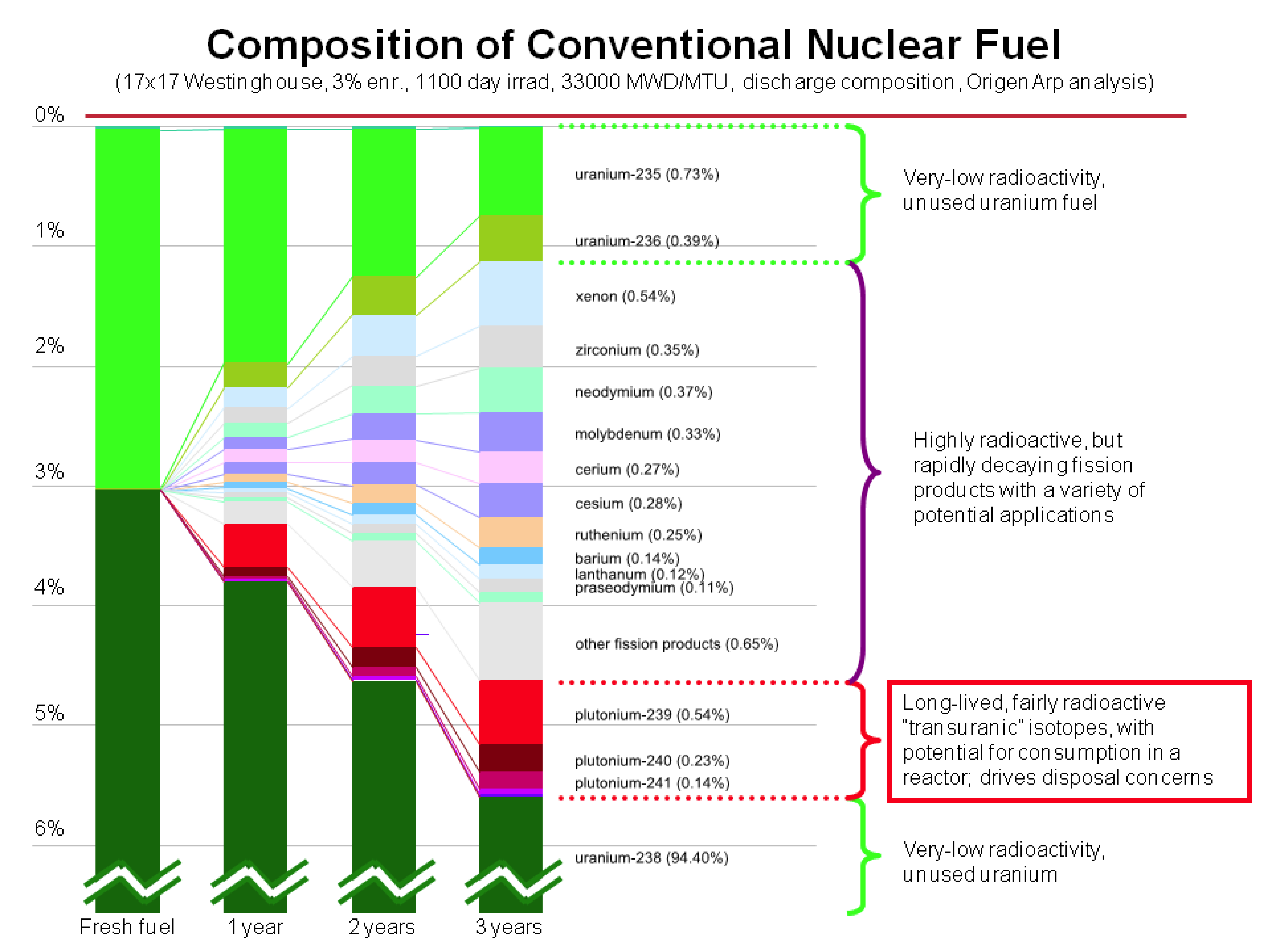


Beginning in 2028, nuclear power plant retirements will increase dramatically.

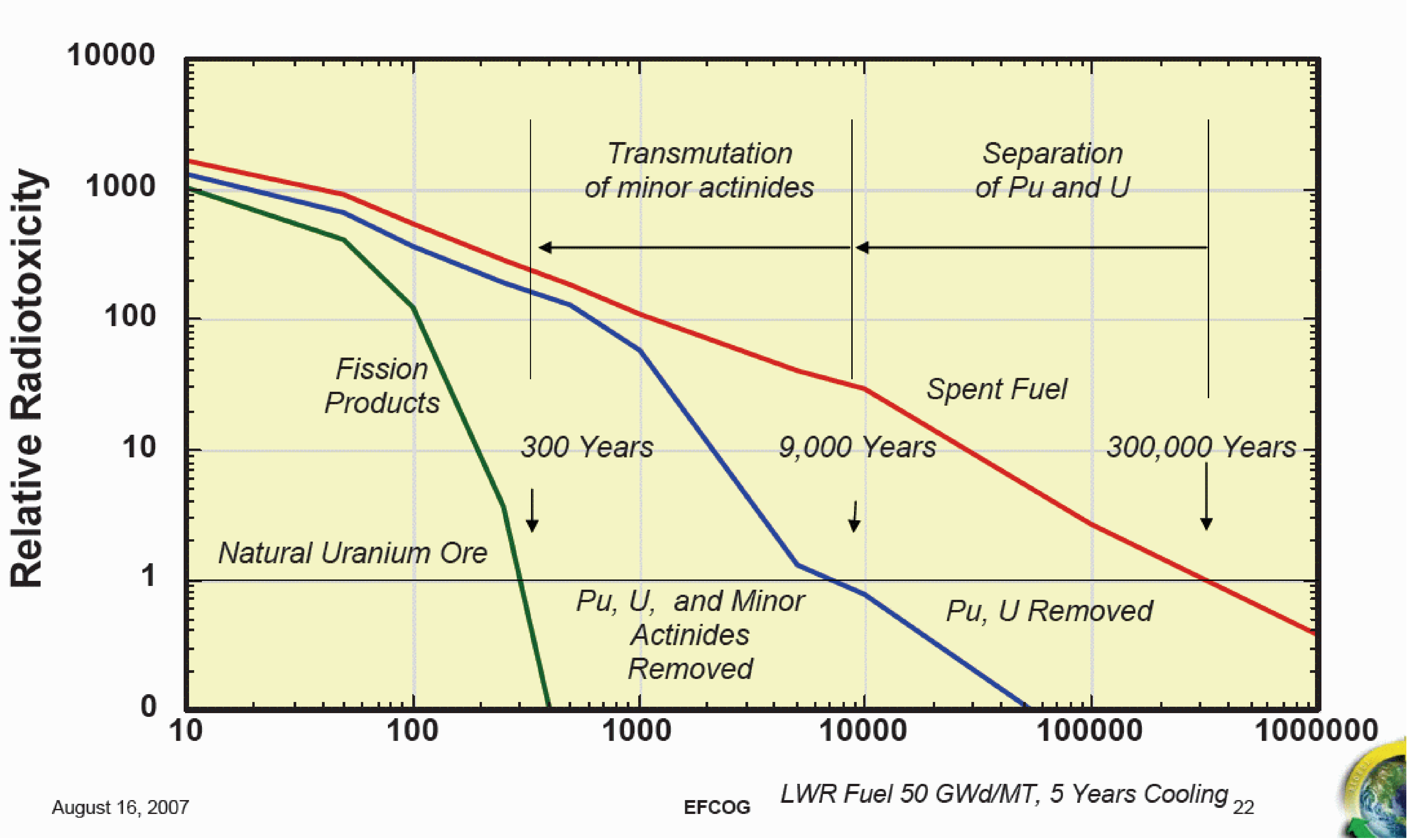
How can we do this?

- How can we get rid of nuclear waste?
  - Burn our fuel up completely.
  - Destroy the waste already created.
- How can we improve safety?
  - Design reactors with INHERENT safety rather than engineered safety.
- How can we further address proliferation?
  - Use fuel unsuitable for weapons, remove the need for uranium enrichments.
- How can we reduce fuel and mining requirements?
  - Use a more abundant nuclear fuel (thorium) and use it all.
- How can we reduce cooling water requirements?
  - Use high-temperature reactors and power conversion cycles that can be effectively air-cooled.
- How can we build reactors cheaper?
  - Use reactors whose core operate at ambient pressure to reduce the size of the vessel.
  - No pressurized water that can evolve to steam in an accident.
  - Use compact gas turbines instead of steam cycles for power conversion

Legend of St. Prokop


Composition of Conventional Nuclear Fuel
(17x17 Westinghouse, 3% enr., 1100 day irrad, 33000 MWD/MTU, discharge composition, Origen Arp analysis)
0%
1%
2%
3%
4%
5%
6%
uranium-235 (0.73%)
uranium-236 (0.39%)
xenon (0.54%)
zirconium (0.35%)
neodymium (0.37%)
molybdenum (0.33%)
cerium (0.27%)
cesium (0.28%)
ruthenium (0.25%)
barium (0.14%)
lanthanum (0.12%)
praseodymium (0.11%)
other fission products (0.65%)
plutonium-239 (0.54%)
plutonium-240 (0.23%)
plutonium-241 (0.14%)
uranium-238 (94.40%)
Very-low radioactivity, unused uranium fuel
Highly radioactive, but rapidly decaying fission products with a variety of potential applications
Long-lived, fairly radioactive "transuranic" isotopes, with potential for consumption in a reactor; drives disposal concerns
Very-low radioactivity, unused uranium
Fresh fuel
1 year
2 years
3 years

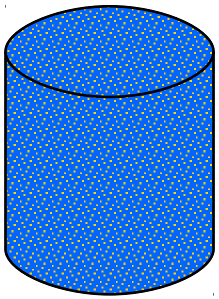
Burning all the fissile fuels will make nuclear waste a 300 years problem, not 300 000 years!



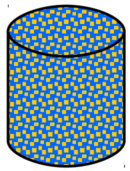
Nuclear fuel cycles

mission: make 1000 MW of electricity for one year

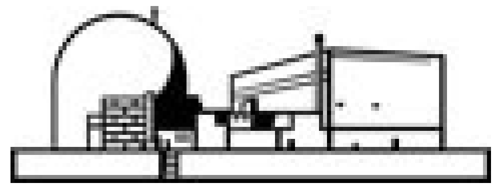
Contemporary nuclear fuel 'cycle'



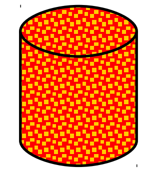
250 tonnes of natural uranium containing 1.75 t U-235



35 t of enriched uranium (1.15 t U-235)



Uranium-235 content is "burned" out of the fuel; some plutonium is bred and burned (1/3 of total burnup)

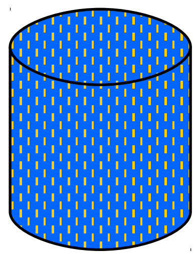


35 t of spent fuel stored on-site until disposal at Yucca Mountain.

It contains:

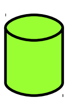
- 1.0 t fission products
- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium + M.A.

useful nuclear fuels



215 t of depleted uranium containing 0.6 t U-235—disposal plans uncertain.

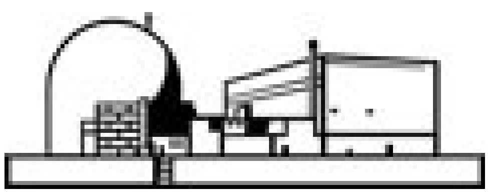
Closed nuclear cycle – ~200x more resource-efficient



One tonne of heavy metal fissile fuel

Actinides from spent nuclear fuel, Natural uranium,

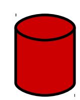
Thorium



Heavy metal fuel is bred and fissioned with (integrated) recycling.

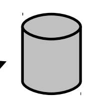
Liquid Metal cooled Fast spectrum Breeder Reactors (LMFBR)

Molten Salt Reactors (MSR)

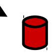


One tonne of fission products; no uranium, plutonium, or other actinides.

Fission products = rare materials with unique properties



Within 10 years, 83% of fission products are stable and can be partitioned and sold.

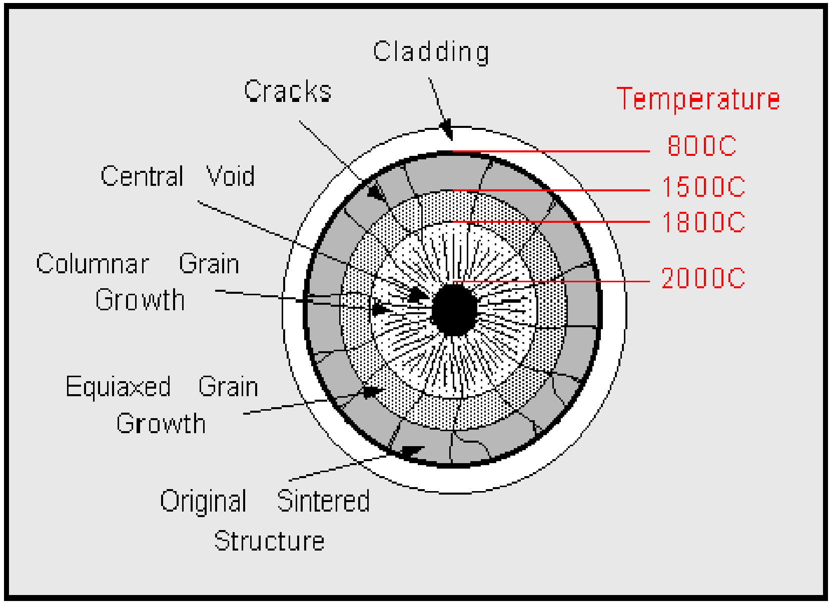


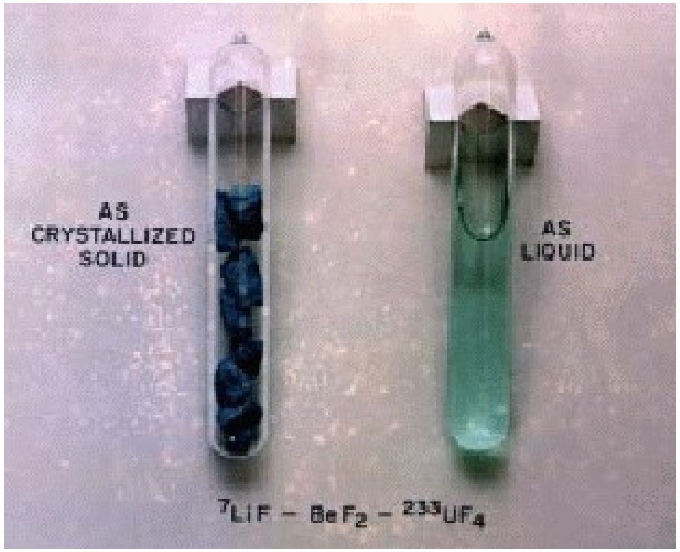
The remaining 17% fission products need isolation for ~300 years.

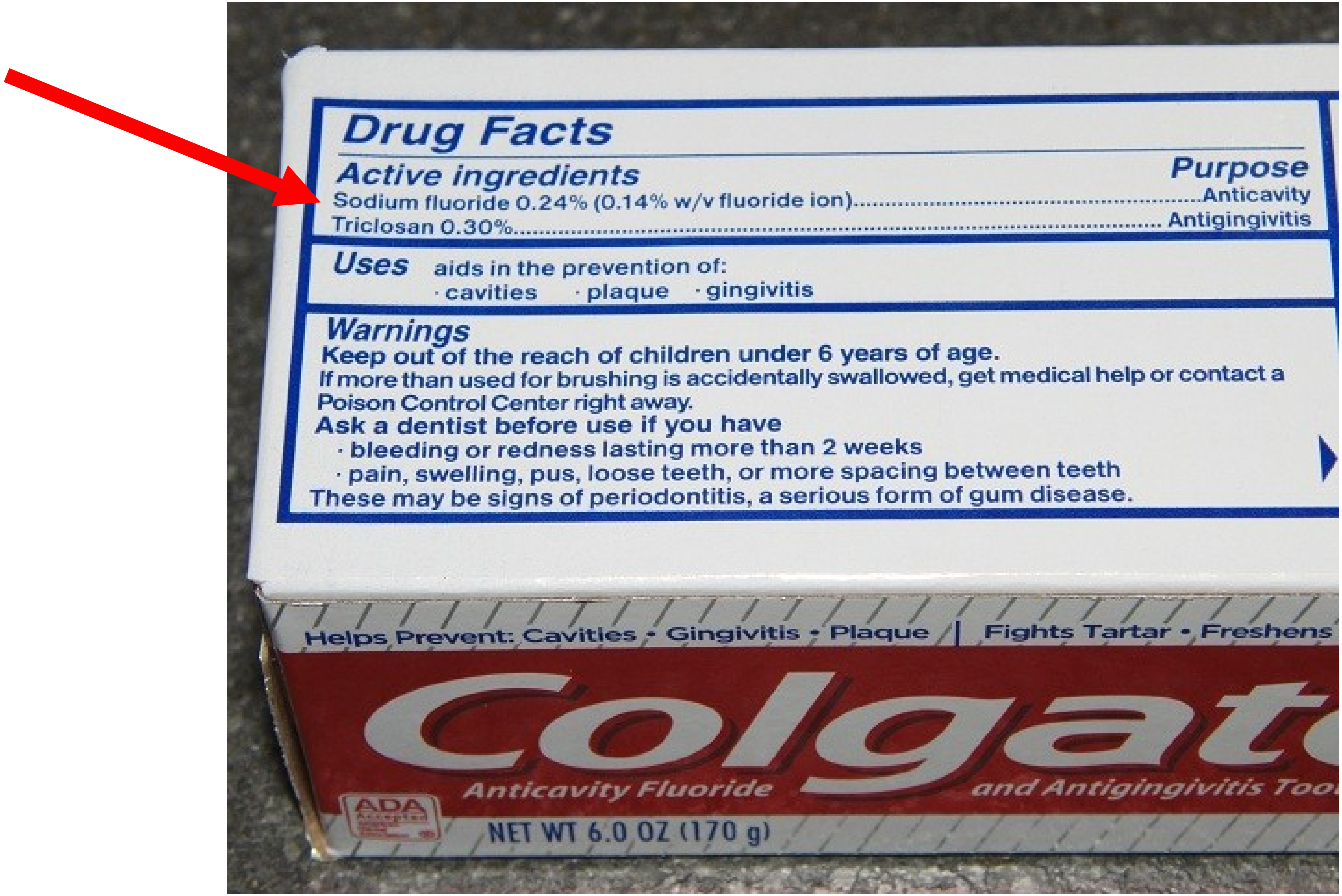
Other uses: Tc99 – strong anti-corrosion agent in alloys and coatings; irradiation sources for medicine, industry, sanitation (destroy complex halides in waste water treatment); valuable catalysts (Ru, R, Pd), Xe for ion engines

How to burn the fuel completely and safely?

- Solid fuel crystalline structure gets damaged by fission, and accumulates neutron absorbing fission products, which limits its lifetime.
- Solution (which I like): **Liquid fuel!**
- Also allows safety improvement.
- To avoid any pressure or chemical driver pushing core out: **molten alkali-fluoride salts**
- That is ionically bonded chemically stable liquids (450C to 1450C).
- Dissolve uranium and other actinides.
- Cs, Sr, etc. form stable fluorides and are not volatile even in accident and containment breach.

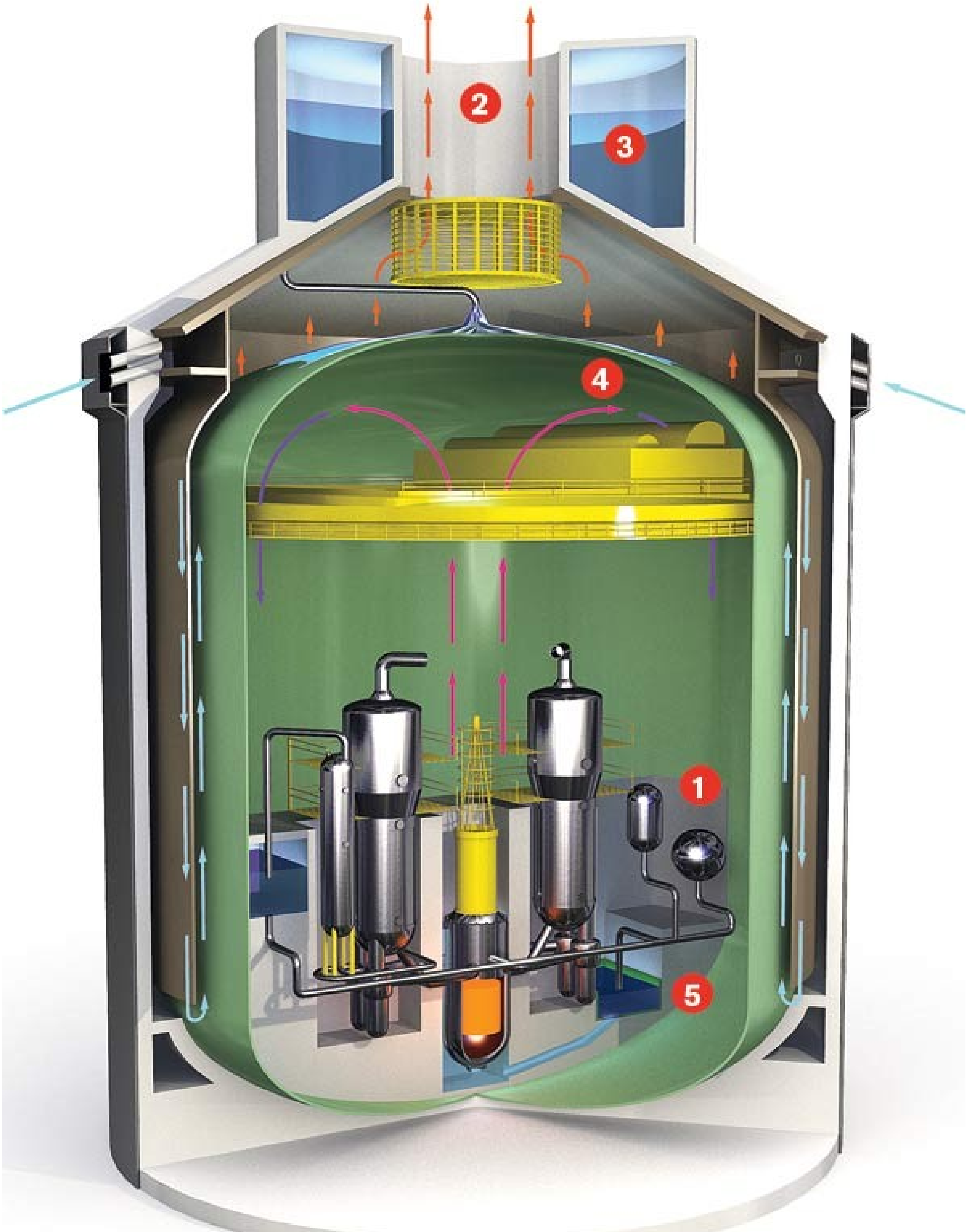






Drug Facts
Active ingredients
Purpose
Sodium fluoride 0.24% (0.14% w/v fluoride ion)....Anticavity
Triclosan 0.30%.... Antigingivitis
Uses aids in the prevention of:
· cavities · plaque · gingivitis
Warnings
Keep out of the reach of children under 6 years of age.
If more than used for brushing is accidentally swallowed, get medical help or contact a Poison Control Center right away.
Ask a dentist before use if you have
· bleeding or redness lasting more than 2 weeks
· pain, swelling, pus, loose teeth, or more spacing between teeth
These may be signs of periodontitis, a serious form of gum disease.
Helps Prevent: Cavities • Gingivitis • Plaque
Fights Tartar • Freshens
Anticavity Fluoride
and Antigingivitis Too
NET WT 6.0 OZ (170 g)

Pressurized-Water Reactor Containment

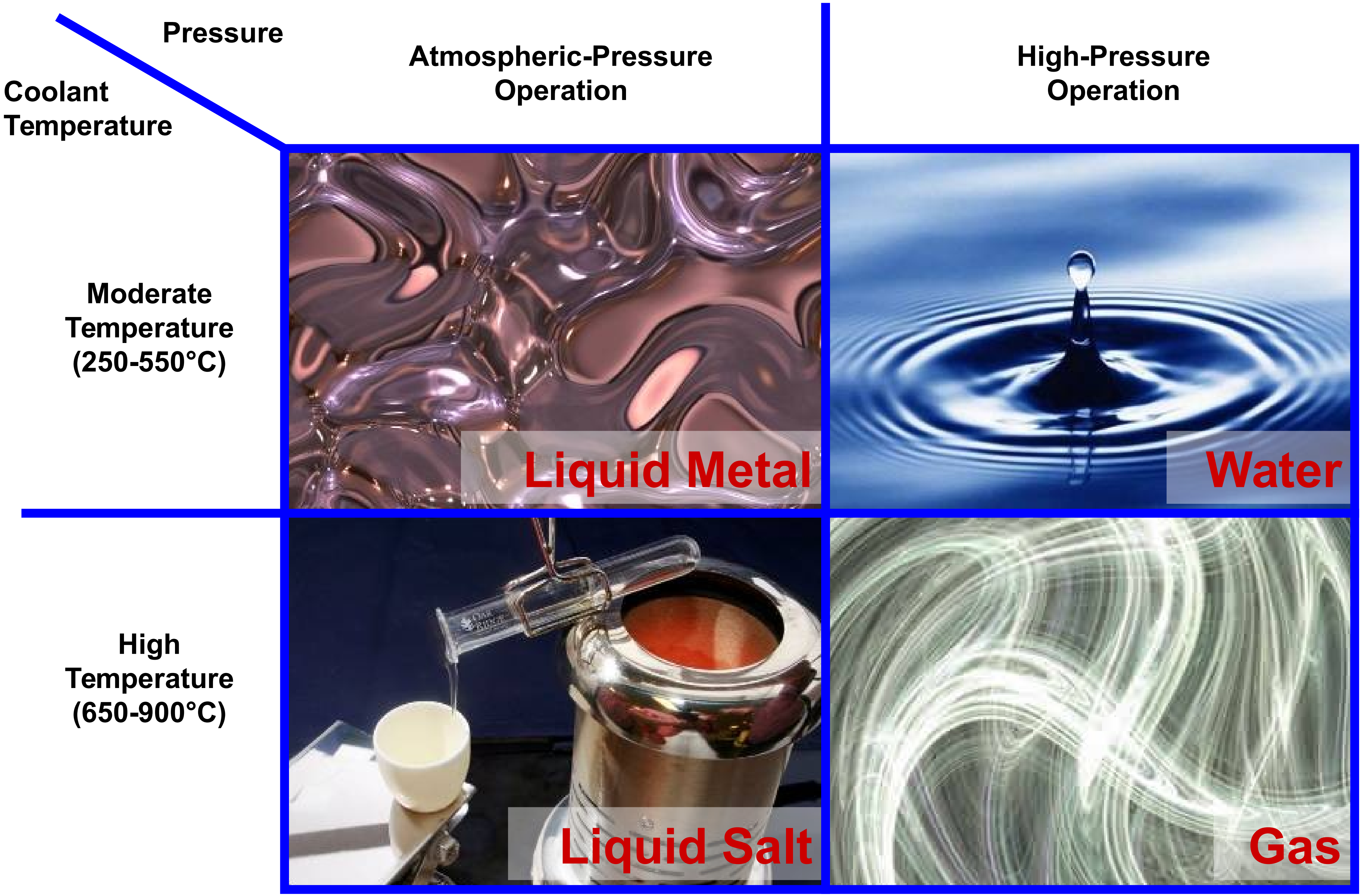


- This structure is steel-lined reinforced concrete, designed to withstand the overpressure expected if all the primary coolant were released in an accident.

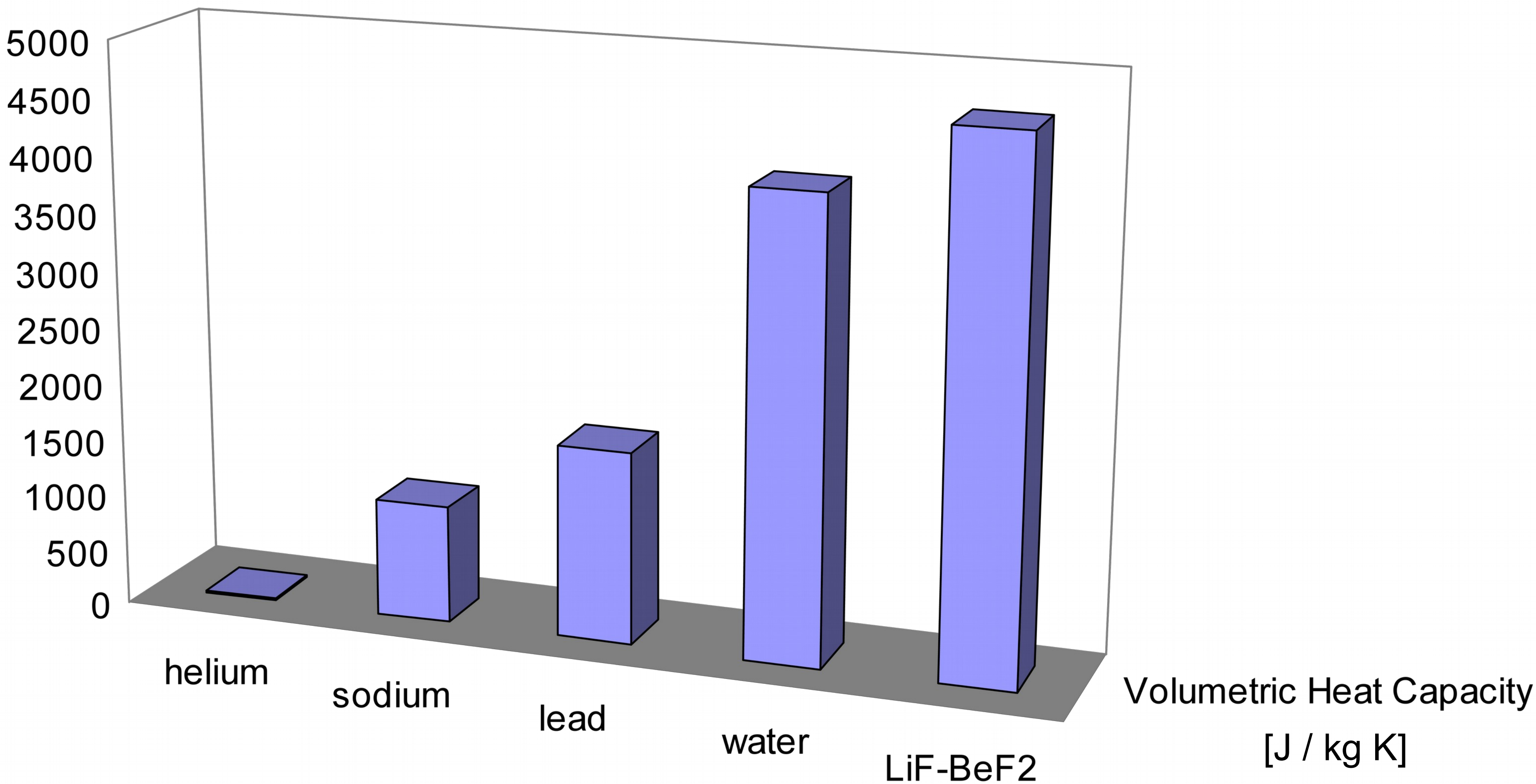
- Sprays and cooling systems wash released radioactivity out of the containment atmosphere coo the internal atmosphere, keeping the pressure below the containment design pressure.

- The basic purpose of the containment system is to minimize the amount of released radioactivity that escapes to the external environment.

Coolant Choices for a Nuclear Reactor

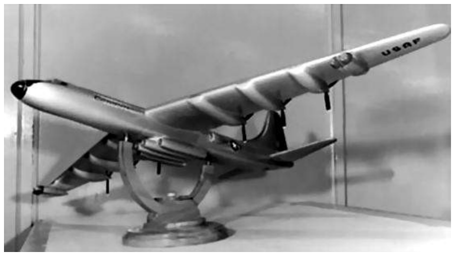


Volumetric Heat Capacity of Coolant Options

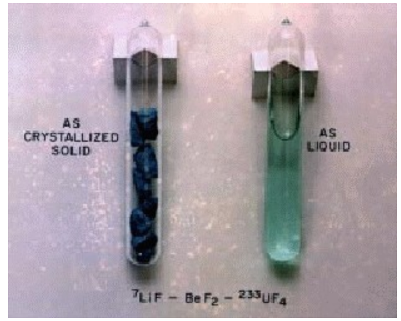


Of the four coolant options, a fluoride salt (LiF-BeF_2) has the greatest volumetric heat capacity. It can also carry this thermal energy at a low—essentially ambient—operating pressure. This reduces size of componenets such as heat exchangers.

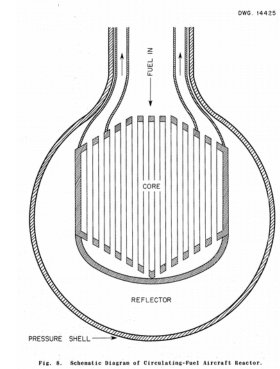
ORNL Aircraft Nuclear Reactor Progress (1949-1960)

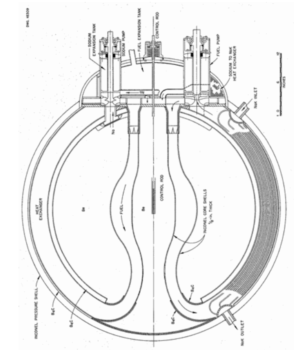


1949 – Nuclear Aircraft Concept formulated

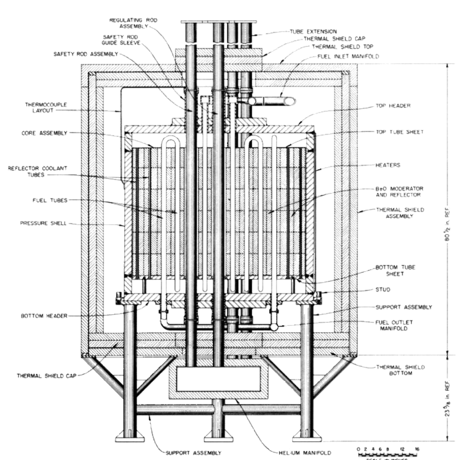


1951 – R.C. Briant proposed Liquid-Fluoride Reactor

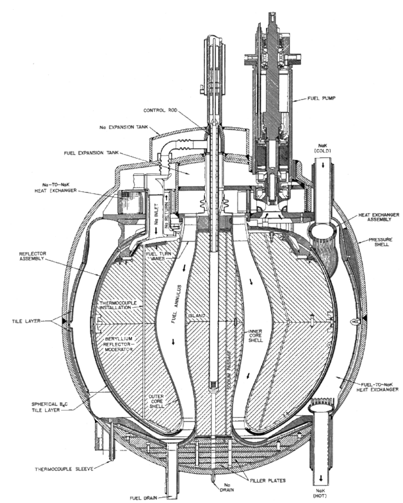




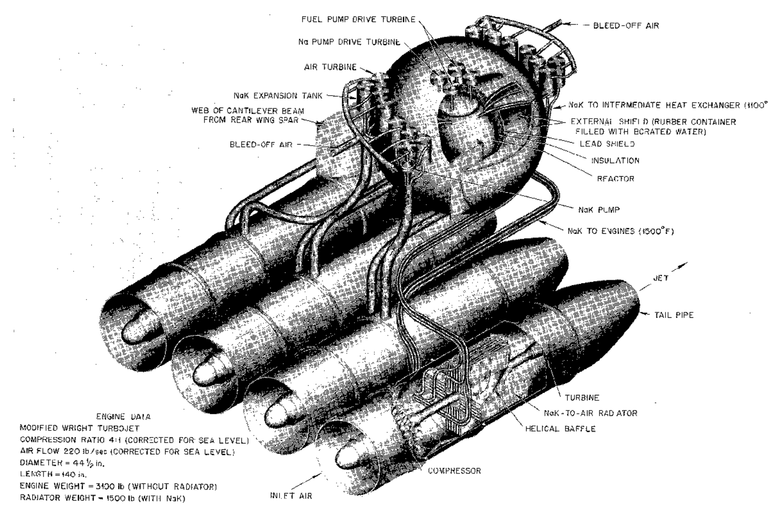
1952, 1953 – Early designs for aircraft fluoride reactor



1954 – Aircraft Reactor Experiment (ARE) built and operated successfully (2500 kWt2, 1150K)

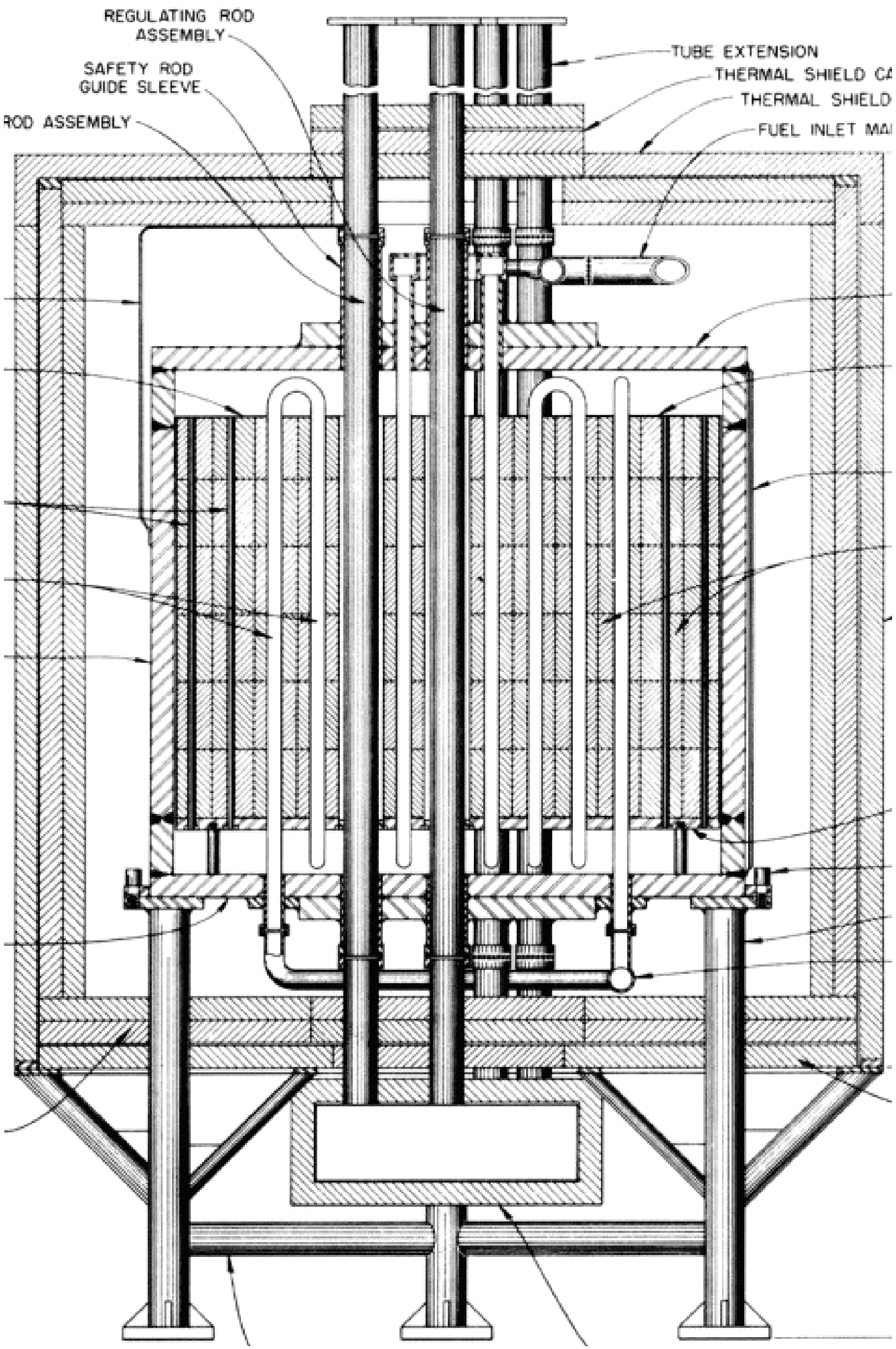


1955 – 60 MWt Aircraft Reactor Test (ART, "Fireball") proposed for aircraft reactor



1960 – Nuclear Aircraft Program canceled in favor of ICBMs

The Aircraft Reactor Experiment (1954)

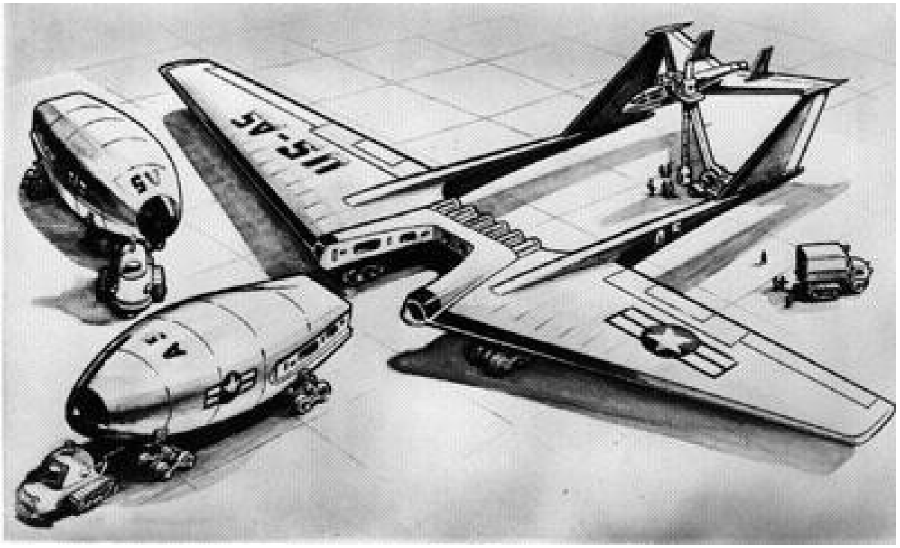


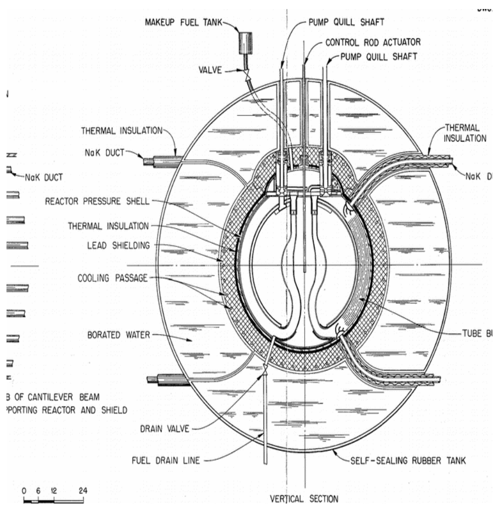
In order to test the liquid-fluoride reactor concept, a non-circulating core, sodium-cooled reactor was hastily converted into a proof-of-concept liquid-fluoride reactor.

The Aircraft Reactor Experiment ran for 1000 hours at the highest temperatures ever achieved by a nuclear reactor (**1150 K**).

- Operated from 10/30/1954 to 11/12/1954
- Liquid-fluoride salt circulated through beryllium reflector in Inconel tubes.
- $^{235}UF_4$ dissolved in NaF-ZrF_4
- Produced 2.5 MW of thermal power.
- Gaseous fission products were removed naturally through pumping action.
- Very stable operation due to a large negative temperature-reactivity coefficient.
- Demonstrated load-following operation without control rods.

Aircraft Nuclear Program Allowed ORNL to Develop Reactors





It wasn't that I had suddenly become converted to a belief in nuclear airplanes. **It was rather that this was the only avenue open to ORNL for continuing in reactor development.**

That the purpose was unattainable, if not foolish, was not so important:

A high-temperature reactor could be useful for other purposes even if it never propelled an airplane…

—Alvin Weinberg

Molten Salt Reactor Experiment (1965-1969)

ORNLs' MSRE: 8 MW(th)
Designed 1960 – 1964
Started in 1965, 5 years of successful operation

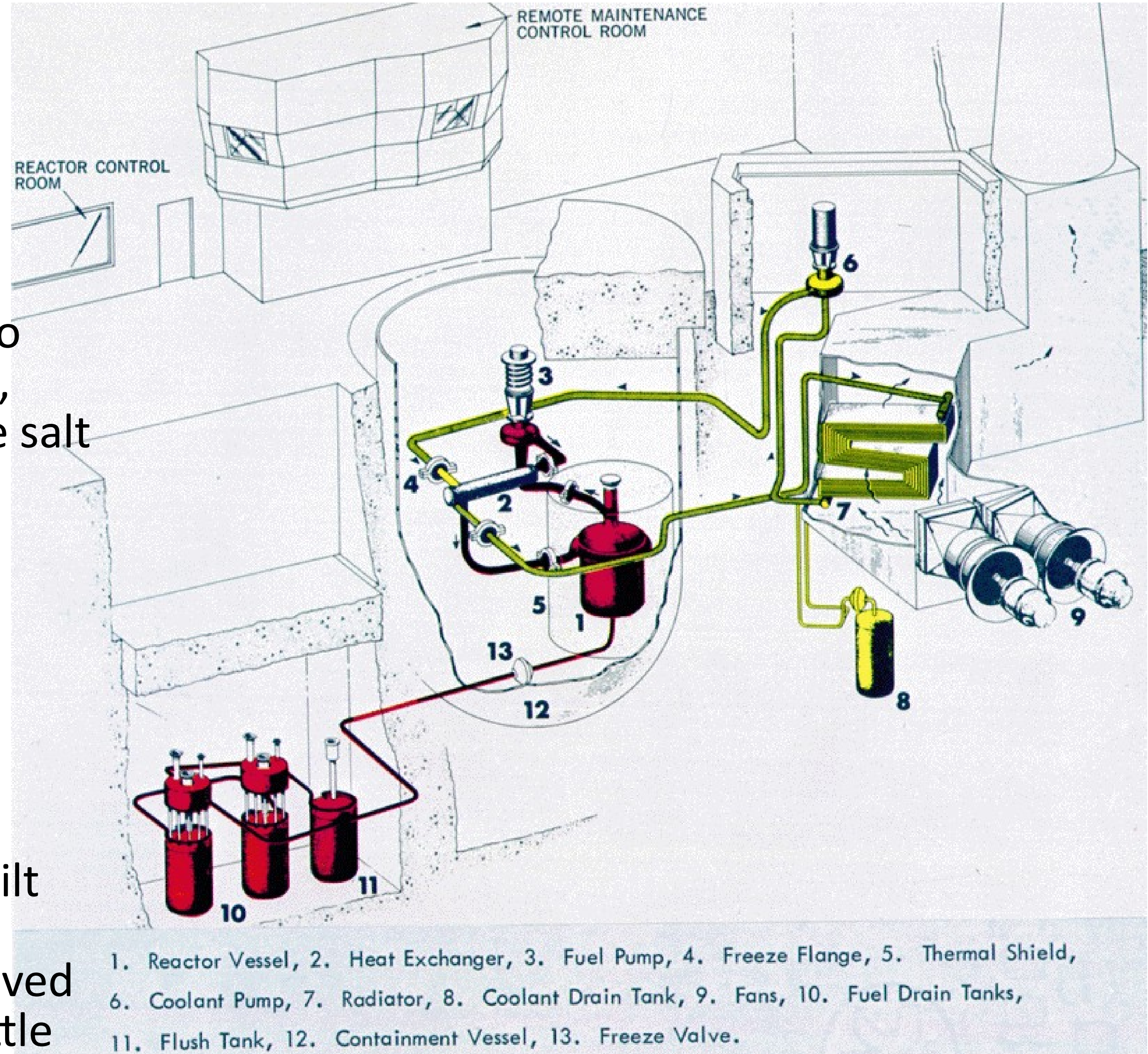
Developed and demonstrated on-line refueling, fluorination to remove uranium $UF_4+F_2 \rightarrow UF_6$, Vacuum distillation to clean the salt

Operated on all 3 fissile fuels
U233, U235, Pu239

Some issues with Hastelloy-N found and solved

Further designs suggested (MSBE, MSBR, DMRS), none built

After Alvin Weinberg was removed from ORNL directorate, very little work done, almost no funding



The Molten Salt Reactor Adventure, H. G. MacPherson, Nuclear Science and Engineering **90**, p. 374-380 (1985)
http://home.earthlink.net/~bhoglund/mSR_Adventure.html

Molten Salt Reactor Experiment (1965-1969)

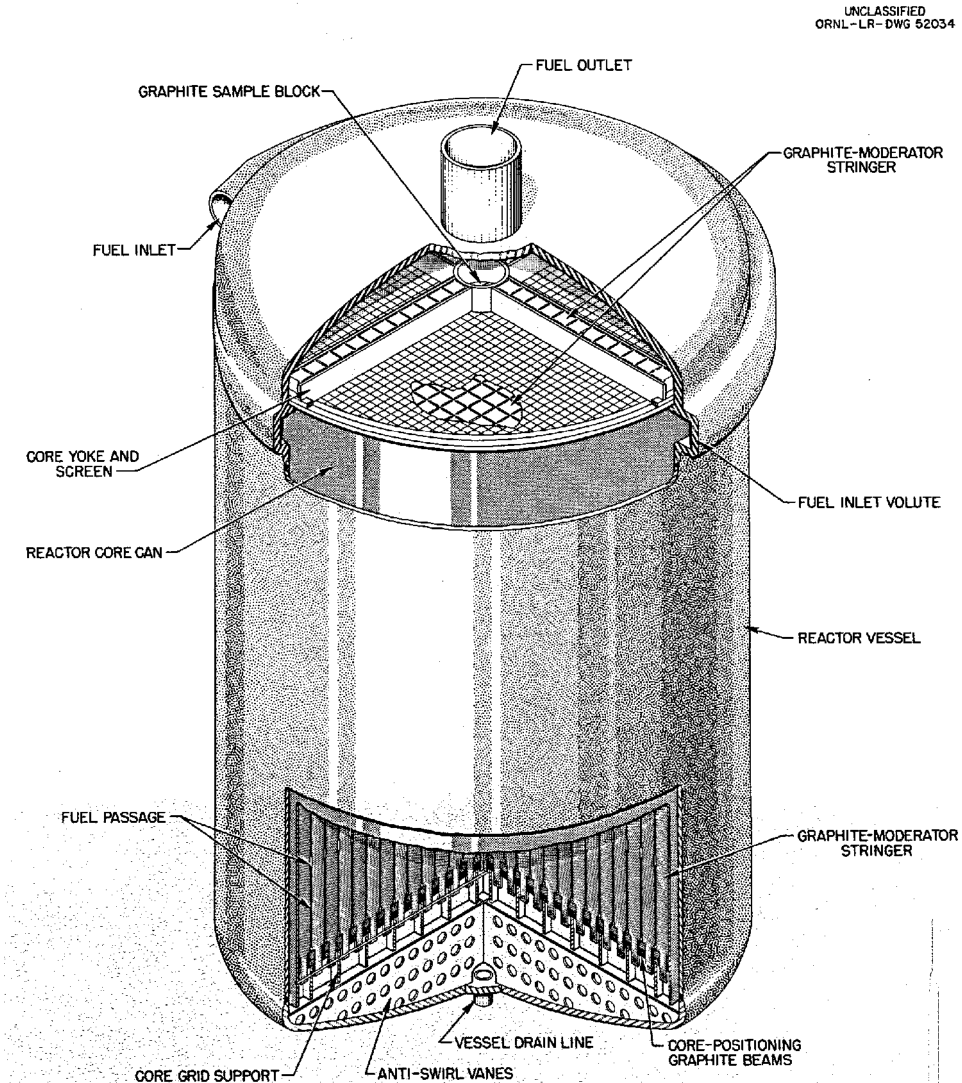
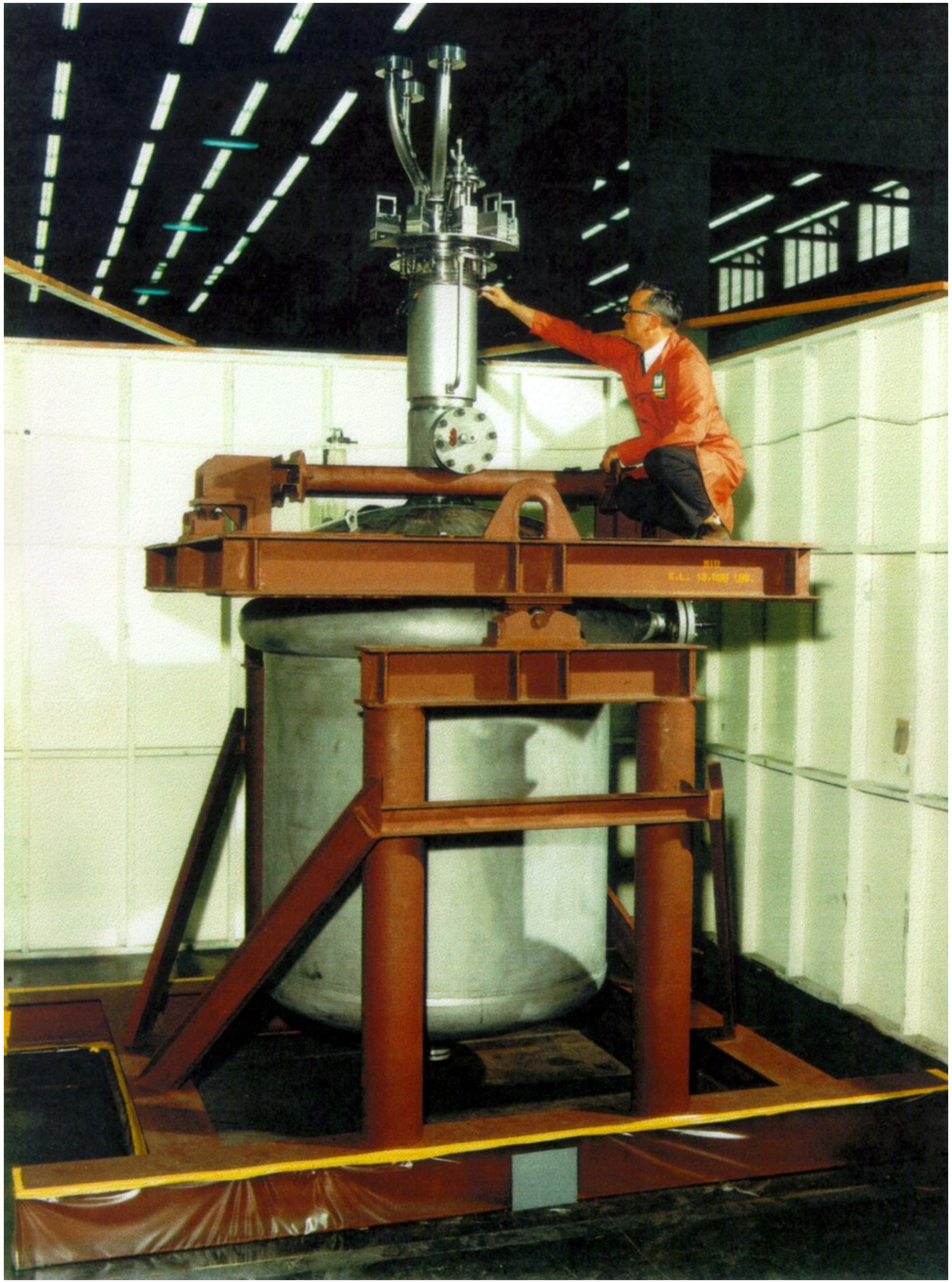
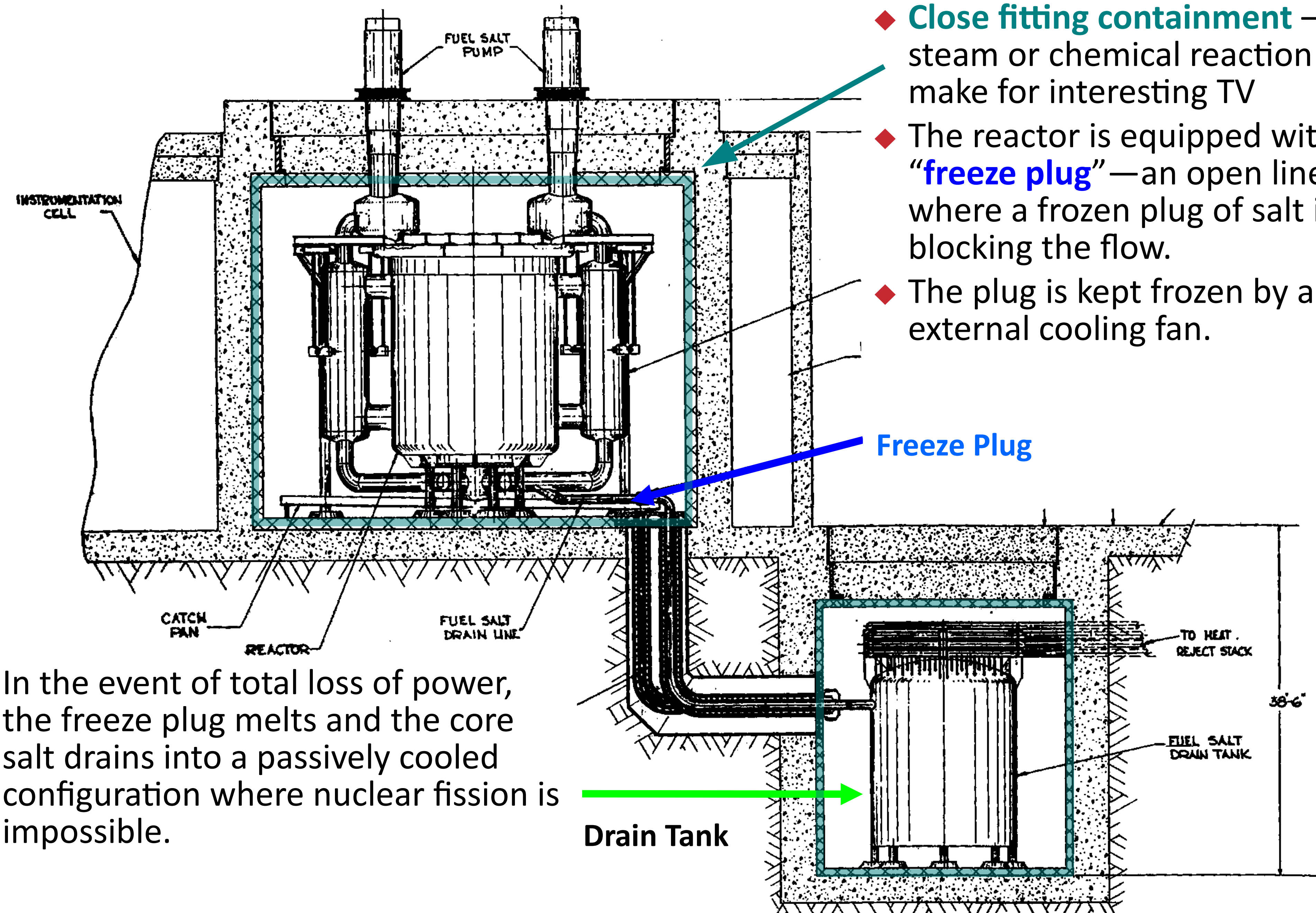


Fig. 1.2. MSRE Reactor.



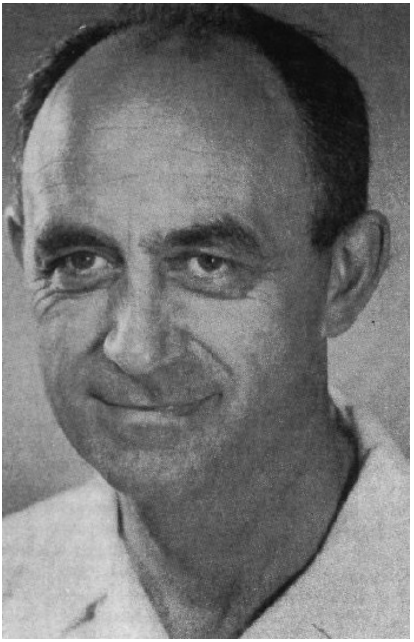
MSR can be passively safe in case of accident

- **Close fitting containment** – no steam or chemical reaction to make for interesting TV
- The reactor is equipped with a "**freeze plug**"—an open line where a frozen plug of salt is blocking the flow.
- The plug is kept frozen by an external cooling fan.

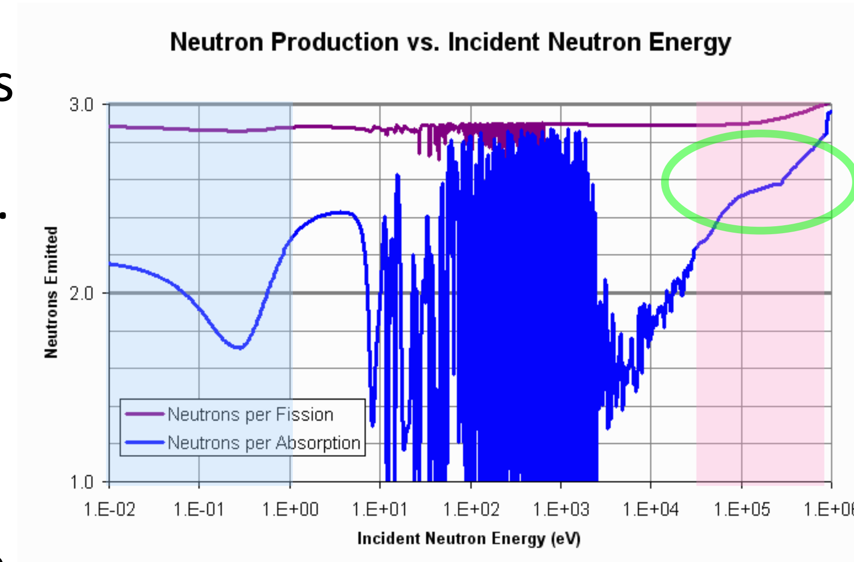


- In the event of total loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear fission is impossible.

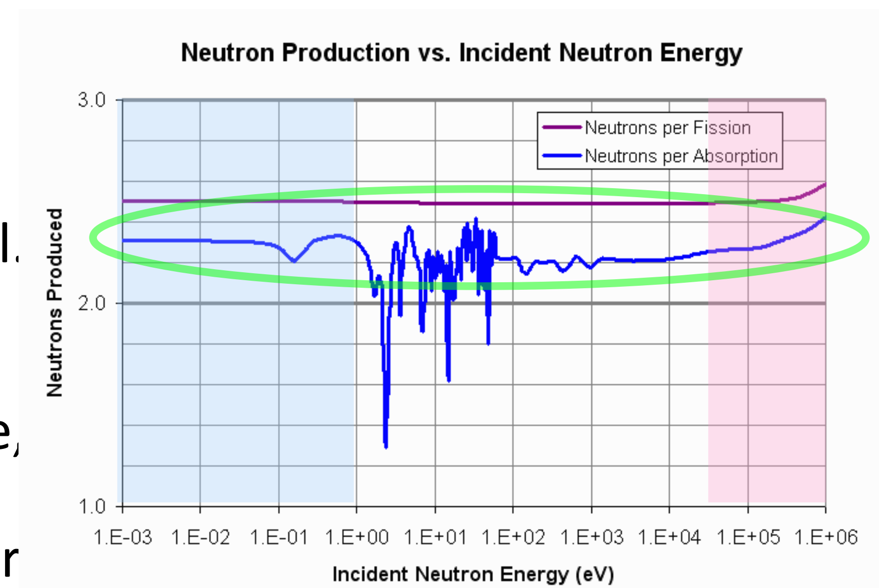
Why not? 1944: A tale of two isotopes…



- Enrico Fermi argued for a program of fast-breeder reactors using fertile uranium-238 to breed fissile fuel plutonium-239.
- Breeding ratio of Pu-239 at fast neutron energies is large.
- Argonne National Lab followed Fermi's path and built Liquid Metal cooled Fast Breeder Reactors (LMFBR): EBR-I & II, IFR.



- Eugene Wigner argued for a thermal-breeder program using thorium as the fertile material and U-233 as the fissile material.
- Although large breeding gains were not possible, thermal spectrum breeding was possible, with advantages
- Wigner's protégé, Alvin Weinber followed Wigner's path at the Oak Ridge National Lab.



Details: **Fluid Fuel Reactors**, James A. Lane,
H.G. MacPherson, & Frank Maslan (1958).
http://www.energyfromthorium.com/pdf/

Dr. Alvin Weinberg: Why wasn't this done?

ORNL Director
(1955-1973)

- **Politically established plutonium industry**
  "Why didn't the molten-salt system, so elegant and so well thought-out, prevail? I've already given the political reason: that the plutonium fast breeder arrived first and was therefore able to consolidate its political position within the AEC."
- **Appearance of daunting technology**
  "But there was another, more technical reason. The molten salt technology is entirely different from the technology of any other reactor. To the inexperienced, [MSR] technology is daunting…"
- **Breaking existing mindset**
  "Perhaps the moral to be drawn is that a technology that differs too much from an existing technology has not one hurdle to overcome—to demonstrate its feasibility—but another even greater one—to convince influential individuals and organizations who are intellectually and emotionally attached to a different technology that they should adopt the new path"
- **Deferred to the future**
  "It was a successful technology that was dropped because it was too different from th`e main lines of reactor development… I hope that in a second nuclear era, the [fluoride-reactor] technology will be resurrected."

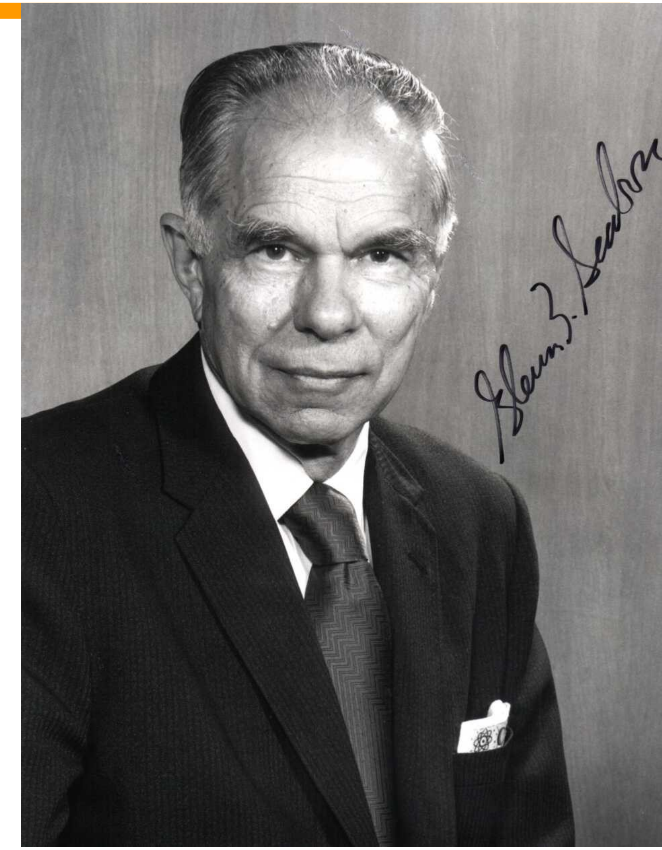
H.G. MacPherson: Why wasn't this done?

ORNL Deputy Director

- **Lack of technical understanding**
  "The political and technical support for the program in the United States was too thin geographically. Within the United States, only in Oak Ridge, Tennessee, was the technology really understood and appreciated."

- **Existing bureaucracy**
  "The thorium-fueled fluoride reactor program was in competition with the plutonium fast breeder program, which got an early start and had copious government development funds being spent in many parts of the United States. When the fluoride reactor development program had progressed far enough to justify a greatly expanded program leading to commercial development, the Atomic Energy Commission could not justify the diversion of substantial funds from the plutonium breeder to a competing program."

Glenn Seaborg: “Status in 1969”



LMFBR success dependent on simultaneous fulfillment of assumptions:

1) Electric demand doubles every decade

2) Nuclear will capture more electricity generation market share

3) Uranium will remain scarce

4) LMFBR R&D will be easy

5) Public and private funding will be available

“The non-fulfillment of any one, or at most two, of these assumptions might be sufficient to bring the whole edifice tumbling to the ground. In the actual event, **none of the assumptions proved correct.**”

from: **The Atomic Energy Commission Under Nixon - Adjusting to Troubled Times**, Glenn T. Seaborg & Benjamin S. Loeb

→ However, the decision to pursue LMFBR was never reconsidered.

Current Predicament

- ORNL's program in the 1960s was predicated on many historical circumstances, which are **not valid any more**.
- Current political priorities: inherent "walkaway" safety, proliferation resistance, TRU actinide minimization and spent nuclear fuel inventory management, among others.
- Economic necessity: **minimization of upfront costs**, maximization of resource utilization, and exploring new markets.
- Any futuristic R&D program needs to get actually funded.
- Any new reactor R&D and deployment (R&D&D) needs:
  - to get regulated using the standard rules tailored to LWR → significant but not insurmountable challenge,
  - necessitates new generation of experts in related areas.

Timeline of selected recent developments

- 2000: Gen4 International Forum recognized MSRs as one of six promising Gen4 concepts.
- 2004: ORNL published a salt-cooled solid fuel reactor concept as an improvement to gas-cooled high-temperature reactor, Advanced High-Temperature Reactor (AHTR).
  Now a member of the Flouride-salt-cooled High-temperature Reactor (FHR) family.
- 2006: ORNL's MSR research papers made freely available online http://energyfromthorium.com/pdf
- 2011: China announced MSR development as a national energy priority, both salt-cooled (solid fuel) and salt-fueled (dissolved fuel).
- 2011-2015: Several commercial startups in North America to develop MSRs.

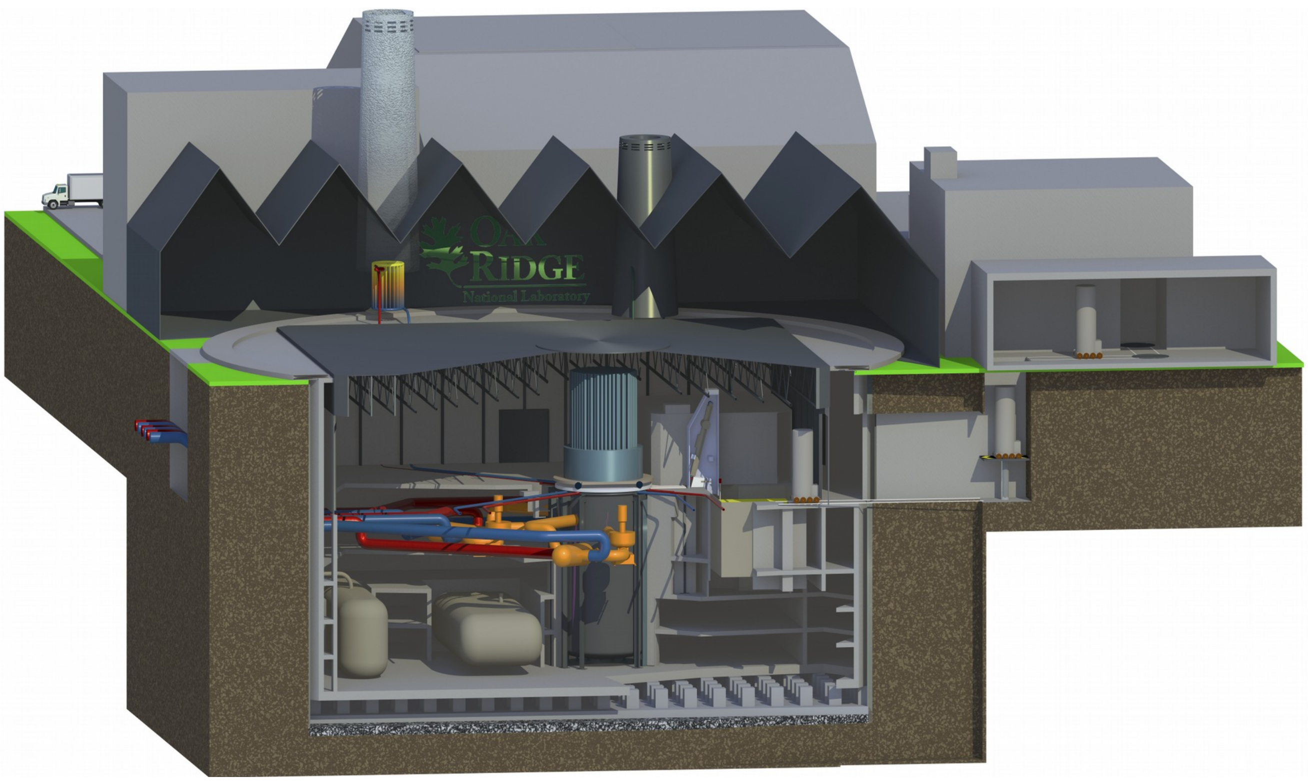
Several International Organizations are Performing Research

- US DoE – growing funding for salt-cooled reactors (FHR)
- China – large $500M crash program at SINAP to develop FHR and MSR, in cooperation with US DoE.
- France – Molten Salt Fast Reactor (MFSR), and AMSTER – U-233 breeder/TRU burner in thermal spectrum.
- Czech Republic – SPHINX – molten salt actinide burner
- Japan – FUJI MSR
- Russia – MOSART – Molten salt actinide burner

Western Commercial Startups

- USA – Flibe Energy – thorium cycle iso-breeder
- USA – Transatomic Power – advanced uranium and TRU burner
- USA – ThorCon Power – simple uranium burner
- Canada – Terrestrial Energy – simple uranium and TRU burner

US DOE Advanced Reactor Concepts - FHR



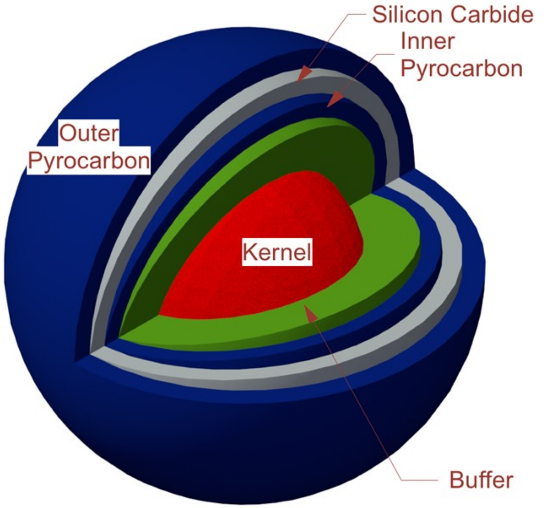
AHTR Properties	
Thermal Power	3400 MW
Electrical Power	1500 MW
Top Plenum Temperature	700 °C
Coolant Return Temperature	650 °C
Number of Loops	3
Primary Coolant	$2^7LiF\text{-}BeF_2$
Fuel	UCO TRISO
Uranium Enrichment	9%
Fuel Form	Plate Assemblies
Refueling	2 batch 6 month

ORNL/TM-2012/320 - AHTR Mechanical, Structural, And Neutronic Preconceptual Design

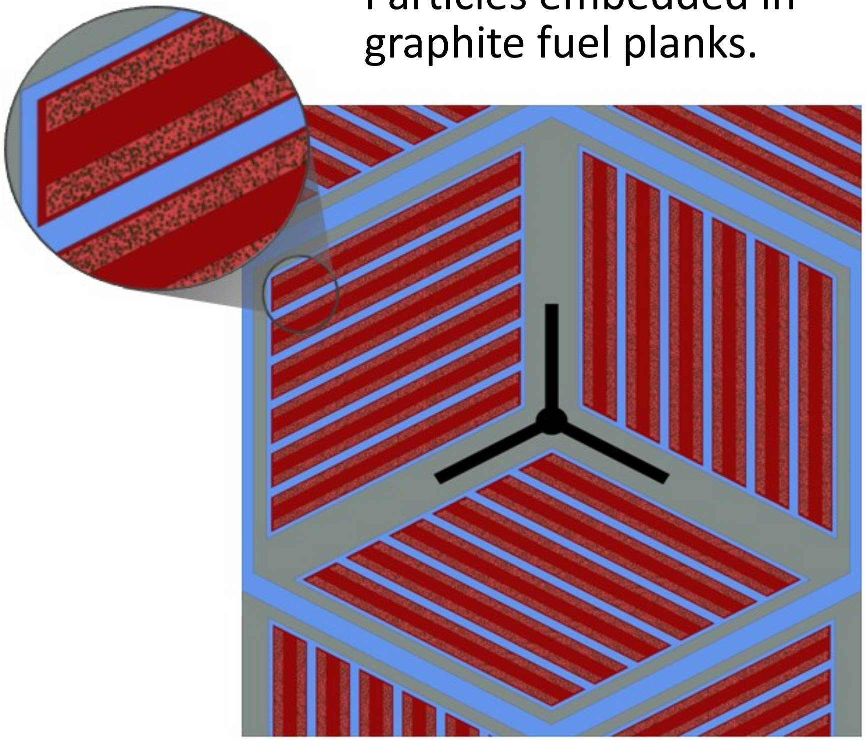
ORNL/TM-2013/401 - Fluoride Salt-Cooled High-Temperature Reactor Technology Development and Demonstration Roadmap (**FHR Roadmap**)

AHTR plank fuel and core configuration

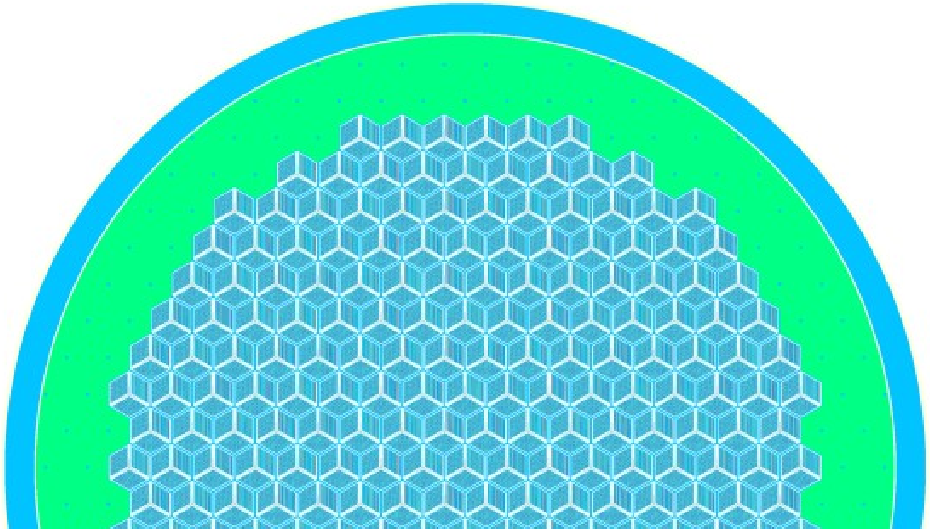
Coated particle fuel, diameter 0.5 mm



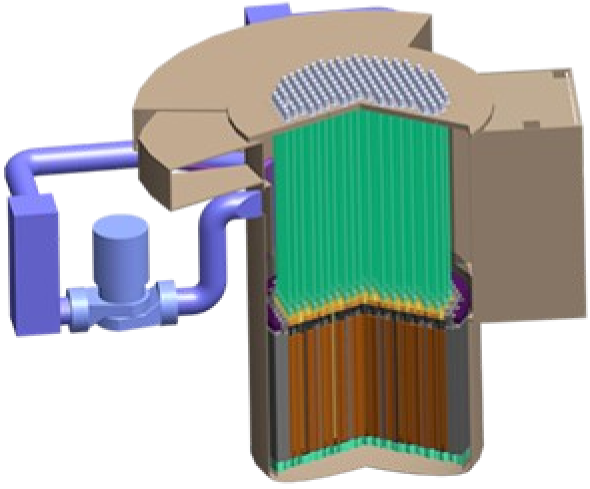
Particles embedded in graphite fuel planks.



AHTR core in radial profile

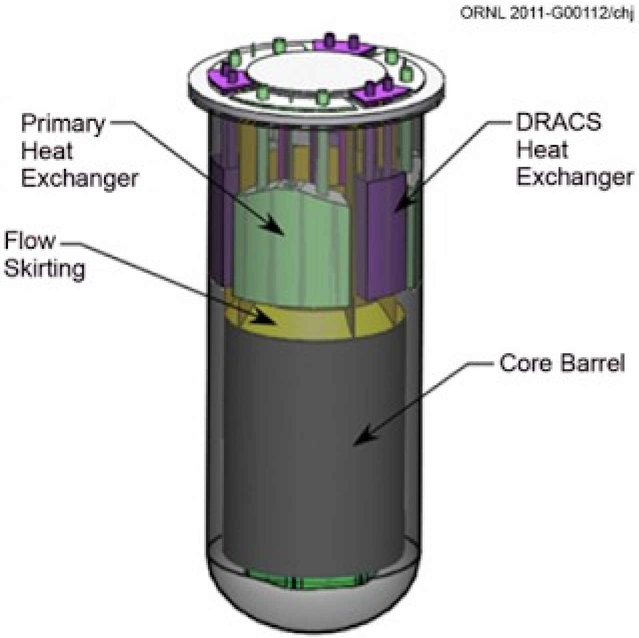


AHTR core & primary circuit



SmAHTR – small modular AHTR

- 125 MWt power
- 700 ºC core outlet temperature
- integral heat exchangers
- cartridge core lasting 4 years



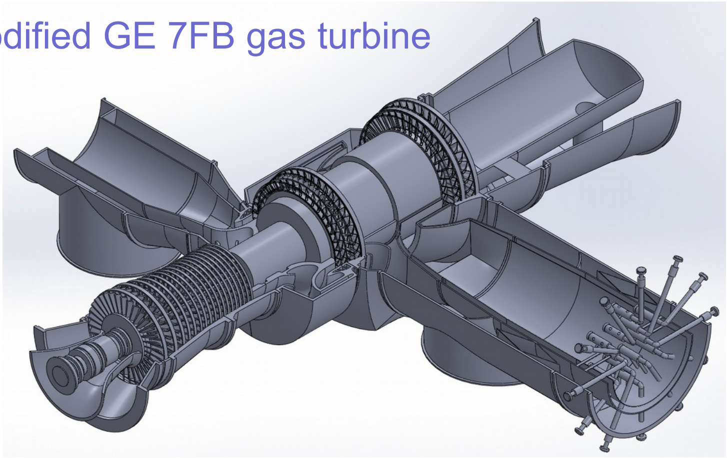
ORNL/TM-2010/199 - Pre-Conceptual Design of a Fluoride-Salt-Cooled Small Modular Advanced High Temperature Reactor (SmAHTR)

http://sustainableenergytoday.blogspot.com/2013/04/post-80-smahtr-approach-to-nuclear-power.html

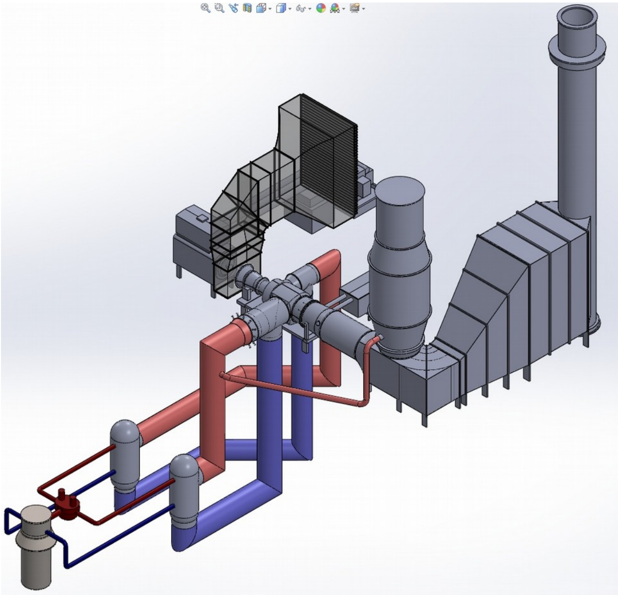
University Program Investigating Potential to Open New Markets via Use of Open Air Brayton Cycle

- **Potential capabilities**
  - Base-load electricity
  - Peak electricity
  - Grid regulation
  - Process steam production
- **May enable nuclear renewable electricity system**
- **Cross over with hybrid energy systems**

Modified GE 7FB gas turbine



Open-air Brayton Combined Cycle could enable use of natural gas to support peak power and grid regulation



slide from Dr. Holcomb's presentation at UTK

FHR Technology Development Roadmap was Generated in 2013

- **Provides a broad overview of the current technology status and required developments to design, evaluate, license, construct, operate, and maintain FHRs**
  - http://www.osti.gov/scitech/biblio/1107839 (ORNL/TM-2013/401)
  - Seeks to inform future policy choices
  - Shows potential for FHRs to be both technically and economically viable
- **Depth and fidelity is limited by technology immaturity**
  - Focused planning will be required in each discipline
  - Roadmap will require updating as development progresses
- **Development strategy is based on minimizing development cost and risk**
  - Employs a proven technology bias
  - Avoids deviations from licensing precedent
- **Roadmap presumes a cooperative multi-national development program featuring two Chinese test reactors**

slide from Dr. Holcomb's presentation at UTK

US-Chinese cooperation on salt reactor technology

SINAP 钍基核能系统

Organizational Overview

The Chinese Academy of Sciences (CAS) and U.S. Department of Energy (DOE) Nuclear Energy Cooperation Memorandum of Understanding (MOU)

MOU Executive Committee Co-Chairs
China – Mianheng Jiang (CAS) 江绵恒
U.S. – Pete Lyons (DOE)

Technical Coordination Co-Chairs
China – Zhiyuan Zhu (CAS) 朱志远
U.S. – Stephen Kung (DOE)

Nuclear Hybrid Energy Systems *
- Zhiyuan Zhu (CAS) 朱志远
  Yuhan Sun (SARI,CAS) 孙予罕
- Steven Aumeier (INL)

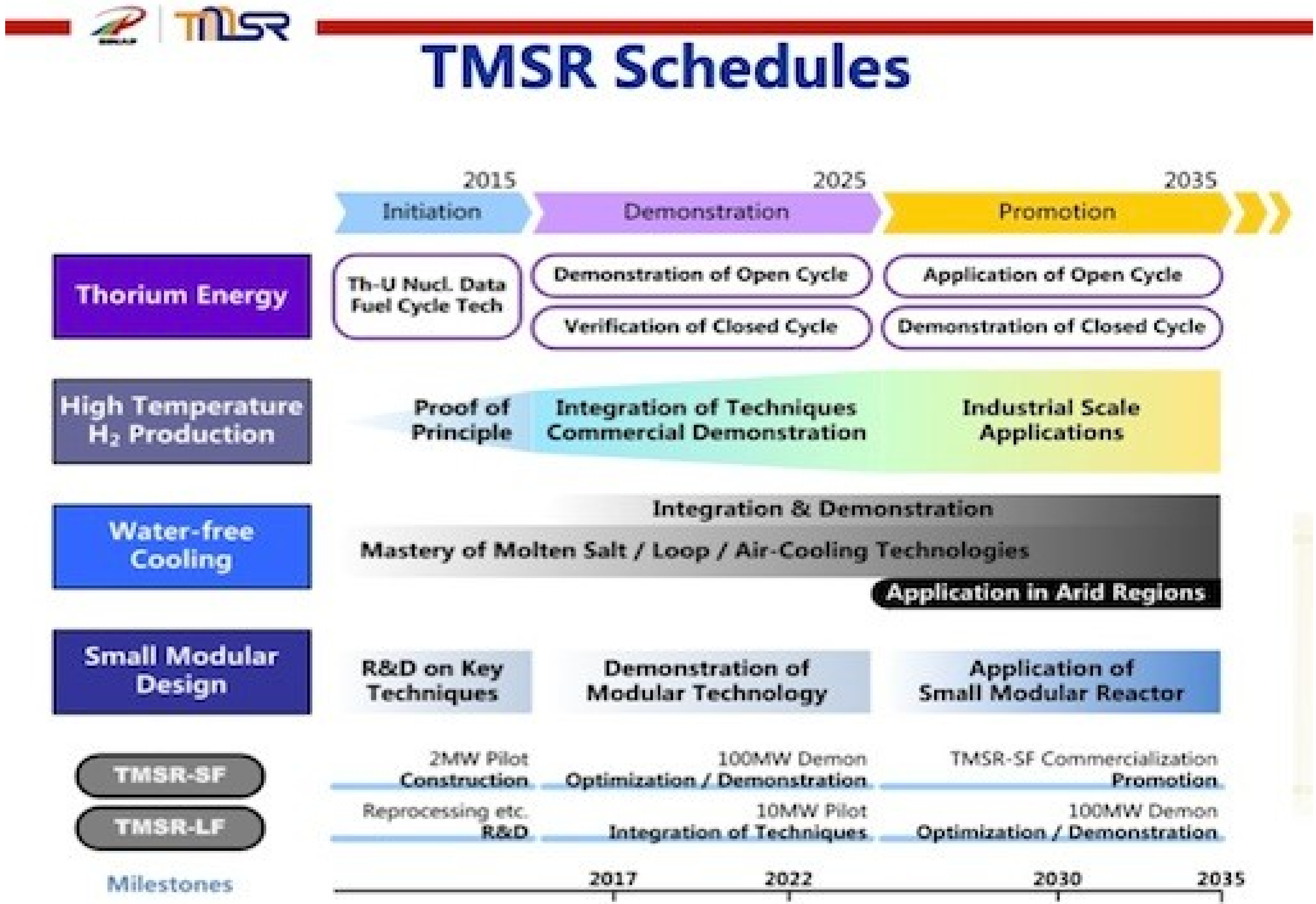
Molten Salt Coolant Systems
- Hongjie Xu (SINAP, CAS) 徐洪杰
  Weiguang Huang (SARI,CAS) 黄伟光
- Cecil Parks (ORNL)
  Charles Forsberg (MIT)

Nuclear Fuel Resources
- Zhimin Dai (SINAP, CAS) 戴志敏
  Biao Jiang (SARI,CAS) 姜标
- Phil Britt (ORNL)
  John Arnold (UC-Berkeley)

* Work scope governed by DOE-CAS Science Protocol Agreement

SINAP :Shanghai Institute of Applied Physics
SARI: Shanghai Advanced Research Institute
ORNL: Oak Ridge National Laboratory
INL: Idaho National Laboratory
MIT: Massachusetts Institute of Technology
UC-Berkeley: University of California at Berkeley

Chinese (SINAP CAS) project schedule

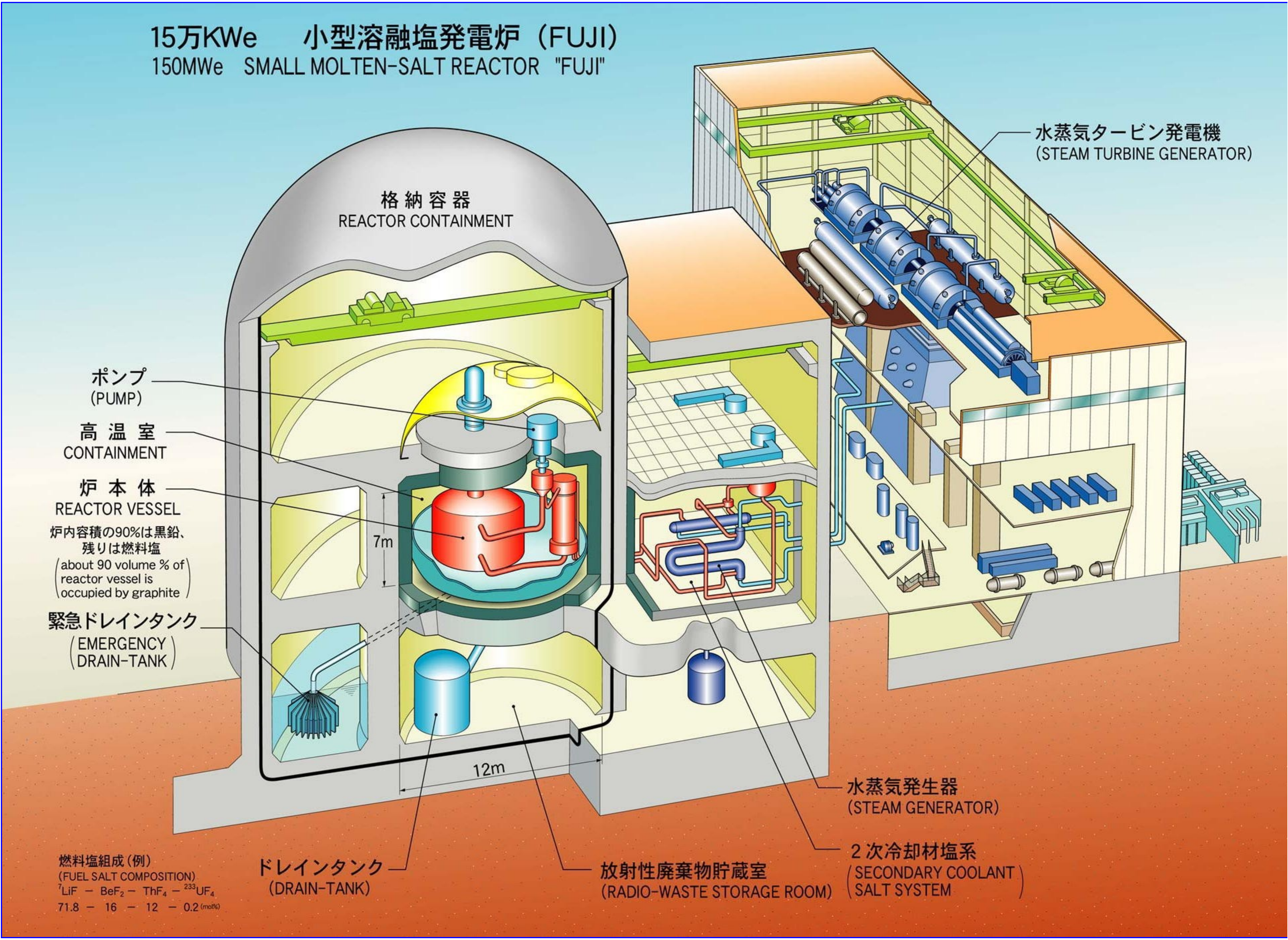


http://www.the-weinberg-foundation.org/2013/11/01/china-eyes-thorium-msrs-for-industrial-heat-hydrogen-revises-timeline

Chinese project run by Jiang Mianheng

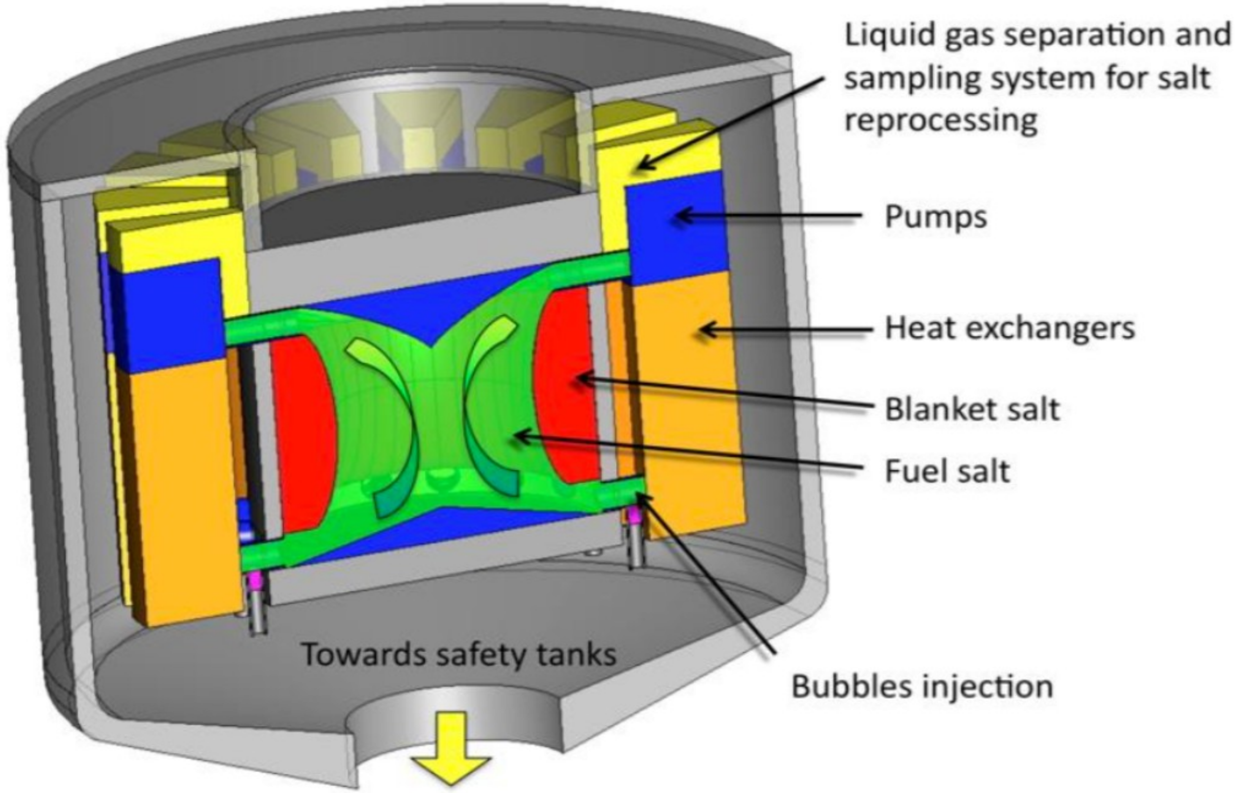
- President of Shanghai Tech University
- President of Shanghai branch of Chinese Academy of Sciences
- PhD in Electrical Engineering from Drexel University, PA
- Son of Jiang Zemin, president of PRC 1993-2003

http://www.smartplanet.com/blog/bulletin/son-of-chinas-ex-president-thorium-will-help-shape-countrys-energy-future/

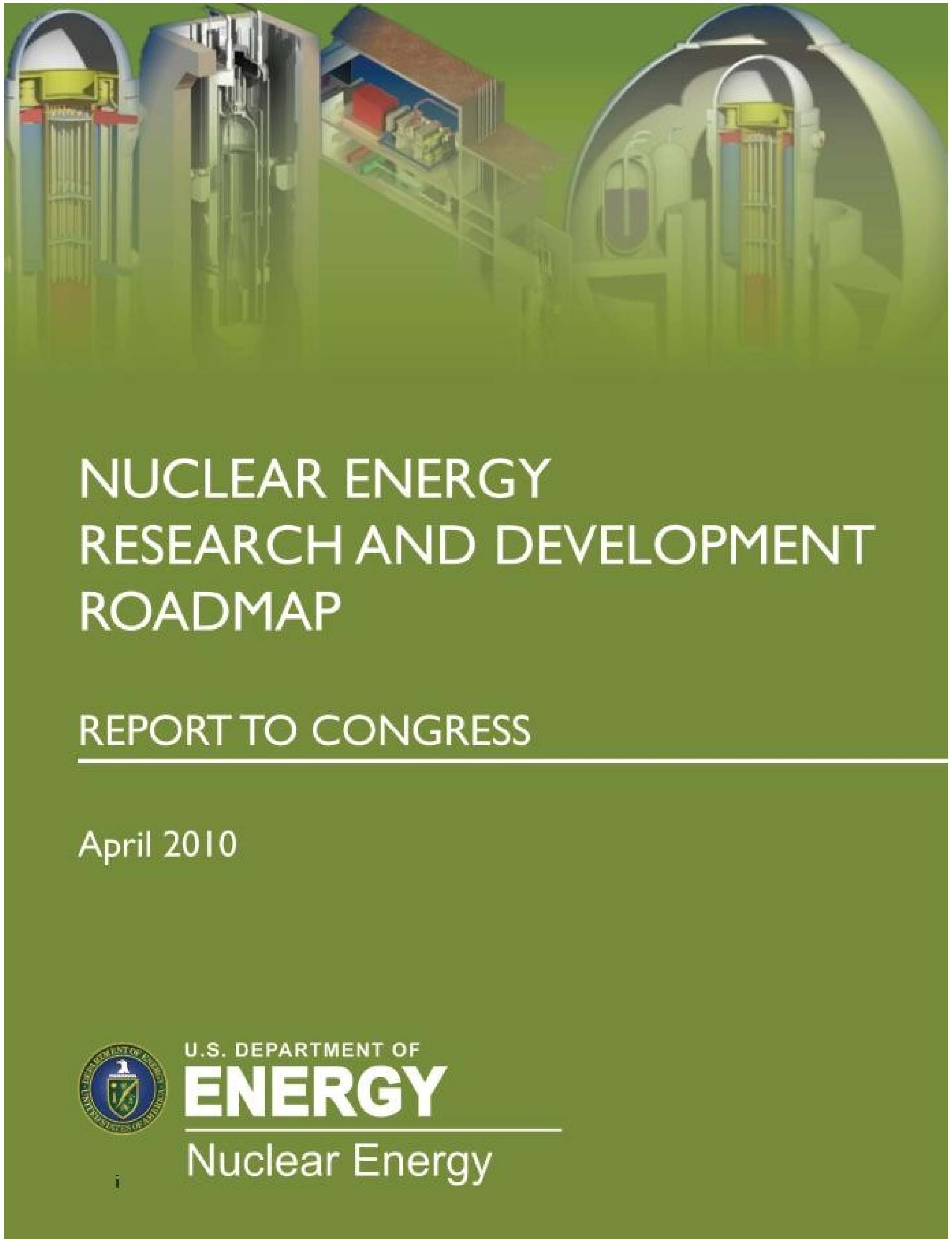

15万KWe　小型溶融塩発電炉（FUJI）
150MWe SMALL MOLTEN-SALT REACTOR "FUJI"
格納容器
REACTOR CONTAINMENT
水蒸気タービン発電機
(STEAM TURBINE GENERATOR)
ポンプ
(PUMP)
高 温 室
CONTAINMENT
炉 本 体
REACTOR VESSEL
炉内容積の90%は黒鉛、
残りは燃料塩
(about 90 volume % of reactor vessel is occupied by graphite)
7m
緊急ドレインタンク
(EMERGENCY DRAIN-TANK)
12m
水蒸気発生器
(STEAM GENERATOR)
2 次冷却材塩系
(SECONDARY COOLANT SALT SYSTEM)
燃料塩組成（例）
(FUEL SALT COMPOSITION)
^{7}LiF − BeF_2 − ThF_4 − $^{233}UF_4$
71.8 − 16 − 12 − 0.2 (mol%)
ドレインタンク
(DRAIN-TANK)
放射性廃棄物貯蔵室
(RADIO-WASTE STORAGE ROOM)

European MSFR – Gen4 Internation Forum effort

- No moderator → Fast spectrum MSR
- Primarily intended to burn recycled actinides from MOX, as an alternative to solid fuel LMFBRs (Phenix, Superphenix, Astrid)
- Academic research in many EU countries + Russia
- Deployment by ~ 2045



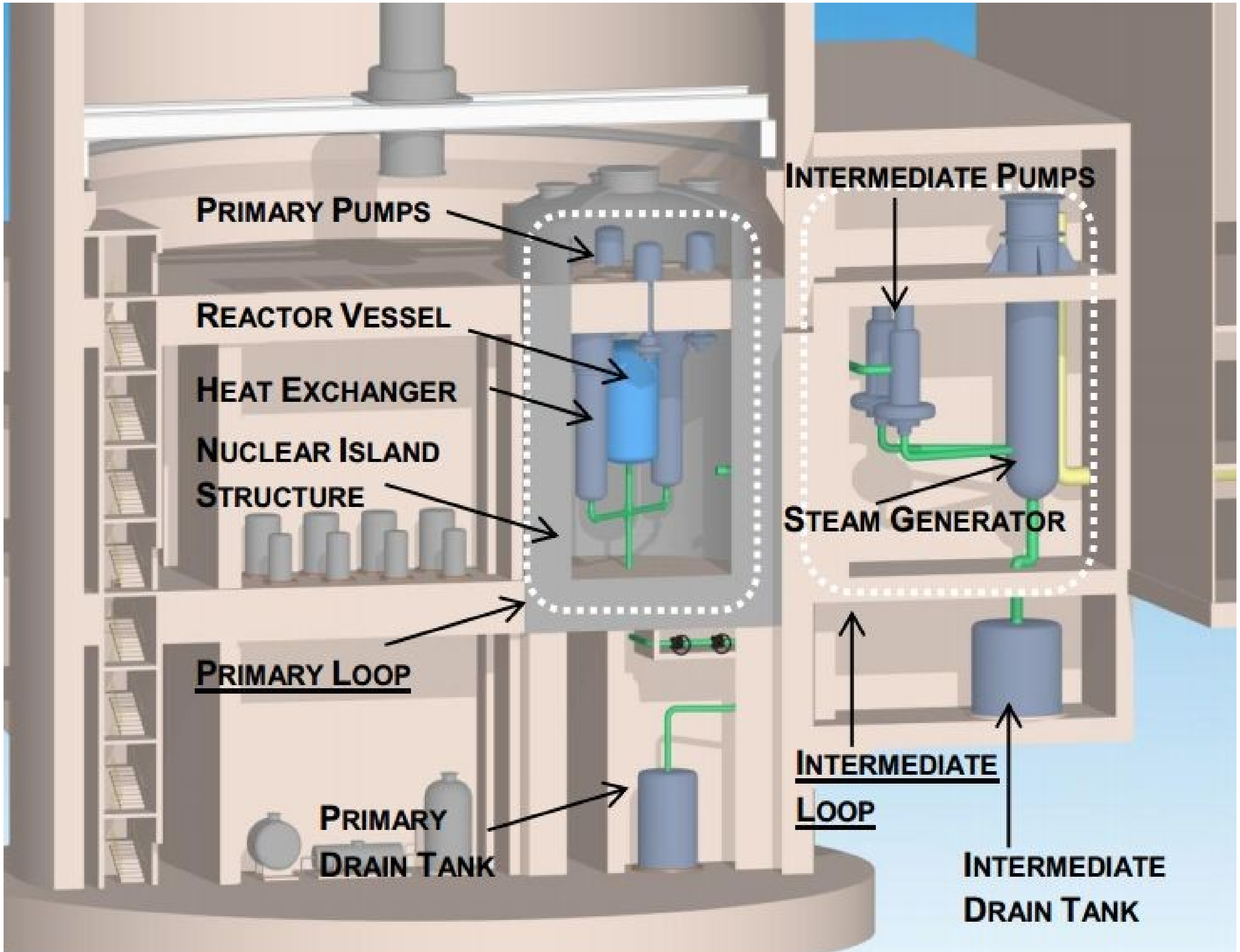
DOE sees Industry Leading Future Nuclear



- "In the United States, it is the responsibility of industry to design, construct, and operate commercial nuclear power plants." (pg 22)
- "It is ultimately industry's decision which commercial technologies will be deployed. The federal role falls more squarely in the realm of R&D." (pg 16)
- "The decision to deploy nuclear energy systems is made by industry and the private sector in market-based economies." (pg 45)

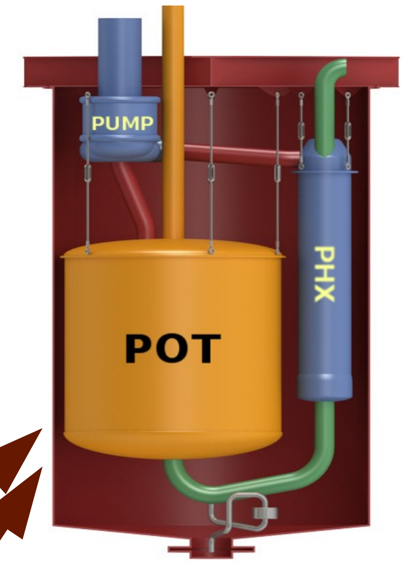
Transatomic Power

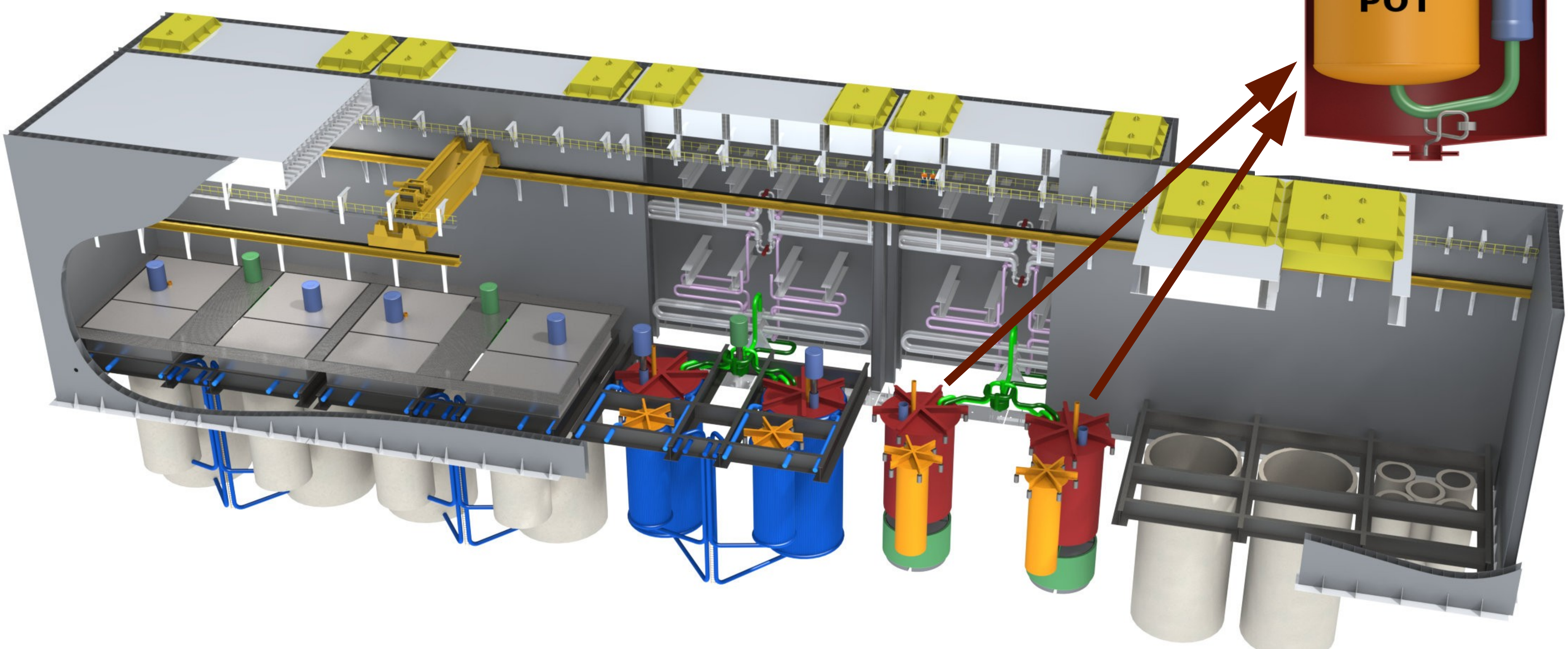
- Recent MIT startup. http://transatomicpower.com/
- Single fluid LEU and TRU burner using ^{7}LiF solvent salt.
- ZrH moderator rods in SiC-SiC composite cladding.



Thorcon Power

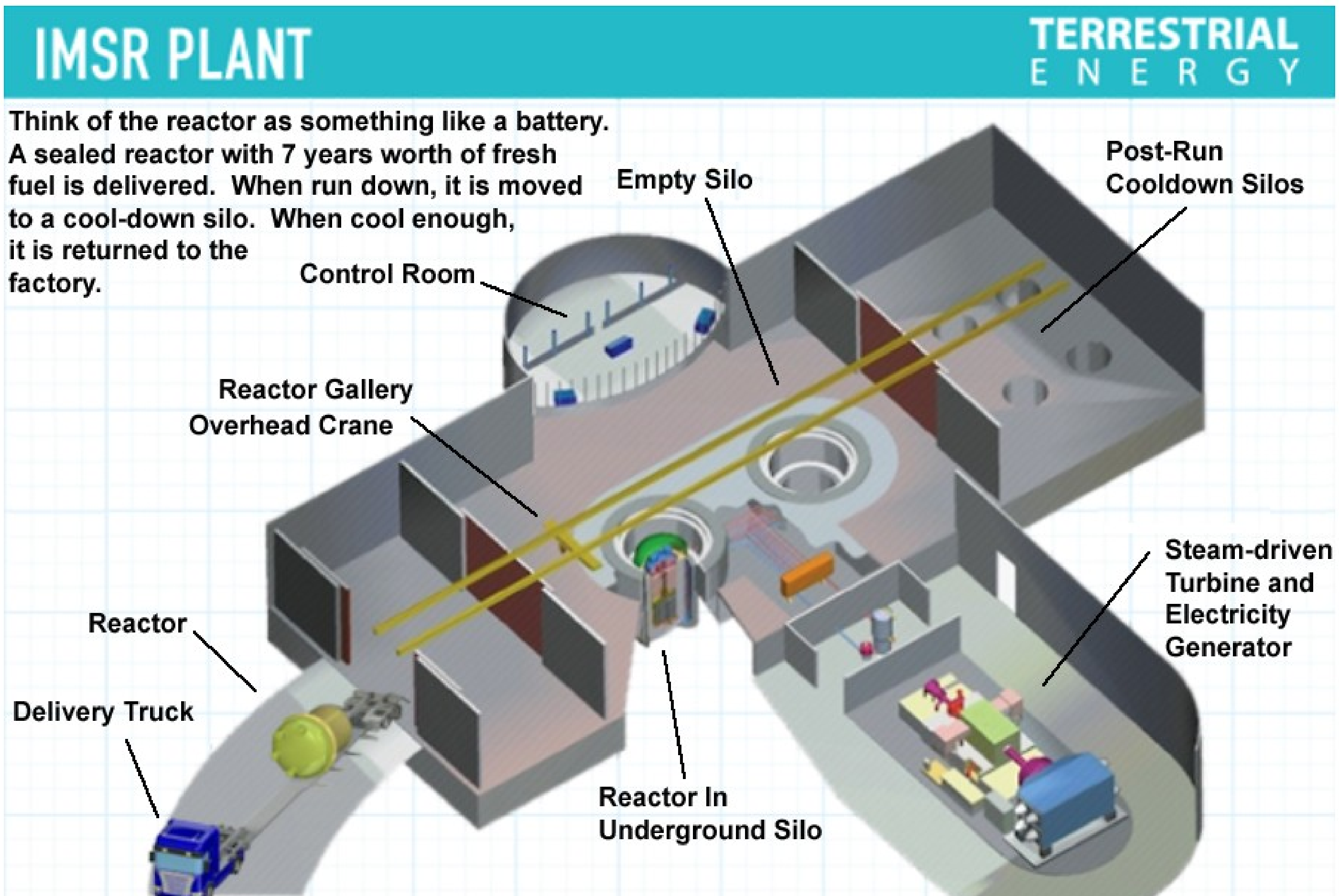
- Recent private “open-source” startup. http://thorconpower.com/
- Focused on simplicity, maintainability, no new technology → scaled up “clone” of MSRE in each silo.
- LEU burner, NaF-BeF$_2$-UF$_4$-ThF$_4$ salt.



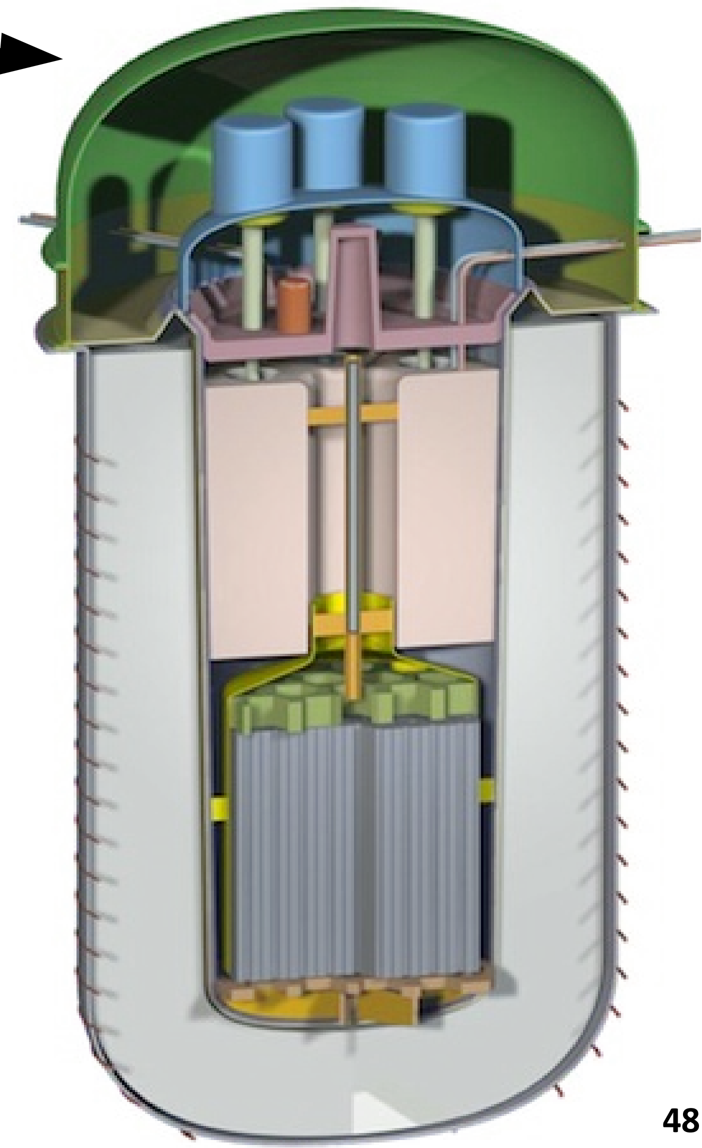


Terrestrial Energy Inc.

- Canadian private startup. http://terrestrialenergy.com/
- Existing technology, simplest posible design, steam power plant.
- Disposable reactor cartridge.
- LEU burner.

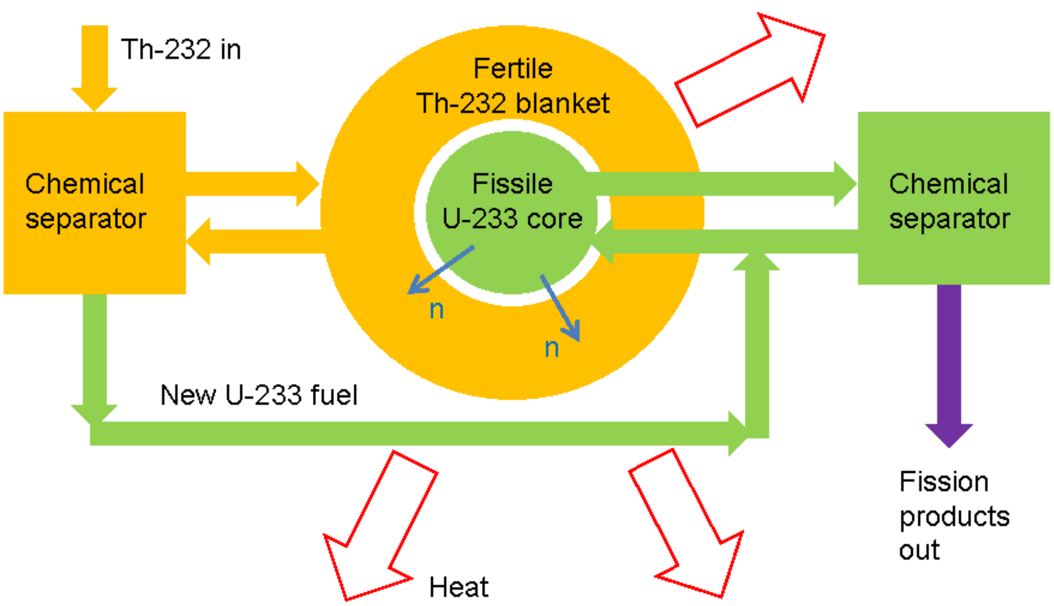


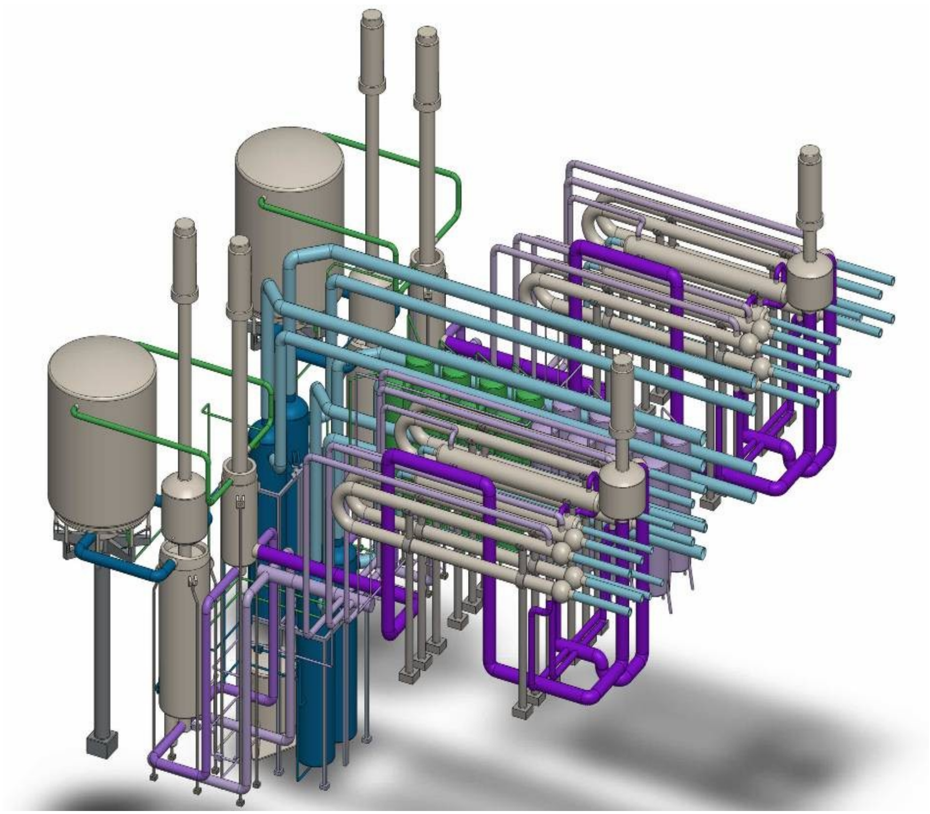
Integral Molten Salt Reactor Steam Power Plant



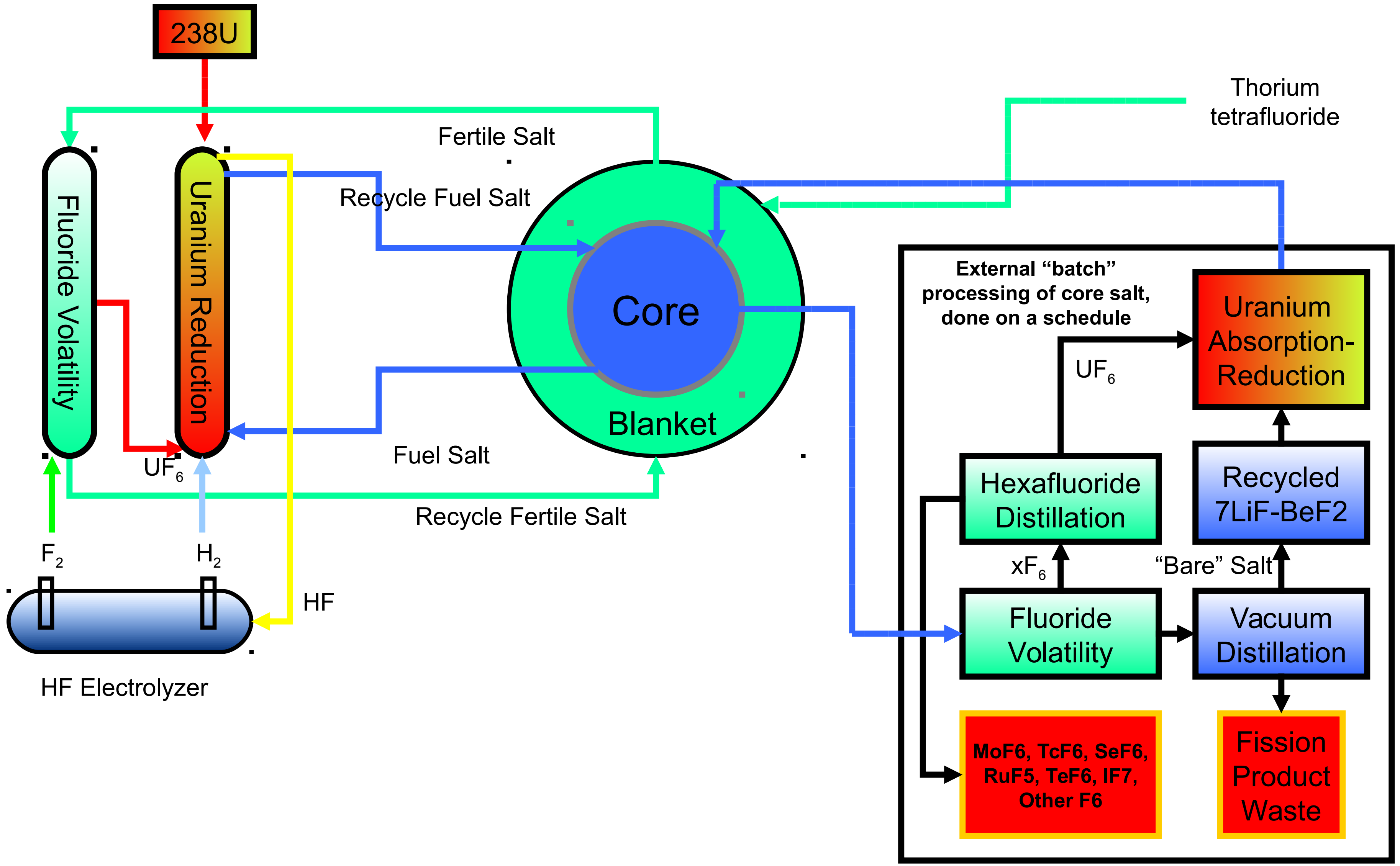
Flibe Energy's LFTR – two fluid Thorium breeder

- U.S. private startup. http://flibe-energy.com/
- Aiming for the final goal of the ORNL program:
  Two-fuid (^{232}Th blanket / ^{233}U driver) core, iso-breeding.
  → Thermal spectrum breeder, eliminating actinide production.
- Burning down LWR's waste actinides (Pu) in the startup core.

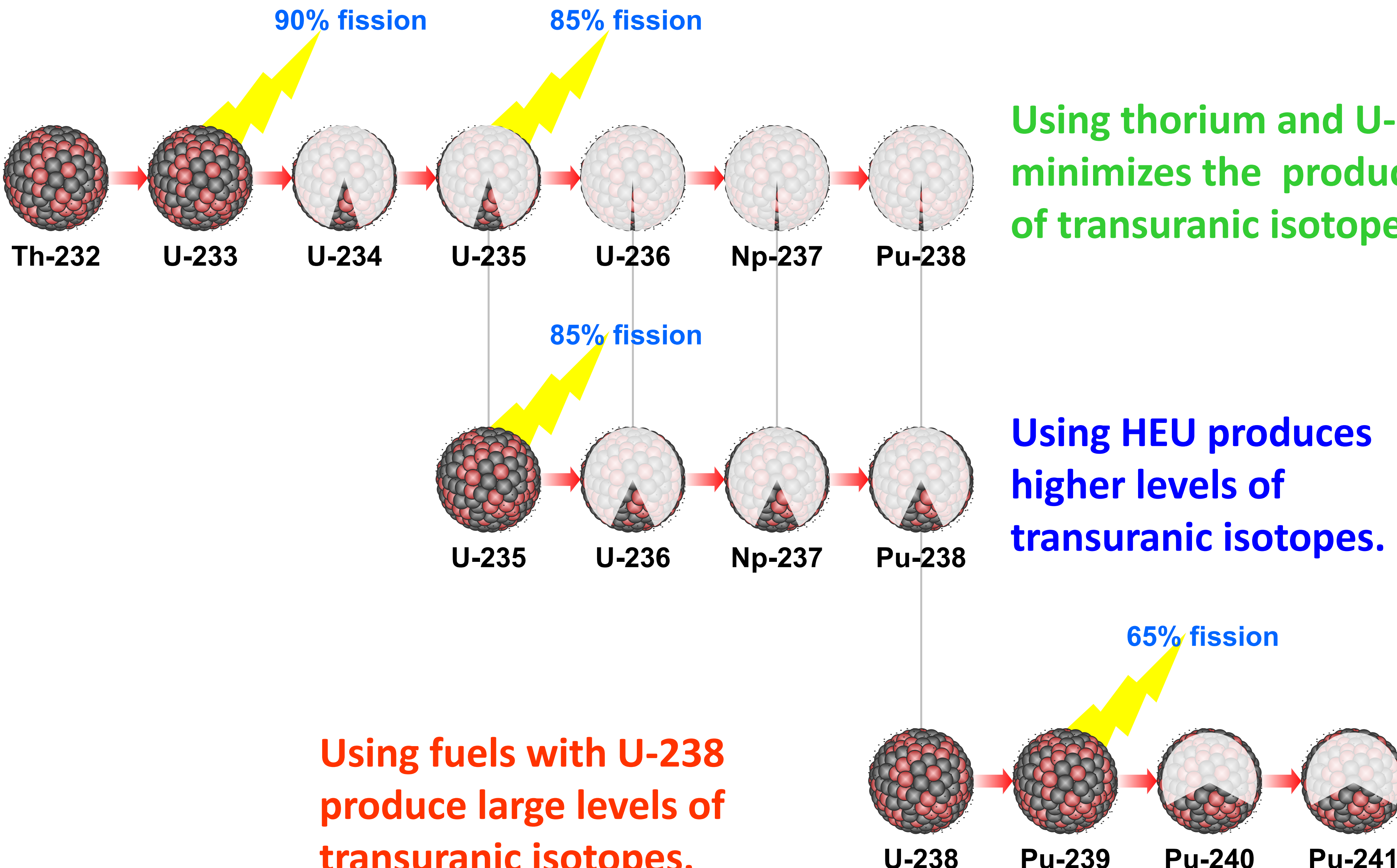




Two-fluid reprocessing for Th/U cycle is simple



Transuranic Waste Production

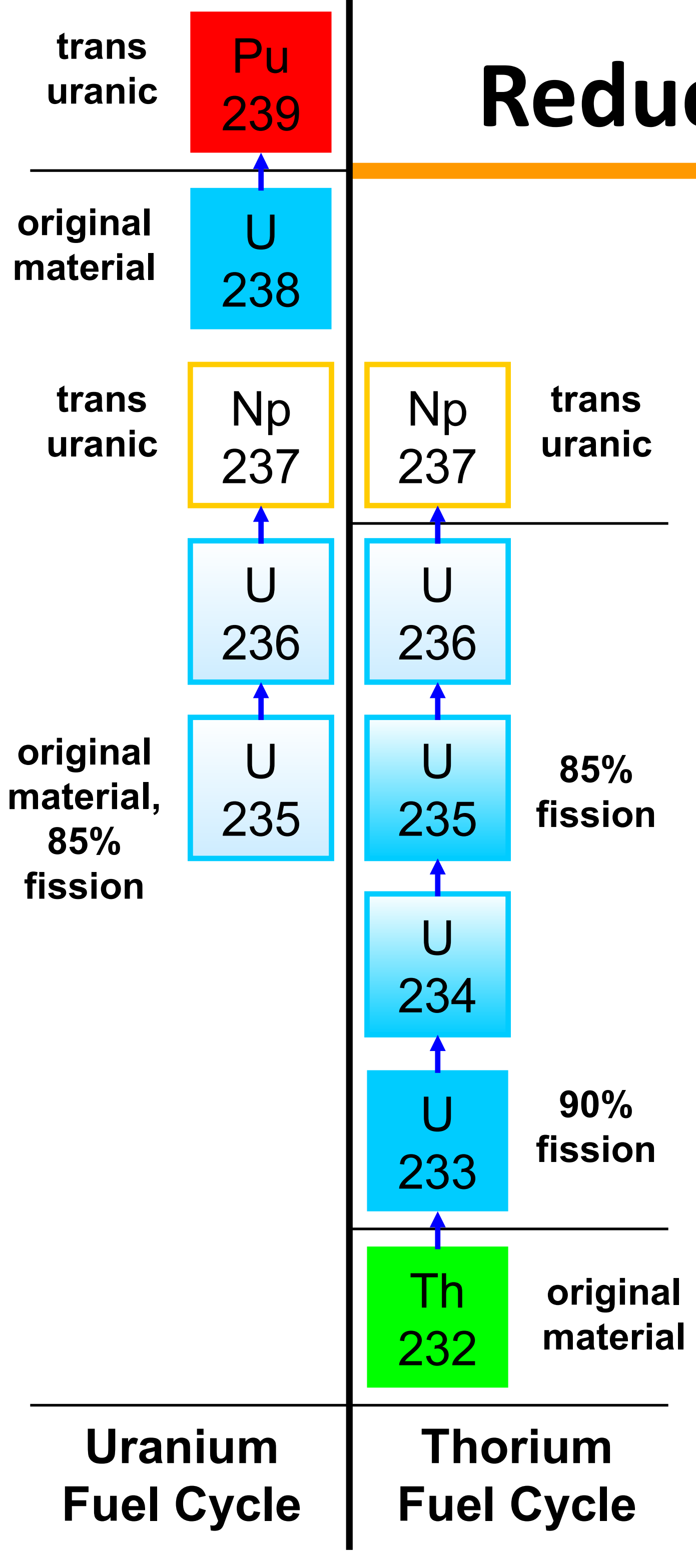


Using thorium and U-233 minimizes the production of transuranic isotopes.

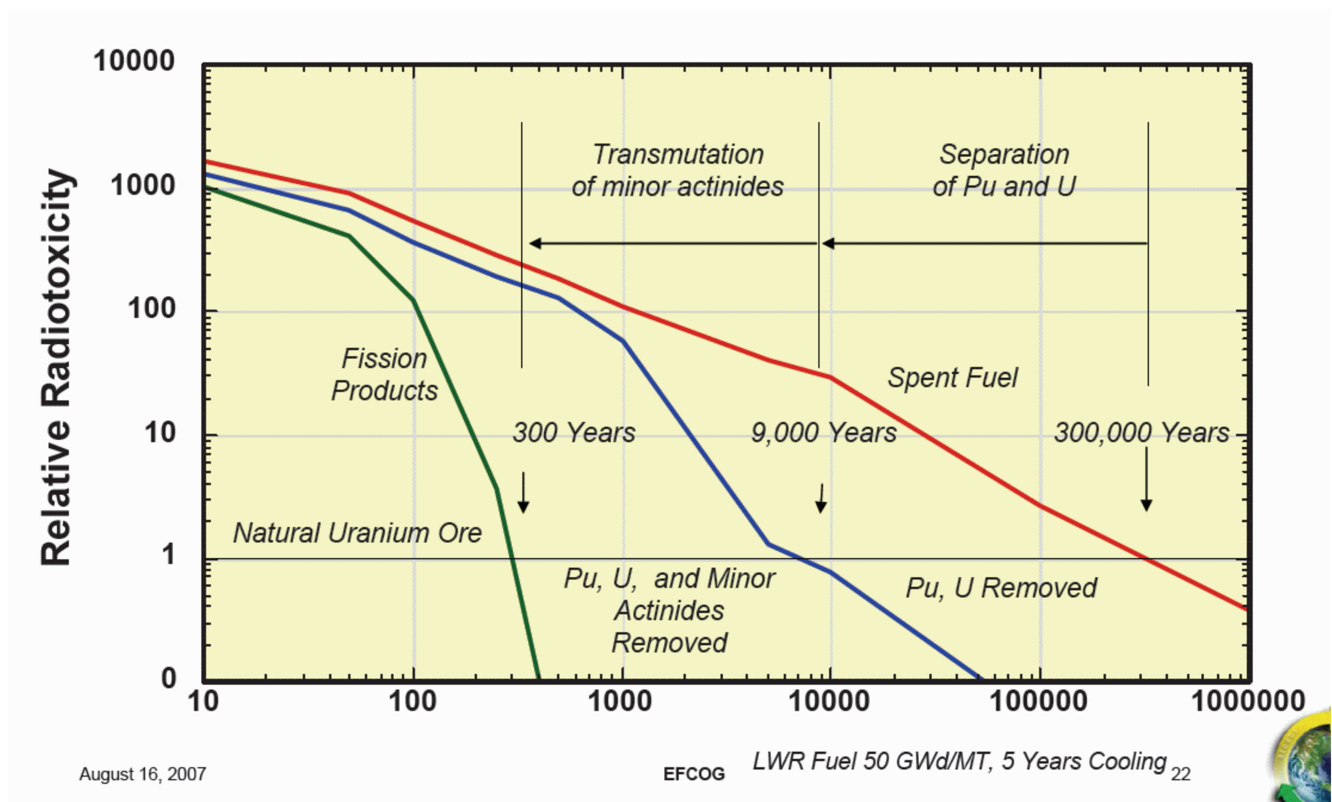
Using HEU produces higher levels of transuranic isotopes.

Using fuels with U-238 produce large levels of transuranic isotopes.

Reducing Long-Lived Waste



- Today's approach to nuclear energy consumes only a small amount of the energy content of uranium while producing "transuranic" nuclides that complicate long-term waste disposal.
- Using thorium/U-233 in a liquid-fueled reactor can more nearly approach the ideal of a fission-product-only waste stream that reaches the same radioactivity as uranium ore in ~300 years.



Possible solution to our Big Problem?

2007 World Energy Consumption

5.3 billion tonnes of coal (128 quads)

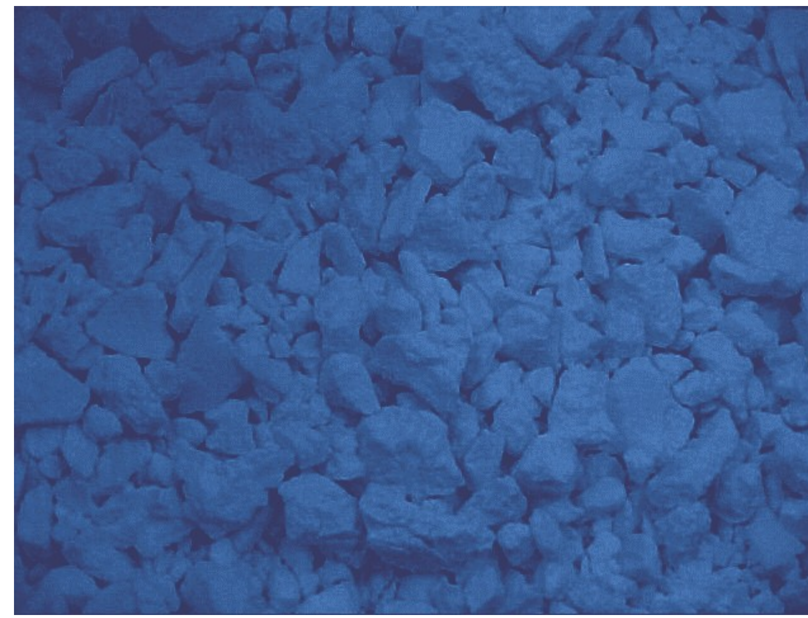
31.1 billion barrels of oil (180 quads)

2.92 trillion m^3 of natural gas (105 quads)

65,000 tonnes of uranium ore (24 quads)

The Future:

Energy from Thorium

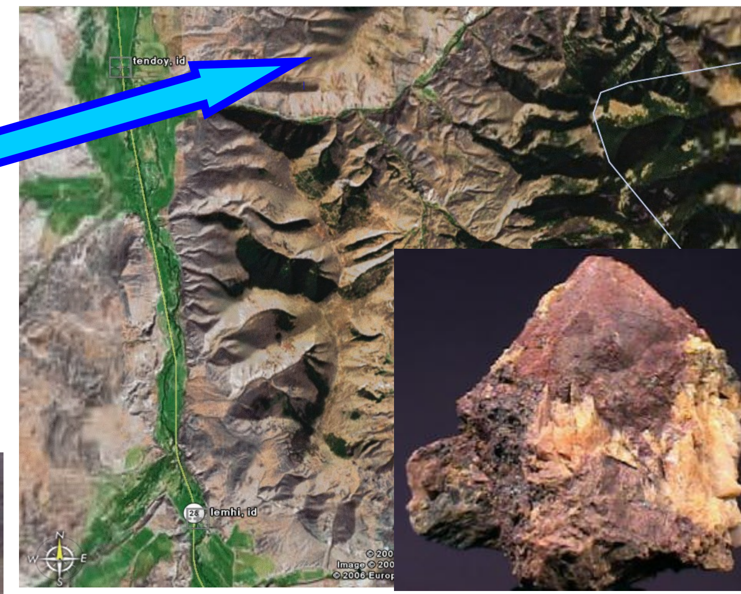


6600 tonnes of thorium
(500 quads)

Thorium is virtually limitless in availability

Fig. 3.3. Artist's rendition of ore-treatment mill. (Taken from U.S. Nuclear Regulatory Commission, Final Environmental Statement Bear Creek Project, NUREG-0129, Docket No. 40-8452, June 1977.)

- Thorium is abundant around the world
  - 12 parts-per-million in the Earth's crust
  - India, Australia, Canada, US have large resources.
  - Today thorium is a waste from rare earth mining
    - a liability thus **better than for free**
- There will be no need to horde or fight over this resource
  - A single mine site at the Lemhi Pass in Idaho could produce 4500 tonnes of thorium per year.
  - 2007 US energy consumption = 95 quads = 2580 tonnes of thorium



The United States has buried 3200 metric tonnes of thorium nitrate in the Nevada desert.

There are 160,000 t of economically extractable thorium in the US, even at today's "worthless" prices!

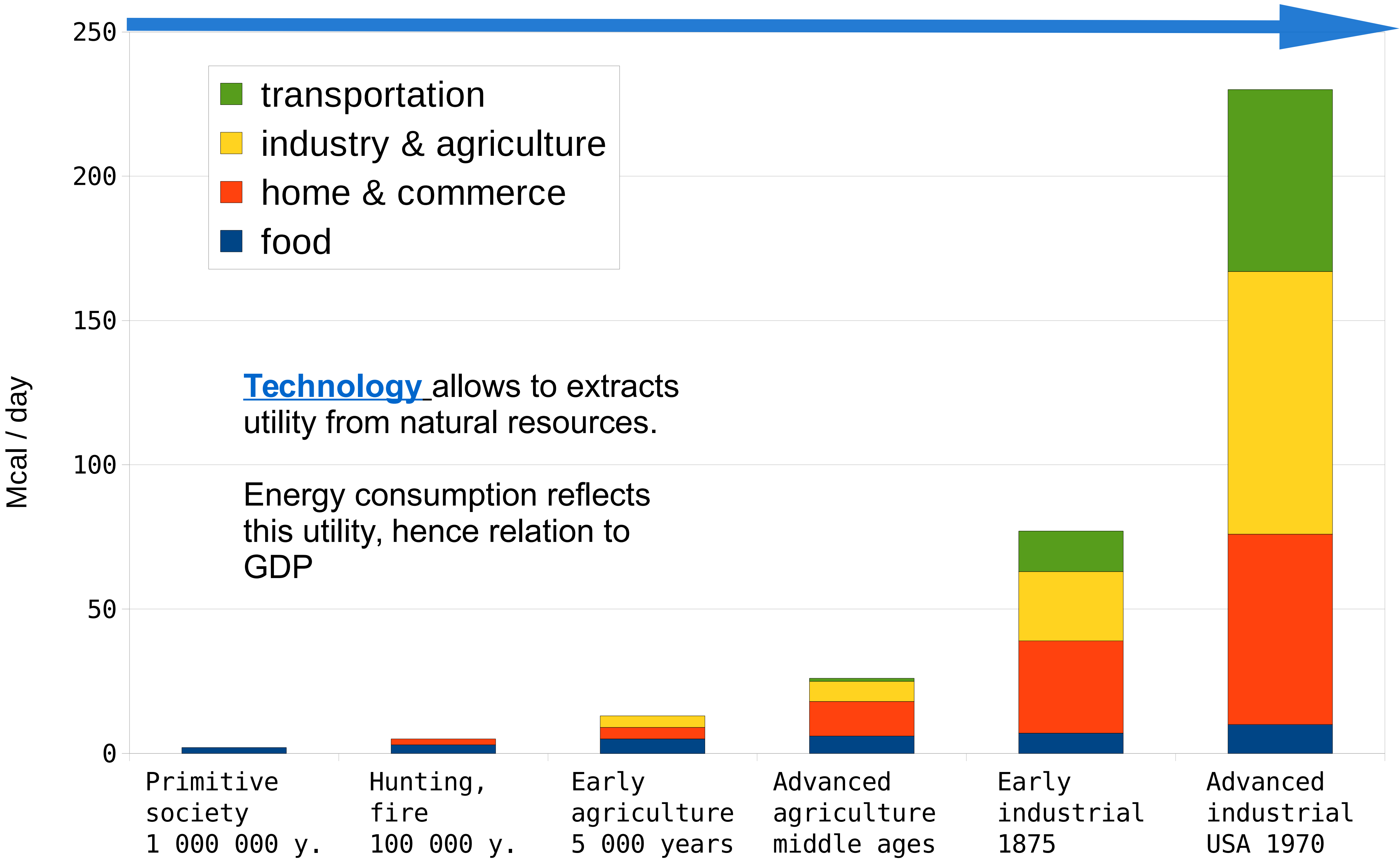
Conclusions

- Clean, safe, affordable energy is mandatory for humanity to thrive.
- Molten salt based advanced nuclear power can solve all issues with existing LWRs, from inherent safety to resource use minimization to destruction of existing long-lived nuclear waste and weapons fuels.
- There are many ways to skin a Molten Salt Rector.
- Europe and Russia lead Gen4 MSR academic effort.
- China has a well funded Thorium MSR program based on extensive ORNL's work.
- Several North American startups provide private investment opportunities.

Contact: Ondřej Chvála <ochvala@utk.edu>

Backup Slides

Energy extraction per capita in history



References: http://www.wou.edu/las/physci/GS361/electricity%20generation/HistoricalPerspectives.htm

Development of human civilization is closely connected to energy consumption

Energy consumption per capita in several stages of development

Mcal / day	Primitive society 1 000 000 y.	Hunting, fire 100 000 y.	Early agriculture 5 000 years	Advanced agriculture middle ages	Early industrial 1875	Advanced industrial USA 1970
food	2	3	5	6	7	10
home & commerce	0	2	4	12	32	66
industry & agriculture	0	0	4	7	24	91
transportation	0	0	0	1	14	63
total Mcal / day / person	**2**	**5**	**13**	**26**	**77**	**230**
total GJ / year / person	3.1	7.6	19.9	39.7	117.7	351.5
total average kW / person	**0.1**	**0.2**	**0.6**	**1.3**	**3.7**	**11.1**

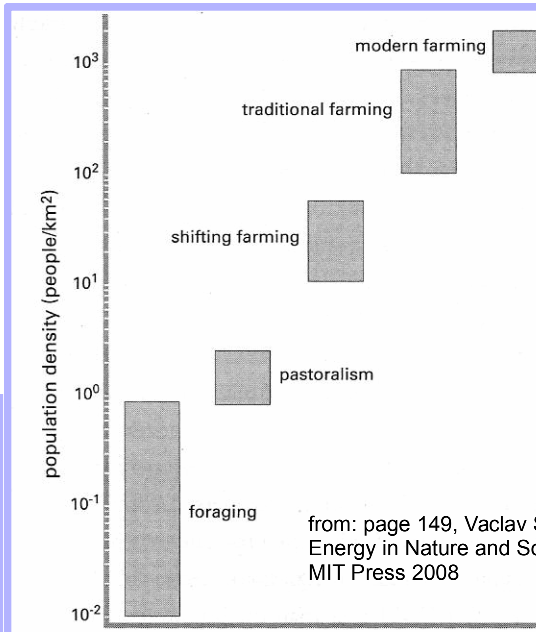
* http://www.wou.edu/las/physci/GS361/electricity%20generation/HistoricalPerspectives.htm

Adapted from: E. Cook, "The Flow of Energy in an Industrial Society" Scientific American, 1971 p. 135.

Total per capita use in technological age is ~100x that of the primitive society
non-SI unit: "Energy slave" (ES) - 8h/day 60 W useful work.
500 energy slaves/capita which heat homes, water, transport people and stuff, drive machines in factories etc.
Can two ES provide a 120W computer? We live in golden times!

Most of the energy consumption growth occurs and is expected in developing countries (>3G people)
- rising from early industrial-like poverty
- transfer of heavy manufacturing from developed world

"Carrying capacity" for humans depends on civilization stage and resp. technology (now from Haber-Bosch to satellite controlled farming)

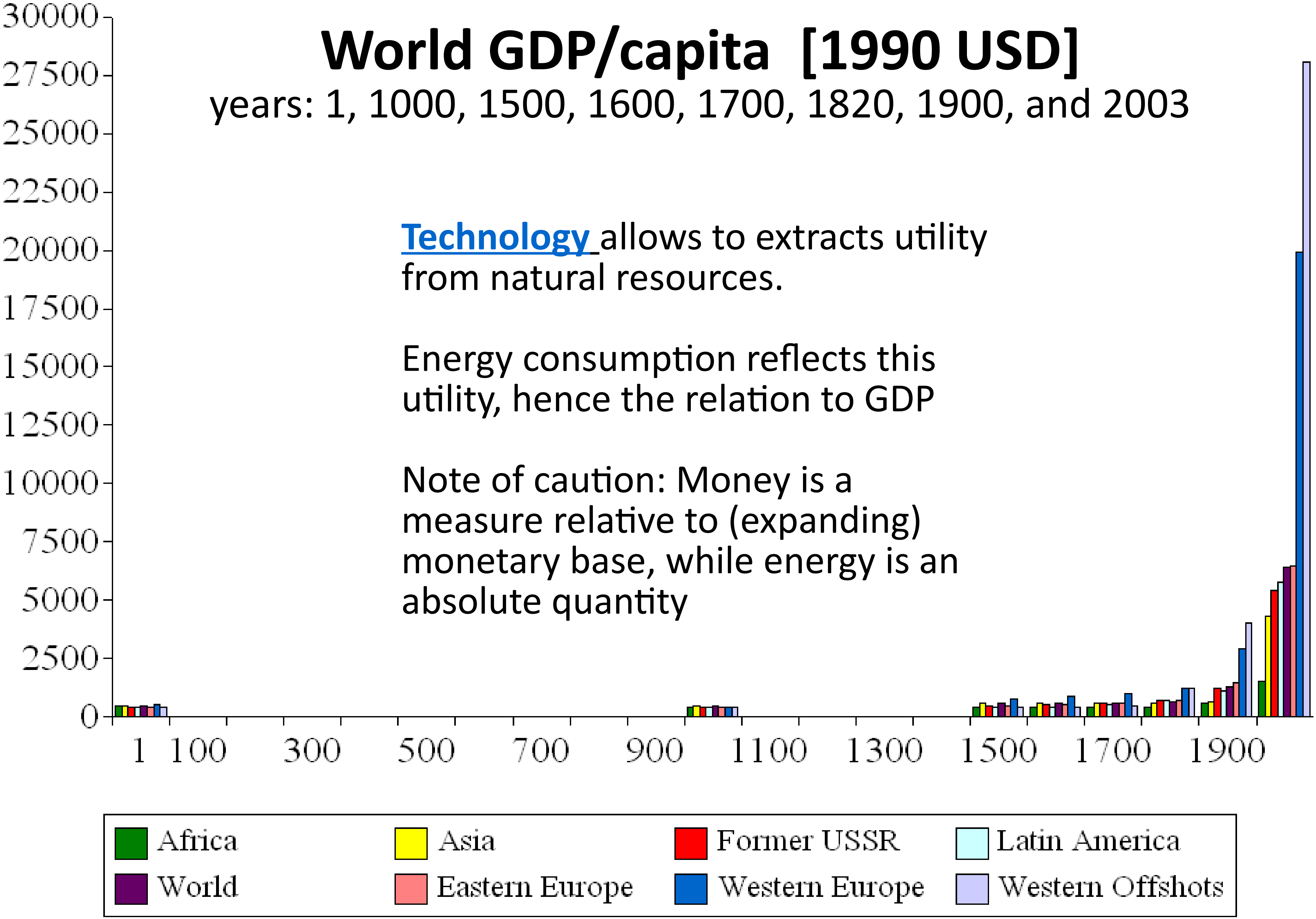


from: page 149, Vaclav Smil: Energy in Nature and Society MIT Press 2008

6.1 Ranges of population densities supportable by intensifying modes of food provision.

World GDP/capita [1990 USD]

years: 1, 1000, 1500, 1600, 1700, 1820, 1900, and 2003



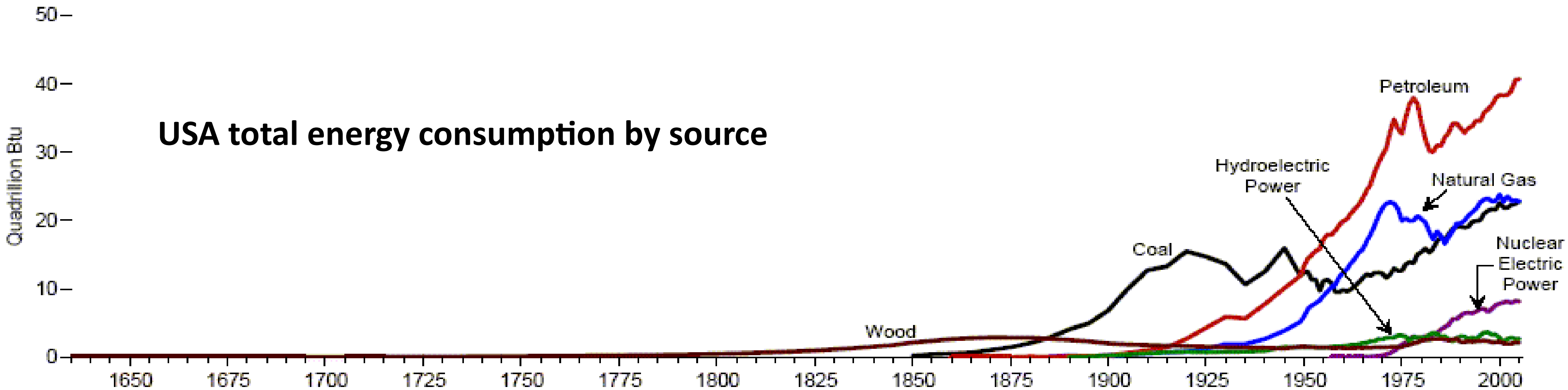
Technology allows to extracts utility from natural resources.

Energy consumption reflects this utility, hence the relation to GDP

Note of caution: Money is a measure relative to (expanding) monetary base, while energy is an absolute quantity

References:http://en.wikipedia.org/wiki/Gross_domestic_product#Standard_of_living_and_GDP

USA – historic perspective of energy use



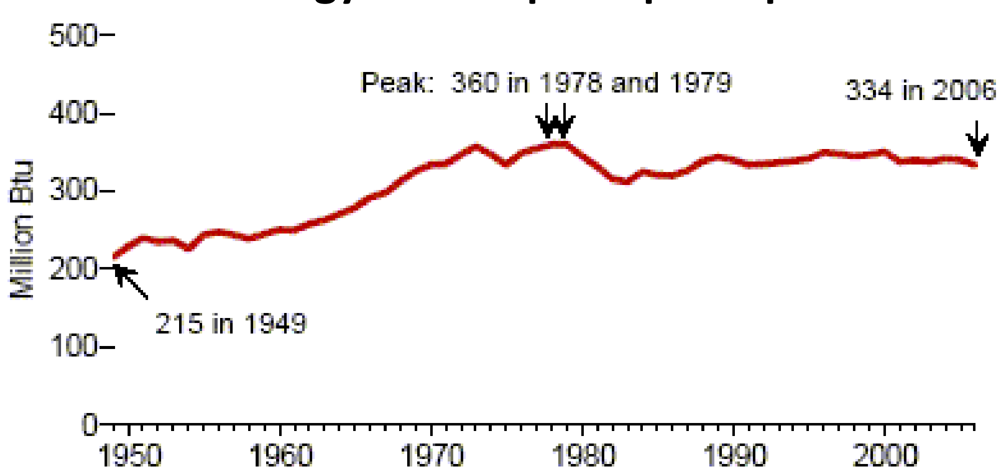
(*) plots from:
http://www.eia.doe.gov/emeu/aer/ep/ep_frame.html

Energy consumption per capita is mostly determined by civilization era.

In the technological age, per capita energy consumption growth stops, however we need to change the energy source away from combustion.

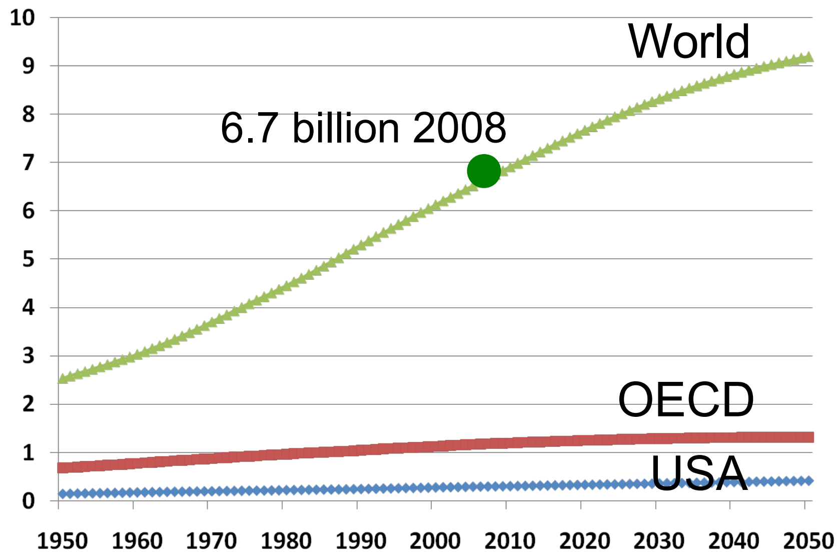
Total energy consumption by humans will rise as billions living in 3[rd] world countries transit from agriculture and industrial civilizations to the technological age.

USA energy consumption per capita



Population is stable in developed countries

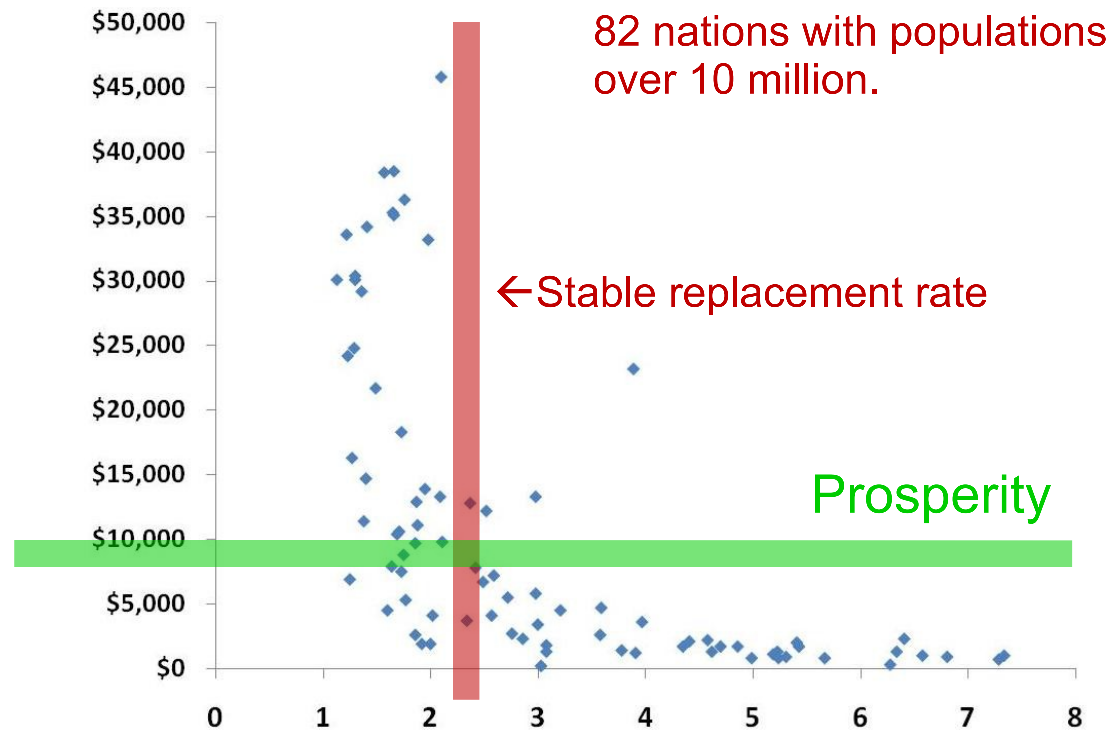
Population [billions]



References:
http://caliban.sourceoecd.org/vl=1260748/cl=17/nw=1/rpsv/factbook/010101.htm
http://www.oecd.org/dataoecd/13/38/16587241.pdf

Prosperity stabilizes population

GDP per capita [2007 USD]

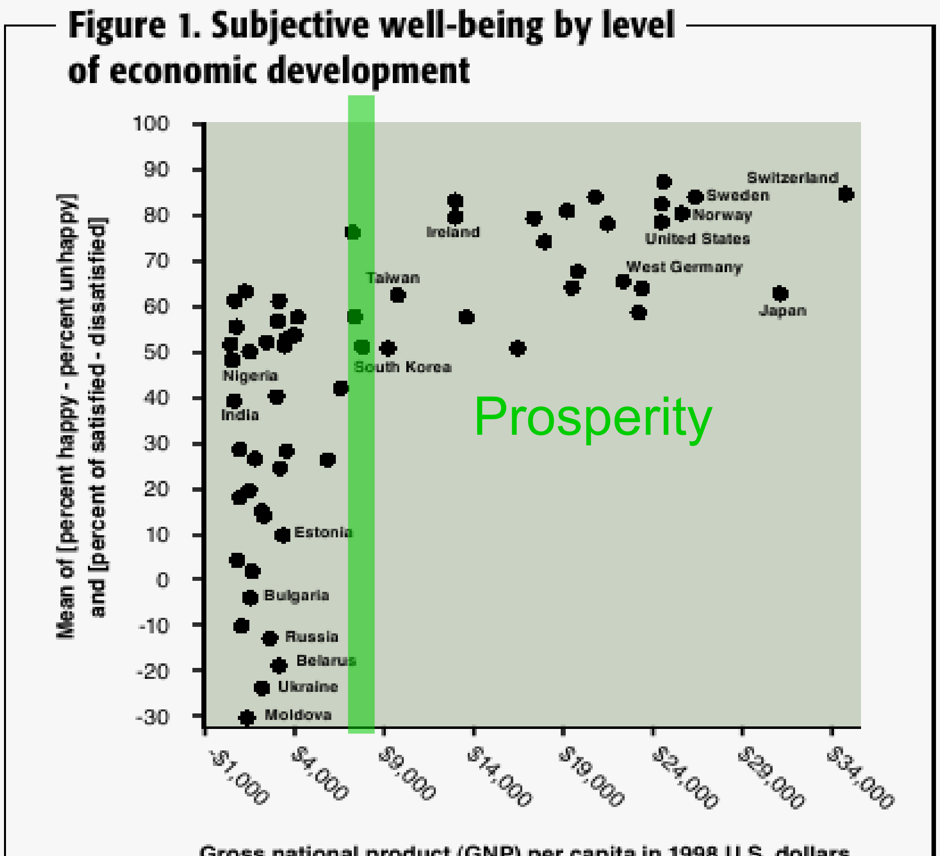


Children per woman

https://www.cia.gov/library/publications/the-world-factbook/docs/rankorderguide.html

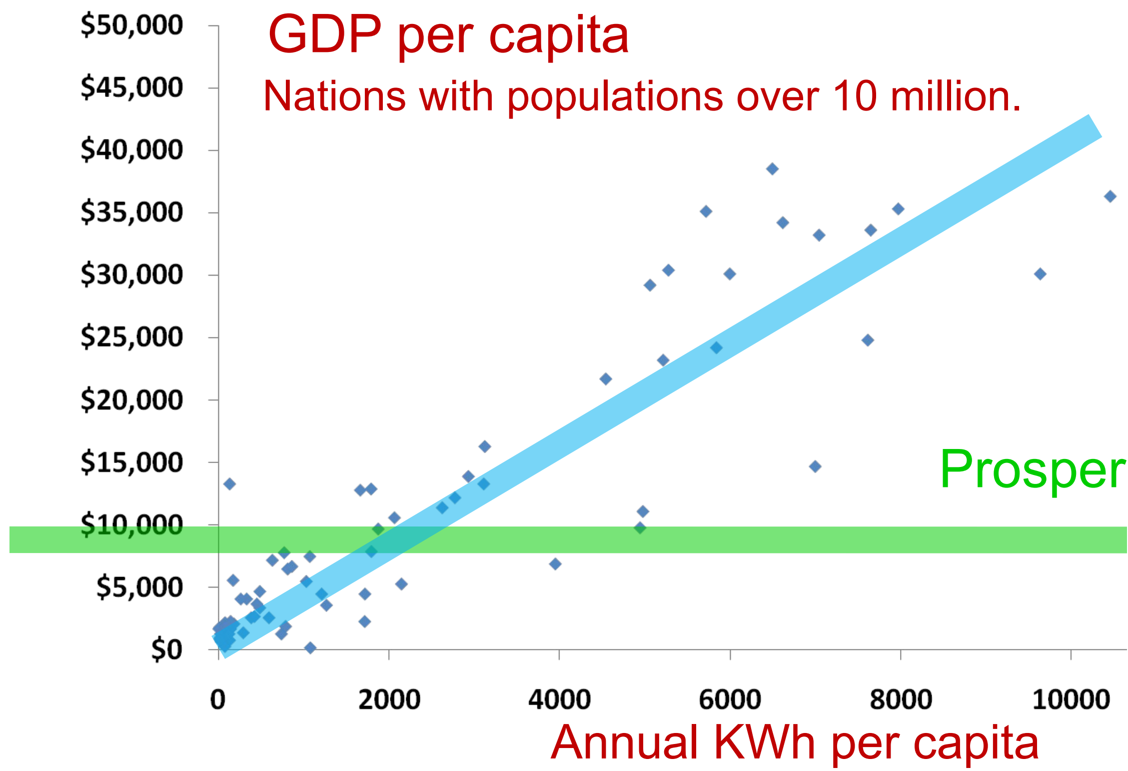
From: http://rethinkingnuclearpower.googlepages.com/aimhigh

Quality of life and energy consumption I



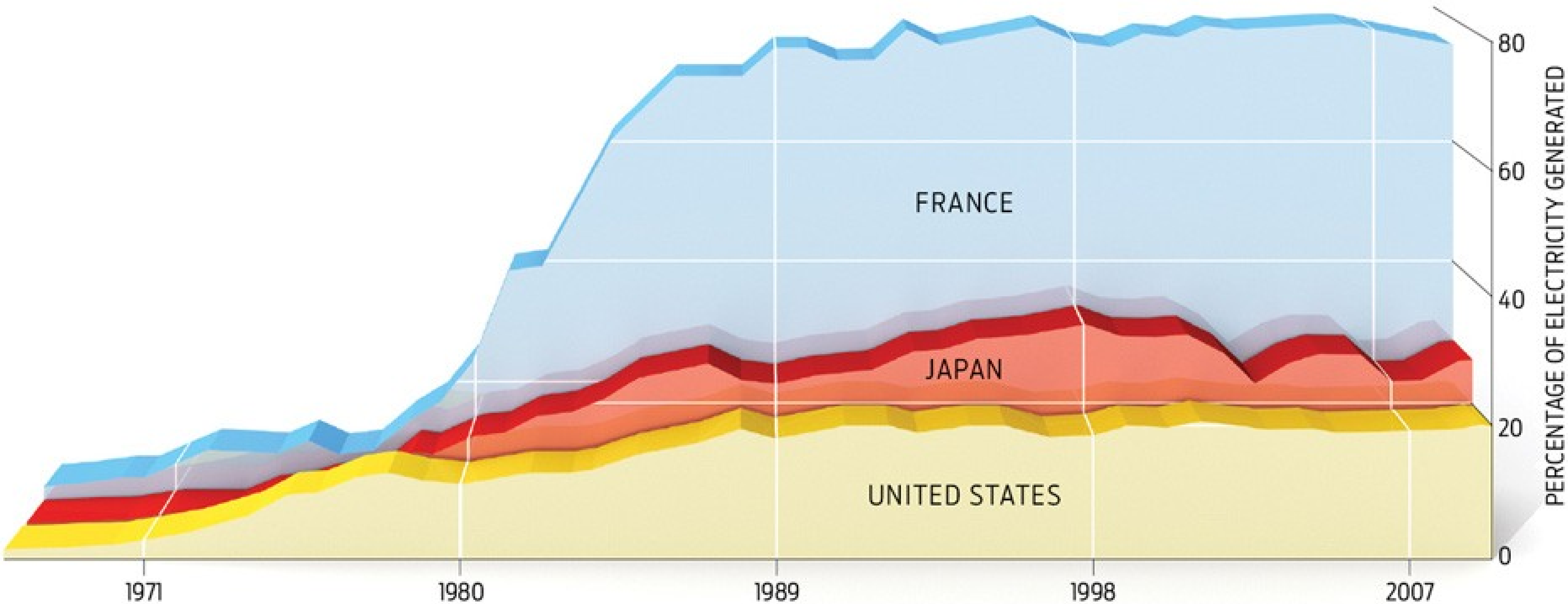
NOTE: The subjective well-being index reflects the average of the percentage in each country who describe themselves as "very happy" or "happy" minus the percentage who describe themselves as "not very happy" or "unhappy"; and the percentage placing themselves in the 7–10 range, minus the percentage placing themselves in the 1–4 range, on a 10-point scale on which 1 indicates that one is strongly dissatisfied with one's life as a whole, and 10 indicates that one is highly satisfied with one's life as a whole.

SOURCE: R. Inglehart, "Globalization and Postmodern Values," Washington Quarterly 23, no. 1 (1999): 215–228. Subjective well-being data from the 1990 and 1996 World Values Surveys. GNP per capita for 1993 data from World Bank, World Development Report, 1995 (New York: Oxford University Press, 1995).

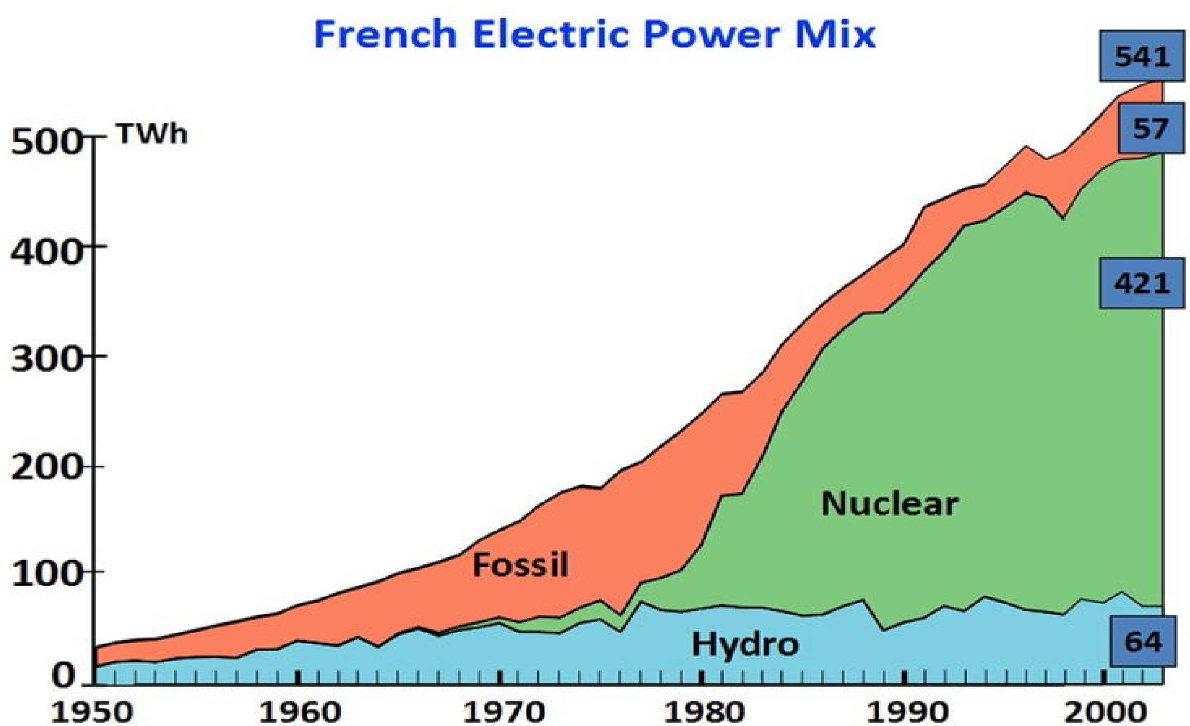


References:
http://rethinkingnuclearpower.googlepages.com/aimhigh
https://www.cia.gov/library/publications/the-world-factbook/rankorder/2042rank.html

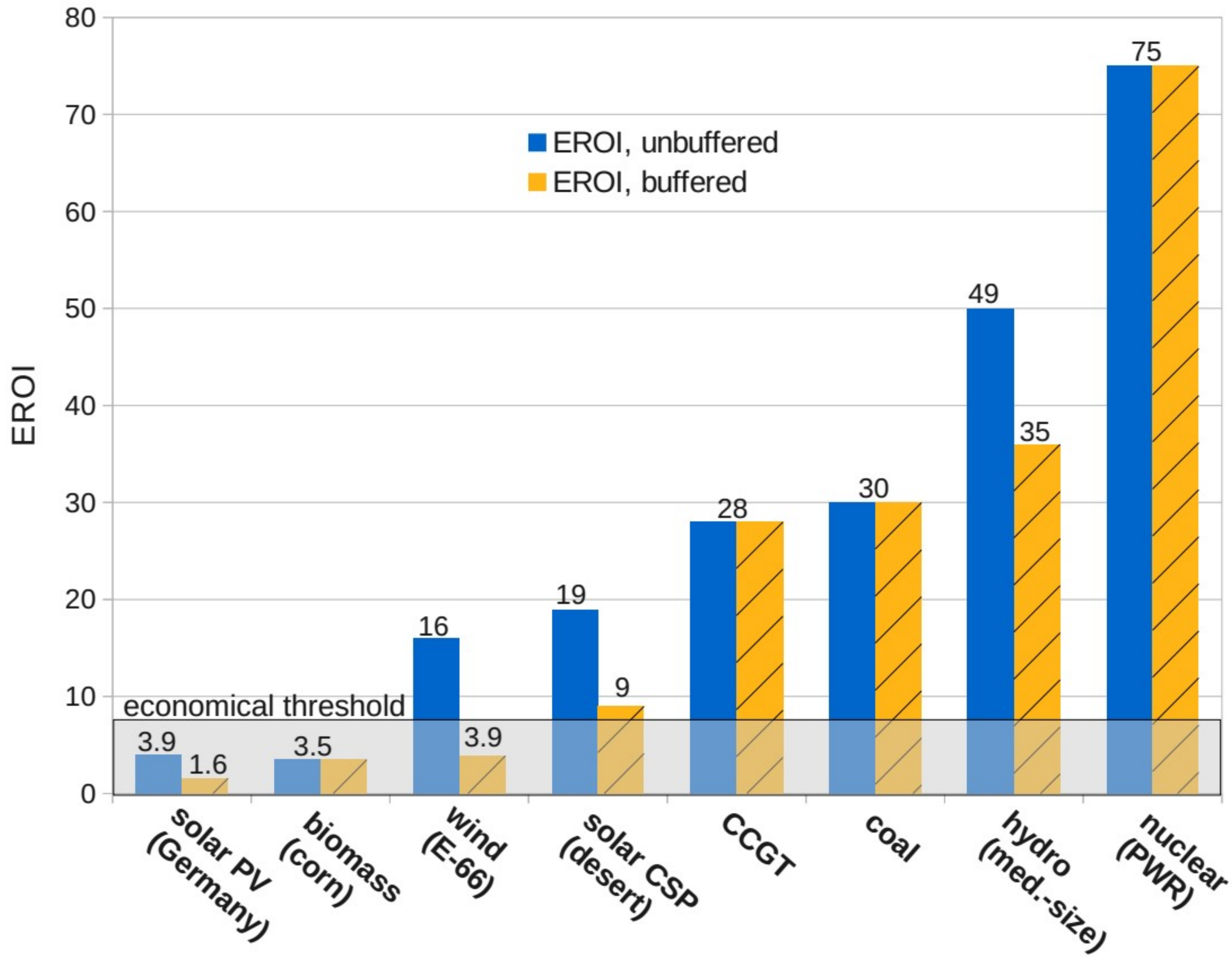
$7500 (1998) = $9500 (2007)
http://www.westegg.com/inflation/infl.cgi



FRANCE
JAPAN
UNITED STATES
PERCENTAGE OF ELECTRICITY GENERATED
0
20
40
60
80
1971
1980
1989
1998
2007



French Electric Power Mix
TWh
500
400
300
200
100
0
541
57
421
64
Nuclear
Fossil
Hydro
1950
1960
1970
1980
1990
2000



Energy Returned on Invested, from [1] with and without energy storage (buffering). CCGT is closed-cycle gas turbine. PWR is a Pressurized Water (conventional nuclear) Reactor. Energy sources must exceed the "economic threshold", of about 7, to yield the surplus energy required to support an OECD level society.

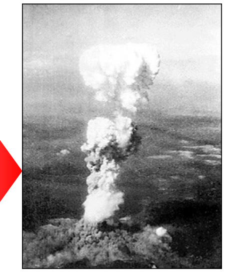
[1] Weißbach et al., Energy 52 (2013) p. 210

Could weapons be made from the fissile material?

Natural uranium

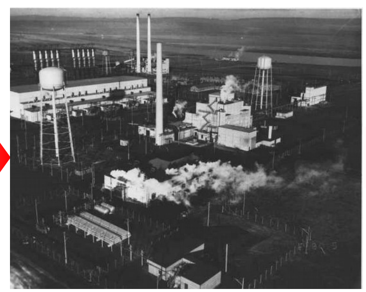
Isotope separation plant (Y-12)

Uranium-235 (“highly enriched uranium”)



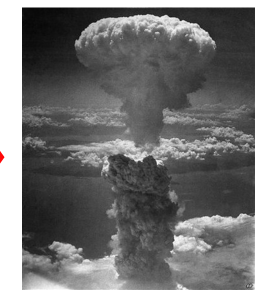
Hiroshima, 8/6/1945

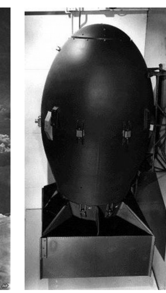
Depleted uranium



Isotope Production Reactor (Hanford)

Pu separation from exposed U (PUREX)





Trinity, 7/16/1945
Nagasaki, 8/9/1945

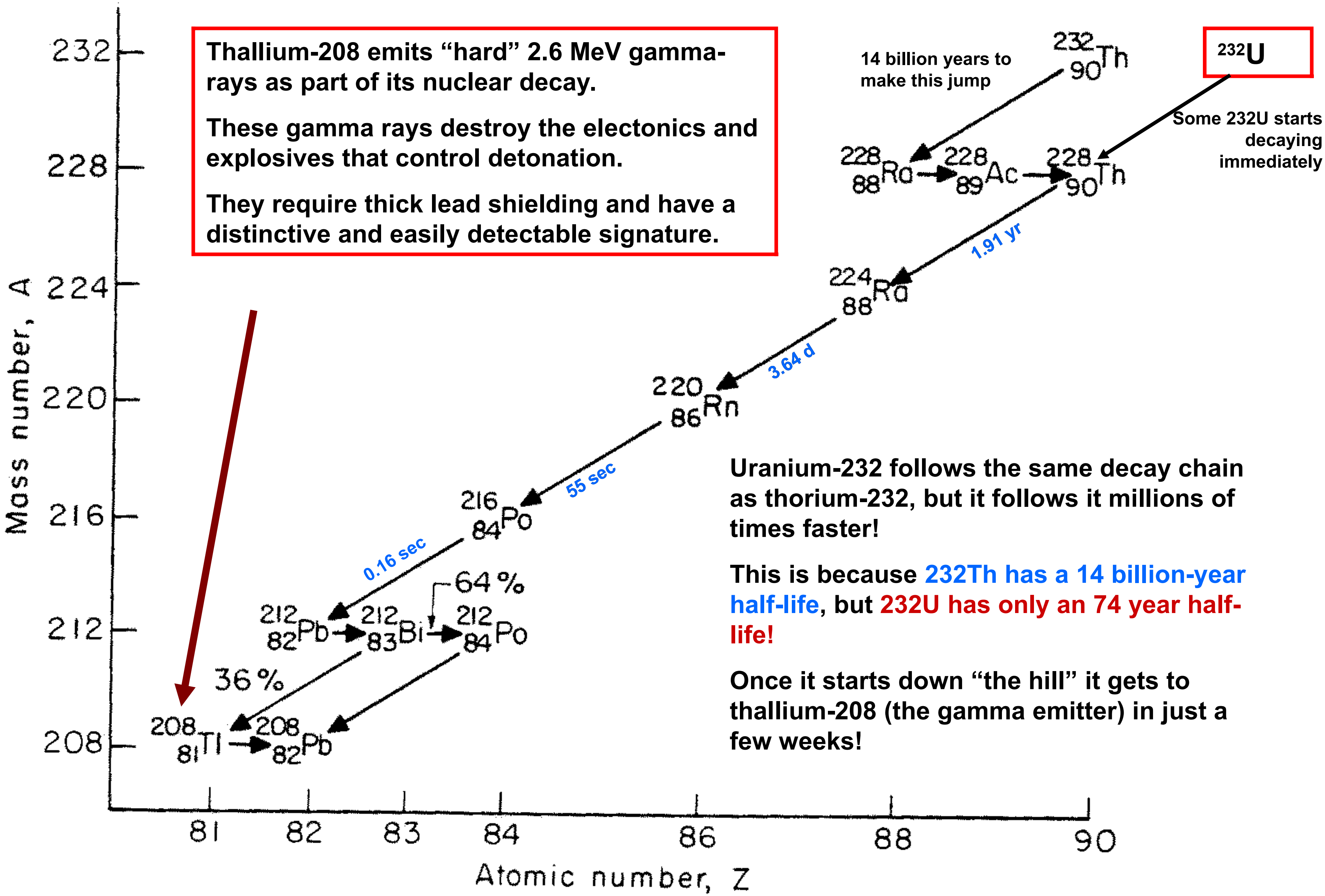
Thorium?

Isotope Production Reactor

uranium separation from exposed thorium

PROBLEM: U-233 is contaminated with U-232, whose decay chain emits HARD gamma rays that make fabrication, utilization and deployment of weapons VERY difficult and impractical relative to other options. Thorium was not pursued.

U-232 decays into Tl-208, a HARD gamma emitter



Thallium-208 emits "hard" 2.6 MeV gamma-rays as part of its nuclear decay.

These gamma rays destroy the electonics and explosives that control detonation.

They require thick lead shielding and have a distinctive and easily detectable signature.

Uranium-232 follows the same decay chain as thorium-232, but it follows it millions of times faster!

This is because 232Th has a 14 billion-year half-life, but 232U has only an 74 year half-life!

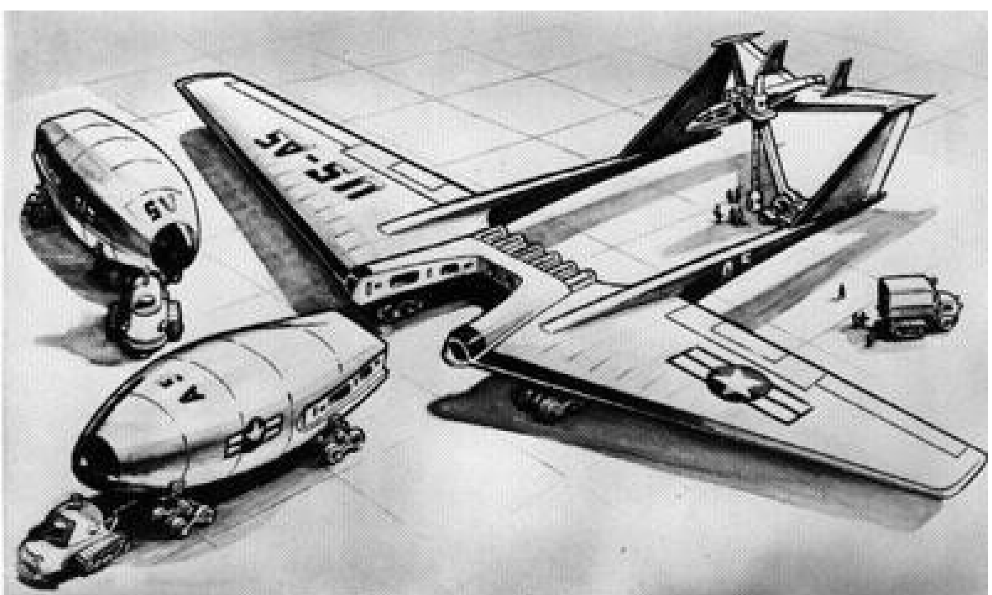
Once it starts down "the hill" it gets to thallium-208 (the gamma emitter) in just a few weeks!

Aircraft Nuclear Program


Convair NB-36H
USAF Museum Photo Archives

Between 1946 and 1961, the USAF sought to develop a long-range bomber based on nuclear power.

The Aircraft Nuclear Program had unique requirements, some very similar to a space reactor.

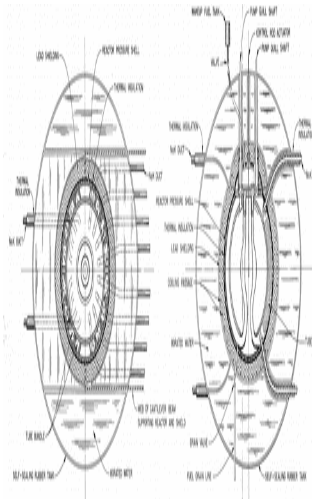


- High temperature operation (>1500° F)
  - **Critical for turbojet efficiency**
  - **3X higher than sub reactors**
- Lightweight design
  - **Compact core for minimal shielding**
  - **Low-pressure operation**
- Ease of operability
  - **Inherent safety and control**
  - **Easily removeable**

Ionically-bonded fluids are impervious to radiation

- The basic problem in nuclear fuel is that it is covalently bonded and in a solid form.
- If the fuel were a fluid salt, its ionic bonds would be impervious to radiation damage and the fluid form would allow easy extraction of fission product gases, thus permitting unlimited burnup.

Aircraft Nuclear Program allowed ORNL to develop reactors



It wasn't that I had suddenly become converted to a belief in nuclear airplanes. **It was rather that this was the only avenue open to ORNL for continuing in reactor development.**

That the purpose was unattainable, if not foolish, was not so important:

A high-temperature reactor could be useful for other purposes even if it never propelled an airplane…

—Alvin Weinberg

Why wasn't this done? No Plutonium Production!

Alvin Weinberg:

"Why didn't the molten-salt system, so elegant and so well thought-out, prevail? I've already given the political reason: that the plutonium fast breeder arrived first and was therefore able to consolidate its political position within the AEC. But there was another, more technical reason. [Fluoride reactor] technology is entirely different from the technology of any other reactor. To the inexperienced, [fluoride] technology is daunting…

"Mac" MacPherson:

The political and technical support for the program in the United States was too thin geographically…only at ORNL was the technology really understood and appreciated. The thorium-fueled fluoride reactor program was in competition with the plutonium fast breeder program, which got an early start and had copious government development funds being spent in many parts of the United States.

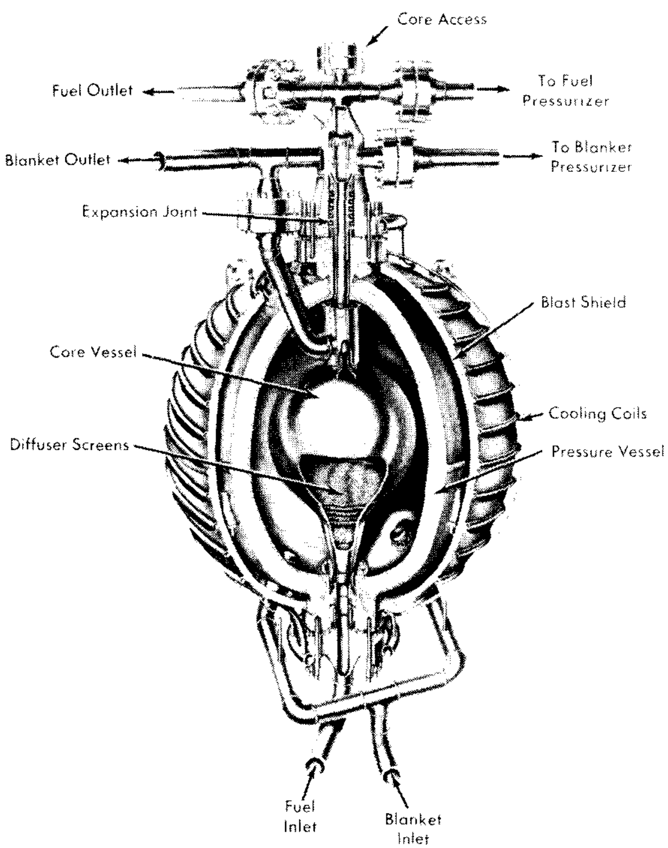
Alvin Weinberg:

"It was a successful technology that was dropped because it was too different from the main lines of reactor development… I hope that in a second nuclear era, the [fluoride-reactor] technology will be resurrected."

Fluid-Fueled Reactors for Thorium Energy

Aqueous Homogenous Reactor (ORNL)

- **Uranyl sulfate dissolved in pressurized heavy water.**
- **Thorium oxide in a slurry.**
- **Two built and operated.**



Liquid-Fluoride Reactor (ORNL)

- Uranium tetrafluoride dissolved in lithium fluoride/beryllium fluoride.
- Thorium dissolved as a tetrafluoride.
- Two built and operated.

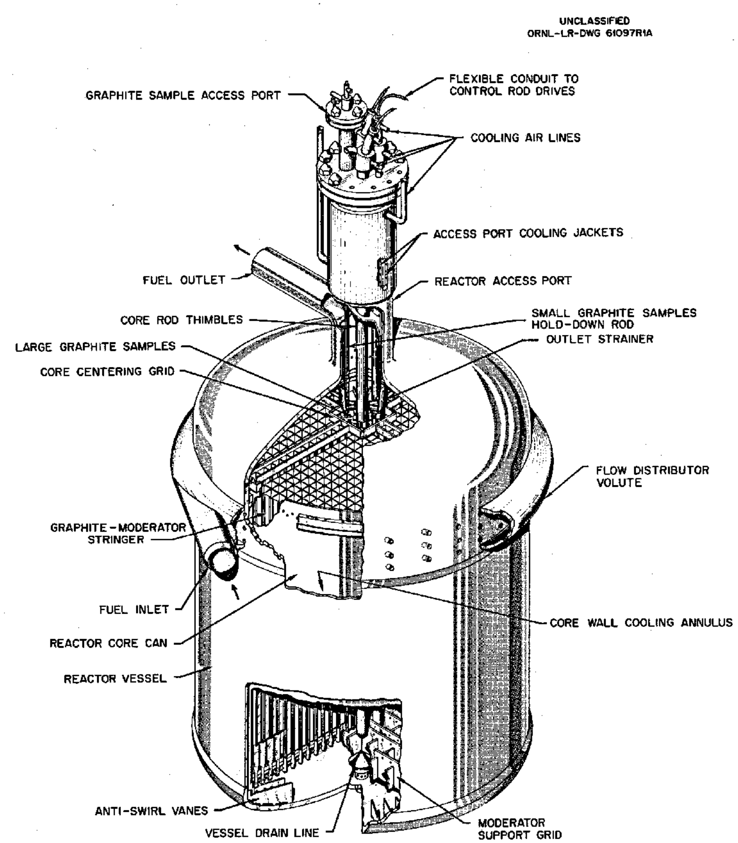
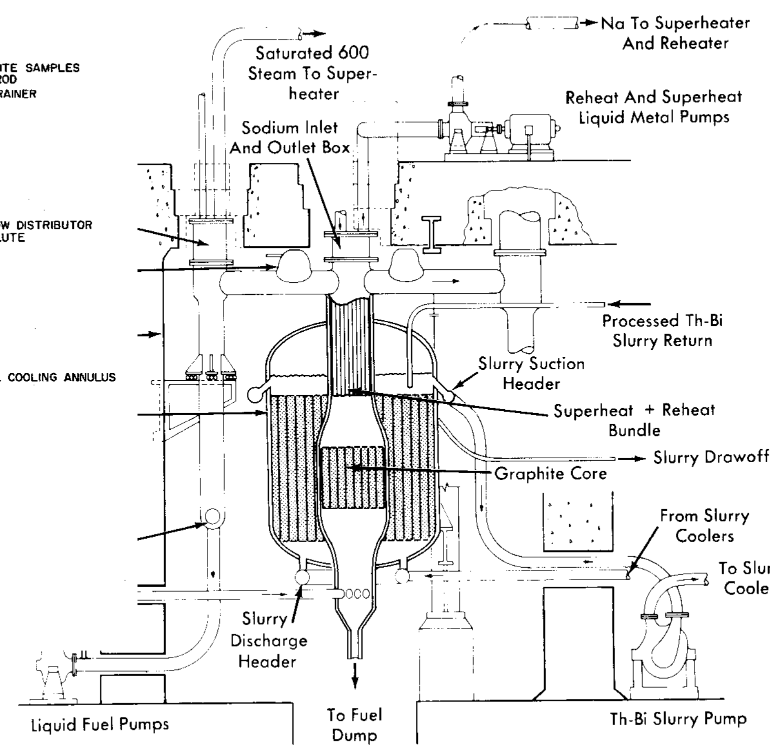


Fig. 6. MSRE Reactor Vessel.

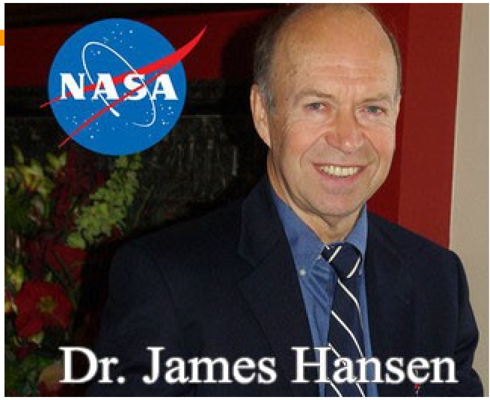
Liquid-Metal Fuel Reactor (BNL)

- Uranium metal dissolved in bismuth metal.
- Thorium oxide in a slurry.
- Conceptual—none built and operated.

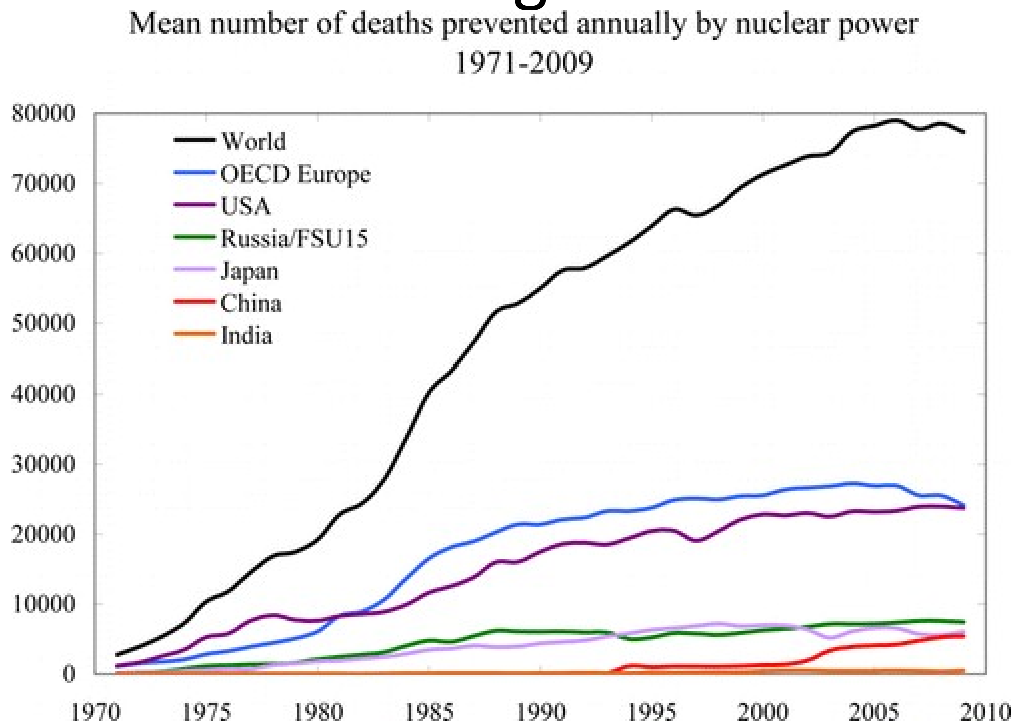


How many lives were saved by nuclear power?

- P. A. Kharecha, J. E. Hansen, "*Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power,*" Environ. Sci. Technol., 2013, 47 (9), pp 4889–4895

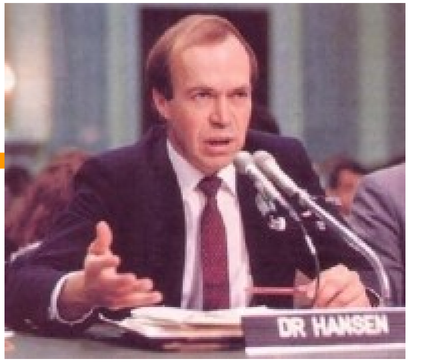


"... nuclear power has prevented an average of **1.84 million air pollution-related deaths and 64 gigatonnes of CO2-equivalent (GtCO2-eq) greenhouse gas (GHG) emissions** that would have resulted from fossil fuel burning."

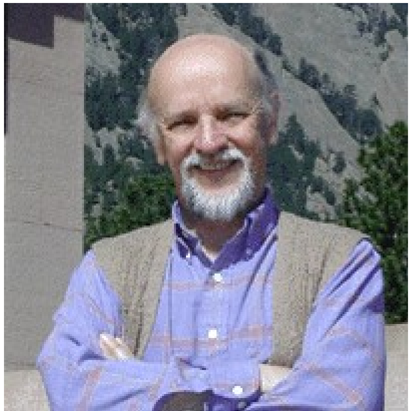


2013 Open letter to policy makers

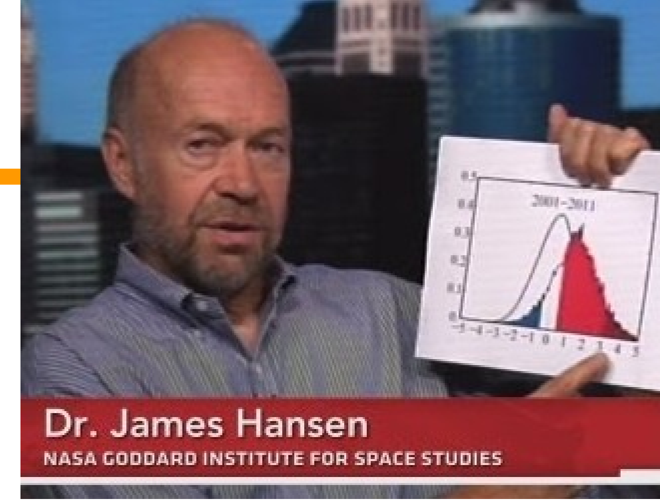
- by U.S. most prominent climate and energy scientists: James Hansen (GISS), Ken Caldeira (CIS), Kerry Emanuel (MIT), Tom Wigley (UCAR).
- "**Continued opposition to nuclear power threatens humanity's ability to avoid dangerous climate change**."
- "[I]n the real world there is no credible path to climate stabilization that does not include a substantial role for nuclear power."
- Full text here: http://www.cnn.com/2013/11/03/world/nuclear-energy-climate-change-scientists-letter/







2014 Speaking Truth to Power



- "**Big Green**", the large $100M per year environmental organizations, have become one of the **biggest obstacles to solving the climate problem**."
- "After I joined other scientists in requesting the leaders of Big Green to reconsider their adamant opposition to nuclear power, and was rebuffed, I learned from discussions with them the major reason: they feared losing donor support. Money, it seems, is the language they understand. Thus my suggestion: the next time you receive a donation request, doubtless accompanied with a photo of a cuddly bear or the like, toss it in the waste bin and return a note saying that you will consider a donation in the future, if they objectively evaluate the best interests of young people and nature."
- Fulltext much recommended reading: http://csas.ei.columbia.edu/2014/10/12/iowa-roots-speaking-truth-to-power/

Why molten salt fuels?

Solid fuels – deformations (swelling) & accumulation of fission products (degradation of solid fuel matrix, neutron poisons) **limit achievable burn-up**
Expensive fuel manufacturing, burnable poisons, excess reactivity to compensate short term FPs, shutdowns for fuel rotation necessary.
Waste accumulation or complicated reprocessing.

Molten fluoride salts – ionic bonds, no neutron damage, no cracking

The birth of the Liquid Fluoride Reactor

The liquid-fluoride nuclear reactor was invented by Ed Bettis and Ray Briant of ORNL in 1950 to meet the unique needs of the Aircraft Nuclear Program.

Fluorides of the alkali metals were used as the solvent into which fluorides of uranium and thorium were dissolved.

- **Very high negative reactivity coefficient**
  - Hot salt expands and becomes less critical
  - Reactor power would follow the load (the aircraft engine) without the use of control rods
- **Salts were stable at high temperature**
  - Electronegative fluorine and electropositive alkali metals formed salts that were exceptionally stable
  - Low vapor pressure at high temperature
  - Salts were resistant to radiolytic decomposition
  - Did not corrode or oxidize reactor structures
- **Salts were easy to pump, cool, and process**
  - Xe135 and other volatile FPS can be sparged out using just He bubbling
  - Chemical reprocessing much easier in fluid form
  - Poison buildup reduced, breeding enhanced
  - “A pot, a pipe, and a pump…”
  - Whole new landscape of possible reactor designs