Can Thorium Fission Solve the World's Energy Problems?

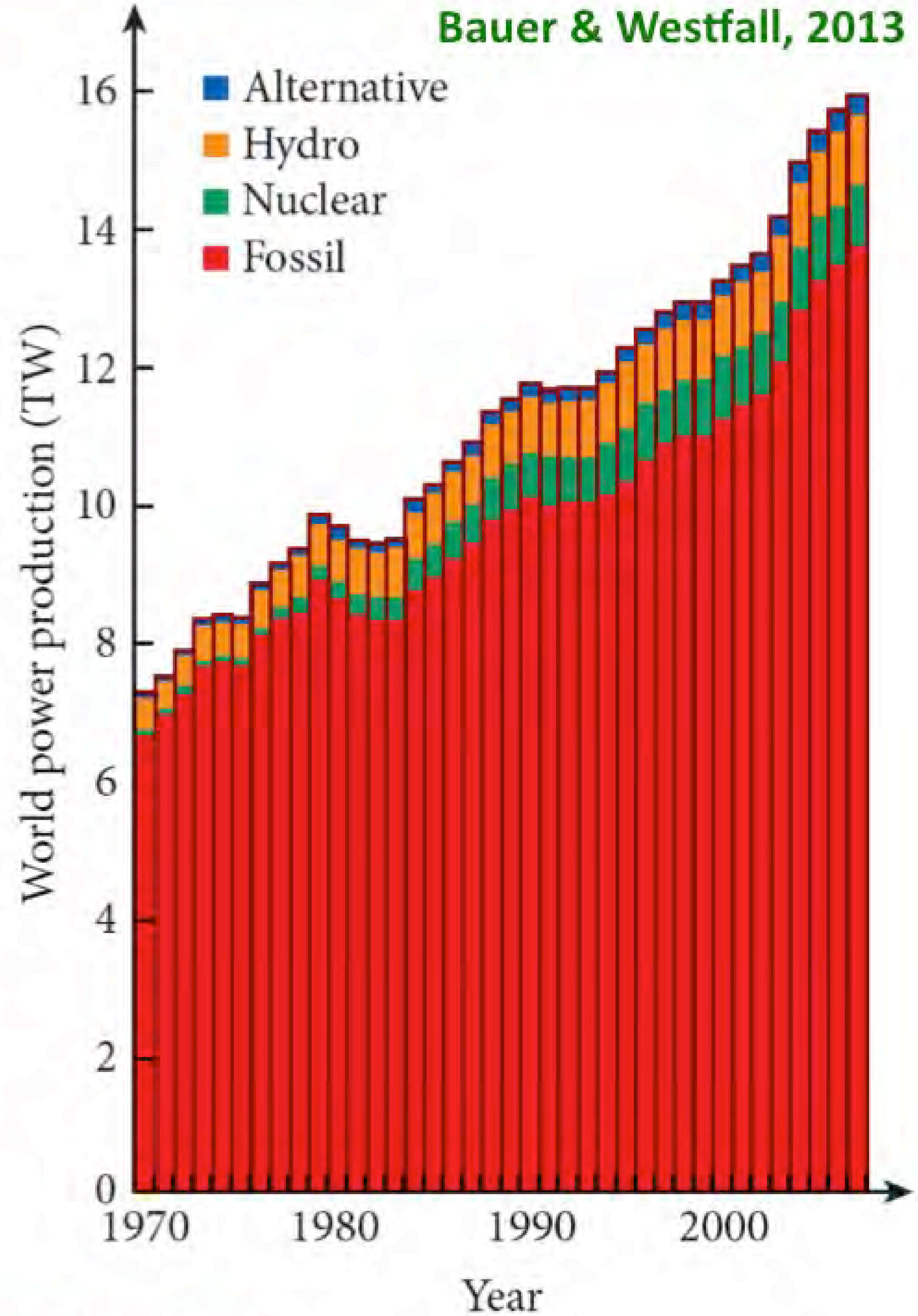
Wolfgang Bauer

Michigan State University

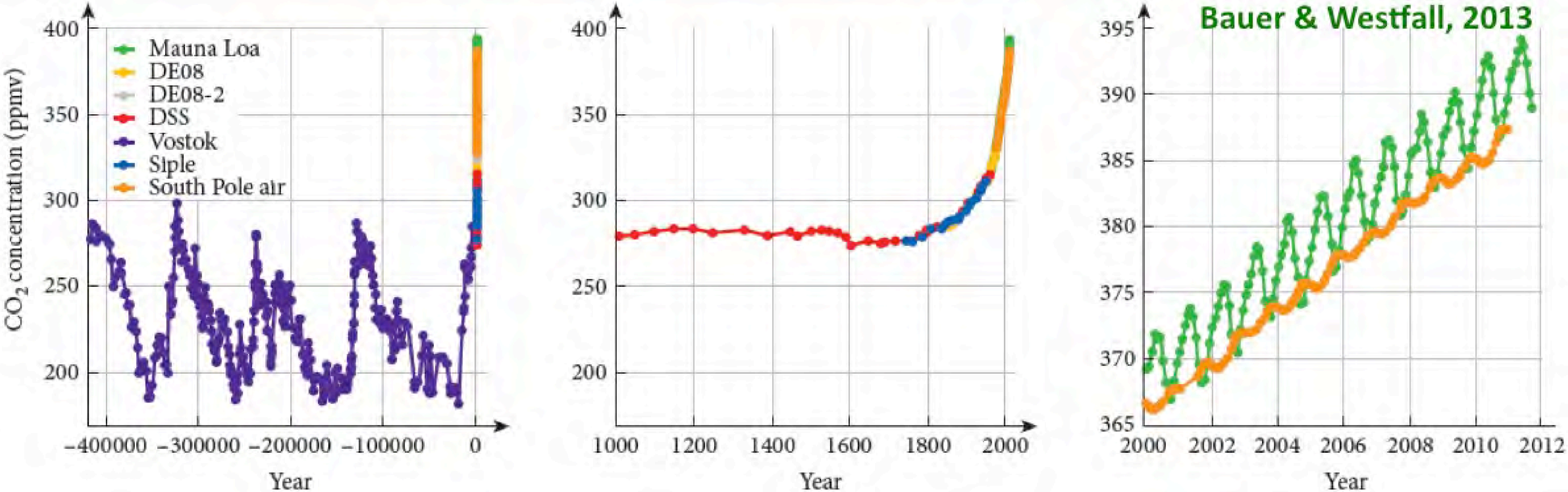
Preamble: The Energy Problem

- World power production relies mainly on fossil fuels (>85%)
- Hydro-power is reaching its limits, and other renewables are still only contributing <5%

Bauer & Westfall, 2013



Preamble: The Energy Problem



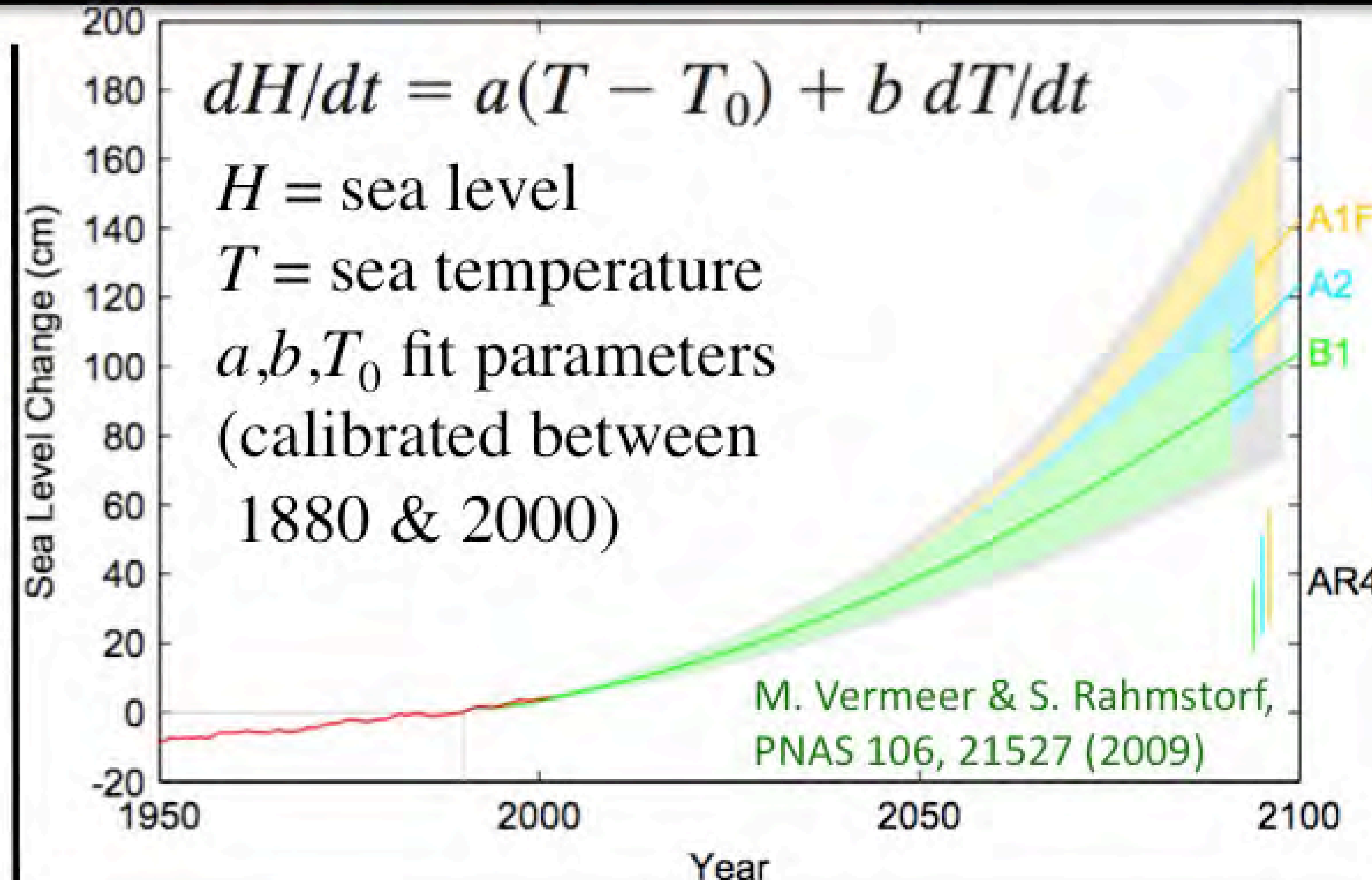
- CO_2 rise from burning fossil fuels
  - Unsustainable
  - Man-made global warming
  - Worst climate change effects are yet to come

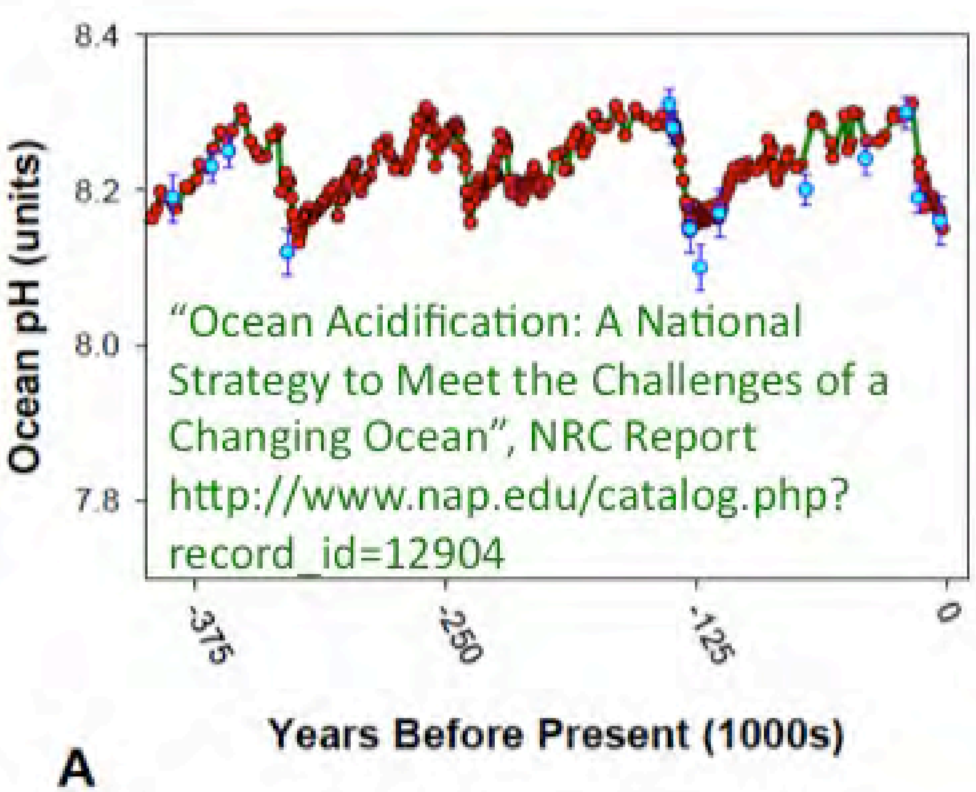
Latest CO_2 reading
October 12, 2014
395.52 ppm
Carbon dioxide concentration at Mauna Loa Observatory

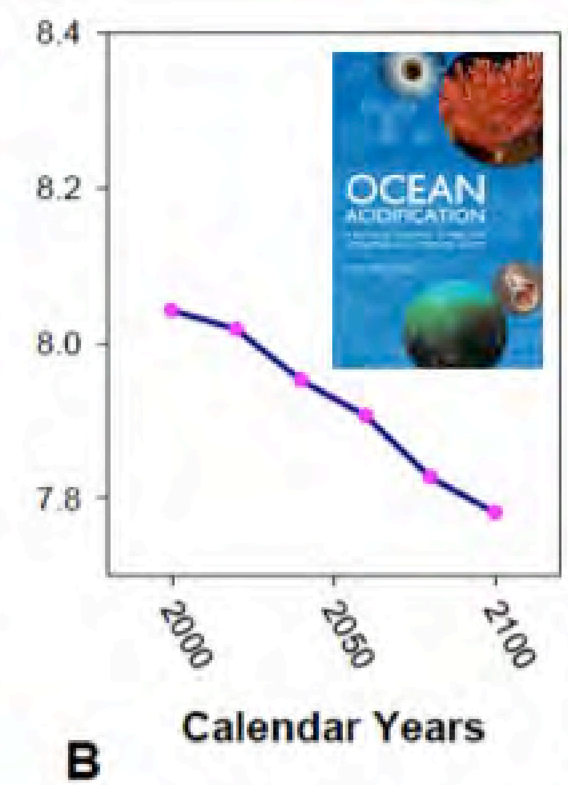
https://scripps.ucsd.edu/programs/keelingcurve/

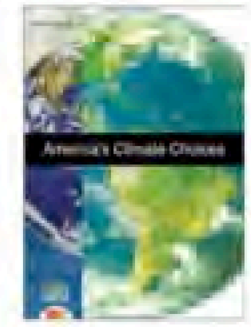
Preamble: The Energy Problem

- Consequences
  - Sea level rise
  - Ocean acidification
  - Heat waves



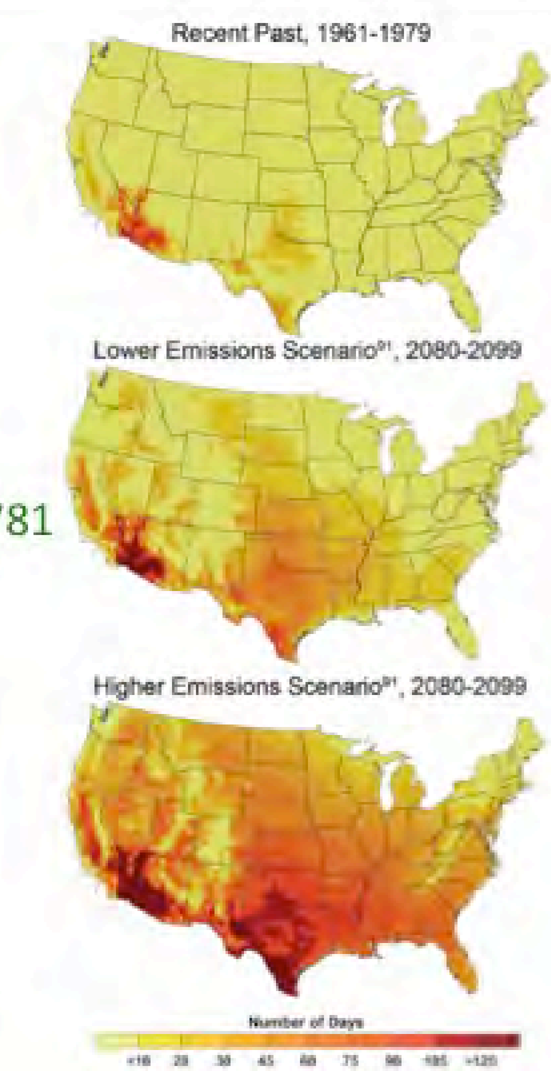




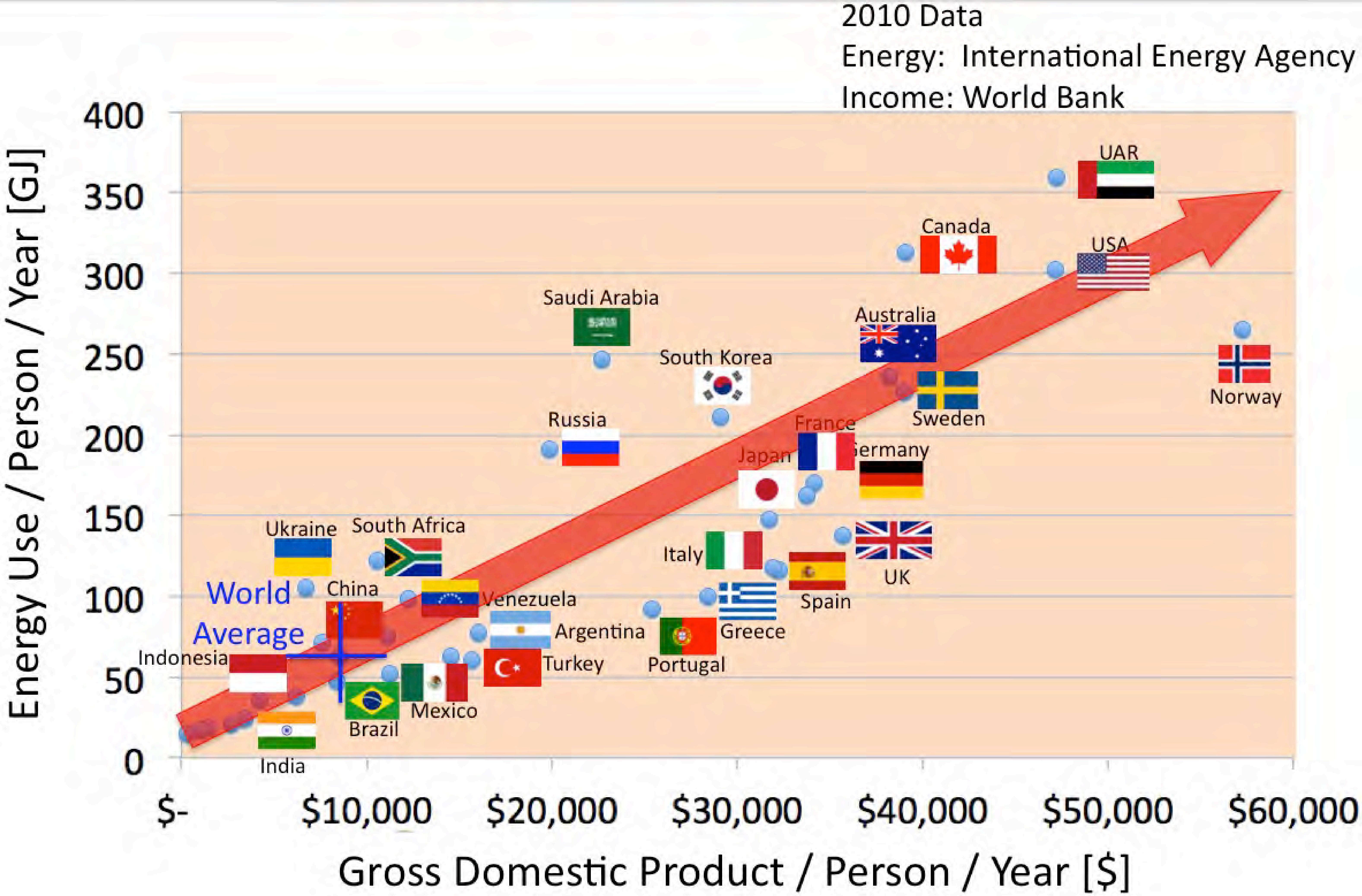


“America’s Climate Choices”, NRC Report

http://www.nap.edu/catalog.php?record_id=12781



Energy Use & Prosperity

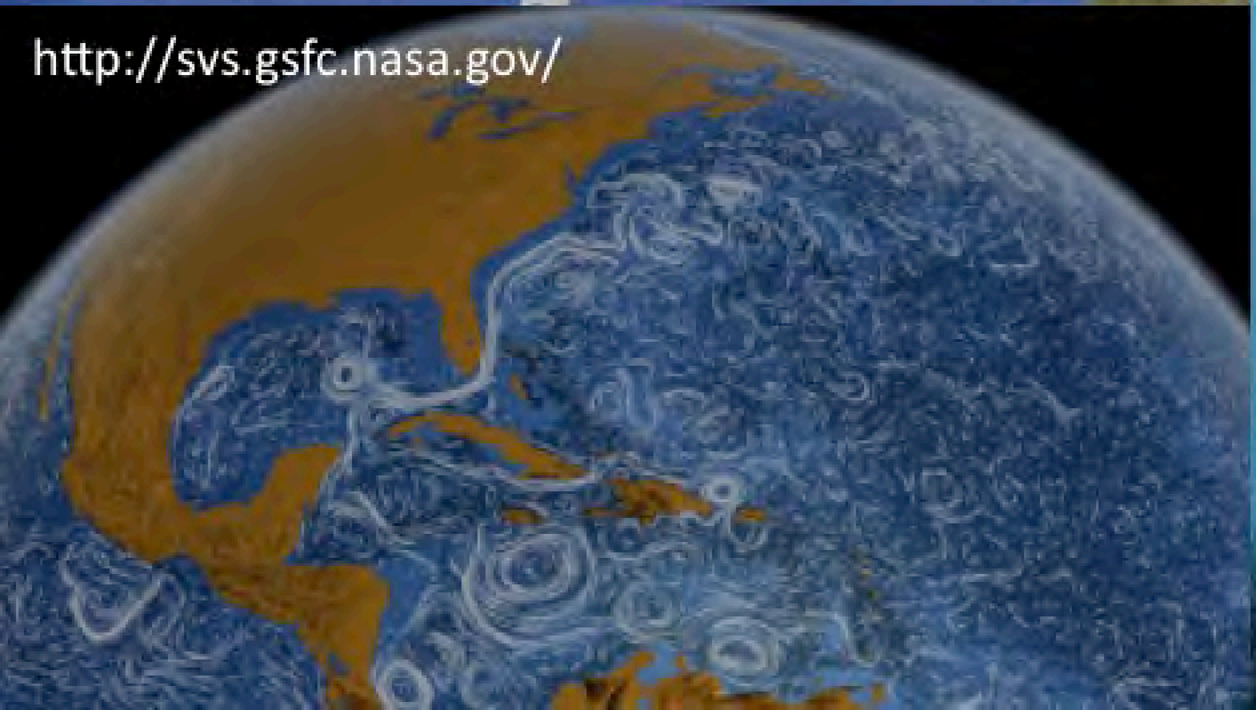


London Array Completed

Destructive Interference

Horns Rev 1 owned by Vattenfall. Photographer Christian Steiness

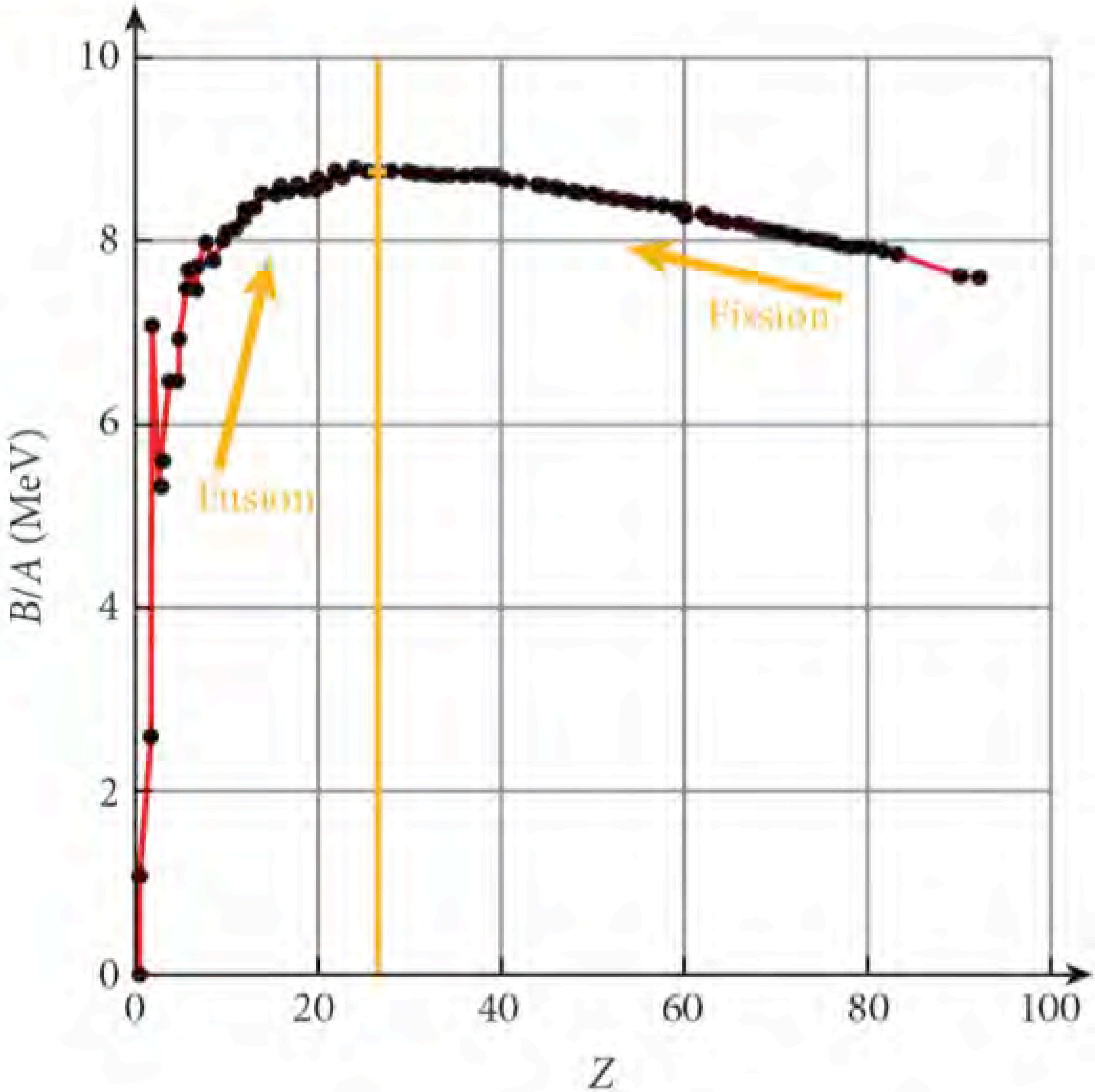
Ocean Currents



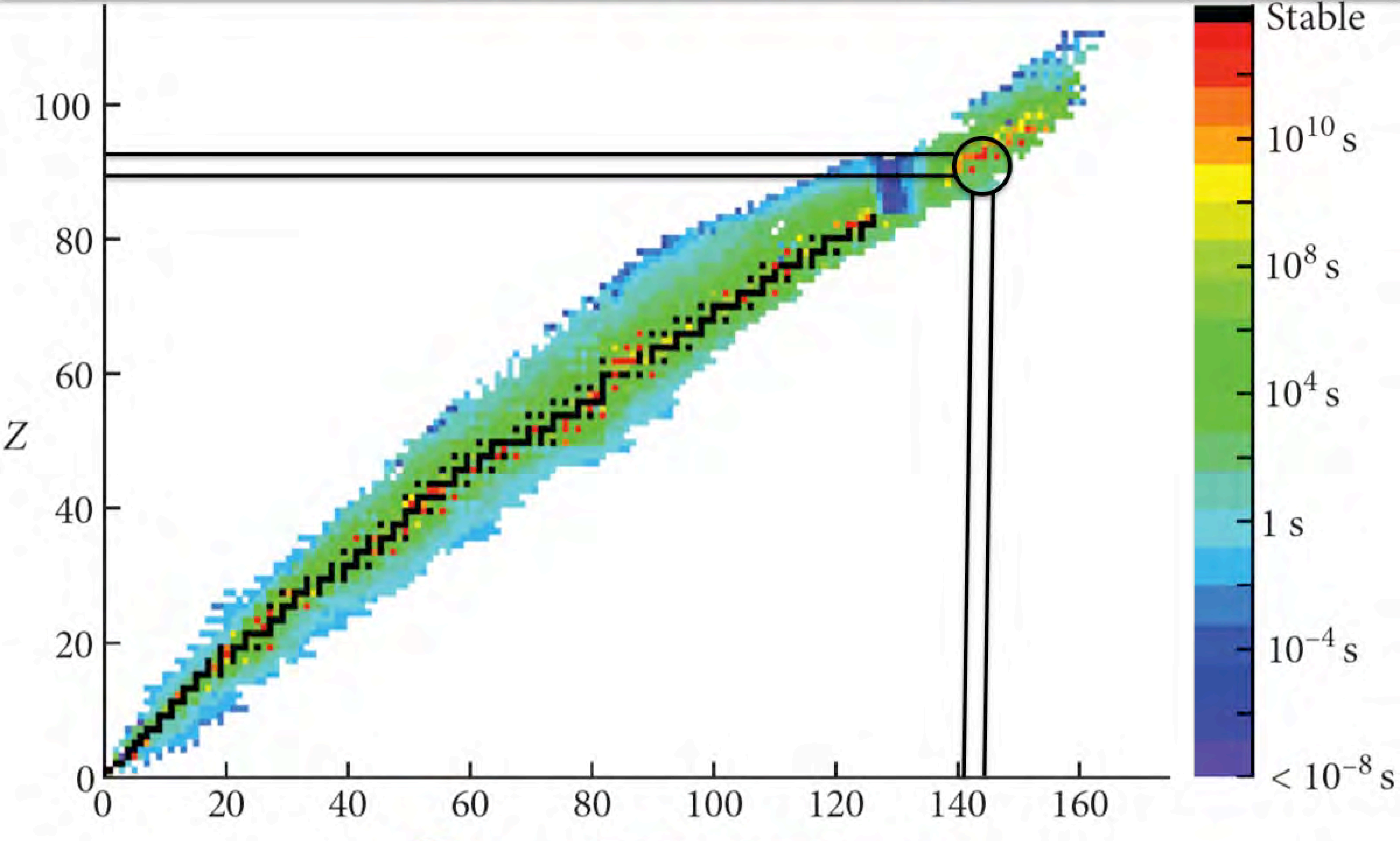
- Sound of Islay, Orkney Islands, UK
- HS1000 sub-sea turbine
- 1 MW
- $11M
- (Almost) no intermittency
- Payoff time ~12 years (@10¢/kWh):

Nuclear Power

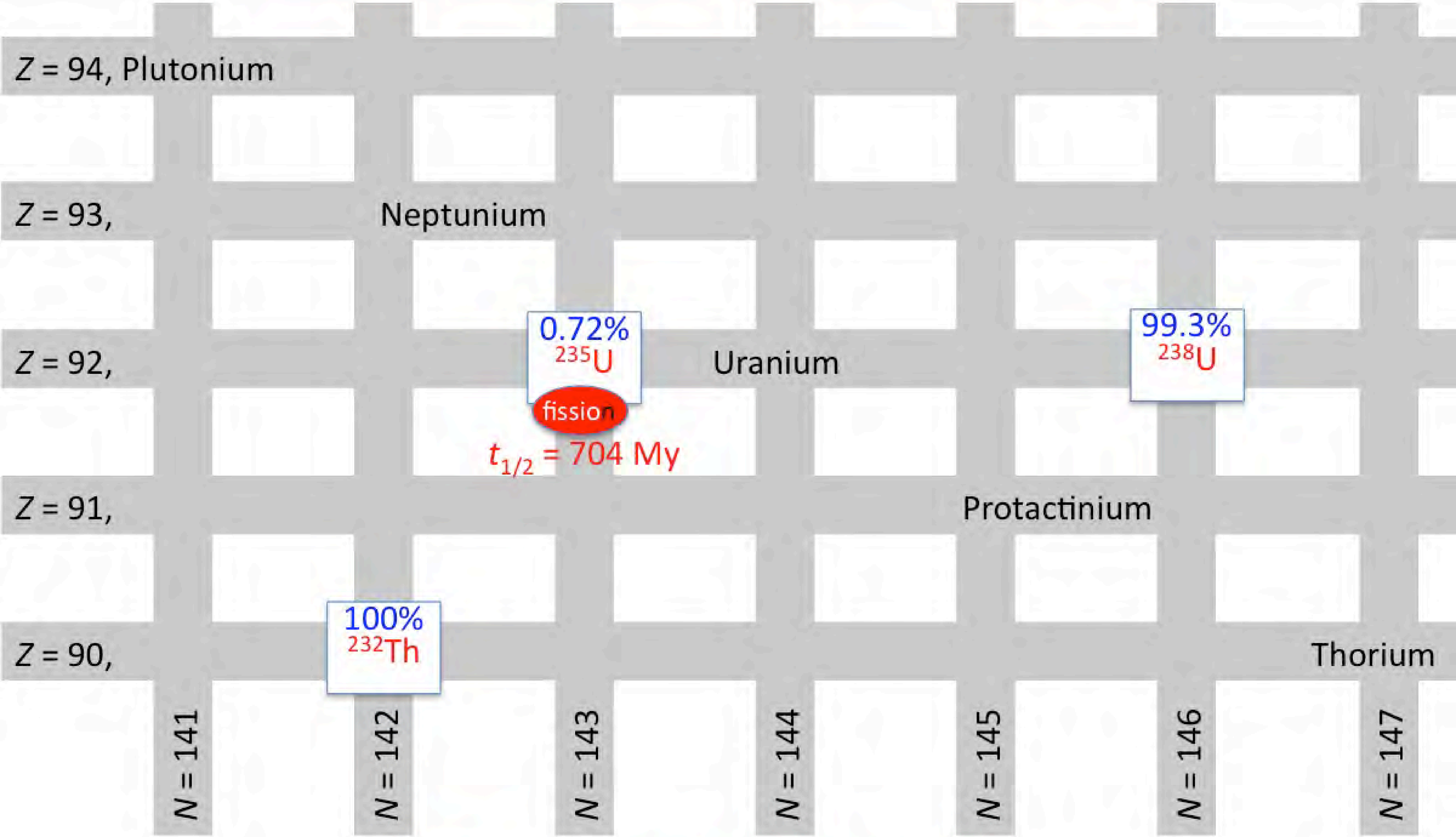
- Fission
  - Splitting of heavy nuclei
  - Main source of internal heating of Earth (~50 TW)
  - Uranium, Plutonium, Thorium
- Fusion
  - Merging of light nuclei
  - Powering the sun (~$3.85 \cdot 10^{14}$ TW)
  - Hydrogen isotopes
  - CNO cycle (0.8% of solar power)



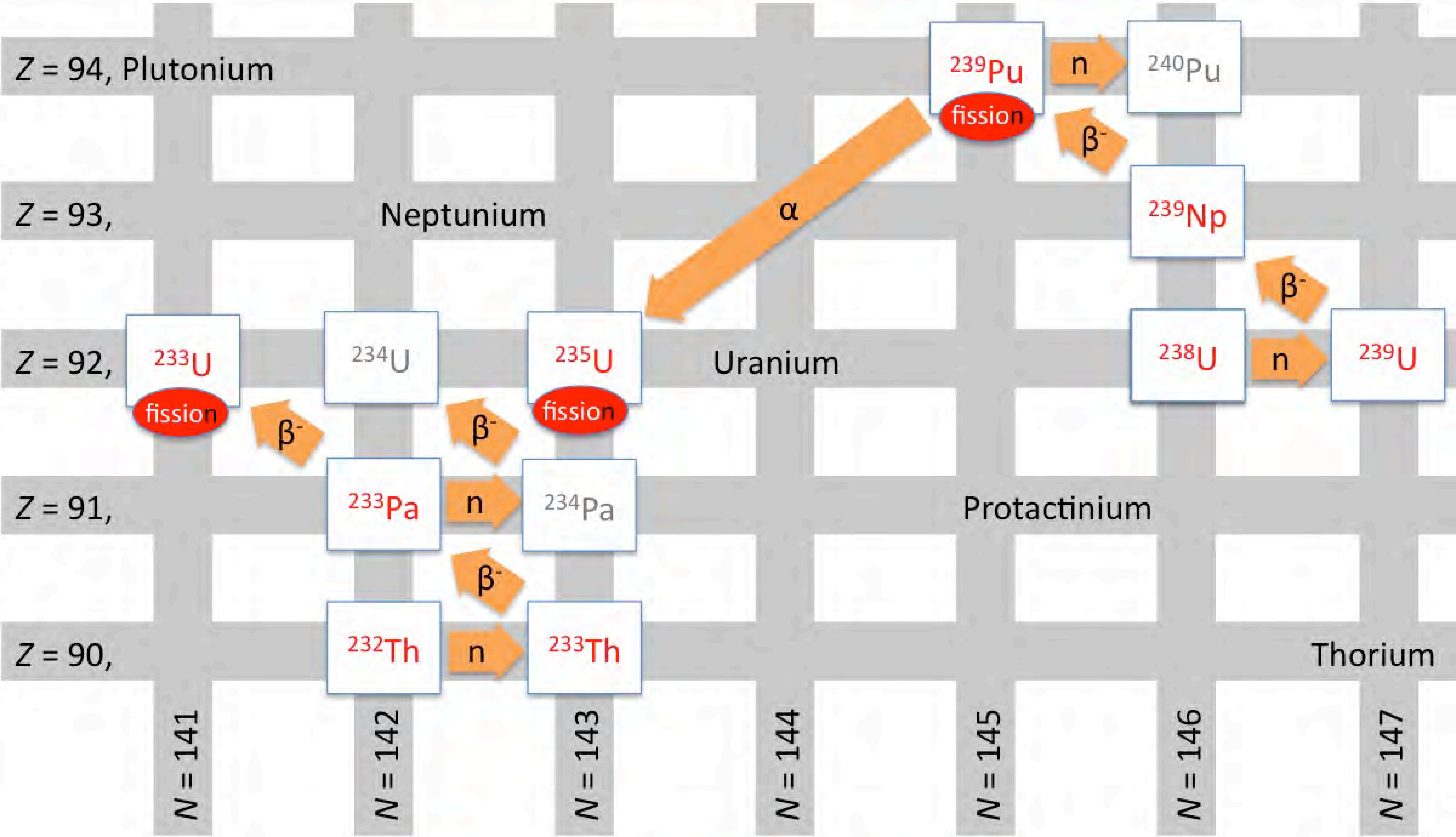
Isotope Half-Life



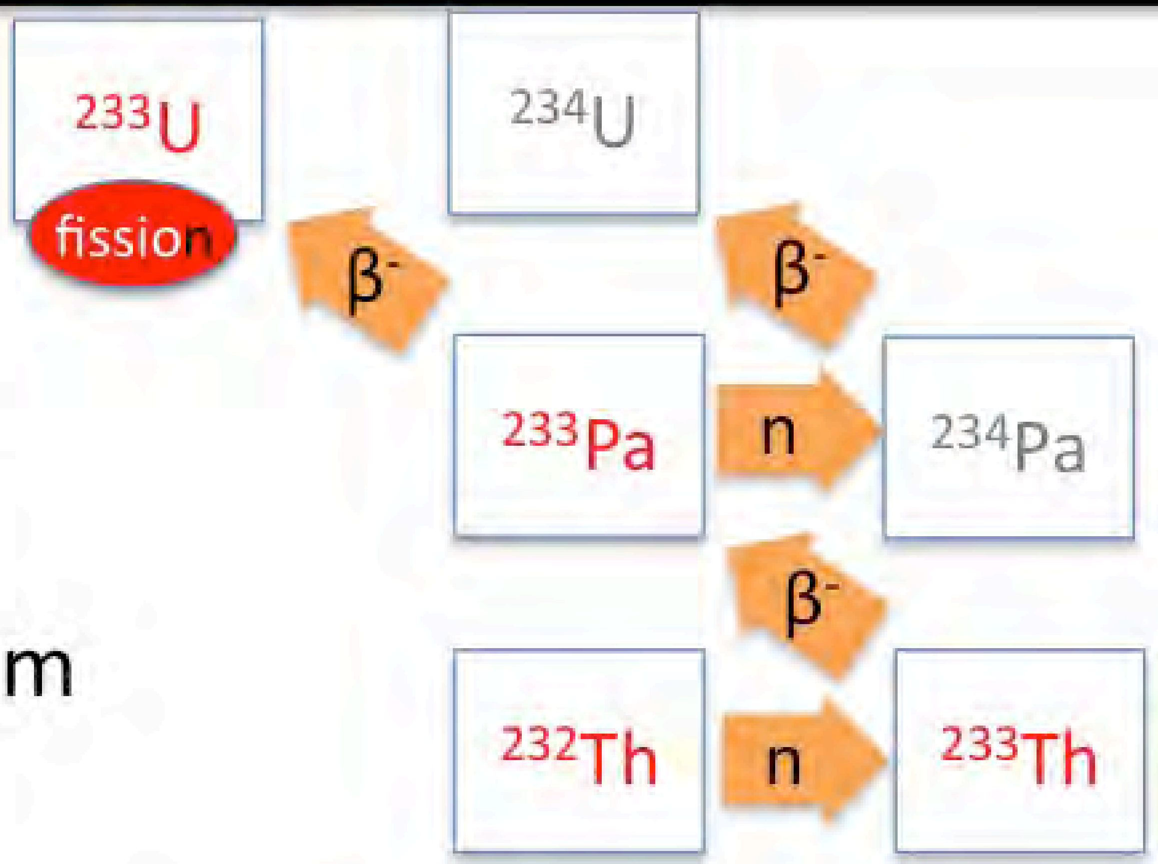
Naturally Occurring Isotopes



Breeder Fission Cycles



Thorium Breeder Cycle



- Fundamental Problem
  - ^{233}Pa n-capture cross section too large
  - preventing a self-sustaining fission cycle
- Two possible remedies
  - Chemically separate ^{233}Pa and remove from n-flux (two-fluid Molten Salt Reactor) [First proposed by Alvin Weinberg]
  - Continually add neutrons (Accelerator-Driven Design) [First proposed by Ernest Lawrence]
- Disadvantage relative to U-breeder
  - Lower net energy yield
- Advantages
  - No runaway chain reaction possible
  - Much less long-lived transuranic waste

United States Patent	**5,774,514**
Rubbia	**June 30, 1998**

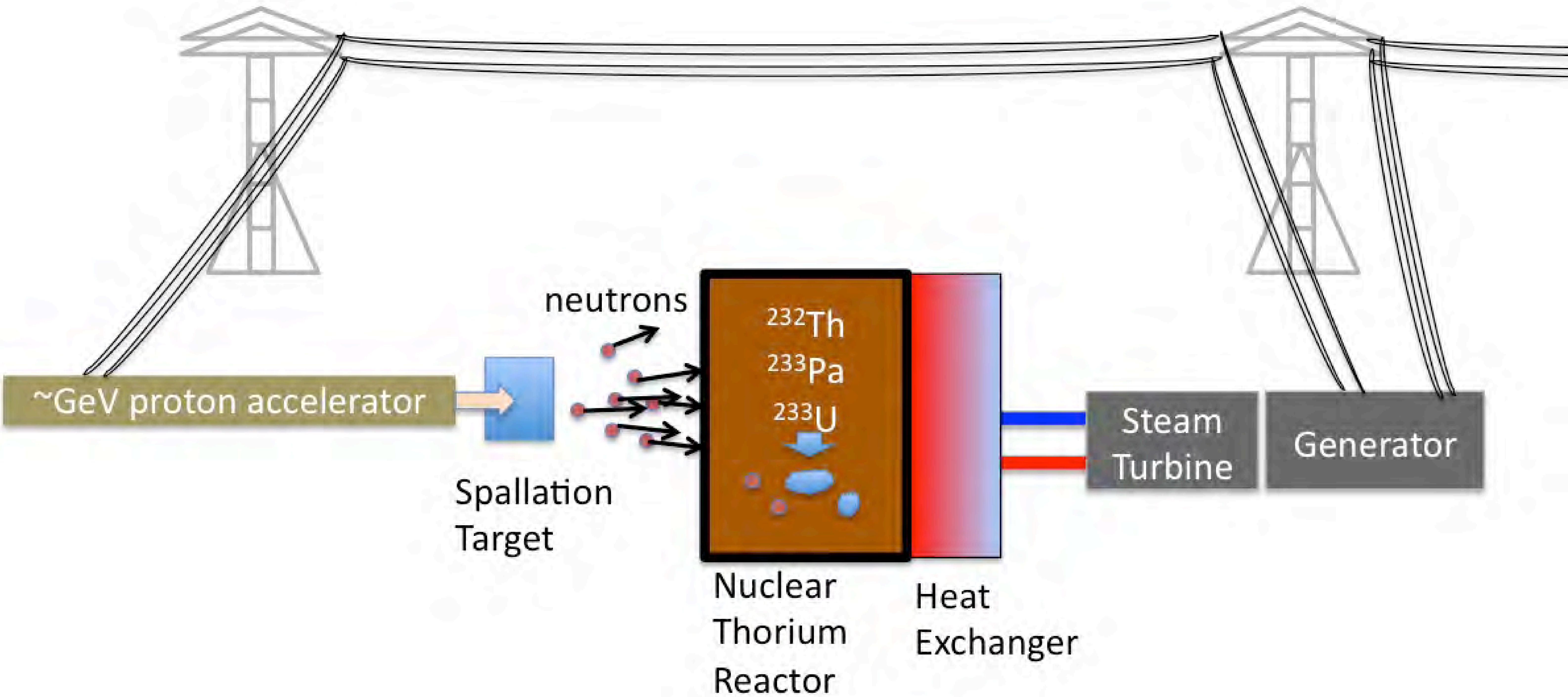
Energy amplifier for nuclear energy production driven by a particle beam accelerator

Abstract

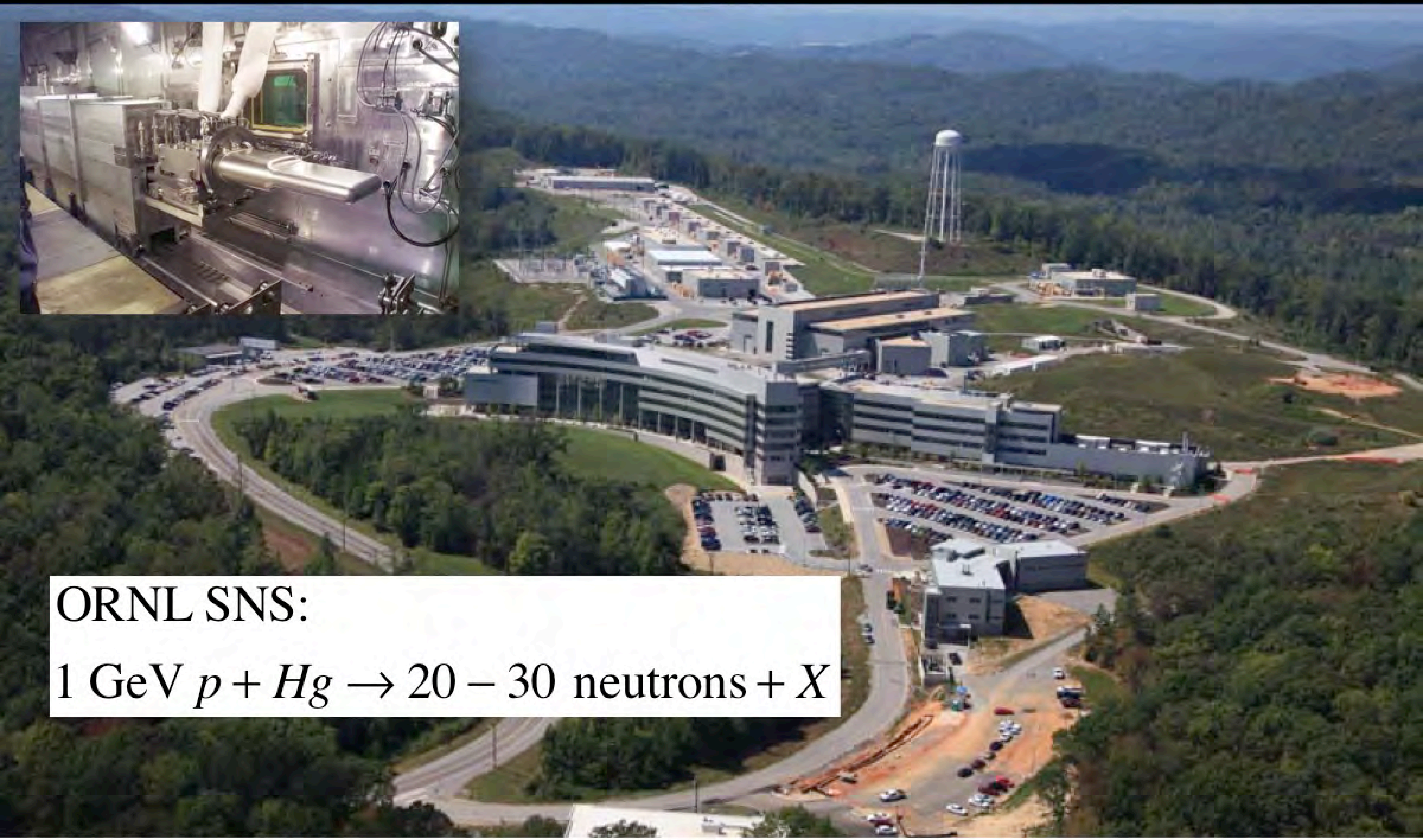
A method for producing energy from a nuclear fuel material contained in an enclosure, through a process of breeding of a fissile element from a fertile element of the fuel material via a .beta.-precursor of the fissile element and fission of the fissile element. A high energy particle beam is directed into the enclosure for interacting with heavy nuclei contained in the enclosure so as to produce high energy spallation neutrons. The neutrons thereby produced are multiplied in steady sub-critical conditions by the breeding and fission process. The breeding and fission process is carried out inside the enclosure.

Inventors:	**Rubbia; Carlo** (Geneve, **CH**)
Family ID:	**8213381**
Appl. No.:	**08/632,424**
Filed:	**April 24, 1996**
PCT Filed:	**July 25, 1994**
PCT No.:	**PCT/EP94/02467**
371 Date:	**April 24, 1996**
102(e) Date:	**April 24, 1996**
PCT Pub. No.:	**WO95/12203**
PCT Pub. Date:	**May 04, 1995**

Accelerator Driven Concept



Neutron Production via Spallation

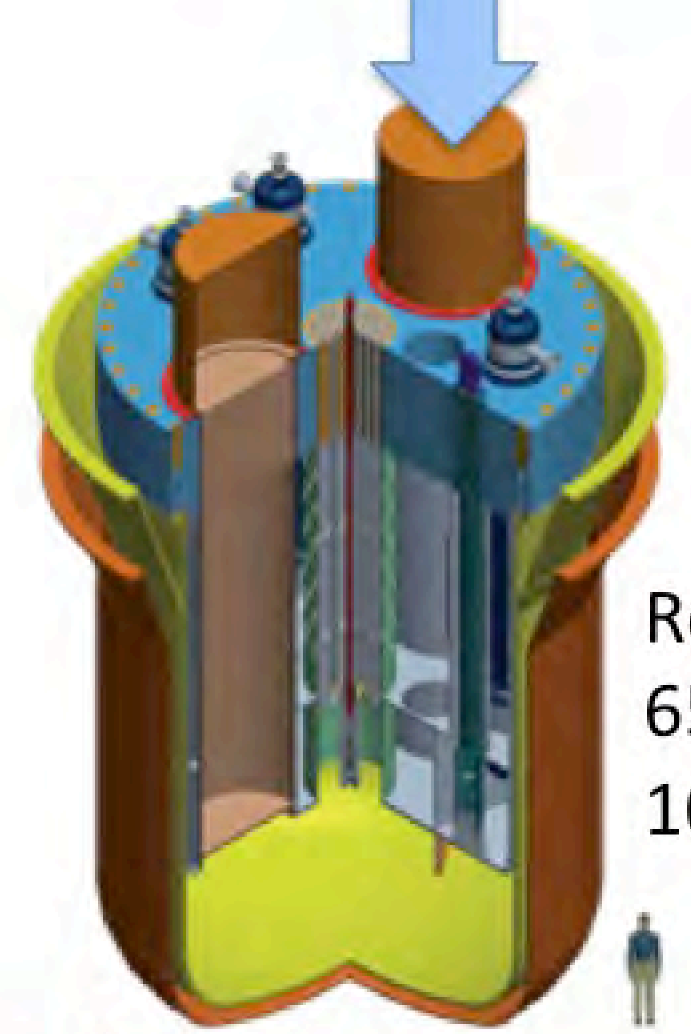


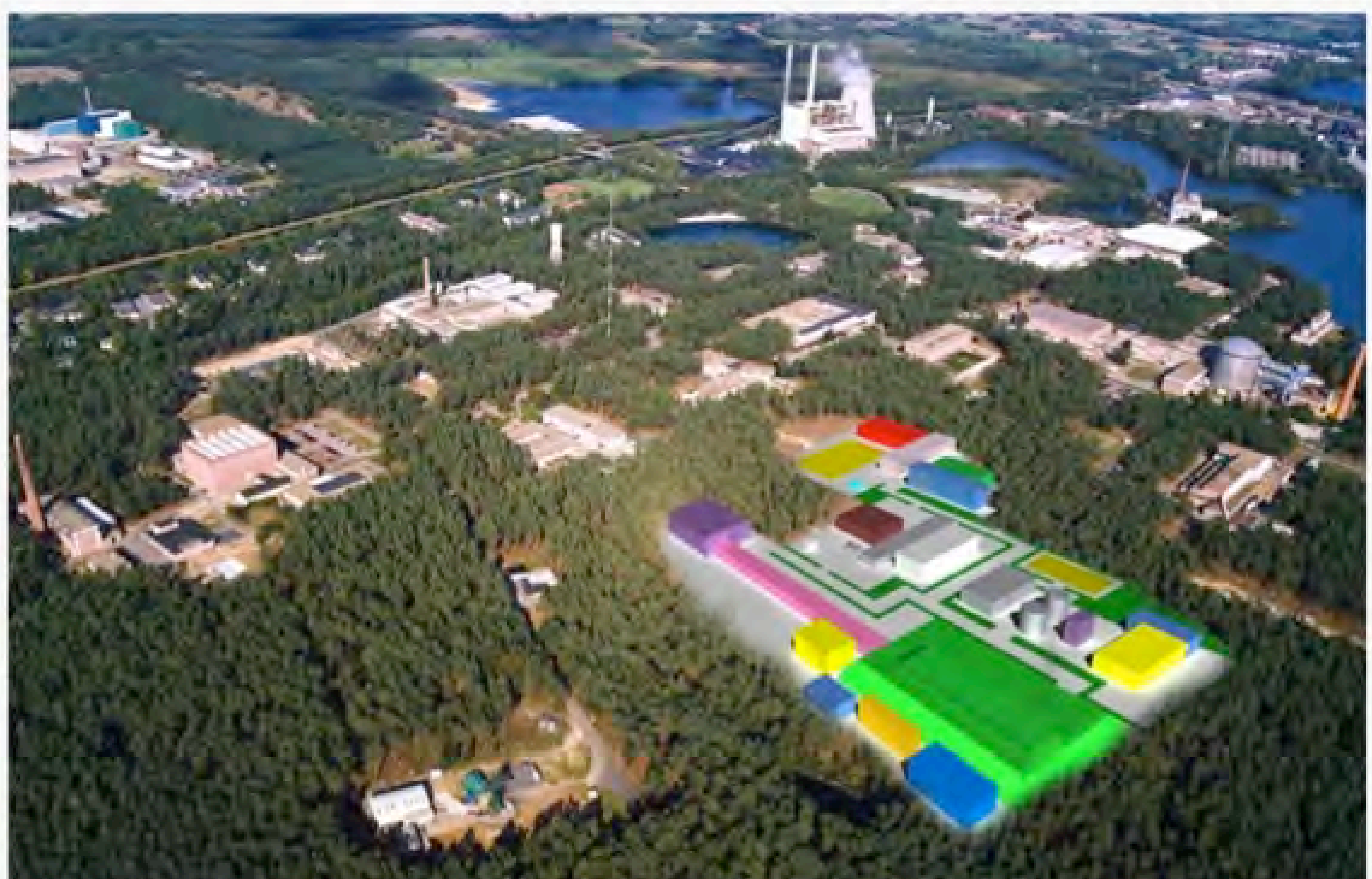
ORNL SNS:

$1\text{ GeV } p + Hg \rightarrow 20 - 30 \text{ neutrons} + X$

Accelerator-Driven System (ADS)

- Example: MYRRHA reactor (Belgium)
  - MOX fuel
  - M€960
  - To be operational in 2023





http://myrrha.sckcen.be/

United States Patent **8,594,268**
Shu **November 26, 2013**

Two-fluid molten-salt reactor

Abstract

A reactor vessel includes a plenum and a reactor core with first and second sets of channels. A blanket salt flows through the first set of channels, and a fuel salt flows through the second set of channels. The plenum receives the blanket salt from the first set of channels. The blanket salt provides a breed-stock for a fission reaction in the fuel salt and transfers heat generated by the fission reaction without mixing with the fuel salt.

Inventors: **Shu; Frank H.** (Solana Beach, CA)

Applicant:

Name	City	State	Country	Type
Shu; Frank H.	Solana Beach	CA	US	

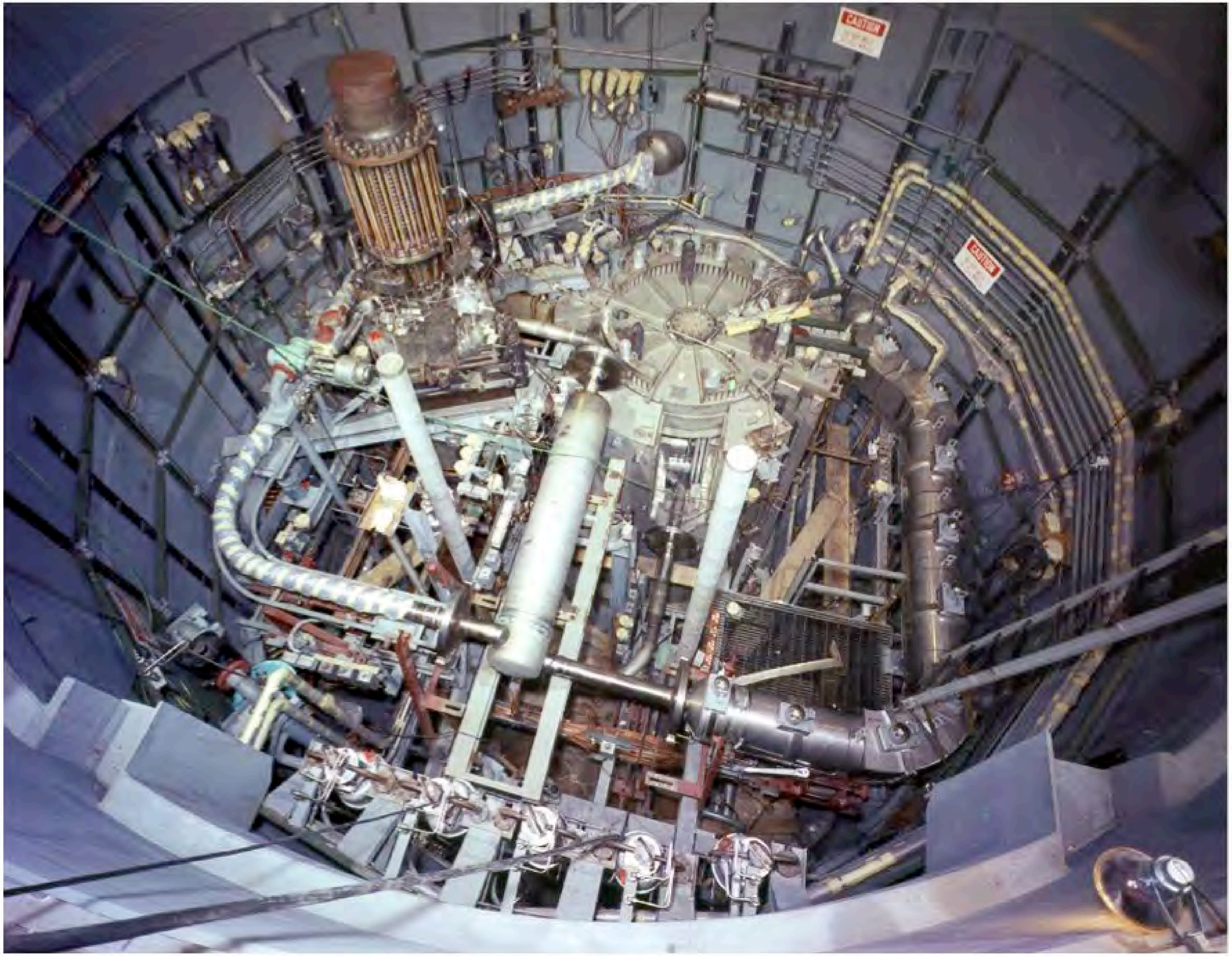
Assignee: **Shu; Frank H.** (Solana Beach, FL)
Academia Sinica (Taipei, **TW**)

Family ID: **42342652**

Appl. No.: **13/290,711**

Filed: **November 7, 2011**

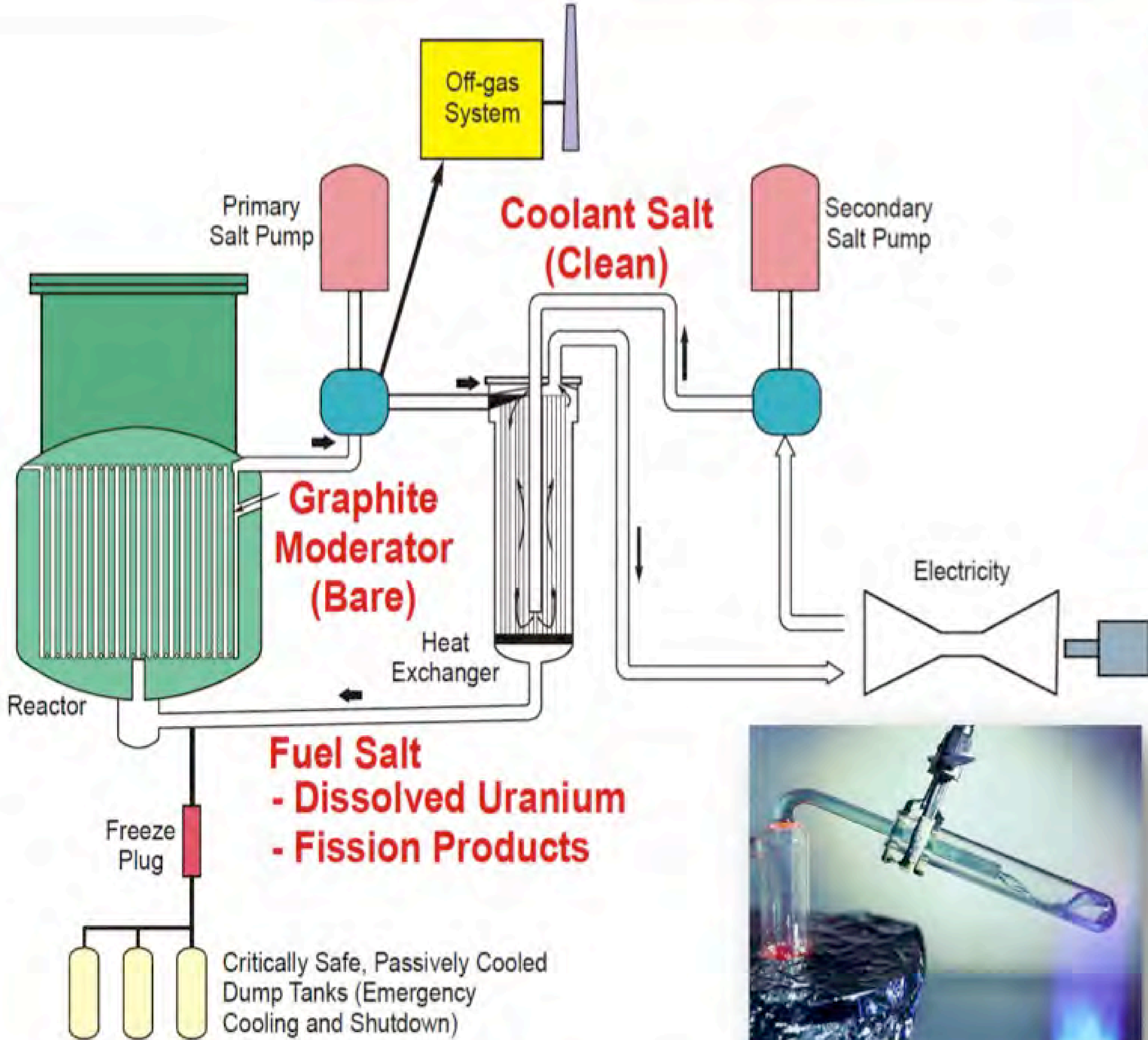
ORNL Molten Salt Reactor



- 8 MW
- Core volume $< 2\ m^3$
- Fuel
  - ^{235}U
  - ^{233}U
- 1965-69
  - ~22,000 hours of operation

Charles Forsberg
DOE LS-VHTR mtg
April 2006

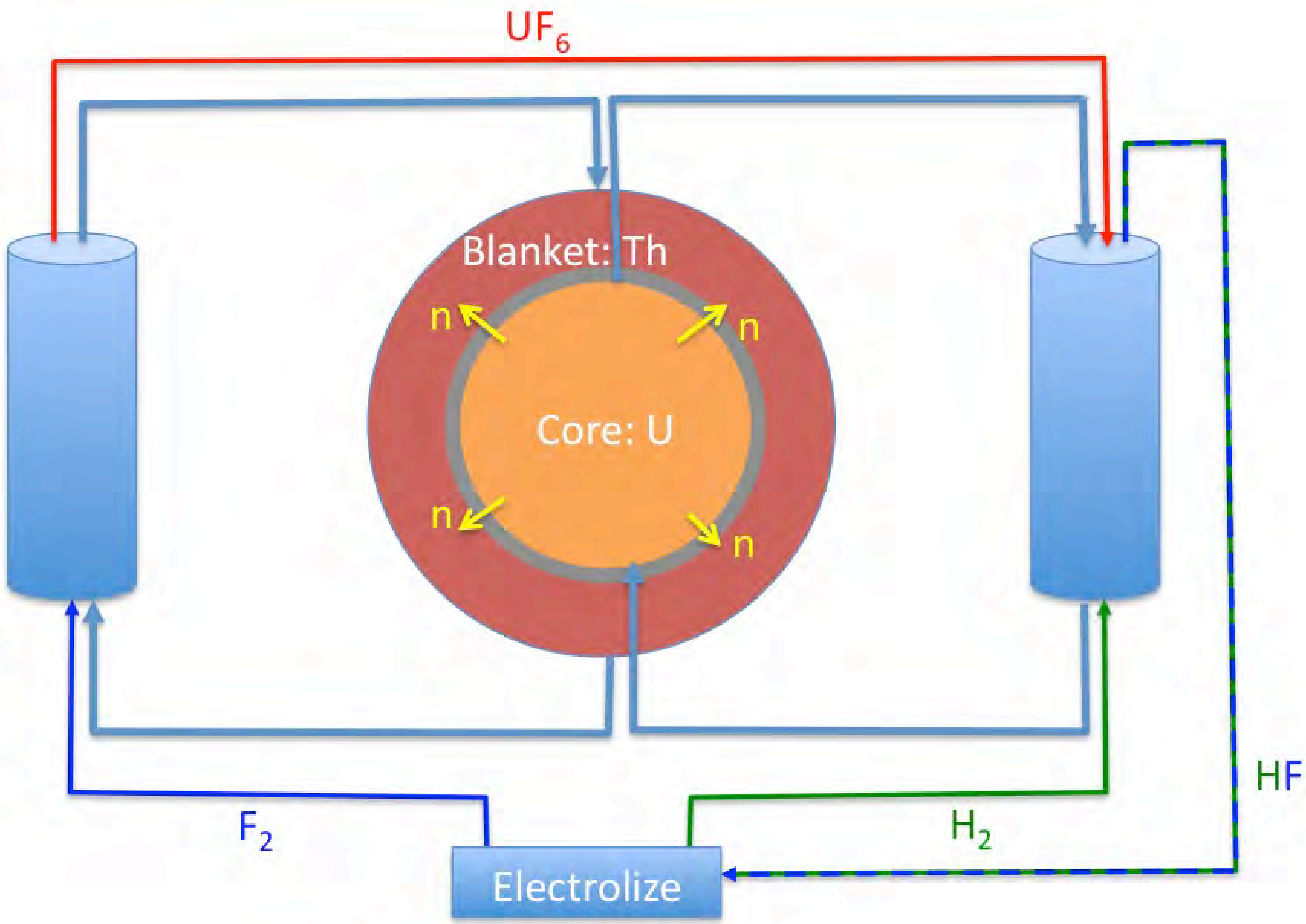
ORNL Molten Salt Reactor



- 2 Liquid Salt Cycles
- Primary (with fuel)
  - $LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$ (65%-29%-5%-1%)
  - U can be removed with F gas via $UF_4 + F_2 \rightarrow UF_6$
- Cooling salt
  - "FLiBe"
  - $LiF\text{-}BeF_2$ (67%-33%)

Charles Forsberg
DOE LS-VHTR mtg
April 2006

2-Fluid Liquid Fluoride Thorium Reactor



Frank Shu

Two-Fluid MSR

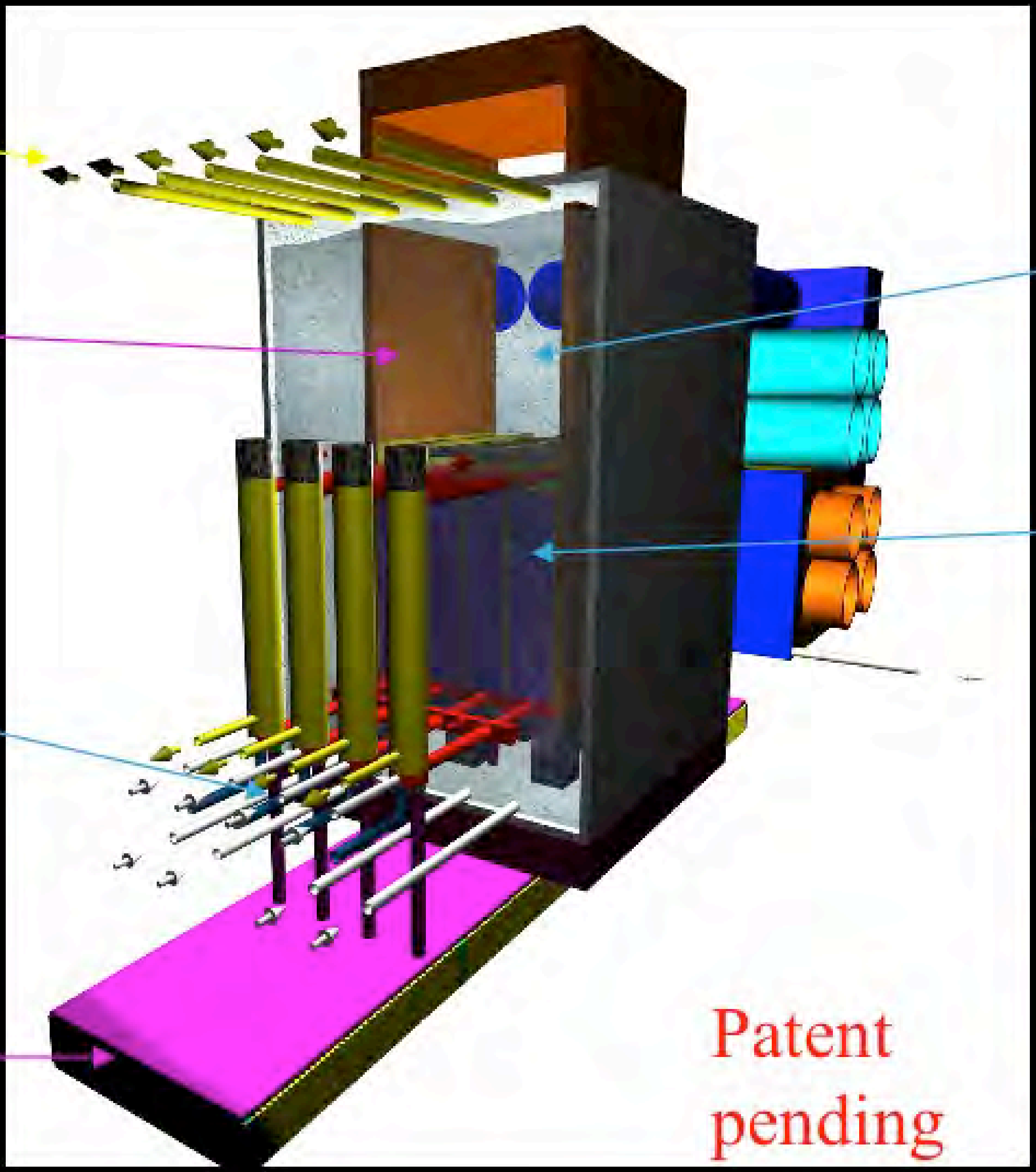
Except for dump tank, system built from C/C composites

He purge of gaseous Xe-135

Active/passive control

Passive safety feature 4: If *T* still rises, solid plug melts, & fuel salt drains into (cooled) dump tank.

Air-cooled dump tank to remove decay heat; cannot lose air coolant



Passive safety feature 2 & 3: Lose coolant salt, lose n reflector; if over-heated, fuel salt expands out of reaction zone.

Breeding ratio for U3/TB can be as high as 1.12 without extracting Pa-233 (diluted in large blanket/pool).

Molten salt, low vapor pressure. Fuel molten: no radiation damage, circulate until 100% burn-up, no meltdown, no TMI. Double-walled outer containment, no Chernobyl nor jet crashes. Burn Pu; U-232 accompanies U-233; no bombs.

THTR-300: Failed Experiment

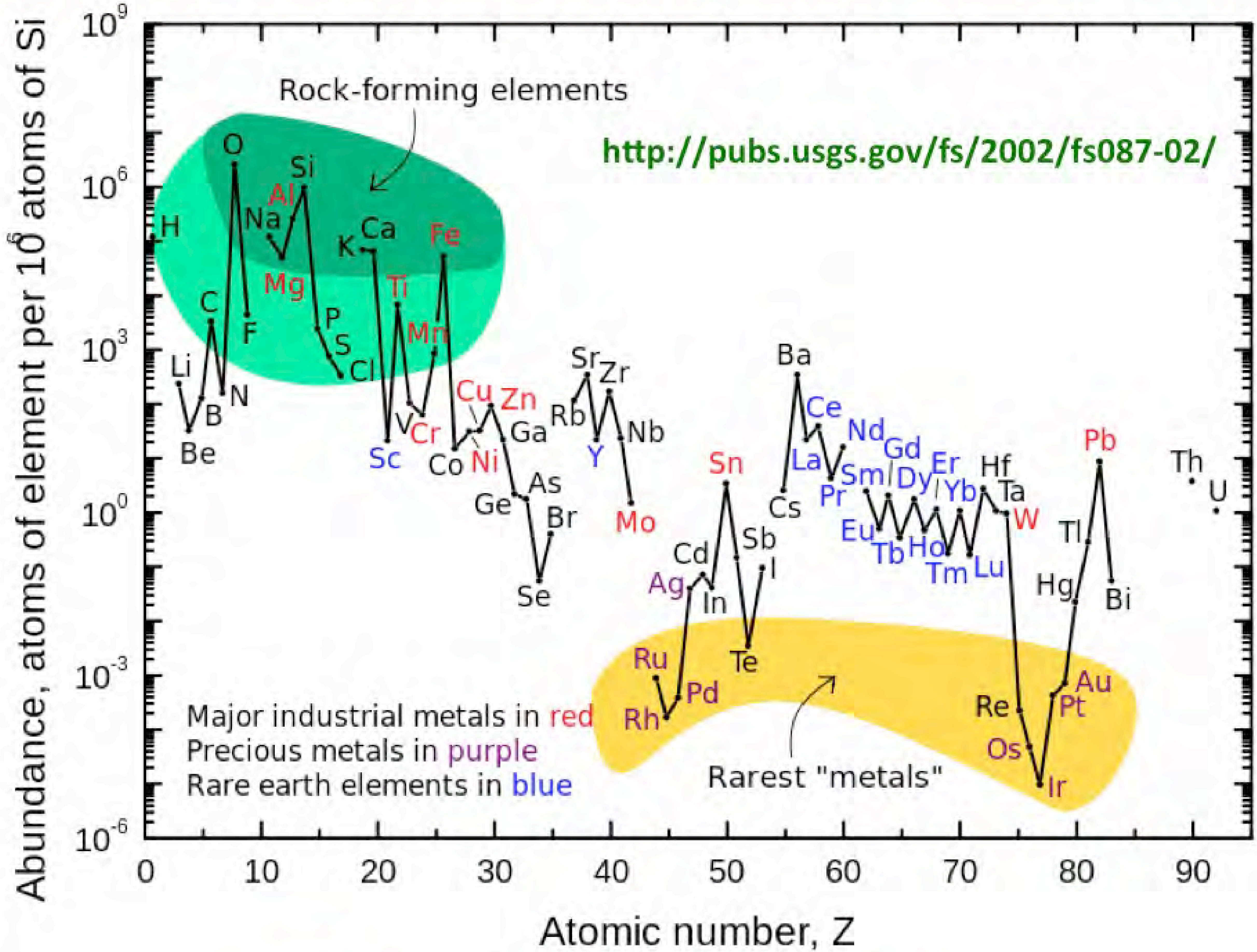
- 300 MW Thorium High Temperature Reactor
- Pebble bed core:
  6 cm diameter graphite pebbles with U and Th embedded
- Ran 1985-1989
- Located in Hamm-Uentrop, Germany
- Was shut down after fuel pebble got stuck and some radioactive gas escaped
- Cost: > €2 billion

Energy Yield

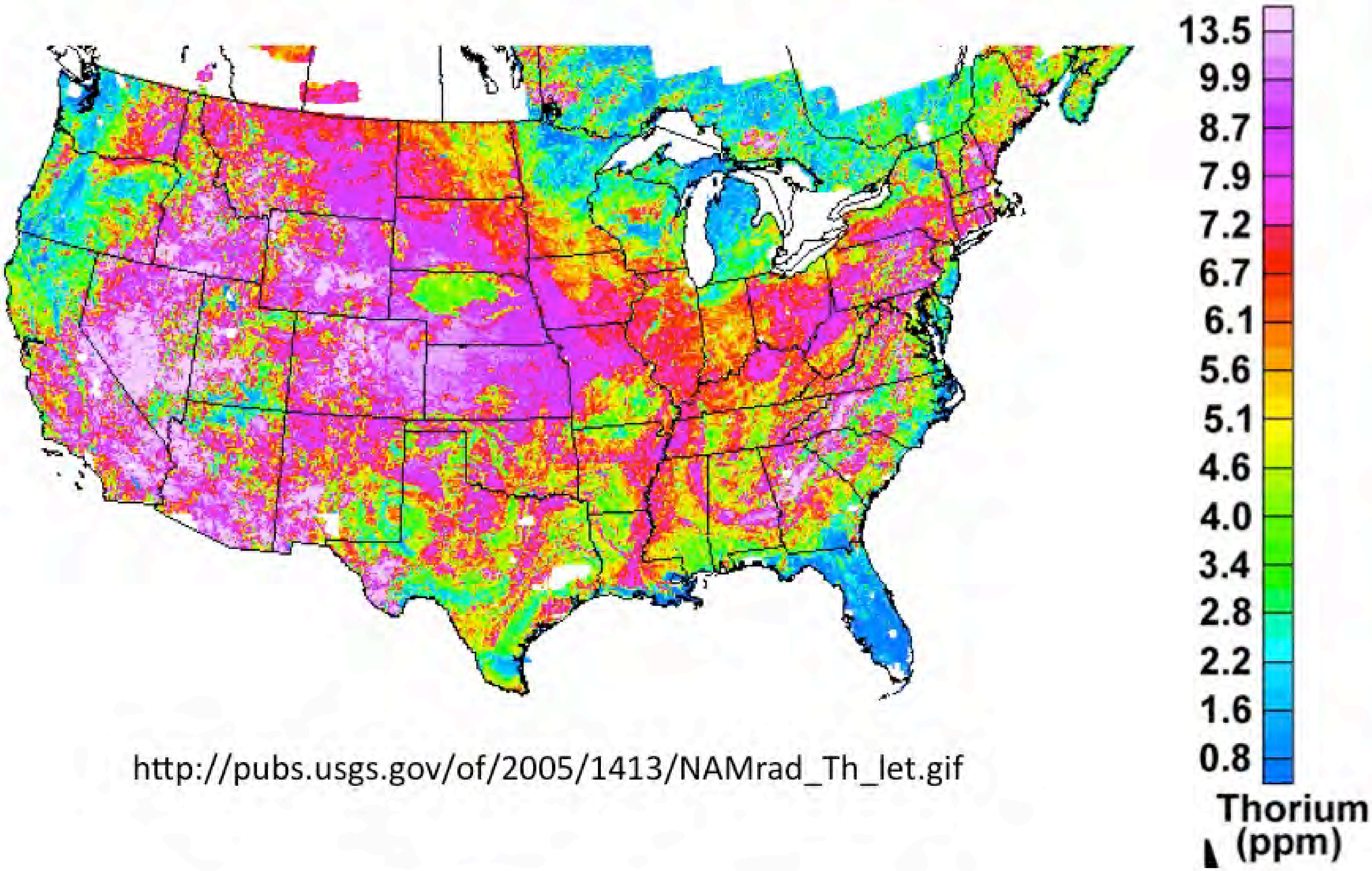
- 1 ton of Th
  - Cost: \$300k
  - Fission energy release ~10 TWh
- 20,000 tons of Th needed per year to satisfy all human power needs

Robert Hargraves "Thorium energy cheaper than coal"

Element Abundances in Earth's Crust



US Thorium Concentration



http://pubs.usgs.gov/of/2005/1413/NAMrad_Th_let.gif

Thorium Mining

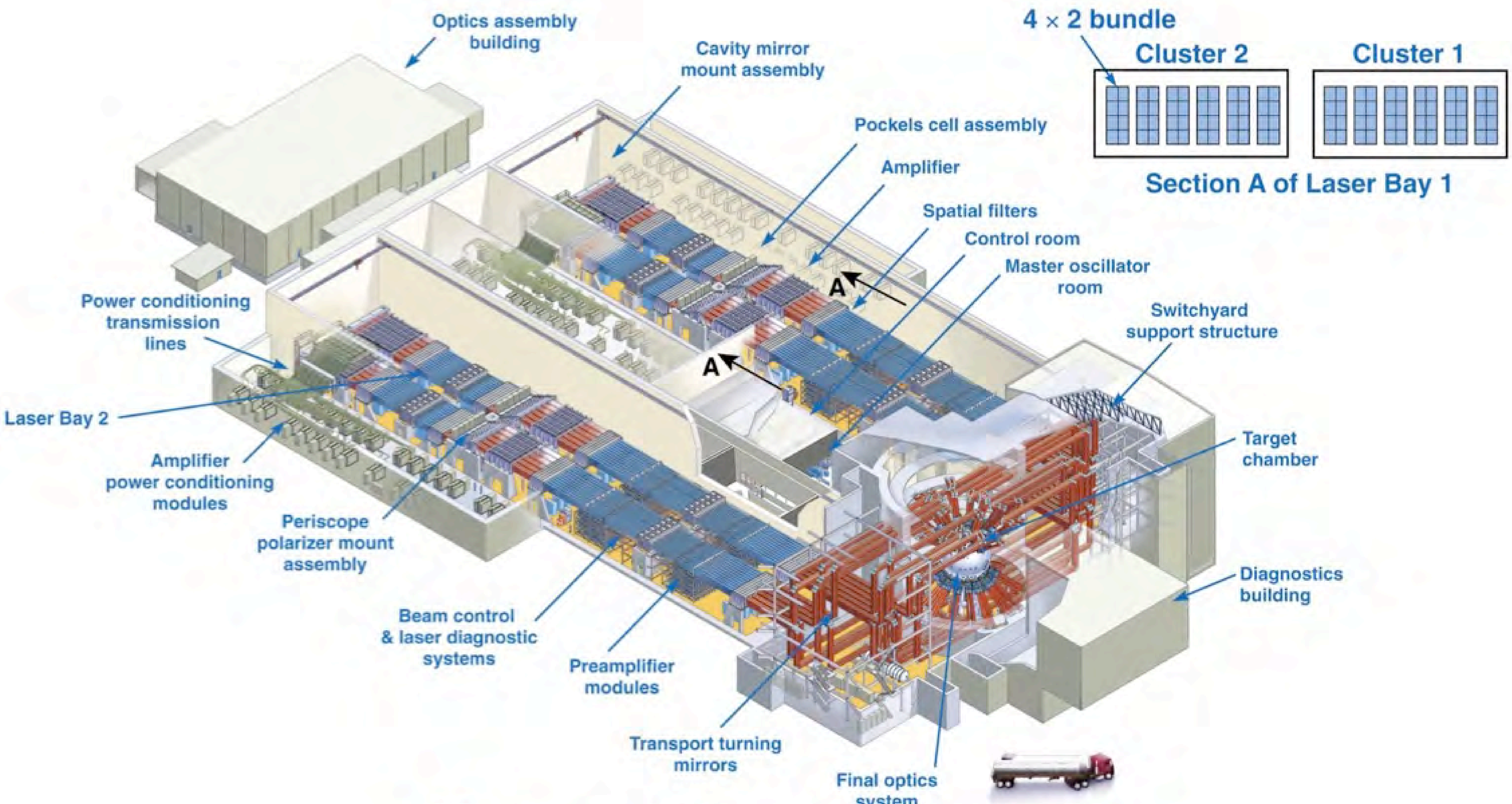
- Monazite (Phosphate rare earth compounds)
  - $(Ce,Th)PO_4$
  - $(Sm,Th)PO_4$
  - …
- Molycorp Mountain Pass
  - Only US rare earth mine
  - In Mojave desert
  - Off I15, near CA/NV border

Thorium Reserves: Sufficient for 1,000 years

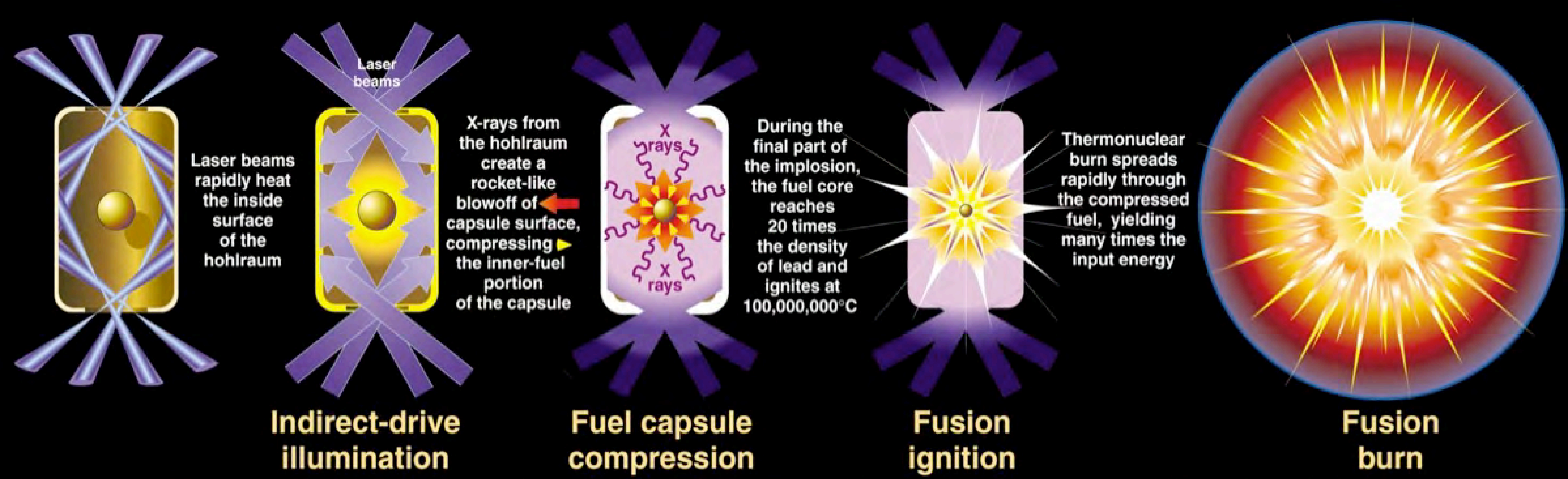
Country	Reserves (1000 metric tons)
India	963
USA	440
Australia	300
Canada	100
South Africa	35
Brazil	16
Malaysia	4.5
Other countries	90
World total	1,913

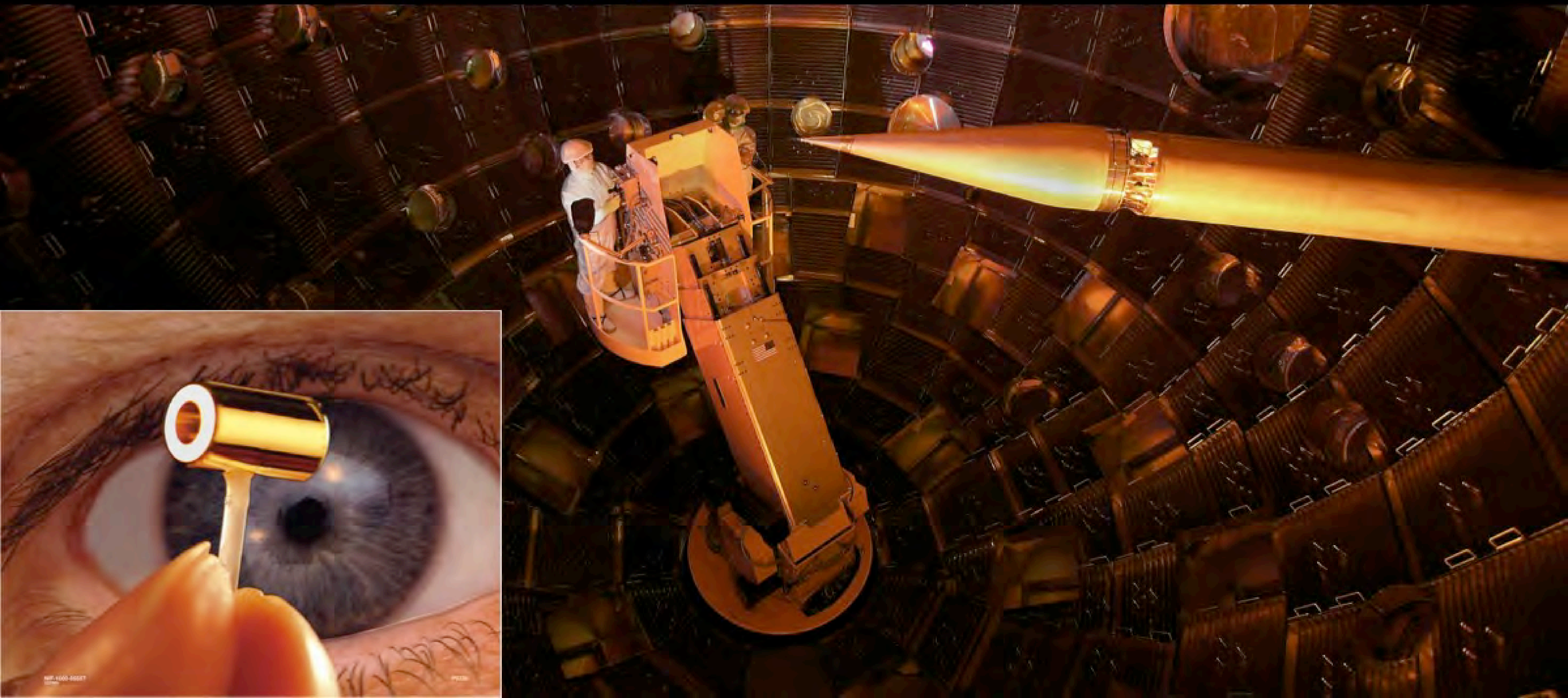
2011 USGS Estimate

NIF

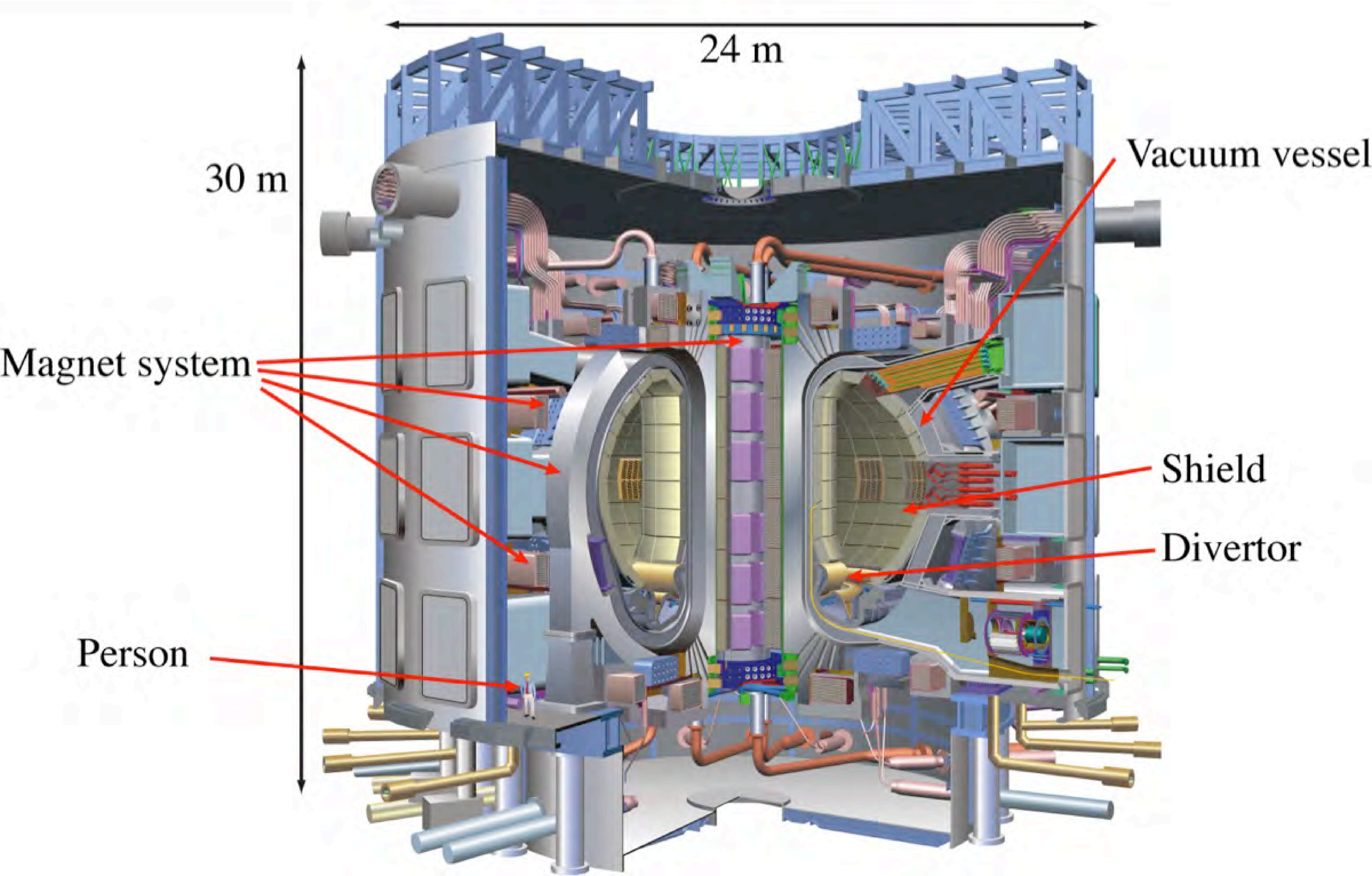


Optics assembly building
Cavity mirror mount assembly
4 × 2 bundle
Cluster 2
Cluster 1
Section A of Laser Bay 1
Pockels cell assembly
Amplifier
Spatial filters
Control room
Master oscillator room
Switchyard support structure
Power conditioning transmission lines
A
A
Laser Bay 2
Amplifier power conditioning modules
Periscope polarizer mount assembly
Target chamber
Diagnostics building
Beam control & laser diagnostic systems
Preamplifier modules
Transport turning mirrors
Final optics system


Laser beams rapidly heat the inside surface of the hohlraum
Laser beams
X-rays from the hohlraum create a rocket-like blowoff of capsule surface, compressing the inner-fuel portion of the capsule
X rays
X rays
During the final part of the implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy
Indirect-drive illumination
Fuel capsule compression
Fusion ignition
Fusion burn



ITER



24 m
30 m
Vacuum vessel
Magnet system
Shield
Divertor
Person

Nuclear Fusion

- ITER, NIF, Z-machine, …:
  always 30-50 years in the future

Nuclear Fusion

- ITER, NIF, Z-machine, …:
  always 30-50 years in the future
- Possible game changer?
  - Lockheed-Martin
    Skunk Works: "will have a commercial fusion reactor in a decade!"