Molten Salt Reactors and Thorium Energy

Thomas J. Dolan

8th Thorium Energy Alliance Conference
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2017.08.21

American Nuclear Society Speakers Bureau

Topics

New book

Thorium fuel

MSR History

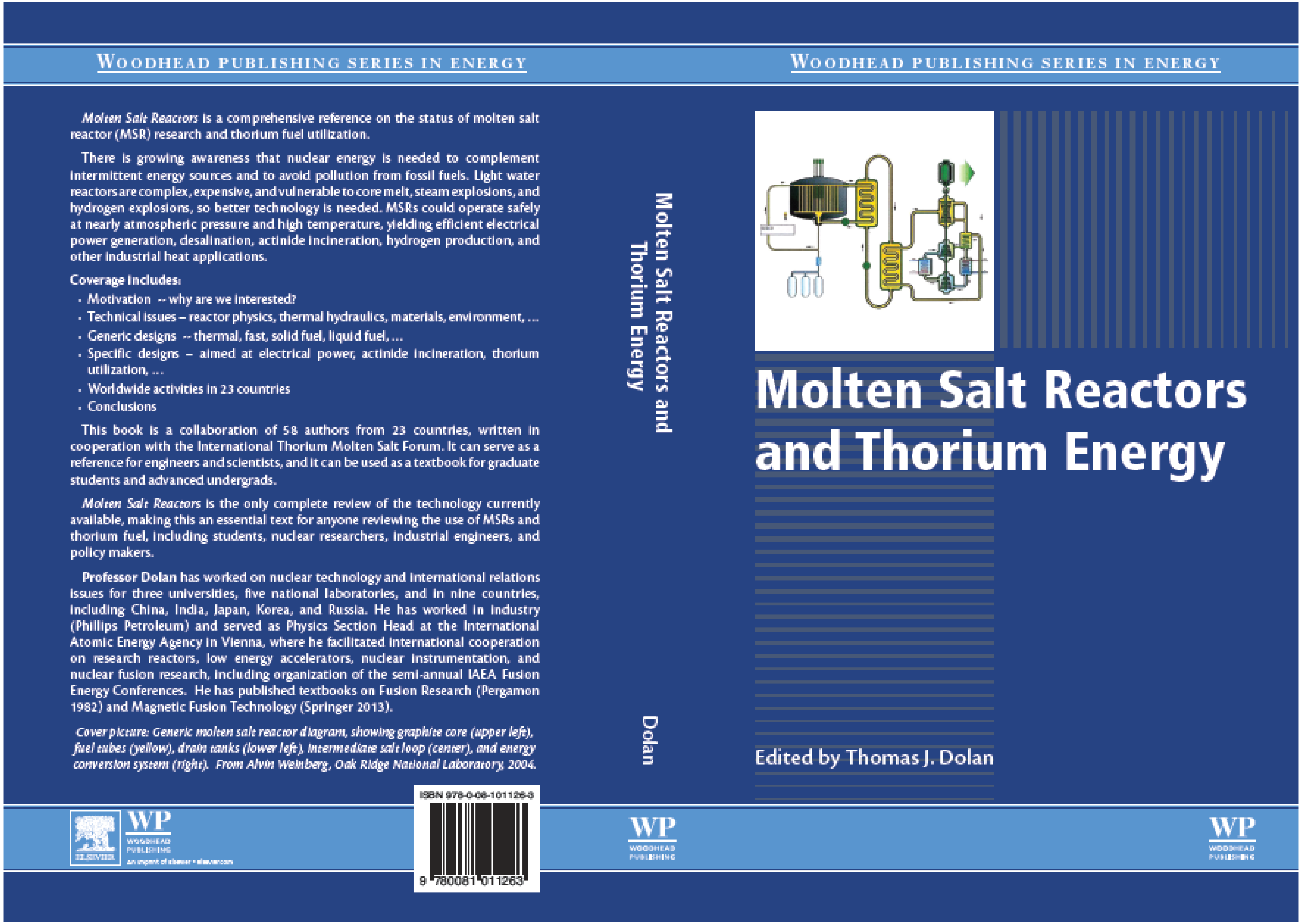
Solid fuel MSR

Liquid fuel MSR

LWR problems

Development Issues

Worldwide activities


WOODHEAD PUBLISHING SERIES IN ENERGY

Molten Salt Reactors is a comprehensive reference on the status of molten salt reactor (MSR) research and thorium fuel utilization.

There is growing awareness that nuclear energy is needed to complement intermittent energy sources and to avoid pollution from fossil fuels. Light water reactors are complex, expensive, and vulnerable to core melt, steam explosions, and hydrogen explosions, so better technology is needed. MSRs could operate safely at nearly atmospheric pressure and high temperature, yielding efficient electrical power generation, desalination, actinide incineration, hydrogen production, and other industrial heat applications.

Coverage includes:

- Motivation -- why are we interested?
- Technical issues – reactor physics, thermal hydraulics, materials, environment, …
- Generic designs -- thermal, fast, solid fuel, liquid fuel, …
- Specific designs – aimed at electrical power, actinide incineration, thorium utilization, …
- Worldwide activities in 23 countries
- Conclusions

This book is a collaboration of 58 authors from 23 countries, written in cooperation with the International Thorium Molten Salt Forum. It can serve as a reference for engineers and scientists, and it can be used as a textbook for graduate students and advanced undergrads.

Molten Salt Reactors is the only complete review of the technology currently available, making this an essential text for anyone reviewing the use of MSRs and thorium fuel, including students, nuclear researchers, industrial engineers, and policy makers.

Professor Dolan has worked on nuclear technology and international relations issues for three universities, five national laboratories, and in nine countries, including China, India, Japan, Korea, and Russia. He has worked in industry (Phillips Petroleum) and served as Physics Section Head at the International Atomic Energy Agency in Vienna, where he facilitated international cooperation on research reactors, low energy accelerators, nuclear instrumentation, and nuclear fusion research, including organization of the semi-annual IAEA Fusion Energy Conferences. He has published textbooks on Fusion Research (Pergamon 1982) and Magnetic Fusion Technology (Springer 2013).

Cover picture: Generic molten salt reactor diagram, showing graphite core (upper left), fuel tubes (yellow), drain tanks (lower left), intermediate salt loop (center), and energy conversion system (right). From Alvin Weinberg, Oak Ridge National Laboratory, 2004.

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Molten Salt Reactors and Thorium Energy

Edited by Thomas J. Dolan

WP WOODHEAD PUBLISHING

Elsevier, 2017

Motivation

1. Introduction **Dolan**

need for MSR
thorium Fuel
liquid fuel reactors
development Issues

2. Electricity Production

electrical power cycles **Dempsey, Dolan, Forsberg**
combined cycles

3. Other MSR Applications **Boyd**

molten salt chemistry
H_2 production
medical isotopes
actinide incineration, …

Technical Issues

4. Reactor Physics — Shimazu

5. Kinetics and Dynamics — Pazsit, Dykin

6. Thermal Hydraulics — Luzzi, Cammi, DiMarcello, Pini

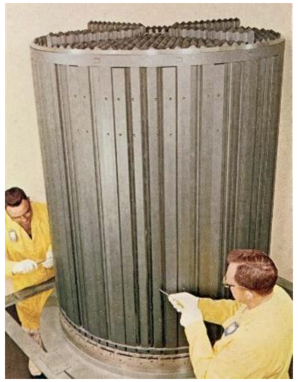
7. Materials — Furukawa, Yoshioka, Kinoshita, Scott

8. Chemical Processing of Liquid Fuel — Uhlir

9. Environment, Waste, Resources — Yoshioka, Kinoshita, Jorgensen, Ragheb

10. Safeguards, Nonproliferation — Grape, Helleson

Generic MSR Designs



MSRE

11. Liquid fuel, thermal reactors	**Yoshioka, Kinoshita**
12. Liquid fuel, fast/epithermal reactors	**Ponomarev**
13. Solid fuel salt-cooled reactors	**Scarlat, Andreades**
14. Static liquid fuel reactors	**Scott**
15. Accelerator Driven Systems	**Furukawa, Yoshioka, Kinoshita, Degtyarev, Myasnikov, Sajo-Bohus, Greaves**
16. Fusion-fission hybrids	**Velikhov**

Specific MSR Designs

17. Thorium Molten Salt Reactor	**Dai**
18. Integrated Molten Salt Reactor	**LeBlanc, Rodenburg**
19. ThorCon Reactor	**Jorgenson**
20. SAMOFAR	**Kloosterman**
21. Stable Salt Fast Reactor	**Scott**

Specific MSR Designs

22. Transatomic Power	**Dewan**
23. Copenhagen Atomic Waste Burner	**Pedersen**
24. Molten Salt Thermal Waste Burner	**Schonfeldt, Klinkby**
25. Dual Fluid Reactor	**Huke**

Chapter 26. Worldwide Activities

Australia
Canada
Czech
China
Denmark
France
Germany
India
Indonesia
Italy
Japan
Korea
Netherlands
Norway
Russia
South Africa
Sweden
Switzerland
Turkey
UK
Ukraine
USA
Venezuela

Thorium Fuel Cycle

Breeding ^{233}U from ^{232}Th

$$n + {}^{232}Th \rightarrow {}^{233}Th \xrightarrow[22\min]{\beta^-} {}^{233}Pa \xrightarrow[27d]{\beta^-} {}^{233}U$$

Fissile fuel

Avoid $^{233}Pa + n$ *reactions*

One ton ThO_2 (MSR) ≈ 293 tons U_3O_8 (LWR)

enrichment

293 ton U_3O_8 → 1.15 ton ^{235}U → 1 GWe-yr

neutron absorption

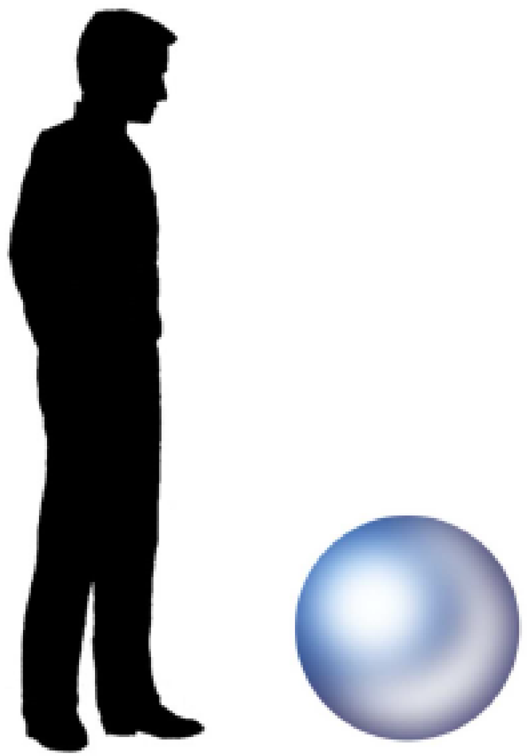
1 ton ThO_2 → 1 ton ^{233}U → 1 GWe-yr

Th abundance ≈ 4 times U abundance

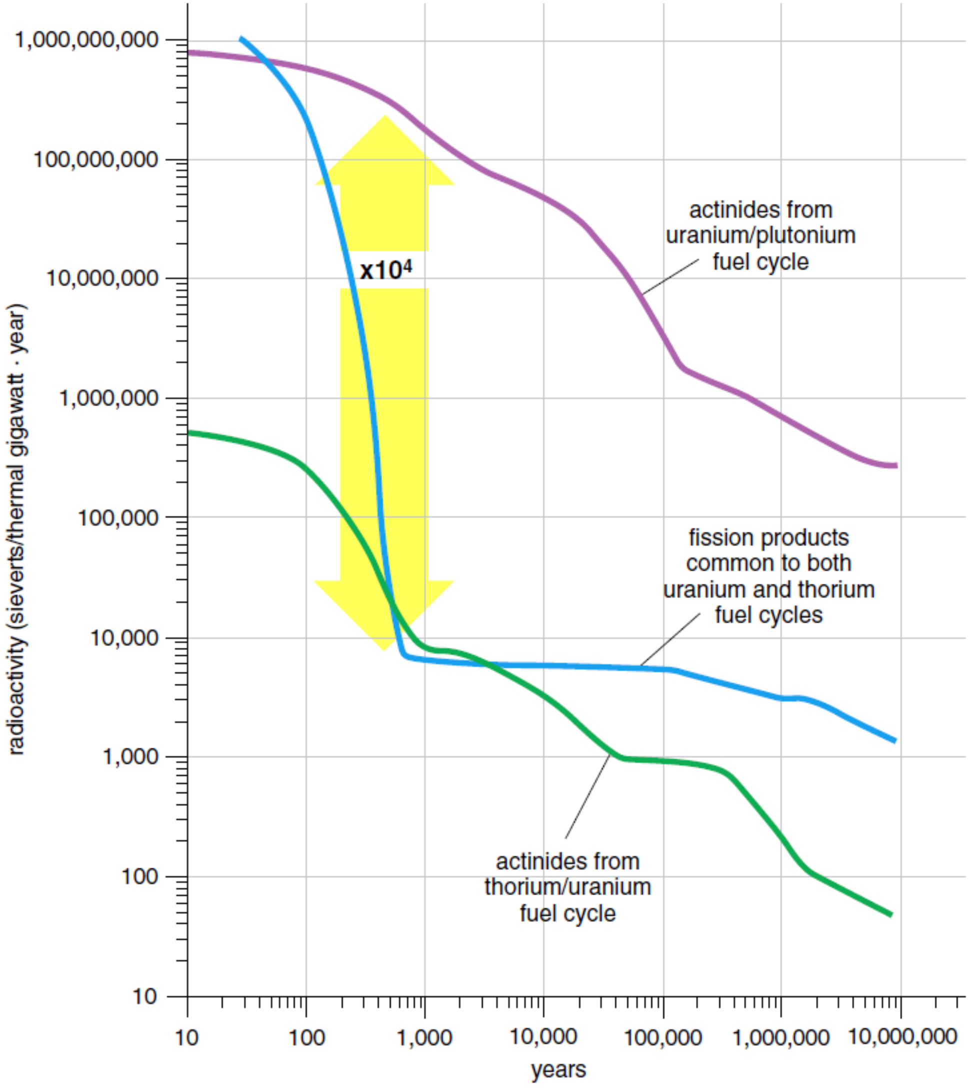
One ton of Thorium

Cost ≈ 0.3 M$

500 tons → one year US electricity



Th-^{233}U fuel cycle → fewer actinides than U-Pu



Actinides: Z > 89

Hargraves & Moir,
American Scientist 98 (2010) 304

Molten Salts

A molten chloride salt

Courtesy of T. Goto

Melting temperatures of coolant salts

$NaNO_3$-KNO_3-$NaNO_2$ [HTS]	142 °C
$NaBF_4$-NaF	384
Li_2CO_3-Na_2CO_3-K_2CO_3	399
LiF-NaF-KF [FLiNaK]	454
LiF -BeF_2 [FLiBe]	459
NaCl	801

MSR History

1954 Aircraft Reactor Experiment 2.5 MW, 880 C, 100 hours

Airborne refueling & ICBMs → nuclear airplane not needed

1960s Alvin Weinberg et al. $^{232}Th + n \rightarrow {}^{233}U$

Molten Salt Reactor Experiment (MSRE) at ORNL

$LiF\text{-}BeF_2$ ("FLiBe") salt

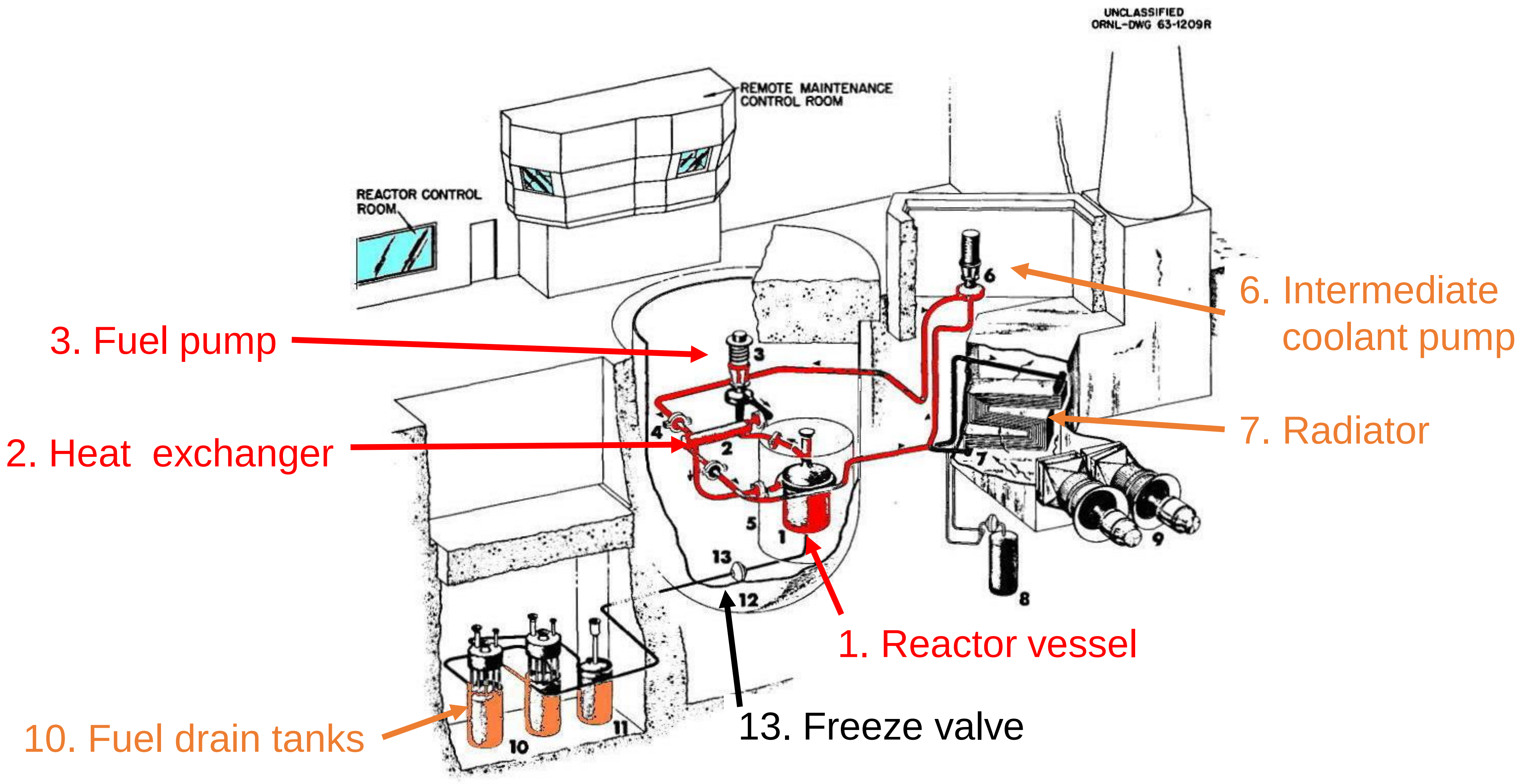
$^{235}UF_4$ fuel

Hastelloy-N structure

Operated successfully 1965-1969

Government terminated MSR studies in 1970s

Molten Salt Reactor Experiment (MSRE) at ORNL

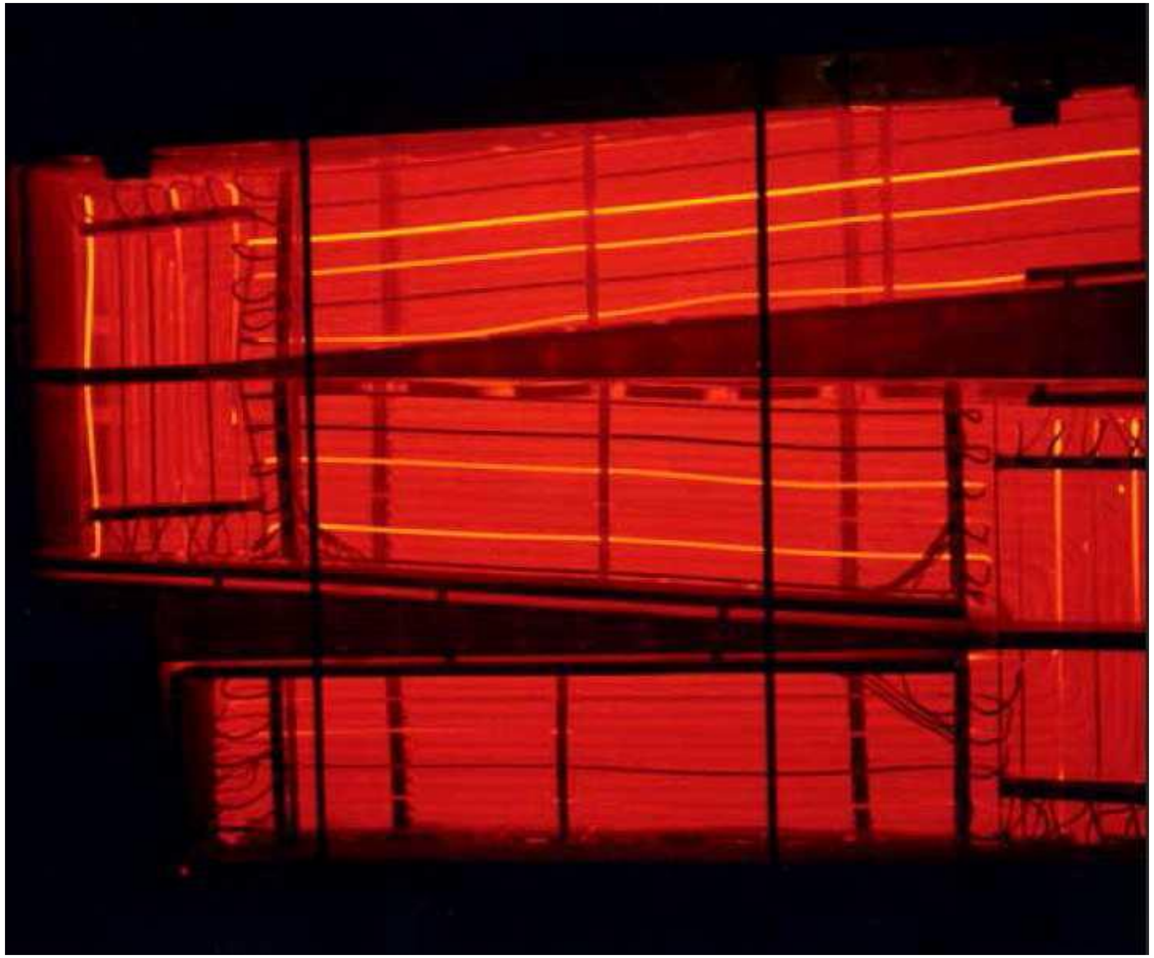


Molten Salt Reactor Experiment (MSRE) Graphite Core

Molten salt fuel flowed up through graphite channels.

Oak Ridge National Laboratory, 1965-1969

MSRE Air-cooled radiator

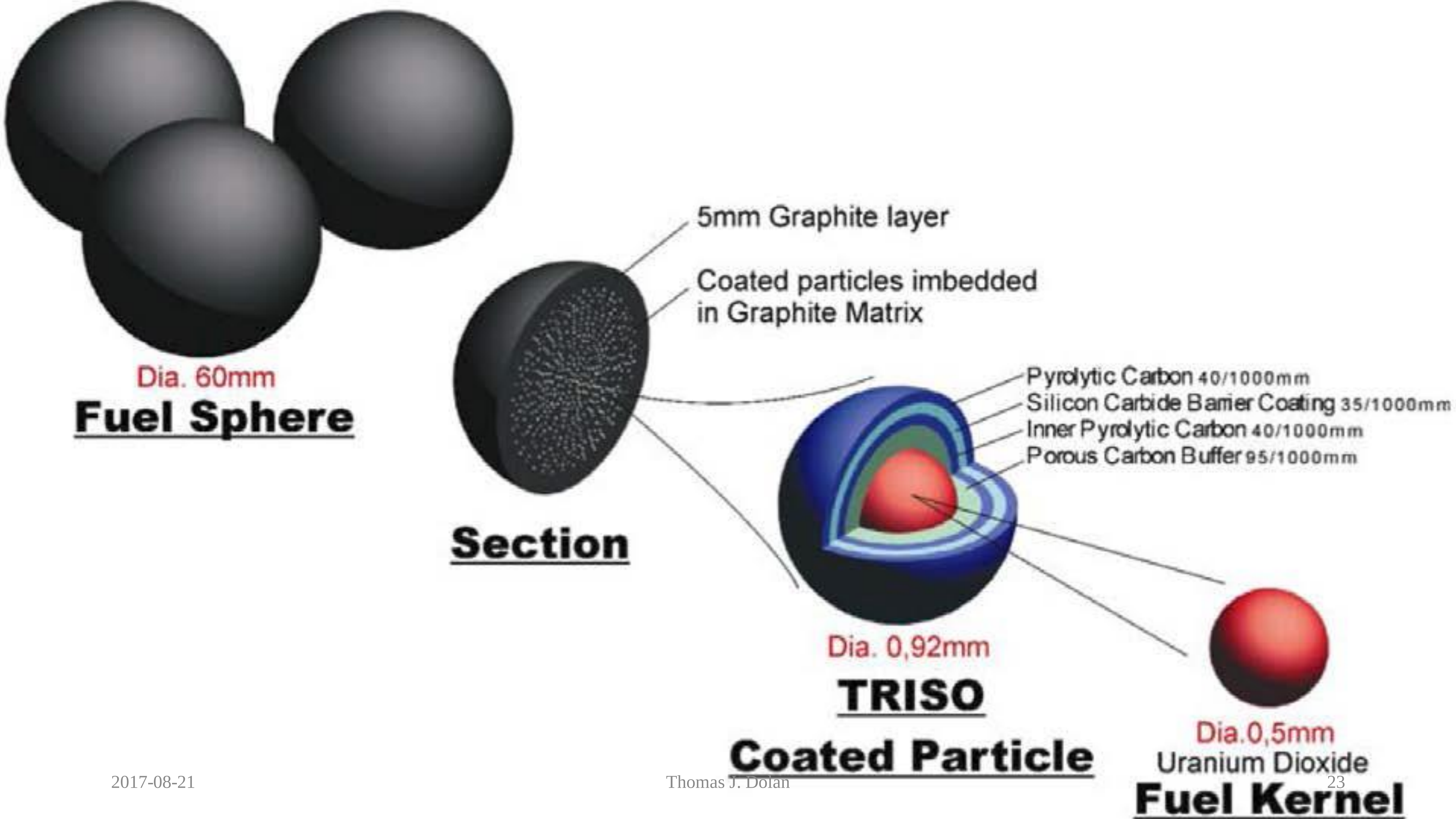


Solid Fuel MSR

Rods

Plates

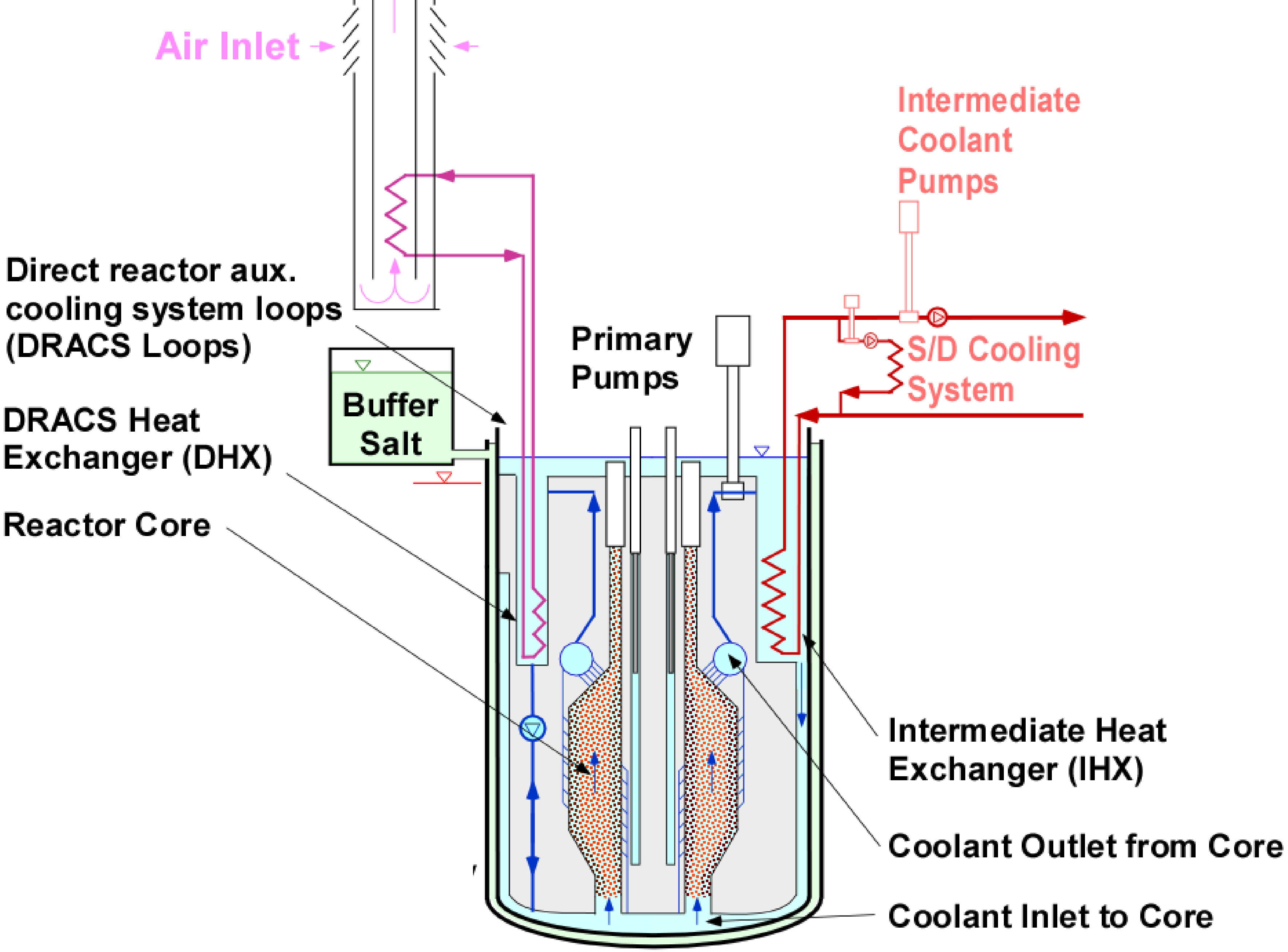
Pebbles


5mm Graphite layer
Coated particles imbedded in Graphite Matrix
Pyrolytic Carbon 40/1000mm
Silicon Carbide Barrier Coating 35/1000mm
Inner Pyrolytic Carbon 40/1000mm
Porous Carbon Buffer 95/1000mm
Dia. 60mm
Fuel Sphere
Section
Dia. 0,92mm
TRISO
Coated Particle
Dia.0,5mm
Uranium Dioxide
Fuel Kernel

Fluoride-Salt Cooled High-Temperature Reactors (FHRs)

UC-Berkeley, MIT, Wisconsin, ORNL

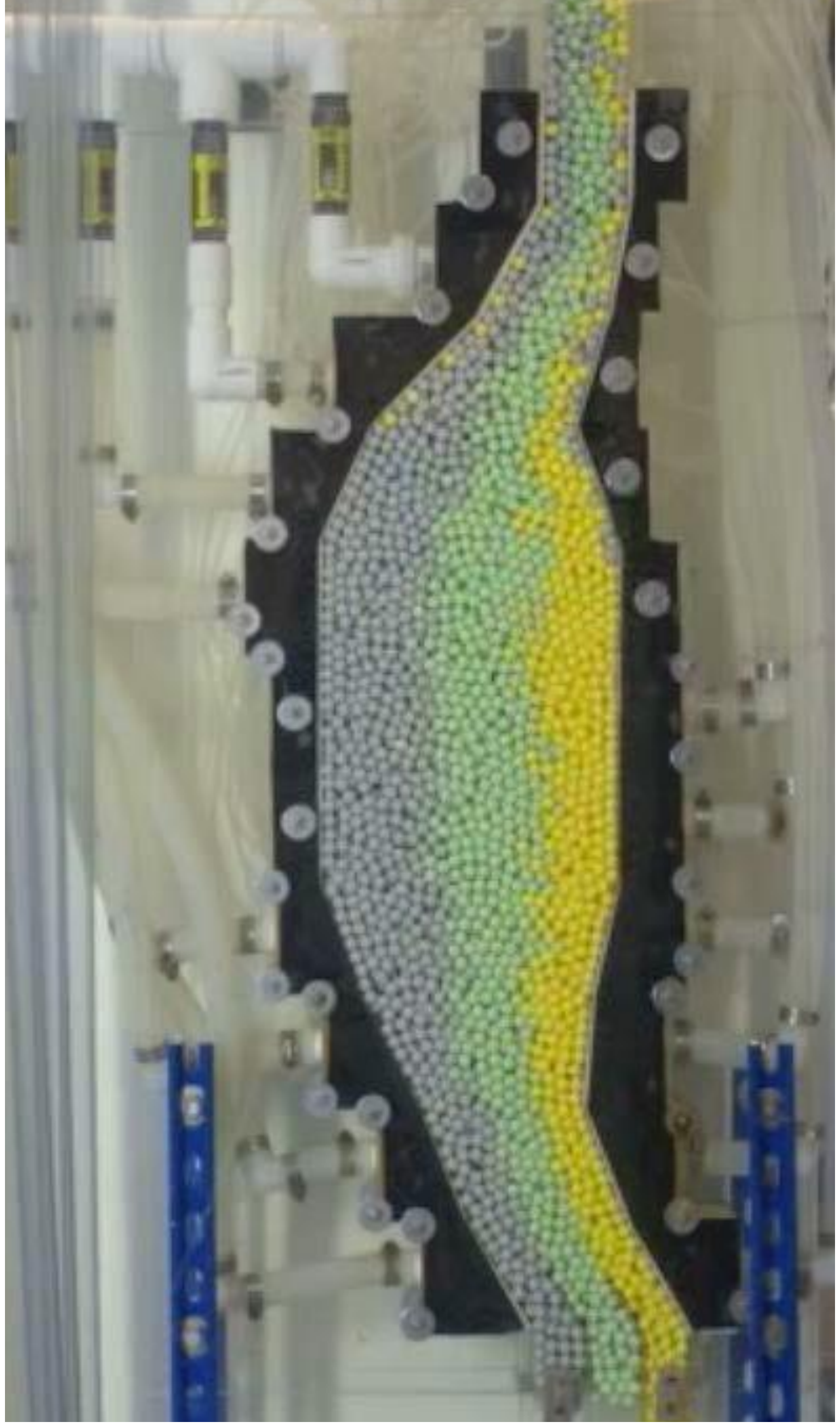
TEAC-8 Prof. Scarlat



Fluoride-Salt Cooled High-Temperature Reactors (FHRs)

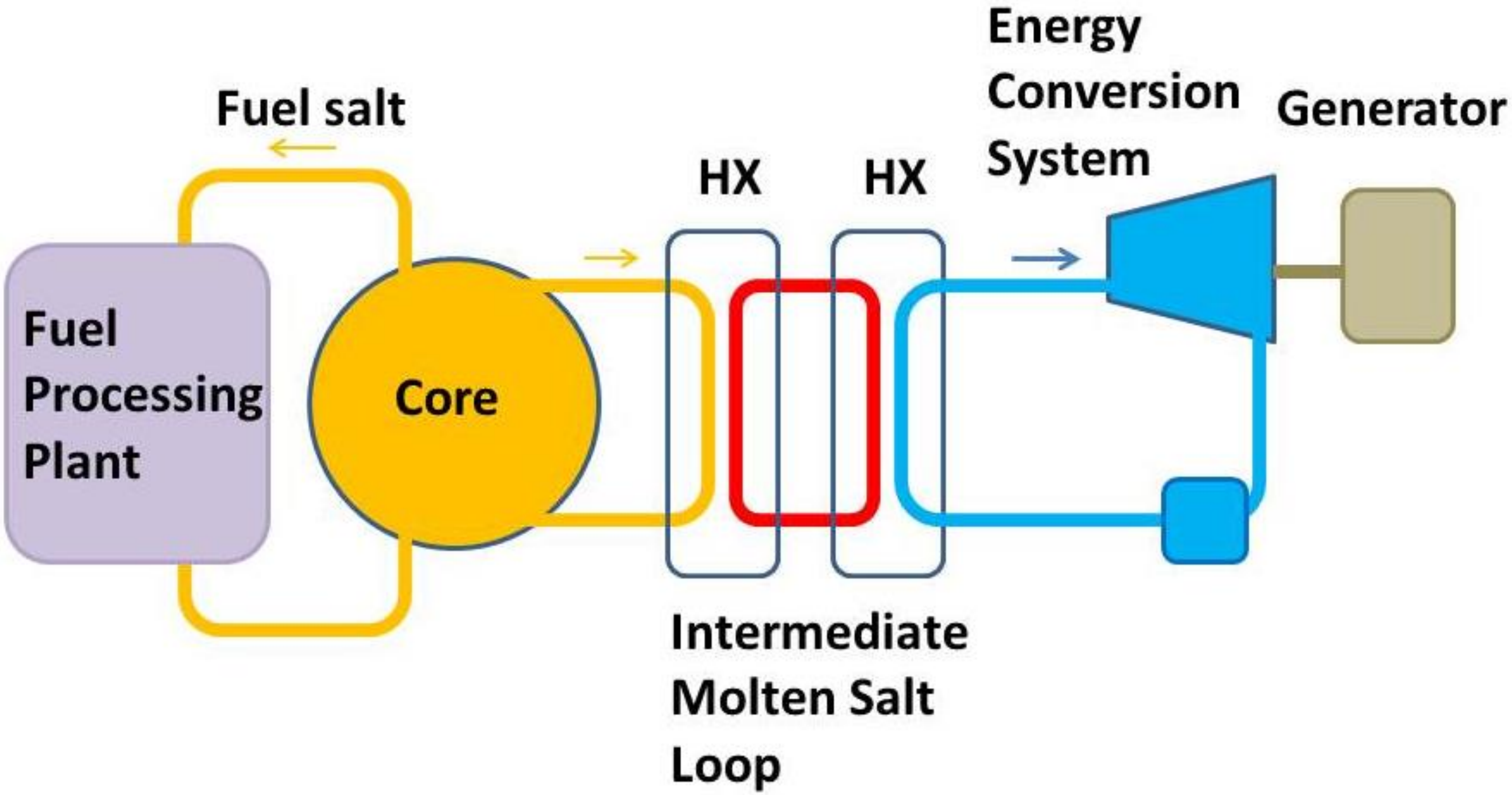
Colored pebbles simulate flow in a pebble bed reactor.

Prof. Per Peterson’s Lab, UC-Berkeley



Liquid Fuel MSR

Liquid Fuel MSR



Light Water Reactor (LWR) Problems

LWR	**Liquid Fuel Thorium MSR**
Manufacture of pellets & rods	Not needed
Radiation damage limits fuel life	No burnup limit
Refueling shutdown every 3 years	Continuous refueling
Water evaporation → TMI	No boiling at T < 1400 C
Steam pressure → Chernobyl	No water or steam
Pressure vessel danger → Chernobyl	Low pressure
Hydrogen explosion → Fukushima	No H_2O or Zr → no H_2

Light Water Reactor (LWR) Problems

LWR	**Liquid fuel thorium MSR**
Xe-135 poisoning → excess core reactivity	Xe-135 removed → low excess reactivity
Decay heat → fuel melt	Fuel already molten
High core radioactivity	Removal of some fission products
Long-lived actinide waste	Actinides recycled and incinerated
No recycling → <3% of uranium energy utilized	Recycling → >95% of Th energy utilized
Thermal efficiency ≤ 35%	> 44% possible

Liquid fuel economic advantages over LWRs

No **manufacture** of fuel pellets, rods, clad

T > 700 C → **efficiency** ~ 44%   (LWRs ~ 33%)

Low-pressure → thinner vessel

Containment simpler (no H_2 or steam pressure)

Compact air-cooled Brayton cycle -- arid regions

Startup with used LWR fuel

^{235}U **enrichment** plants not required.

Fuel **burnup** not limited by radiation damage.

Liquid fuel environmental advantages over LWRs

Recycling of actinides (elements 89–103) → less **fuel** waste

Incinerate actinides from LWR used fuel → less **radwaste**

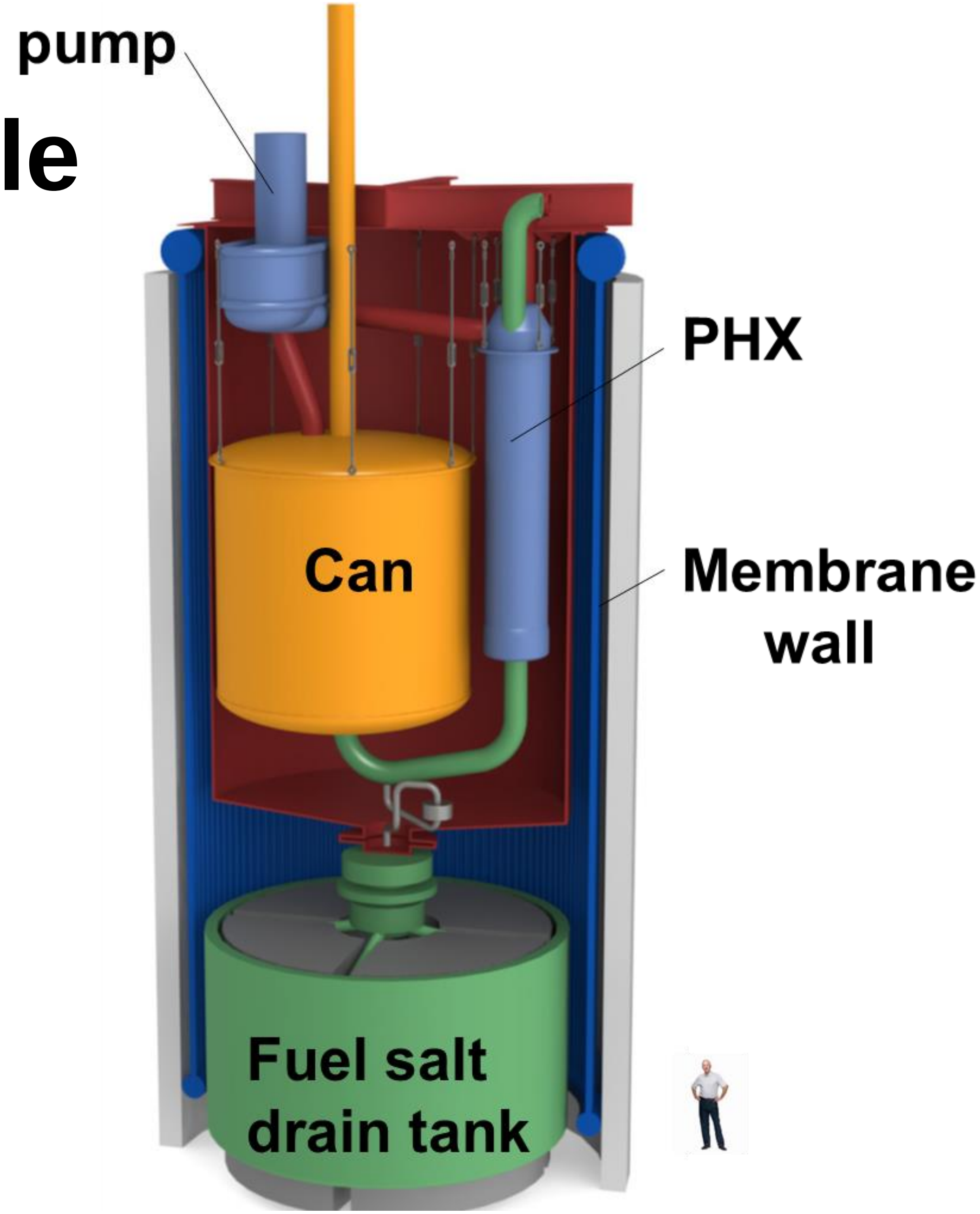
Higher efficiency → less **waste heat** rejected

Thorium available from **rare-earth mining**, 3700 tons

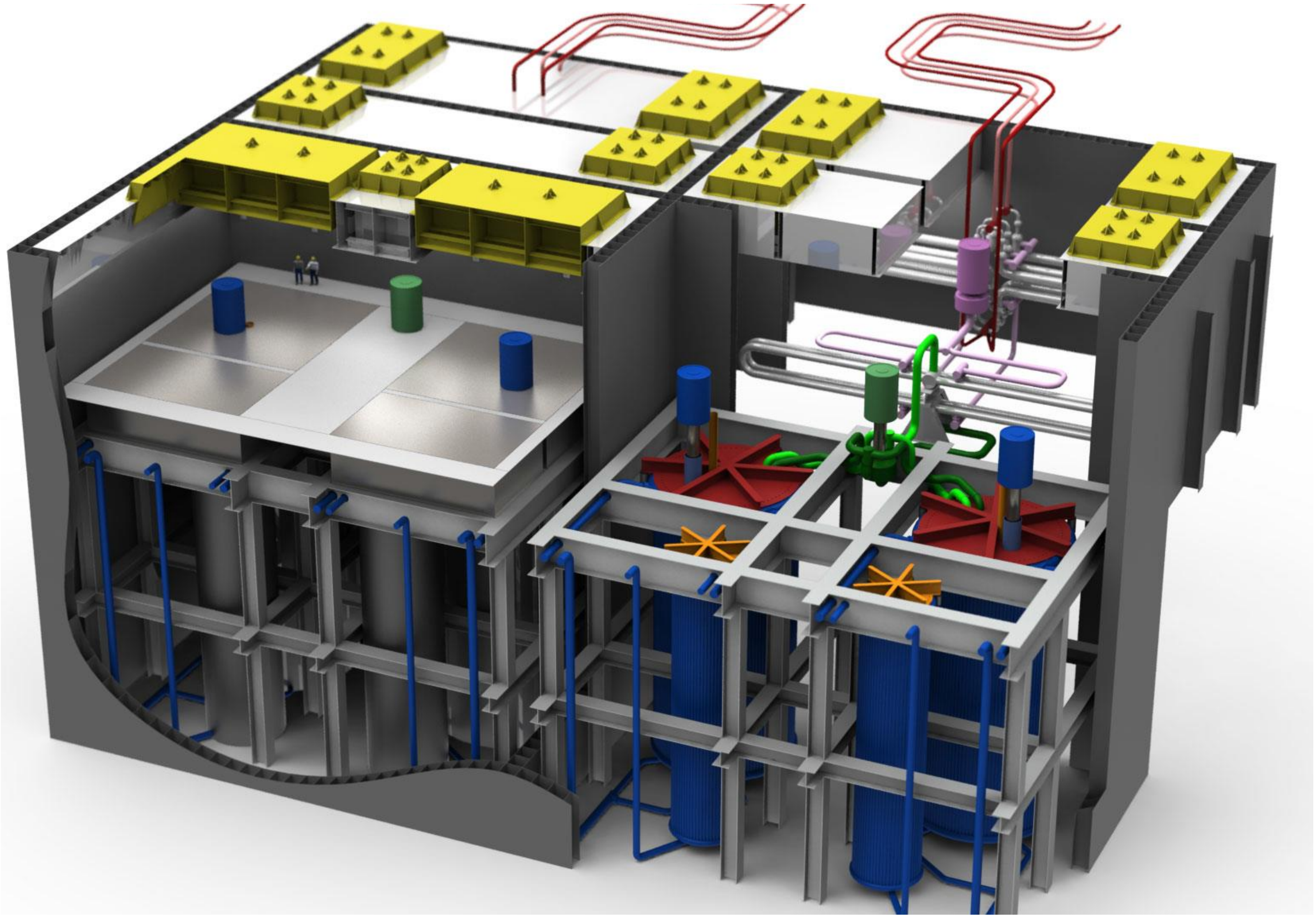
Thorium four times as **abundant** as uranium

An example liquid fuel design

250 MWe ThorCon Module

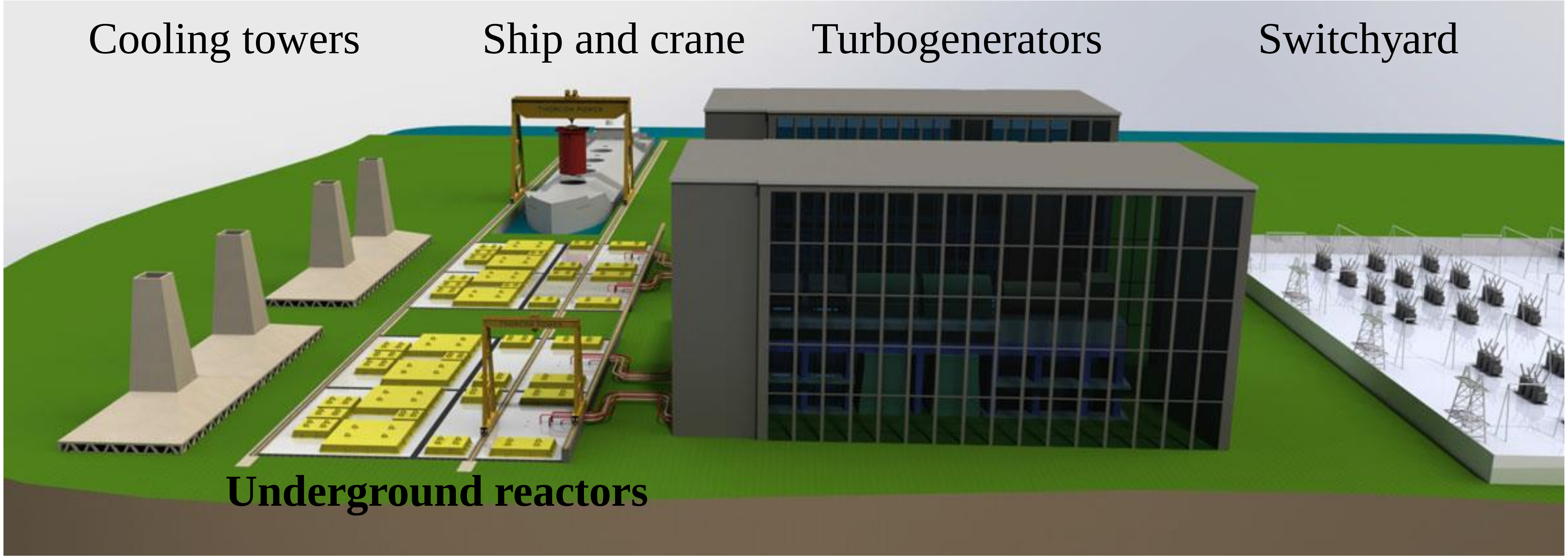


ThorCon Reactors



Underground siting

ThorCon Power Plant



MSR Deployment

Boeing factories produce a $200 million aircraft every day.

Hellespont Metropolis oil tanker

67,000 tons steel
Built in < 1 year
Cost 89 M$

ThorCon MSR
18,000 tons steel
31 blocks barged to site
Dropped into place, wall cells filled with concrete

Big shipyard could produce **100 ThorCons/year**.

Steel and concrete needs for 1 GWe plant

	Coal	**ThorCon**
Steel, tonne	109,000	36,000
Concrete, m^3	178,000	85,000

Direct capital cost of ThorCon ≈ 1200 $/kW

MSR fuel cost = 0.53 cents/kWh
Coal fuel cost = 2.3 cents/kWh

Devanney J et al. (2015) ThorCon™ , The Do-able Molten Salt Reactor, © 2015 Martingale, Inc.

MSR Development Issues

Chemical processing system

- Separate U, Th, actinides, fission products, and tritium
- Hot, radioactive environment

Corrosion-resistant, high temperature **materials** , such as Hastelloy-N

Reactor physics & thermal hydraulics simulations

Heat exchangers – avoid freeze-up

Tritium control

Tritium Management Techniques

- Removing Li-6 (isotope separation)
- Avoid lithium – use NaF, ...
- Bubbling He gas through the salt
- Spray salt droplets into vacuum
- Intermediate coolant loop
- Impermeable barriers

CANDU heavy water reactors have tritium experience.

Worldwide Activities

Organizations

Thorium Energy Alliance, USA, John Kutsch, conferences www.thoriumenergyalliance.com/

International Thorium Energy Organization (IThEO), Europe, Andreas Norlin, Mumbai 2015 http://www.itheo.org/

International Thorium Molten Salt Forum, Japan, Ritsuo Yoshioka, MSR book http://msr21.fc2web.com/english.html

Organizations

The Generation-IV International Forum (GIF) 6 concepts, including MSR

Alvin Weinberg Foundation, London, promotes thorium energy (http://www.the-weinberg-foundation.org/)

International Atomic Energy Agency (IAEA), Vienna, Meetings, Coordinated Research Projects, TECDOCs, f.reitsma@iaea.org

MSR/Th Research Activities

Moltex	UK	Scott
Seaborg Waste Burner	Denmark	Schonfeldt
Copenhagen Atomics	Denmark	Pedersen
Dual Fluid Reactor	Germany	Huke
Fuji	Japan	Yoshioka
Fusion-Fission hybrids	Russia	Velikhov
Accelerator Driven Systems	India, Russia,Venezuela…	
Fast breeders	India, Japan,…	

MSR/Th Research Activities

SAMOFAR	EU	Kloosterman
Terrestrial Energy	Canada	LeBlanc
ThorCon	USA	Devanney
Transatomic Power	USA	Dewan
Flibe Energy	USA	Sorenson
TerraPower	USA	Latkowski
Elysium	USA	Pheil
Thorium MSR	**China**	Dai

Thorium Molten Salt Reactor (TMSR) in China

Shanghai Institute of Applied Physics (SINAP)

~500 full-time scientists and engineers
~200 students

2 MWth TMSR-SF -- graphite pebbles, TRISO fuel particles

2 MWth TMSR-LF -- molten FLiBe with ThF_4 and UF_4

Pump

Chemical Pump

Prototype FLiNaK Pump

- Parameters

Temp：550~700°C

Flow：300m^3/h

Lift： ~20m

Rot Speed：1480r/min

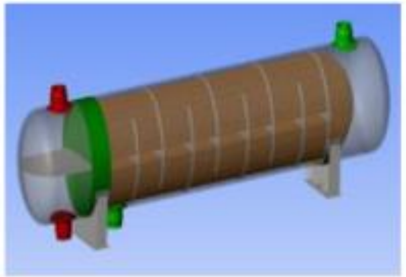
Valve

Principle prototype

Pre-engineering prototype

Heat Exchanger

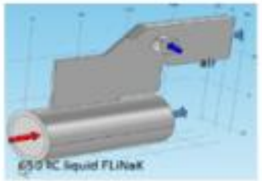
Salt – Air HX



Salt – Salt HX

Instrumentation

Pressure gage



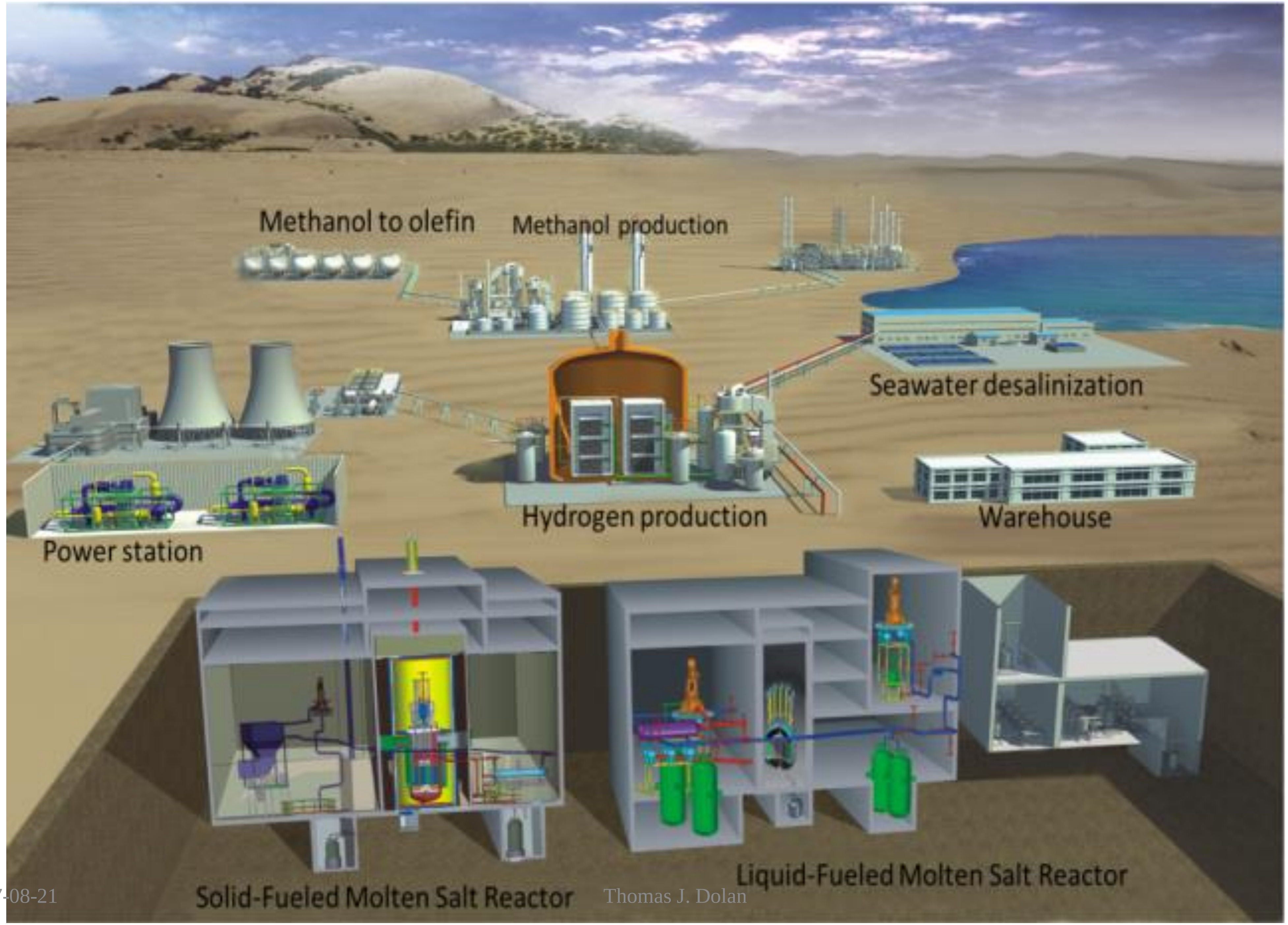
HT ultrasonic flowmeter

Loop

HTS nitrate test loop

FLiNaK test loop

Natural circulation test loop


Methanol to olefin
Methanol production
Seawater desalinization
Power station
Hydrogen production
Warehouse
Solid-Fueled Molten Salt Reactor
Liquid-Fueled Molten Salt Reactor

Summary: Benefits of Thorium MSRs

Low pressure & high temperature → passive safety

Fuel abundance & utilization

Electricity generation efficiency & cost

Actinide recycling & incineration→ low waste

Vision

We envision a world with affordable molten salt reactors

burning thorium, uranium, and actinides;

producing electricity, hydrogen, and desalinated water,

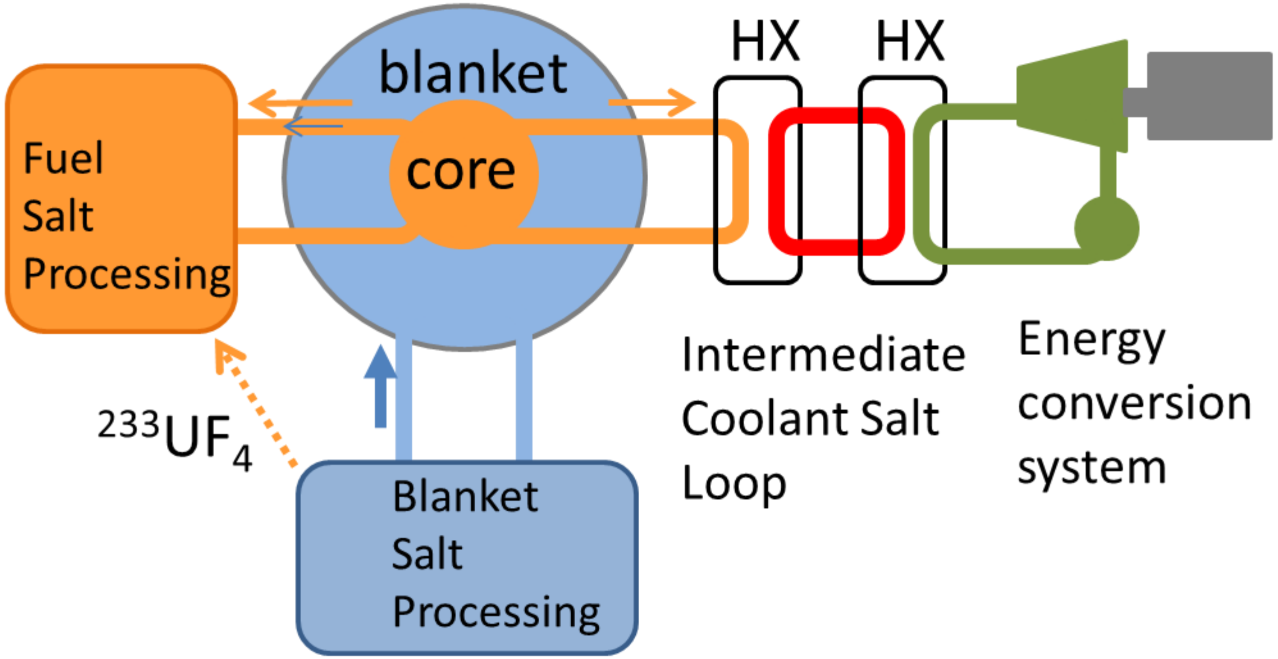
with no serious accidents.

Extra slides

Other Institutes in China

The Shanghai Institute of Organic Chemistry	lithium isotope separation Preparation of molten salt
The Shanghai Advanced Research Institute	Thermal power conversion Production of methanol with CO_2 lithium isotope separation
The Institute of Metal Research	nickel-based alloy with corrosion resistance to molten salt
The Changchun Institute of Applied Chemistry	nuclear grade thorium
The Shanghai Institute of Ceramics	SiC-SiC composite materials and carbon-based materials
The Institute of Coal Chemistry	nuclear graphite

Two-region reactor



Liquid fuel nonproliferation advantages over LWRs

Bred Pu-239 **recycled and burned** onsite

Low on-site **Pu inventory**

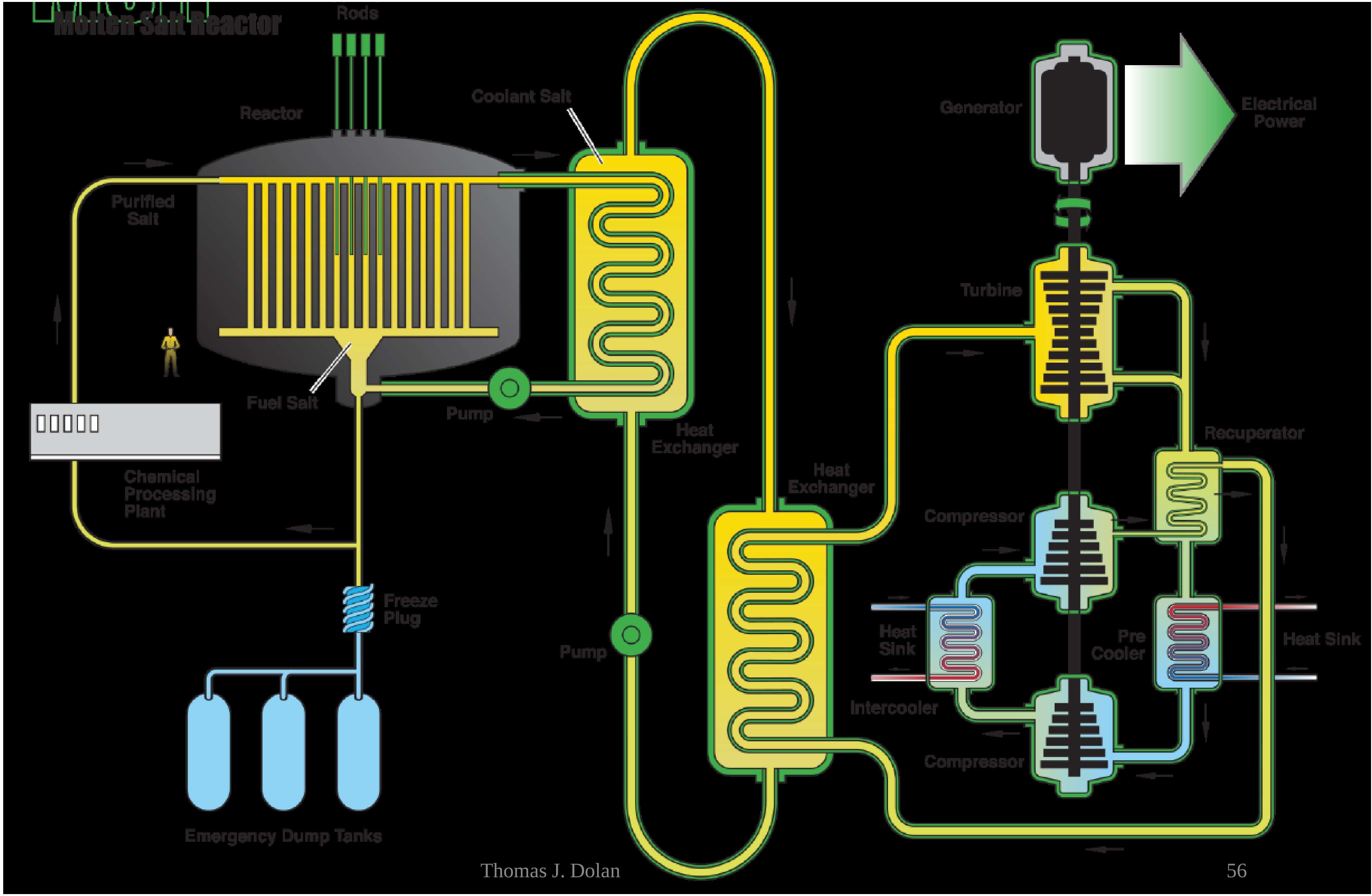
U-232 emits 2.6 MeV gamma → bomb making hazardous

Bred U-233 diluted with U-238 → "denatured" low-enriched fuel

Fissile materials stay at the secure **reactor site**, difficult to steal

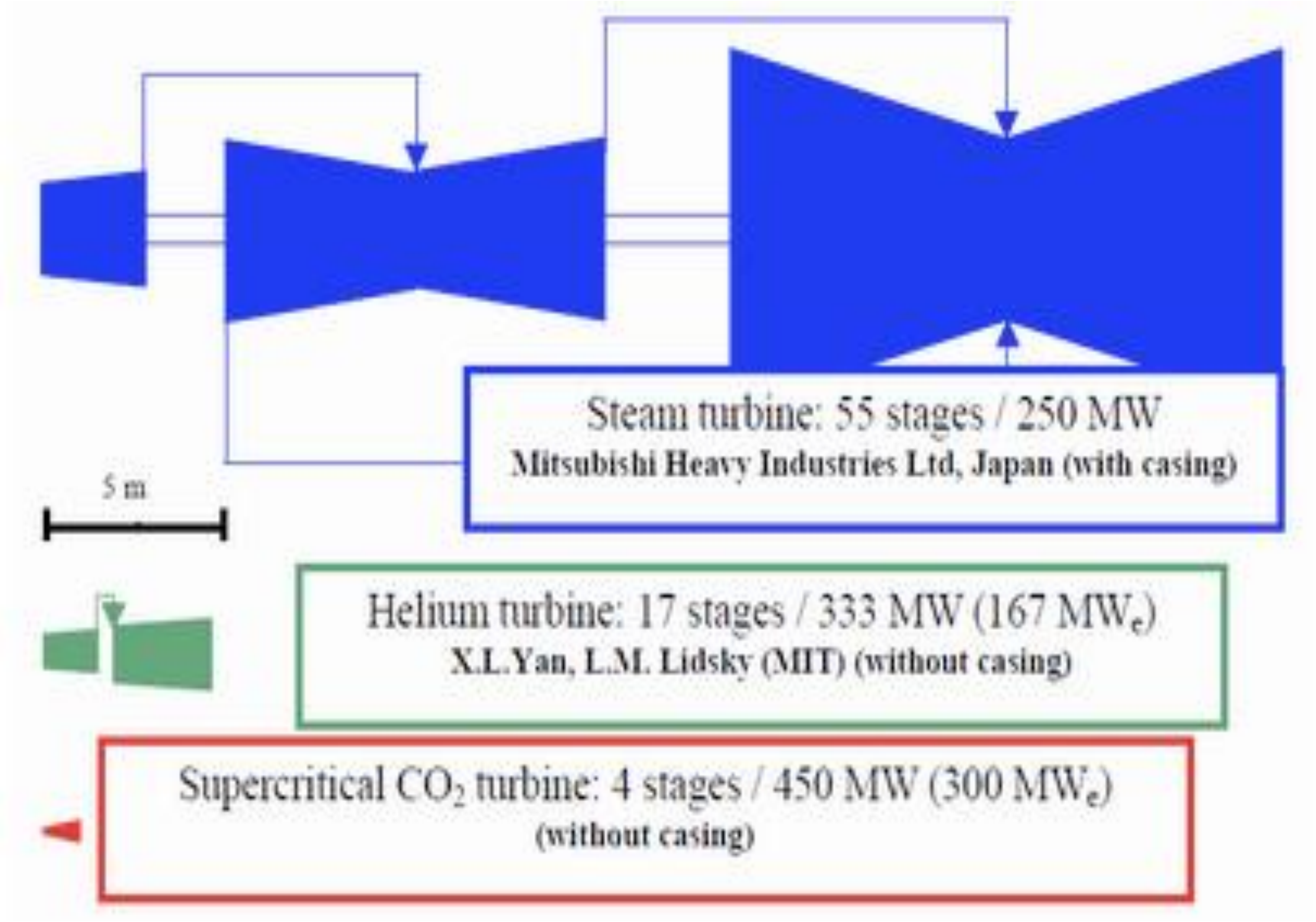
Could consume Pu-239 from **dismantled nuclear weapons** without the LWR MOX fuel manufacture and control problems

MSR



Molten Salt Reactor
Rods
Reactor
Coolant Salt
Generator
Electrical Power
Purified Salt
Turbine
Fuel Salt
Pump
Heat Exchanger
Recuperator
Chemical Processing Plant
Heat Exchanger
Compressor
Freeze Plug
Heat Sink
Pre Cooler
Heat Sink
Pump
Intercooler
Compressor
Emergency Dump Tanks

Comparison of Heat Engine Sizes



DOSTAL, V., MIT PHD. DISSERTATION

Energy Cheaper than Coal?

100 MW LFTR	$ Cost	$ per mo, 40 yrs, 8%	$ per KWH @ 90%
Construction	200,000,000	1,390,600	0.0214
100 kg U startup	5,000,000	35,000	0.00054
Thorium fuel	30,000/yr	2500	0.000004
Decomm (½ const)	100,000,000	960	0.0000015
Operations	1,000,000/yr	83,333	0.00128
TOTAL			0.023

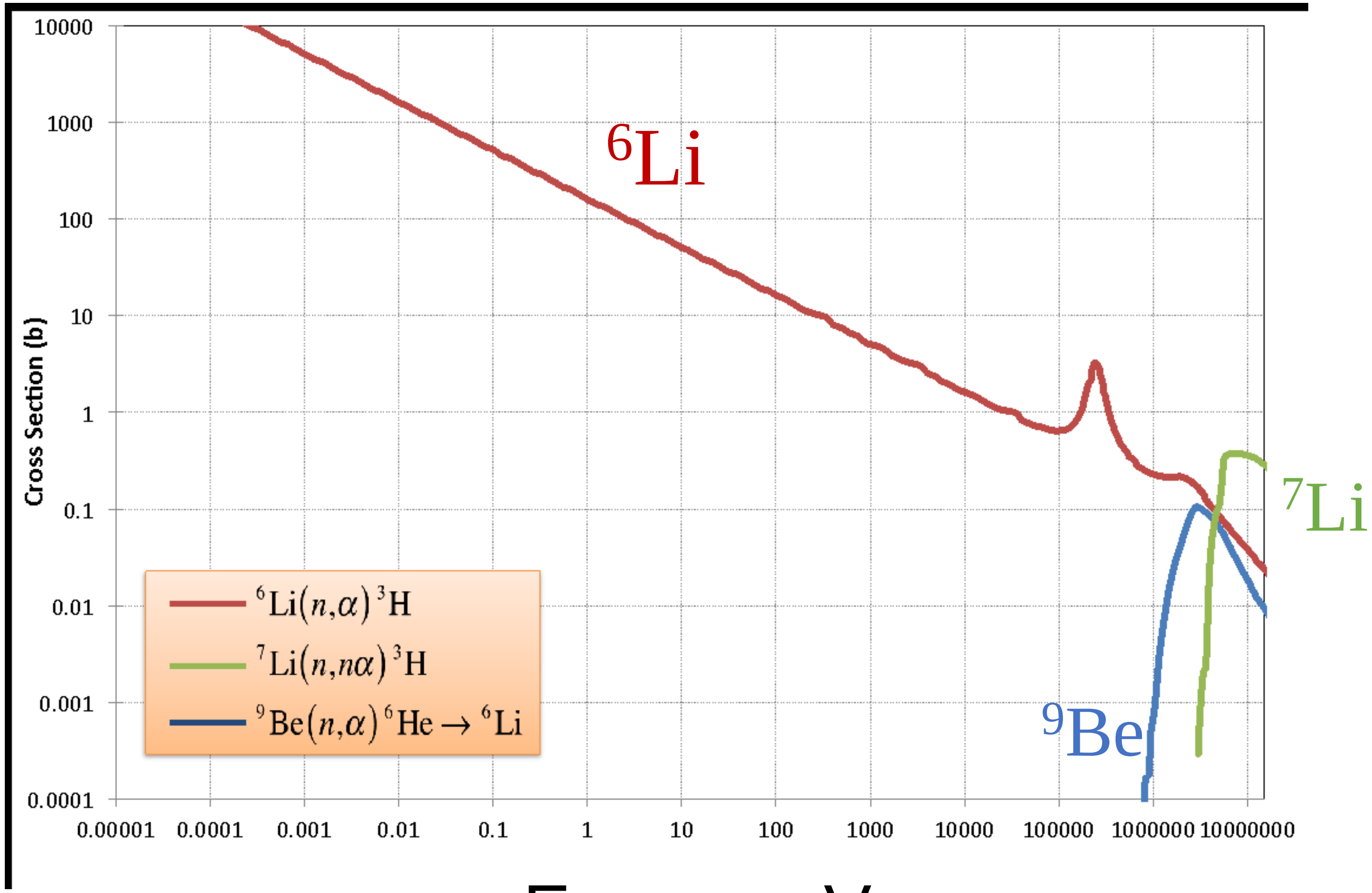
Hargraves, Robert, Thorium, Energy Cheaper than Coal, © Robert Hargraves, Hanover, NH 2012.

Tritium Production Rates

	(Ci/GWe day)
CANDU (Darlington)	15,100
PB-AHTR (Berkeley FHR)	6,119
PWR (average)	2
MSR	2,420

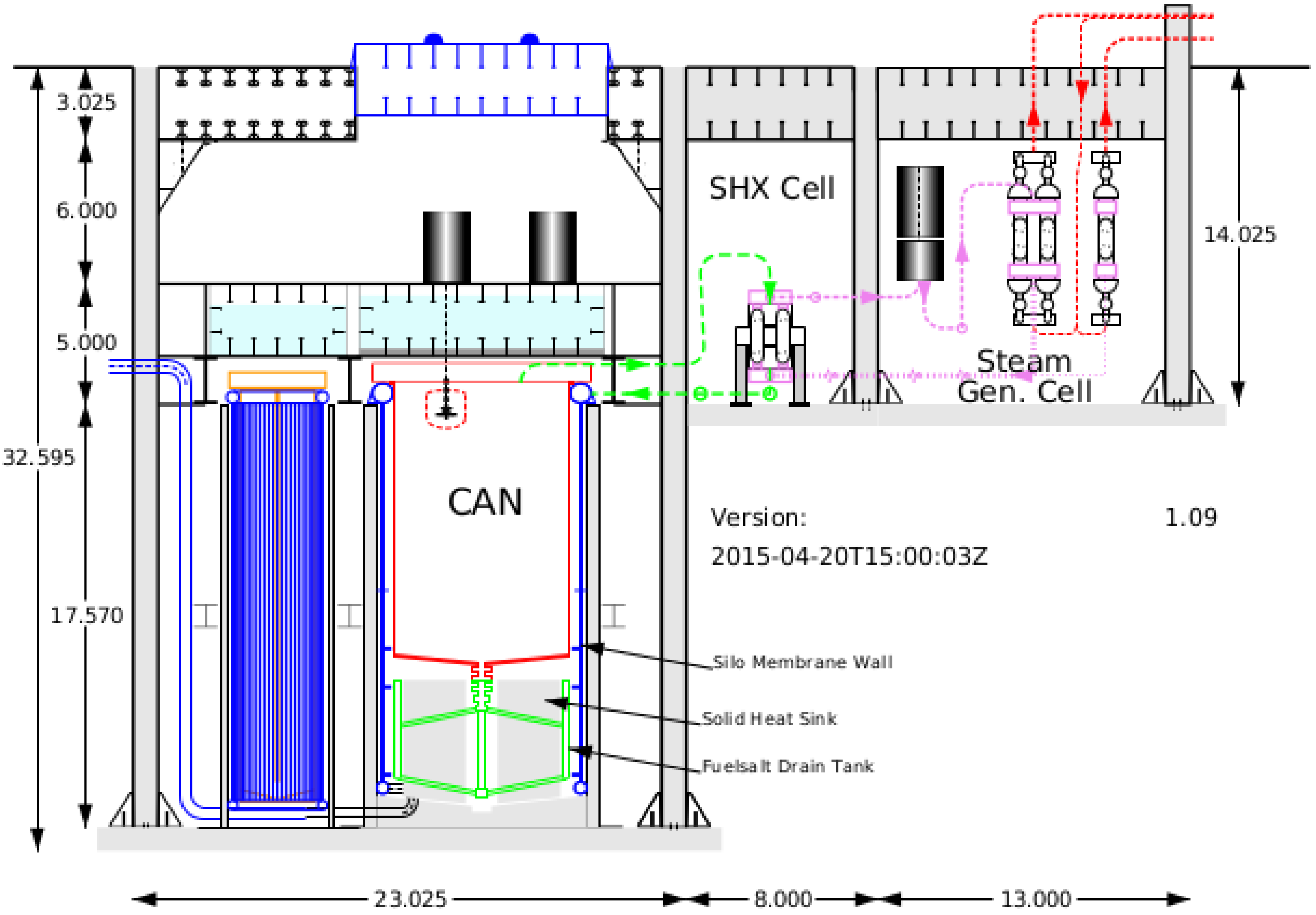
Tritium breeding cross sections

Cross section, barns

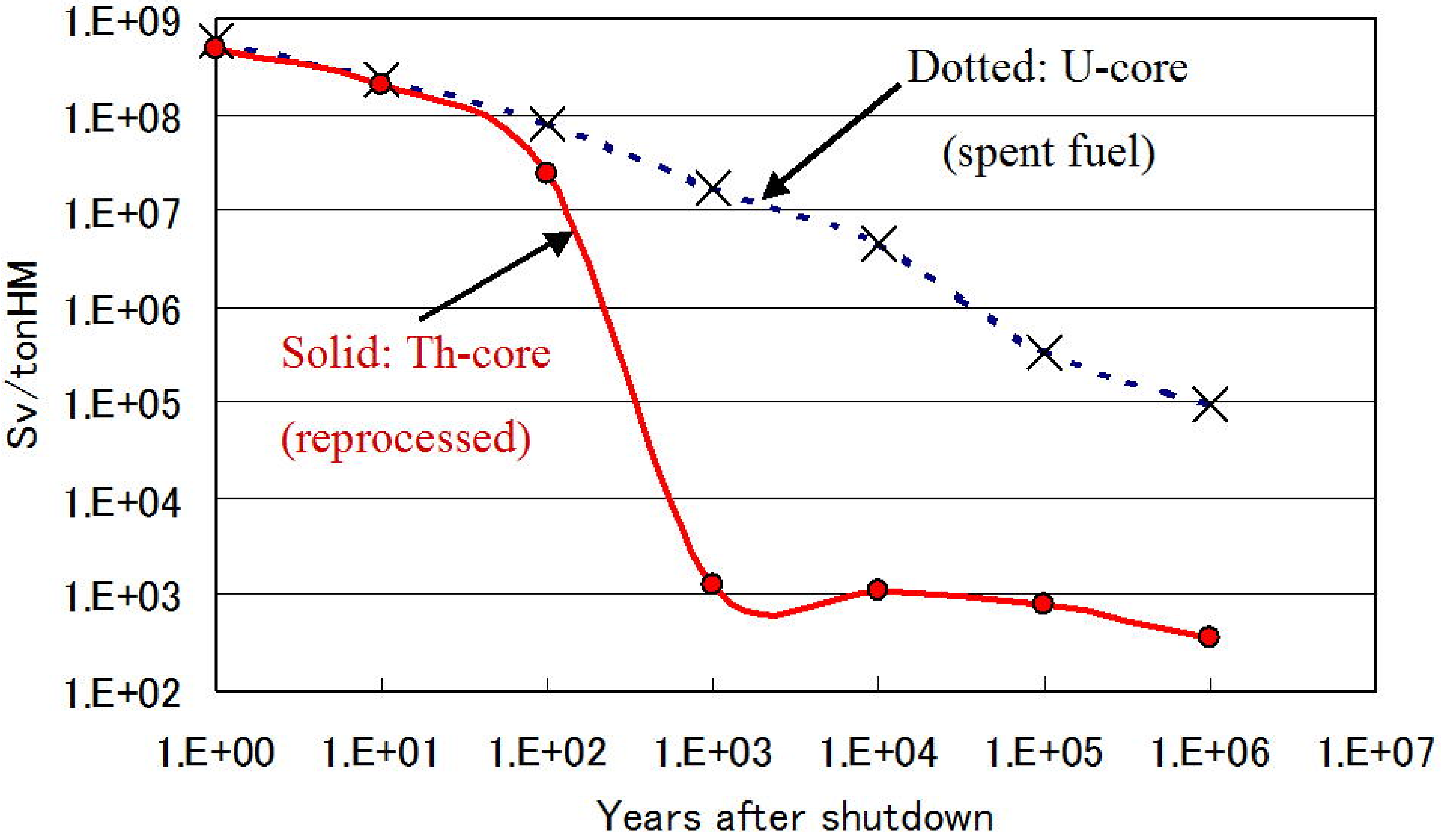


Energy, eV

ThorCon underground reactor



Radiotoxicity of Uranium vs. Thorium Cores



Courtesy of R. Yoshioka

Book on MSR and Thorium Energy

Motivation -- why are we interested?

Technical issues – reactor physics, thermal hydraulics,
materials, environment, …

Generic designs -- thermal, fast, solid fuel, liquid fuel, …

Specific designs –electrical power, actinide incineration,
thorium utilization, …

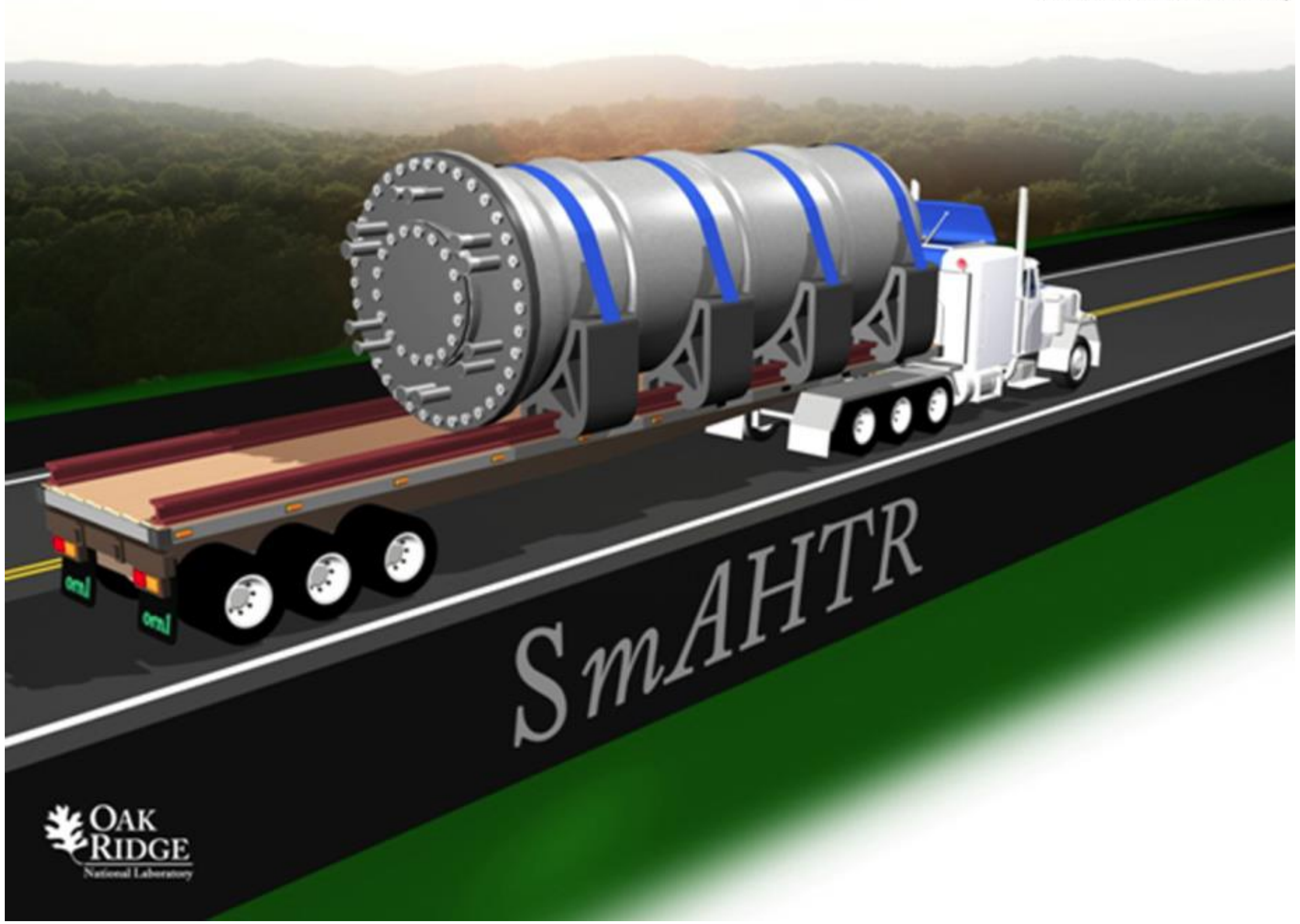
Worldwide activities – 23 countries

Conclusions

Elsevier, June 2017

MSR vessels are lighter than LWR vessels

ORNL 2011-G00113/chj



Sources

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Robert Hargraves and Ralph Moir, “Liquid Fluoride Thorium Reactors, an old idea in nuclear power gets reexamined”, *American Scientist 98*, 304-313, 2010.

Robert Hargraves, *Thorium, Energy Cheaper than Coal*, © Robert Hargraves, Hanover, NH 2012.

Richard Martin, Superfuel, *Thorium, the Green Energy Source for the Future*, Palgrave Macmillan, New York, 2012.