ThorCon

Powering Up Our World

Advancing Prosperity

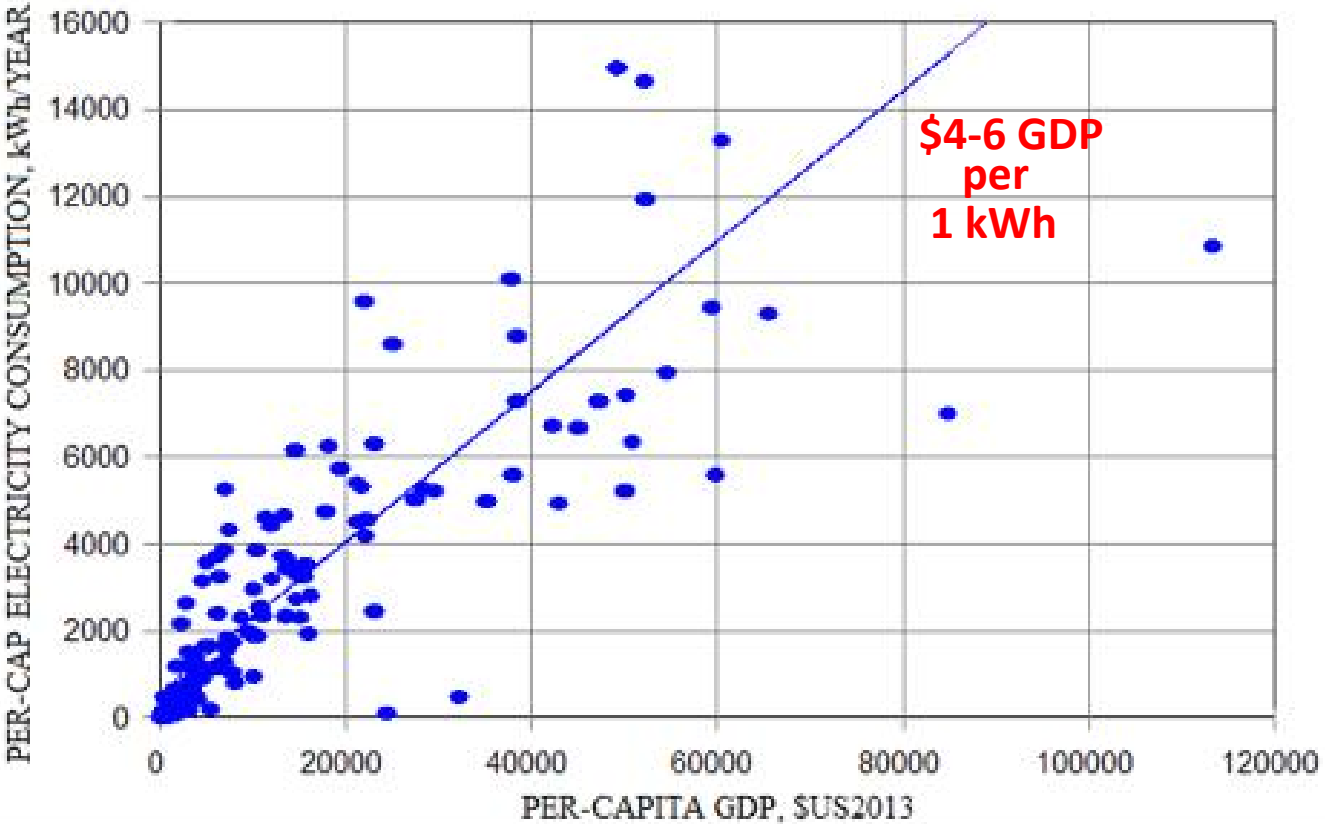
Checking Global Warming

Japan US China International Forum on Molten Salt Reactors

June 14, 2018 Tokyo

Robert Hargraves

A single 1 GW electric power plant enables $32 billion of GDP in developing nations.



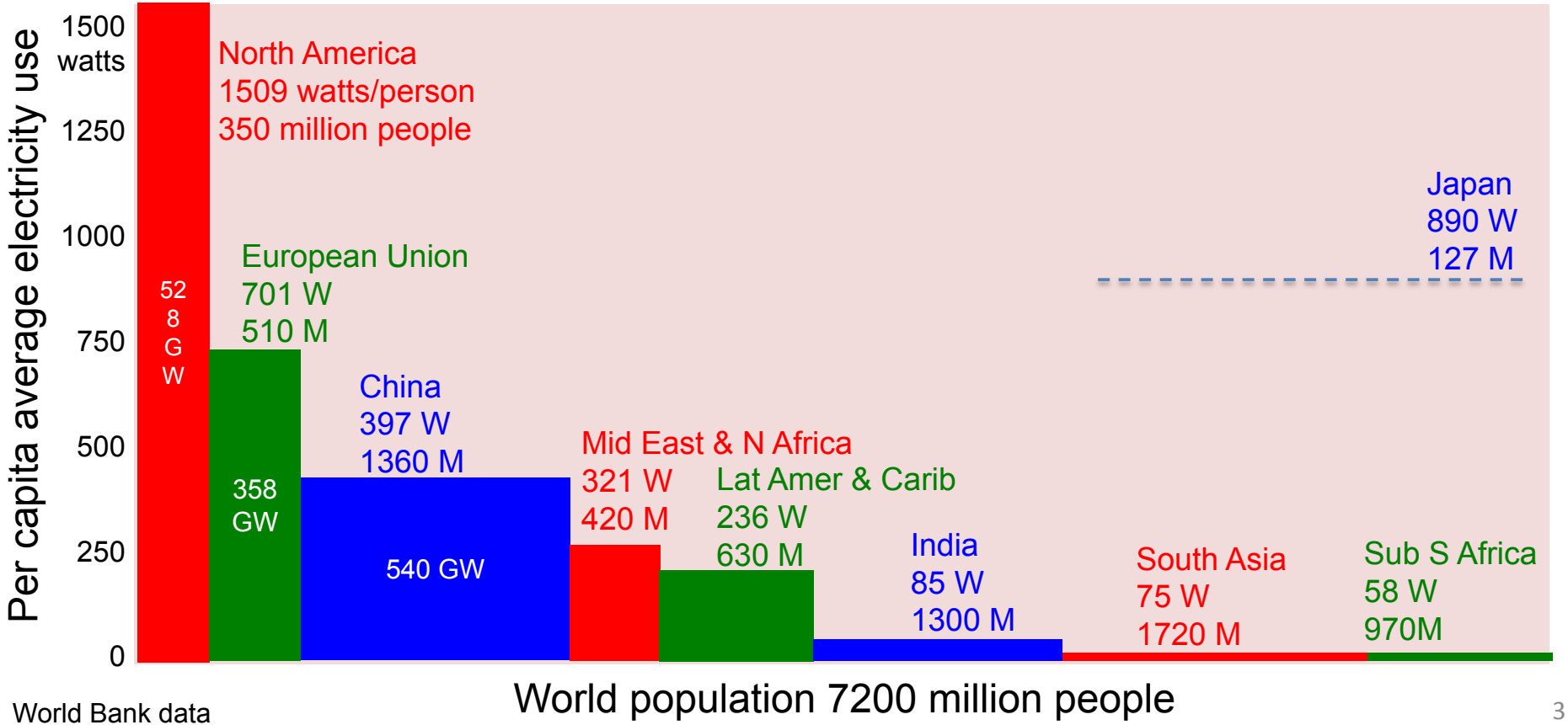
$GDP vs kWh/yr

per capita
each dot a nation

Sources
http://euanmearns.com/electricity-and-the-wealth-of-nations/

Robert Ayres and Benjamin Warr, The Economic Growth Engine: How Energy and Work Drive Material Prosperity (The International Institute for Applied Systems Analysis)

World electricity use of 2300 GW will double.



World Bank data

1400 GW of new power plants will be coal fired, the economic choice of developing nations.

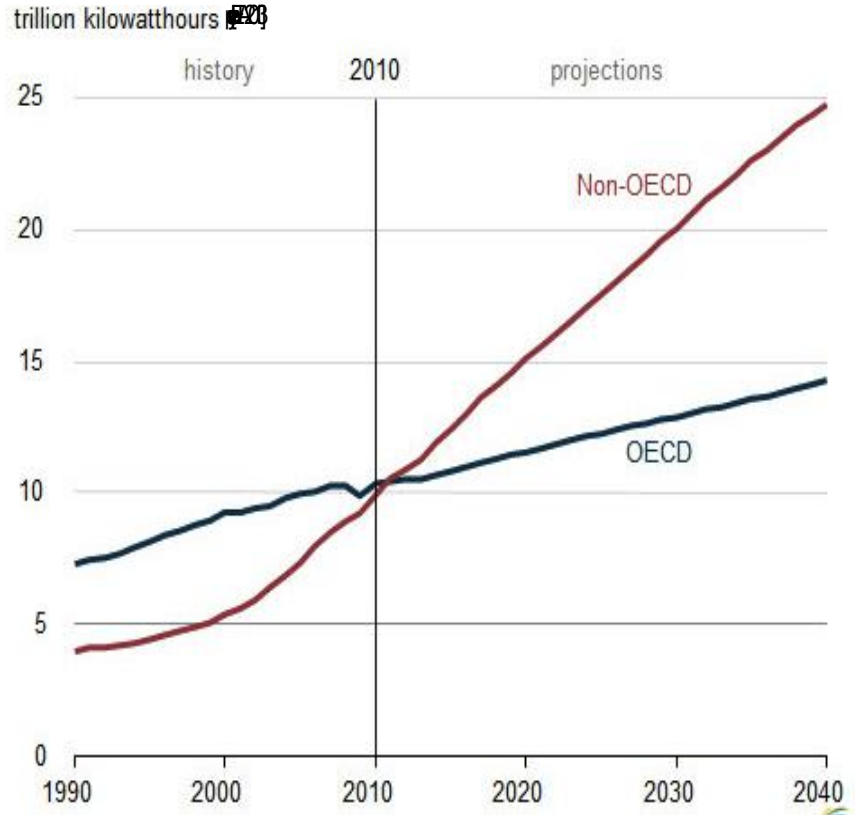
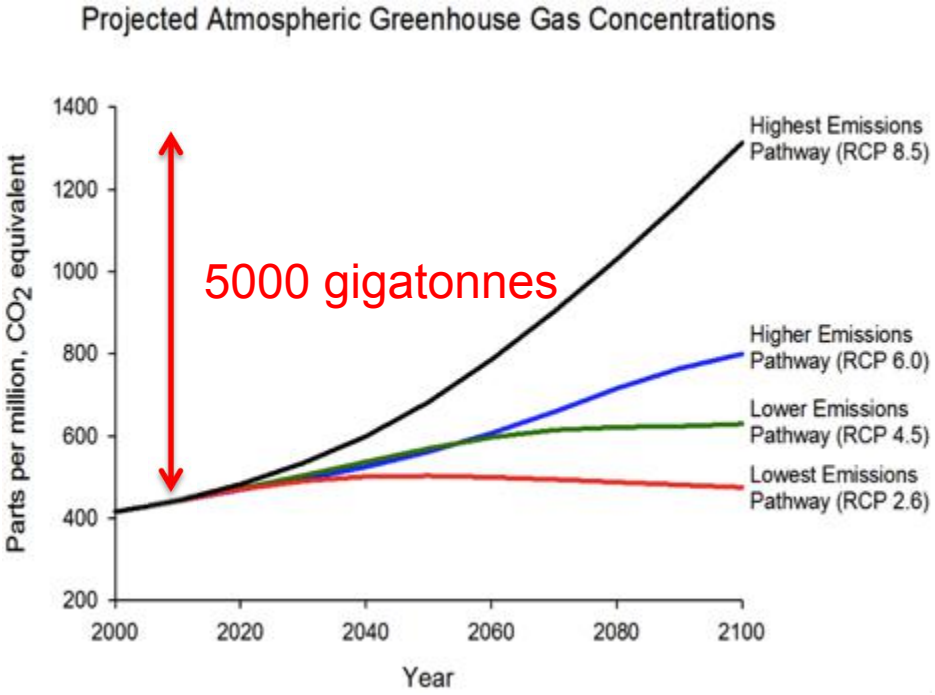


Table 2. Proposed Coal Plants by Region, January 2017 (MW)

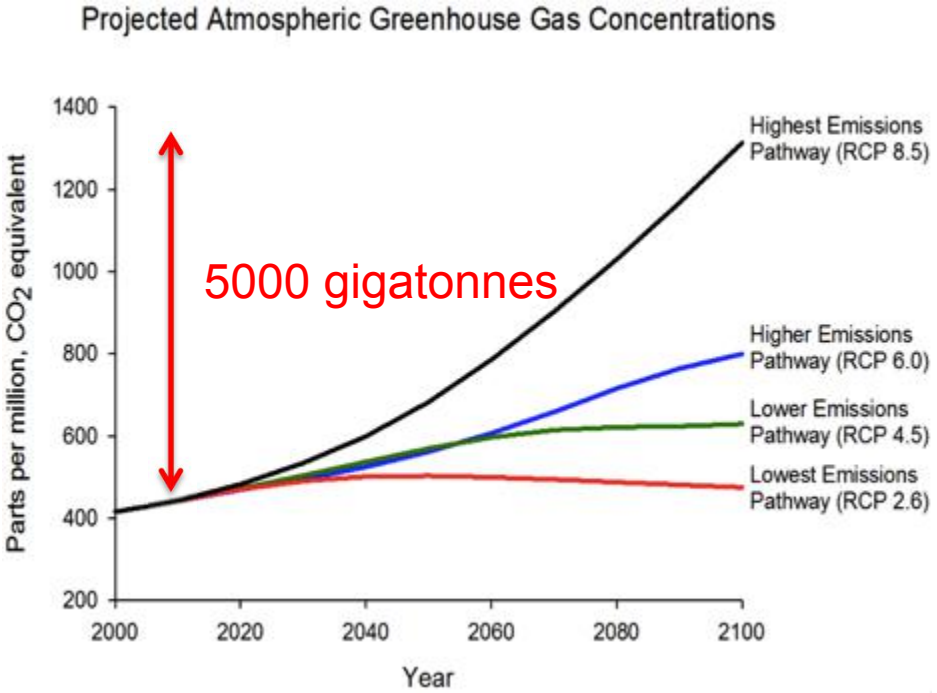
Region	Pre-Construction	Construction	On Hold
East Asia	167,083	161,146	451,059
South Asia	156,018	53,303	91,740
SE Asia	93,499	31,808	20,992
non-EU Europe	75,626	2,640	19,874
Africa and Middle East	49,842	12,838	8,595
Eurasia	9,156	980	2,200
EU28	9,360	7,468	7,050
Latin America	6,372	2,175	3,541
Canada/US	1,295	582	1,000
Australia/NZ	1,350	0	1,316
Total	**569,601**	**272,940**	**607,367**

As CO_2 emissions accumulate…

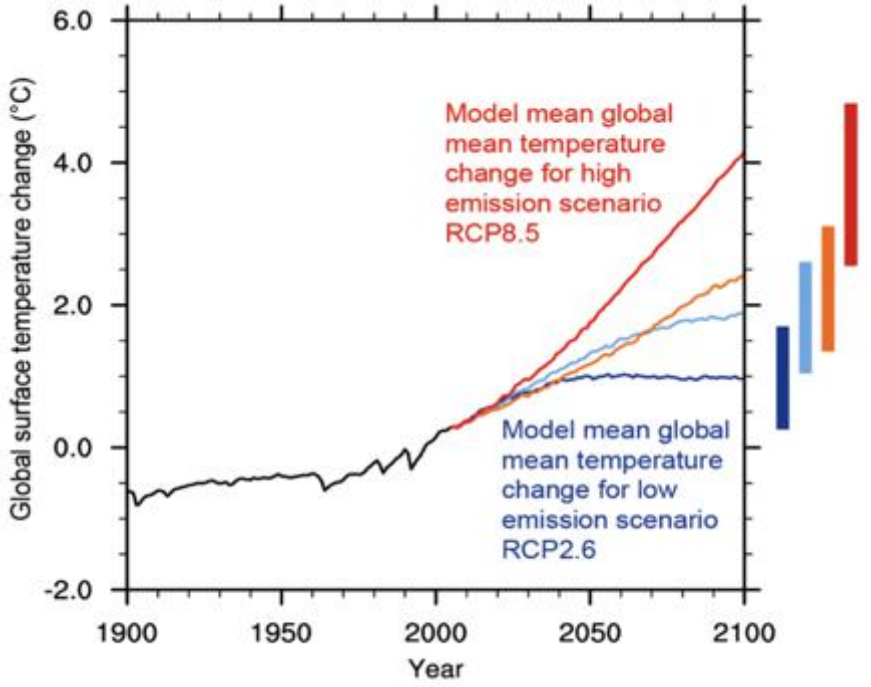


CO_2 in atmosphere, ppm

As CO_2 emissions accumulate, temperatures rise: IPCC



CO_2 in atmosphere, ppm



Temperature rise, °C

***Business As Usual*: adding 1000 ppm (5000 Gt) will add 4°C**

Building ThorCons instead of 1400 GW of coal plants will avoid more CO_2 emissions than ***Paris***.

1 GW coal plant emits
6 Mt CO_2/year

x 1400 coal plants
= 8 Gt CO_2/year

Pre-Paris policy	59 Gt/y
Paris cuts	-6 Gt/y
ThorCon cuts	-8 Gt/y
Needed 2° cuts	-18

ThorCon liquid fission is cheaper than coal.

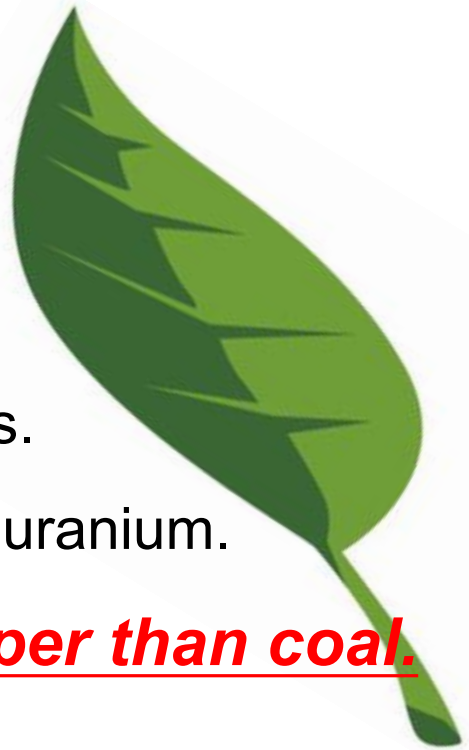
Economics	ThorCon	Coal
Capital cost, $millions/GW	1200	2000
Fuel cost, cents/kWh	0.53	2.27
Electricity, cents/kWh	3.0	5.6

- Developing nations **already choose** nuclear power.
  - 50 under construction; 150 planned
- They **will choose** ThorCon liquid fission.
  - cheaper than today's nuclear
  - cheaper than coal

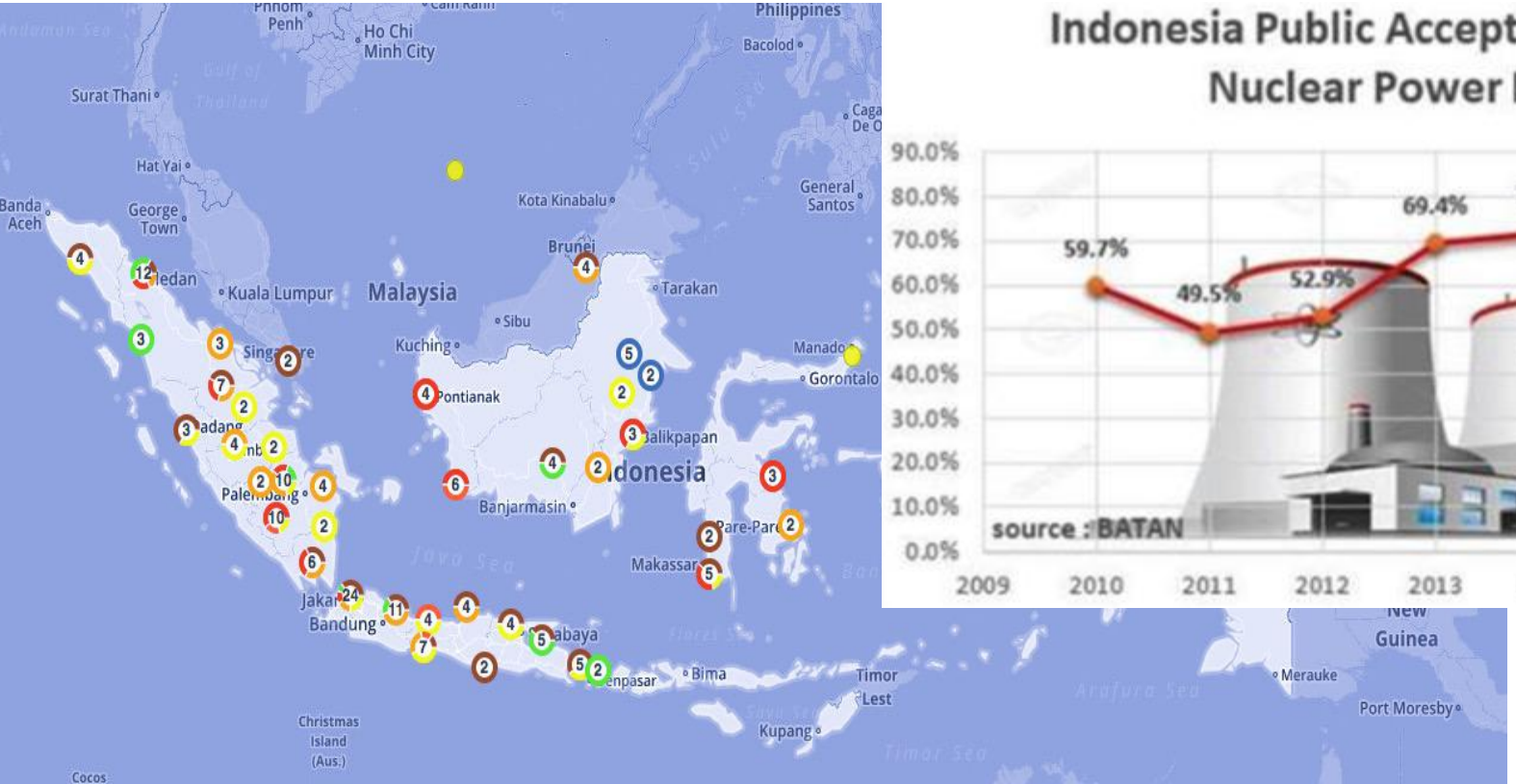
Why? Energy density

ThorCon is environmentally attractive.

- Replaces **coal** mining, excavation, and burning.
- Cuts **CO_2** emissions from coal, natural gas plants.
- Ends deaths from atmospheric **particulates.**
- Stops **deforestation** from burning wood.
- Cuts **flooding** of fertile land by hydroelectric dams.
- Provides **inexhaustible** energy from thorium and uranium.
- ***Requires no subsidies because it's cheaper than coal.***



To supplement its coal power plans, Indonesia wants energy from thorium.



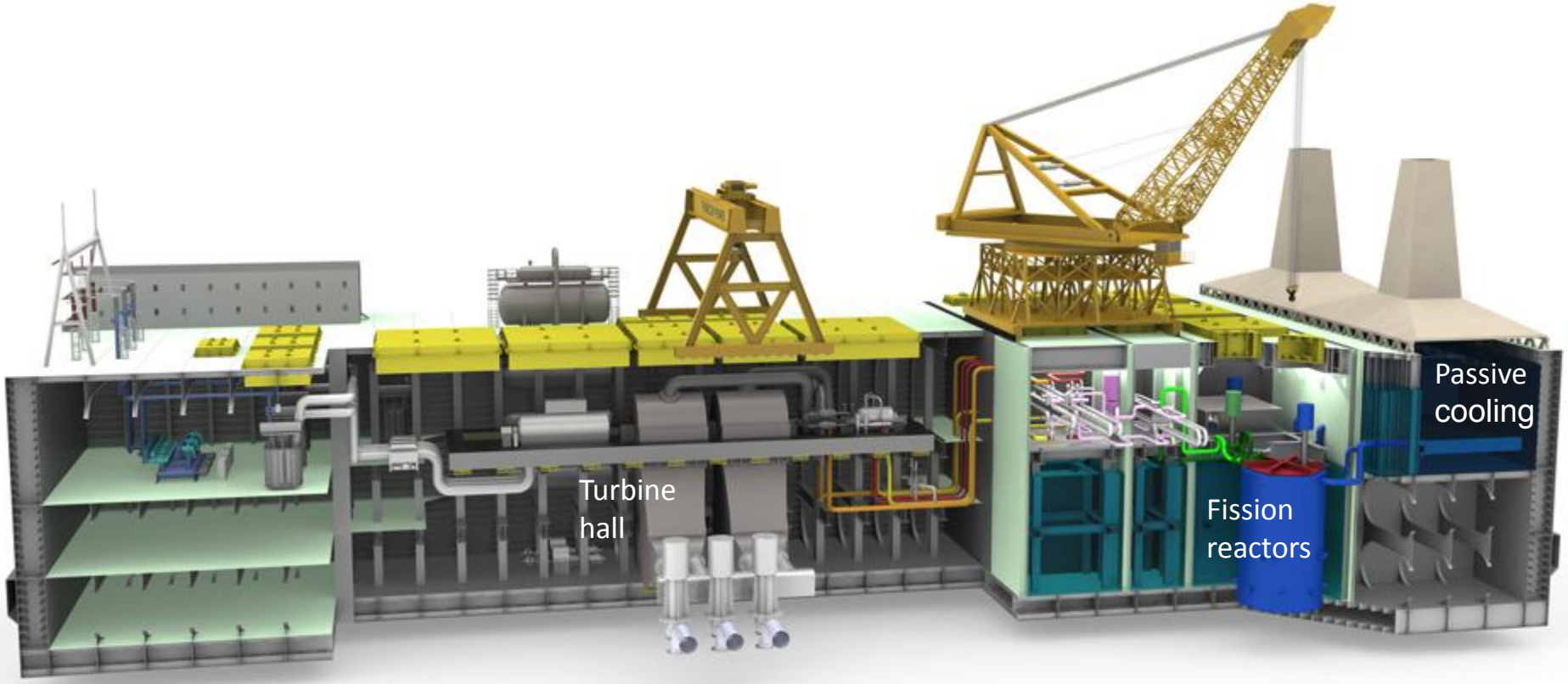
Indonesia conducted a ThorCon pre-feasibility study.

Lars Jorgensen, CEO, ThorCon; Yudiutomo Imardjoko, CEO, INUKI; Nicke Widyawati, Director, PLN; Rachmad Hardadi, Refinery Director, Pertamina; Dave Devanney, Director, ThorCon

US Dept of Energy nuclear head Ed MGinnis discussed ThorCon LEU20 fuel with Indonesia representatives.

Indonesia is developing a roadmap for nuclear power.

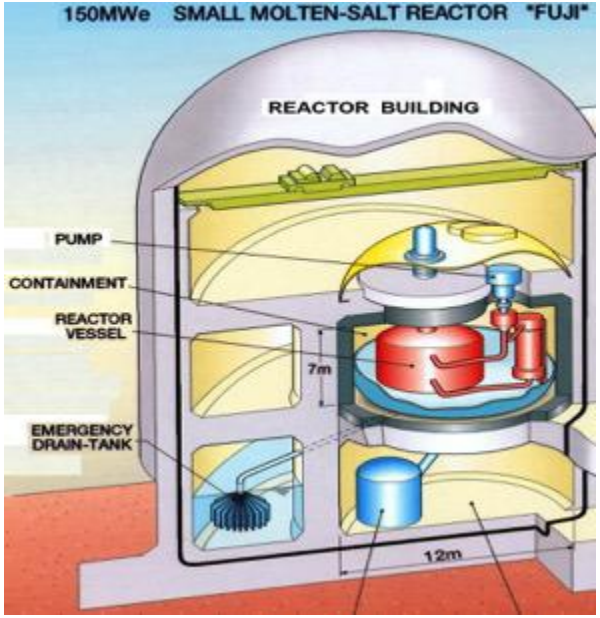
ThorConIsle prototype will be built on a hull, pretested, towed to Indonesia, settled shoreside, and powered up.



ThorCon Reactor Concept

ThorCon is a graphite-moderated thermal spectrum molten salt reactor that produces 250 MWe power.

The basic concept is similar to the MSRE (Molten Salt Reactor Experiment) in ORNL and the Japanese FUJI design.



(Ref: Molten Salt Reactors and Thorium Energy, Elsevier, 2017)

US Dept of Energy grants aid for MSRs.

ThorCon	Measuring fuel salt ionic concentrations in operation, with Argonne Laboratory
Terrestrial Energy	Magnetic bearing molten salt pump
Elysium	Synthesis of molten chloride molten salt fast reactor fuel salt from spent nuclear fuel
Transatomic	Fuel salt characteristics, with Argonne

Liquid fission is proven.

Thorium and uranium fuel dissolved in fluoride salts.

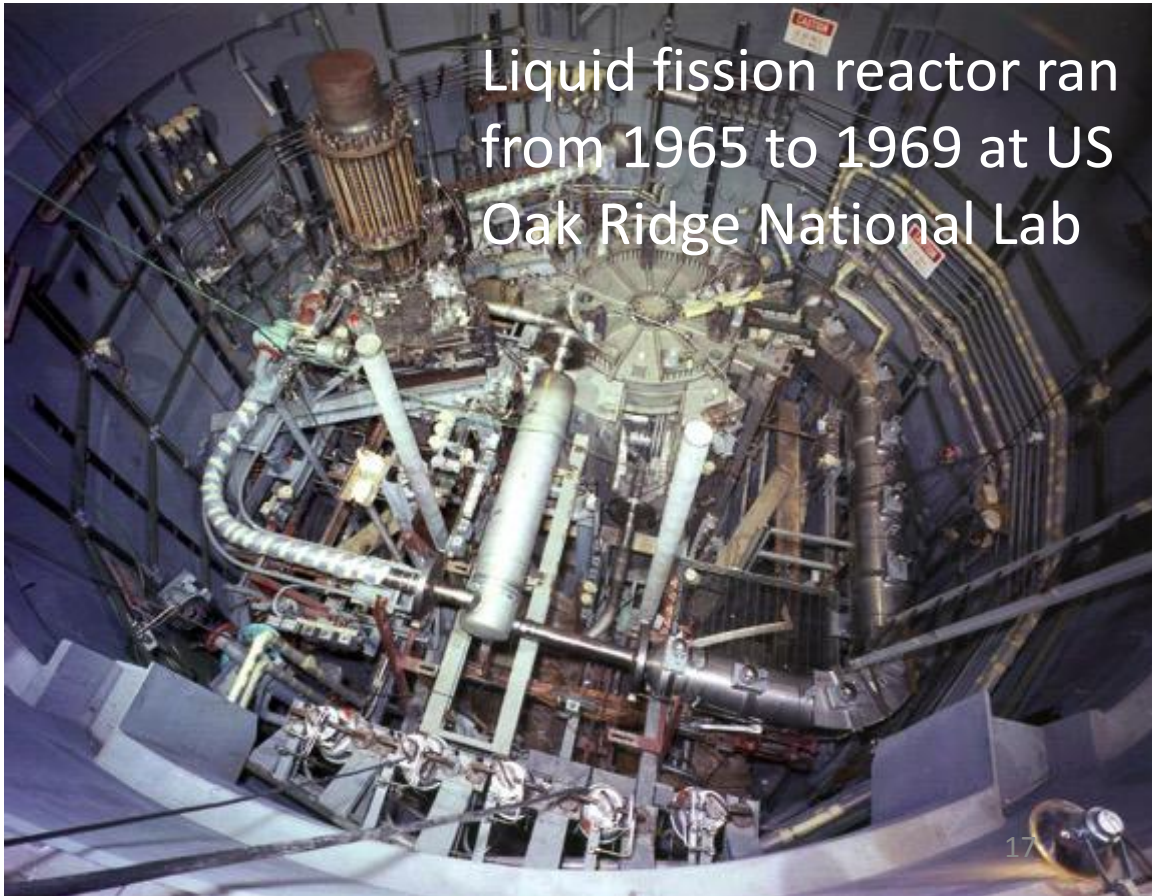
- low pressure
- high temperature
- intrinsic safety physics

ThorCon redesign:

- modular production
- 50 years of science
- modern materials
- fast computers

Result:

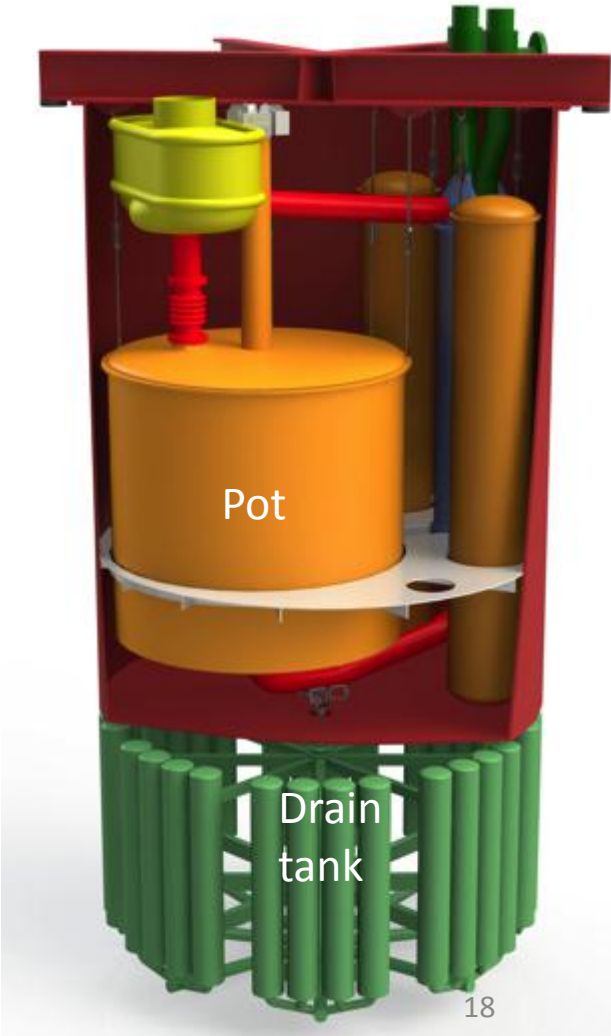
- rapid production
- cheaper than coal



ThorCon reactor is in a Can.

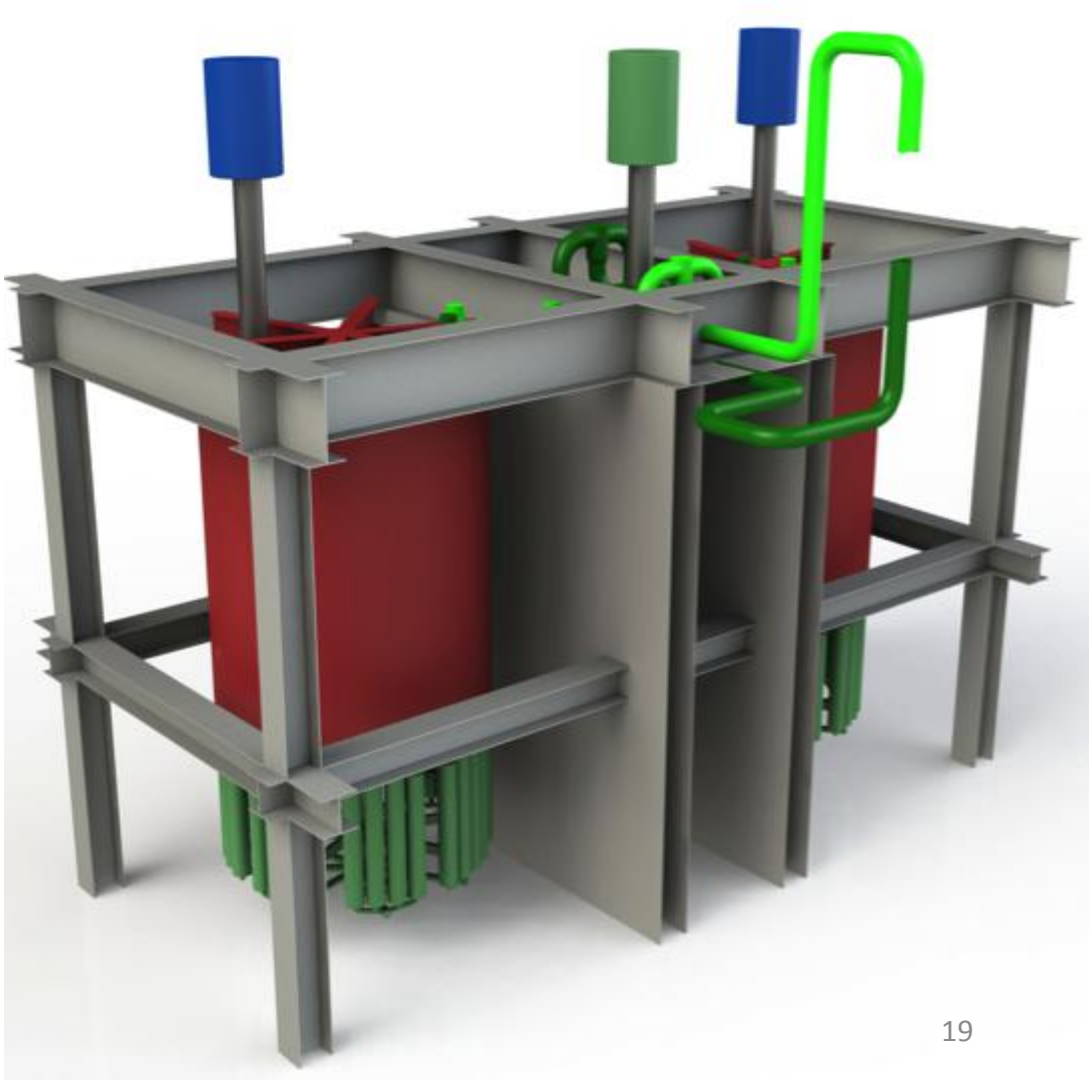
Safer than Fukushima and Chernobyl…

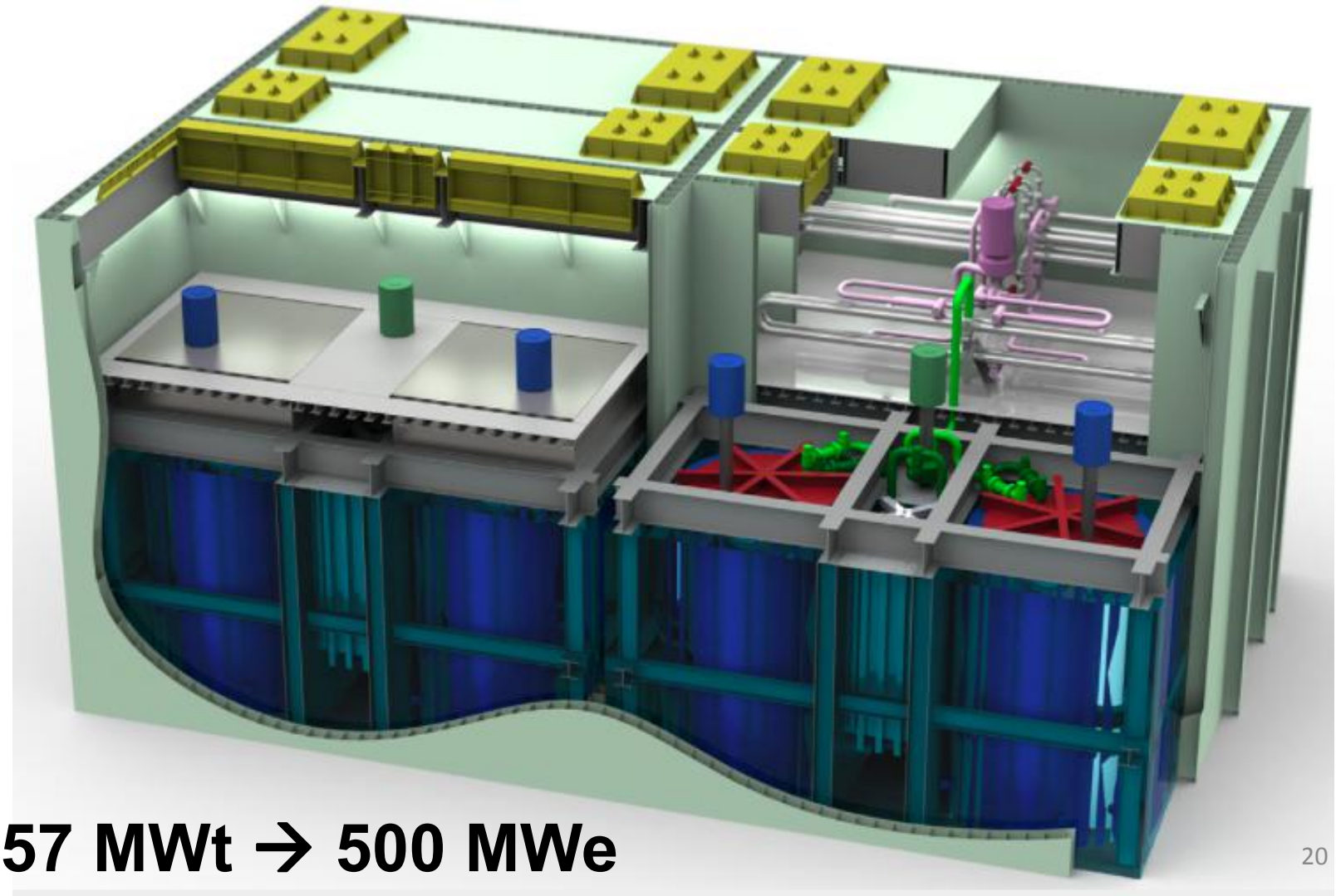
- Safety is **intrinsic** from physics, not add-on safety systems; overheating stops chain reaction.
- Any break will **drain** reactor fuel to cold shutdown fuel salt drain tank.
- Decay heat is removed by silo cooling wall continuous **passive** water circulation, even in power blackout.
- Radioactive fuel salt at **low**, garden-hose pressure can't disperse in catastrophe.
- Fluoride salt chemically **locks up** hazardous fission products iodine-131, cesium-137, strontium-90.



Cans are duplexed.

- Can operates for four years, then cools down for four years, and then is changed out.
- Each power module has two Cans housed in silos.
- Liquid fission plant comprises 1 to 4 power modules of 557 MW (thermal) generating 250 MW (electric).



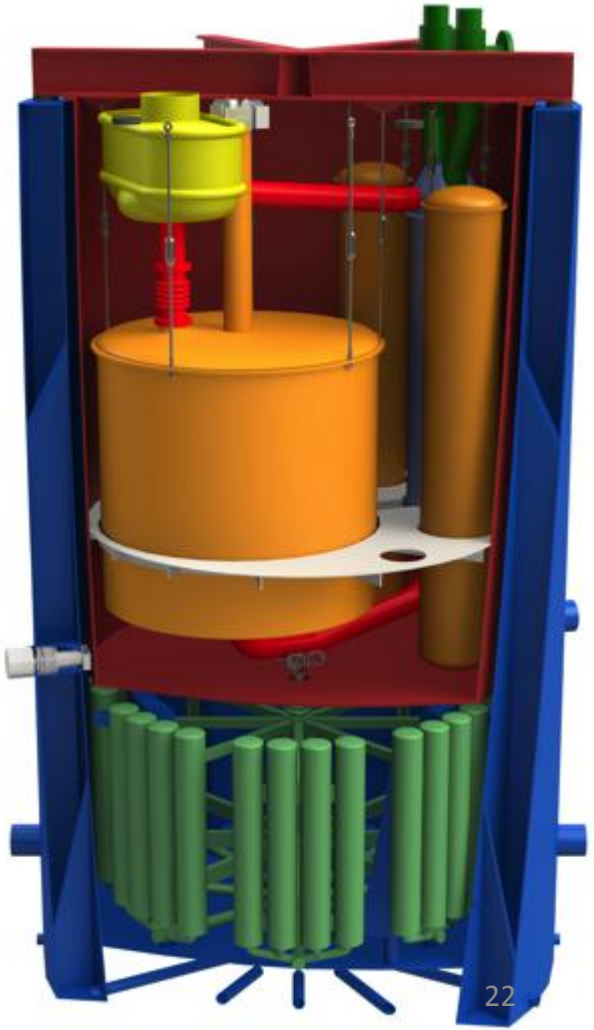


2 X 557 MWt → 500 MWe

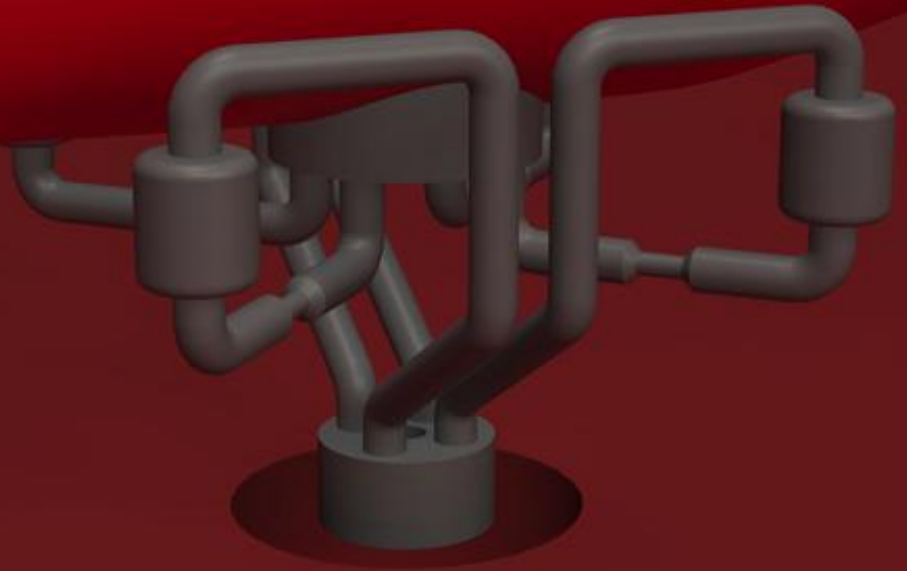
Cold Wall envelops Can.

Can radiates heat to Cold Wall.

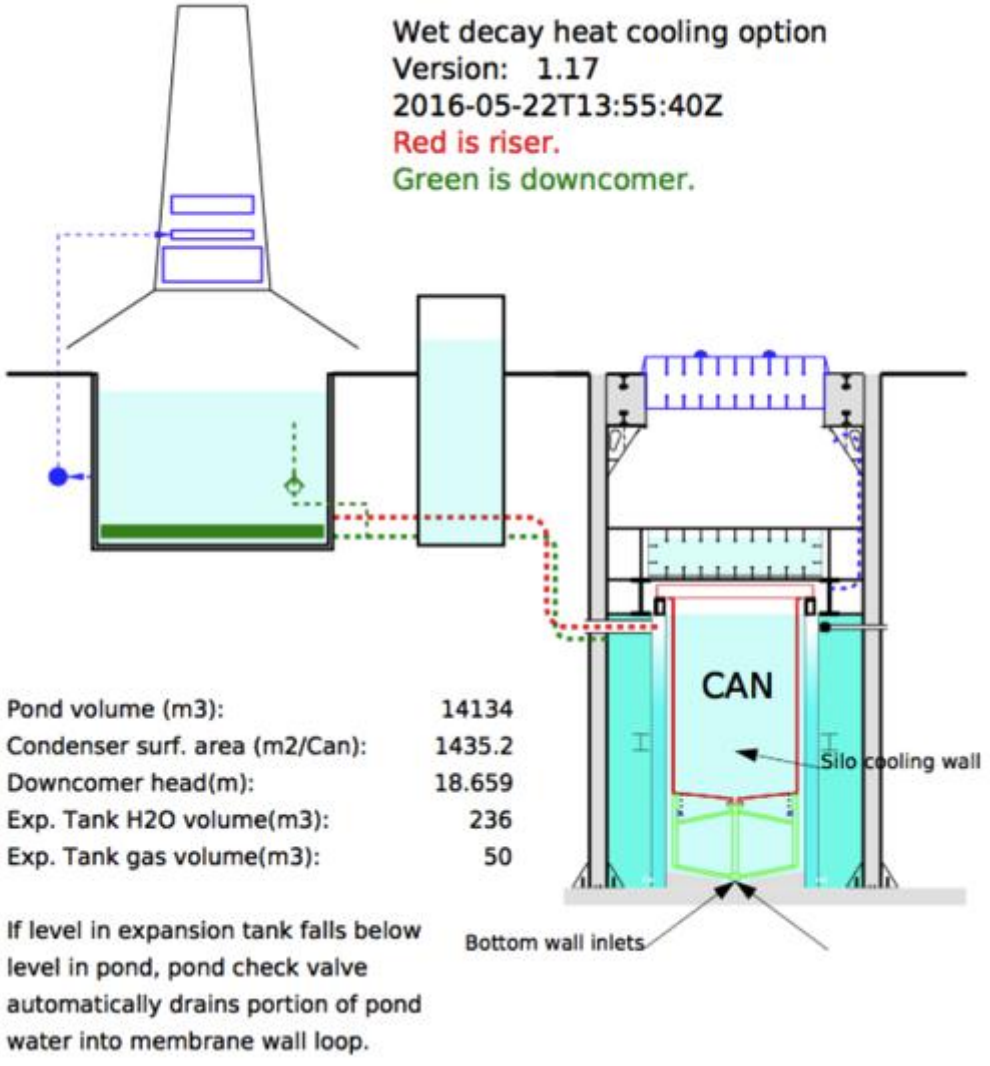
- Primary heat removal is via ocean water cooling.
- On loss of main power generation, sentry turbine generator continues running on decay heat, thereafter on fired steam boiler.
- If all fail, loop overheats, freeze valve thaws, primary loop drains to Fuelsalt Drain Tank.
- Nothing operators can do to stop this drain.
- Primary loop rupture would also drain to FDT.



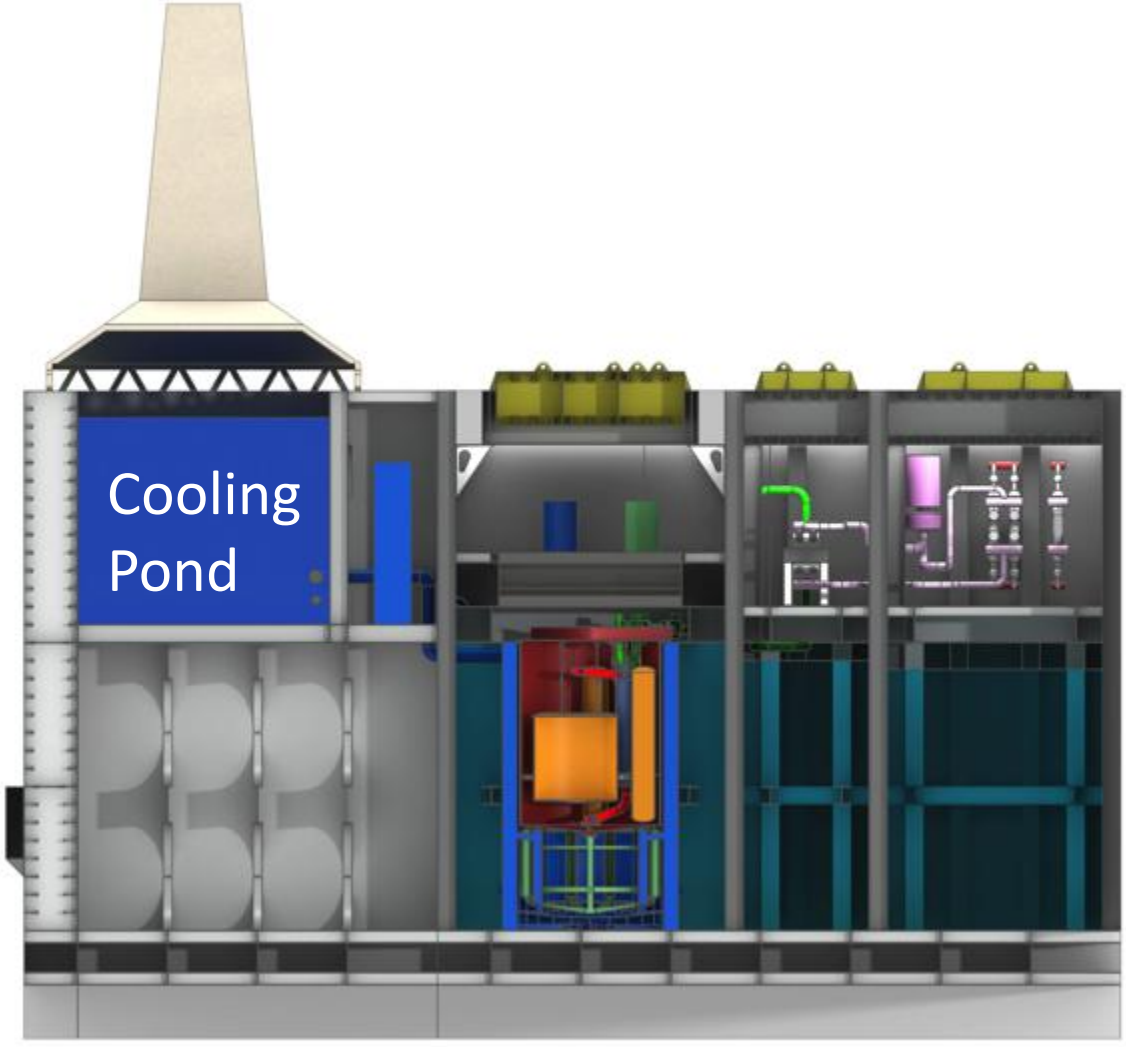
ORNL MSRE freeze valve design quadrupled.

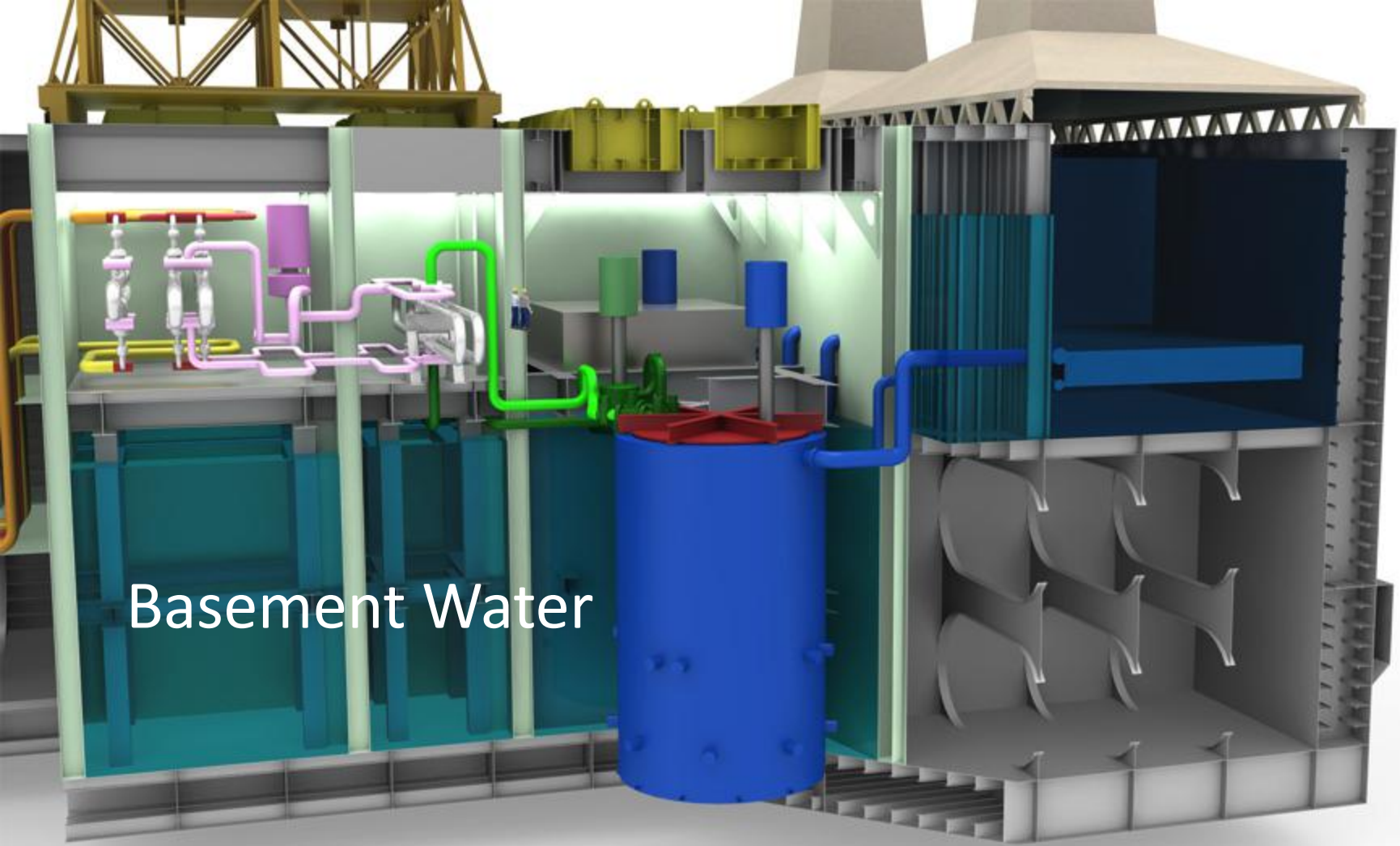


Cold Wall decay heat removal is passive



- Can radiates heat to water-cooled silo cooling wall.
- Natural circulation water operates continuously: always under test; no valves; operator can not disable it.
- Cooling pond has 145 day water supply.
- If all water evaporates, air cooling suffices indefinitely.
- If Cold Wall ruptured, basement water suffices 1.5 years.


Cooling
Pond

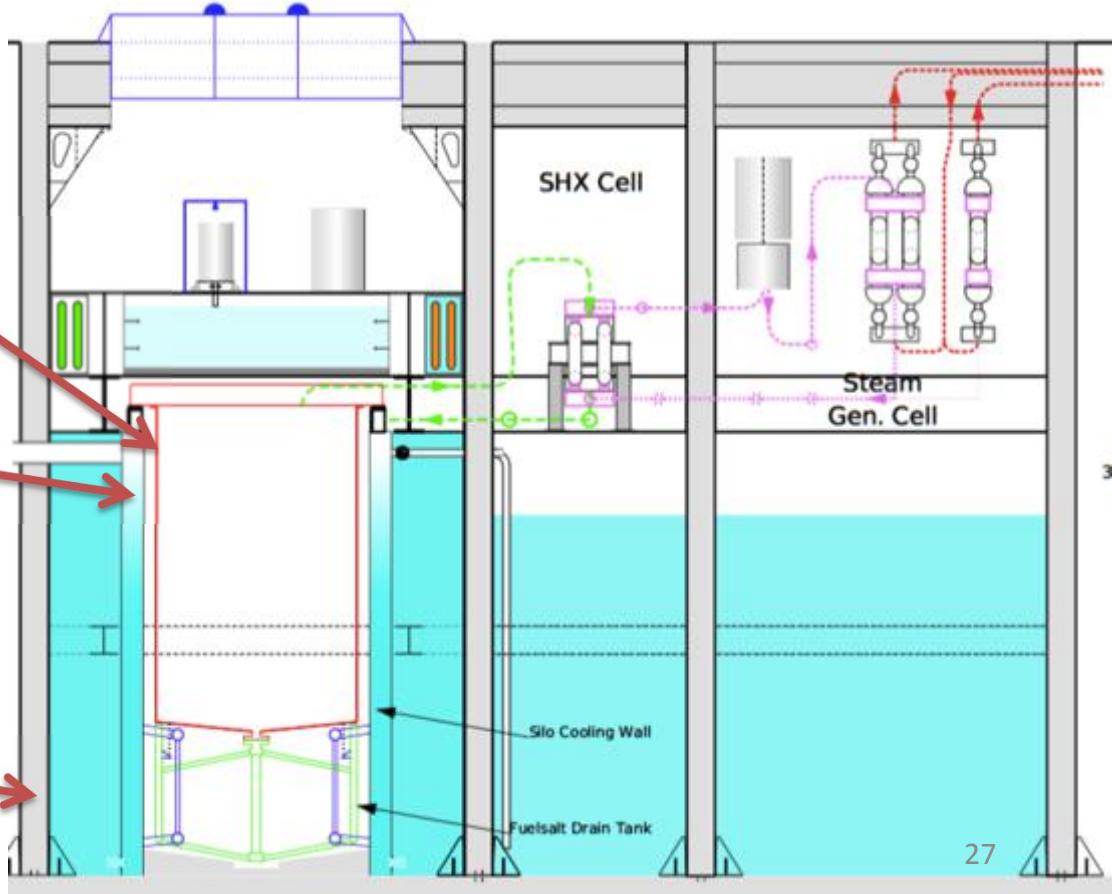

Basement Water

ThorCon has at least 3 radioactivity barriers.

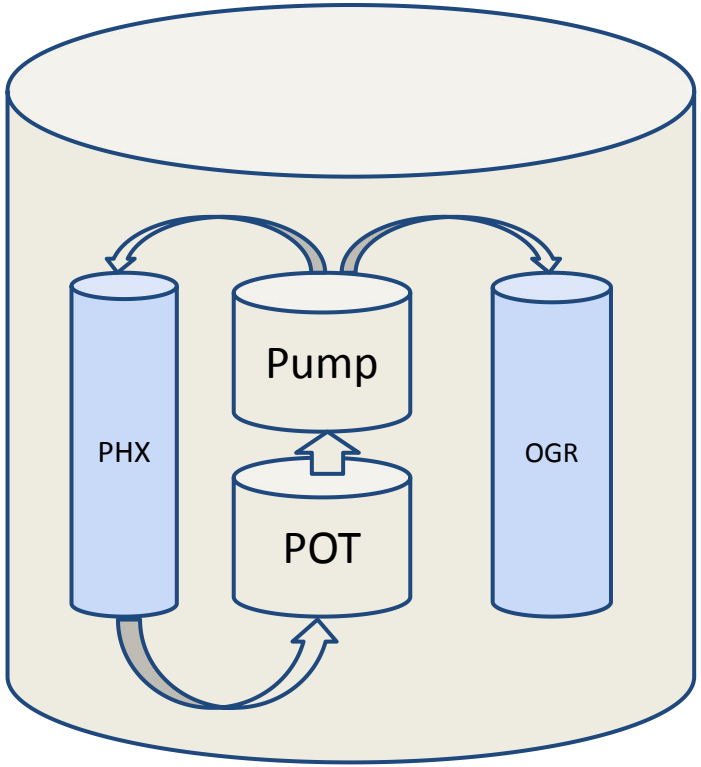
1. Can/Drain Tank:
   25 to 50 mm steel

2. Silo Cavity:
   double steel layers

3. Hull:
   3 m concrete in 25 mm
   steel sandwich



Fission product gases are removed.

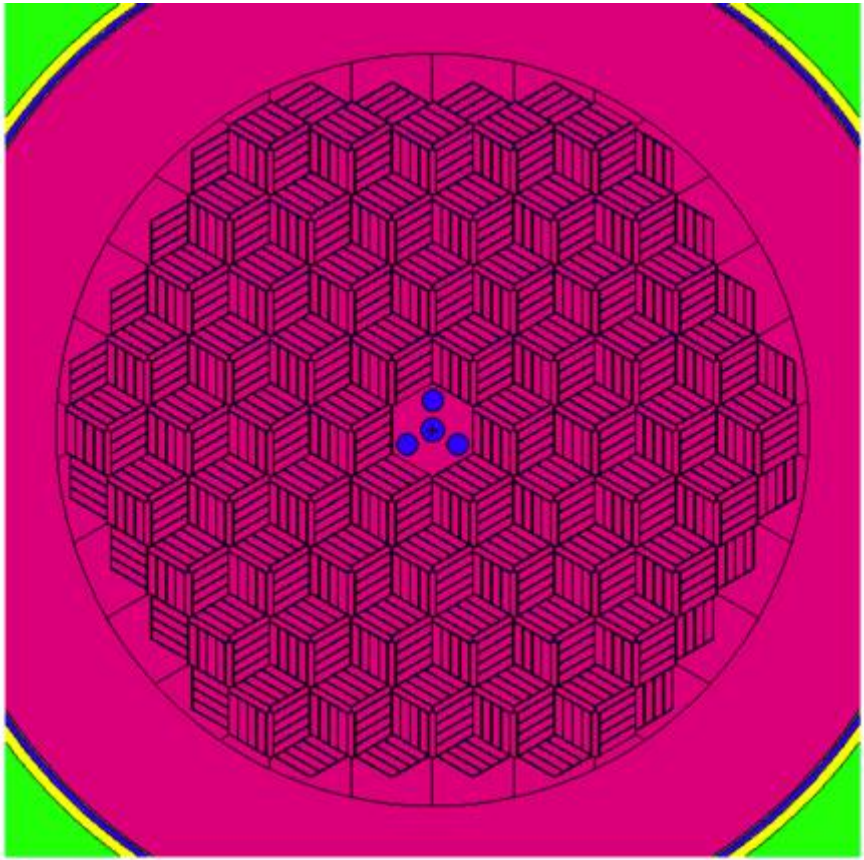


- Off-Gas Recovery involves He sweep, hold-up tanks, charcoal delay, low turbulence flows.
- Gases (Kr, Xe)
  - Removed by spray bubbling
  - 216 kg/Gwe-yr
- Noble metals (Nb-Te)
  - Plate out into OGR and PHX
  - 234 kg/Gwe-yr
- Solubles (Rb, Sr, Y, Zr, Cs-Gd, Pu-Cm, Br, I)
  - stay in the salts
  - 409 kg/Gwe-yr

- Trifluorides saturate fuel salt after 8 years.

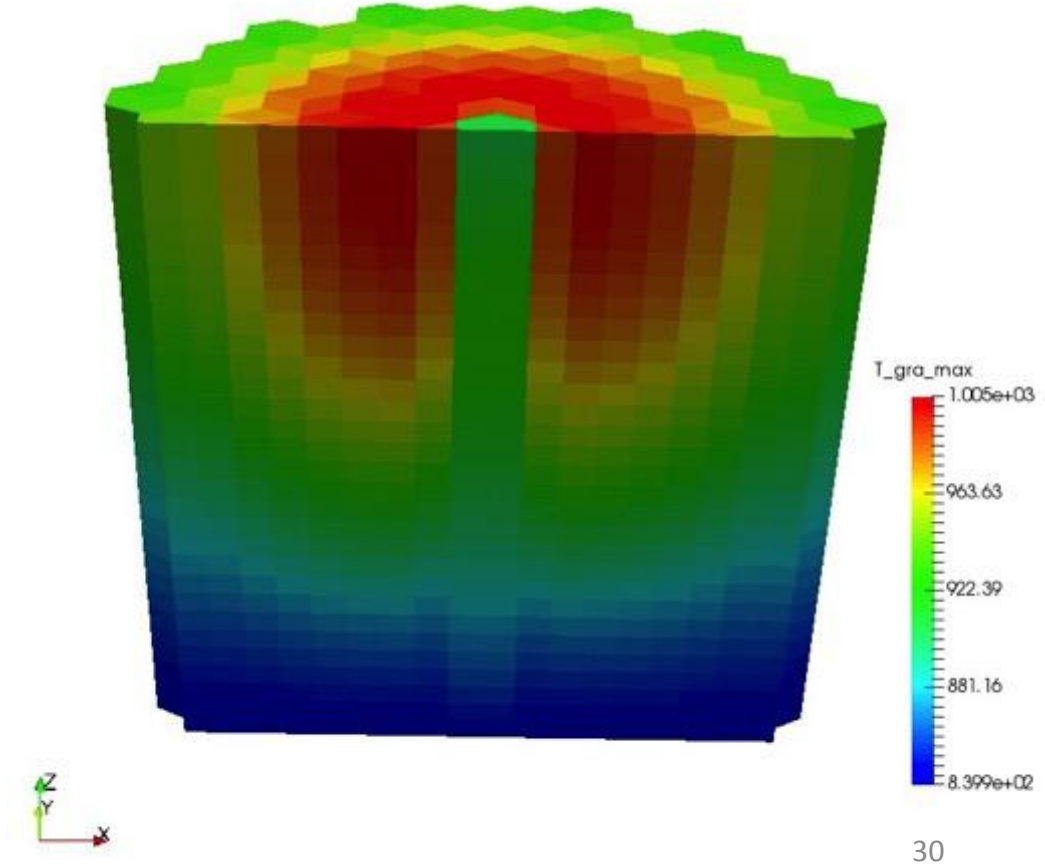
ThorCon graphite core

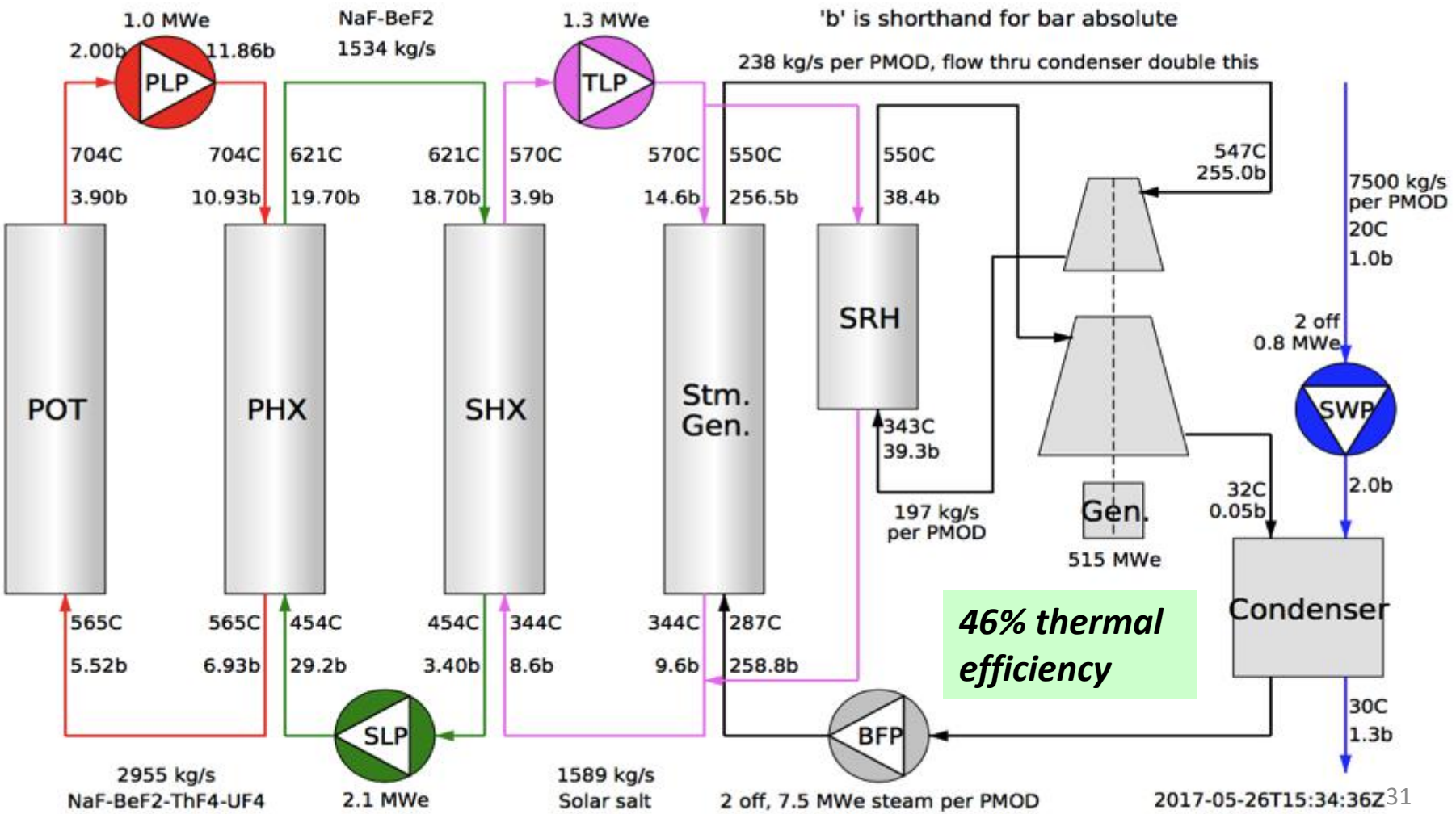
- Core made up of hex graphite logs in 5 m cylinder.
- Easy to fabricate. Easy to disassemble. Lots of surface area.
- Central log has with 3 shutdown rods and instrumentation.
- Moderator mounting system allows graphite changes with temperature and fluence.



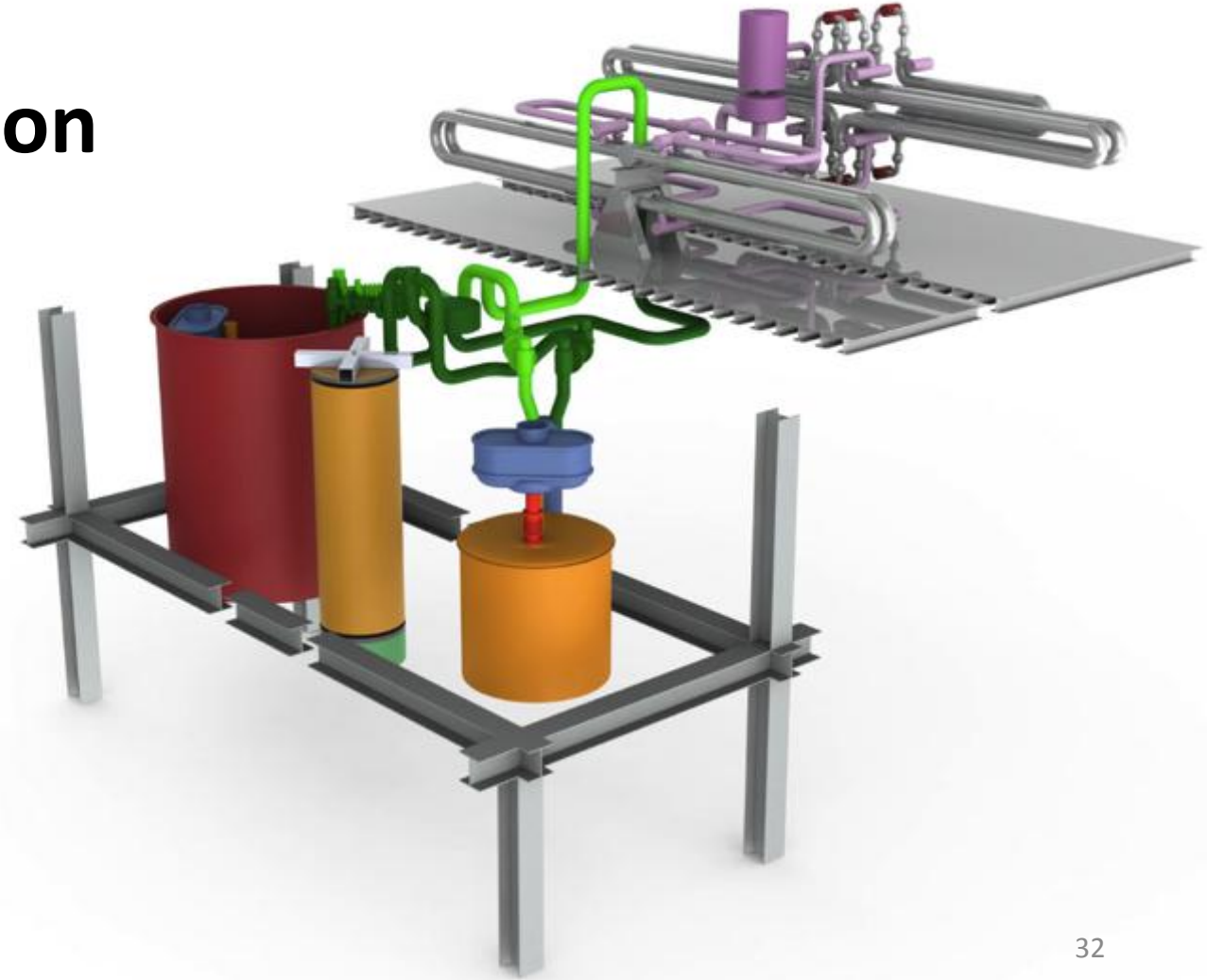
Graphite temperature model example

- Neutronics, burnup, salt temperature, graphite temperature and changes modeled with MCNP, Serpent, OpenFOAM
- Strongly negative temperature coefficient throughout fuel cycle.
- Load response via pump speed confirmed.

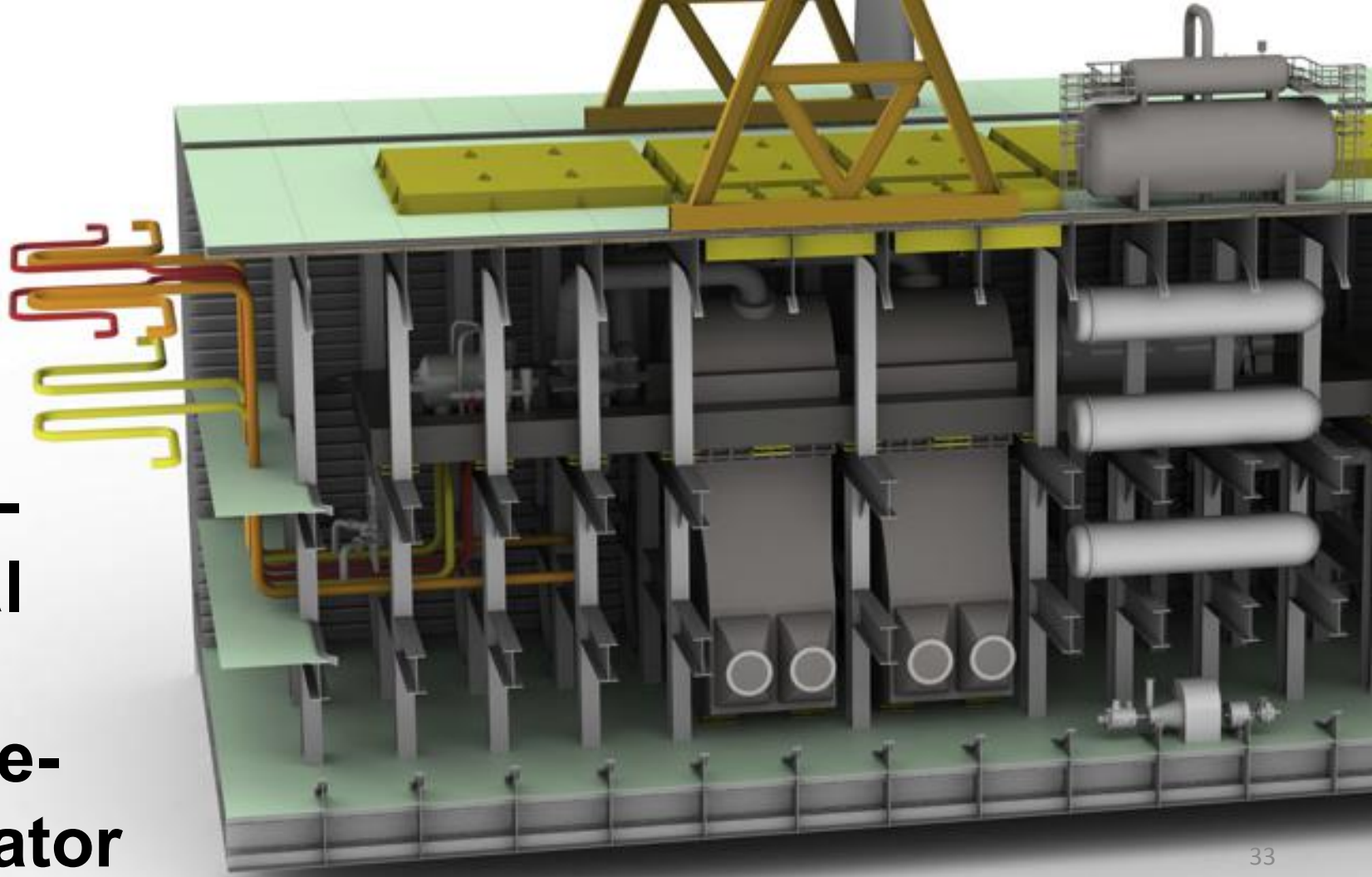


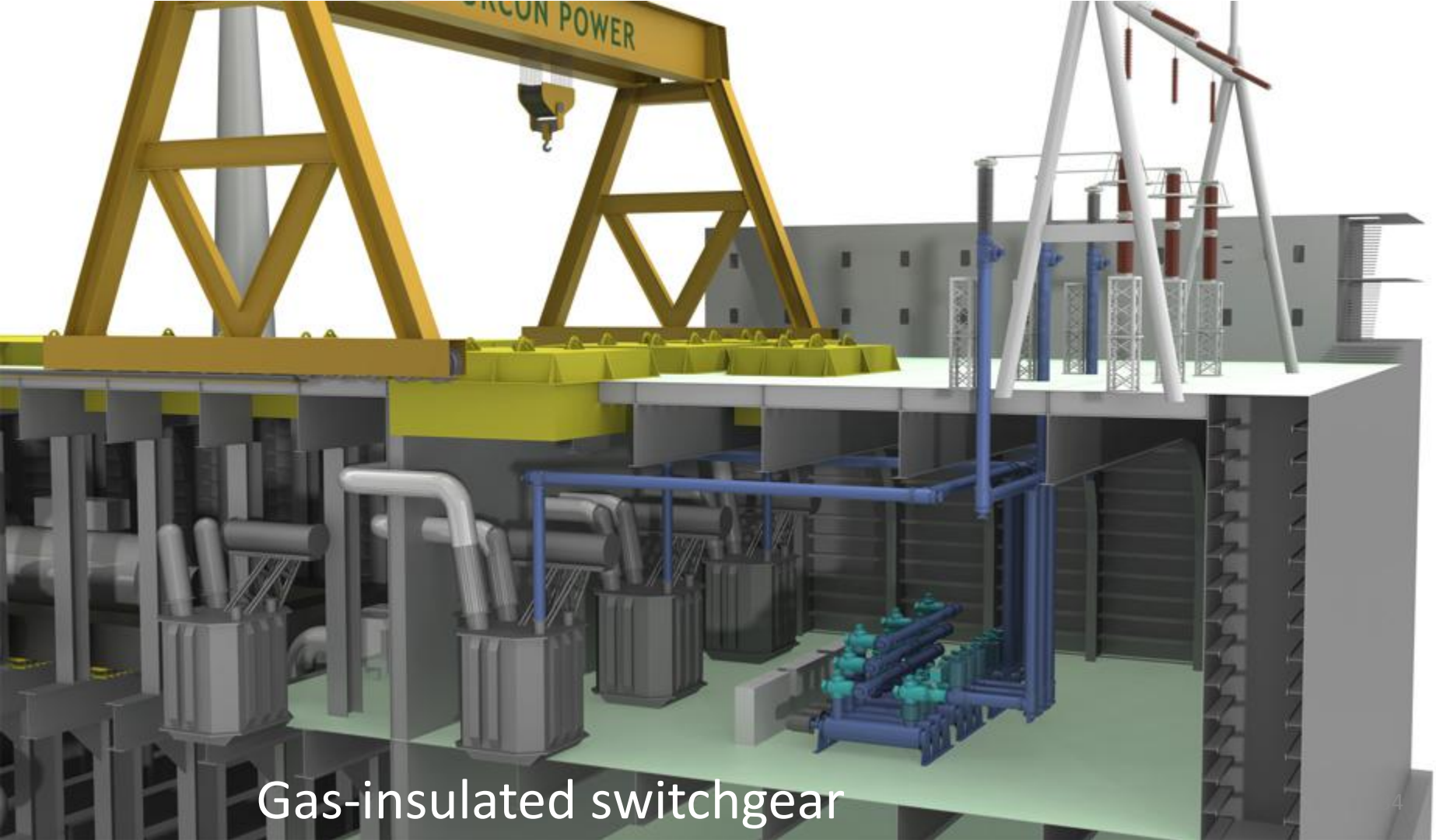

1.0 MWe
2.00b
11.86b
PLP
NaF-BeF2
1534 kg/s
1.3 MWe
TLP
'b' is shorthand for bar absolute
238 kg/s per PMOD, flow thru condenser double this
704C
3.90b
704C
10.93b
621C
19.70b
621C
18.70b
570C
3.9b
570C
14.6b
550C
256.5b
550C
38.4b
547C
255.0b
7500 kg/s
per PMOD
20C
1.0b
POT
PHX
SHX
Stm.
Gen.
SRH
2 off
0.8 MWe
SWP
343C
39.3b
197 kg/s
per PMOD
Gen.
515 MWe
32C
0.05b
2.0b
565C
5.52b
565C
6.93b
454C
29.2b
454C
3.40b
344C
8.6b
344C
9.6b
287C
258.8b
46% thermal
efficiency
Condenser
30C
1.3b
SLP
BFP
2955 kg/s
NaF-BeF2-ThF4-UF4
2.1 MWe
1589 kg/s
Solar salt
2 off, 7.5 MWe steam per PMOD
2017-05-26T15:34:36Z

Power conversion heat transfer system makes 550°C steam.



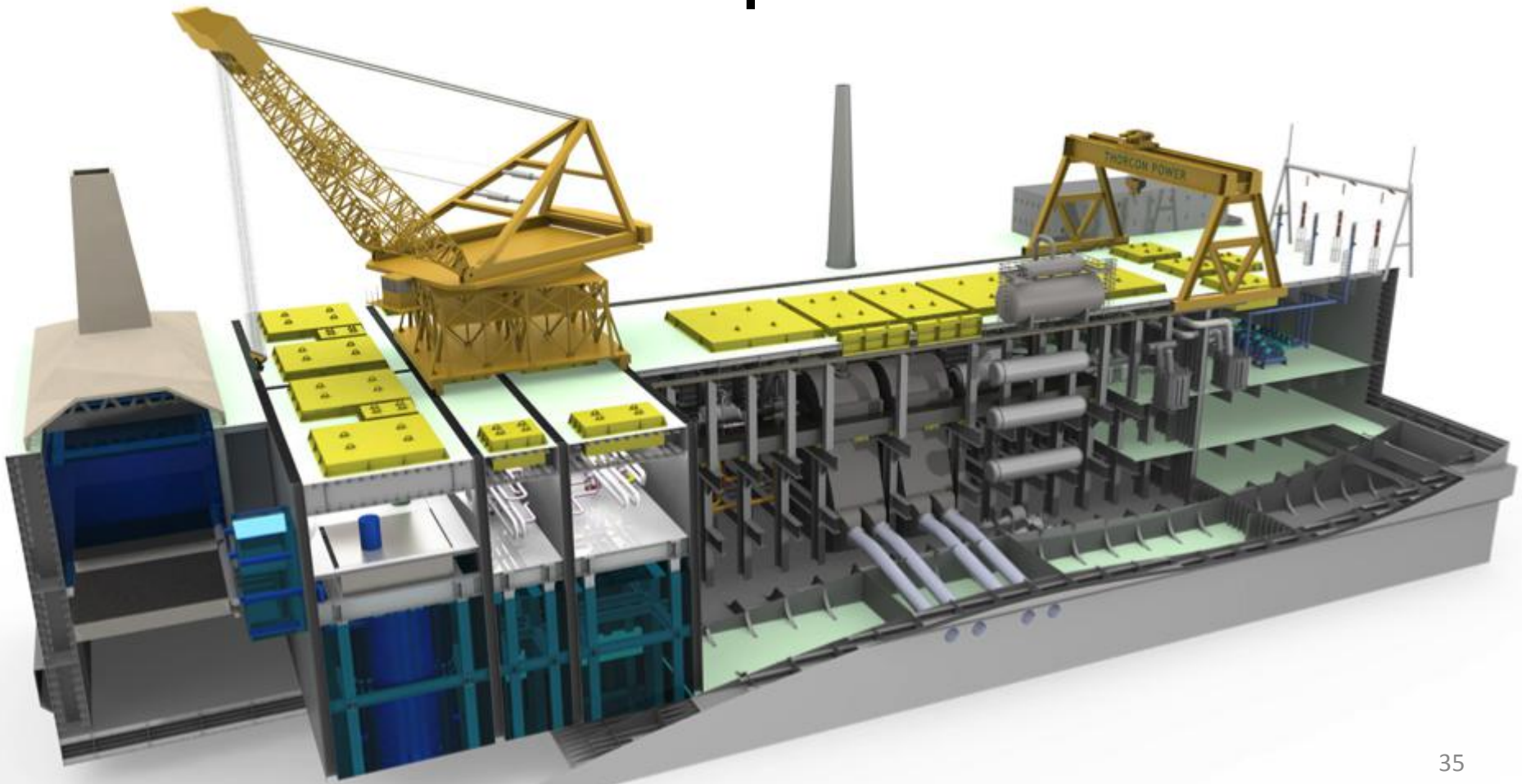
Super-critical steam turbine-generator



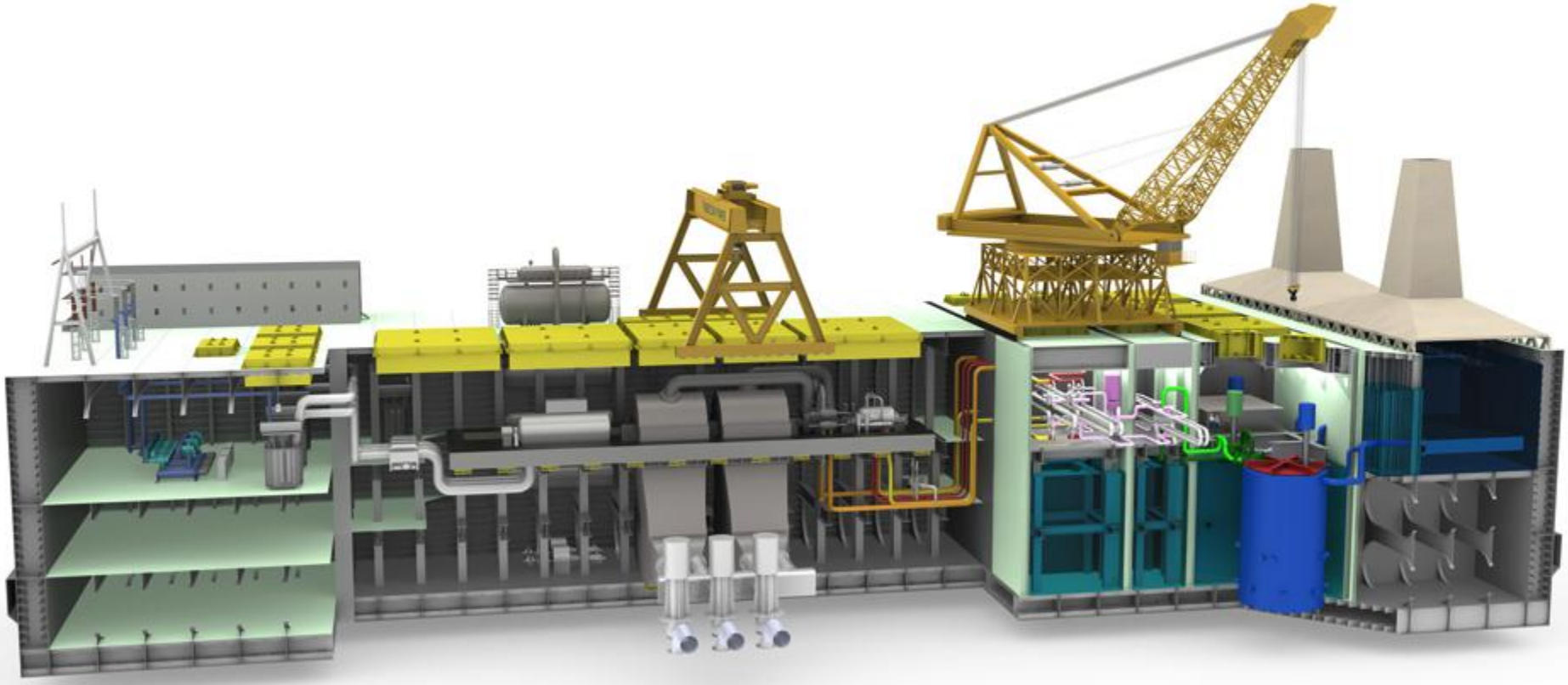


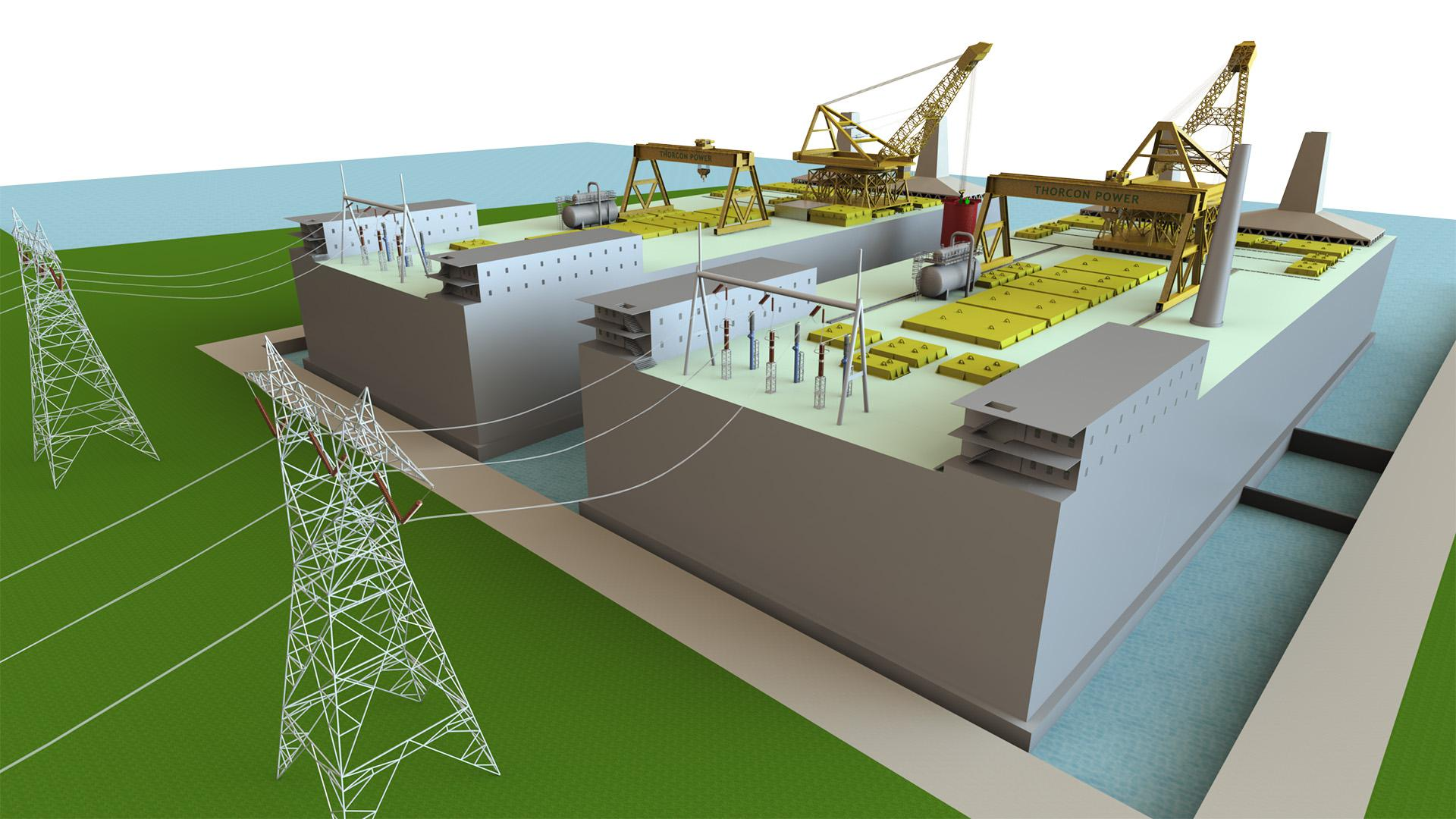
Gas-insulated switchgear

ThorConIsle port view

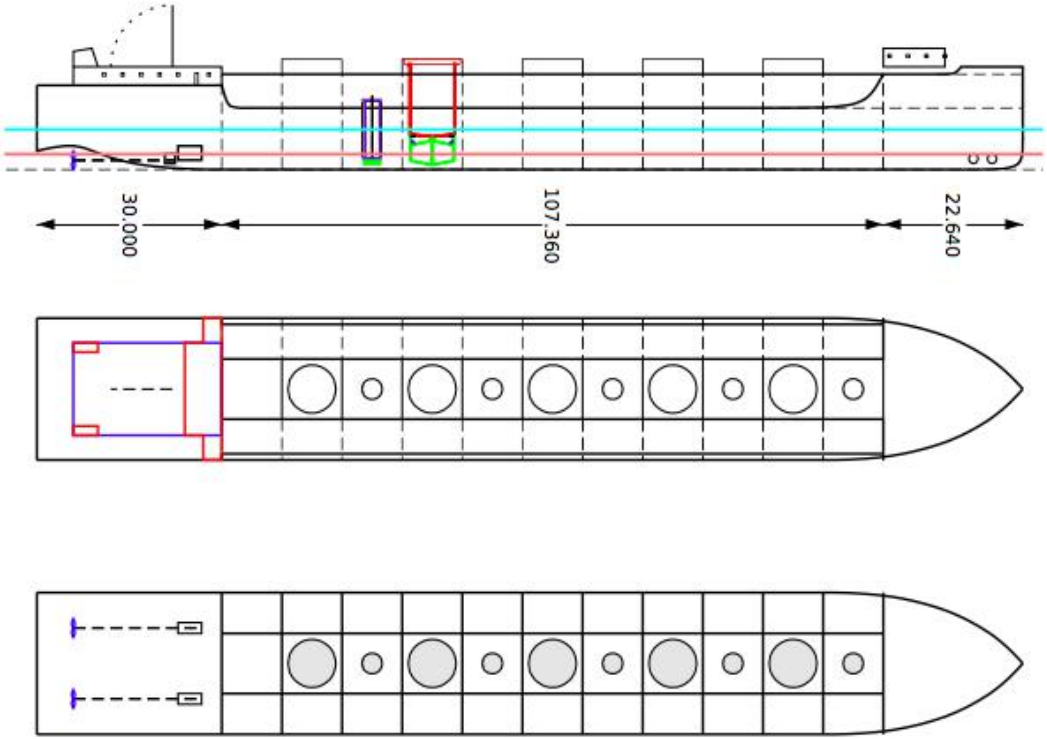


Starboard view with seawater cooling pumps.

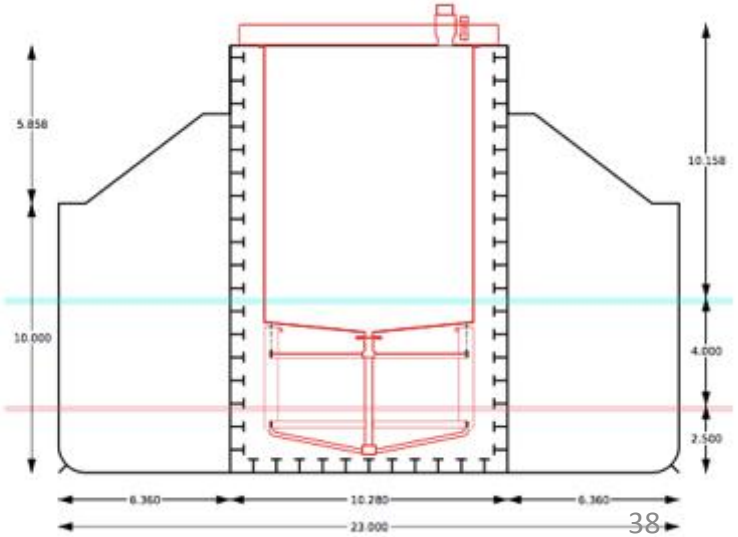


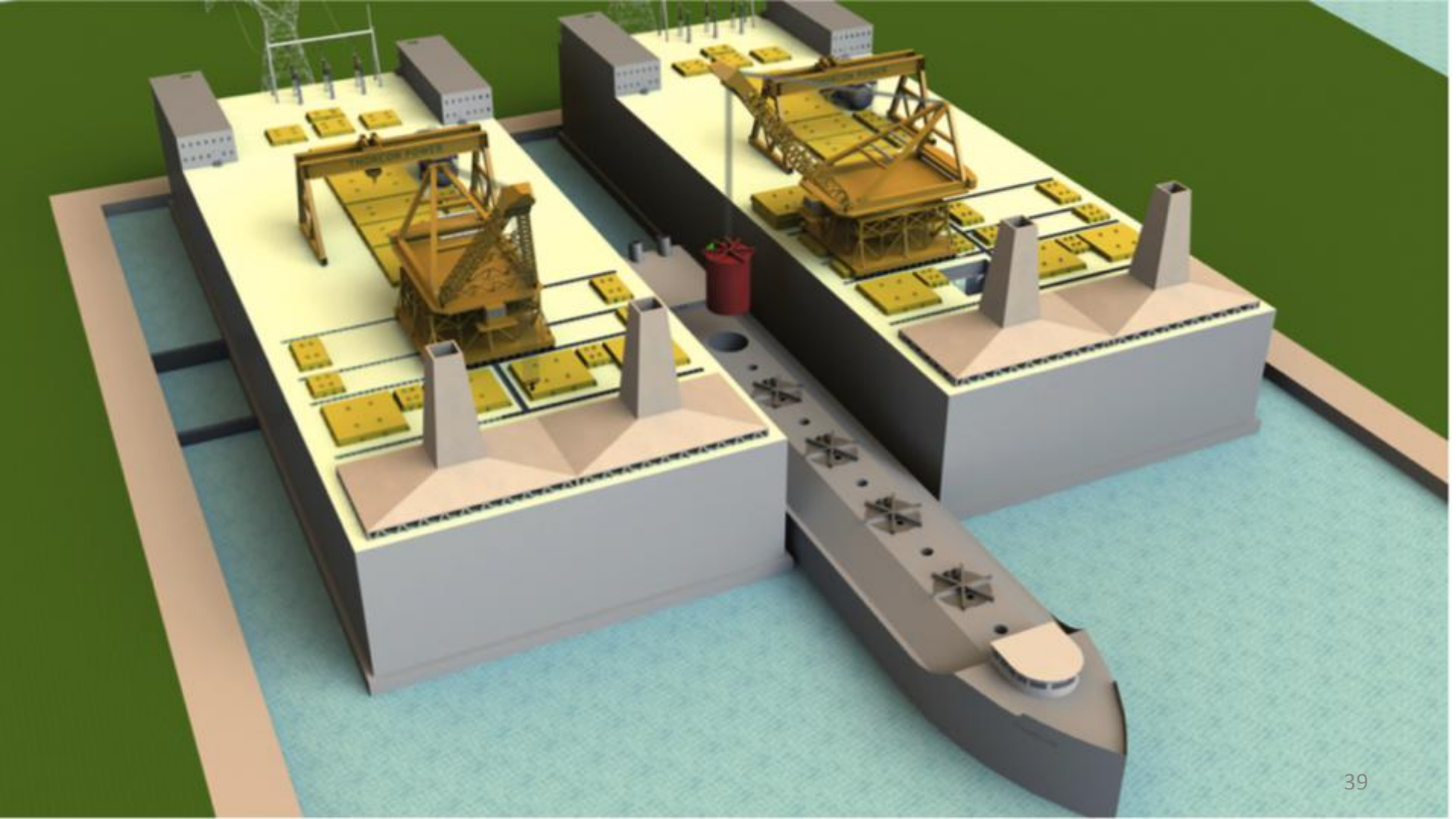

THORCON POWER
THORCON POWER

ThorCon CanShip exchanges Cans and Fuel Casks.



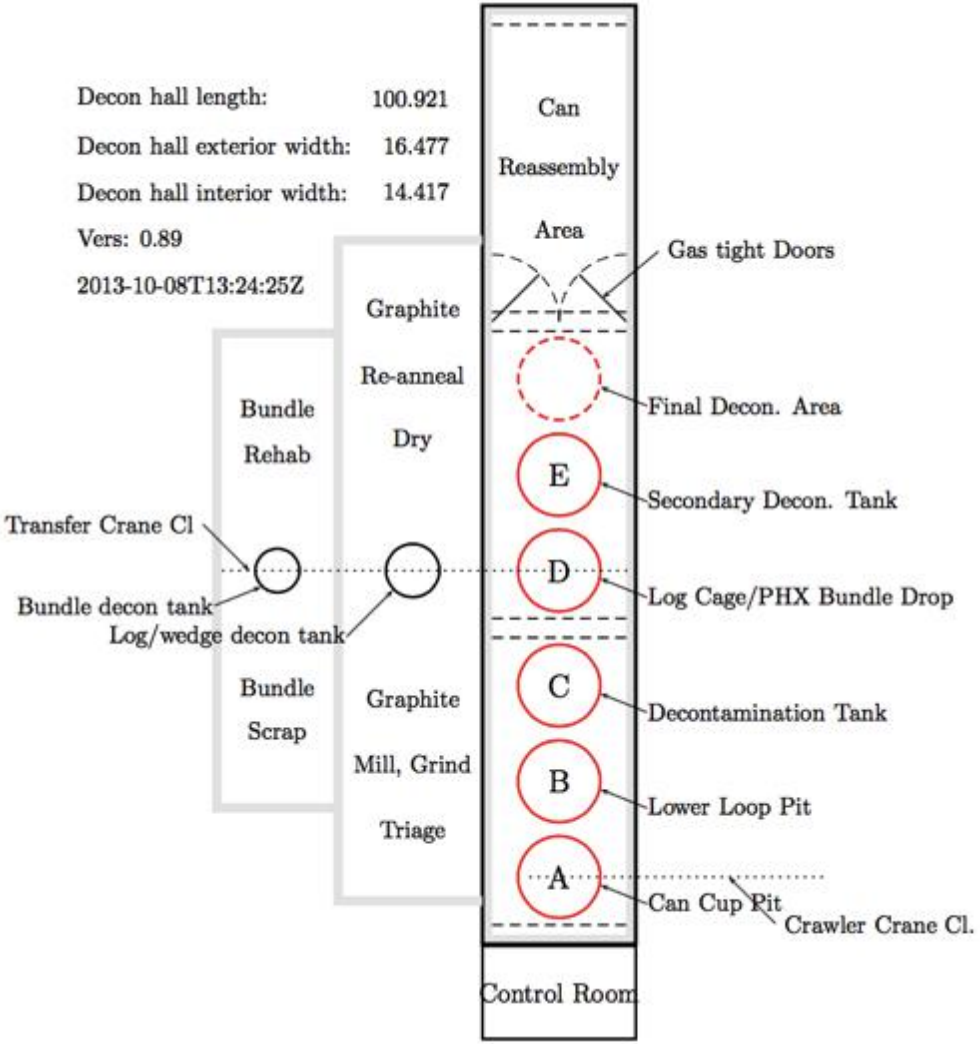
River draft(m):	2.500
River displacement(tons):	7,000
Deep draft(m):	6.500
Deep displacement(tons):	17,000
Engine:	2 by MAN V23/30A-VO derated to 1620 kW
12 cyl Vee, 900 RPM, bore=225mm, stroke=300mm	
Prop MCR RPM/diameter	233/2900 mm
River draft speed at derated power(kts):	14.5
Deep draft speed at derated power(kts):	12.0
Vers: 1.21	2017-06-23T12:48:17Z





Can recycling center

Can recycling center cleans and inspects cans, replaces graphite, stores offgas and graphite wastes.



Spent fuel in dry casks before processing.

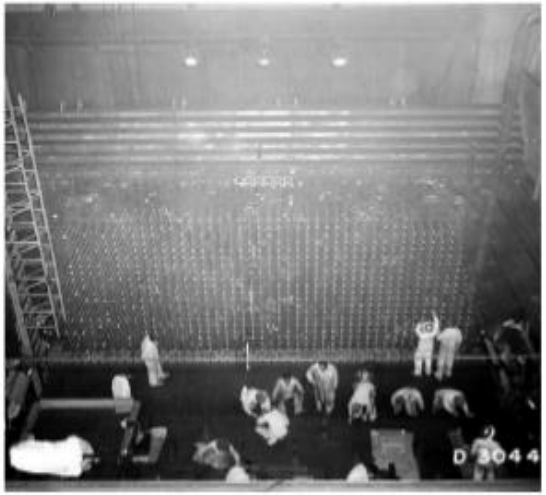
- Each 250MWe module fuel salt lasts 8 years (2 GWe-yrs).
- Generates 20 m3 spent fuel.
- Spent fuel salt stored in Can cools for four years, to 80 kW.
- Fuel salt shipped in one fuel cask (11m high x 3 m diameter).

- Photo: 28 years of dry cask storage for 620 MWe Connecticut Yankee power plant.

A prototype nuclear power plant *can* be built quickly.

Camp Century
2 MWe
Greenland glacier
American Locomotive
factory modules
1959 + 2 years

Nautilus
10 MWe
First ever PWR
Electric Boat
full scale prototype
1949 + 4+2 years



Hanford
250 MWt
Pu production
Dupont, GE
1942 + 2 years

Designers are experienced in block construction technology.

- built eight of the world's largest supertankers
- $600 million program
- responsible for all specifications, financing, yard negotiations and supervision
- World-class shipyards will fabricate blocks quickly, reliably, at low cost.

ThorCon designed for high-quality, low-cost shipyard block construction technology.

High-precision steel-fabrication builds ships for $2000 per ton.

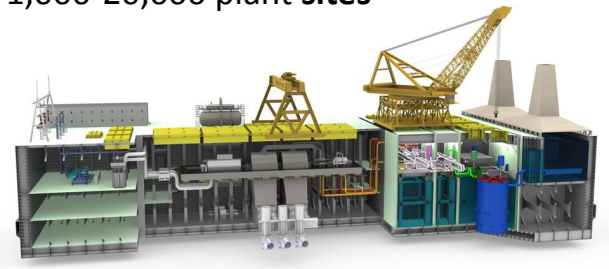
World shipyards can build **100** 1-GW ThorCon power plants per year.

CanShip moves Cans and fuel salt casks between power plants and recycling facilities.

Shipyard builds new power plants

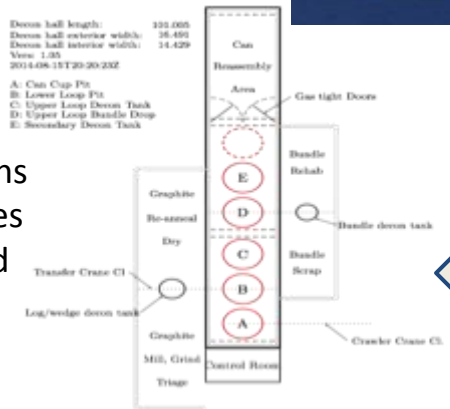
Tow to plant site

1,000-20,000 plant **sites**



CanShip delivers new Cans and takes old Cans back for recycling. Also transports new fuel and returns spent fuel in fuel casks. One round trip every four years to each 1 GWe site.

Can recycling facility cleans and inspects Cans, replaces graphite, stores offgas and graphite wastes.



Fuel salt handling facility stores spent fuel. Will later extract, re-enrich, and recycle uranium.

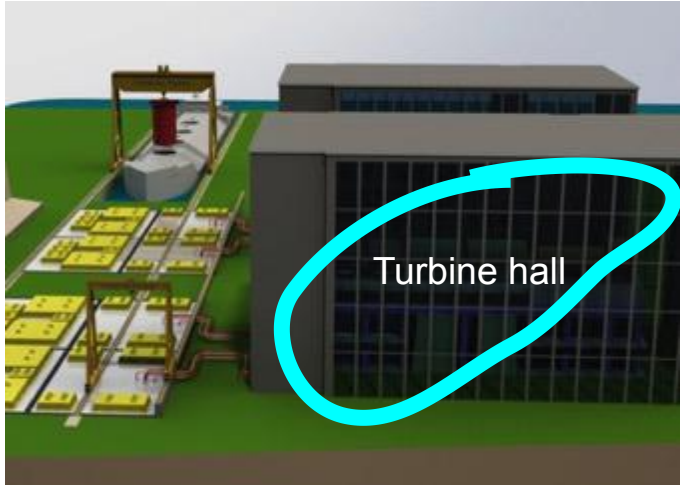
ThorCon is fuel and salt flexible.

		Startup					Makeup thorium plus			
Mission	Salt 12% HM	Th	U	U233	U235	Other U	U233	U235	U238	Self generated fuel
1) Initial tests	NaBe	0	100 %	0	3%	97%	0	5%	95%	30%
2) Economic baseline	NaBe	82 %	18%	0	20%	80%	0	20%	80%	50%
3) Better fuel utilization	FLiBe	82 %	18%	0	20%	80%	0	20%	80%	60%

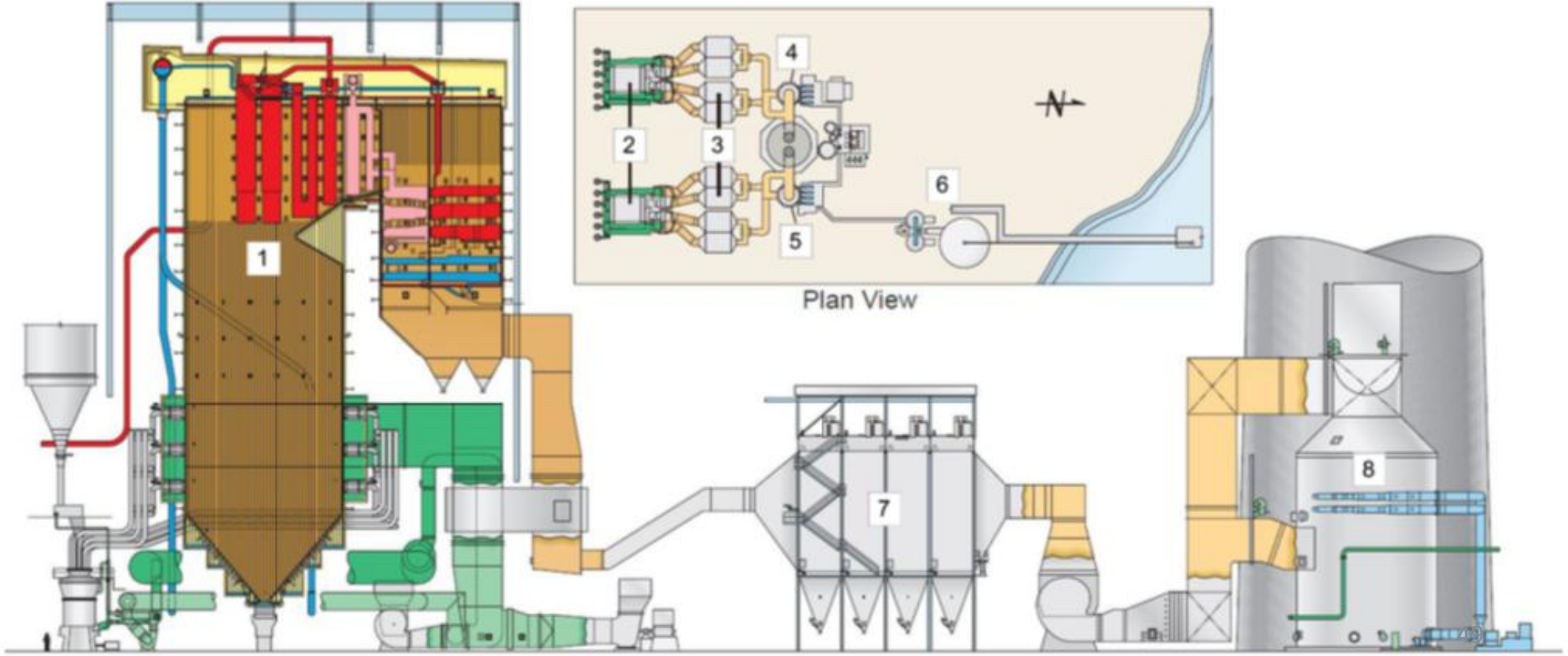
Economics

Cheaper than coal, or don’t bother.

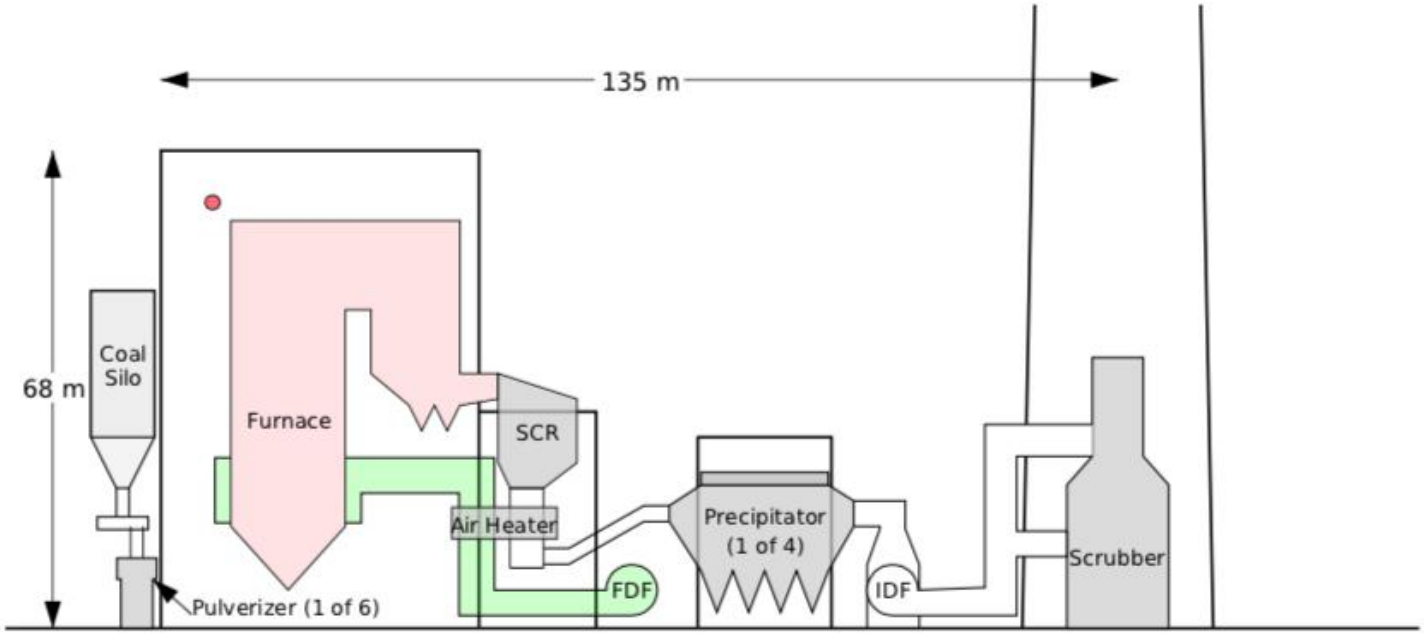
Why cheaper than coal?

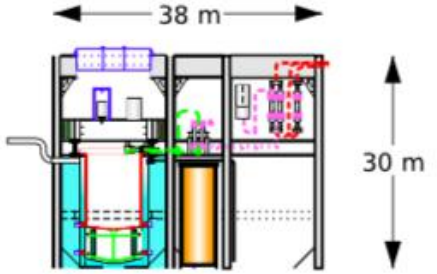


660 MW Tanjung Jati coal-burning boiler and exhaust gas processing steam-generation…



…compared to ThorCon fission steam generator.





coal burning

fission

ThorCon avoids three costly LWR issues:

low temperature, high pressure, solid fuel.

- Thanks to **high temperature**, ThorCon uses the same, competitively-sourced, $500/kW supercritical steam turbine-generator as a modern coal plant.

- Thanks to **low pressure**, ThorCon avoids reinforced concrete mausoleum and 9-inch-thick forgings.

- Thanks to **liquid fuel**, ThorCon can move fuel around with a pump. No exacting fuel pin fabrication. No complex reshuffling refueling systems.

Summary of ThorCon economic advantages.

Liquid fuel: simple fuel handling, higher temperature efficiency, no cladding.

ORNL R&D. ORNL built two MSRs then designed MSDR guiding ThorCon.

No new technology: commercially available, affordable materials.

Shipyard construction: reduces cost, controls quality, scales to make 100 GW of power plants per year.

Small modular reactor: 250 MWe module has economy of scale and simplifies safety.

Full scale prototype: No scale-up surprises or delays; only design once.

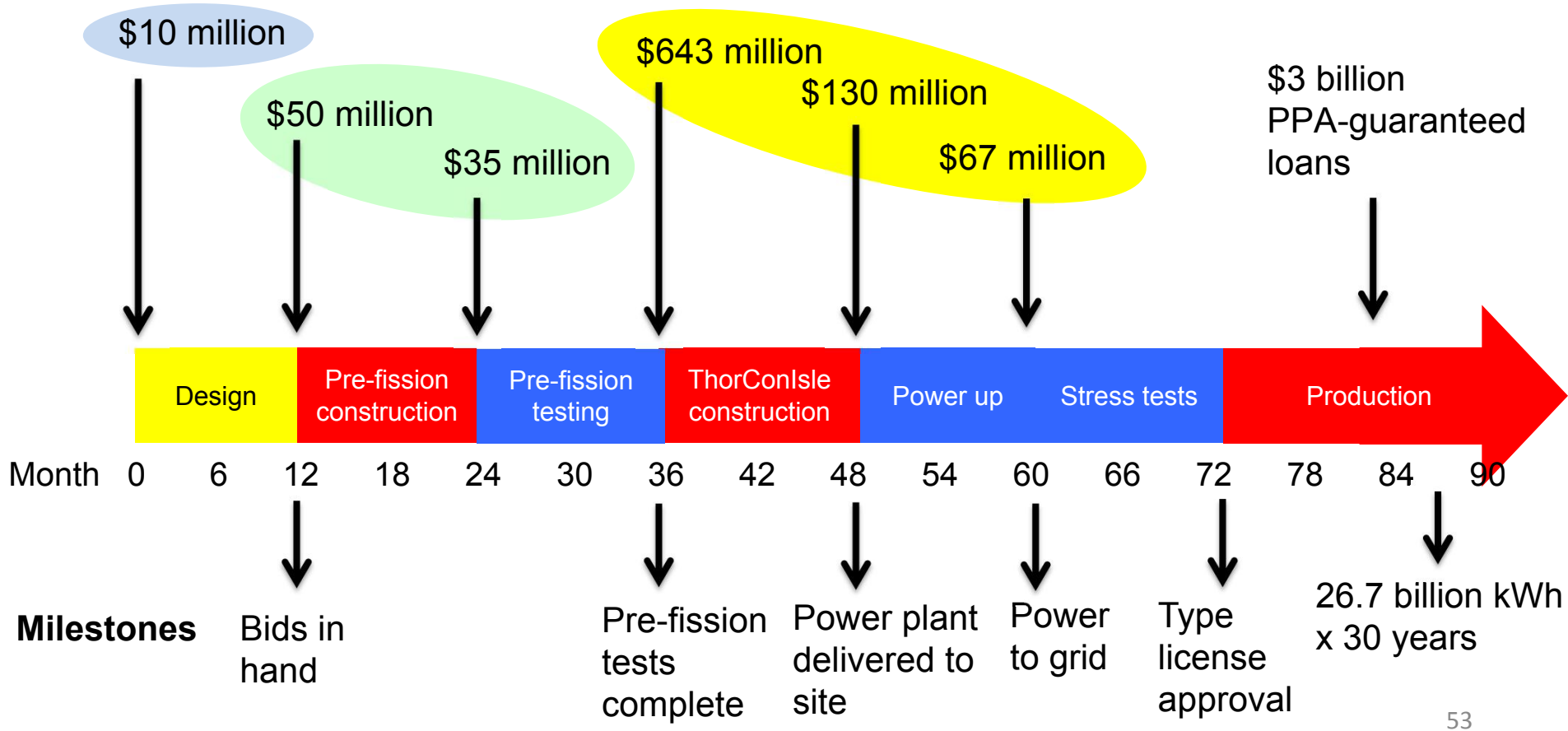
Maintenance by replacement: CanShip moves Can and fuel to recycling facilities.

Thorium: cuts uranium consumption, improves proliferation resistance.

Step by step commissioning: Indonesia will create final regulations as prototype is tested.

Complete power plant design: not just another fission reactor idea.

Indonesia 3.5 GW ThorCon power plant project



Japan industry opportunities

- Investor?
- Supplier?
- Shipbuilder?

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