Low Cost is Mandatory for Widespread Success

Lars Jorgensen - ThorCon Power

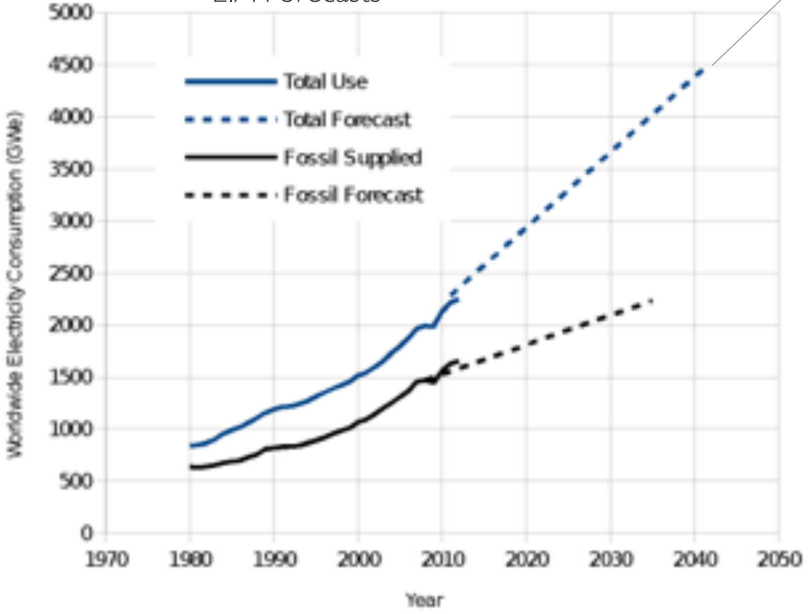
Outline:

- **Define widespread success**
- **Present one system that targets this market**
- **Present a few requirements for an ADS system that wants to target this market.**

ljorgensen@thorconpower.com

Target Market 70-100 GWe/year for 100 Years

EIA Forecasts



10,000 GWe in 2110

One large nuclear plant is around 1GWe
Total US usage is 500 Gwe

Roughly 1kW/person in Europe & Calif.
World population currently 7B people
May stabilize at 10-12B => 10-12,000 GWe

Oil unlikely to expand 5x.
Electricity applications will expand
transport
Industrial heat

Demand could go as high as 70,000 GWe

Nuclear is the only energy source that can do the job with low environmental impact.

Dominated (70%) by coal – but that leads to problems.

Mostly greenfield in the developing world.
World electricity production < 300W/person currently

Widespread success means we deploy nuclear instead of coal/gas to meet this demand.

Nuclear is the safest energy source.

death rate per watts produced

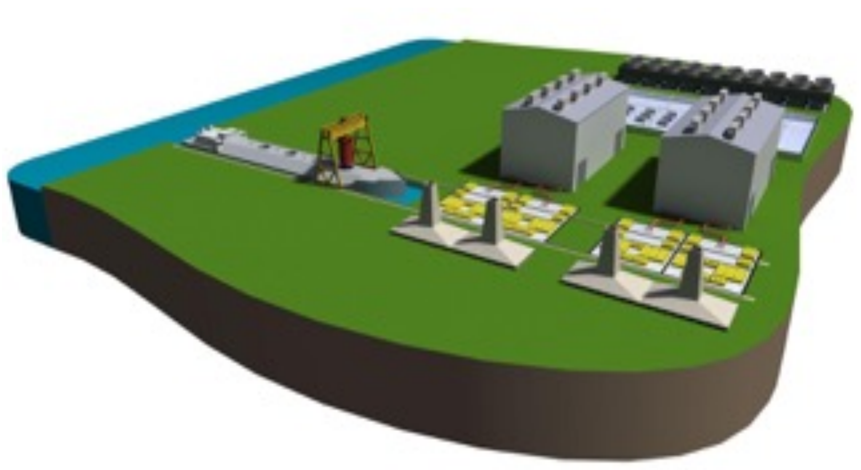
	deaths per GWy
Coal – world average	1410
Coal – China	2435
Coal – USA	131
Oil	315
Natural Gas	35
Biofuel/Biomass	105
Peat	105
Solar (rooftop)	3.85
Wind	1.31
Hydro	.88
Hydro - world including Banqiac	12
Nuclear	.35

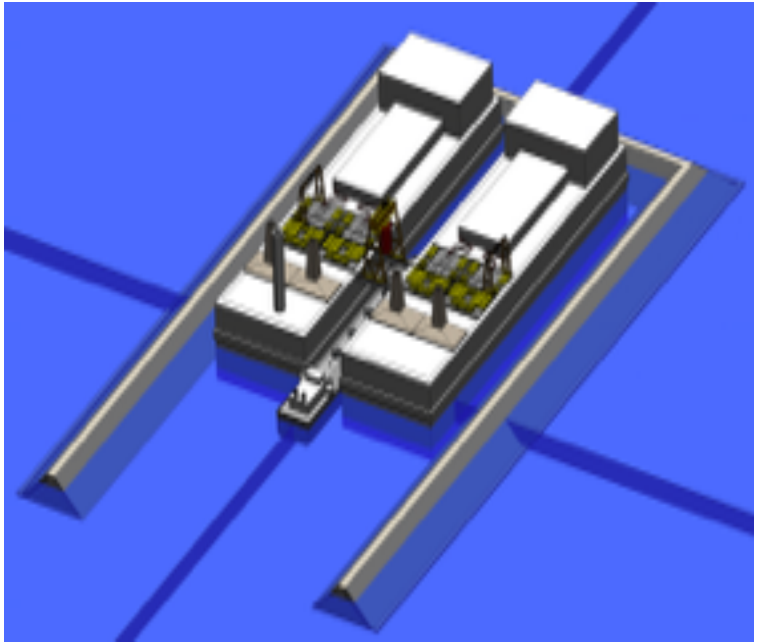
Coal sets the cost target

Electricity Project	Coal (high)	Coal (low)
Interest rate	8.00%	8.00%
Capital cost, $millions	2200	1800
Generating capacity, MW	800	1200
Lifetime, years	40	40
Capacity factor	0.8	0.8
Capital cost per kWh*	**$0.033**	**$0.018**
Operating cost estimate	0.0049	0.0049
Fuel cost	0.0145	0.0145
Total cost per kWh	**$0.052**	**$0.037**

Riau www.thestar.com.my/business/business-news/2015/11/10/indon-coal-plant-for-msia/
800-1200 MW coal power plant for $1.8-2.2 billion

ThorCon: Low Cost, Dependable, CO2-free Power





ThorCon is a thorium converter, molten salt reactor using 80% thorium and 20% uranium by heavy metal content.

ThorCon Targets

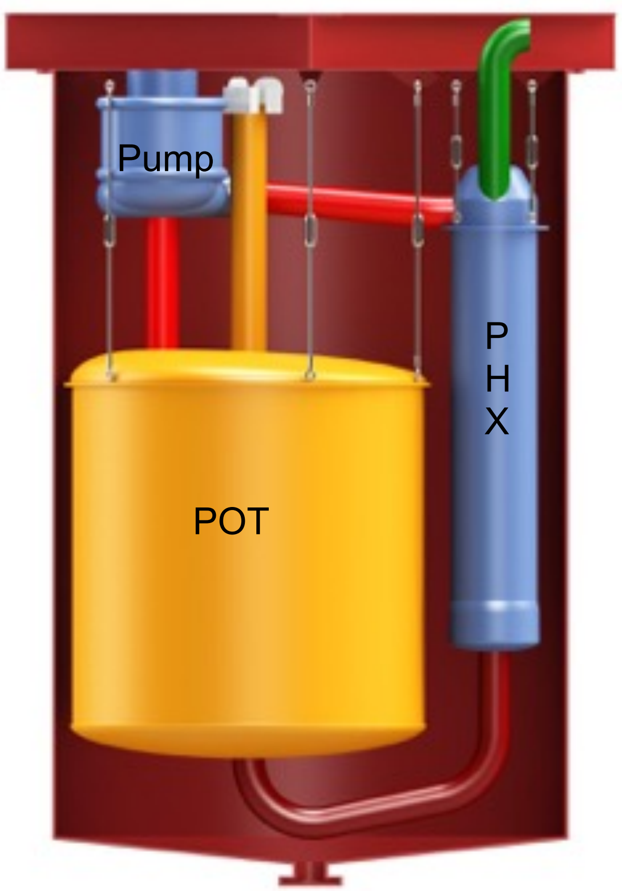
Safe - fully passive safety due to physics (not electricity, operators, or equipment)

Low Cost - to make a big difference we need to be cost competitive with coal and must be manufacturable at a scale like large ships or airplanes

Now - the world is electrifying now so we need to get to to market as soon as possible. Make choices to allow rapid deployment. Redesign to avoid new technology. Accept good enough now rather than the best later.

Test - require that the reactor be tested in accident scenarios. Boeing 787.

ThorCon's Heart: The Can



Pot full of graphite slows neutrons produced by fuel creating chain reaction which heats fuelsalt from 564C to 704C.

Pump pushes fuelsalt around loop at just under 3000 kg/s. 14 sec loop time.

Also converts portion of Th to U-233, portion of U-238 to Pu-239.

Primary Heat Exchanger transfers heat to secondary salt cooling.

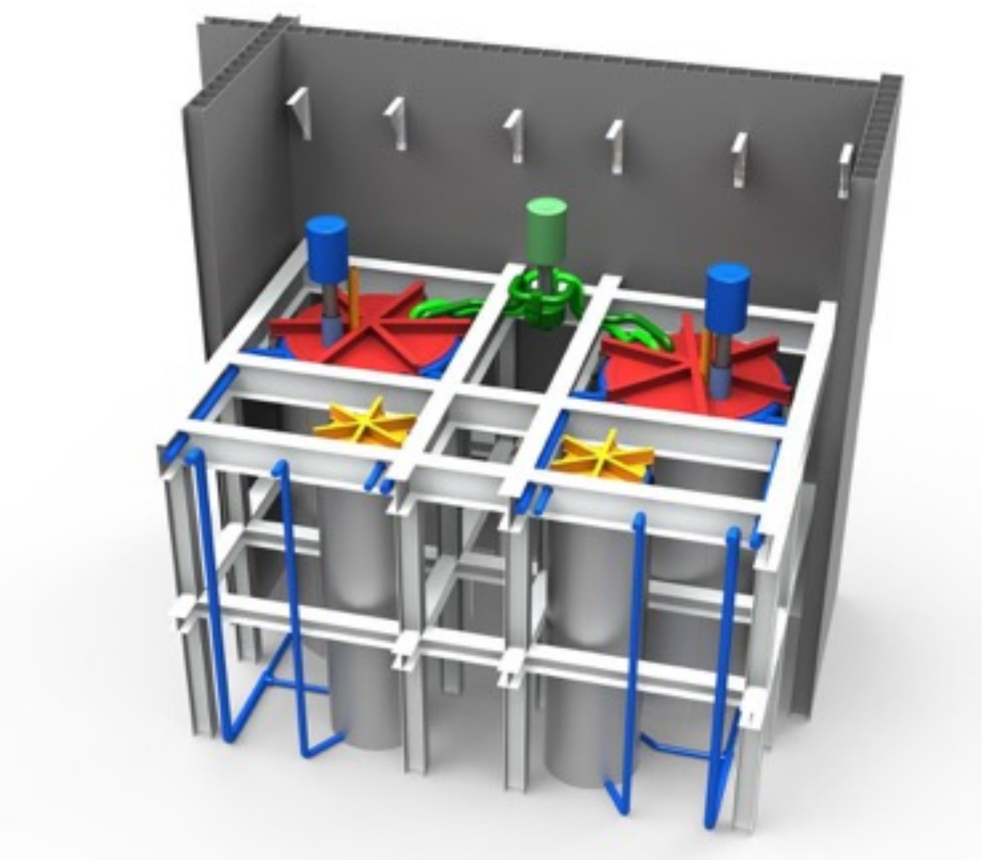
One major moving part.

Pot pressure about 4 bar gage.

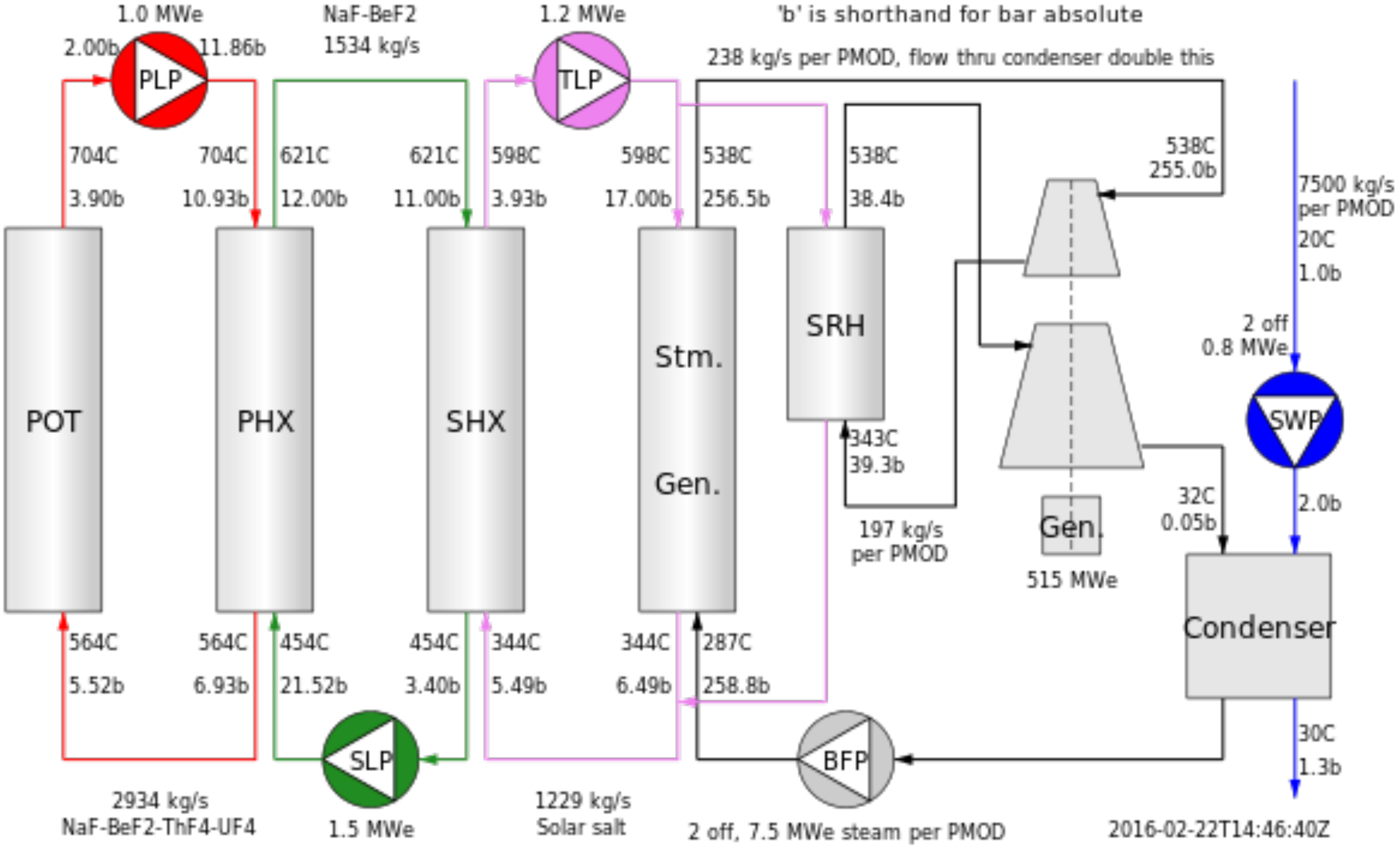
Pump header tank extracts fission product gases.

Pot -> Pump -> PHX   is called the primary loop

Nuclear Island Modularity is 250 MWe



- Nuclear plant divided into 250 MWe/ 557 MWt underground power modules.
- Each module is made up of two *Cans* housed in silos.
- Each Can contains a 250 MWe reactor, primary loop pump, and primary heat exchanger.
- Cans are duplexed. To accommodate 4 year moderator life, Can operates for four years, then cools down for four years, and then is changed out.


1.0 MWe
2.00b
11.86b
PLP
NaF-BeF2
1534 kg/s
1.2 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
12.00b
621C
11.00b
598C
3.93b
598C
17.00b
538C
256.5b
538C
38.4b
538C
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
Condenser
564C
5.52b
564C
6.93b
454C
21.52b
454C
3.40b
344C
5.49b
344C
6.49b
287C
258.8b
30C
1.3b
SLP
BFP
2934 kg/s
NaF-BeF2-ThF4-UF4
1.5 MWe
1229 kg/s
Solar salt
2 off, 7.5 MWe steam per PMOD
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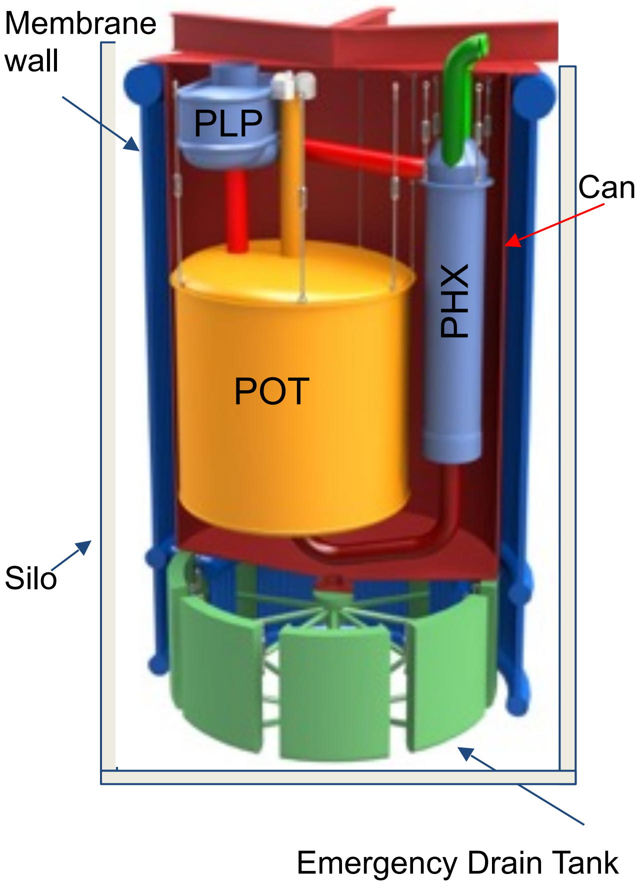
Decay Heat Removal

- Primary heat removal via once through ocean water cooling.
- Backup decay heat removal is fully passive using radiative coupling to a wall of water with the ultimate heat sink being an external cooling pond (72 day grace period).
- 2nd backup decay heat removal uses a supply of water in the basement (30 day grace period).



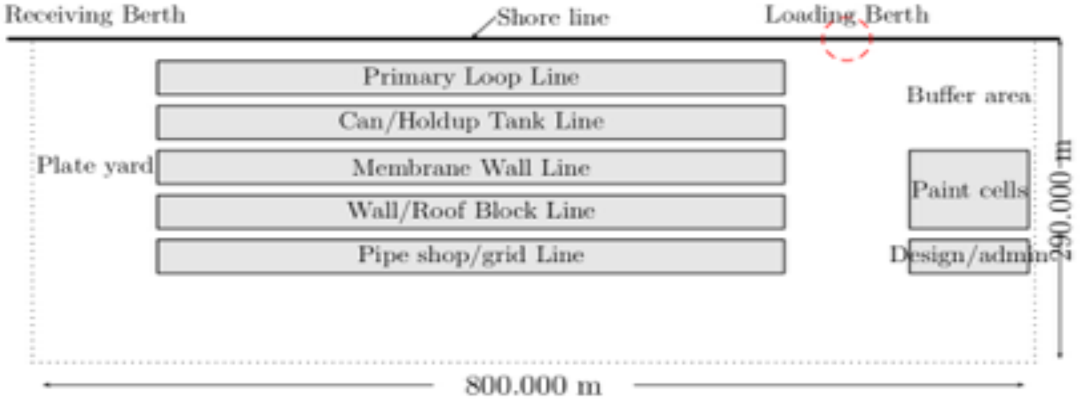
Response to SBO + Loss of Main Cooling

- Worse than Fukushima scenario.
    - Instantly lose grid connection, diesel generators, batteries, and sentry turbine to all plants at the site.
    - Simultaneously lose ocean cooling
    - Further assume that the operators are unavailable to command a fuel drain.

- Fuel salt flow will slow due to no power to the primary loop pump.
- Shutdown rods work -> minimal creep damage. Reactor can be restored to service as soon as the cause of problems are repaired. Temperature peaks at 840℃.
- Shutdown rods fail -> noticeable creep damage but primary loop holds. Peak temperature 890℃. We can only sustain one additional such incident. Replace primary loop at next major service interval.

Build **Everything** On An Assembly Line

- Reactor yard produces 150--500 ton blocks. About 200 blocks per 1GWe Isle plant.
- Blocks are pre-coated, pre-piped, pre-wired, pre-tested.
- Focus quality control at the block and sub-block level.
- Blocks dropped into place, and welded together at the shipyard berth.
- 100% labor at factory
- Hyundai shipyard in Ulsan, South Korea pictured below is sufficient to manufacture 50 GWe ThorConIsle power plants (or 100GWe land based ThorCon) per year.



Proposed shipyard sufficient to manufacture 10 ThorConIsle 500MWe power plants per year.

ThorConIsle:
Build the whole power plant at the factory

Power plant is built into a large barge including nuclear island, turbine/generator, cooling, emergency cooling, switchyard, and conversion to HVDC if appropriate.

Barge is 235m long by 65m wide by 35m high - roughly 60% the size of a ULCC.

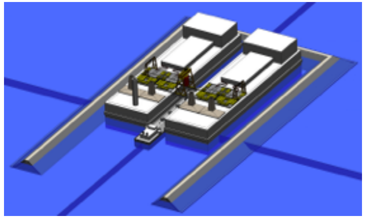
On site work is to:

a) build the breakwater if needed
b) if needed dredge a 6m deep by 70m wide access channel for construction
c) if needed dredge 3m deep by 70m wide access channel for refueling
d) grid access
e) cooling access

One large shipyard to factory-build new power plants

Tow to power plant site (one hull per 500 MWe)

Power plant sites (1 GWe site shown) 1,000-20,000 GWe total)



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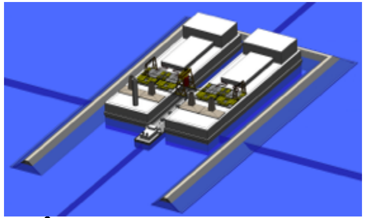
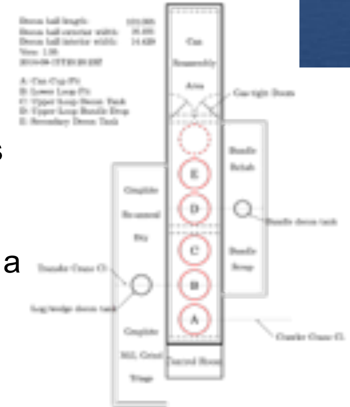


Canship delivers new cans and takes old cans back for recycling. Also transports new fuel and returns spent fuel. One round trip every four years to each 1GWe site.

Can recycling center cleans and inspects cans, replace graphite, stores offgas and graphite wastes. Similar to a shipyard.



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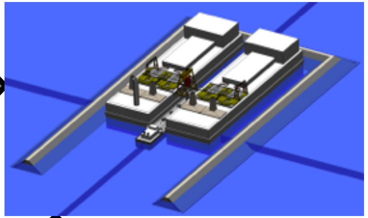

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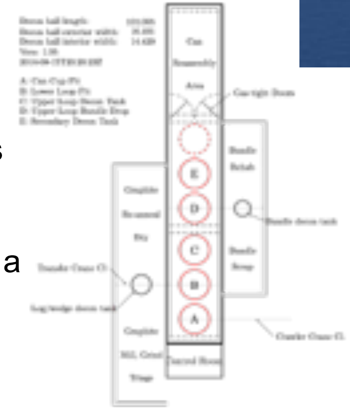

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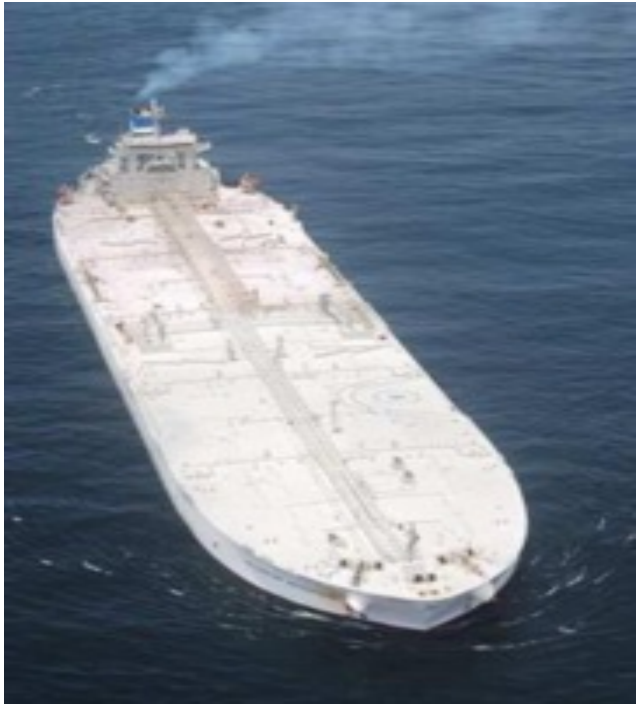
Fuel Handling Facility (FHF)
Initial fluorination to separate the uranium.
Store spent fuel for future processing.

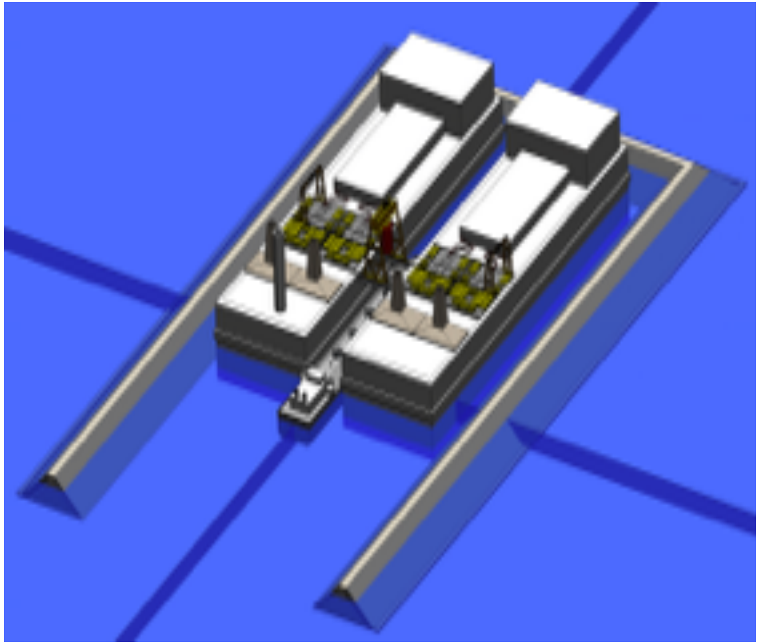
Future IAEA secure site.
Uranium re-enrichment and Pu extraction to recover remaining valuable content.

Build Nuclear Power Plants Like ULCC's

Ultra large crude carrier cost $89M in 2001
Largest operating oil tankers in the world.
Hellespont Alhambra, Tara, Fairfax, Metropolis
Architected and managed by Jack Devanney



ThorConIsle
Each hull is 500 MWe
60% the size of ULCCs
Graphic shows two 500 MWe hulls plus
a jetty surrounding them



Coal plant is bigger than ThorCon.

- coal reception (10,000 t/d), storage, pulverization;
- 125 m high boiler, stack gas treatment;
- 1000 to 2000 t/d ash handling and storage

DWARF TURBINE HALL

ThorCon energy is cheaper than coal.

Electricity Project	Westinghouse AP1000	ThorCon	Coal (high)	Coal (low)
Interest rate	8.00%	8.00%	8.00%	8.00%
Capital cost, $millions	16000	1200	2200	1800
Generating capacity,	2200	1000	800	1200
Lifetime, years	40	40	40	40
Capacity factor	0.9	0.9	0.8	0.8
Capital cost per kWh*	**$0.077**	**$0.013**	**$0.033**	**$0.018**
Operating cost estimate	0.01	0.0056	0.0049	0.0049
Fuel cost	0.007	0.005	0.0145	0.0145
Total cost per kWh	**$0.094**	**$0.024**	**$0.052**	**$0.037**

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A Prototype 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

Cost of Fissile Based Neutrons

U235 costs around $40/gram. Each U235 atom consumes 1.2 neutrons to fission and releases 2.4 neutrons. So roughly releases one surplus neutron per atom.

Using enrichment then is a neutron source at a cost of $40*235 = $9,400/gram of neutrons. For accelerator based electricity production costs need to be competitive with enrichment.

Required Reliability

A 1 GWe power plant produces electricity worth more than 1M pounds/day. Any outage needs to be minimized.

Planned maintenance should be once per four years and require less than two weeks so it can overlap with other maintenance activities.

Unplanned outages should be very rare. In addition to the lost income there are consequential costs to an outage. In small grids unplanned outages could result in black-outs.