ThorCon's Path to Thorium Utilization

ThorCon the Do-able Molten-Salt Reactor

ThorCon Design Philosophy

Inherently safe: combat nuclear fear, no mechanism to spread radioactivity, no loss of investment upon failure or external event.

Goal: safe, cheap, reliable, carbon-free electricity. **Now.**

Producible. Nuclear island under $1/watt.

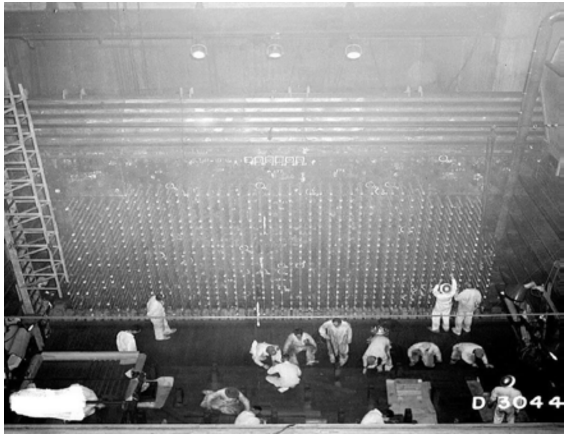
Fixable. Major failures have modest impact on plant output.

Fast. Full scale prototype ***within four years***.

4 years may sound crazy, but prototype nuclear power plants have been built quickly.

Camp Century
Iceland
2 MWe
American Locomotive
factory modules
1959 + ***2 years***

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

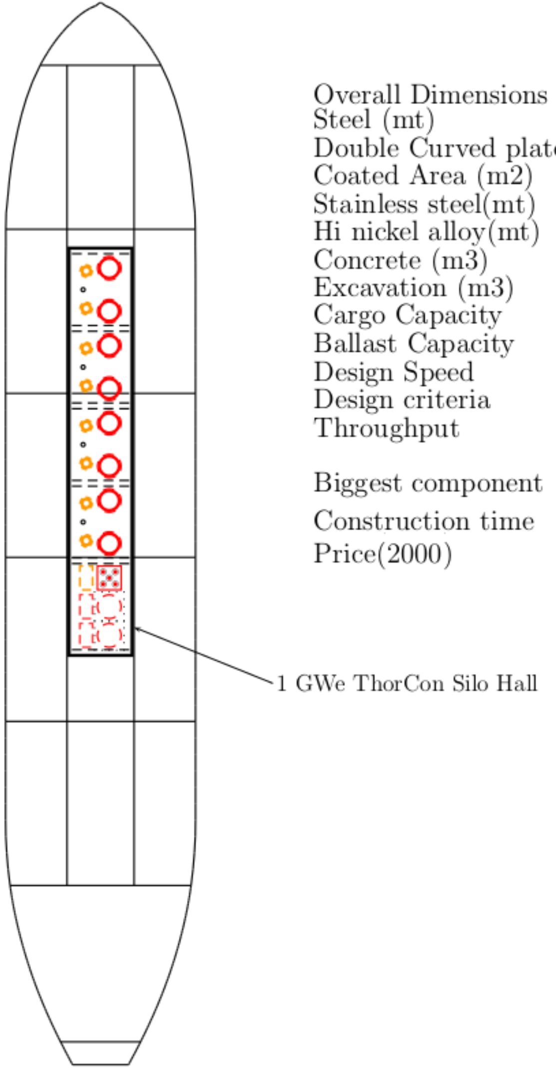


Hanford
Pu production
250 MWt
DuPont, GE
1942 + ***2 years***

Large Steel Ships (ULCC) are Cheap

Length 380 m
Contract Dec 1999
Beam 68 m
Keel-laying Jun 2001
Depth 34 m
Delivery Mar 2002
Overall height 74 m
Detail design 18 months
Mass 67,600 tonnes
Construction 9 months
Cargo 511,000 m^3
Custom Single Unit Cost **$89M**
Coated Area 350,000 m^2

Engines 37,000 kW
Propeller 10.5 m
Generators 3 x 1450 kW
Steam Boilers 2 x 45,000 kg/hr
Cargo pumps 3 x 5000 m^3/hr
Ballast pumps 2 x 5000 m^3/hr
Accommodation 50

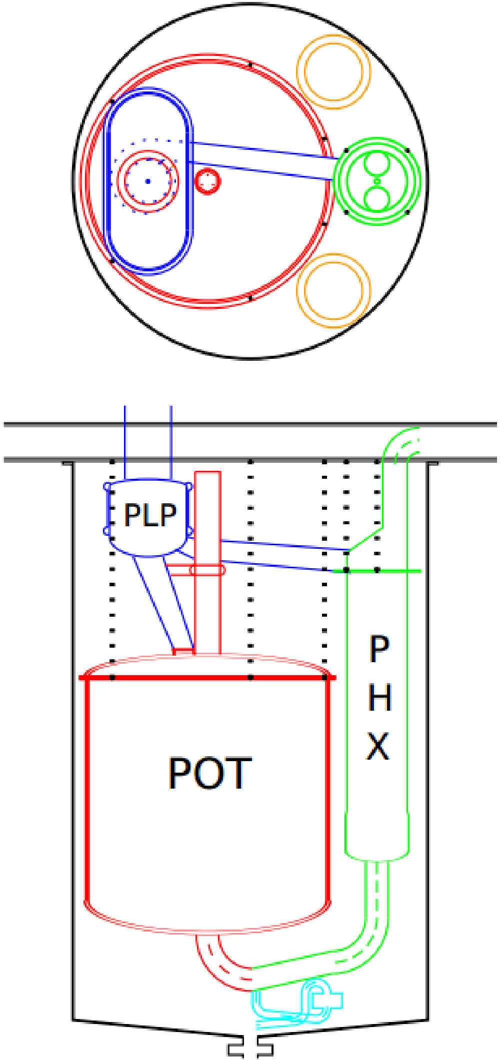


	ULCC	ThorCon
Overall Dimensions	380 x 68 x 35	146 x 23 x 29
Steel (mt)	67,591	14,700
Double Curved plate	Lots	None
Coated Area (m2)	350,000	30,000
Stainless steel(mt)	100	1,950
Hi nickel alloy(mt)	0	253
Concrete (m3)	0	42,000
Excavation (m3)	0	192,000
Cargo Capacity	445,000 tons oil	0
Ballast Capacity	150,000 tons	0
Design Speed	16 knots	Just sits there
Design criteria	Hurricane at sea	0.6g earthquake
Throughput	Discharge 15,000 m3 oil per hour	Heat 14,000 m3 salt per hour
Biggest component	35 MW low spd diesel	500t SWL crane
Construction time	10 months	???
Price(2000)	$89,000,000	???

Nuclear is small

Thorcon fits in the center tanks of a ULCC
Mechanical complexity is similar

A pot, a pump, and a still

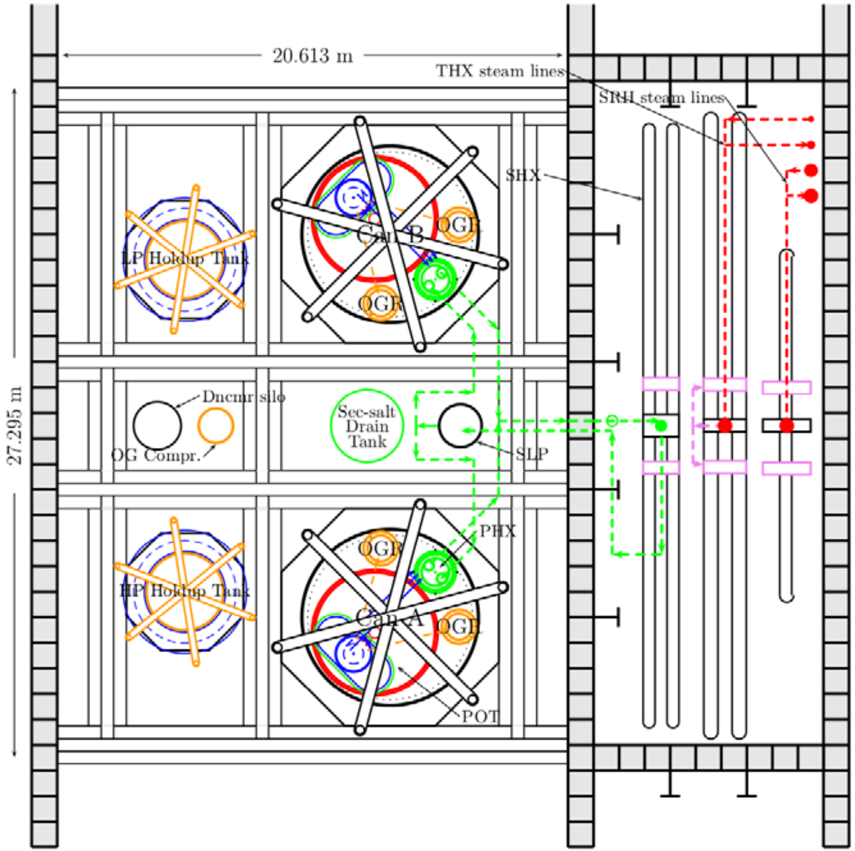


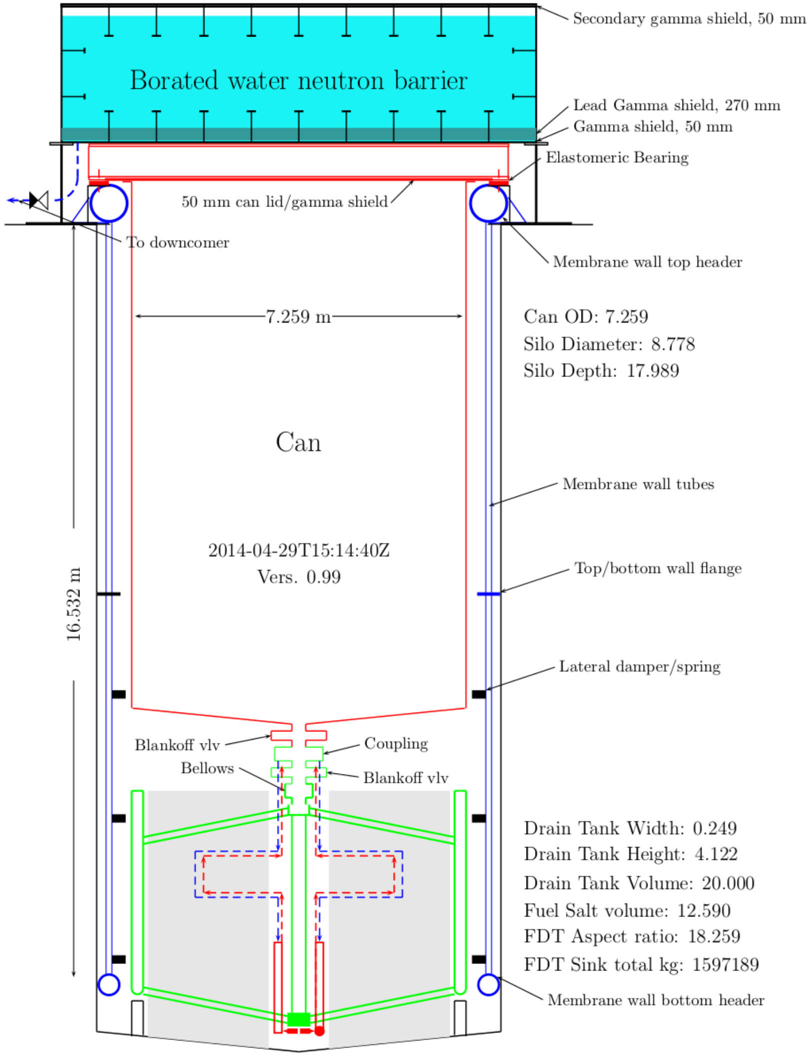
Can electrical output(MW):	250.0
Can thermal output(MW):	550.0
Fuelsalt:	NaF-BeF2-ThF4-UF4
Mol percent:	76/12/9.5/2.5
Fuelsalt flow rate(kg/s):	2934
Pot temperature in(C):	564.0
Pot temperature out(C):	704.0
Loop transit time(seconds):	13.8
Pot inlet pressure(bar g):	1.65
Primary Loop Pump(kW):	1006
Annual 20% LEU fuel(kg):	880
Annual 20% LEU fuel(liters):	460.0
Overall plant efficiency(%):	45.0
Percent thorium fueled(%):	abt 25
Can OD(m):	7.259
Can Height(m):	11.738
Pot OD(m):	4.961
Pot Height(m):	5.717
Can weight (no salt) (kg):	381,767
Fuelsalt weight (kg):	40,515

A very simple, cheap, critical (not accelerator driven) reactor that gets about ¼ of its energy from thorium, but can run initially on 5% LEU or reactor grade plutonium, or a mixture.

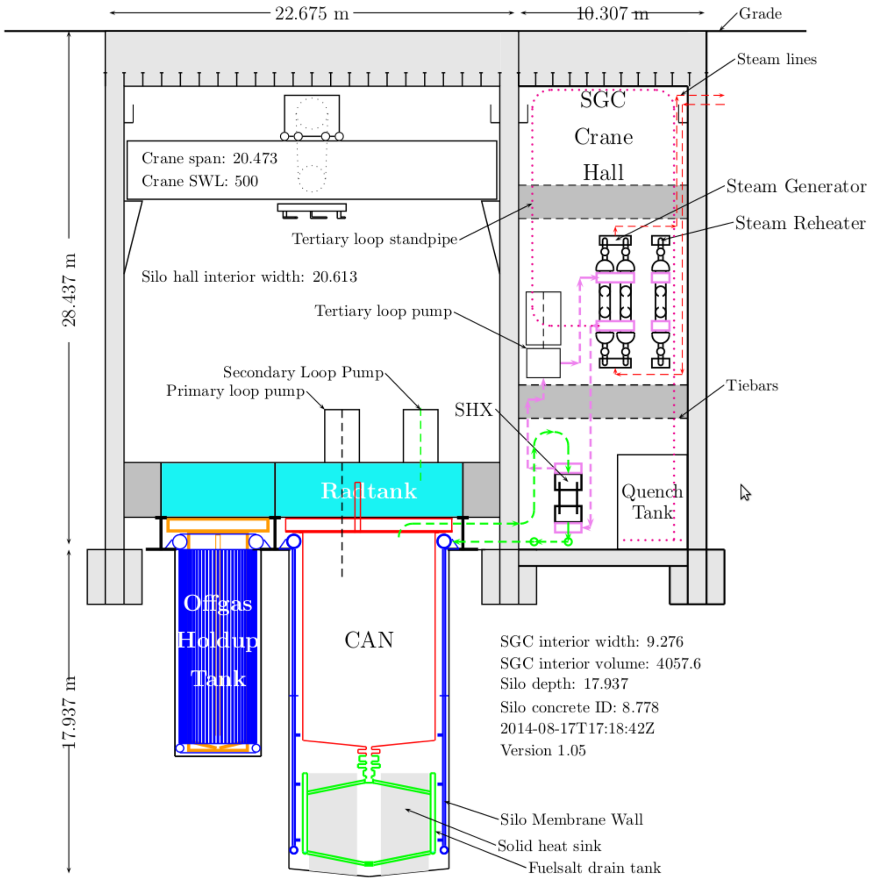
Molten salts are very flexible.

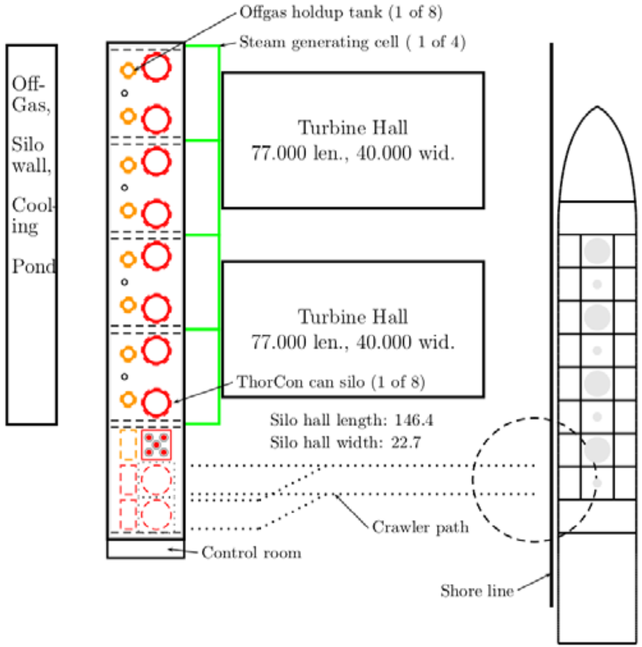
Grid block & Silo

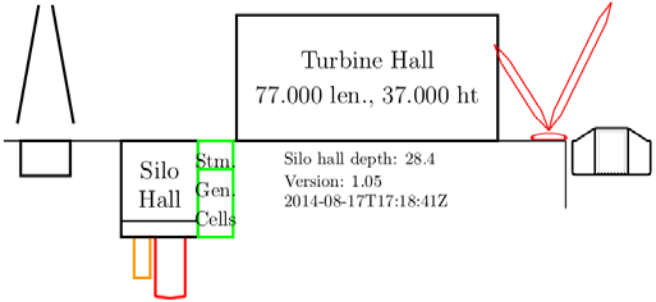




Containment & Site Plan







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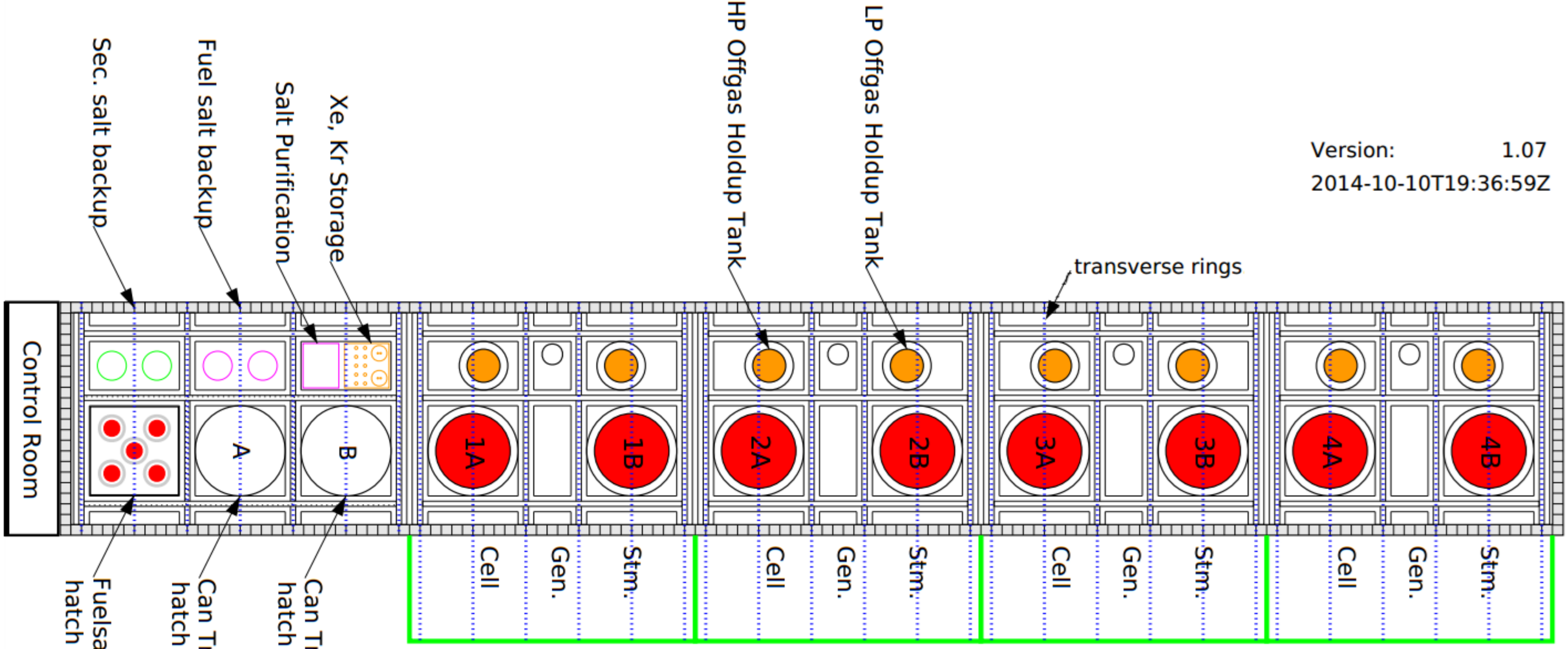
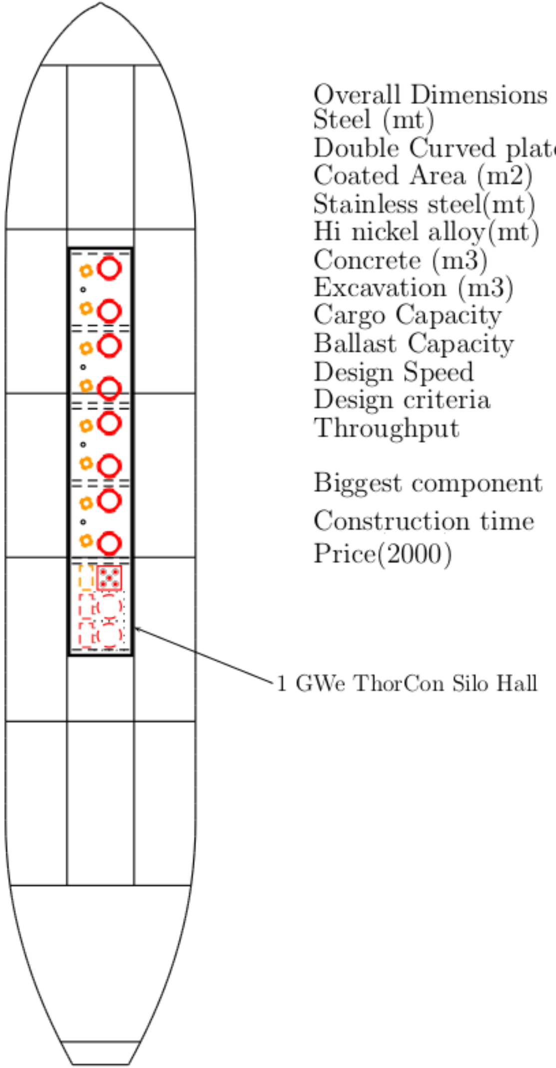


Exterior lengthm):	146.427	Wall volume (m3):	10,830		
Interior length(m):	144.315	Excavation volume (m3):	126,285		
Silo hall height(m):	28.437	Wall steel tons:	5,692		
Exterior width(m):	22.707	Wall concrete vol(m3):	10,104		
Interior width(m):	20.620	Roof steel tons:	1,544		
Silo hall area (m2):	3325	Roof concrete vol(m3):	9,974	Wall plate thk(mm):	25.0
Silo hall volume (m3):	94,549	Wall web CTC(mm):	1031.0	Wall web thk(mm):	20.0



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Nuclear is small

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Shipbuilding is a mature industry

ULCC Costing details
Detailed design: 18 months
Construction: 9--12 months
Direct labor: 700,000 man-hours, $15M; 40% hull, 60% outfitting
5-6 man-hours per ton of steel
Relatively complicated double hull structure with curved plates.
About 140 350 tonne blocks. Precise dimensional control.

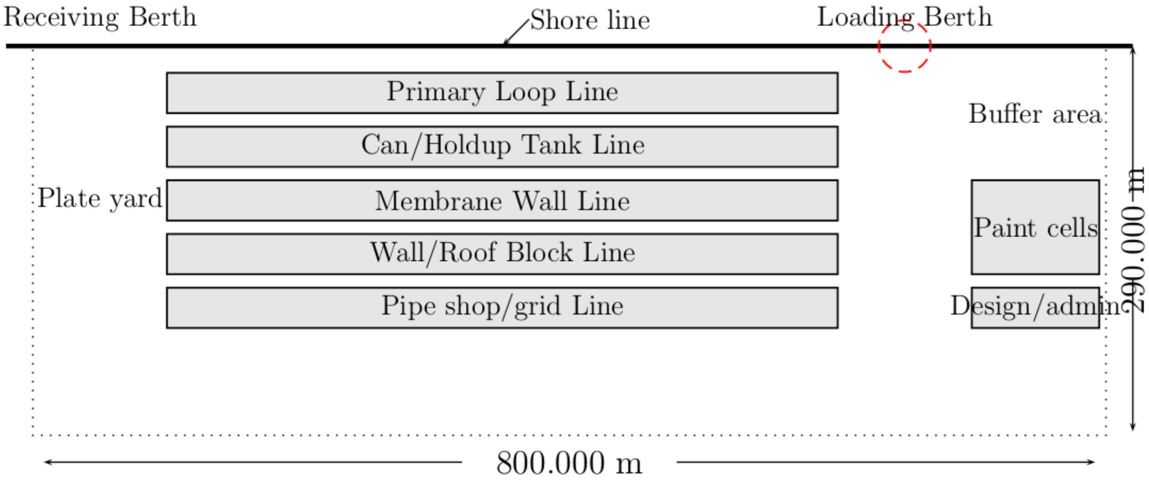
Overall cost about $90M
15% direct labor, 15% overhead, 70% purchased material

High availability: If ship has more than 15 days off-hire a year, operating in a hostile environment, including scheduled dockings, it’s a lemon. 15 days annual off-hire is 96% availability.

Goal: Build reactors like we build ULCC ships, but even more standardized.
Bring shipyard-like productivity to nuclear.

Build everything on an assembly line

- Reactor yard produces 150 to 500 ton blocks. About 100 blocks per 1GWe plant.
- Blocks are pre-coated, pre-piped, pre-wired, pre-tested.
- Focus quality control at the block and sub-block level.
- Blocks barged to site, dropped into place, and welded together.



10 GWe/year yard block diagram; 200,000 tons steel per year

Full-scale prototype within 4 years

- No New Technology implies...
- Can’t wait for enriched lithium ^7Li, cannot use Flibe.
- Can’t do any fancy fuel processing or waste burning.
- Can’t go for ultimate neutron efficiency breeder.
- Best use an existing steam plant and water cooling.
- Just build a scaled up non-FLiBe MSRE.
- Straight to 250 MWe prototype. ***No further scale-up***.
- ***Go fast*** → ***No New Technology***

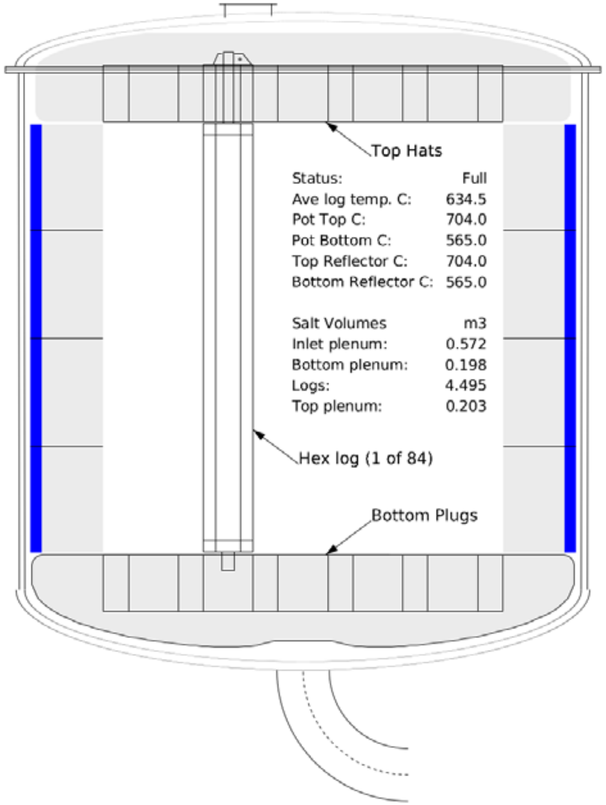
Why liquid fuel?

- Fuel flexible
  - nil fuel fabrication
  - high thermal efficiency. 44% vs 32%
  - Xe bubbles out, high burn up
  - burn any fissile in many combinations
  - **step to thorium cycle**
- Walk-away safety
  - low pressure, no phase change
  - low chemical energy
  - low excess reactivity
  - passive fuel drain
  - big temperature margins
    - 700℃ → 1250℃ → 1400℃
  - many fission products form stable fluorides including ^{90}Sr and ^{137}Cs and iodine is also non-volatile in fuelsalt.
  - **no energy to drive release and all the bad boys are locked up**
- Move fuel around with a pump
  - homogeneous fuel, no hotspots
  - adjust fuel on the fly
  - **low part count**
  - **no refueling kluges**
- Compatible with all block construction
  - highly automated processes
  - strict quality control
  - easy to repair, no mausoleum
  - factory tested subsystems
  - **nil rebar**
  - reinforced concrete used only in footings
- Heavy lifting has already been done by ORNL. MSRE was our pilot plant.

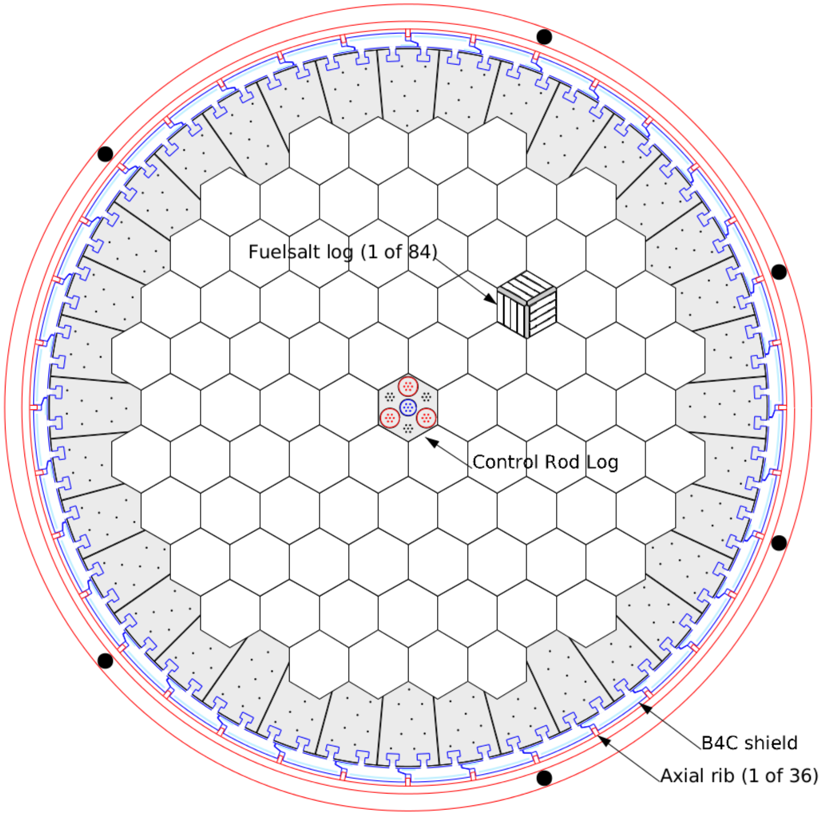
ThorCon design: from the outside in

- Relying on learnings from ORNL’s MSRE, we can concentrate on the rest of the system.
- Opposite of normal nuke thinking. Rather than the plant being an afterthought wrapped around an all-important reactor, we design a power-plant with a generic reactor as a component.
- Reactor/primary loop is a rather small black box.
- What should the plant look like?
- What should the production/replacement/decommissioning system look like?
- Then get into the details of the black box.

Reactor core



Number of fuelsalt logs:	84	Hot Pot vessel ID(mm):	4860.96
Salt Volume in logs(m3):	4.495	Cold salt annulus width(mm):	5.00
Moderator kg:	66089	Hot salt annulus width(mm):	25.24
Side reflector kg:	42197	Salt volume in annulus(m3):	1.75
Shield kg:	10402	Shield thickness(mm):	100.00
B4C Fraction:	0.100		



ThorCon Neutronics Rules

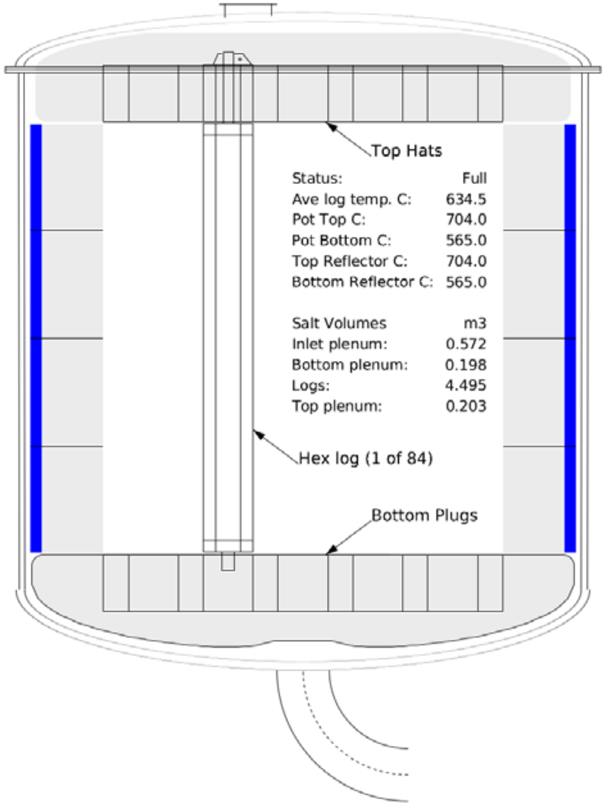
- Fuelsalt is always denatured (<20%) LEU
- No Flibe
- No blanket
- No online reprocessing
- Noble gas removal via MSRE-like spray system
- Assume slow noble gas removal (300 seconds) and no salt phobe removal
- In adjusting fuelsalt, we keep Th+U content constant.
    - Corollary: fissile content of adjustment fuelsalt must be higher than fissile content of primary loop fuelsalt.
- Salt changed out every 8 years
    - cools for 4 years
    - then transferred to Fuelsalt Recycle Plant
- Uranium removed by fluoride volatility and returned to plants

Operating Rules

- No complex repairs --- everything but the building must be easily replaceable.
- No need for 30-plus-year life with nil maintenance.
- No onsite fuelsalt processing other than noble gas removal --- every 8 years fuelsalt is changed out and after 4 year cooldown in silo shipped to a Fuelsalt Recycling Facility.
- Every 4 years the entire canned primary loop is changed out and shipped to Can Recycling Plant which supports ~50 powerplants.
- Improved fuelsalt processing can be introduced without any changes at the plants.
- Improved reactor core designs can be introduced with minor changes at the plants.
- At Can Recycling Plant, Cans are decontaminated, disassembled, inspected and refurbished. Incipient problems are corrected before they turn into casualties.
- Major upgrades (adding modules) can be introduced with little effect on power generation.
- Such renewable power plants can operate indefinitely. Decommissioning is little more than pulling out but not replacing all the replaceable parts. The steel building is recyclable.

- ThorCon is a system, not a bunch of fortresses

Reactor core



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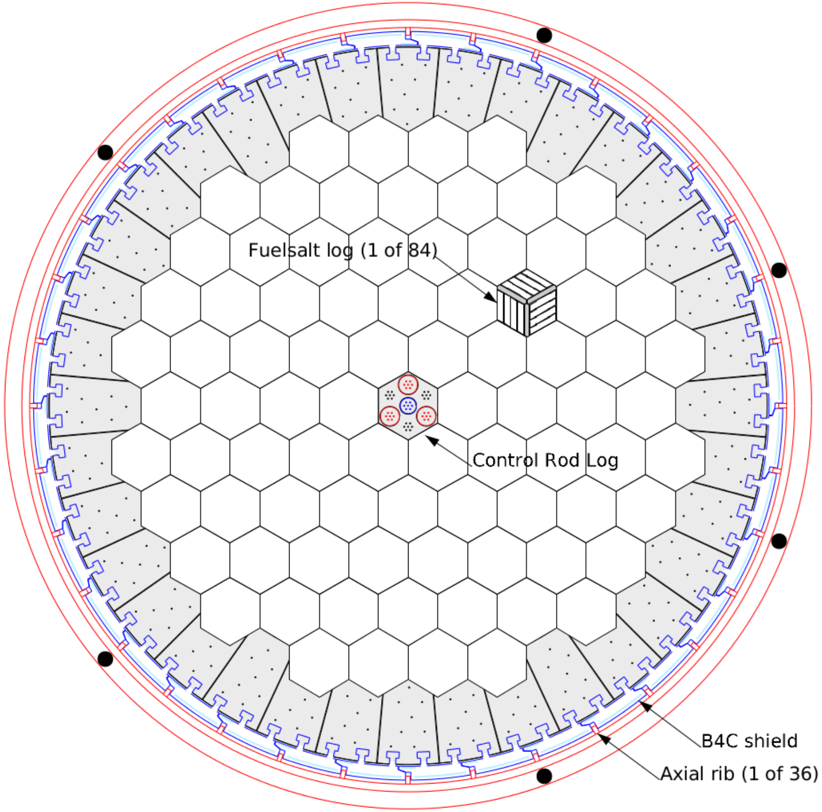
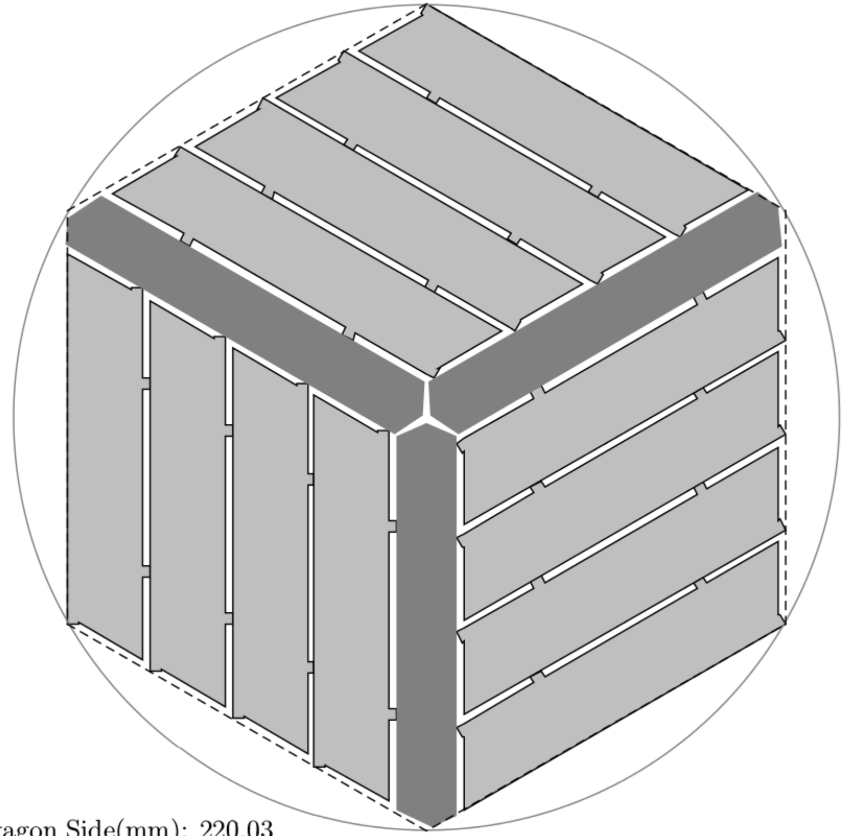


Ebasco Log Looking Down.

(this is not a 3D drawing)



Hexagon Side(mm): 220.03
Log OD(mm): 440.06
Log Apothem (mm): 190.55
Log ID/width (mm): 381.10
Slab Thick (mm): 39.84
Nub height (mm): 3.80
Nub width (mm): 6.00

Fraction salt: 0.1112
Log moderator kg: 778
Log salt volume(m3): 0.0529
Slot hydraulic diameter(mm) 7.45

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Baseline Fuelsalt choice

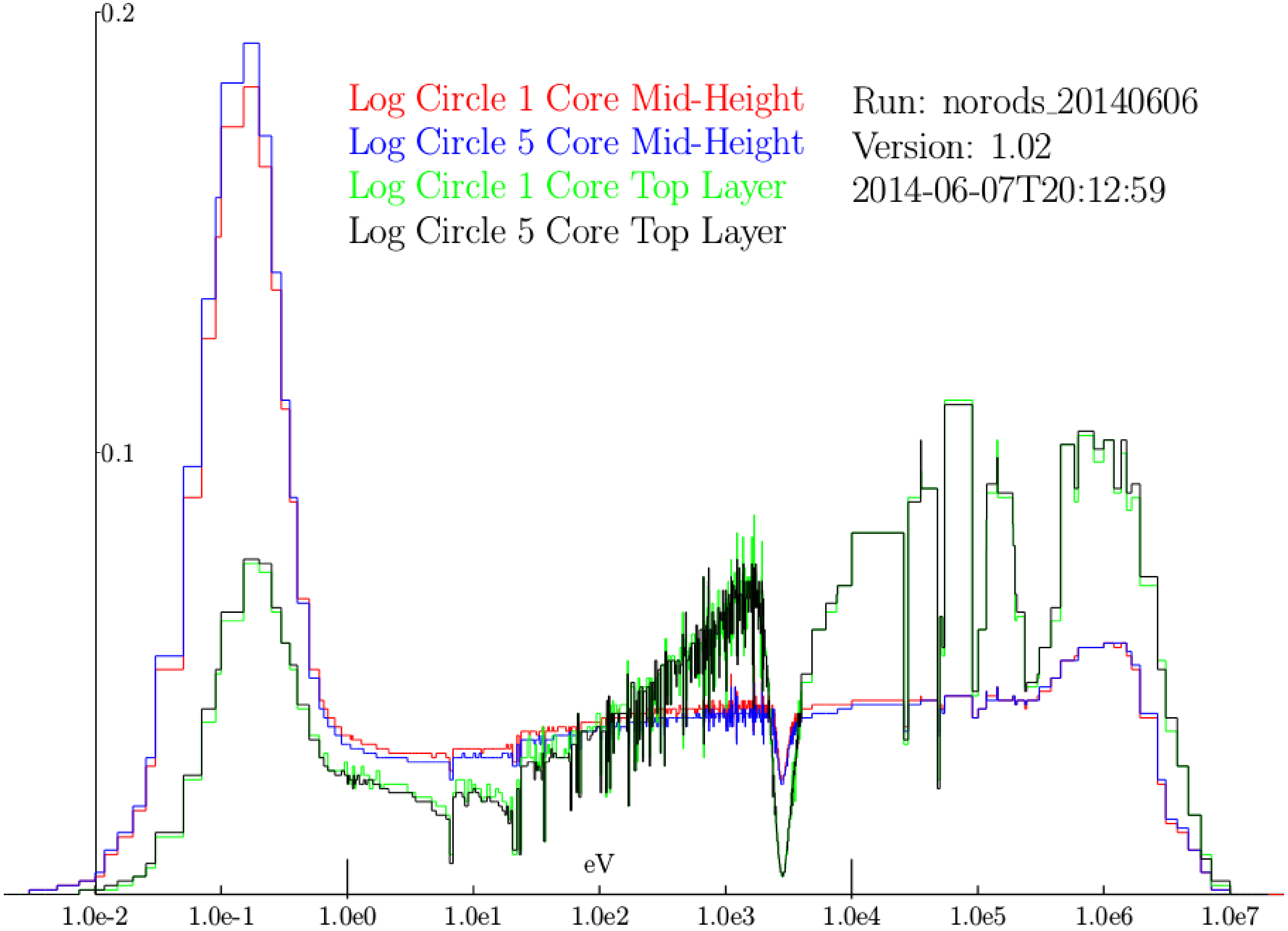
- Ran a range of fuelsalts and nub heights
- Must stay close to eutectic at 76/12/12 mol% NaF/BeF_2/MF_4 to keep melting below 500℃
- Baseline fuelsalt: 76/12/9.8Th/2.2U 20%LEU

- Adjustment salt same except no thorium.
  - Fissile ratio about 5.5
- Nub height = 3.8mm, salt fraction 11.1%
  - Still strongly under-moderated.
  - May end with a bit smaller nub height.

k_{eff} as a function of nub height and salt composition

Nub ht. (mm)	Salt vol fraction	nabe 20%	nabe 15%	nabe 10%	nabe 5%	flibe 7207BOL	nabe No Th 5%
0.5	0.0174	1.310	1.216	1.089	0.953	0.997	1.102
1.0	0.0308	1.346	1.267	1.142	0.956	1.037	1.170
2.0	0.0574	1.299	1.233	1.125	0.936	1.044	1.177
4.0	0.109	1.178	1.124	1.035	0.873	0.990	1.115
6.0	0.159	1.086	1.035	0.956	0.821	0.927	1.046
8.0	0.208	1.014	0.965	0.893	0.778	0.871	0.986
U235 af		0.00484	0.00362	0.00242	0.00121	0.00106	0.00242

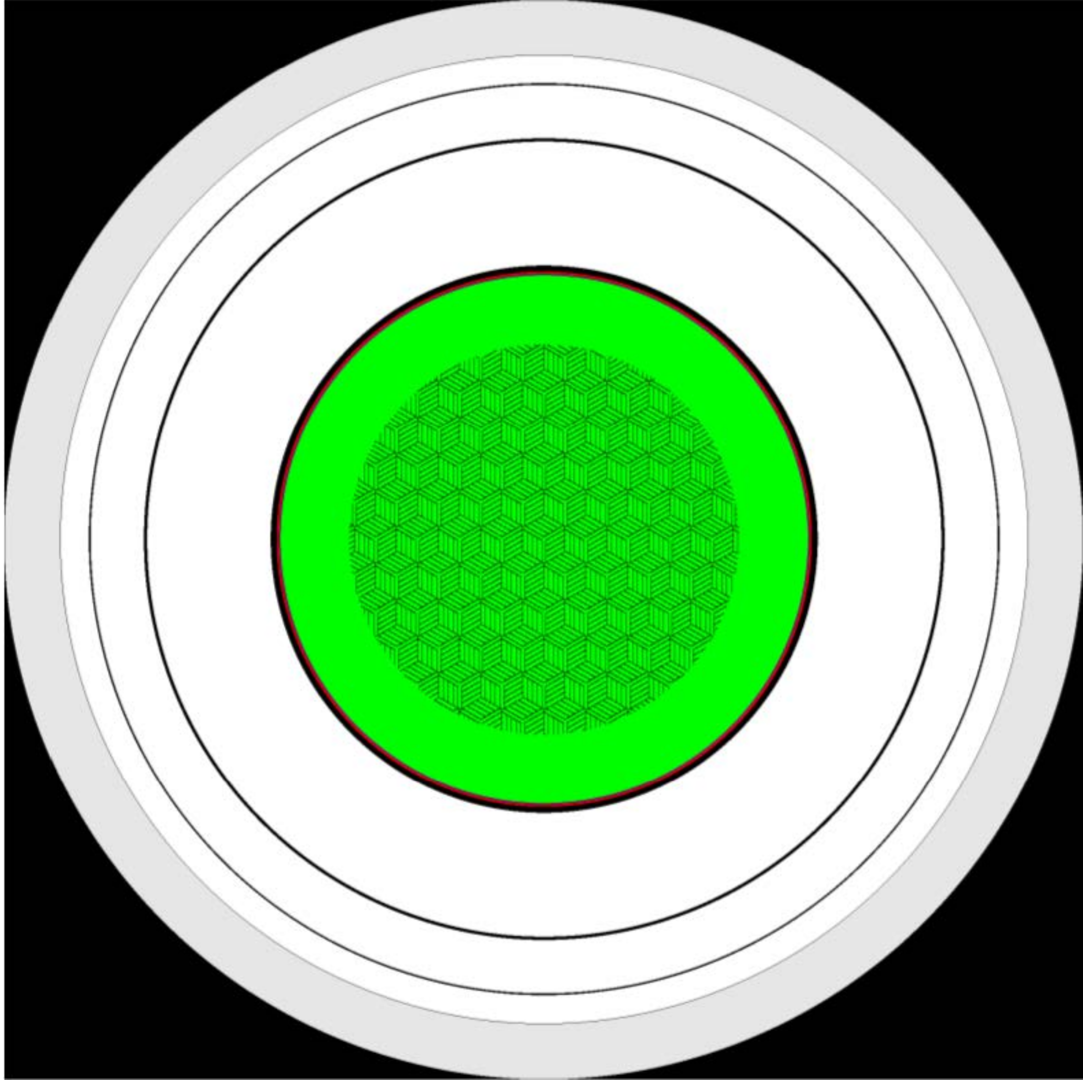
Neutron Energy, baseline system, fresh fuelsalt



Serpent Model

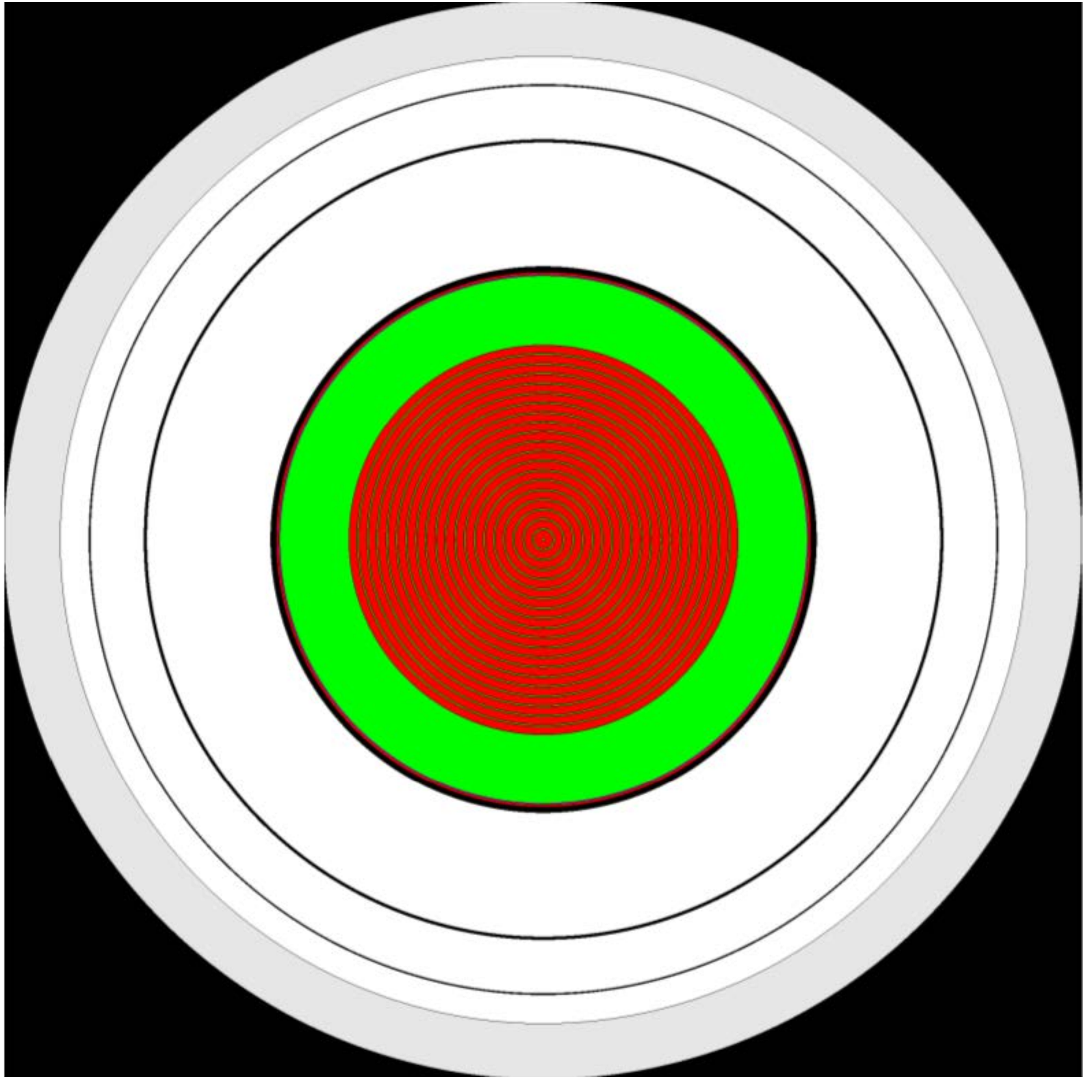
1. Bit simpler than MCNP model, but far, far faster,
2. Preprocessor and postprocessor tied to ThorCon DNA model
3. Neutronics plus burnup plus decay.
4. Uses clever algorithm devised by Dr. Manuele Aufiero which adjusts fuelsalt composition to get $k_{eff} \approx 1.0$ after each burn-up step.
5. User may specify Xe/Kr/noble metal extraction rates.
6. Ran 8 year chunks.
   a. Every 8 years fuelsalt is changed out.
   b. Uranium is extracted and combined with fresh salt/thorium keeping heavy metal at 12% mol.

Serpent Model plan view core mid height



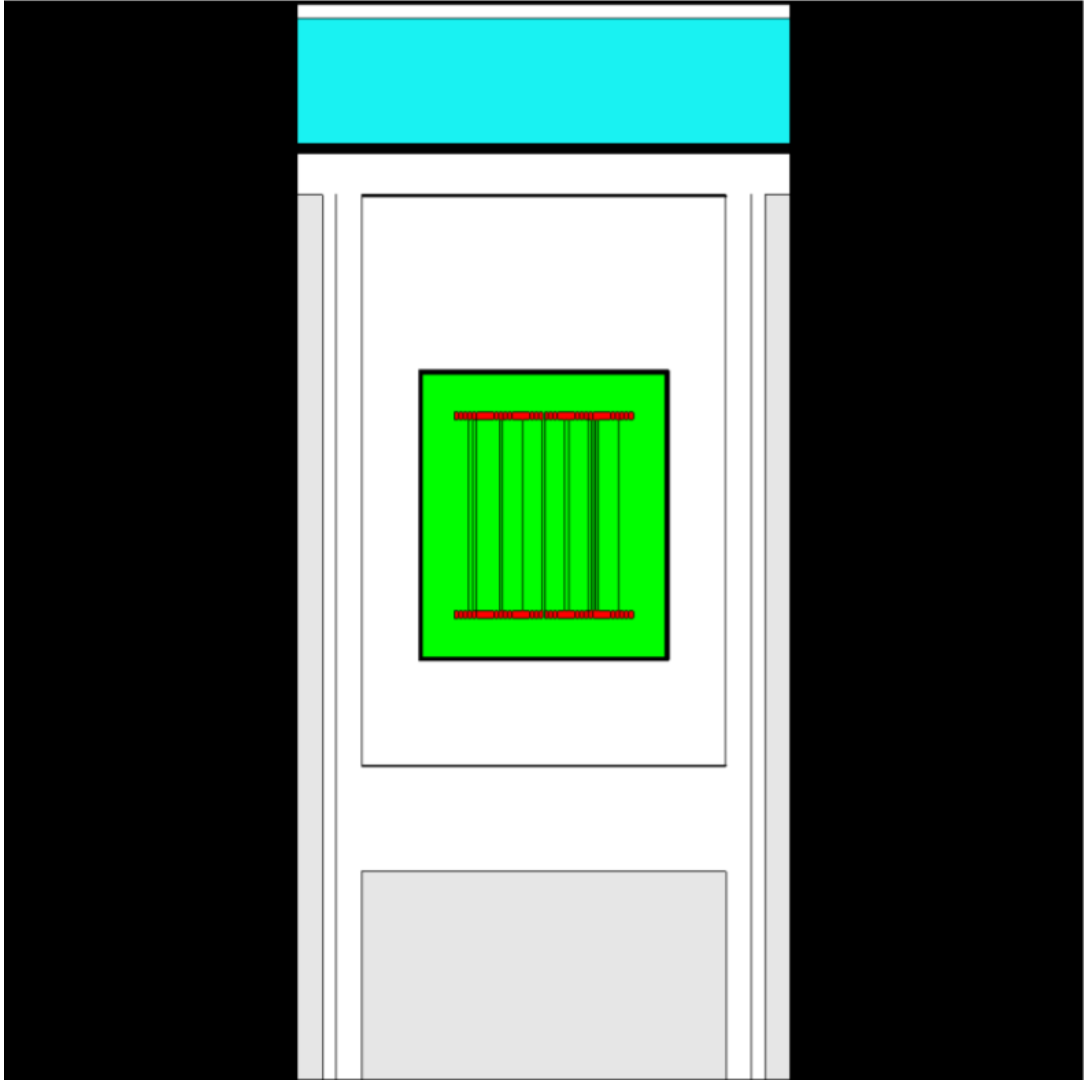
red - fuelsalt
green - graphite

Serpent Model plan view plenum



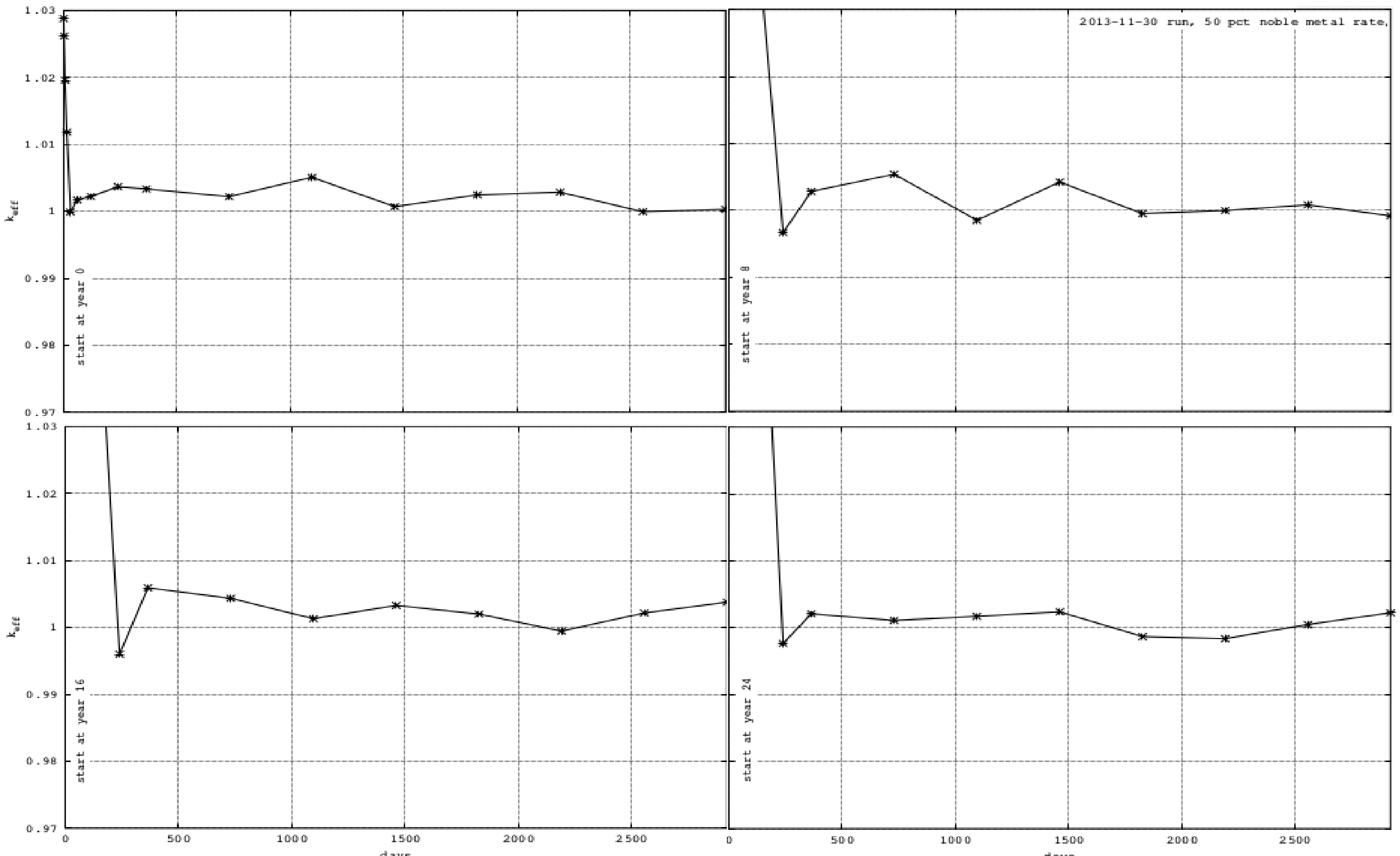
red - fuelsalt
green - graphite

Serpent Model section view

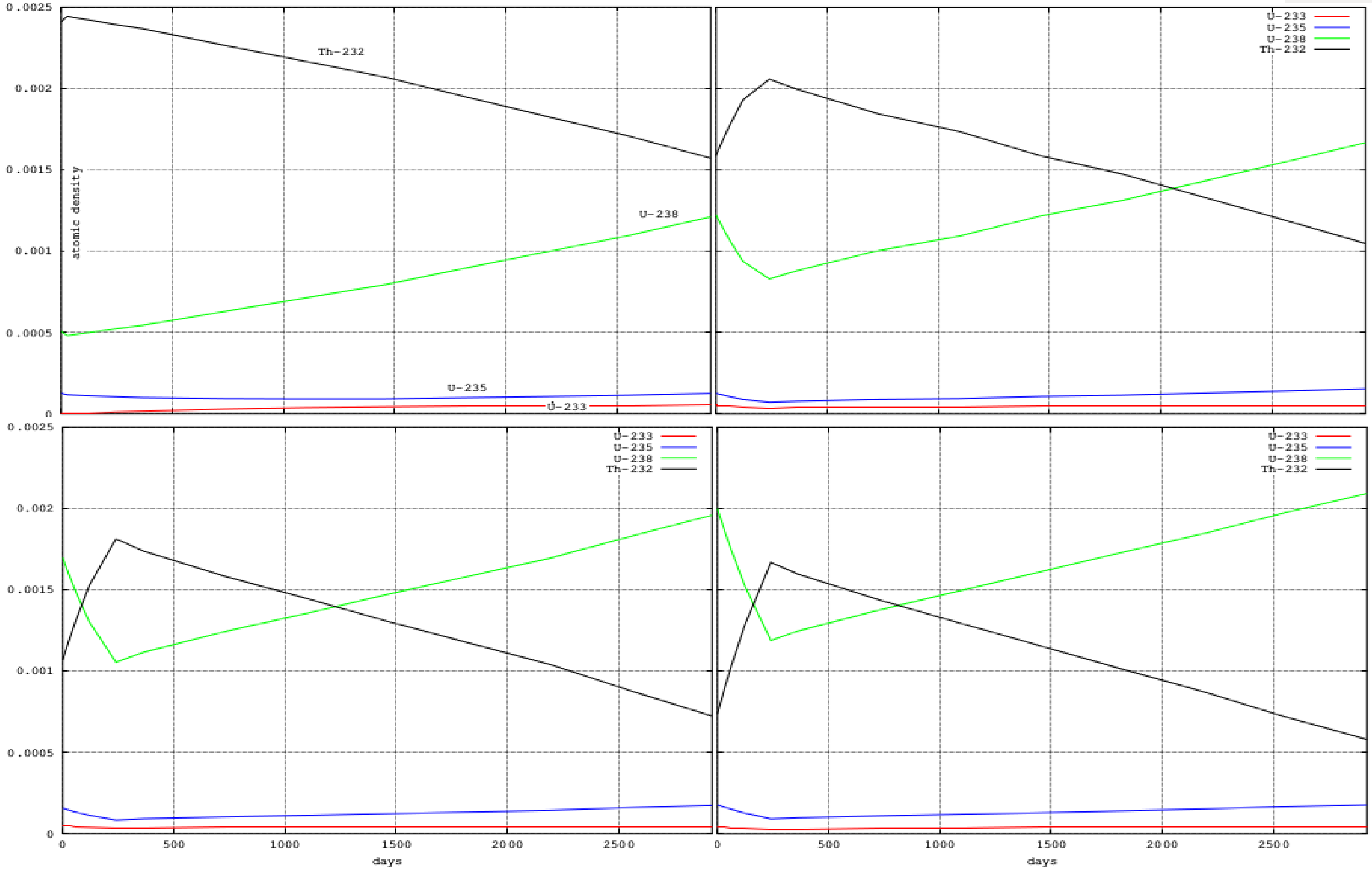


blue - rad tank
red - fuelsalt
green - graphite

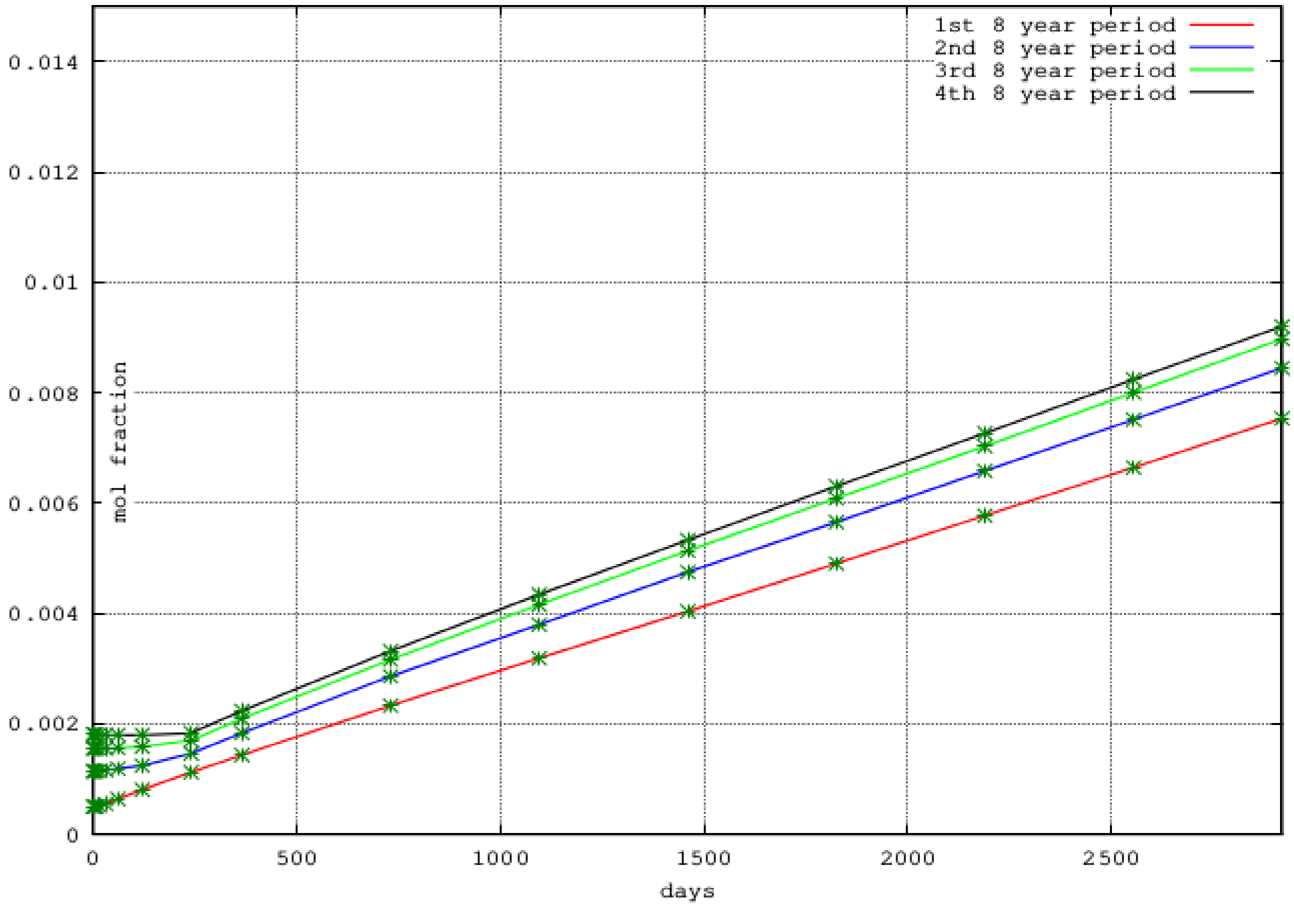
K_{eff} vs time, 32 years



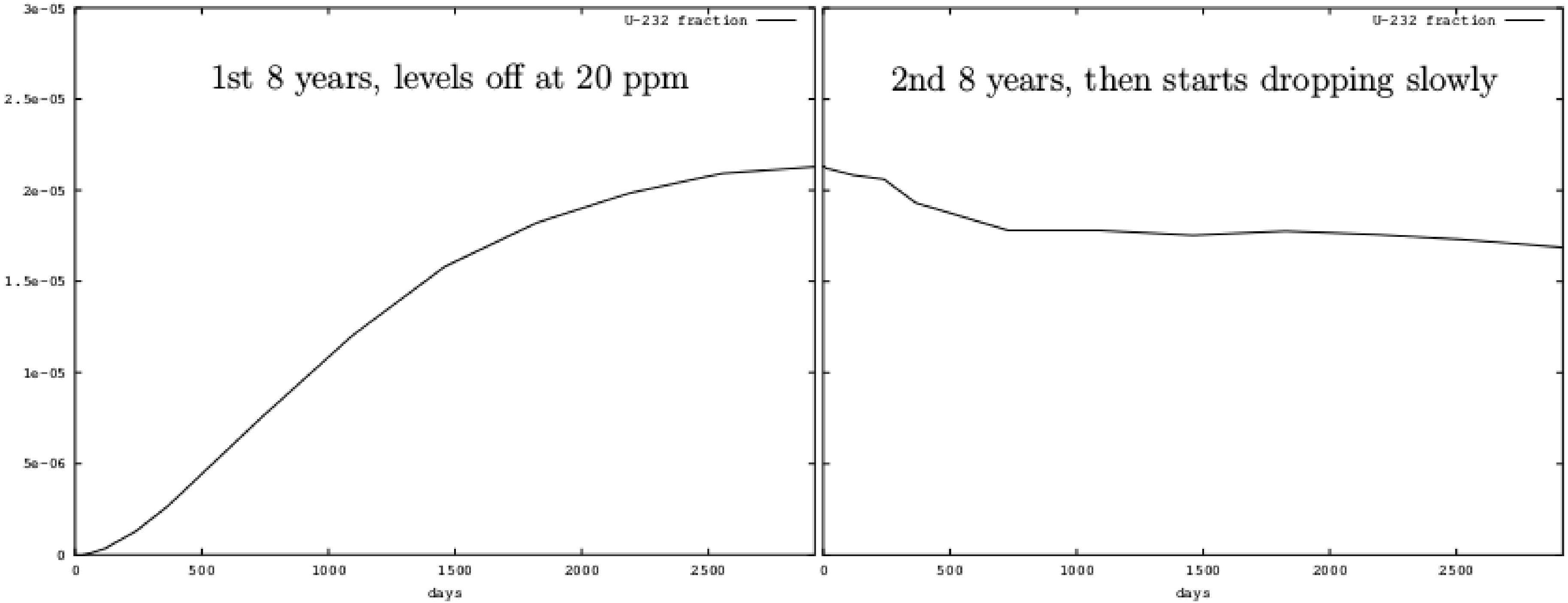
Uranium-Th atom densities, 32 years



Trifluoride mol fraction



^{232}U fraction of all Uranium



Energy from thorium (base case)

- ThorCon on NaBe gets about 23% of its energy from Thorium
- Limited by:
    - NaBe
    - remaining denatured (<20% LEU)
    - heavy metal salt melting point limit
- ThorCon's excellent economics result from other liquid fuel features
    - shipyard-like production
    - cheap NaF salt
    - recycling
    - modest contribution from thorium
- But it's still a real step toward a thorium cycle because the reactor is very flexible with respect to fuel composition changes

Fission Fractions

	Th-232 U-233	U-235	*U-238* Pu-239
Average 1st 8 year	*24.7%*	*52.7%*	*17.4%*
Average 2nd 8 year	*26.3%*	*46.9%*	*20.9%*
Average 3rd 8 year	*21.6%*	*49.6%*	*22.7%*
Average 4th 8 year	*18.8%*	*51.1%*	*23.8%*
Average 32 years	*22.9%*	*50.1%*	*21.2%*

More Energy from thorium (Flibe)

- ORNL-7207 FLiBe salt 74/16.5/8.2/13 LiF/BeF_2/ThF_4/UF_4 20% LEU, 99.995% ^{7}Li.
- Fresh salt K_{eff} = 1.00331
- 35% of energy from Thorium, up from 23%
  - the NaBe penalty is not so bad
- Still limited by:
  - remaining denatured (<20% LEU)
  - heavy metal salt melting point limit
- Flibe has 10–20% better β_{eff}, neutron life, better α_K
- ORNL-7207, Table 10, says 55% of fissions are ^{233}U at year 15. ThorCon's peak is 43% at year 4.
- ORNL-7207 assumed 100.0% ^{7}Li

Fission Fraction on ORNL 7207 Flibe

		U-233	U-235	Pu-239
Average 1st 8 years	:	*37.0%*	*43.3%*	*14.8%*
Average 2nd 8 years	:	*37.4%*	*38.5%*	*18.2%*
Average 3rd 8 years	:	*33.1%*	*40.8%*	*19.9%*
Average 4th 8 years	:	*30.6%*	*42.0%*	*20.8%*
Average 32 years	:	*34.5%*	*41.2%*	*18.4%*

We may switch to flibe when the price comes down

How much more does the additional makeup fissile cost?

- Net additions
  - Nabe needs 630 kg LEU/yr
  - Flibe saves 238 kg LEU/yr (~⅓)
  - Nabe additions about $7M/yr per pot
  - or about 6.5% of 5¢/kWh wholesale electricity produced
- Caveat: volume out = volume in
- Additions must be denser in fissile to work
- Burnup calculations indicate we can reuse uranium for 32 years, then still 9% ^{235}U
- Recycled uranium → fast reactors
- Or re-enrichment
  - Only 4 SWU/kg required 9% → 20%
- For now, uranium is cheap, so accept a performance penalty for speedy deployment
- flexible liquid fuel is adaptable to changing market conditions

20% LEU required, 550 MWt ThorCon Pot

	nabe	flibe	Ratio
Initial	636 kg	497 kg	78%
1st 8 yrs	2.094 kg/d	1.428 kg/d	68%
2nd 8 yrs	2.378 kg/d	1.724 kg/d	72%
3rd 8 yrs	2.534 kg/d	1.838 kg/d	73%
4th 8 yrs	2.607 kg/d	1.897 kg/d	73%

- flibe saves (per module)
  - $1.4M on startup
  - $28M (PV) over 32 years of operation
  - ~30% of fuel cost
  - ~$0.001/kWh

Additional future improvements?

- Higher enrichment (not denatured)
- Higher temperature → more metal
- Online removal of more FPs
- Pa removal for offline decay

With a progression of future modules,
eventually you’ve got MSBR with CR > 1.0
In the same physical plant.

ThorCon as a Plutonium Burner

- we looked at low-burnup Candu Pu as a startup fuel
    - 67% ^{239}Pu, 27% ^{240}Pu, 5% ^{241}Pu, 2% ^{242}Pu
- diluted with 9% thorium to keep $K_{eff} = 1$
- even though only 3.5% fissile, this fuel performs like 20% LEU
- makeup fuel additions are still 20% LEU
- initial makeup fuel requirements are high, but they stabilize
- 3000 kg ^{239}Pu is down to 270 kg at year 8* — it does burn up RG Pu

Molten salt reactors are remarkably fuel flexible

* these results are preliminary and not trustworthy

Conclusions

- No New Technology → low thorium usage
- But the key is not fuel cost
    - ThorCon fuel comes in at 0.6 cents/kWh without re-enrichment and this cost is dropping.
- The key is building NPPs like Koreans build ships, not like US Navy build ships. If we do, unit capex is less than 2¢/kWh. If not, nuclear will be forever too expensive to compete with coal.
- Choose technology compatible with assembly line production of everything.
- We must have a regulatory system informed by what we now know about how organisms respond to radiation, a system that can balance risk vs benefit. Use commercial aircraft as a model.
- Only then can we provide reliable, pollution-free, carbon-free electricity cheaper than coal.

END

^{233}U the Moir Plan

- Produce self-protected ^{233}U in $Q < 1$ fusion device.
- 14 MeV neutrons end up with 5% ^{232}U
- Burn in ThorCon as 76/12/11.73/0.2565/0.0135 $NaF/BeF_2/ThF_4/^{233}UF_4/^{232}UF_4$
- Need very little of this fuel, close to 50% Th conversion rate
- ^{232}U ~ 10,000 ppm at year 8
- nil plutonium, never close to weapons grade
- ThorCon would pay $100,000/kg for this fuel

other slides from my ThorCon overview in case you want to borrow any.

Producibility

- Current world electricity consumption, about 2500 GWe → 3750 GWe by 2030.
- Need roughly one hundred 1 GWe plants per year, 2 plants per week.
- These are aircraft numbers. 747 production averaged 31 airplanes per year, 1966--2012.
- Unless you are cheaper than coal with zero CO_2 cost, less than $0.05/kWh, don't bother.
- We need a mass-producible system, not individual fortresses.
- The system must encompass the entire plant, not just the reactor.
- The plants should NOT be responsible for recycling or disposing of used material.

Build a system, not a plant

Should-Cost versus Did-Cost

- Should-cost is based on resources consumed: steel, concrete, nickel, productive labor, etc.
- Only gas and oil are cheaper energy systems than a LWR on a should-cost basis.
- Low pressure, high temperature, liquid fuel nuclear beats LWR by >2x.
- Block construction for every thing — which LWR cannot do — can reduce labor requirements to shipyard numbers, less than 1M man-hours for a 1 GWe plant.
- And nuclear dramatically beats gas and coal on fuel cost.
- As long as we build nuclear power plants like the Navy builds ships, it won’t do us any good.
- Unless we narrow the gap between should-cost and did-cost drastically, no nuclear technology will be able to compete.

There’s no limit to how much poorly executed regulation can increase costs, slow innovation, and retard improvements.

Fixability

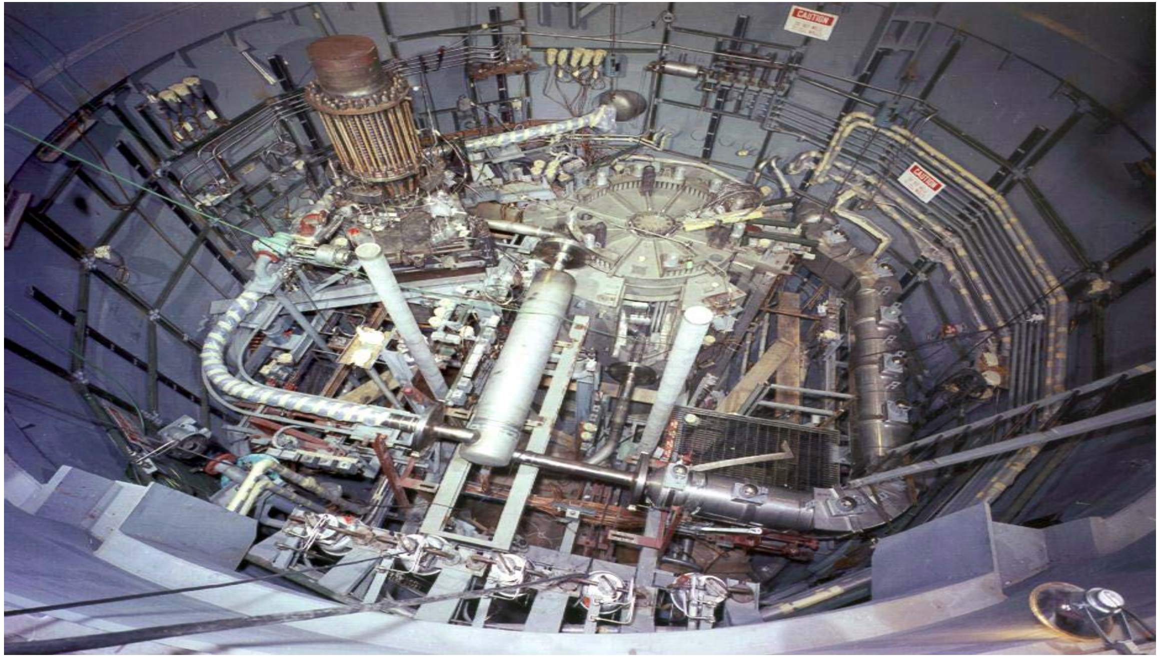
- The Nuclear Problem
    - o Something breaks, can’t go in and fix it.
    - o The design must address this dilemma.
- ThorCon is designed for replacement of all components.
- Don't pretend things are going to last for 30 or 40 years. In most cases, we don’t know the MTBF. Even if we did, things are going to break, and we don’t know when.
- Everything but the building must be replaceable with modest impact on plant output.
- Everything is upgradable.
- Investment is preserved.
- Low pressure molten salt makes this possible.

ThorCon is based on Oak Ridge labs' proven nuclear power technology.

Uranium and Thorium
in molten salt.

ThorCon redesign:
- modular production
- 50 years of science
- modern materials
- fast computers

Result:
- rapid production
- cheaper than coal

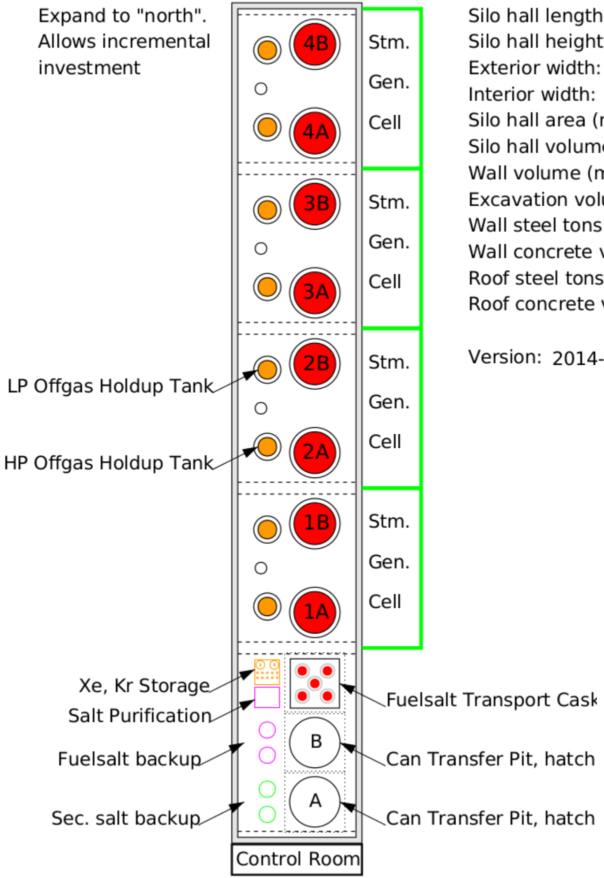


Oak Ridge molten salt reactor ran from 1965 to 1969.

Molten Salt Reactor Experiment

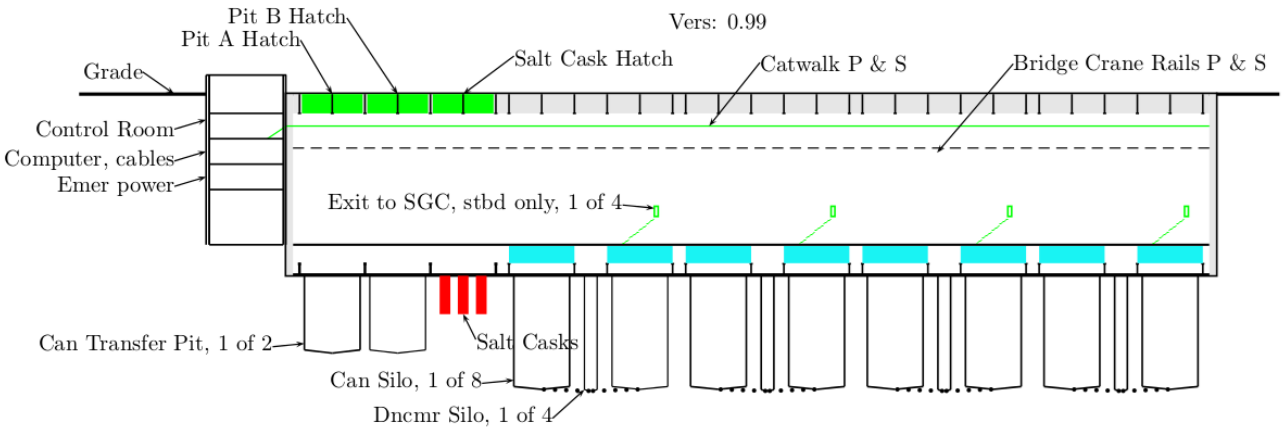
- Hundreds of millions spent on the Aircraft Reactor Experiment. Tried many ideas, ended up with fluoride salt ARE which operated successfully for 1000 hours in 1954.
- 1956 $2M ($18M 2014 equiv) budgeted for commercial MSR.
- 1959 $4M ($33M 2014 equiv) approved for MSRE.
- Summer 1960, Design started
- Early 1962, construction started
- Jan 1965, salt circulated thru core.
- Jun 1965, first criticality (5 years after design began)
- May 1966, full power
- Dec 1966, 30 day run at full power followed by 15 months mostly at full power on U-235.
- Jan 1969, Full power on ^{233}U.
- Dec 1969 shut down to concentrate on breeder.
- Total 11,555 full power hours. Last 15 months, 87% availability.
- 1974 funding abruptly halted after Weinberg fired for honesty on PWR problems, Nixon LMFBR politics.

Silo hall / containment building

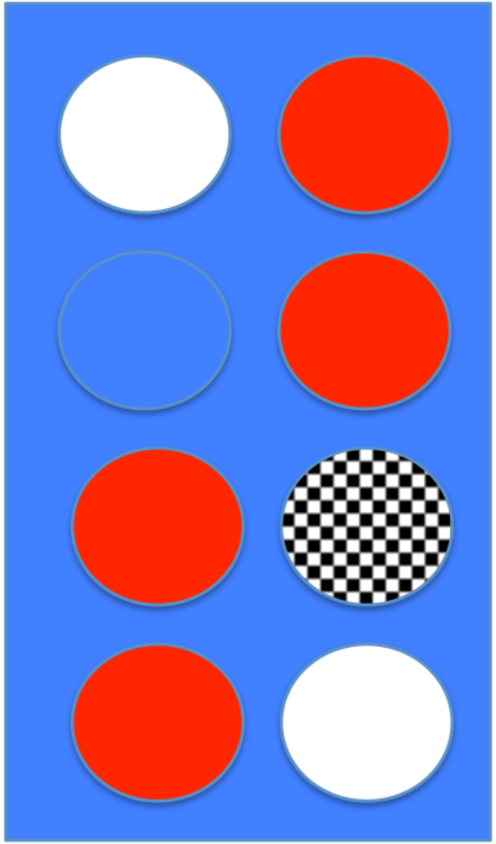


Silo hall length:	146.354
Silo hall height:	28.437
Exterior width:	22.675
Interior width:	20.613
Silo hall area (m2):	3319
Silo hall volume (m3):	94,367
Wall volume (m3):	9,787
Excavation volume (m3):	115,076
Wall steel tons:	5,145
Wall concrete vol(m3):	9,131
Roof steel tons:	1,542
Roof concrete vol(m3):	9,955

Version: 2014-07-12 1.04



ThorCon module pairs generate 250 MWe each.



Each operates 4 years, cools 3 years, then swapped out

- Empty
- Ready, with fresh fuel
- Active, generating power
- Used, passively cooling

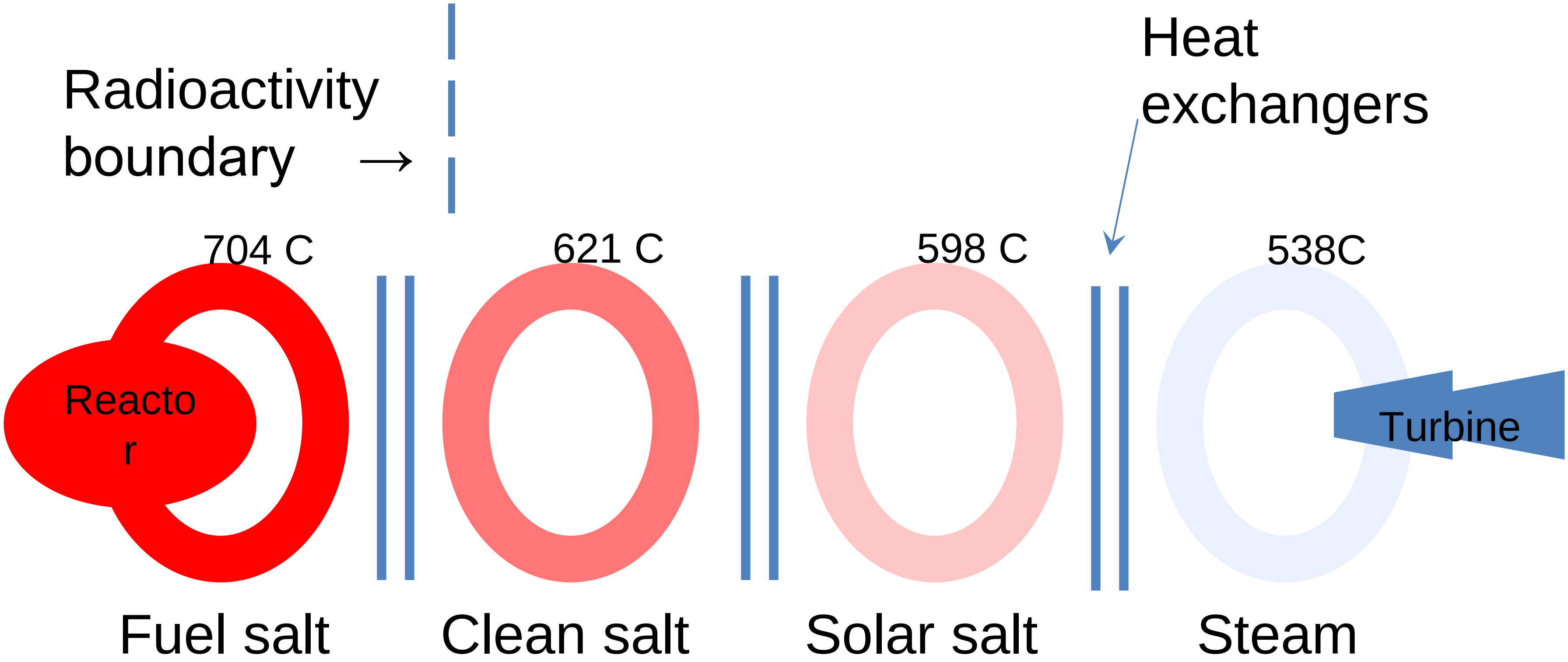
The Duplex Can System

- Power density is 25 MW/m^3 → 5+ year moderator life.
- Flip Cans every 4 years
- Old Can sits in silo for 4- years
- At transfer to Canship, Can decay heat is under 1 kW
- Can is shielded during transfer ~0.062 mSv/hr.
- Change out fuel salt every 8 years --- with NaBe salt, cost not an issue.
- At change out, old salt stays in a fuel dump tank for 4- years.
- At transfer via pump to transport casks salt decay heat under 15 kW.
- No separate vulnerable, spent fuel facility.
- Fixability. Transfer in 60 days (40 kW) if necessary.
- Extremely high availability.

Silo Membrane Wall

Keeps the Can interior at about 270C during normal operation. (Primary loop is insulated)
Cools the drain tank in the event of a drain.
The wall is always operating so problems show up before casualty, not during.
Fuse valve rather than a freeze valve.
Cold steel wall stops tritium, inert gas processing captures dry tritium.
Radiation heat flow goes as T^4 so it cools rapidly if the Can heats up, but slowly as the Can cools down → great for emergencies, always on yet low power loss in the nominal case.
Even with a primary loop breach, we maintain a double barrier between the fuelsalt and the membrane wall water, and a triple barrier to the environment.
All this with no penetrations into the can or the drain tank.
Protects the silo’s concrete lining from thermal shock.
Wall temperature is independent of the heat flux to the wall.
Totally passive. Pond sized to go 72 days without make-up water. ~6 months with passive tower.
Robust against mistakes.

ThorCon converts energy via four heat transfer loops.



Four Loops

Four loop system: NaBe fuel/NaNe/sol-salt/water-steam

Vertically stacked. 5% natural circulation in all four loops → second passive decay heat path, avoids drain in many casualties, handles fail-to-drain.

Tritium flashed off as steam by tertiary loop solar salt and captured.

Sol-salt (222C freeze) → standard steam generator, standard steam cycle.

Simple peaking capability with enlarged Sol-salt volume.

Another barrier between super-critical steam and fuelsalt.

High pressure steam leak creates no nasty chemistry, no ^{24}Na dispersal.

Tertiary loop pressure release is a simple open standpipe.

Steam Generator shell speced to fail (at 5 bar) well before SHX tubes.

SHX loop has blow out panels. SHX shell speced to fail well before PHX tubes.

SGC contains even the extremely unlikely Triple Tube Rupture casualty.

Four barriers

4 gas-tight barriers between fuelsalt and environment.
Primary loop plumbing.
Can. Sealed. 5 bar over-pressure, vents to very large volume 5-bar SGC.
Silo cavity. Inerted space. Normally slightly less pressure than silo hall.
Silo Hall. Speced to 1 bar over-pressure, 0.1% leak/24 h. Normally slight under-pressure.

Walk-away safety

- Four barriers, deep underground.
- One week of excess reactivity in fuel rather than multi-years.
- 700C temperature margins. Strong negative temperature coefficient. Reactor will shut itself down even if control rods fail.
- Passive drain on over-temperature. Nothing operators can do to prevent it. Primary loop rupture drains to FDT. Most casualties confined to a Can change out.
- Two nearly independent, totally passive decay heat paths. No valves to realign as in some so-called passive systems. Massive margin in membrane wall. Membrane wall always running, so you know it works.
- No need for any outside aid for at least 72 days.
- Low pressure, no phase change. No dispersion energy in reactor. Initial offgas decay in Primary Loop. Most fission products including ^{90}Sr, ^{131}I, and ^{137}Cs are salt seekers. Even if all four barriers are breached, they stay in the salt. They will not disperse.
- Barring triple tube rupture, no dispersion energy anywhere in the system.
- Tertiary loop, open standpipe, designed weaknesses makes triple tube rupture barely credible. But contained in SGC if it happens.

Building and Erection

- Steel sandwich walls 1 m thick with 25 mm steel plate. Ship bottom style structure for roof.
- 1GWe ThorCon will require 17,000 tons of steel for silo hall, SGC cells, all simple flat plate. Much of it repetitive.
- Everything but footing manufactured on a shipyard assembly line in 100 to 300 ton blocks.
- About 100 blocks per 1 GWe plant.
- All blocks are pre-coated, pre-piped, pre-wired, pre-tested.
- Blocks barged to site. Dropped in place. Welded together by automatic hull welding machines. No scaffolding.
- Key is the 21 x 28 meter grid block. Almost all pipe runs, most wiring are in the grid block. Module grid (160 tons plus piping) will be a single lift. Barge transportable on many rivers.
- Yards figure about 5 man-hours per ton of erected steel. 1GWe silo hall, SGC erection labor should be less than 100,000 man-hours ($5M), a lot less if we do it right.
- Outfitting about the same.

Costing is about resources, not dollars

Under textbook competition, not much difference between should-cost and did-cost.
When rules change, costs change.
LPD is 25,000 ton transport for 700 marines, two Ospreys and a couple of air cushion vehicles. Should cost $50M or less with out-of-service time of 15 days per year or less.
LPD costs $1500M+ or more. And availability stinks.
Costs automatically rise to whatever level market imperfections allow.
Oyster Creek, 550 MW, $0.13/W, 1964; CPI says $0.97/W, 2012. USA now $8.00/W+.
In competitive markets, immature technologies get cheaper. The nominal cost of a VLCC today is about the same as it was in the mid 1970’s. Real cost about one-third. Fuel consumption halved.
Nuclear has demonstrated a negative learning curve.
For should cost, look at the resources.

Should Cost

Cast iron	12,778	tonnes
Steel	14,640	
Lead	2,472	
316 stainless	1,428	
Graphite	1,300	
304 stainless	758	
Hayes 230	188	
Metal Packing (IMTP)	127	
Nickel	77	
Graphite Rings	57	
TiZrMo (TZM)	4	
Carbon-Carbon	2	
NaBe fuel salt	152	
NaBe clean salt	50	
KNO_3 solar salt	30	

Hitemp concrete	2,333	cubic meters
Ordinary concrete	40,211	
excavation	197,011	

4 Module (1 GWe) ThorCon Top-Level Resource Requirements
Not including steam turbines, generators, and switchyard

well under $100M worth of material

should cost under $200M for 1 GWe

CapEx: 20¢/watt

Fuel: ~0.2¢/kWh

Status of ThorCon

We have a complete *basic* design.
The design includes some 60 drawings.
We have a full set of weight estimates by material. We know what the plant should cost.
We have both MCNP and Serpent neutronics. The original MCNP model was done by PNNL. (Thanks Jim Livingston.) Both are full 3-D models encompassing the reactor vessel and its surroundings.
Using Serpent (thanks Jaakko), we have full burn up results including on the fly fuelsalt extraction and addition. (Thanks to Manuele Aufiero and his colleagues at Politecnico di Milano).
We have stability coefficients and a point kinetics model. (Thanks Dr. Yoshioka.)
The whole thing is driven by the totally rubbery ThorCon DNA model. The DNA model is set of programs which allow us to change any of the plant's independent variables, issue a command, and regenerate layout and design calculations, update weight and costing, and produce a new set of 2-D and 3-D drawings.
We need to fill in a number of important gaps and produce a specification that the yards and vendors can bid on.

Technical concerns

Component designs must be detailed and tested

- Main molten salt pump and seals are critical path
- Twisted tube, fluoride salt HX. Koch wants 9 months and $0.07M to test. Fallback is conventional shell and tube.
- Sleeve valves. Fallback is freeze valves.
- Quatenary NaBe fuelsalt properties. Czechs and Indians have capability. ORNL, U of Wisconsin
- Better model of fuel dump tank circulation/cooling/shock
- Ceramic membranes. Good chance we can replace cryogenic separation of helium with room temperature membranes. But need tests.
- Low overall experience handling hot molten salt. We need to build a team with experience.

Neutronics Tasks

- MCNP/Serpent Runs
    - No thorium, low enrich. How low can we go given removal problem?
    - Weapons Grade Pu What happen if we burn weapons grade Pu?
    - Flibe. Thorum conversion on flibe?
- Bring Serpent Model up to date
- Refactor Aufiero code so extraction rates etc are true input.
- Improve top and bottom reflector model. See if we are going to get fission if go straight thru.
- Do temperature layers, check what happens at half-full during drain.
    - Do we get more moderation?
- Check out 316 tube sheet. Idea is to spread expansion throughout core, improve temperature coefficient. Lars estimates should get -1.5 pcm/K.
- Figure out Na-24 activation
- How soon can we move old fuelsalt out of FDT?
- Improve MCNP/Serpent FDT model. Do FDT full surrounded by water to check criticality.
- Do layer of fuelsalt on bottom of silo covered with layer of water to check criticality.
- Do side entry model.
- Expand point kinetics model to multi-node model. Exercise on all sorts of upsets.

Non-Neutronics Tasks

- Finite Element capability for structures.
- Seismic loads, structural dynamics
- Piping thermal expansion, deflection, stresses, shock.
- Natural circulation model of secondary/tertiary/steam loops.
- More detail in the design of fuse valve, control rods.
- Closed loop mwall cooling system.
- 3-D visualization model. DNA model driven.
- Prepare spec for yard, OFE vendors.

We must have a rational regulatory environment

- There is no limit on how costly regulation can make any technology.
- Commercial aircraft model, not NRC model.
- Do not rely on paperwork. Paperwork rules quash competition and improvement, encourage/guarantee dishonesty. Certificates breed dependence, cost, complacency and lock-in, not quality. The wrong people get promoted. See Navy.
- Don’t rely on the computer, to tell you if something is safe.
- Build prototypes early and build big. Big is cheap and fast.
- Bid everybody; trust nobody. Inspect as you go. Test as you go.
- Put full-scale prototype in a safe area and test every casualty you claim you can handle. Expect surprises, good and bad, set up to modify quickly, and re-test. Prototypes should be tortured, not licensed. See Proto-park proposal.
- Plant must be modular to make such testing feasible, but we need big modular, not small.
- May make sense to stay “non-nuclear” as long as possible to avoid regulatory delay/costs in pre-nuclear testing.

a country that wants us

- We must have a country that wants us
- A country that wants cheap, reliable, carbon free power.
- A country that wants a Boeing style manufacturing industry.
- A country that is willing to host waste and fuel recycling facilities.
- A country that is willing to regulate intelligently.