ThorCon Design Philosophy: The Do-able Molten Salt Reactor

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presented by

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ThorCon Design Philosophy

Goal: cheap, reliable, carbon-free electricity.

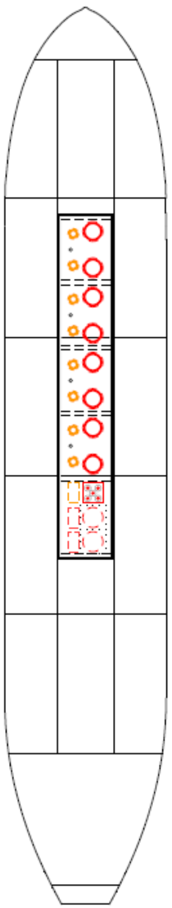
Now

- ***Producible*****.** Nuclear island <1 USD/W
- ***Fixable*****.** Major failures have modest impact on plant output
- ***Now: Full scale prototype within four years***

Producibility

LOA(m)	380.00
Beam(m)	68.00
Depth(m)	34.00
Keel to Mast	73.96
Lightweight(mt)	67,591
Cargo Cubic(m^3)	511,000
Ballast Cubic(m^3)	149,500
Bunkers Cubic(m^3)	12,900
Coated Area(m^2)	350,000
Main Power(kW)	37,000
Prop diam (mm)	10,500
Steering gear(t-m)	870
Gen Power(kW)	3 x 1450
Boilers(kg/h)	2 x 45,000
Cargo pumps(m^3/h)	3 x 5000
Ballast pumps(m^3/h)	2 x 5000
IGS sys(m^3/h)	18,750
Cranes(SWL)	2 x 20
Anchors(mt)	2 x 22
Windless	2 x 76
Winches	24 x 30
Firefight	CO2/foam
Accommodation	50
Lifeboats	2 x 50
Contract	1999-12-17
Keel-laying	2001-06-11
Delivery	2002-03-07
Essentially one off	
Cost	???

Producibility. Nuclear Is Small



	ULCC	ThorCon
Overall Dimensions	380 x 68 x 35	146 x 23 x 29/47
Steel (mt)	67,591	14,700
Double Curved plate	Lots	None
Coated Area (m^2)	350,000	30,000
Stainless steel(mt)	100	1,950
Hi nickel alloy(mt)	nil	253
Concrete (m^3)	0	42,000
Excavation (m^3)	0	192,000
Cargo Capacity	445,000 tons oil	0
Ballast Capacity	150,000 tons	0.0
Design Speed	16 knots	Just sits there
Design criteria	Hurricane at sea	0.6 g earthquake
Throughput	Discharge 15,000 m^3 oil per hour	Heat 14,000 m^3 salt per hour
Biggest component	35 MW low spd diesel	500 t SWL crane
Construction time	10 months	???
Price(2000)	\$89,000,000	???

1 GWe ThorCon nuclear island fits into 3 center tanks of ULCC

Producibility

ULCC Costing

- USD 89,000,000 ThorCon would fit in the center tanks
- Build time: about 12 months
- Direct labor: 500,000 man-hours, 250 man-years
- About 40% hull, 60% outfitting
- 5-6 man hours per ton of hull steel, complicated double hull structure, lots of single curved plate, some double curved, everything one-off
- About 140 blocks, average about 350 tons each (Forces precise dimensional control)
- Main engine about USD 10,000,000 or $270/kW including testing
- Marginal cost of power all in $150/kW
- Overall 15% direct labor, 15% overhead, 70% purchased material
- If ship has more than 15 days offshore a year, operating in a hostile environment, including scheduled dockings, it's a lemon. 15 days annual offshore is 96% availability

Of course, there's nothing special about ships.

Navy Ships Are Special

		VLCC	LPD
Length Overall(m)	333.0	208.5	
Beam(m)		60.0	31.9
Full Load Draft(m)	22.0	7.0	
Displacement(mt)	360,000	25,300	
Lightweight(mt)		40,000	abt 20,000
Accommodations	40	1002	
Power(MW)		1 x 35	2 x 15
Speed(kt)		16	(flank) 22
Cargo capacity		350,000m3	2229m2+2190m3
Ballast capacity(m3)		150,000	abt 5000
Construction time(yr)		<1	3 to 8
Armament		none	2 RAM close in 1 30 mm gun 4 50 cal MG
Did Cost		**$80,000,000**	**$1,700,000,000**
Should Cost		**$70,000,000**	**$50,000,000**

Table 1: LPD is 15X smaller than VLCC, 21X dearer. LPD should cost < 50MM

But Navy ships have extensive design calculations of every detail, interminable design reviews, careful certification of yards, vendors, materials, welders, janitors. Ubiquitous documentation of everything with strictly followed sign-off procedures, all sort of special standards and procedures which must be precisely adhered to.

Meticulous review of the tiniest of changes

Nothing is too good for our sailors

Record of Lead Ship, San Antonio, LPD-17

1996-12 Contract awarded. The budgeted cost of the ship is $617 million.

2000-08 Construction started. Supposed to be commissioned in 2002-07. Navy admits cost is now up to $861 million. CBO estimates cost at 1.3 billion.

2003-07 San Antonio launched.

2004-12 Towed from Avondale to Pascagoula. Could not move under own power despite being christened in 2003.

2005-?? Attempted sea trials. Navy came up with 15,000 deficiencies. Some of these were major enough to compromise watertight integrity.

2006-01 Inexplicably Navy accepts ship waiving the unresolved issues. She is commissioned, but still can't deploy. Northrop-Grumman gets extra money "for post-shake-down availability". Having accepted the ship, Navy's legal options are non-existent.

2007-03 Failed to finish sea trials, complete failure of one steering system, major defects found in 3 of 17 sub-systems. Ship is now 840 million dollars over budget.

2007-06 Sec. Navy Winter writes builder "23 months after commissioning of LPD 17, the Navy still does not have a mission capable ship". (Winter visited Hyundai and marveled at the quality of the welding).

2008-08 San Antonio finally deployed on first mission in late August 2008. Cost now 1.7 or 1.85 billion depending on source. Stern gate failure delays departure 2 days.

2008-10 Got as far as Bahrain in October. Extensive oil leaks. 30 welders and fitters flown out from USA for two + weeks of repairs.

2008-11 All four main engines out of commission.

2009-02 During transit of Suez, one screw suddenly went into reverse, sending the ship out of control and aground.

2009-?? Ship's XO Sean Kearns refuses Captain's mast, is court-martialed, and then acquitted after testifying that ship officers had been pressured to declare the ship was ready to deploy when she wasn't. Defense provided copious evidence supporting claim.

2009-07 Inspections reveal that 300 m of piping must be replaced. Reduction gear shavings found in main engines.

2010-03 San Antonio to Norfolk for 4-5 month overhaul costing 5 million. But inspectors finds bolts in the main engine foundation improperly installed, extensive bearing damage. Problems include bent crankshaft. Repairs now expected to take about 11 months and cost at least $30 million.

2011-04 San Antonio still in repair. Navy starts an investigation into "issues with the San Antonio." Maintenance firm Earl Industries fired. Earl had won the 75 million dollar contract despite not being low bidder on the basis of "exceptional" performance on past contracts. Earl still has USN carrier maintenance contracts.

2011-05 San Antonio leaves yard, and after trials declared ready for duty.

2011-07 Unable to maintain full power. Returns to yard for repairs.

2012-03 San Antonio given the Navy's Battle Effectiveness Award, beating out four of her sisterships. Gets to paints a big E on super-structure. Both Admirals in charge of LPD program 2000-2010 promoted.

What's special about Navy ships is that they are built the Navy way.

Will we build NPP's the way the Koreans build ships or the way the Navy builds ships?

Should-Cost vs. Did-Cost

- Should-cost is based on how much of the planet's precious resources we consume: steel, concrete, nickel, productive labor, etc.
- Based on resource usage, only gas (and oil) has a smaller capital cost than conventional nuclear.
- Low pressure, high temperature, liquid fuel nuclear can beat the LWR by better than a factor of two on nuclear island material resource usage.
- Block construction for every thing — which LWR cannot do — can reduce labor requirements to shipyard numbers, less than 1,000,000 man-hours for a 1 GWe plant.
- And nuclear wallops fossil fuel on fuel cost.
- But 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.

Producibility

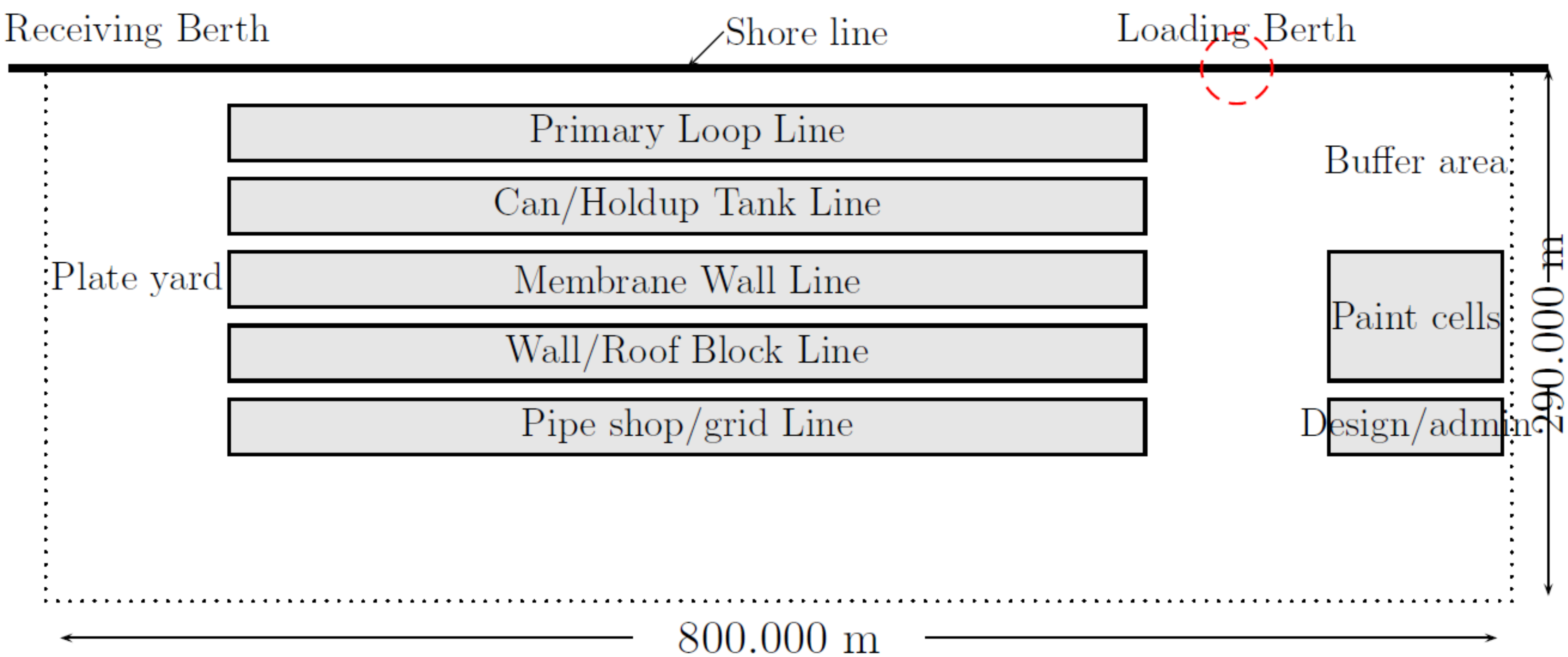
- Current world electricity consumption, about 2500 GWe.
- Probably go to around 3750 GWe by 2030.
- Need roughly one hundred 1 GWe plants per year, 2 plants per week.
- ***These are aircraft numbers***. 747 production averaged 31 airplanes per year, 1966-2012.
- Unless you are cheaper than coal with zero CO_2 cost, less than 0.05 USD/kWh, don't bother.
- We need a 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.

Producibility

Build ***everything*** on an assembly line.

- Reactor yard produces 150 to 500 ton blocks. About 100 blocks per 1 GWe plant.
- Blocks are pre-coated, pre-piped, pre-wired, pre-tested.
- Focus quality control at the block and sub-block level.
- Barge/ship transported to site.
- Dropped in place.

Producibility



10 GWe/y Yard block diagram, 200,000 tons steel per year

Fixability

- 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. Plan for it.
- The Nuclear Problem: ***something breaks, can't go in and fix it.*** The design must address this dilemma.
- Everything but the building must be replaceable with modest impact on plant output.

MTBF=mean time between failure.

Full-Scale Prototype Within 4 Years

- ***No New Technology***.
- Forget about flibe.
- Forget about breeder.
- Forget about fancy fuel processing, waste burning.
- Forget about Brayton. Use existing steam plant.
- Just a scaled up non-flibe MSRE.
- Straight to 250 MWe prototype. ***No further scale-up***.

Full-Scale Prototype Within 4 Years

Hanford chronology

1942-04 Wigner arrives in Chicago.
1942-07 Rough sketches of a water cooled pile. Told he's crazy. No way it can go critical. Helium is only way.
1942-09 Wigner group starts design of 250 MWt water-cooled pile.
1942-12 First sustained chain reaction ever.
1943-01 Wigner completes design. Group of 5 using adding machines and slide rules.
1943-01 Decision is made to locate at Hanford.
1943-02 Decision is finally made to go water. 500 MWt.
1943-08 Construction starts
1944-09 Pile goes critical. Wigner furious it took so long. Blames "too much money".
1944-11 First Plutonium.

Schedule is do-able. Only question is how?

Full-scale Prototype Within 4 Years

Nautilus chronology

1949-02	Rickover given control of naval nuclear propulsion. Still leaning to sodium.
1950-03	Decision to go PWR. At the time, no PWR of any scale had ever been built. Just a Weinberg patent and some sketches. No one knew how to make control rods, cladding, bearings that could handle PWR conditions.
1950-??	Decision to go straight to full scale prototype, S1W, in Idaho. No pilot plant. Nil sub-system testing. Westinghouse, Navy Bureau Ships aghast.
1950-08	Construction of S1Wstarts. Delayed by bad winter.
1951-08	Electric Boat awarded Nautilus contract.
1953-03	S1W, the first PWR ever built, goes critical.
1954-01	Nautilus keel laid.
1954-09	Nautilus commissioned.
1955-01	"Underway under nuclear power."

Rickover later sarcastically extolled the benefits of non-LWR concepts, one of which was "unavailable". At the time, most of these concepts were far further along than the PWR was when he committed to a full-scale prototype.

Rickover put in place the extensive paperwork system that became the NRC regulatory process, guaranteeing that his feat would never be repeated in the USA.

But a younger Rickover: "Good ideas are not adopted automatically. They must be driven into practice with courageous impatience."

Full-Scale Prototype Within 4 Years

Camp Century PM-2A chronology

1959-01-23	4.5 MUSD contract with American Locomotive Company signed 10 MWt, 2 MWe Plant Designed, Built, Tested.
1960-07-10	Plant arrives Thule on ship. 27 packages. Sledded inland. Erected in 78 days.
1960-10-03	First Criticality, all in cost 5.7 MUSD
1960-11-12	Plant operating on Greenland Icecap. Total time 22 months.

Camp Century was at 77.2 N, 61.1 W, 6180 feet above sea level on the Greenland plateau, 800 miles from the North Pole. In summer of 1964, Camp Century was shut down, PM-2A disassembled, and returned to the US.

- Non-standard nuclear manufacturer.
- Plant built entirely on assembly line.
- Transported by ship in blocks to site.
- Erection time measured in weeks.
- Dis-assembled by reversing the process.

Why Liquid Fuel?

- Good control characteristics (if DMSR), low excess reactivity, big temperature margins
- High thermal efficiency. 44% vs 32%.
- Xenon bubbles out, High burn up, 1/3 fuel, 1/12th waste.
- Low U usage, nil fuel fabrication. Step to thorium cycle
- Low Pressure, no phase change, low chemical energy.
- Walkaway safety, passive fuel drain, many fission products stable fluorides including Sr-90 and Cs-134, Cs-137.
- ***Low part count.***
- ***Move fuel around with a pump.***
- ***Compatible with all block construction. Nil rebar.***
- No mausoleum to get in the way of repair.
- Heavy lifting has already been done by ORNL.

MSRE History

- 1954, Hundreds of millions spent on the ARE. Tried many ideas, ended up with fluoride salt Aircraft Reactor Experiment, ARE which operated successfully for 1000 hours.
- 1956, Two million budgeted for commercial MSR.
- 1959, Four million approved for MSRE.
- Summer 1960, Design started
- Early 1962, construction started
- January 12, 1965, salt circulated thru core.
- June 1, 1965, first criticality
- May 23, 1966, full power
- Dec 14, 1966, 30-day run at full power followed by 15 months mostly at full power on U-235.
- Jan 28, 1969, Full power on U-233.
- 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 decided to focus on LMFBR to funnel funds to CA for political reasons.

Working Outside In

- ORNL work allowed us to work outside in.
- Opposite of normal nuke thinking.
- Reactor/primary loop treated as 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.

Where We Are

- In shipyard parlance, we have a basic design. That is, a design that is complete enough and detailed enough so that it can be costed and bid.
- We have a full set of weight estimates by material. We know what the plant should cost.
- The design includes some 60 drawings.
- 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 fuel salt extraction and addition. (Thanks to Manuele Aufiero and his colleagues at Politecnico di Milano).
- We have quasi-static estimates of the stability coefficients. A remaining gap is dynamic analysis of transients.
- 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 (almost) all the layout and design calculations are redone, key tables recreated, weight and costing updated and a new set of 2-D and 3-d drawings produced.

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. Wrong people get promoted. See Navy.
- Do not 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 retest. **Prototypes should be tortured, not licensed.**
- Plant must be modular to make such testing feasible, but
- **We need big modular, not small**.

We Must Have A Country That Wants Us

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