ThorCon: Low cost, dependable, CO2-free power

Ganapati Myneni
info@thorconpower.com
ThorCon target market: 70-100 GWe/year for 100 years

One large nuclear plant is 1GWe. Total US usage is 500 GWe.

Demand: 1kW/person in Europe & Calif. Future world population of 10 billion demands 10,000 GWe.

Additional electrification opportunities:
transport
Industrial heat
synfuels

Demand could rise to 70,000 GWe.

Only nuclear energy can do this job with low environmental impact.
To successfully compete against coal we need

- **Volume production**
  Add 100 1-GWe units per year.
  *These are aircraft numbers.*
  Boeing and Airbus produce more than 100 wide-body airplanes a year.

- **Safe**
  No way to threaten cities
  Fewer skilled operators required

- **Lower cost electricity**
  Base cost target $0.03/kW-hr and $2/Watt

- **Now**
  The market is now; compete against 1400 GWe of new coal plant builds.
  Can’t economically displace operating coal plants.
Build nuclear power plants like ULCC’s

Devanney Ultra Large Crude Carrier cost $89M

ThorCon: ¼ the steel and simpler construction
Shipyard Productivity

- Productivity comes from semi-automation.
- 67,000 tons of complex steel vs 18,000 simple steel for ThorCon nuclear island.
- Direct labor: 700,000 man-hours. About 40% steel, 60% outfitting.
- 4 to 5 man-hours per ton of hull steel.
Shipyard Quality

150 to 500 ton blocks. Forces precise dimensional control.

Inspection and testing far easier at sub-assembly, assembly, and block level.

Defects found early. Most corrected without affecting overall schedule.

A ship, operating in a hostile environment, is a lemon if it’s off hire 15 days a year (96% availability)
Build **everything** on an assembly line

- Reactor yard produces 150--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.
- Blocks barged to site, dropped into place, and welded together.
- 90+% labor at factory
- Hyundai shipyard in Ulsan, South Korea pictured below is sufficient to manufacture 100 1 GWe power plants per year.

Proposed shipyard above sufficient to manufacture 10 1 GWe power plants per year.
Build the largest blocks at the factory we can

- Block size is limited by transport
- 80% of world population lives within 500 miles of coast or major river
- Target using barges - allows much larger blocks than train or truck.
- Barge up to 23 meters wide. Height depends on river or open ocean. Length essentially unlimited.
- Crane soft limit of 500 tonnes.
One large shipyard to factory-
build new power plants

Barge to NPP site (around 20
barge loads per GWe)

NPP sites (1 GWe site shown)
1,000-20,000 GWe total
One large shipyard to factory-build new power plants

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

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

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.
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Fuel recycling center.
Initial fluorination & vacuum distill to recover most of fuel salt. Store spent fuel for future processing.

Future IAEA secure site.
Uranium re-enrichment and Pu extraction to recover remaining valuable content.
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Outside-in overview of ThorCon design
1 GWe ThorCon Baseline Site Plan

Nuclear power modules are 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 duplexed to accommodate 4-year moderator life.
- Can operates for four years, then cools down for four years, and then is changed out.
Typical power plant modularity is 500 MWe.

- Two nuclear power modules.
- Typical deployment uses 600 MWe turbine-generators.
- Oversized to increase reliability and lifetime.
- Same spec as coal plant t-g.
- Most cost-efficient size.
- Small markets could use a single module and a smaller turbine/generator.
ThorCon’s Heart: The Can

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

Graphite in Pot slows neutrons creating chain reaction, heating fuelsalt from 564°C to 704°C.

Converts portion of Th to U-233, and 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.

Fuse valve (grey) melts on Can over-temperature.
ThorCon **Fuelsalt Drain Tank**

- If Can overheats for whatever reason, fuse valve melts and primary loop drains to Fuelsalt Drain Tank (FDT).

- No moderator, geometry designed to reduce reactivity, => no chain reaction.

- No operator intervention required.
  No valves to realign.
  Nothing operators can do to stop this drain.

- If primary loop ruptures - (equivalent to a meltdown and primary containment breach) then the fuelsalt drains to FDT.

- In most cases, damage limited to Can change out
Membrane Wall

- M-wall cooled by natural water circulation.
- Keeps Can at 270°C in normal operation; cools FDT.
- 750 kW heat loss at full power.
- Always operating, so problems solved before a casualty.
- Cold steel wall stops tritium, removed with inert gas.
- Radiation goes as $T^4$, so cools Can rapidly as heats up.
- No passive cooling penetrations into Can or FDT.
- Two barriers between fuelsalt and m-wall water.
Membrane Wall Decay Heat Loop

- 3 hours after drain at max power, FDT decay heat to m-wall peaks at 5 MW.
- Heat sink within FDT provides thermal inertia.
- Fuelsalt temp peaks at 960°C, 470°C < boiling.
- Membrane wall can handle 30 MW.
- Pond contains 72 days worth of water.
- With wet towers, passive cooling > 6 months.
- Cooling drops rapidly as salt temp drops.
- Over 100 days before salt freezes.
- **Passive cooling for several months**

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For Membrane Wall Decay Heat Loop:

- **Pond volume (m³):** 14134
- **Condenser surf. area (m²/Cani):** 1435.2
- **Downcomer head (m):** 19.976
- **Exp. Tank H₂O volume (m³):** 462
- **Exp. Tank gas volume (m³):** 50

If level in expansion tank falls below level in pond, pond check valve automatically drains portion of pond water into membrane wall loop.
ThorCon is a Four Barrier Design

1. Primary Loop Piping, Pump, Pot, HX
ThorCon is a Four Barrier Design

2. **Can/Drain Tank.** 5 bar over-pressure.
ThorCon is a Four Barrier Design

1. Primary Loop Piping
2. Can/Drain Tank, 5 bar over-pressure.
4. Silo Hall, 1 bar over-pressure. Triplex barrier.
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ThorCon is a Four Barrier Design

1. **Primary Loop** Piping, Pump, Pot, HX
2. **Can/Drain Tank**, 5 bar over-pressure.
3. **Silo Cavity.** Inerted. Duplex/triplex barrier.
4. **Silo Hall**, 1 bar over-pressure. Triplex barrier.

- At least one internal barrier between modules.
- All but top of silo hall barrier well underground
- Fuelsalt chemistry: the 5th barrier?
ThorCon Neutronics

- Both MCNP and Serpent models tied to ThorCon DNA model by pre-processors and post-processors.
- Core made up of 380 x 22 x 4 cm slabs, arranged into hex logs in 5 m cylinder. Easy to fabricate. Easy to disassemble. Lots of surface area.
- 84 moderator logs. Central log replaced with one regulator, 3 shutdown rods, and instrumentation.
- Accurate 3-D model of Pot.
- Model includes membrane wall, silo and radtank. Less accurate outside Pot.
- Burnup based on Serpent and clever fuel adjustment algorithm by Dr. Manu Aufiero, currently at Grenoble.
- Current work aimed at extending Aufiero’s work including explicitly modeling decay outside Pot.
## ThorCon is Fuel and Salt Flexible

<table>
<thead>
<tr>
<th>Mission</th>
<th>Startup</th>
<th>Makeup: thorium plus</th>
<th>Self generated</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Salt</td>
<td>Th</td>
<td>U</td>
</tr>
<tr>
<td>1) Initial tests</td>
<td>NaBe</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>2) Economic Baseline</td>
<td>NaBe</td>
<td>82%</td>
<td>18%</td>
</tr>
<tr>
<td>3) Better fuel utilization</td>
<td>FLiBe</td>
<td>82%</td>
<td>18%</td>
</tr>
<tr>
<td>4) Best Fuel Utilization</td>
<td>FLiBe</td>
<td>82%</td>
<td>18%</td>
</tr>
<tr>
<td>5) Breeder</td>
<td>FLiBe</td>
<td>97%</td>
<td>3%</td>
</tr>
</tbody>
</table>

### Notes
- 4) Onsite vacuum distillation at 1.6L/hour to separate seeker fission products + Pu,Am,Cm. Sends plutonium to a fast reactor and receive LEU U233 back. Makeup is almost all thorium.
- 5) Same as 4) but allows HEU in reactor and in shipping generated fuel back. Makeup is all thorium.
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ThorCon Economics
Should-Cost Versus 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, ThorCon should have a smaller capital cost than coal.

And ThorCon wallops coal on fuel cost.

But there is no limit on how costly regulation can make any technology.

Unless we narrow the gap between should-cost and did-cost drastically, no nuclear technology will be able to compete.
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.
Overnight Cost Versus Coal

Steel and Concrete Required for the Steam Generation of a 1 GWe Plant

<table>
<thead>
<tr>
<th></th>
<th>ThorCon</th>
<th>Coal</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (metric tonnes)</td>
<td>18,000</td>
<td>91,000</td>
<td>1/5th</td>
</tr>
<tr>
<td>Concrete (cubic meters)</td>
<td>42,000</td>
<td>135,000</td>
<td>1/3rd</td>
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</table>

ThorCon requires an extra $100M of nuclear specialty items: Graphite, SUS316, Haynes 230, Lead, & Excavation

Estimated overnight cost of a coal plant $1,000 to $2,000 / kW

60,000 to 120,000 Rs/kW

Estimated overnight cost of ThorCon $1,000/kW
## Levelized Cost, Coal Versus ThorCon

<table>
<thead>
<tr>
<th></th>
<th>$/kWh</th>
<th>Rs/kWh</th>
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<th>$/kWh</th>
<th>Rs/kWh</th>
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<tr>
<td></td>
<td>Coal</td>
<td>ThorCon</td>
<td>Coal</td>
<td>ThorCon</td>
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<tr>
<td>Capex</td>
<td>0.0154</td>
<td>0.0154</td>
<td>0.92</td>
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<tr>
<td>Cans</td>
<td></td>
<td>0.0034</td>
<td></td>
<td>0.20</td>
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<tr>
<td>Fuel</td>
<td>0.0227</td>
<td>0.0053</td>
<td>1.36</td>
<td>0.32</td>
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<tr>
<td>Salt</td>
<td></td>
<td>0.0002</td>
<td></td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>O&amp;M</td>
<td>0.0056</td>
<td>0.0049</td>
<td>0.34</td>
<td>0.29</td>
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<tr>
<td>Total</td>
<td>0.0437</td>
<td>0.0293</td>
<td>2.62</td>
<td>1.74</td>
<td></td>
</tr>
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</table>

- 10% real discount rate
- 32 year analysis life
- 4 year construction period
- 90% capacity factor
- Australian Thermal Coal (25MJ/kg LHV), $80/ton landed.
- No recycling of Can materials
- No value to 9% LEU and U-233
Fixability

Don’t pretend things will last 30 or 40 years. Often we don’t know the MTBF. Even if we did, things are going to break and we do not know when. Plan for it.

Everything but the building must be replaceable with modest impact on plant output.

The existing nuclear challenge: {when something breaks, it can be very hard to go in and fix it.}

ThorCon addresses this key problem with duplexing, easy access (due to low pressure), and swappable modules.
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ThorCon is About NOW.

• Straightforward scale up of the MSRE.
• **No New Technology**
  - cannot wait for FLiBe.
  - forget about breeder.
  - forget about fancy fuel processing, waste burning (but ThorCon can burn Pu)
  - forget Brayton; use standard steam cycle.
• Just a scaled up non-FLiBe MSRE.
• Straight to full-scale prototype.
  **No further scale-up.**
• We can put the prototype out to bid in six months.
• We can start pre-fission testing on a full scale prototype 24 months from now.
• If all goes well, will be in a position to start zero power testing 48 months from now.

MSRE: ThorCon’s pilot plant.
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
ThorCon design philosophy conquers the enemy *time*.

**NOW = no new technology**

- no new research
- no unobtainable materials
- shipyard production speed
- replaceable irradiated materials
- steam power conversion
- factory quality control
- fixable, replaceable parts
- no scale-up delay

<table>
<thead>
<tr>
<th>Year</th>
<th>Seed</th>
<th>Phase 1 tests</th>
<th>Phase 2 nuclear tests</th>
<th>Yard</th>
<th>Deploy ThorCons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>
ThorCon prototype testing

- Start out minimalist, 1 module, 1 can
- Year of pre-fission testing including over-pressuring containment to 1 bar.
- Seek approval to go to zero power test, Change out pre-fission Can, add other Can, offgas system.
- Ramp up slowly with regulator approval required for each step up.
- In parallel, add another module for long run and casualty testing.
Complete 3D model
FE/seismic calcs
Prototype specs
Negotiate contracts
Twisted tube tests
NaBe tests
Primary loop pump
Build prototype
Pre-fission tests
Order turbine-generator
Expand 1st module
Ramp up to full power
Order, build 2nd module
Full power test
Casualty tests
We must have an efficient 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.

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.

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.

...wants a Boeing style export industry.

...is willing to host waste and fuel recycling facilities.

...is willing to regulate efficiently.

Does India want to be that country?