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.

Sources

World electricity use of 2300 GW will double.

- **North America**: 1509 watts/person, 350 million people
- **European Union**: 701 W, 510 M
- **China**: 397 W, 1360 M
- **Mid East & N Africa**: 321 W, 420 M
- **Lat Amer & Carib**: 236 W
- **India**: 85 W, 630 M
- **South Asia**: 75 W, 1300 M
- **Sub S Africa**: 58 W, 970 M

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)

<table>
<thead>
<tr>
<th>Region</th>
<th>Pre-Construction</th>
<th>Construction</th>
<th>On Hold</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Asia</td>
<td>167,083</td>
<td>161,146</td>
<td>451,059</td>
</tr>
<tr>
<td>South Asia</td>
<td>156,018</td>
<td>53,303</td>
<td>91,740</td>
</tr>
<tr>
<td>SE Asia</td>
<td>93,499</td>
<td>31,808</td>
<td>20,992</td>
</tr>
<tr>
<td>non-EU Europe</td>
<td>75,626</td>
<td>2,640</td>
<td>19,874</td>
</tr>
<tr>
<td>Africa and Middle East</td>
<td>49,842</td>
<td>12,838</td>
<td>8,595</td>
</tr>
<tr>
<td>Eurasia</td>
<td>9,156</td>
<td>980</td>
<td>2,200</td>
</tr>
<tr>
<td>EU28</td>
<td>9,360</td>
<td>7,468</td>
<td>7,050</td>
</tr>
<tr>
<td>Latin America</td>
<td>6,372</td>
<td>2,175</td>
<td>3,541</td>
</tr>
<tr>
<td>Canada/US</td>
<td>1,295</td>
<td>582</td>
<td>1,000</td>
</tr>
<tr>
<td>Australia/NZ</td>
<td>1,350</td>
<td>0</td>
<td>1,316</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>569,601</strong></td>
<td><strong>272,940</strong></td>
<td><strong>607,367</strong></td>
</tr>
</tbody>
</table>
As CO$_2$ emissions accumulate…

CO$_2$ in atmosphere, ppm

Projected Atmospheric Greenhouse Gas Concentrations

5000 gigatonnes
As CO$_2$ emissions accumulate, temperatures rise: IPCC

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 Gt/y
ThorCon liquid fission is cheaper than coal.

<table>
<thead>
<tr>
<th>Economics</th>
<th>ThorCon</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost, $millions/GW</td>
<td>1200</td>
<td>2000</td>
</tr>
<tr>
<td>Fuel cost, cents/kWh</td>
<td>0.53</td>
<td>2.27</td>
</tr>
<tr>
<td>Electricity, cents/kWh</td>
<td>3.0</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Why? Energy density

- 0.006 tons/day uranium
- 10,000 tons/day coal

- 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

- 10,000 tons/day coal
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.
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.**

<table>
<thead>
<tr>
<th>Company</th>
<th>Activity Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ThorCon</td>
<td>Measuring fuel salt ionic concentrations in operation, with Argonne Laboratory</td>
</tr>
<tr>
<td>Terrestrial Energy</td>
<td>Magnetic bearing molten salt pump</td>
</tr>
<tr>
<td>Elysium</td>
<td>Synthesis of molten chloride molten salt fast reactor fuel salt from spent nuclear fuel</td>
</tr>
<tr>
<td>Transatomic</td>
<td>Fuel salt characteristics, with Argonne</td>
</tr>
</tbody>
</table>
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

Liquid fission reactor ran from 1965 to 1969 at US Oak Ridge National Lab.
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.
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.

Pond volume (m³): 14134
Condenser surf. area (m²/Can): 1435.2
Downcomer head (m): 18.659
Exp. Tank H₂O volume (m³): 236
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.
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.
46% thermal efficiency
Power conversion heat transfer system makes 550°C steam.
Supercritical steam turbine-generator
Gas-insulated switchgear
ThorConIsle port view
Starboard view with seawater cooling pumps.
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 (11 m 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.

**Shipyards** build new power plants

**CanShip** 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.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Salt 12% HM</th>
<th>Th</th>
<th>U</th>
<th>U233</th>
<th>U235</th>
<th>Other U</th>
<th>U233</th>
<th>U235</th>
<th>U238</th>
<th>Self generated fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Initial tests</td>
<td>NaBe</td>
<td>0</td>
<td>100%</td>
<td>0</td>
<td>3%</td>
<td>97%</td>
<td>0</td>
<td>5%</td>
<td>95%</td>
<td>30%</td>
</tr>
<tr>
<td>2) Economic baseline</td>
<td>NaBe</td>
<td>82%</td>
<td>18%</td>
<td>0</td>
<td>20%</td>
<td>80%</td>
<td>0</td>
<td>20%</td>
<td>80%</td>
<td>50%</td>
</tr>
<tr>
<td>3) Better fuel utilization</td>
<td>FLiBe</td>
<td>82%</td>
<td>18%</td>
<td>0</td>
<td>20%</td>
<td>80%</td>
<td>0</td>
<td>20%</td>
<td>80%</td>
<td>60%</td>
</tr>
</tbody>
</table>
Economics

Cheaper than coal, or don’t bother.
Coal handling system

Why cheaper than coal?

ThorCon similar turbine hall compared

Flue gas treatment system
660 MW Tanjung Jati coal-burning boiler and exhaust gas processing steam-generation...
compared to ThorCon fission steam generator.
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.

<table>
<thead>
<tr>
<th>Liquid fuel</th>
<th>simple fuel handling, higher temperature efficiency, no cladding.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORNL R&amp;D</td>
<td>ORNL built two MSRs then designed MSDR guiding ThorCon.</td>
</tr>
<tr>
<td>No new technology</td>
<td>commercially available, affordable materials.</td>
</tr>
<tr>
<td>Shipyard construction</td>
<td>reduces cost, controls quality, scales to make 100 GW of power plants per year.</td>
</tr>
<tr>
<td>Small modular reactor</td>
<td>250 MWe module has economy of scale and simplifies safety.</td>
</tr>
<tr>
<td>Full scale prototype</td>
<td>No scale-up surprises or delays; only design once.</td>
</tr>
<tr>
<td>Maintenance by replacement</td>
<td>CanShip moves Can and fuel to recycling facilities.</td>
</tr>
<tr>
<td>Thorium</td>
<td>cuts uranium consumption, improves proliferation resistance.</td>
</tr>
<tr>
<td>Step by step commissioning</td>
<td>Indonesia will create final regulations as prototype is tested.</td>
</tr>
<tr>
<td>Complete power plant design</td>
<td>not just another fission reactor idea.</td>
</tr>
</tbody>
</table>
Indonesia 3.5 GW ThorCon power plant project

- **Month 0**: Design
  - $10 million
- **Month 6**: Pre-fission construction
  - $50 million
- **Month 12**: Pre-fission testing
  - $35 million
- **Month 18**: ThorConIsle construction
  - $643 million
- **Month 24**: Power up
  - $130 million
- **Month 30**: Stress tests
  - $67 million
- **Month 36**: Power to grid
- **Month 42**: Power plant delivered to site
- **Month 48**: Type license approval
- **Month 54**: 26.7 billion kWh x 30 years
- **Month 60**: PPA-guaranteed loans
  - $3 billion
- **Month 66**: Milestones
  - Bids in hand
  - Pre-fission tests complete
  - Power plant delivered to site
  - Power to grid
  - Type license approval
  - 26.7 billion kWh x 30 years

**Milestones**

- Bids in hand
- Pre-fission tests complete
- Power plant delivered to site
- Power to grid
- Type license approval
- 26.7 billion kWh x 30 years

**Finances**

- $10 million
- $50 million
- $35 million
- $643 million
- $130 million
- $67 million
- $3 billion
Japan industry opportunities

• Investor?

• Supplier?

• Shipbuilder?