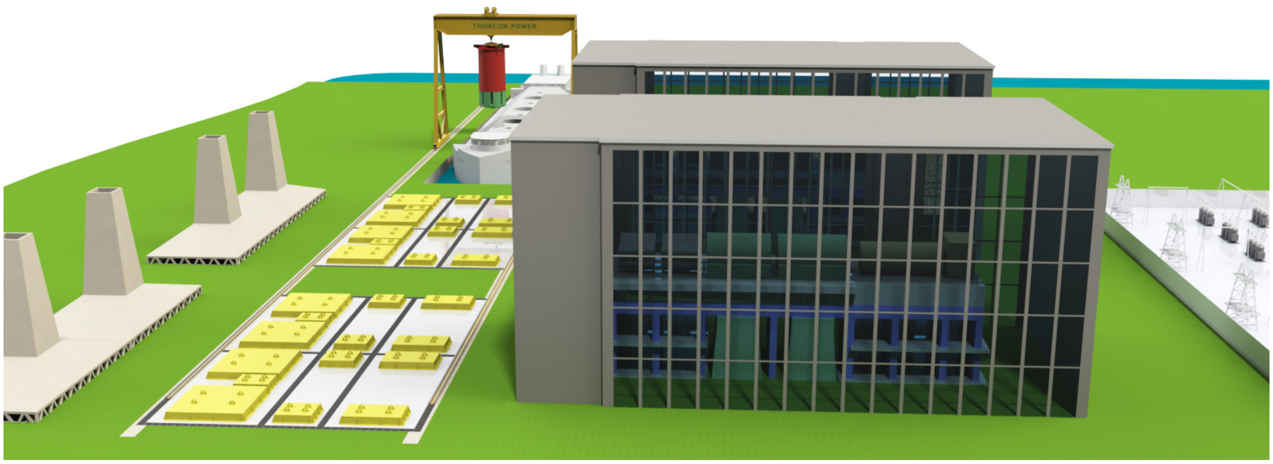

ThorCon™
The Do-able Molten Salt Reactor

The ThorCon Team

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The Five Fundamental Features of ThorCon

ThorCon is Fixable No complex repairs are attempted on site. Everything in the fission island except the building itself is replaceable with little or no interruption in power output. Every four years the entire primary loop is changed out, returned to a centralized recycling facility, decontaminated, disassembled, inspected, and refurbished. Incipient problems are caught before they can turn into casualties. Major upgrades can be introduced without significantly disrupting power generation. Such renewable plants can operate indefinitely; but, if a ThorCon is decommissioned, the process is little more than pulling out but not replacing all the replacable parts.

ThorCon is Walkaway Safe ThorCon is a molten salt reactor. Unlike all current reactors, the fuel is in liquid form. If the reactor overheats for whatever reason, ThorCon will shut itself down, and passively handle the decay heat. There is no need for any operator intervention. There is nothing the operators can do to prevent the shutdown and cooling.

The ThorCon reactor is 15 m underground. ThorCon has at least three gas tight barriers between the fuelsalt and the atmosphere. The reactor operates at garden hose pressure. In the event of a primary loop rupture, there is no dispersal energy and no phase change. The spilled fuel merely flows to a drain tank where it is passively cooled. The most troublesome fission products, including ^{90}Sr and ^{137}Cs, are chemically bound to the salt. They will end up in the drain tank as well.

ThorCon is Ready to Go ThorCon requires no new technology. ThorCon is a straightforward scale-up of the successful Molten Salt Reactor Experiment (MSRE). There is no technical reason why a full-scale 250 MWe prototype cannot be operating within four years. The intention is to subject this prototype to all the failures and problems that the designers claim the plant can handle. As soon as the prototype passes these tests, commercial production can begin.

ThorCon is Rapidly Deployable The entire ThorCon plant including the building is manufactured in blocks on a shipyard-like assembly line. These 150 to 500 ton, fully outfitted, pre-tested blocks are barged to the site. A 1 GWe ThorCon will require less than 200 blocks. Site work is limited to excavation and erecting the blocks. This produces order of magnitude improvements in productivity, quality control, and build time. A single large reactor yard can turn out one hundred 1 GWe ThorCons per year. ThorCon is much more than a power plant; it is a system for building power plants.

ThorCon is Cheaper than Coal ThorCon requires far less resources than a coal plant. Assuming efficient, evidence based regulation, ThorCon can produce clean, reliable, carbon free, electricity at less than the cost of coal.

Contents

1 Clean, CO2-free Power Cheaper than Coal, NOW

Currently mankind consumes electricity at a rate of about 2,300 GWe. But the distribution is highly uneven as Table 1 shows. The USA consumes 1,400 watts per person. The Scandinavian

	watts/person		watts/person
Norway	2,922	Mexico	208
USA	1,401	Egypt	163
Australia	1,064	Iraq	125
Russia	831	Columbia	113
France	815	Indonesia	71
Germany	772	India	65
Italy	582	Philippines	61
South Africa	550	Angola	28
China	396	Nigeria	13
Iran	261	Afganistan	9
Brazil	258	Haiti	3

Table 1: Electricity consumption per person

countries considerably more. But most of Latin America is below 250 W. Most of South Asia below 100 W. Most of Africa below 25 W. A billion humans have no access to electricity at all. ***If mankind is to prosper, then clean, affordable, dependable power must be available to all.*** And we must provide this power without polluting the air we breath, without poisoning the land we live on, and without impacting the climate we depend on.

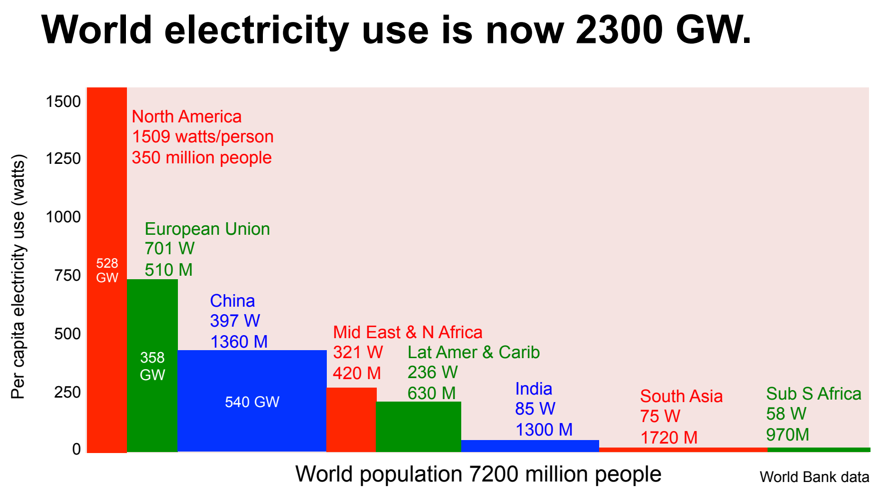
The developing countries are aggressively moving to close the power gap. As Figure 1 indicates, this will require at least 2,000 GWe of new capacity over the next 20 years, or 100 one GWe plants per year, about 2 per week. As things stand now, most of these plants will be coal fired. According to the MIT Technology Review, as of June, 2013, 1,199 coal plants are planned worldwide, with a nameplate capacity of 1,401 GWe.

Each one of these coal plants will require about 4 million tons of coal per year. Each one will produce between 400,000 and a million tons of ash per year. Each one will produce about 10 million tons of CO2 per year. Each one will kill at least 9 miners per year (European numbers). Each one will shorten the lives of at least 300 people per year (European numbers) via pollution. In aggregate, these 1200 new coal plants will require 5 billion tons of coal annually, kill or shorten the lives of at least 400,000 people per year, and produce 12 billion tons per year of CO2.

ThorCon proposes an alternative:

- an alternative that produces nil pollution, nil CO2, and 100,000 times less waste than coal,
- an alternative that uses dramatically less of the planet's precious resources, less steel, less concrete than coal,
- an alternative that can be deployed more rapidly than coal.

This note outlines how ThorCon proposes to turn these outrageous claims into reality.



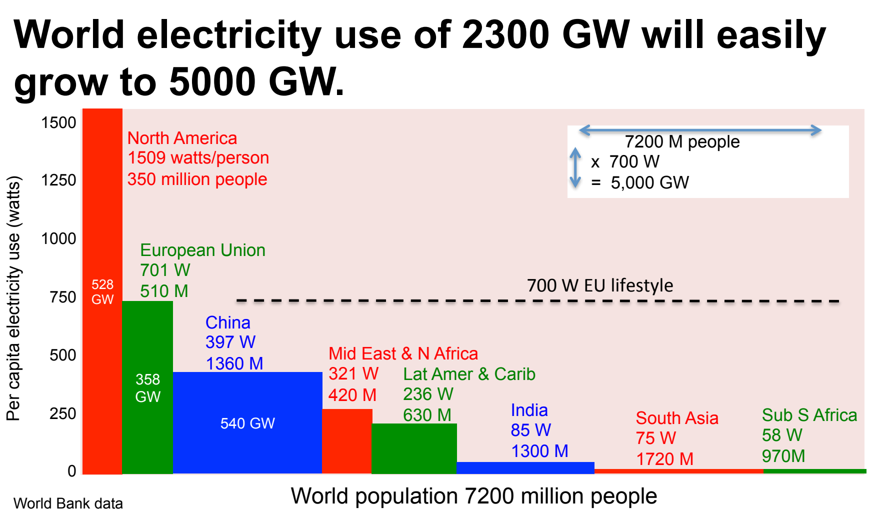


Figure 1: Regional distribution of electricity consumpion

2 Under pressured and under ground

ThorCon is a molten salt fission reactor. Unlike all current nuclear reactors, the fuel is in liquid form. It can be moved around with a pump, and passively drained in the event of a casualty.

ThorCon operates at about the same pressure as your garden hose. Standard nuclear reactors operate at over 130 bar (2000 psi). They require 9 inch thick pressure vessels and massive piping. The key forgings can only be done by a few specialized foundries. Worse, if we have a big piping failure, the pressurized water explodes into steam, spraying radioactivity all over the place. This means the reactor, heat exchangers and all sorts of plumbing must be entombed in a massive, reinforced concrete mausoleum, where they are extremely difficult to repair or replace. Therefore, we pretend they will need essentially no maintenance for the life of the plant. Reinforced concrete construction is horribly slow, nearly impossible to automate, difficult to inspect, and even more difficult to repair.

ThorCon uses normal piping thicknesses and easily automated, ship-style steel plate construction. The entire fission portion of the plant is underground as shown in Figure 2. This drawing shows a 1 GWe ThorCon. The decay heat cooling towers are on the left. The underground fission island, ThorCon's boiler, is center left. The yellow rectangles are hatches. These hatches are served by gantry cranes. The turbogenerator halls are center right, and the switchyard is on the right. The main cooling towers if required are to the right of the switchyard.

The cranes allow periodic replacement of all critical components including the reactors and fuelsalt. The reactors and fuelsalt are transported by a special purpose ship shown in the background.

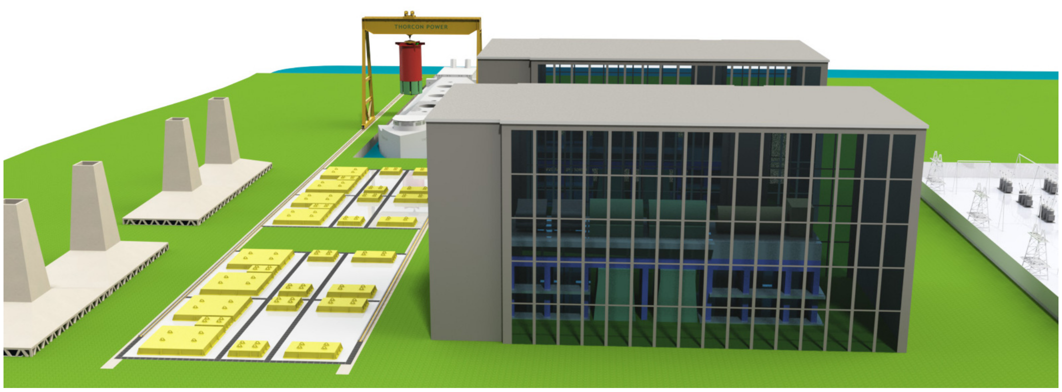


Figure 2: Birdseye View of 1 GWe ThorCon

Figure 3 is a cutaway view of the underground structure. ThorCon is divided into 250 MWe power modules. The drawing shows two such modules. Each module contains two replaceable reactors in sealed *Cans*. The Cans are depicted in red in the drawing. They sit in silos. At any one time, just one of the Cans of each module is producing power. The other Can is in cooldown mode. Every four years the Can that has been cooling is removed and replaced with a new Can. The fuelsalt is transferred to the new Can, and the Can that has been operating goes into cool down mode.

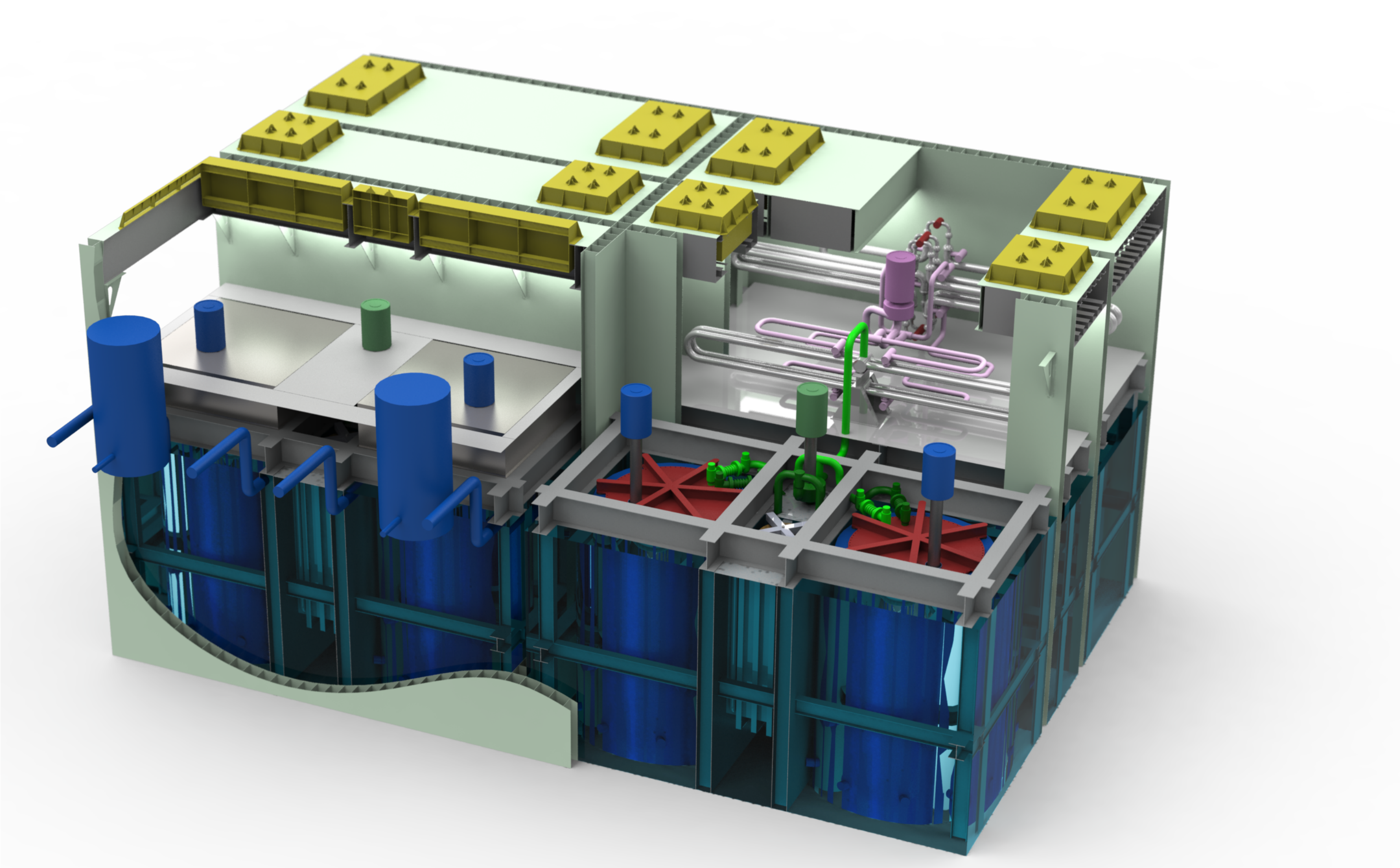
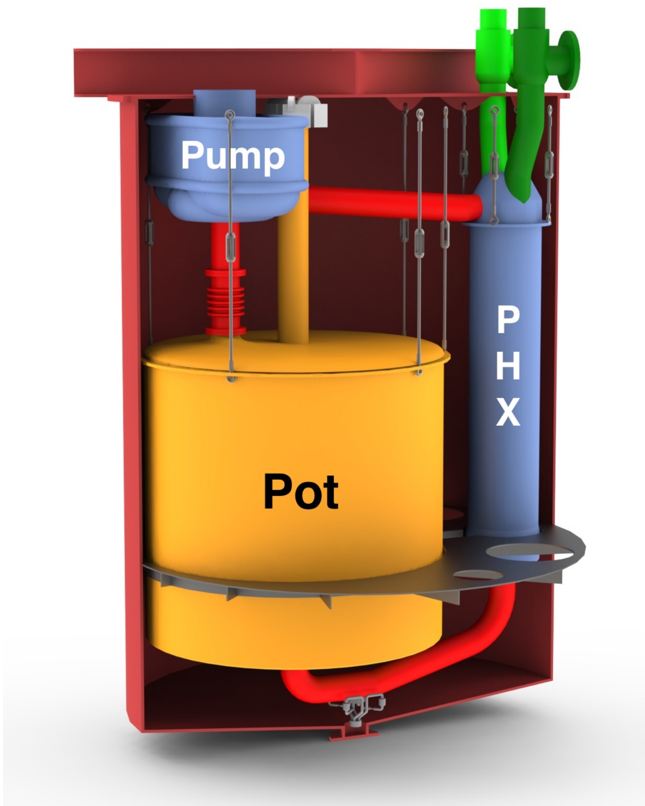


Figure 3: Cutaway view of two module Silo Hall

The Can, Figure 4, is ThorCon's heart. The Can contains the reactor, which we call the *Pot*, a primary loop heat exchanger (PHX), and a primary loop pump (PLP).



Can electrical output	250 MW
Can thermal output	557 MW
NaF-BeF2-ThF4-UF4	fuelsalt
76/12/9.8/2.2	mol pct
Fuelsalt flow kg/s	2934
Pot inlet C	565
Pot outlet C	704
Loop transit time	11.6 sec
Pot outlet press	2.9 barg
Plant efficiency	44.9%
Can diameter	7.775 m
Can height	10.250 m
Pot diameter	4.916 m
Pot height	5.590 m
Can weight(no salt)	343 tons
Fuelsalt weight	38 tons
α_K:pcm/K	-4.5/-6.5

Figure 4: ThorCon Can: a Pot, a Pump, and a Still. Some components not shown for clarity.

The pump takes liquid fuelsalt — a mixture of sodium, beryllium, uranium and thorium fluorides — from the Pot at 704C, and pushes the fuelsalt over to the PHX at a rate of just under 3000 kg/s. Flowing downward through the PHX, the fuelsalt transfers heat to a secondary salt, and is cooled to 564C in the process. The fuelsalt then flows over to the bottom of the Pot, and rises through the reactor core, which is mostly filled with graphite slabs, called the *moderator*. This graphite slows the neutrons produced by the fissile uranium, allowing a portion of the uranium in the fuelsalt to fission as it rises through the Pot, heating the salt to 704C, and (indirectly) converting a portion of the thorium to fissile uranium. It's just that simple; and just that magical.

The Pot pressure is 3 bar gage, about the same as a garden hose. The outlet temperature of 704C results in an overall plant efficiency of about 45%, and a net electrical output per Can of 250 MW. The Can's net consumption of fissile uranium is 112 kg per year. The Can is a cylinder 11.6 m high and 7.3 m in diameter. It weighs about 400 tons. The Can has only one major moving part, the pump impeller.

As shown in Figure 5, ThorCon employs four loops in converting fission heat to electricity:

1. The primary loop inside the Can
2. The secondary salt loop
3. A solar salt loop
4. A supercritical steam loop.

Unlike almost all current nuclear reactors, ThorCon is a high temperature reactor. This translates to thermal efficiency of 45% compared to about 32% for a standard light water reactor. This reduces capital costs and cuts cooling water requirements by 60%. It also allows us to use the same steam cycle as a modern coal plant.

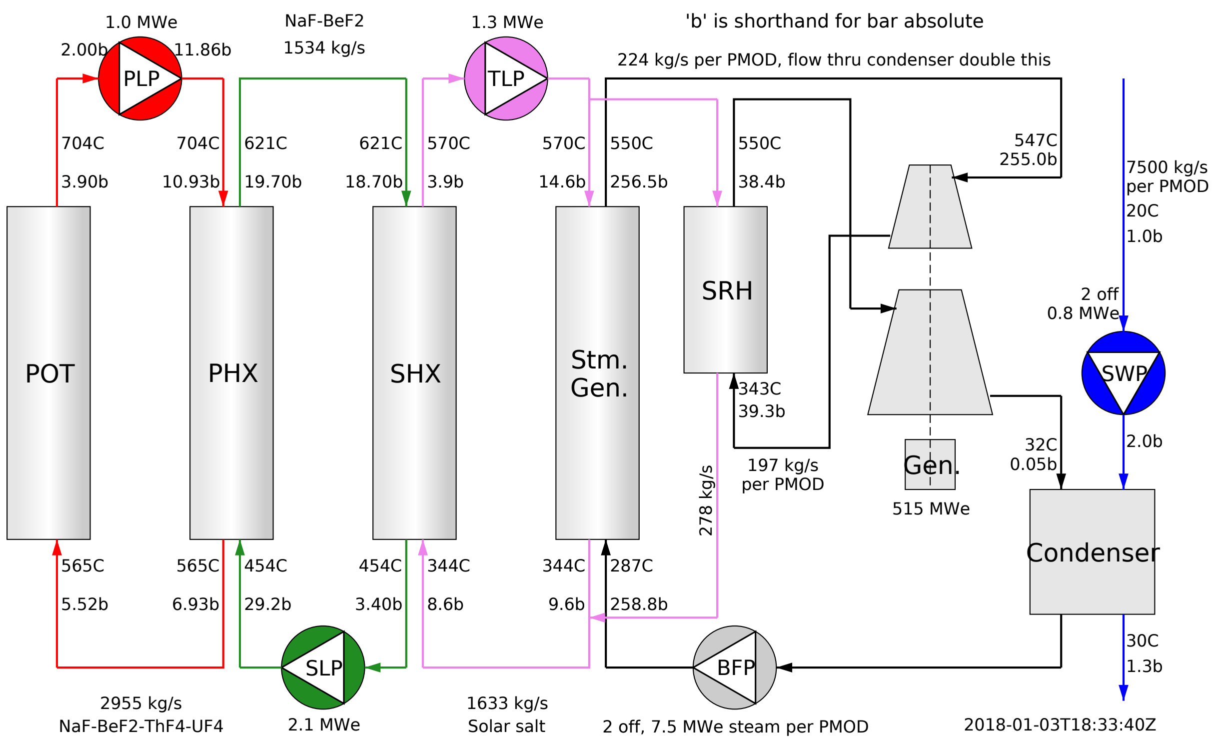


Figure 5: ThorCon's Four Loops

Each Can is located in a Silo as shown in Figure 6. The top of the Silo is 14 m underground. Figure 6 shows the secondary salt loop in green. The secondary salt is a mixture of sodium and beryllium fluoride containing no uranium or thorium. Hot secondary salt is pumped out of the the top of the Primary Heat Exchanger to a Secondary Heat Exchanger where it transfers its heat to a mixture of sodium and potassium nitrate commonly called solar salt from its use as an energy storage medium in solar plants. The solar salt, shown in purple in Figure 6, in turn transfers its heat to a supercritical steam loop, shown in red. Figure 7 is a view of the salt piping.

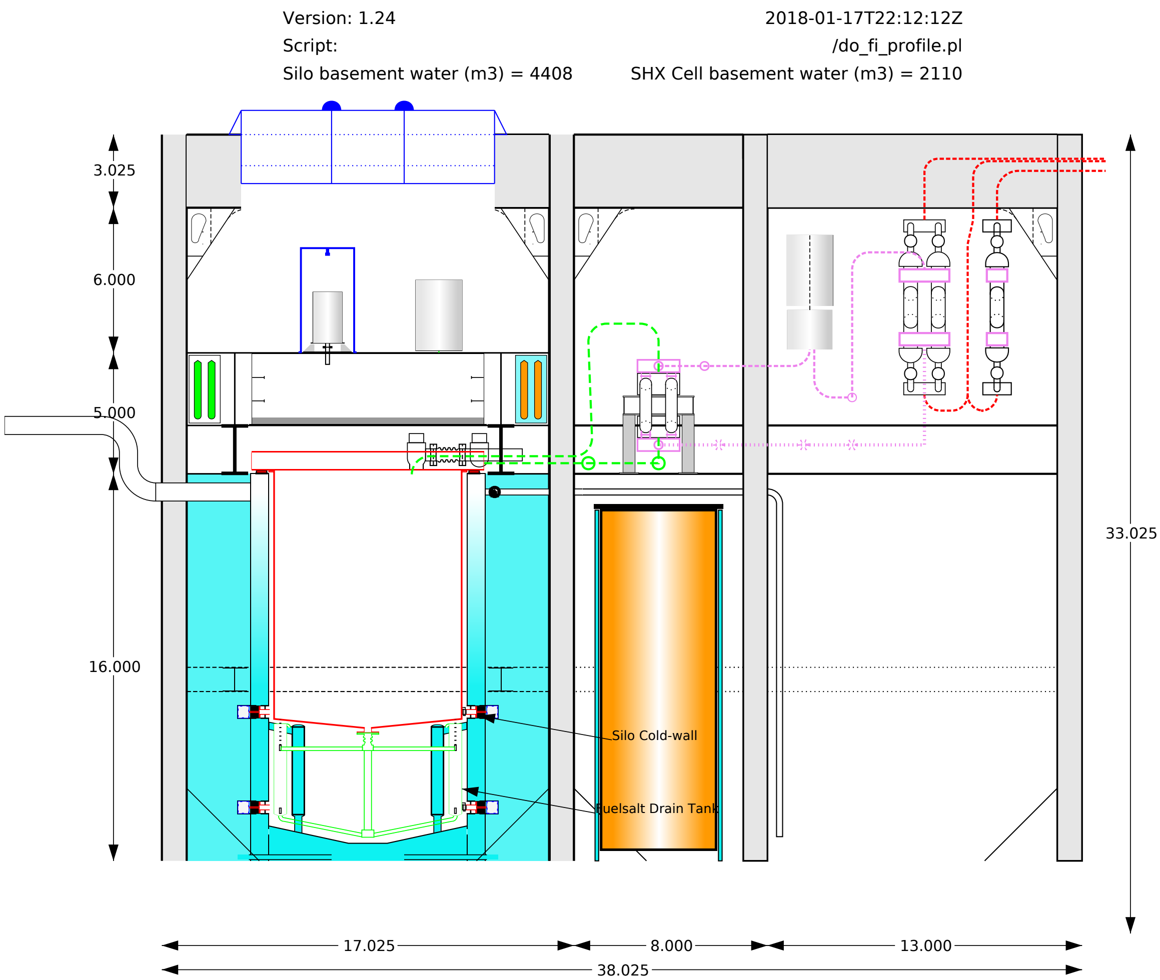


Figure 6: ThorCon Fission Island Cross-section

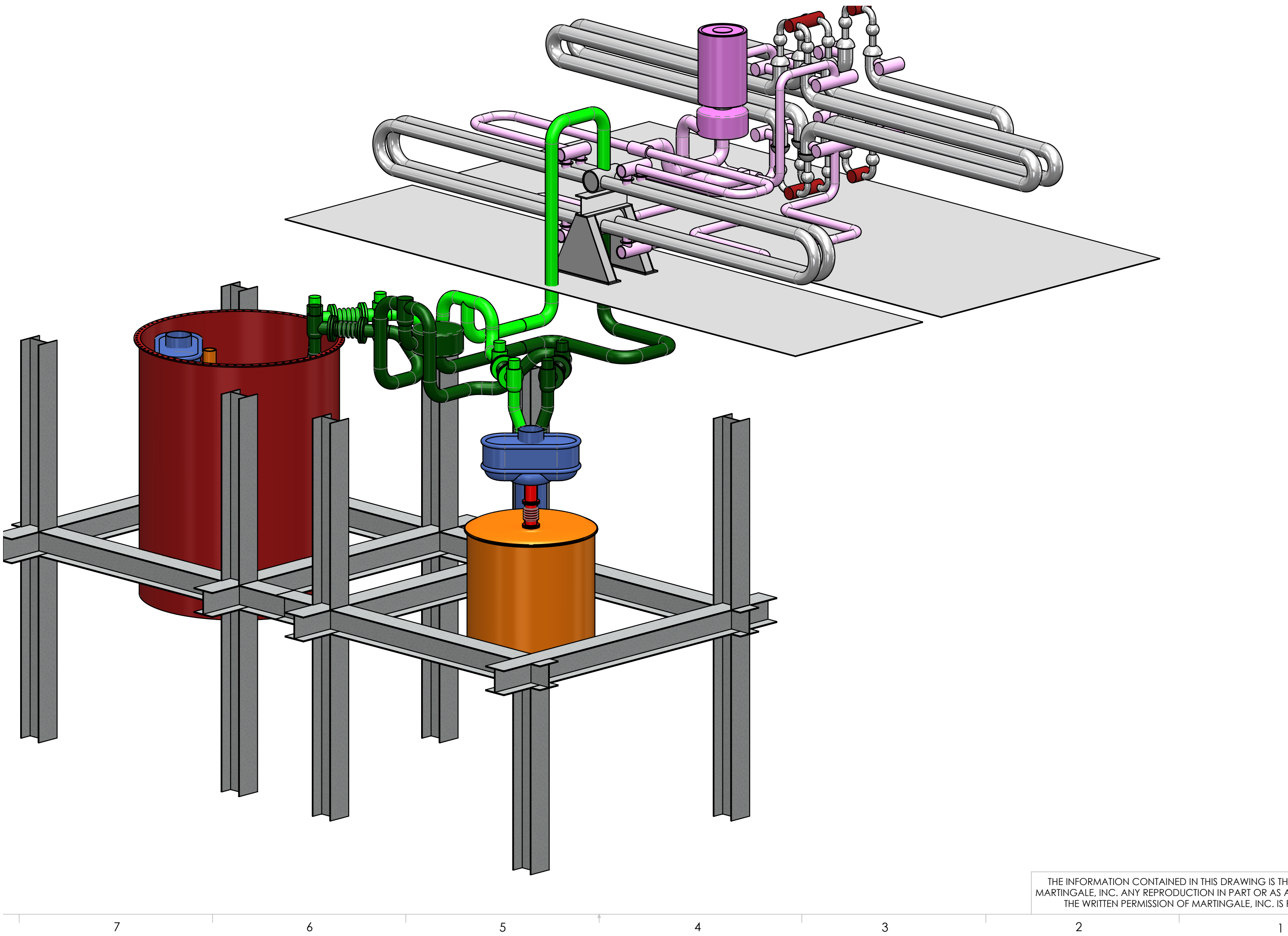


Figure 7: 3D View of Salt Plumbing

Directly below the Can is the Fuelsalt Drain Tank (FDT), shown in green in Figure 8. In the bottom of the Can is a *fuse valve* shown in gray in Figure 8. The fuse valve is merely a low point in a drain line. At normal operating temperatures, the fuelsalt in the fuse valve is frozen creating a plug. But if the Can heats up for any reason, the plug will thaw, and the fuel salt will drain to the FDT. Since the drain tank has no moderator, fission will stop almost immediately. This drain is totally passive. There is nothing an operator can do to prevent it.

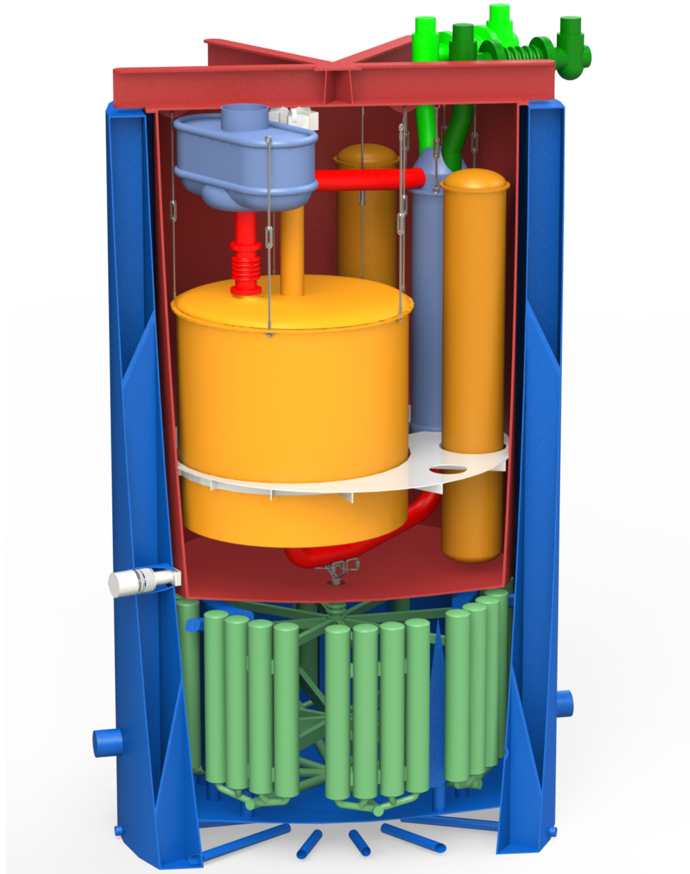


Figure 8: 3D View of Can Silo

A critically important feature of ThorCon is the silo cooling wall, or *cold wall* for short. The cold wall is made up of two concentric steel cylinders, shown in blue in Figure 8. The annulus between these two cylinders is filled with water. The top of this annulus is connected to a condenser in a decay heat pond as shown in Figure 9. The outlet of this condenser is connected to the *basement* in which the Can silos are located. This basement is flooded. Openings in the bottom of the outer silo wall allow the basement water into the bottom of the annulus.

The Can is cooled by thermal radiation to the cold wall. This heat converts a portion of the water in the wall annulus to steam. This steam/water mixture rises by natural circulation to the cooling pond, where the steam is condensed, and returned to the bottom of the cold wall via the basement. In this process, some of the water in the pond is evaporated. The decay heat cooling towers maintain the pond near the wet bulb temperature. If the pond cooling line is lost, there is enough water in the basement to handle the first 354 days of decay heat.

The cold wall also cools the Fuelsalt Drain Tank (FDT). The drain tank is a circular ring of cylinders. This arrangement provides sufficient radiating area to keep the peak tank temperature after a drain within the limits of the tank material. This cooling process is totally passive, requiring no operator intervention nor any outside power.[1]

[1] Some recent light water reactor designs claim to be passive. But they require a set of valve operations to realign the system. Both an active response and power to implement that response are needed.

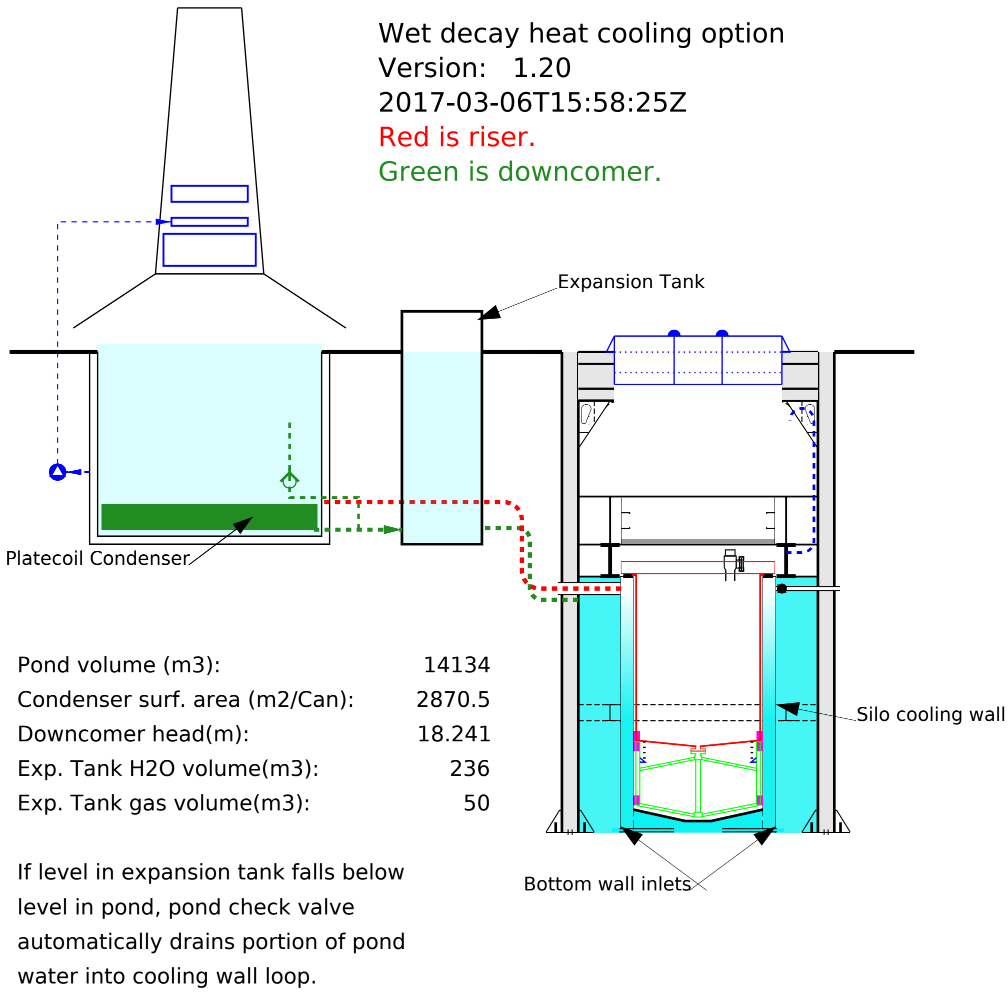


Figure 9: Can Silo Cooling Loop, Profile View

3 Walkaway Safety

Totally passive, totally unavoidable shutdown and cooling ThorCon combines a negative temperature coefficient with a massive margin between the operating temperature of 700C and the fuelsalt's boiling temperature (1430C). In any casualty that raises the temperature of the salt much above operating level, ThorCon will passively shut itself down. If the high temperature persists, the fuse valve will thaw and drain the fuel from the primary loop to the drain tank, where the silo cold wall will passively handle the decay heat.

There is no need for any operator intervention. Not in 3 days, not in 300 days, not in 3000 days. Nor are there any valves that must be realigned by either system or operator control as in some so called passive systems. In fact ***there is nothing the operators can do to prevent the drain and cooling***.

Release Resistant The ThorCon reactor is 15 m underground. ***ThorCon has at least three gas tight barriers between the fuelsalt and the atmosphere.*** At least two of those barriers are more than 10 m underground. Unlike nearly all current reactors, the ThorCon reactor operates at near-ambient pressure. In the event of a primary loop rupture, there is no dispersal energy and no phase change. The spilled fuel merely flows to the drain tank where it is passively cooled.

Moreover, the most troublesome fission products, including iodine-131, strontium-90 and cesium-137, are chemically bound to the salt. They will end up in the drain tank as well. Even if all the barriers are somehow breached, almost all these salt seekers will not disperse.

No separate, spent fuel storage ThorCon uses an 8 year fuelsalt processing cycle, after which the used salt is allowed to cool down in the non-operating Can for four years, ***eliminating the need for a separate, vulnerable spent fuel storage facility.*** The fuelsalt that is cooling is as well-protected as the fuelsalt that is currently being burned.

Four loop separation of steam and fuelsalt. ThorCon employs four loops in transferring heat from the reactor to the steam turbine.

1. The primary fuel salt loop
2. The secondary fluoride salt loop
3. A solar salt loop. This is the same salt used in thermal solar plants.
4. A high pressure steam loop

The solar salt loop captures any tritium that has made it to the secondary loop, and more importantly ensures that a rupture in the steam generator creates no nasty chemicals and harmlessly vents to the Steam Generating Cell via an open standpipe.

4 Rule 1: No New Technology. Rule 2: see Rule 1

ThorCon is about NOW. ThorCon requires no new technology. ThorCon is a straightforward scale-up of the Molten Salt Reactor Experiment (MSRE), which ran successfully for four years at the Oak Ridge National Laboratory. The MSRE is ThorCon's pilot plant. There is no technical reason why a full-scale 250 MWe prototype cannot be operating within four years. The intention is to subject this prototype to all the failures and problems that the designers claim the plant can handle. This is the commercial aircraft model, not the Nuclear Regulatory Commission model. As soon as the prototype passes these tests, commercial production can begin. By using only existing technology, we intend to be in full scale commercial production in year 7.

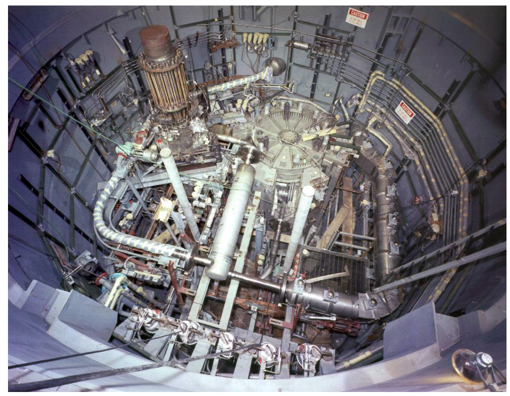
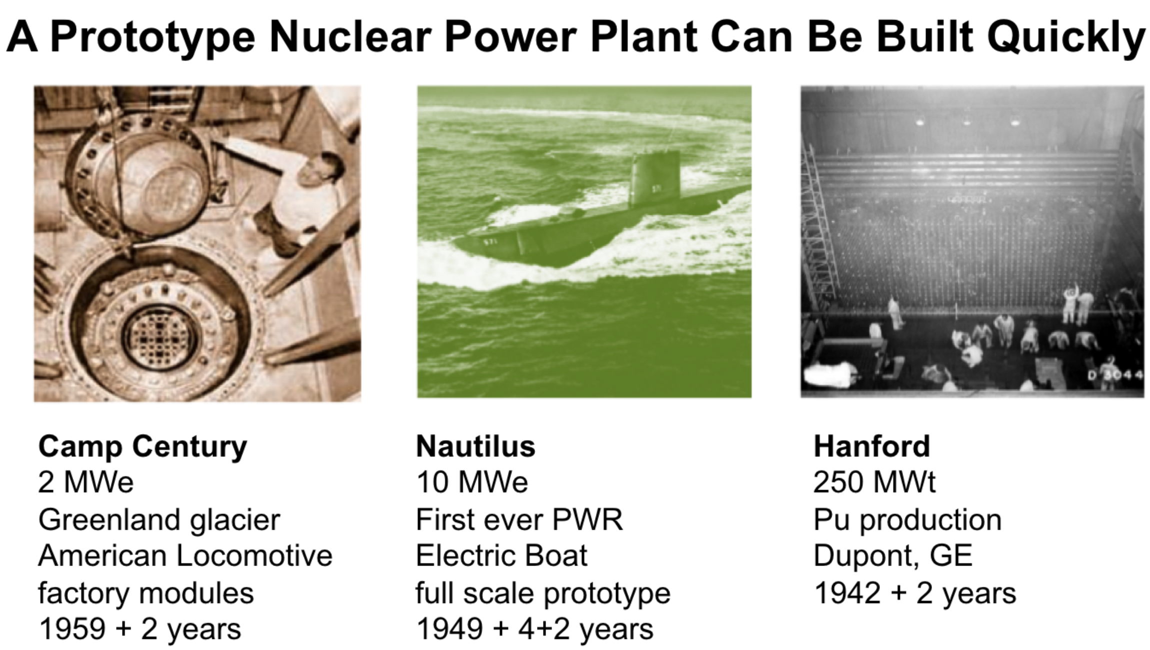


Figure 10: A Plan View of the Molten Salt Reactor Experiment

Some will scoff. The conventional wisdom is that there is something fundamentally different about fission energy that mandates multi-decade long project times.



Here are three counter examples, projects which faced far more difficult problems than ThorCon does.

4.0.1 Wigner and Hanford

In April, 1942, Eugene Wigner arrived in Chicago and set out to make a reactor to produce plutonium for what turned out to be the second atom bomb. At the time, no one had even demonstrated that a chain reaction was possible. Little was known about fission cross sections or just about anything else. Wigner went straight to 500MWt when no zero MWt plant existed. In five months, his five man team using adding machines and slide rules completed the design. In February 1943, Wigner convinced the Army to use his design In October, 1944, the plant located at Hanford WA, started producing plutonium. In 2.5 years, Wigner went from literally zero to 500 MWt. Wigner was furious that it took this long, blaming "too much money".

4.0.2 Rickover and the Nautilus

The Nautilus chronology is more well known so I will just make one comment. The decision to go pressurized water was not made until March, 1950. Shortly thereafter Rickover, against the advice of all, decided to go straight to a full scale prototype. At the time no such thing as a PWR existed at any scale. Rickover wasn't scaling up. He was going from nothing to full scale.

4.0.3 Camp Century

An instructive exception to Rickover's control of American fission effort was the Army's successful small reactor program in the very late 1950's. Camp Century was one of those plants. Camp Century was located at 77N in one of the most inhospitable places on the planet, 6000 feet above sea level on the Greenland Plateau, 800 miles from the North Pole. In January, 1959, the Army signed a 4.5 million dollar contract with the American Locomotive Company (ALC) for 10 MWt fission plant, dubbed PM-2A. ALC designed, built, and tested the plant in 16 months. The plant comprised 27 blocks. In mid-summer of 1960, the blocks were shipped to Thule, sledded 150 miles north, and erected in 78 days. In the summer of 1964, Camp Century was shut down. The PM-2A was disassembled and returned to the USA. Points to ponder:

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

When you consider what these three projects accomplished, the ThorCon schedule not only becomes feasible, but appears downright dilatory. Eugene Wigner, for one, would not be impressed.

5 Shipyard productivity, shipyard quality

If we are to put a dent in coal's dominance of electricity production, we will need 100 one GWe ThorCons per year for the foreseeable future. And we need them soon. We need a ***system*** for producing fission power plants, not individual fortresses. Fortunately such a system exists. It's called a shipyard.

ThorCon's genesis is in ship production. Figure 11 shows one of eight ships built by ThorCon's predecessor company. This ship is the largest double hull tanker ever built. She can carry 440,000 tons of oil. Her steel weight is 67,000 tons. She required 700,000 man-hours of direct labor, a little more than 10 man-hours per ton of ship steel. About 40% of this was expended on hull steel; the rest on outfitting. She was built in less than 12 months and cost 89 million dollars in 2002.

Figure 11: The Hellespont Metropolis, 500,000 tons on the move, 89 million dollars

A good shipyard needs about 5 man-hours to cut, weld, coat, and erect a ton of hull steel. The yards achieve this remarkable productivity by block construction. Sub-assemblies are produced on a panel line, and combined into fully coated blocks with piping, wiring, HVAC (and scaffolding if required) pre-installed. In the last step, the blocks, weighing as much as 600 tons, are dropped into place in an immense building dock.

ThorCon uses exactly the same production process except the blocks are barged to the site and dropped into place, as indicated in this demo. The essential difference between shipyards and most other assembly lines, such as aircraft manufacturing, is that shipyards build blocks on the assembly line, not the final product. The final product is put together elsewhere. Thinking in terms of blocks rather than final product is a key element in the ThorCon philosophy.

Block construction is not just about productivity. It's about quality. Very tight dimensional control is automatically enforced. Extensive inspection and testing at the sub-assembly and block level is an essential part of the yard system. Inspection at the block level can be thorough and efficient. Defects are caught early and can be corrected far more easily than after erection. In most cases, they will have no impact on the

Figure 12: Shipyard Productivity, 5 man-hours per ton of erected steel

overall project schedule.

ThorCon is designed to bring shipyard quality and productivity to fission power. But ThorCon's structure is far simpler and much more repetitive than a ship's. The silo hall employs concrete-filled, steel plate, sandwich walls. This results in a strong, air-tight, ductile building. A 1 GWe ThorCon requires about 18,000 tons of steel for the fission island, all simple flat plate. A properly implemented panel line will be able to produce these blocks using less than 2 man-hours per ton of steel.

Similarly, all the other components will be manufactured on an assembly line and delivered to the site as fully outfitted and pre-tested blocks. Each power module will require a total of 31 blocks. Upon arrival at the site, the blocks will be dropped into place and the wall and roof blocks welded together using the automatic hull welding machines the yards have developed for this purpose. The wall cells will then be filled with concrete. Almost no form work is required.

To make the system work we must have big blocks — blocks that are far larger than can be transported by truck or rail. ThorCon blocks are up to 23 m wide and 40 m long. Such blocks can be barged well up most major rivers, including the St. Lawrence and into the Great Lakes.

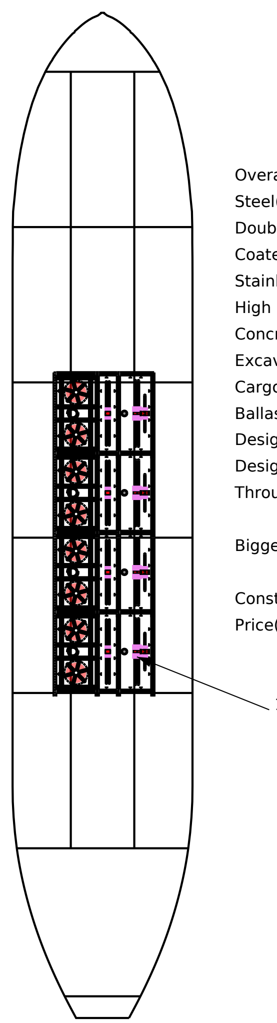
6 Small is beautiful

Fission power is one million times denser than fossil fuel. Not only does this mean that fuel requirements (and waste) for a big power plant are measured in kilograms per day rather than thousands of tons per day; but it also means that, if you operate at low pressure, the plants can be small. The ThorCon reactor operates at near ambient pressure. ThorCon does not need much space. Nor does it consume a lot of resources.

In fact, a 1 GWe ThorCon is so small that the fission island almost fits into two center tanks of the Hellespont Metropolis, and requires one-fourth as much steel.

This steel requirement is roughly equivalent to a medium size, Suezmax tanker. Compared to a 1GWe ThorCon, the Suezmax requires more steel (23,000 tons vs 17,000) and is larger overall (270 m by 50 m by 23 m versus 121 x 28 x 30). The ships structure is far more complex and subject to tougher loads. The Suezmax has far more coated surface. The Suezmax can move herself at 15 knots, survive a hurricane, and discharge her cargo in about a day. A good shipyard can profitably build a Suezmax for 60 million dollars.

A big shipyard can turn out 100 of these ships a year. It could easily manufacture 100 one GWe ThorCons per year. In terms of resource requirements, a 1GWe ThorCon is not a big deal.



	ULCC	ThorCon
Overall Size(m)	380 x 68 x 35	121 x 38 x 30
Steel(MT)	67,591	16,800
Double curved plate	Lots	None
Coated area (m2)	350,000	45,000
Stainless steel(mt)	100	2,220
High nickel alloy(mt)	nil	253
Concrete(m3)	0	42,000
Excavation(m3)	0	182,000
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	0.8g earthquake
Throughput	Discharge 15,000 m3 oil per hour	Heat 14,000 m3 salt per hour
Biggest component	35MW low speed diesel	500t SWL crane
Construction time	10 months	???
Price(2001)	$89,000,000	???

Figure 13: 1 GW ThorCon Fission Is. in a very large tanker

7 If it breaks, send it back

In the ThorCon system, no complex repairs are attempted on site. Everything in the fission island except the building itself is replaceable with little or no interruption in power output. Rather than attempt to build components that last 40 or more years in an extremely harsh environment with nil maintenance, ThorCon is designed to have all key parts regularly replaced.

Up to 50 ThorCon plants are supported by a Centralized Recycling Facility (CRF) and a separate Fuel Handling Facility (FHF). Normally, the Cans are changed out every four years. When the Cans need replacing, they are shipped to the CRF in a special purpose Canship. At the CRF, the Cans are disassembled, cleaned, inspected, and worn parts replaced. The problems of decontamination and waste disposal are shifted from the plant to this facility. Figure 14 depicts the overall system.

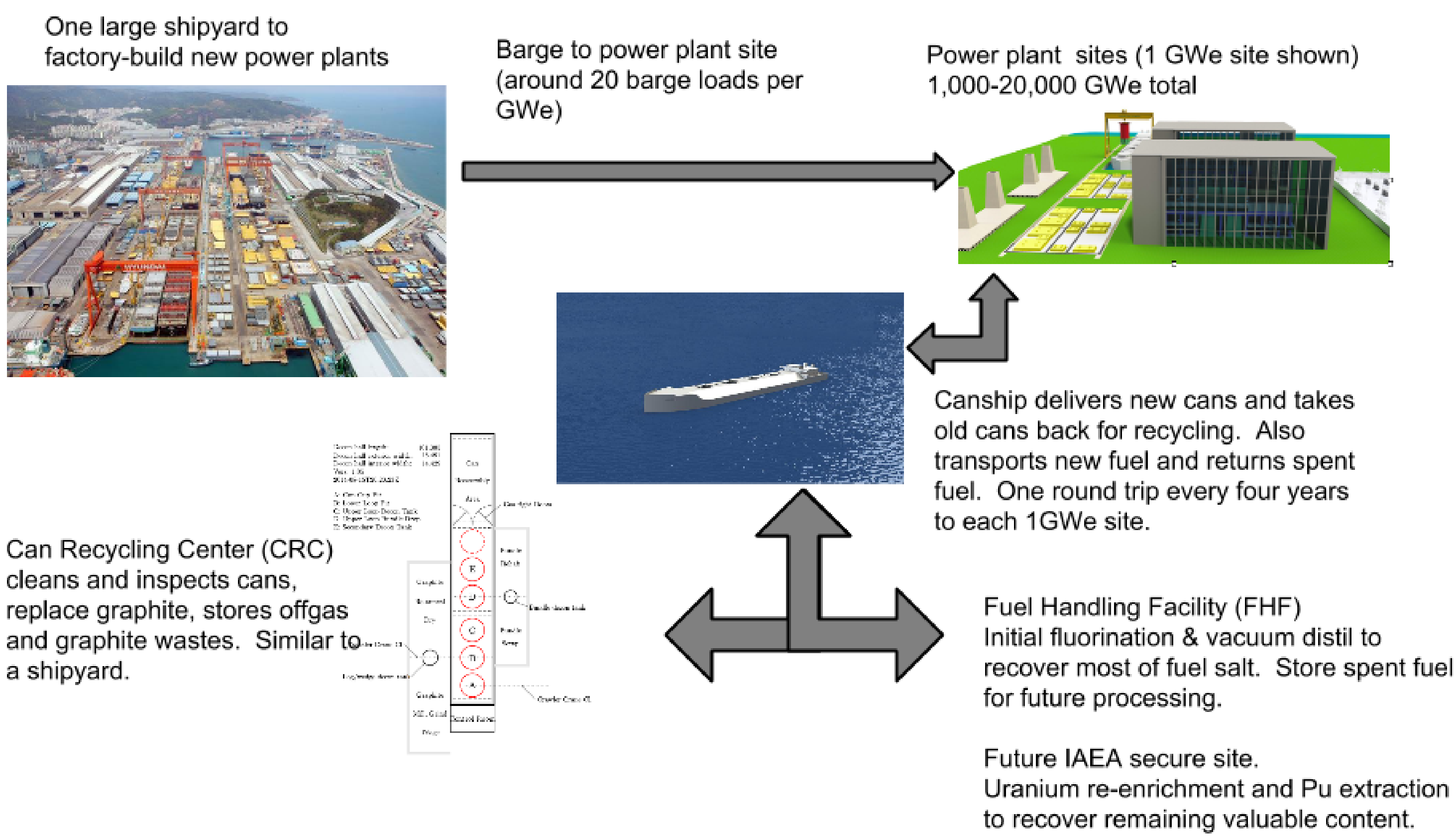
After eight years of operation, the build up of fission products will require us to change out the fuelsalt. The old fuelsalt will remain in its Can for four years. During this cool down period, the old fuelsalt is as well protected as the salt in the operating Can. There is no need for a separate, vulnerable spent-fuel cooling and storage system. By the time we pump the old fuelsalt to a shipping cask, its decay heat will be down to 80 kW, 0.25% of the original. The casks will then be transferred to the FHF in the Canship.

The fuelsalt going both ways will be unattractive weapons material. The uranium will be both fully denatured and, after the initial load, contain enough U-232 to further complicate a bombmakers life, while at the same time allow tracking of any diversion. The returning plutonium will be reactor grade. More importantly, it will be mixed with 50 times as much neutron absorbing thorium. To produce even a weak fizzle weapon, the plutonium must be separated from the thorium. This is even more difficult than separating plutonium from fission products. ThorCon's fuelsalt will be far more anti-proliferation resistant than the MOX fuel which is currently being transported.

This system of regular replacement of the most critical components means that major upgrades can be accomplished without significantly disrupting power generation. And since the returned Cans are disassembled and fully inspected, incipient problems will be caught before they can turn into casualties.

Such renewable plants can operate indefinitely; but, if a ThorCon is decommissioned, the process is little more than pulling out but not replacing all the replaceable parts.

Figure 14: The Overall ThorCon System



8 Unless you are cheaper than coal, forget about it.

In order to be successful, ThorCon must be able to compete with coal with zero CO2 price.

A big coal plant is a marvelous piece of engineering. Take a look at Manjung 4, Figure 15. This 1 GW Malaysian plant is on a man made island next to shore. Figure 16 is an overview. It has its own import terminal using a 2.3 km long pier to get to deep enough (18 m) water. See Figure 17.

The terminal, which also serves three older 700 MW plants on the island, will be busy. Manjung 4 alone will require 10,000 tons of coal per day or one large bulk carrier every ten days. Discharging this ship will take 3 to 4 days. Impressive amount of space required for coal storage. What is not shown is the ash lagoon. 10 to 20 percent of the incoming coal is ash.

The contract with Alstrom (now GE) was signed in March, 2011 and the plant went on the grid in April, 2015. Manjung 4 cost $1.5 billion or $1.5/W. Sumitomo signed a contract in 2013 for another 1 GW plant at the site for 1300 billion yen, about 1.2 billion at current exchange rates. It's clear you can build a state of the art coal plant for $1.5/W or less.[2]

An important feature of molten salt reactors is that they produce the same 570C steam as a super-critical coal boiler.[3] ThorCon and a super-critical steam plant use the same, nearly-off-the shelf, power conversion equipment, the same turbine hall and the same switchgear. The power conversion side of the plant will cost about $500/kW for both coal and ThorCon. What's different is the steam generation side.

Figure 18 is a nice drawing of a 660 MW boiler. This particular boiler is part of the Tanjung Jati complex in central Java. The boiler is 75 m tall and requires 14,000 tons of steel. The pressure parts alone weigh about 5900 tons. The plan view shows the boiler is a smallish part of the overall layout.[4]

Figure 19 is a cartoonish sketch comparing the Tanjung boiler to a 500 MW ThorCon Fission Island. The coal plant drawing has been scaled so that both the boiler and the fission island generate the same amount of steam. The obvious point: a 500 MW ThorCon Fission Island is a lot smaller than a 500 MW coal boiler and its panoply of coal, ash, and gas handling equipment.

[2] Asian wage rates are not a big factor. The Dutch brought the 2x800 MW Eeemshaven plant on line in 2015 for 2.2 billion Euros, about $1.5/W.

[3] Manjung 4 is an ultra super-critical plant using 600C steam. ThorCon's steam temperature is 570C but ThorCon is more thermally efficient. The main reason is stack losses. A coal plant boiler sends 10% of the fuel's HHV up the stack. But parasitic loads are higher as well. For a 4%S coal, about 1.9% of the coal plant's output goes to the scrubber. Pulverization alone consumes more than 0.5% of the plant's power. Overall Manjung 4 has a thermal efficiency of 40%. ThorCon has a thermal efficiency of 45%.

[4] The plan view shows a pair of these boilers sharing the same stack.

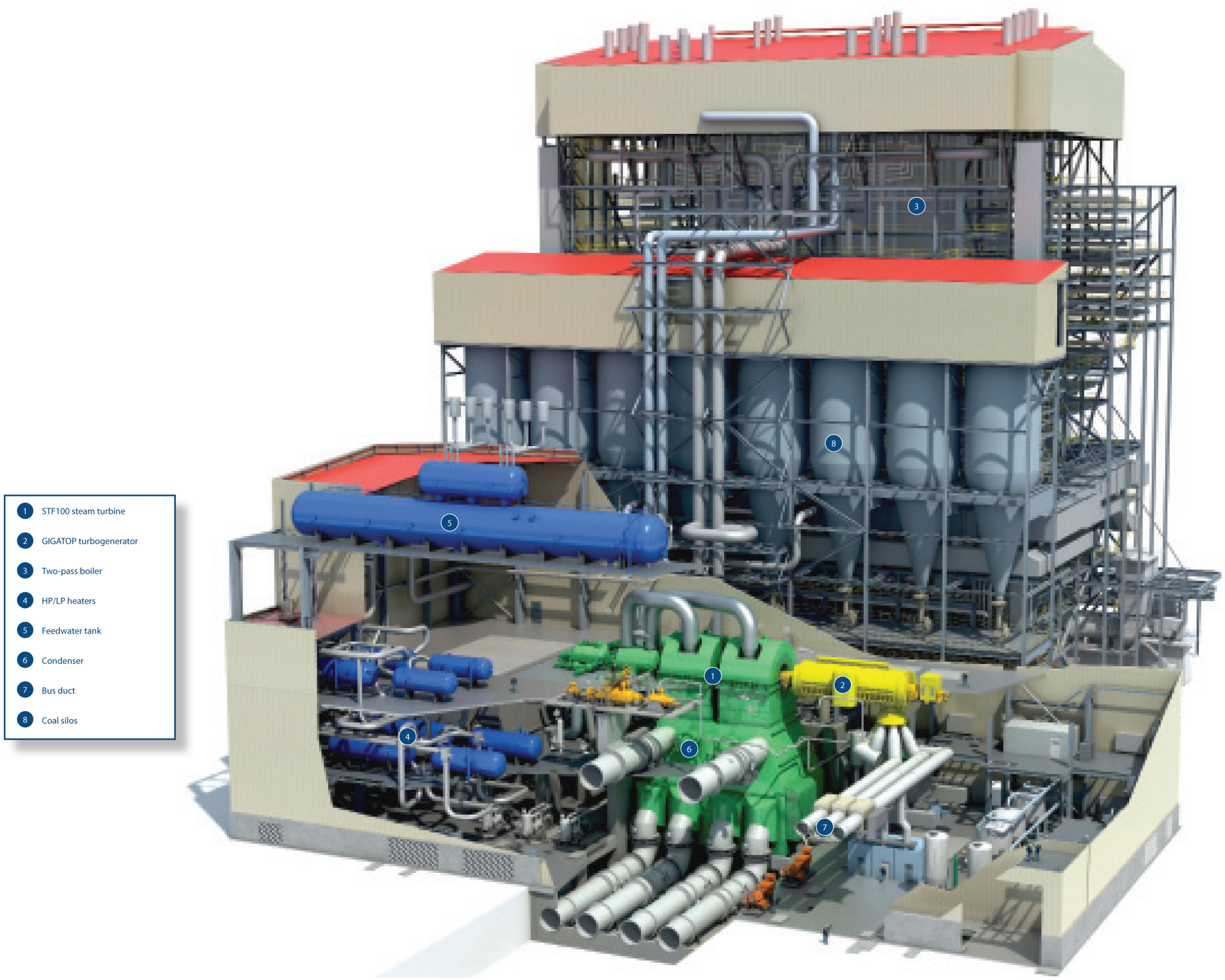


Figure 15: Manjung 4 from turbine hall side

Figure 16: Manjung 4 looking north

Figure 7: View of Manjung 4 from the North (Manjung 1 - 3 and the Coal Unloading Jetty can be seen in the Background (as of April 2015)

Figure 17: Manjung 4 looking south

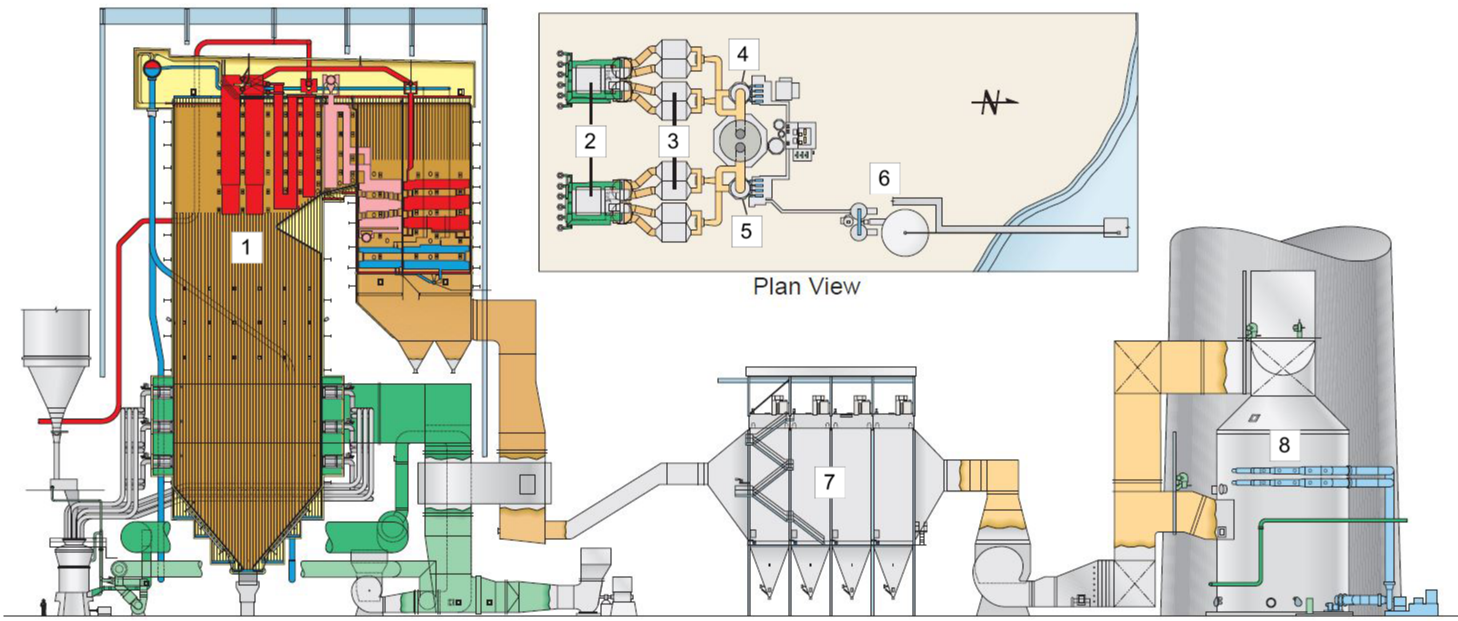


Figure 18: 660 MW Tanjung Jati boiler and gas handling equipment. 1. Furnace, 2. boiler house, 3,7. Electrostatic Precipitators (modern baghouse), 4,5,8 scrubbers, 6. wet scrubber limestone silo

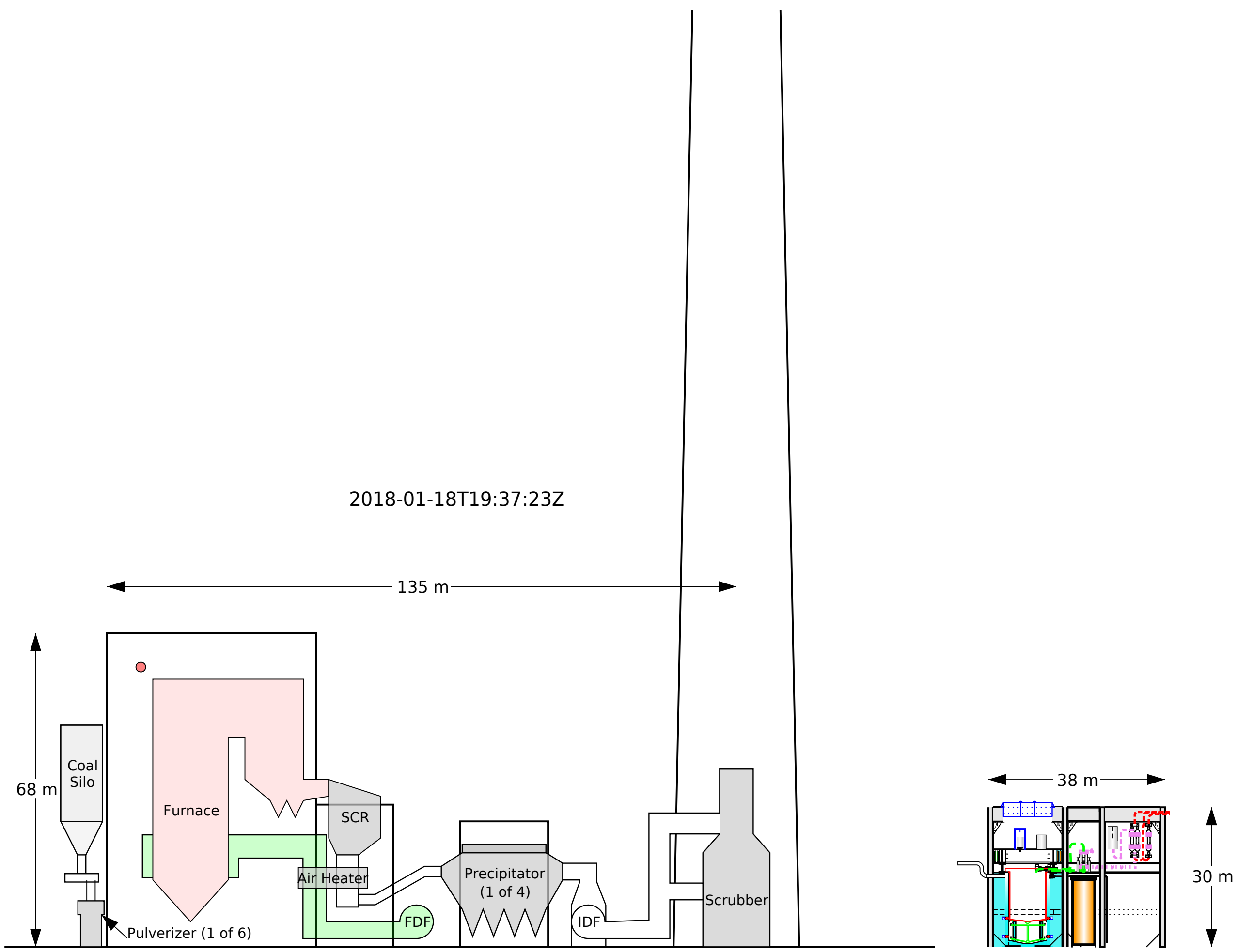


Figure 19: Coal steam generation vs ThorCon steam generation

Table 2 puts some numbers on this comparison, basis 1 GW. Since coal and ThorCon use the same $500/kW turbine island, the right side of the table is a wash. However, the ThorCon fission island requires one-fifth as much steel and one third as much concrete as the coal plant boiler, fuel handling, gas treatment, and ash handling systems.

Table 2:
Steel and Concrete Required for a 1 GWe Plant

	Steam Generation Fission Island/Boiler		Power Conversion Turbine Hall, Switchgear	
	ThorCon	Coal	ThorCon	Coal
Steel(tons)	17,000	91,000	18,000	18,000
Concrete(m3)	42,000	135,000	43,000	43,000

Moreover, almost all the ThorCon concrete is non-structural, simply dumped into the steel sandwich walls; while a large part of the coal plant concrete is slow, labor intensive, reinforced concrete.[5] On a resource basis, everything else being equal, the overnight cost of the ThorCon fission island should be less than one-third that of the coal plants steam generation side.

Everything else is not equal. A 1GW ThorCon requires 1500 tons of very high quality graphite, 1300 tons of SUS 316, 220 tons of the superalloy Haynes 230, and 2,500 tons of lead. But these and other adjustments add a little more than 100 million dollars to the cost of a 1 GWe plant or about $100/kW.

Overall the resource cost of the ThorCon fission island is less than one-half that of the coal plants steam generation system, or about $500 per kW. ThorCon is cheaper than coal, even before we compare fuel costs.

[5] On top of the huge amount of material resources that a coal plant consumes, coal plant builders face two additional problems:

1. A large amount of the effort has to take place on site. The plant is just too damn big to put on a ship, or even use a lot of shipyard style block construction.
2. Coal is so variable that just about every plant, — at least the steam generation side — is a one-off. A boiler designed for one coal will function properly only over a fairly narrow range of coals. The result is a tremendous amount of engineering has to be done for each project.

9 10,000 tons per day or 10 kg's per day?

Table 3 shows the annual fuel requirements of a 1 GWe coal plant at 90% capacity factor.

This table assumes Australian Thermal Coal at a landed cost of $80 per ton, and 45% plant efficiency. This is about as good as it gets for coal. This plant burns 7600 tons of this high quality coal per day. The table also shows the main waste streams. The unit fuel cost is 2.27 cents per kilowatt hour.

Table 3: 1 GW coal plant fuel and waste flows

Capacity Factor	90%
Coal Type:	Australian Thermal
LHV (MJ/kg)	25.36
Coal, Tons/Year	2,487,000
Sulfur Tons/Year	17,400
Ash Tons Per Year	298,000
CO2 Tons Per Year	6,318,000
USD per kWh	0.0227

A 1 GWe ThorCon requires an initial fuel charge of 9,400 kg of 20% Low Enriched Uranium. We also need to add 7.6 kilograms of this fuel per day. Every 8 years the fuel must be changed out. The uranium is easily recoverable, but we do not give ourselves any credit for this. Assuming a yellowcake cost of $40 per pound, a conversion to UF6 cost of $7.50, and 50 dollars per SWU, — all well above current market — ThorCon's levelized fuel cost is less than 0.4 cents per kilowatt-hour. See the Executive Summary for details.

10 Two Cubic Meters of High Level Waste every 1 GW-year

The nuclear waste problem is largely a political construct. The volumes are tiny. The "waste" can be very valuable. And after a few hundred years, it is fairly easily handled since almost all the penetrating gamma radiation will be gone. The remaining radiotoxicity is almost all alpha which must be ingested or inhaled in order to do harm. Since almost all this alpha is in ceramic form, e.g. plutonium oxide, this would require eating rocks. The amounts are so small that, if the USA went all fission using light water reactors and recovered none of its high level waste, the country would have to allocate 200 acres of desert every 20 years for dry cask storage.[6] As McKay puts it, the nuclear waste problem is a "beautifully small" problem.

For ThorCon the situation is even better. Every 8 years, a 1 GW ThorCon will return 226 tons of used fuelsalt to the Fuelsalt Handling Facility, 28 tons per GW-y. This is about 9 m3.

The first step will be to separate the uranium from the fuel salt via fluoride volatility, the same process that was used in the enrichment step. That will remove about 4 tons of 10% LEU from the 28 ton/GW-y waste stream. This uranium can be used as is as part of the initial fuel charge for other ThorCons or better yet re-enriched. Either way it will be returned to the plants. In the re-enrichment case, we will have about 2 tons (100 liters) of depleted uranium to store until any residual U-232 has decayed to background levels.

The next step will be vacuum distillation to recover the salt. This will remove over 70% of the volume. The recovered salt will be returned to the plants. We will be left with about 7 tons of *ash*. This ash will be mostly ThF4 but will contain 100 kg of transuranics and 400 kg of fission products. The volume of this ash will be less than 2 m3. This leads to the approximate ThorCon Rule of Thumb: ***2 m3 of HLW for every 1 GW-y of power.***[7]

This 2 m3 will be stored in dry casks until a combination of the reduction in gamma and technological progress makes it economic to separate out the transuranics. The transuranics can be fed back to the plants where the fissile isotopes will be burned.

The remaining fission products can be mined for the valuable isotopes or simply stored in dry casks for 500 years at which point they will have decayed to near background levels.

Table 3 shows that a typical 1 GWe coal plant produces roughly 300,000 tons of solid waste annually. This ash is much lighter than ThorCon solid waste, roughly 1000 kg/m3 in bulk form. In terms of volume a coal plant produces over 100,000 times more solid waste per kWh than ThorCon.

[6] Devanney, The Nuclear Waste Problem, http://thorconpower.con/docs/ct_yankee.pdf

[7] There will also be some ancillary waste streams:

Krypton and xenon stored in 100 L cylinders	90 kg/GW-y
Graphite mixed with fission products	250 kg/GW-y
Metal from Primary Heat Exchanger/Pump Impeller	10,000 kg/GW-y

The gases are valuable and will probably be separated and sold. With experience, we should eventually be able to recycle most of the contaminated primary loop material.

11 ThorConIsle

There are two variants or *packages* of ThorCon:

ThorConLand A landside version in which 150 to 500 tons blocks are manufactured shipyard style, barged to the site, and erected.

ThorConIsle An offshore version in which an entire 500 MW plant is encapsulated in a hull, entirely built in a shipyard, towed to a nearshore or offshore site with a water depth of 0 to 10 m, ballasted down to the seabed, and if necessary surrounded by a breakwater.

Both packages use exactly the same fission island and steam cycle. The only difference is in the packaging. Up to now, we have been talking about ThorConLand. Here's a brief summary of ThorConIsle.

Each ThorConIsle plant is based on one or more *hulls*, each containing two PMODs, a 500 MW super-critical turbogenerator, room for gas insulated switchgear(GIS), a decay heat pond, and room for auxiliaries. Figures 21 and 22 indicate the overall layout of a ThorCon hull.

The *fission island* is at the forward end of the hull. It is made up of two 250MWe ThorCon power modules. These are exactly the same as the landside power modules including the cold wall loops and cooling pond.

Aft of the fission island is the *turbine hall*, which contains the turbogenerator, exciter, condensers, feedheaters, pumps, and condensate treatment. The auxiliary boiler and sentry turbine are also located in the turbine hall. These components are used during start up — ThorCon has the capability of a black start — and the sentry turbine plays an important role in certain casualties,

The *switchgear hall* is at the aft end. It contains space for the Gas Insulated Switchgear, which steps up the 25 kV generator voltage to 345 kV or higher. The superstructure above the switch gear hall contains support systems, the control room, and accommodations. Blackstart diesel generators are located on either side of the superstructure.

Figures 24 and 25 show 3D sectional views of the hull. The structure is similar to the cargo hold section of a very large tanker with a double bottom and double sides. In addition a double roof is provided in way of the fission island. Wing ballast tanks are provided except for the fission island and a section of the turbine hall in way of the condensers.

The pluses of moving offshore are obvious:

1. No land acquisition costs, no excavation.
2. Easy access to once through cooling. Easy, and effectively unlimited expansion.
3. Essentially all the erection work is shifted to the yard. Higher productivity, better quality control, more complete testing before transport. The overall construction schedule will be shortened and less susceptible to delays.
4. A plant 10 miles offshore will have zero residential population within most countries' Emergency Planning Zone. Nimby, evacuation issues will be greatly eased. This could be crucial, making a fission plant politically palatable where otherwise it would not be.

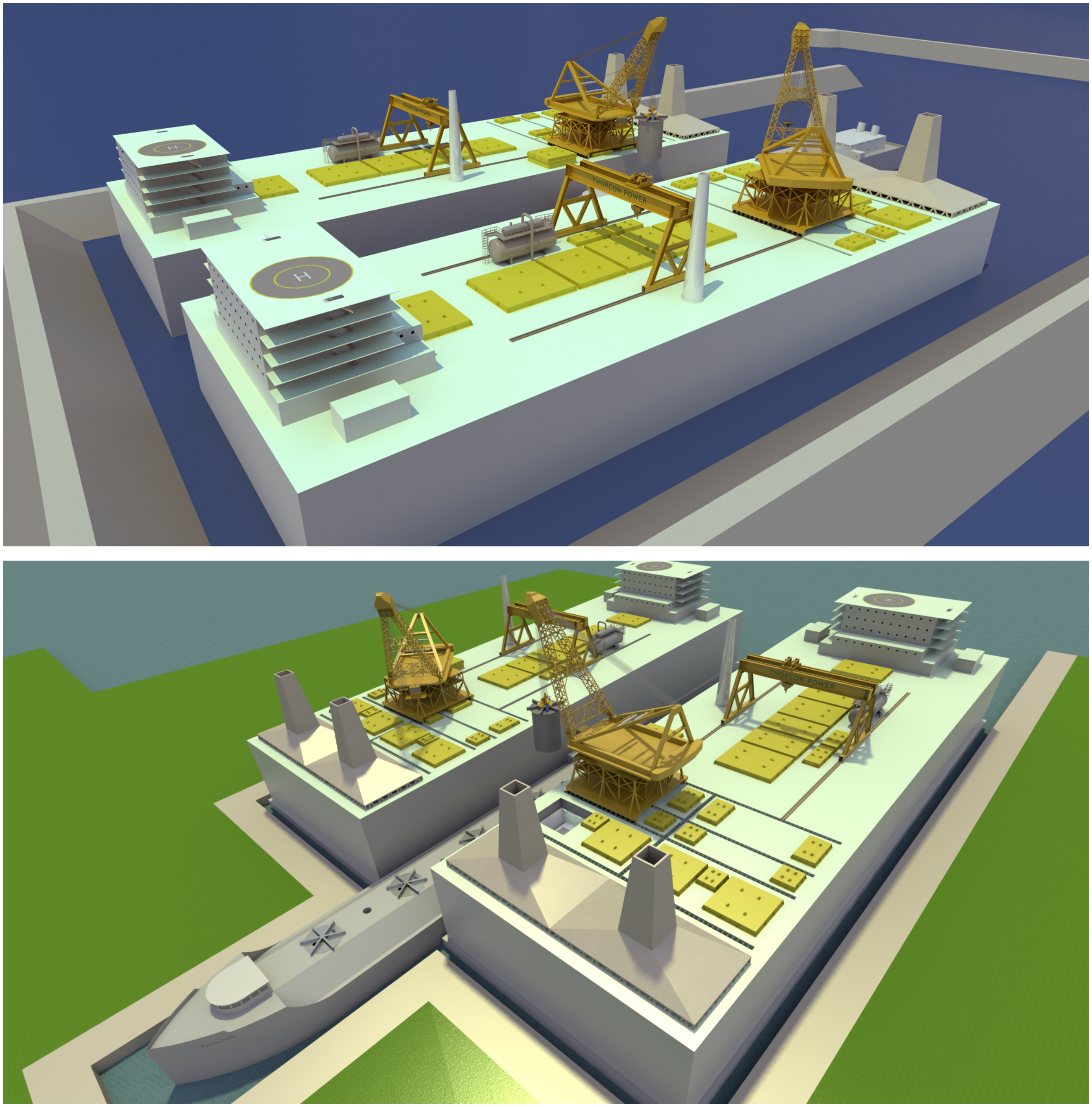


Figure 20: Two views of ThorConIsle: well offshore, and next to shore

5. A hull can be refloated if necessary and towed to shipyard for repairs. It can be decommissioned by refloating.

Of course, there are some negatives:

1. ThorConIsle requires much more steel than ThorConLand. The hull envelope results in an extra steel weight of about 25,000 tons per 500 MW Isle, or about 50,000 tons more per GWe than the landside plant. But steel is cheap in a shipyard. The extra 50,000 tons, fully erected and coated, will cost the yard a good deal less than 50 million dollars.
2. Unless we are quite close to shore, we will have the logistical problems of operating offshore.
3. Unless the site is very close to shore, we will have the cost of transmitting power underwater to shore.
4. We will have the cost of dredging and providing breakwaters. This will be very site dependent. And it will be partly balanced by avoiding on-shore land purchase cost and excavation.

For a site less than 20 km offshore, the marginal cost of the Isle over Land will be between 0.2 to 0.5 cents/kWh.

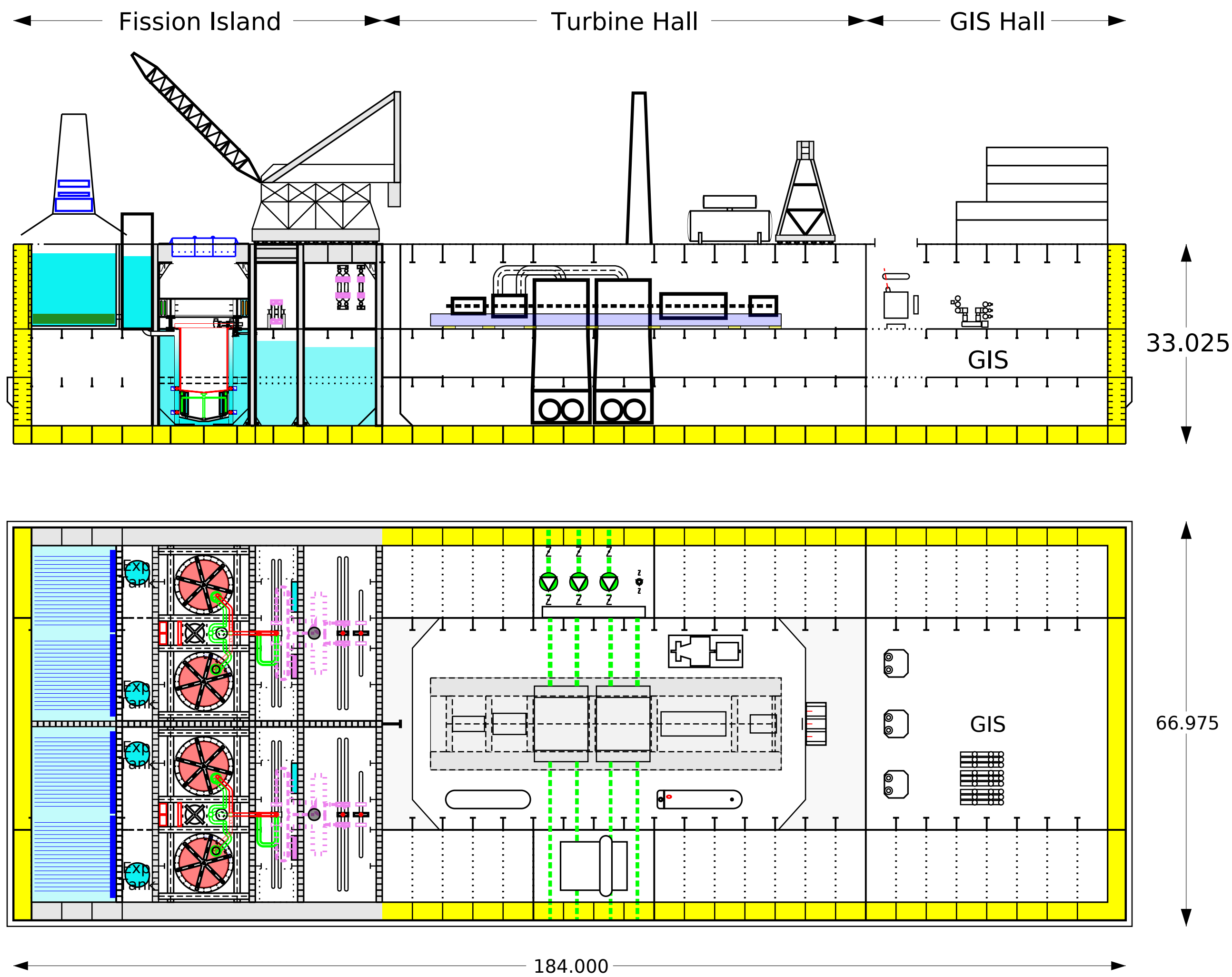


Figure 21: Plan View of Isle. Fission island is 1/3 of the total length.

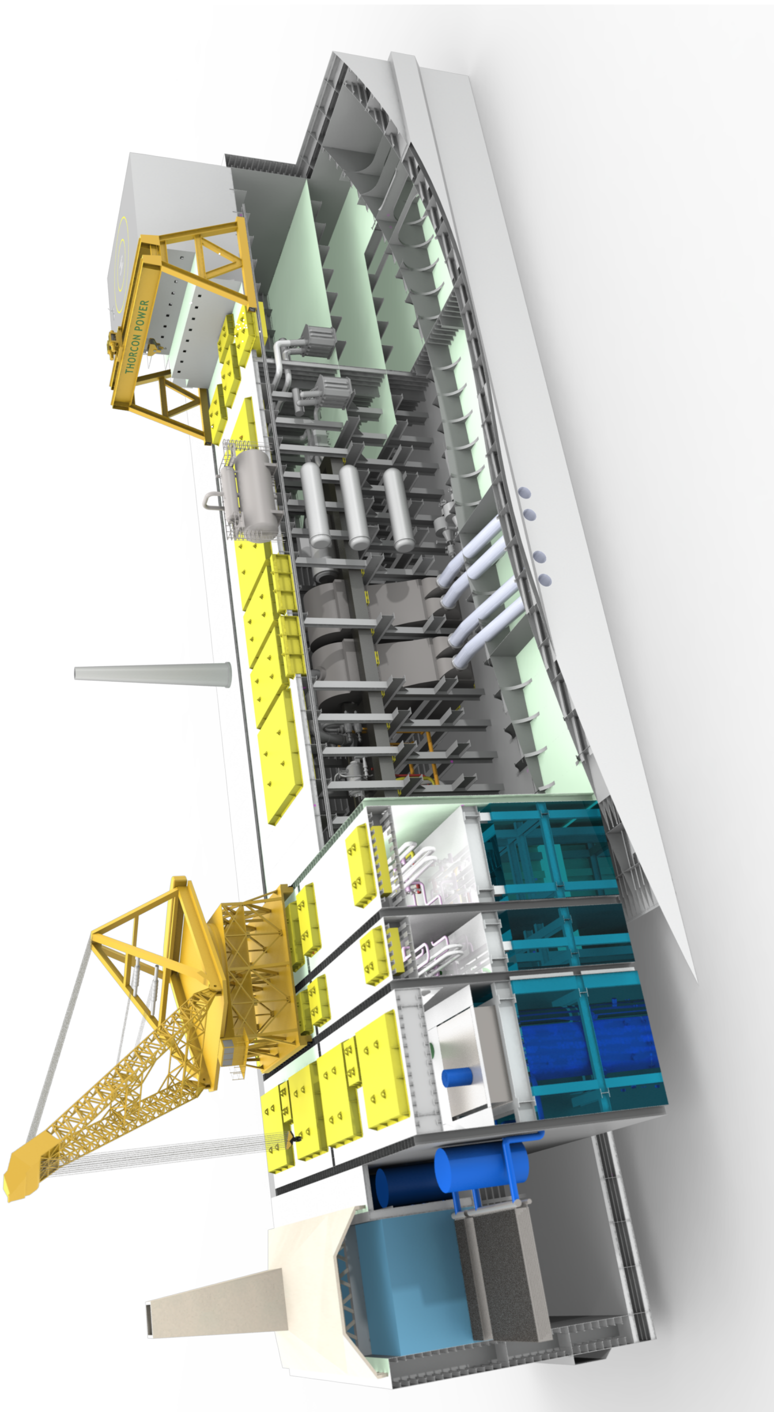


Figure 22: Cutaway view of a ThorCon Hull

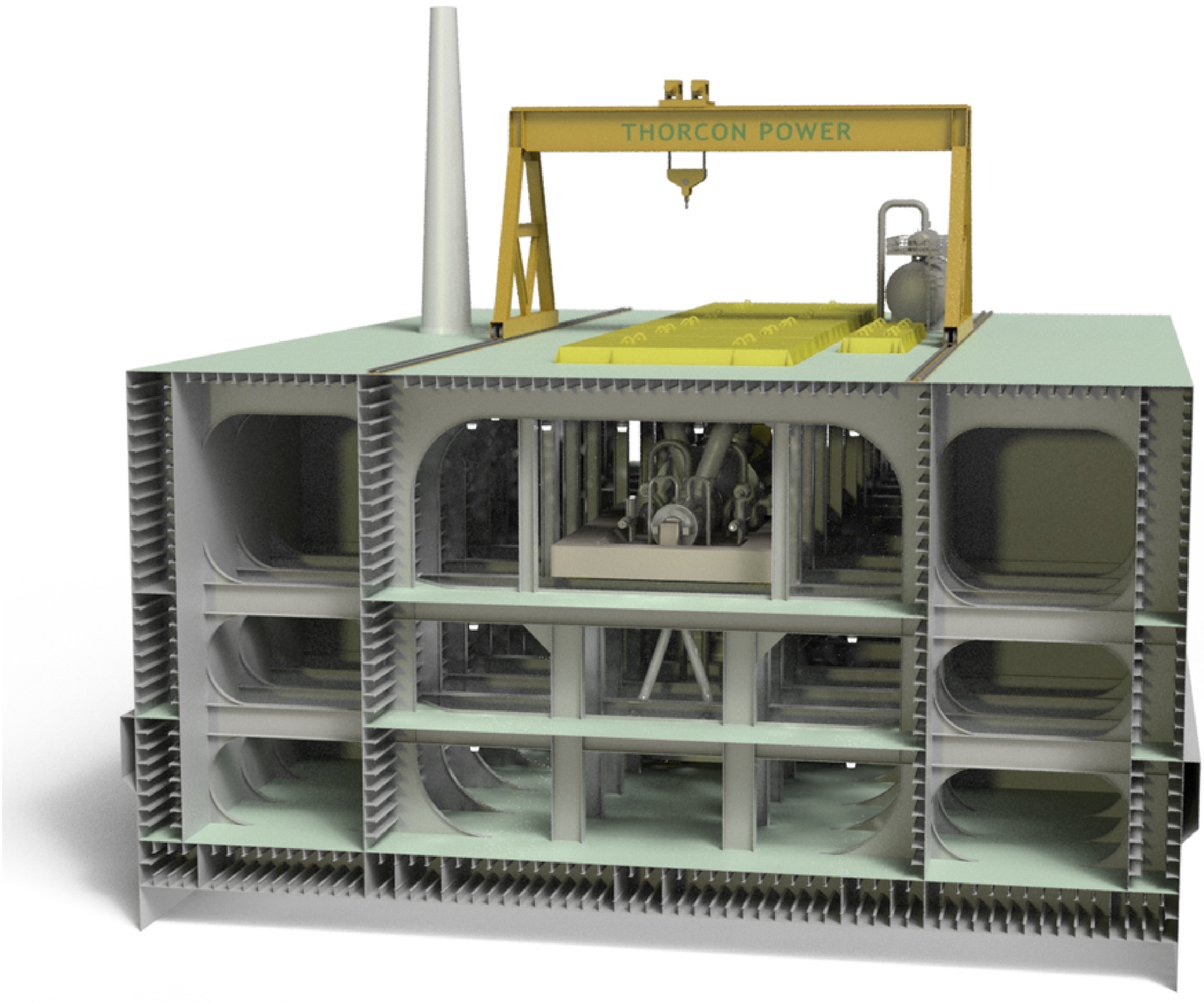


Figure 23: 3D View of Turbine Hall looking aft.

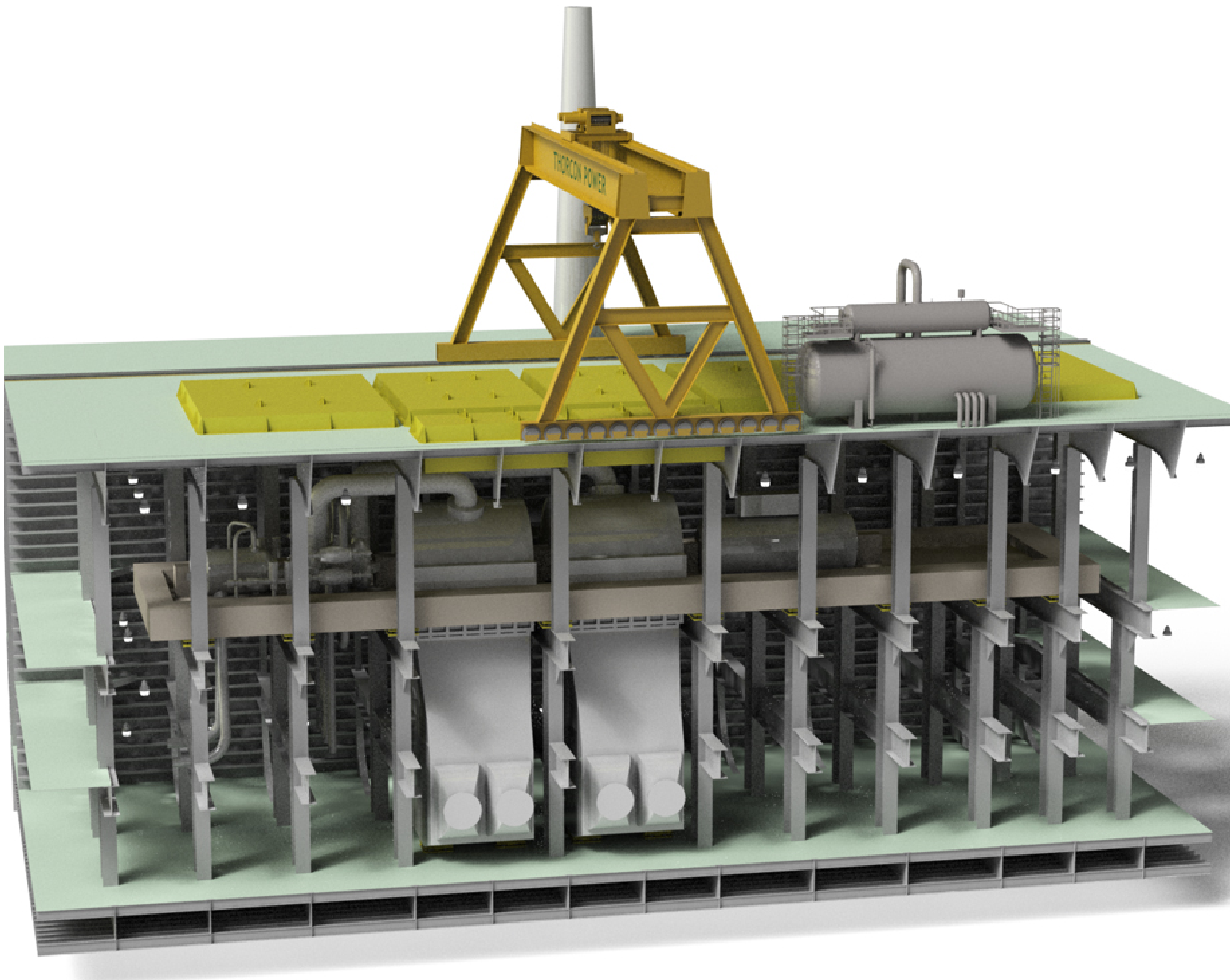


Figure 24: 3D View of Turbine Hall looking starboard.

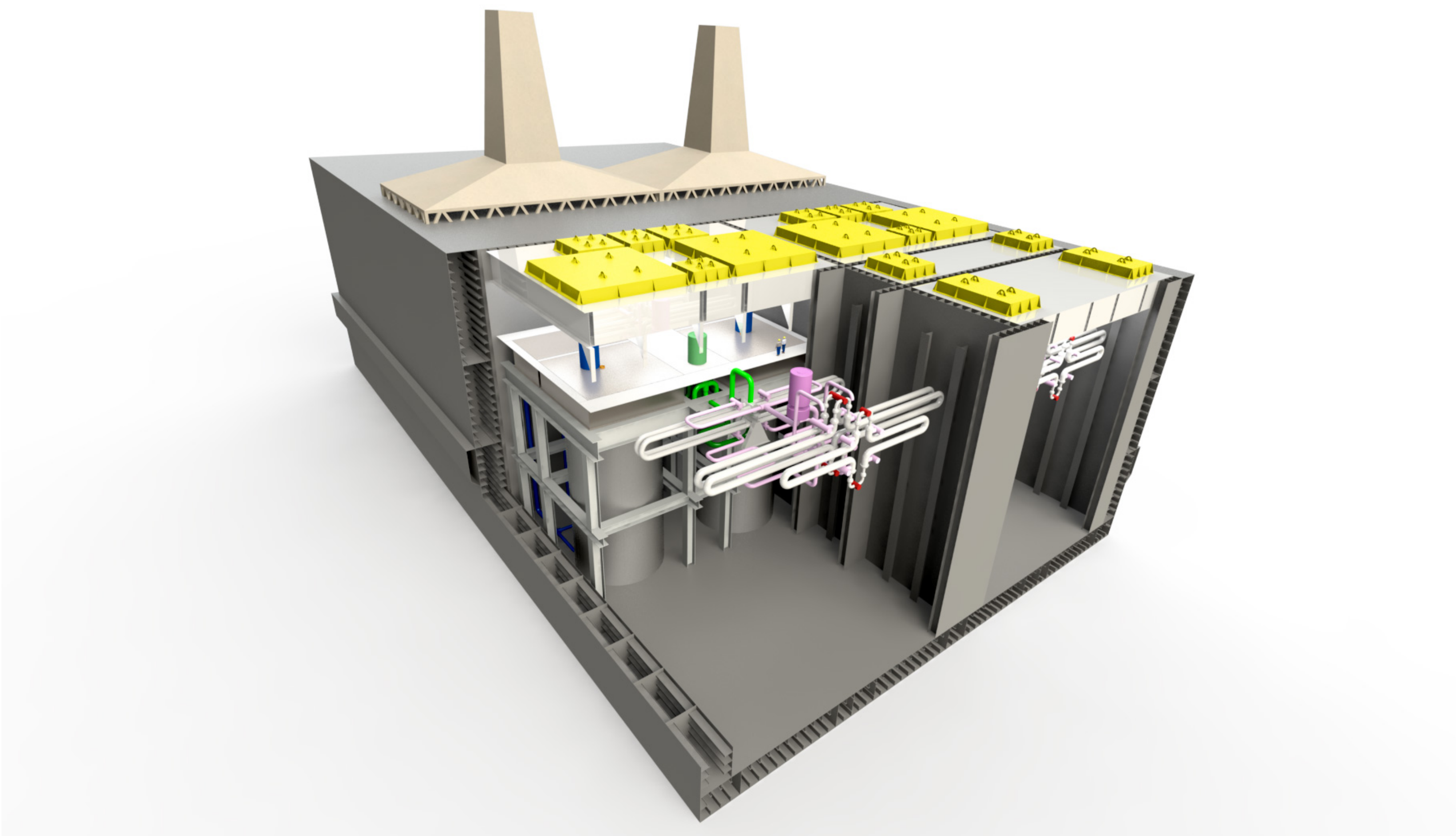


Figure 25: 3D View of Fission Island looking forward.

12 Prototypes should be tortured, not licensed

ThorCon is based on a test-then-license process. Table 4 shows the prototype testing schedule.

Year	Objective
1	Complete design, prepare specs for yard and other vendors. Get quotes, negotiate pre-fission, full scale prototype contracts. Sub-system tests.
2	Build pre-fission prototype, sub-system tests, detailed design/specs of fission prototype
3	Pre-fission tests. Confirm thremo-hydraulics, stresses at operating temperature, exercise safety, instrumentation and replacement systems. Long lead time contracts for fission prototype, Obtain approval for 0 power fission testing.
4	Convert pre-fission module to fission. Start build of second module
5	Ramp up Module 1 to full power in a step wise fashion over the year. Complete build of 2nd module
6	Long-run tests on one module; casualty testing on other. Prototype self-supporting from power sales. Start accepting orders.

Table 4: Prototype Testing Schedule

The prototype is a complete 500 MWe ThorCon. No further scale up is required. After the tests are successfully completed, we can begin deployment.

The major milestones are:

1. At the end of Year 1, when we have the yard and other vendor quotes in.
2. At the of year 3, when the results of the pre-fission tests are available.
3. At the end of year 5, when the results of the first year of fission testing are available.

The project can be aborted at any of these points.

If the prototype is successful, we will ramp up toward an annual production of 50 or more GWe plants per year.

> If a man can make a better mousetrap than his neighbor, you will find a broad, hard beaten path to his house though it be in the woods. [Emerson, misquoted]

13 The Team

Jack Devanney Jack Devanney is the principal engineer and architect of ThorCon. Since 2011 he has pursued the idea of using ship construction technology to mass produce safe, inexpensive power plants that can bring the benefits of electricity to all with nil CO2 emissions. His prior 25-year career dealt with designing, building, and operating oil tankers, including the largest double hull tankers ever built. Before that he served on the faculty of the Ocean Engineering department at MIT for ten years. Jack's MIT education includes an MS in naval architecture and a PhD in management science.

Lars Jorgensen Lars Jorgensen is one of the lead architects of the ThorCon molten salt reactor. Lars designed the off-gas system and conducted analyses of neutronics and decay heat. Most recently from Texas Instruments, Jorgensen was Chief Technical Officer for the Digital Radio Product group. Prior to that he was Vice President of Engineering at Graychip, Inc., a semiconductor company specializing in dedicated signal processing. Previously he was a Principal Engineer at ESL/TRW. His education includes a Master of Science in Electrical Engineering from Stanford.

Ralph Moir Ralph Moir is a nuclear engineer who produced several hundred papers while working at Livermore labs. In 2004 together with Manhattan Project veteran Edward Teller, he published a design for an underground molten salt reactor. He has reviewed and improved the ThorCon design. Dr Moir is a fellow of the American Physical Society and of the American Nuclear Society. He holds BSc and PhD degrees in nuclear engineering from MIT.

Chris Uhlik Chris Uhlik is an Electrical Engineer with a broad experience in robotics, automotive assembly, Internet service applications. He earned his BS, MS, and PhD in Electrical Engineering from Stanford 1979–1990. He is currently an Engineering Director at Google. At Google Chris managed hundreds of engineers and was responsible for a wide range of Internet applications including Gmail, BookSearch, and StreetView. Chris has been contributing to the design of ThorCon for three years believing ThorCon to be the most scalable, resource-efficient opportunity for humanity to advance its living standards while minimizing impact on the global environment.

Robert Hargraves Robert Hargraves is physicist, teacher and author. His book, Thorium: Energy Cheaper than Coal, highlights the importance of a carbon-free energy source that can compete with coal. Dr Hargraves taught energy policy courses at OSHER@Dartmouth. Previously he managed information technology as vice-president of Boston Scientific and senior consultant at Arthur D Little. Hargraves taught mathematics and computer science at Dartmouth College where he founded a software company. He earned an AB in mathematics from Dartmouth College and a PhD in physics from Brown University.

Dane Wilson Dane Wilson has decades of experience in corrosion science and technology. He recently retired from Oak Ridge National Laboratory where he worked on materials and systems for use in molten fluoride salts, high temperature gaseous environments, and other pernicious working fluids of interest to energy and hydrogen production. and operations management, highlighting business links to science and He earned a BSc in physics (solid state), MS in material science and engineering, PhD in metallurgy (corrosion and surface science), and an MBA.

David Devanney Mr. Devanney has a history of starting up new companies in a variety of areas including education, power generation, real estate development and marine transportation. His most successful venture was the founding and management of Tankship Transport, a ship owning and operating company which managed one million deadweight tons of its own large oil tankers and another million tons of tankers for outside owners. At ThorCon, Dave's focus is raising financing for the technology and finding a host country for the prototype power plant. Mr. Devanney received a BA in philosophy from Loyola University and a MA in education from New York University.

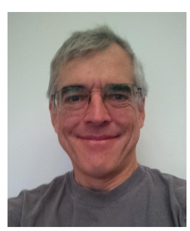

Ralph Moir

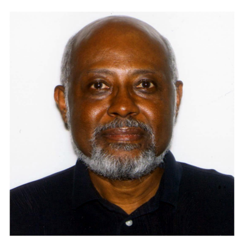

Jack Devanney


Lars Jorgensen


Dave Devanney


Bob Hargraves


Chris Uhlik


Dane Wilson