Using ThorCon to Downgrade Weapons Grade Plutonium

Lars Jorgensen and Jack Devanney

Sisyphus Beach

Tavernier, Florida

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This is an incomplete draft for internal discussion.

Precis

- ThorCon can burn or downgrade the 34 tons of excess weapons grade plutonium in the US inventory, required by our treaty with Russia.
- To do this, ThorCon requires far less fuel preparation than a solid fuel reactor.
- If the nations wills it, ThorCon can begin burning this plutonium in 5 years.
- The plutonium will produce about 2 GW of pollution-free, CO2-free, dispatchable power for over 20 years.
- The process will also produce 300 million dollars of fissile in the form of ^{233}U which can be downblended to commercial reactor fuel.
- The resulting waste, occupying 225 m3 of dry cask storage, will be useless as weapons material, even a low yield fizzle bomb.

1 Introduction

ThorCon is a molten salt reactor. For a brief summary, see thorconpower.com/docs/domsr.pdf. ThorCon is a straightforward scale up of the highly successful MSRE. ThorCon requires no new technology. ThorCon is walkaway safe. ThorCon does not depend on non-available fluoride salts. In an efficient regulatory environment, ThorCon can begin deployment inside of 5 years, less if the nation wills it.

ThorCon is sharply focused on providing cheap, non-intermittent, carbon-free electricity. However, liquid fuel reactors are inherently flexible. ThorCon can run on a remarkably wide range of fertile and fissile. The baseline fuel is thorium mixed with 19.5% LEU. But ThorCon will run on 3% LEU, U-233, thorium, reactor grade Pu and weapons grade Pu in a variety of combinations. All this without any changes to the design.

Liquid fuel reactors have several crucially important advantages when it comes to burning spent fuel.

1. Relatively tolerant of residual fission products. The fuel can be contaminated with a range of fission products and still be consumed as is. In some case, additional fissile or fertile will be required — ThorCon needs the total heavy metal content in the fuelsalt to be within a fairly narrow range — but this is easily mixed in.[1]
2. ThorCon operates with less than a day's excess reactivity depending on liquid make up fuel to maintain reactivity. As burn up progresses, we can adjust the make up fuel composition to compensate for the build up of fission products and TRU. This leads to long burn ups and the ability to respond to any surprises.
3. No need to fabricate fuel elements. The requirements for fuel elements are exacting. This is particularly difficult and expensive, when one is dealing with radioactive material. For example, nuclear fuel pellets must be ground to a very tight tolerance. In the case of weapons grade plutonium, this produces ^{239}Pu dust. ^{239}Pu is an alpha emitter that must be inhaled or ingested to be harmful. Dust creates an inhalation pathway.[2] This turns a standard manufacturing process into a difficult and very expensive robotic procedure.
4. Tolerant of inhomogeneities in the fuel. Solid fuel reactors require tight control of fuel composition. Otherwise, hot spots can develop which could lead to major casualties. In a liquid fuel reactor, any inhomogeneities in the fuel are quickly evened out by mixing.

In short, it is far, far easier to process spent nuclear fuel for a liquid fuel reactor than for a solid fuel. Instead of a Purex plant, we need a mixer.

This note outlines some runs we did on weapons grade plutonium (WG Pu). ^{239}Pu is an excellent fuel. To burn it in a ThorCon, all we have to do is mix it with fluorine, and dissolve it in our fuelsalt.[3] As we shall see, the output will be a great deal of pollution-free, carbon-free electricity, and a waste that not only meets the requirements for reactor grade plutonium, but cannot be used to make a low yield, fizzle weapon.

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[1] ThorCon requires that the fuelsalt composition be maintained close to the eutectic.

[2] And the proliferation folks want us to keep track of every spec of weapons grade dust.

[3] With considerable care. The mixing must be done in small batches to avoid criticality. But once the ^{239}Pu is dissolved in a salt with fifty times as much thorium, then the fuelsalt can only go critical in the highly moderated ThorCon core.

2 The Importance of Thorium

In most of our WG Pu runs, we included a sizable amount of thorium in the fuel. This is not absolutely necessary. We could have used natural uranium or depleted uranium to reach the heavy metal content ThorCon needs to be close to the eutectic. But thorium has a number of fundamentally important advantages:

1. Using ^{238}U is counter-productive since ^{238}U transmutes to ^{239}Pu.
2. Some of the thorium is transmuted to ^{233}U, an excellent fuel. This is very cheap electricity.
3. A thorium bearing fuel produces five times as much ^{238}Pu as a ^{238}U based fuel. This is a problem for a would be bombmaker. ^{238}Pu is a prolific alpha emitter, putting out heat at about 570 W/kg. It is the preferred source of power for deep space probes. Our bombmaker will have to figure out a way of dissipating this heat. This is not so easy since a plutonium bomb must be wrapped in a tight blanket of explosives.

   To make matters worse, this level of ^{238}Pu exacerbates the pre-detonation problem. ^{238}Pu emits three times as many neutrons per gram-second (2700) from spontaneous fission as ^{240}Pu (920).[4] An MSR over time also produces a substantial amount of ^{242}Pu. ^{242}Pu emits twice as many neutrons per gram-second as ^{240}Pu. Despite this, the treaty's definition of acceptable downgrading is based solely on ^{240}Pu. The requirement is the ratio of ^{240}Pu to ^{239}Pu be larger than 0.1. In this note, we convert the total spontaneous fission rate in neutrons per gram-sec to equivalent ^{240}Pu content.
4. A reactor grade Pu — or even WG Pu — diluted with thorium cannot go critical. This is an obviously important safety feature. But still more importantly, in a theft scenario, the standard assumption within the proliferation community is that any yield which exceeds a conventional chemical explosion is a *nuclear threat*. See for example Bathke et al. [5] To be overly conservative, both heat load and spontaneous fission are deemed not to be significant problems in achieving such modest yields. However, at the same time the sub-national group is assumed to have no enrichment or reprocessing facilities.

   Bathke et al suggest diluting the plutonium with thorium.[6] If sufficient thorium is mixed with the plutonium, it will absorb enough neutrons to prevent criticality. According to their Figure of Merit, a Pu + Th mixture in which the thorium concentration is greater than two thirds is *Unattractive* material even for a group that is satisfied with a very low yield. A mixture which is more than 90% thorium has a Bathke *attractiveness* of zero.[7] It is useless even for a very low yield fizzle device.

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[4] Shultis, J. and Faw, R., Fundamentals of Nuclear Science and Engineering, CRC Press, 2008, p 141

[5] Bathke, C. et al, The Attractiveness of Materials in Advanced Nuclear Fuel Cycles for Various Proliferation and Theft Scenarios, Proceedings of Global 2009, Paper 9543, September,2009.

[6] For Bathke et al, uranium is also an effective dilutent; but it is hard to imagine an outfit that can make a fizzle device out of extremely low grade plutonium but is unable to remove the uranium by fluorine volatility. Separating thorium and plutonium is far more difficult.

[7] Bathke et al, Figure 7.

In our runs, the ratio of thorium to all plutonium is always over 40. To make even a low yield, fizzle weapon, a successful thief would have to have access to a Thorex plant. No such plant currently exits.

3 ^{239}Pu Makeup Fuel Requirements

Table 1 shows an initial WG Pu based fuelsalt composition for a 250 MWe power module. The initial ^{239}Pu charge is only 165 kg.

Isotope	kilograms
Be9	663
F19	17236
Na23	10721
Th232	17075
Pu239	165

Table 1: Initial fuel composition

Makeup fissile is ^{239}Pu, fertile is thorium. ThorCon uses a clever variant of Serpent developed by Dr. Manu Aufiero which automatically adjusts the make-up fuel volume and content to maintain the k_{eff} very close to 1.0 throughout the burn up period. Table 2 shows the amount of make up ^{239}Pu through time. The striking feature is the drop in ^{239}Pu after year 1 despite the build in fission products.[8]

Figure 1 shows why the ^{239}Pu consumption goes down. With no ^{238}U around to sop up neutrons less than uselessly — ends up making new ^{239}Pu — the ^{233}U content builds pretty quickly. In year 1, about 10% of our power is from ^{233}U. By year 5 ThorCon is getting more power from thorium than from ^{239}Pu. By year 8, ^{233}U is producing close to 50% of the power.[9] At this point, two-thirds of our power is from self-generated fuel.

Table 3 and Figure 2 show the plutonium content of the fuelsalt through time. It only takes a little more than 60 days to meet the lenient treaty requirements. The conventional definition of Reactor Grade plutonium is ^{240}Pu must be more than 20% of all plutonium. ThorCon reaches that at the end of year 1. Interestingly, after year 4 the ^{240}Pu fraction starts going down. According to the conventional definition, the bombmaking quality of the plutonium is getting better. In fact, the spontaneous fission rate is rising rapidly due to the build in ^{238}Pu and ^{242}Pu. At the end of year 8, the fuelsalt contains more ^{242}Pu than ^{240}Pu and the spontaneous fission rate is equivalent to a plutonium that is 68% ^{240}Pu. No sentient bombmaker would mess with this stuff.

The ^{239}Pu behavior in Figure 2 is interesting. In the first year, the ^{239}Pu burn does not keep up with the ^{239}Pu additions. But after that, ThorCon needs less new ^{239}Pu and the ^{239}Pu

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[8] These are the net additions required to maintain criticality. The Serpent model does not account for the fuel that is pushed out of the primary loop by the added fuelsalt. The gross additions must reflect this adjustment, but in this case the adjustment will not be large.

[9] The fission fractions in Figure 1 do not add up to one. Most of the missing fission is from ^{241}Pu.

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Burn step	days	years	Pu239 g/cm3-s	Pu239 kg/day	cumulative Pu239 kg	average Pu239 kg/d	average fuel kg/d	annual kg/y
1	0	0.00	5.4185e-10	0.673	0.0	0.000	0.000	
2	2	0.01	1.3884e-09	1.725	3.4	1.725	1.725	
3	6	0.02	1.6294e-09	2.024	11.5	1.924	1.924	
4	14	0.04	1.4163e-09	1.759	25.6	1.830	1.830	
5	30	0.08	1.1996e-09	1.490	49.5	1.649	1.649	
6	60	0.16	1.0312e-09	1.281	87.9	1.465	1.465	
7	120	0.33	8.3826e-10	1.041	150.4	1.253	1.253	
8	240	0.66	6.6231e-10	0.823	249.1	1.038	1.038	
9	365	1.00	5.0737e-10	0.630	327.8	0.898	0.898	327.8
10	730	2.00	3.7886e-10	0.471	499.6	0.684	0.684	171.8
11	1095	3.00	2.9951e-10	0.372	635.4	0.580	0.580	135.8
12	1460	4.00	2.7203e-10	0.338	758.7	0.520	0.520	123.3
13	1825	5.00	2.7192e-10	0.338	882.0	0.483	0.483	123.3
14	2190	6.00	2.7496e-10	0.342	1006.7	0.460	0.460	124.7
15	2555	7.00	2.8182e-10	0.350	1134.4	0.444	0.444	127.8
16	2920	8.00	2.8870e-10	0.359	1265.3	0.433	0.433	130.9

Table 2: Net ^{239}Pu makeup to maintain criticality.

content drops fairly rapidly through year four, then levels off and late in the period starts to climb slowly. This reflects the leveling off of ^{233}U and the build in fission products.

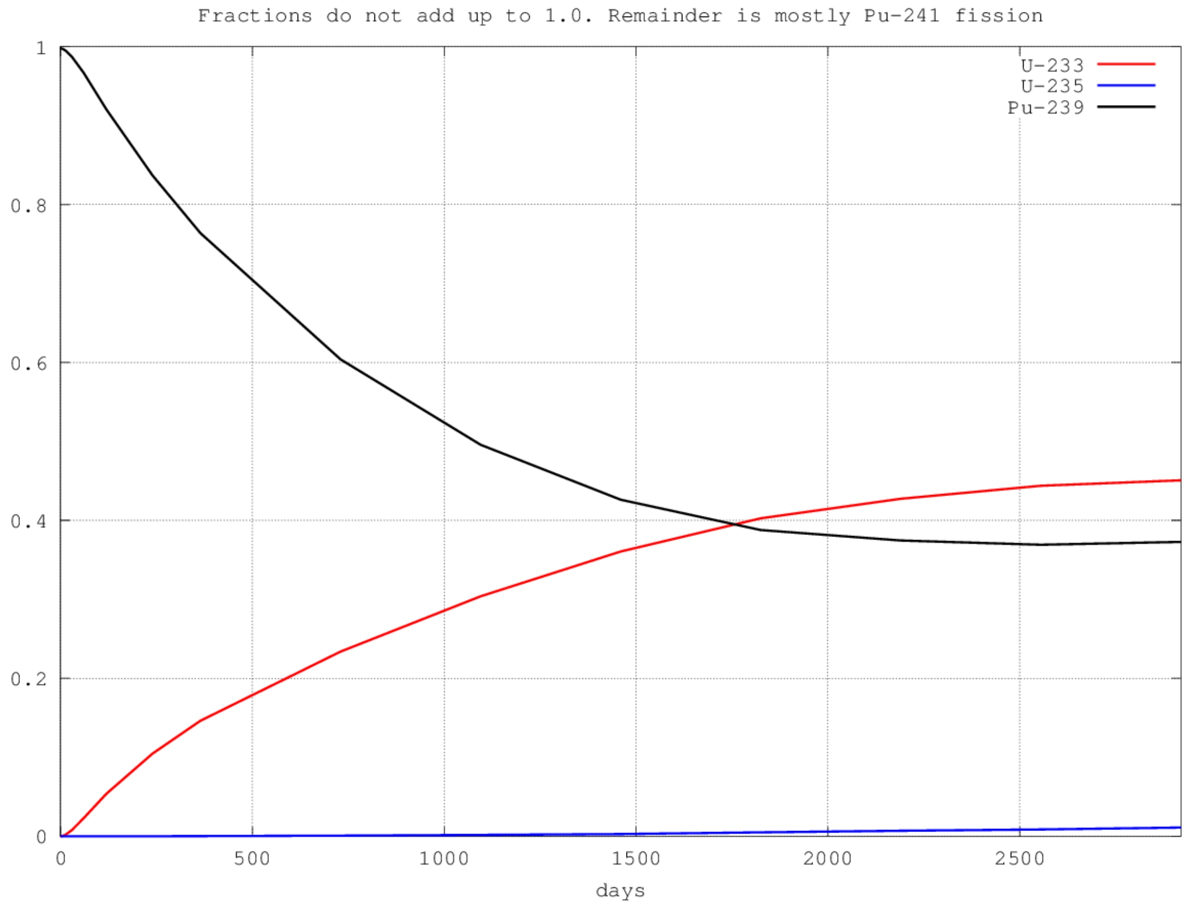

Figure 1: Fission fractions as a function of burn-up time

Burn step	days	years	Pu-238 kg	Pu-239 kg	Pu-240 kg	Pu-241 kg	Pu-242 kg	Total Pu kg	Pu-240 /Pu-239	Pu-240 /All-Pu	Eqv-240 /All Pu
1	0	0.00	0.00e+00	1.71e+02	0.00e+00	0.00e+00	0.00e+00	1.71e+02	0.000	0.000	0.000
2	2	0.01	9.63e-07	1.71e+02	7.00e-01	2.96e-03	2.29e-06	1.72e+02	0.004	0.004	0.004
3	6	0.02	2.93e-06	1.76e+02	2.09e+00	2.62e-02	6.01e-05	1.78e+02	0.012	0.012	0.012
4	14	0.04	7.02e-06	1.85e+02	4.83e+00	1.36e-01	7.19e-04	1.90e+02	0.026	0.025	0.025
5	30	0.08	1.58e-05	1.96e+02	1.00e+01	5.82e-01	6.32e-03	2.06e+02	0.051	0.049	0.049
6	60	0.16	4.09e-05	2.11e+02	1.91e+01	2.04e+00	4.25e-02	2.32e+02	0.090	0.082	0.082
7	120	0.33	2.76e-04	2.28e+02	3.44e+01	6.54e+00	2.57e-01	2.69e+02	0.151	0.128	0.130
8	240	0.66	4.40e-03	2.40e+02	5.70e+01	1.83e+01	1.34e+00	3.17e+02	0.237	0.180	0.188
9	365	1.00	2.35e-02	2.38e+02	7.24e+01	3.09e+01	3.31e+00	3.45e+02	0.305	0.210	0.229
10	730	2.00	2.99e-01	2.05e+02	9.19e+01	6.05e+01	1.28e+01	3.70e+02	0.449	0.248	0.318
11	1095	3.00	1.07e+00	1.68e+02	9.21e+01	7.51e+01	2.49e+01	3.61e+02	0.548	0.255	0.399
12	1460	4.00	2.34e+00	1.41e+02	8.49e+01	7.83e+01	3.74e+01	3.44e+02	0.603	0.247	0.480
13	1825	5.00	3.92e+00	1.27e+02	7.68e+01	7.48e+01	4.87e+01	3.31e+02	0.607	0.232	0.555
14	2190	6.00	5.56e+00	1.24e+02	7.05e+01	7.02e+01	5.80e+01	3.28e+02	0.570	0.215	0.611
15	2555	7.00	7.05e+00	1.23e+02	6.68e+01	6.61e+01	6.52e+01	3.29e+02	0.541	0.203	0.655
16	2920	8.00	8.33e+00	1.30e+02	6.57e+01	6.36e+01	7.07e+01	3.38e+02	0.507	0.194	0.677

Table 3: Plutonium content for a single power module as a function of burnup.

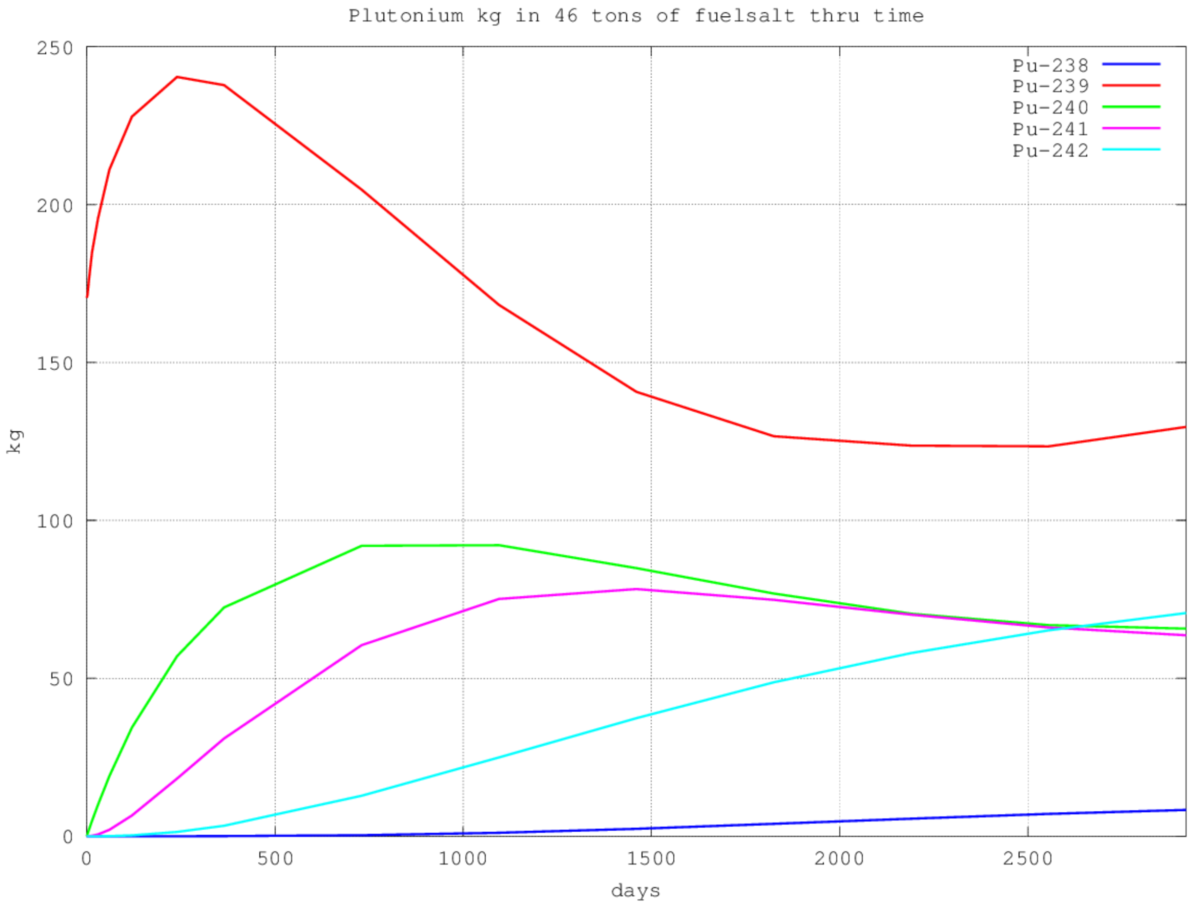

Figure 2: Plutonium content for a single power module as a function of burnup.

4 Options

The terms of the treaty require 1300 kg of WG Pu per year to be downgraded or burned.[10] Assuming the US abides by these terms, Table 4 shows the number of ThorCon Power Modules (PMOD's) required as a function of the fuelsalt change out period. These numbers do not yet account for the fuel pushed out of the primary loop. So the actual downgrade rate per PMOD will be somewhat higher. On the other hand, however many PMOD's we choose to install, we will want to use them to capacity. This will increase the power output a bit.

Change out period yrs	ave ^{239}Pu burn rate	PMODS required	GW
2	332.5	3.9	0.98
4	231.0	5.6	1.41
8	179.0	7.3	1.82

Table 4: ThorCon Power Modules to maintain 1.3 tons/yr

We as a nation have a range of options. At one extreme, we can view the problem as simply meeting the letter of the treaty pretty much ignoring anything else, including the value of the electricity produced. At the other extreme, we can choose to burn our ^{239}Pu efficiently. The bureaucratic mindset points to a short fuelsalt change out period which minimizes the capital investment in PMODs.[11] A more intelligent approach would be to take a broader perspective and include the value of the electricity in the calculus. For example, if we go with 8 years rather than 4, the nation gains 400 MW of pollution-free, CO2-free electricity at essentially zero fuel cost. We will of course have to pay the CAPEX of two more PMODs.

Going the opposite way, we could replace all or part of the thorium with ^{238}U either in the form of natural uranium or depleted uranium. We would then have considerably less electricity for the same amount of ^{239}Pu downgrade. We would also end up with a far less proliferation resistant waste. This would be economically stupid and proliferation-wise stupid; but politics often results in stupid solutions. ThorCon will do what we tell it to do.

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[10] The original treaty called for 34 tons in 20 years (1700 kg/y). But in 2010, the Russians demanded and received

1. The right to use fast reactors.
2. A decrease in the minimum downgrade rate.

[11] Another problem with the two year change out period, is the old fuelsalt will have cooled for only two years prior to change out. The baseline ThorCon design assumes a four year cooldown. The two year change out period imposes additional constraints on the design and forces us to multiple fuelsalt transfer casks. For a 4 year cooldown, we need one transfer cask; for a 2 year cooldown we will have to divide the fuelsalt into five transfer casks.

5 The Leftovers

If, for example, we run for 8 years and then change out, we will have 46,200 kg or about 15 m3 of spent fuelsalt, less than 2 m3 per year per PMOD.[12] The salt composition will be:

Elements	Weight fraction
Salt(Na, Be, F)	0.613
Thorium	0.355
Uranium	0.019
Plutonium	0.007
FP and 95+	Remainder

^{239}Pu will be about 38% of all plutonium followed by ^{242}Pu at 21%, ^{240}Pu at 19%, and, just for fun, we have thrown in 2.5% of ^{238}Pu. This is very poor bombmaking material. More importantly, it will be mixed in with 50 times as much thorium. This material is useless even as a fizzle weapon if stolen.

The uranium on the other hand will be highly enriched. It is about 55% ^{233}U and 1% ^{235}U. It would require more enrichment to become bomb quality, and it contains about 6 ppm ^{232}U. However, this is far above the legal limit of 12% ^{233}U. The smart move here is to remove the uranium by fluorine volatility, and then downblend to LEU. The 394 kg of ^{233}U is worth roughly 20 million dollars as reactor fuel.[13] Removing the uranium also avoids the possibility of radiolysis to UF_6 in cask storage whose release would be deemed unacceptable in the USA. This removal will have almost no impact on the volume of spent fuel.

All this will be happening at a single secure site. The current American plan envisions shipping MOX containing WG Pu all around the country. This creates a flagrant vulnerability which will require all sorts of expensive security to mitigate. Not to mention, that commercial reactor operators have shown no enthusiam for handling and burning a fuel with which they are unfamiliar.

Shorter change out periods will result in proportionally higher spent fuel volumes and the plutonium will be higher quality. But it will be treaty legal and, as long as it is mixed with a large amount of thorium, it will still be useless even for a fizzle weapon.

Once the salt has cooled for four years — automatic if the change out period is four years or more — it can go directly to air cooled casks, and stay there indefinitely. An important feature of MSR waste is that many fission products are chemically bound to the salt. This includes cesium and strontium. If a cask is breached, they will go nowhere by themselves. After a few

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[12] These numbers will have to be adjusted for the fuel pushed out of the primary loop; but, as long as we stay away from ^{238}U, the increase in waste volume will be less than 25%.

[13] The ^{232}U content may restrict this fuel to liquid fuel reactors, but ThorCon for one for one would be happy to pay the market for it.

Figure 3: Dry cask storage facility

weeks, ^{137}Cs and ^{90}Sr represent nearly all the gamma and alpha respectively in a spent fuel release.

If the change out period is 8 years, after burning or downgrading all 34 tons of ^{239}Pu, we will end up with about 15 casks. Figure 3 shows what the storage facility might look like.