Have A Little Imagination

All seven billion of us are creating climate change. We burn carbon; and this changes the climate. This is a problem for our planet; now. And it will get worse. This is the greatest issue facing mankind. But you will not hear about it on TV or in the newspaper. That is because of a basic fact: when people cannot change something they do not think about it. A person could live in a terrible slum. They get up every day and go to work and come home every night. If you ask them, they will tell you it is terrible. But they will fail to make the next cognitive step and think about changing it. They will say something like: "that is just the way it is". This embodies public perception on this issue. We are here to say: No. We can fight this. Fusion makes the impossible, possible. We compare this effort to the early attempts in human flight. Everyone says it is impossible, till someone does it - then everyone will say it was inevitable.

There are a number of arguments for and against this reactor working. One general set of physics arguments is that the plasma inside forms some kind of structure. Whether it is a virtual anode, a diamagnetic whiffle ball, an edge annealing effect or an efficient electron recirculation; the plasma has some kind of structure. The opposing view is that the plasma is a disorganized, thermalized, cloud. Opponents argue that structure would create plasma instabilities, which causes structure to fall apart. Proponents argue the clouds' electric and magnetic fields, force some kind of structure. This is not a settled argument. Not by a long shot. Data should settle this. Another argument posits that there exists an operational sweet spot, balancing both sets of effects: a resonance condition. But this is just a hypothesis. There are also engineering tricks to explore such as: x-ray reflection, changing ring size and ring configuration. Given enough bells and whistle would the reactor work? and after that, would it be economical? These are open questions. We need experimentation. We need data.

Have a little imagination. What would happen if the Polywell worked? This is a machine which could produce cheap, abundant, carbon-free energy. This is a machine which could tackle oil, gas and coal. It could beat them on price, availability and scale. Market forces alone, could solve the climate crisis. What would be the impact of this technology? What would it do on global water, starvation, poverty, resources and the economy? Let us make some practical predictions. This post addresses a few issues, we welcome others to argue or extend this analysis.

What is the price point?

The key starting point for analyzing any possible impact is: the price. But, this is a tough question to tackle. A working rector could lead to a seemingly endless list of products; small reactors, big reactors, military power systems, mobile power systems, desalination plants and power stations. Each product would have its' own cost. So we skipped that step - and assumed the reactor was already built. Bussard prepared a lengthy analysis for building a power plant for the Navy in 1994 [28]. Unfortunately, the reactor design has evolved and changed since then - making chunks of the work unusable. Someone should go through Bussards' report and update it. The analysis here focused on the fuel cost. Based on fuel costs and a machine efficiency of 1% we estimate a starting price of 91 cents a kilowatt hour for machine operation. The analysis is in the appendix. If the reactor was burning P-B11, under the worst scenario, we predict a price of 16 cents a kilowatt hour. The national average for 2011, is 11.09 cents [5]. This price estimate can fall precipitously by increasing efficiency.

What is the durability?

The Polywell creates neutrons, which "burn out" the reactor core. In the appendix we try to forecast what this means in time and money. What are the conclusions? These cores would get about the same neutron flux as current PWR fission cores. That is damn exciting. Bussards' work also came to a similar conclusion [28]. The average PWR core can last more than 21 years [30]. However, we did not consider how thermal stress, embrittlement, transmutation and other issues would affect the cores' life time [31]. This would vary widely based on the materials and fuels used. Reactor durability is still very much an open question.

Where are the break-in markets?

A working polywell would create a new avenue, industry and machine for making power. This seems deceptively easy to sell; everyone needs energy, right? Wrong. Think about this. The ideal customer would have deep pockets, technical expertise and be fusion friendly. They should need electricity – lots of it. Add more attributes and you adjust your perfect customer. Can it be small enough to be considered mobile power? If so, you contrast this against the mobile generator market. Would it play in the renewable energy space? If so, utilities could buy machines to meet state level renewable energy regulations. In 2011, regulations like these were on the books in over 30 states [43]. Does this machine require big supply lines? If not, then isolated communities and the military would be interested. The market for the early machines would focus on where the value added is more important than the starting price.

In considering niche markets the issue of "fusion friendly" deserves extra attention. There is going to be harsh energy industry resistance. One in seven jobs in the US is connected to oil and gas. Yikes. Consider the case of Edwin Armstrong. In 1922, he invented FM radio. This technology directly challenged RCA's dominance in radio. The company fought back and delayed the widespread adoption of FM on till the late 1950's. In his book "The art of the start" Guy Kawasaki points out that new technology always kills old technology. Hence a good spot to launch a polywell company would be one which is not dominated culturally, politically and economically by oil, gas and coal. An emerging market or a high technology market might be a good fit. In terms the ideal customers, we want clients who do not feel threatened by this technology. They may even benefit from the decline in oil, gas and coal. Below are three beach head markets we identified and examined.

The Army:

This reactors' niche would be in powering army bases. In 2007, the center for naval analysis, a Washington think tank convened a panel to look at the problem of powering the US military. The findings from their report were pretty stark [26]. Army field bases are powered by towed-in generators which run on JP-8 fuel. The fuel has to be shipped in, protected and represents a variable cost. For example, a $10 change in the per-barrel cost of oil translates to a 1.3 billion dollar change to the Pentagon's energy costs [26]. In fact, fuel represents 70% of the tonnage delivered to the battlefield. If a reactor could reduce fuel costs by 20 percent this would represent a huge cost savings. The report also identified the department of defense as an early adopter and test-bed for national solutions. Great; this is a perfect place to start from. The military also has the correct outlook for this. It views having this tool as a straight combat advantage. Energy production is a powerful tool. Also I like their work attitude. Retired admiral John Nathman summed it up appropriately: "This is America; we're pretty good at getting stuff done. We need to get this one done." I agree completely.

Water Desalination:

For humans, the need for water can outstrip all other needs. Almost everyone – except maybe water sellers – can see that making clean water, for less, as a good thing. This will hopefully make polywell powered desalination, too sacred, and too apolitical to be stopped. Water and energy are connected – it takes 2.8 KJ of energy to make one liter of desalinated water [1]. In the appendix, we estimated under the best conditions this reactor could generate tens of thousands of gallons of clean eater for each operating dollar spent. The early clients would live in a place which needs water, is not dominated by oil and gas has an educated workforce and an accepting culture. They also need the finances for the project. In 2007, it was estimated that 1.6 billion people face economic water shortage [49]. This need is so vast, that one could envision a product specifically packaged as fusion powered desalination plant.

We started by looking across the Middle East. Unfortunately, many countries in the region were bad fits, because the dominance of oil and gas, political instability and cultural resistance. One interesting case was the city of Sana'a in Yemen. This city of 2.1 million may be one of the most water stressed capitals in the world, the country's economy is not based on oil or gas and the city is the seat of the national government. The solution we toyed with was the government financing and supporting a polywell desalination project, and using an existing pipeline to move the water in. This would be a political boon for any ruling party and the possibility of having the government's blessing would overcome any cultural resistance, poverty problems or workforce concerns.

Another city we considered was Mumbai. It appears to be a great fit. The city has the funds to finance the project – with an economy not dominated by oil and gas. It has the right workforce and cosmopolitan culture suitable to accepting new technologies. It is already home to several nuclear research institutions. The city is also strapped for water. The population has increased 12% in the past six years and combined with climate change has stressed the water supply [51, 50]. The solution we saw was to use the reactor to pump in and purify the water from the Arabian Sea – with the government supporting the project.

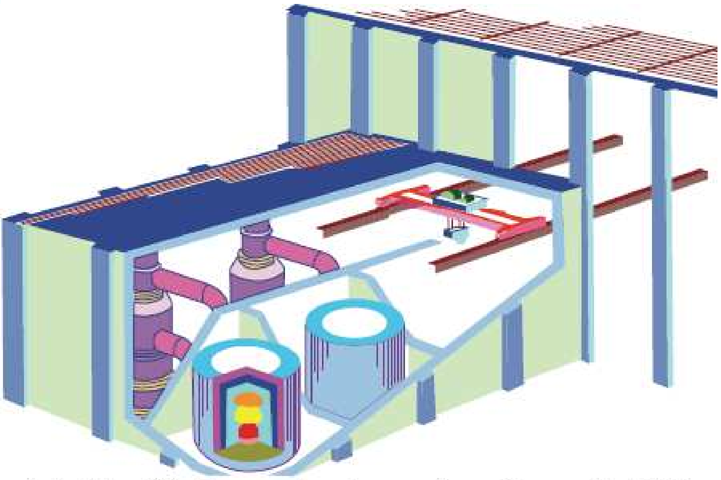
Steel Making or Copper Mining:

Many heavy industries need on site, abundant energy. We looked at tar sands, oil refining and coal mining. But, steel stood out because it benefits both from lowering coal costs and energy prices. Coal becomes coke, a needed ingredient in steel. We hope cheaper energy would increase coal supplies and therefore lower the price. These savings are then passed onto the steel companies. Steel making is a very energy intensive process. In 2003, it took 12.6 million BTU of energy for every ton of steel shipped [47]. A good player in this space might be Nucor, or US steel. Collectively, in the last two years they had revenues of 28 billion dollars. The model we envisioned was a reactor onsite, with operations contracted to an outside company. Copper mining was an alternate market for this model. Copper mining requires even more energy than steel making. For example, the outokempu flash smelting process requires 18.9 million BTU for every ton of copper. Moreover, 45 percent of the energy used is in processing, grinding and concentration [44]. A working polywell could take a bite out of these costs. The mining industry has the capital to afford this reactor. In 2007, the industry produced 98.4 billion dollars' worth of finished products [45].

Conclusion:

This is a two sided post. Part one illustrates a potential product. To whet your imagination about what a working reactor would be, look like and be used for. It is full of predictions. Part two explains how these predictions were made. It dives into the gritty details and engineering analysis. There are many questions we would have liked to address. Who would be needed to build, operate and test a machine? How many jobs would it create? How large would the machine be? How would it be designed, and what is the build price? We invite you to mull these over. There are certainly enough unanswered questions to go around. This technology could break paradigms. It should make you think differently about our energy options. Most of the world agrees: our current energy solutions will not cut it. This has to change. A working reactor should make us all think differently about mankind's future.

A sketch of IEC power plant from Bussard's 1992 Navy report.



A sketch of fusion reactors in use, from Bussard's 1992 report for the Navy.

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Appendix 1: Tuning to the Slam Energy:

The DD reaction is the second easiest fusion reaction in the world to do. The easiest in the world is DT. Unfortunately, that reaction involves tritium which is radioactive. The DD reaction is actually three different reactions, but only two are important. Which reaction dominates? Basically neither, both reactions happen with equal probability. This fact changes slightly based on what energy the DD hit one another at. I call this the slam energy – what energy the ions slam into one another. This is an important number. At a lower energy this fusion reaction will yield more tritium. At the higher energy, this reaction will yield more helium 3 [24]. The chart below estimates the fusion reactions probability, this is a rough estimation based on their cross sections. This shows the slight impact, that slam energy has on these reactions.

Reaction Probability

	Slam Energy (KeV)			
Reaction:	10	100	1250	1750
D & D -> T + p	49.73%	52.86%	50.79%*	52.75%*
D & D -> He3 + n	50.27%	47.14%	49.20%*	47.24%*

* estimated from Reference [24]

Each fusion reaction does have an optimum slam energy. This hints at a very important Polywell concept: that the machine could be “tuned” for the specific fuel being fused. For example, the PB11 reaction operates best at a slam energy of 550 keV. Presumably, the polywell would try and contain enough electrons create that slam energy. This creates a high voltage drop. Ions are shot into the center at some energy. They see this voltage. They fly towards the center, building up kinetic energy and they slam into one another. They hit at some energy: the slam energy. This can be adjusted by varying the amount of electrons in the center or it may be adjusted by changing the way ions are injected. The slam energies, the cross sections and the energy released in each reaction is included below [24]. For this analysis, we assume each fuel is being burned at the energy listed here. This is important when looking at the core's durability and the amount of x-rays the machine produces. Though, there is good reason to think that these energies should be adjusted [25, 42].

	(eV)	(Barns)	(MeV)
Reaction:	Optimum Slam Energy	Cross sec*	Energy Made:
D & T -> a + n	64,000	5.0	17.59
D & D -> T + p	1,250,000	0.096	4.04
D & D -> He3 + n	1,750,000	0.11	3.27
P & B11 -> 3a	550,000	1.2	8.68

* This is the peak cross section, at the optimum energy, listed here

This chart can be deceptive. If boron fusion has such a relatively low energy - why are the government labs only using deuterium and tritium? It is because boron fusion is basically non-existent, under 100,000 electron volts. At energies where the DT reaction happens, boron is barely fusing. That is because at that energy, the boron cross section is roughly fifty thousand times less than the DT cross section.

Appendix 2: Summary of Operating Price

To estimate the price point, you need a few bits of information. You need to know the price of the pure fuel, the amount of energy per molecule and some properties of the fuel. This can predict how much energy you make, per dollar you spend. Then you need to estimate the machines' efficiency. You can do worst, better and best case scenarios. In an effort to keep the message from getting lost in the numbers, a summary chart is included below. The key parameters are how efficient the machine is, and how much fuel it burns. A low efficiency could account for many unforeseen costs, machine issues, extra fuel costs, input energy, machine maintenance, staffing, ect… The worse price would be the beta machine or the "model T" version. This is the first step in taking this technology down the cost-volume curve. Eventually, this price could be competitive with current nuclear fuel. In 2010, nuclear fuel cost 0.65 cents a kilowatt hour [27]. The sections below goes into more detail on how these forecasts were made.

Worst Case Scenario:

Reaction:	$/1Kg	MeV Energy	MeV Per 1$	Fuel Conversion %	Efficiency	KJ/1$	Clean Water Gal./1$	Kw/Hour	$/ KwH
D & T -> a + n	$50,022,222	17.6	4.21E+19	20	10	135	11	1,875,320	$2,667
D & D -> T + p	$44,444	4.04	1.23E+22	20	1	3,944	309	48,697	$0.91
D & D -> He3 + n	$44,444	3.27	1.23E+22	20	1	3,955	309	48,830	$0.91
P & B11 -> 3a	$7,000	8.68	6.80E+22	20	1	21,800	1,705	42,389	$0.17

Better Scenario: **Reaction:**	**$/1Kg**	**MeV Energy**	**MeV Per 1$**	**Fuel Conversion %**	**Efficiency**	**KJ/1$**	**Clean Water Gal./1$**	**Kw/Hour**	**$/ KwH**
D & T -> a + n	$50,022,222	17.6	4.21E+19	35	10	236	18	3,281,810	$1,524
D & D -> T + p	$44,444	4.04	1.23E+22	35	5	34,514	2,700	426,097	$0.10
D & D -> He3 + n	$44,444	3.27	1.23E+22	35	5	34,609	2,707	427,262	$0.10
P & B11 -> 3a	$7,000	8.68	6.80E+22	35	5	190,752	14,920	370,907	$0.02

Best Scenario: **Reaction:**	**$/1Kg**	**MeV Energy**	**MeV Per 1$**	**Fuel Conversion %**	**Efficiency**	**KJ/1$**	**Clean Water Gal./1$**	**Kw/Hour**	**$/ KwH**
D & T -> a + n	$50,022,222	17.6	4.21E+19	45	17	516	40	7,173,100	$697
D & D -> T + p	$44,444	4.04	1.23E+22	45	12	106,501	8,330	1,314,815	$0.03
D & D -> He3 + n	$44,444	3.27	1.23E+22	45	12	106,792	8,353	1,318,407	$0.03
P & B11 -> 3a	$7,000	8.68	6.80E+22	45	12	588,607	46,037	1,144,514	$0.01

Remember this is fuel costs. Staffing, maintenance and construction costs need to be added on top. To keep costs low, DD would probably be the best fuel to start with, though this is subject to debate. The key to burning better fuels revolves around increasing the voltage drop, improving operation and increasing the injection energy. Initially tritium should be avoided. Its' radioactivity adds expenses for safe handling and makes the machine less marketable.

Ideally, a beta version would run DD fusion, with a price point of $0.91 a kWh. That is roughly less than the current solar power price point. This assumes 20% conversion and recovering 1% of the energy. This low efficiency is supposed to account for the energy needed to run the reactor as well. Could we push these efficiencies? If the reactor is burning P-B11, under the worst case scenario this predicts a price of 0.16 a kWh, though it should take more energy to burn PB11. That is five cents higher than the national average for electricity in 2011 [5]. This fuel would also give the reactor a very long durability, with regards to neutrons, as will be shown.

Deuterium, Deuterium Calculations:

For the economic calculation, I used both DD energies. The cost of deuterium is 400 dollars for 50 liters at 99.999% purity [23]. I also figured in gallons how much clean water per dollar this reactor could make – it takes 2.8 KJ to make one liter of clean water [1]. It was assumed that this reactor burned a kilogram per hour. Example calculations are shown below.

$$Energy\ Per\ Dollar = \mathbf{1.359E22\ MeV}\ Per\ \$\mathbf{1} = \mathbf{1}/\left(\frac{\$400}{0.05m^3}\right) * \left(\frac{1m^3}{0.18\ Kg}\right) * \left(\frac{2.014Kg}{1000\ mol}\right) * \left(\frac{1\ mol}{6.022E23\ molecule}\right) * \left(\frac{2\ molecule}{4.04\ MeV}\right)$$

$$KJ\ Per\ \$\ With\ Efficency = 4{,}354\ KJ\ per\ dollar = \left(\frac{1.359E22\ MeV}{\$1}\right) * \left(\frac{1.602E-16KJ}{1MeV}\right) * 0.2 * 0.01$$

$$Clean\ Water\ Made\ Per\ Dollar = 341\ Gallons\ = \left(\frac{4354\ KJ}{1\ dollar}\right) * \left(\frac{0.219\ Gallon}{2.8\ KJ}\right)$$

$$Kilowatt\ Per\ Hour = 53{,}753 = \left(\frac{4354KJ}{\$1}\right) * \left(\frac{\$44{,}444}{1Kg}\right) * \left(\frac{1Kg}{1Hour}\right) * \left(\frac{1\ hour}{3600\ Seconds}\right)$$

$$Price\ Per\ Kilowatt\ Hour = 82\ cents\ per\ KwH = \left(\frac{\$44{,}444}{53{,}753}\right) * \left(\frac{100\ cents}{1}\right)$$

Deuterium, Tritium:

Tritium is expensive. You cannot really stockpile it because it has a half-life of about 12 years. The price estimate I used was 100K a gram [23]. Why pay so much? Because fusing this material is easier. But, can we put that advantage into dollars? You can measure the "fusibility" of a fuel by looking at its cross section. Cross sections are measured by shooting a beam of atoms into a wall of atoms and measuring how many fusion reactions occur. The higher the cross section, at a lower energy, the better the fuel is. From the table above, we see that the cross section is 45 times higher than the DD reaction. Let us assume then, that the baseline efficiency of this machine increases to 10%. Below shows the critical calculation made. Note that the D and T properties are averaged.

$$Energy\ per\ 1\$ = 4.21E19\ MeV = \left(\frac{1000g}{\$50{,}022{,}222}\right) * \left(\frac{1mol}{2.515g}\right) * \left(\frac{6.022E23}{1\ mole}\right) * \left(\frac{17.6\ MeV}{2}\right)$$

$$KJ\ Per\ \$\ With\ Efficency = 135\ KJ\ per\ dollar = \left(\frac{4.21E19\ MeV}{\$1}\right) * \left(\frac{1.602E-16KJ}{1MeV}\right) * 0.2 * 0.10$$

$$Clean\ Water\ Made\ Per\ Dollar = 11\ Gallons\ = \left(\frac{135\ KJ}{1\ dollar}\right) * \left(\frac{0.219\ Gallon}{2.8\ KJ}\right)$$

$$Kilowatt\ Per\ Hour = 1{,}875{,}320 = \left(\frac{135KJ}{\$1}\right) * \left(\frac{\$50{,}022{,}222}{1Kg}\right) * \left(\frac{1Kg}{1Hour}\right) * \left(\frac{1\ hour}{3600\ Seconds}\right)$$

$$Price\ Per\ Kilowatt\ Hour = \$2{,}667\ per\ KwH = \left(\frac{\$50{,}022{,}222}{1{,}875{,}320}\right)$$

This calculation was striking. It shows that the excessive price for tritium basically kills hope of burning it in a commercial reactor. Even if the reactor converted 99.999% and captured 90% of all the energy – the price would still be ~60 dollars a kilowatt hour. Run these same numbers for DD and electricity prices would fall 60 fold. Electricity would basically be free.

Proton – Boron 11:

I assumed you could buy a kilogram of the pure boron-11 isotope for Seven thousand dollars. Crystalline boron is supposed to have a price of about Five thousand dollars and the extra money is for purification [6]. In fact, the isotope makes up ~80% of normal boron - so extraction should not be too expensive [8]. Additionally, if there is money to be made selling this product, the price should drop. The price would drop even further, if the electricity used in extraction was cheaper. The pessimist seven thousand dollar price is still kept in however, to account for other fuel expenses, such as shipping and handling. Some of the same assumptions from calculations above are kept in. Below are the calculations.

$$\text{EnergyPerDollar} = 6.80\text{E}22\text{MeV Per }\$1 = \left(\frac{1\text{Kg}}{\$7{,}000}\right)*\left(\frac{1000\text{g}}{1\text{Kg}}\right)*\left(\frac{1\text{mole}}{11\text{g}}\right)*\left(\frac{6.022\text{E}23\text{Molecule}}{1\text{mole}}\right)*\left(\frac{8.7\text{MeV}}{1\text{molecule}}\right)$$

$$\text{KJPerDollarWithEfficency} = 21{,}800\text{ kJ Per }\$1 = \left(\frac{6.80\text{E}22\text{MeV}}{\$1}\right)*\left(\frac{1.602\text{E}-13\text{J}}{1\text{MeV}}\right)*\left(\frac{1\text{KJ}}{1000\text{J}}\right)*(0.2)*(0.01)$$

$$\text{Clean Water Made Per Dollar} = 1{,}713\text{Gallons Per }\$1 = \left(\frac{21{,}800\text{KJ}}{\$1}\right)*\left(\frac{1\text{liter}}{2.8\text{KJ}}\right)*\left(\frac{0.219\text{Gallon}}{1\text{Liter}}\right)$$

$$\text{Kilowatts Per Hour} = 42{,}394 = \left(\frac{21{,}800\text{KJ}}{\$1}\right)*\left(\frac{\$7{,}000}{1\text{Kg}}\right)*\left(\frac{1\text{Kg}}{1\text{hour}}\right)*\left(\frac{1\text{hour}}{3600\text{ seconds}}\right)$$

$$\text{Price Per Kilowatt Hour} = 16.51\text{ Cents Per KwH} = \left(\frac{\$7000}{42{,}394\text{KwH}}\right)*\left(\frac{100\text{ cents}}{\$1}\right)$$

Appendix 3: Ring Construction

We needed to estimate how much the rings cost. To do this we needed to know what material to make the rings from, how much material and what construction might cost. Picking the ring material was difficult. We needed a material that was good at allowing magnetic fields through. It may be desirable for the material to have a low electrical conductivity, to prevent arching. It had to be durable against a bombardment of neutrons and hopefully it could handle heat well. We also would prefer something low cost and easily machinable. There may be other concerns as well [42]. Listed below are candidate materials, with the relevant properties included [33, 34, 38, 39, 40, 41, 42].

	[Henrys/Meter] Relative Magnetic Permeability	[electron-volts] Neutron Activation Threshold:	[Kelvin] Melting Point:	[Watts/Meter*Kelvin] Thermal Conductivity ~20C	[$/Kg] Price:	[Siemens/Meter] Electrical conductivity
Graphite	1.5999999	< 1.00E-4	3925	112	$2.75	1.4E+05
316 Stainless Steel	-	< 1.00E-4	1672	15.16	$0.91	1.3E+06
Neodymium	-	1.00E+04	1297	16.5	$340.00	1.6E+06
Molybdenum	1.0000901	< 1.00E+05	2896	138	$29.00	1.7E+07
Tungsten-Carbide	1.0000008	< 1.00E-4	3143	84.02	$0.48	5.0E+06
silicon carbide	0.9999989	< 1.00E-4	3003	3.6	$8.81	1.0E-06
Boron	0.9999794	<1.00 E-5	2349	27.4	$2,000.00	5.0E-02
Teflon	-	< 1.00E-4	600	0.25	$20.55	1E-25 to 1E-23
Aluminum	0.9994930	< 8.00E+5	933	237	$2.19	3.50E+07

We want a material with a high relative magnetic permeability. This measures how hard it is for the magnetic field to get through the ring walls. This would be indicated by a number of one or higher on the chart above. When neutrons hit a material, they can make it radioactive. The neutron needs at least a certain amount of energy for this to happen. This is called the neutron activation threshold. Ideally, we want this to be as high as possible. Unfortunately, many of these metals have their value artificially lowered because they contain carbon. A high thermal conductivity tells us that this material lets heat out of the reactor – this is desirable. Rings which transmit heat better are less likely to heat up and melt. We cannot get an ideal material from this list. However based on this information there are two likely choices for an initial reactor: stainless steel and tungsten-carbide. Of these options stainless steel may be better because it has an electrical conductivity one fourth that of tungsten-carbide. These two materials are relatively cheap.

Estimating Reactor Durability:

The Polywell will produce heat and neutrons, which will "burn out" the reactor core. Can we measure that effect into dollars and time? This burn out effect is actually several processes happening at the same time. There is embrittlement – where the neutrons knock holes in the surrounding materials. There transmutation – where alphas and neutrons hit the chamber walls and fuse with these materials. There is thermal stress – where the rapid heating and cooling causes problems in the walls. There may be other problems as well [31]. It is unclear which of these effects will have the biggest impact. This section will focus on the effect of bombardment. This is the "threat" - it is a mixture of nuclei, neutrons and protons hitting the walls. We do a simple analysis of this. We then try to connect that to an estimated price. That is why this calculation can only give us an estimate of how durable the reactor core will be.

Metals under attack from neutrons, protons and nuclei will crack. The degradation rate is hard to predict. Fortunately, how neutrons attack materials has already been studied. This is because existing reactors have to deal with neutrons. A U-235 nucleus, undergoing fission, releases an average of 2.4 fast neutrons [29]. The goal in fission plants is to slow down, but not absorb these neutrons. This is done using a moderator. The moderator also protects the reactor core is from the neutrons – giving the core a long durability. The goal is the same in a Polywell. Slow down these neutrons, so they can be used to heat a working fluid. But, these reactors will have no moderator. The core – the rings and chamber – will get blasted. As these materials get blasted by neutrons, the atoms are displaced and this leads to equipment failure. Cracks build. These cracks can swell with fusion products. The degradation by neutrons is measured by the rate of atom displacement [31]. The equation used to find the displacements per atom is included below.

$$displacements\ per\ atom = \frac{\#\ of\ Atoms\ Displaced}{\#\ of\ Orginal\ Atoms} = Nuetron\ Flux * Time * Material\ Cross\ Section(energy)$$

Equation 1: This equation estimates how fast a material cracks when bombarded with neutrons of a given flux and energy. The measure of cracking is called: displacements per atom. Cracking starts to become a problem at dpa values higher than 1.

A good rule of thumb is cracking becomes a problems at 1.0 displacement per atom [35]. As a reference point, parts of a 1300 megawatt PWR core can receive between 0 and 90 dpa [32]. Beyond this benchmark, degradation depends on many factors, including: thermal stress, local chemistry and material processing [31]. Also, hot protons and nuclei hitting the surface could degrade the walls as well. This is getting messy. So let us simplify. Let us apply the equation above. Will this equation predict cracks? The materials we use for the wall will be the ones considered elsewhere in this post, plus those common to todays' fission reactors. By burning a fuel, it means that a specific byproduct would shoot out and hit the wall. That byproduct would be at a specific energy. Ideally, we need cross section data: for that specific byproduct, hitting that specific material at that specific energy. Cross sections measure how easily one thing hits something else. Below lists the cross sections we could find, for those energies, byproducts and materials from the Los Alamos's nuclear information service [33].

Cross Sections Used:		**(eV)**								
Reaction:	**Byproduct:**	**Energy:**	**Carbon**	**Tungsten**	**Aluminum**	**Iron**	**Chromium**	**Molybdenum**	**Nickel**	**Neodymium**
D & T -> a + n	Neutron	1.4E+07	1.3	5	1.8	2.5	2.4	3.6	3	4.8
D & T -> a + n	Helium-4	3.5E+06	LANL lacks helium 4 data							

D & D -> T + p	Proton	3.0E+06	0	1.E-20	0.35	4.4E-03	0.02	unknown	5.9E-04	0
D & D -> T + p	Tritium	1.0E+06	LANL only has tritium data for: H, He and Li							
D & D -> He3 + n	Neutron	2.5E+06	1.5	6.2	3	3.1	3.2	4.5	2.8	6.4
D & D -> He3 + n	Helium-3	8.2E+05	LANL only has helium 3 data for: He & Li.							
P & B11 -> 3a	Helium-4	8.7E+06	LANL lacks helium 4 data							

Crap. The ideal analysis will not work in this case because the numbers needed are unavailable. Of all the byproducts hitting the wall, the neutrons are the most damaging. They penetrate deepest and they can make the walls radioactive. If all the byproducts were neutrons; then the numbers would be available. We decided to go this route. That makes this analysis: a conservative, worst case scenario. Below is a list of the cross sections for neutrons at the hottest byproduct energy, when they hit that material.

Cross Sections Used		**(eV)**								
Reaction:	**Byproduct:**	**Energy:**	**Carbon**	**Tungsten**	**Aluminum**	**Iron**	**Chromium**	**Molybdenum**	**Nickel**	**Neodymium**
D & T -> a + n	Neutron	1.4E+07	1.3	5	1.8	2.5	2.4	3.6	3	4.8
D & D -> T + p	Neutron	3.0E+06	1.5	5.8	2.5	3.3	3.2	3.8	3	6.1
D & D -> He3 + n	Neutron	2.5E+06	1.5	6.2	3	3.1	3.2	4.5	2.8	6.4
P & B11 -> 3a	Neutron	8.7E+06	0.9	5.3	1.8	3.2	2.7	4.4	3.3	4.4

These cross sections were combined proportionally for each wall material. Steel was considered as 316 steel [34] and the proportions we used are shown below. It was assumed the reactor chamber was 15 feet in diameter with 3 inch wall thickness. Bussard had pushed for a wall with 1 cm tubes with coolant in them, to capture the heat [28]. The reactor was burning 1 kilogram per hour, at the aforementioned efficiencies. Example calculations for the worst, better and best case scenarios are worked out below.

$$D\&T\ Nuetrons\ rate = 2.5E+16\frac{Nuetrons}{cm^2 * sec}$$
$$= \left(\frac{1Kg}{1\ hour}\right) * (20\%) * \left(\frac{1\ mole}{1.0079g}\right) * \left(\frac{1000g}{1Kg}\right) * \left(\frac{6.022e23}{1mole}\right) * \left(\frac{1}{656E5\ cm^2}\right) * \left(\frac{1}{2}\right) * \left(\frac{1\ hour}{3600\ sec}\right)$$

$$Stainless\ Steel_{CS} = 17\% * Chromium_{CS} + 3\% * Molybdenum_{CS} + .8\% * Carbon_{CS} + 63\% * Iron_{CS}$$

$$\frac{Tung.Carb.dpa}{Year} = 1.99\ dpa\ per\ year = 2.5E16\frac{Nuetrons}{cm * s} * \left(\frac{31449600s}{1\ year}\right) * (2.5\ Barns) * \left(\frac{1E-24\ cm^2}{1\ Barn}\right)$$

Using the above equations, we can now compile a list of displacements per atom for each fuel and each material. This is included below.

Worst Case Scenario:								
	(eV)		**Fluence:**	**(dpa per year)**				
Reaction:	**Energy**	**Convert**	**N/(S cm^2)**	**Tung Carb**	**Steel**	**Aluminum**	**Molybdenum**	**Neodymium**
D & T -> a + n	3.5E+06	20%	2.5E+16	2.51	1.67	1.43	2.87	3.83
D & D -> T + p	3.0E+06	20%	1.2E+16	1.43	1.08	0.98	1.49	2.39
D & D -> He3 + n	2.5E+06	20%	1.2E+16	1.45	1.00	1.13	1.69	2.41
P & B11 -> 3a	8.7E+06	20%	4.6E+12	0.0005	0.0004	0.0003	0.0006	0.0006

Better Scenario:

	(eV)		Fluence:	(dpa per year)				
Reaction:	**Energy**	**Convert**	**N/(S cm^2)**	**Tung Carb**	**Steel**	**Aluminum**	**Molybdenum**	**Neodymium**
D & T -> a + n	3.5E+06	35%	4.4E+16	4.39	2.93	2.51	5.02	6.70
D & D -> T + p	3.0E+06	35%	2.2E+16	2.50	1.89	1.72	2.61	4.19
D & D -> He3 + n	2.5E+06	35%	2.1E+16	2.54	1.74	1.98	2.97	4.22
P & B11 -> 3a	8.7E+06	35%	4.6E+12	0.0005	0.0004	0.0003	0.0006	0.0006

Best Scenario:

	(eV)		Fluence:	(dpa per year)				
Reaction:	**Energy**	**Convert**	**N/(S cm^2)**	**Tung Carb**	**Steel**	**Aluminum**	**Molybdenum**	**Neodymium**
D & T -> a + n	3.5E+06	45%	5.7E+16	5.65	3.77	3.23	6.46	8.61
D & D -> T + p	3.0E+06	45%	2.8E+16	3.22	2.43	2.21	3.35	5.38
D & D -> He3 + n	2.5E+06	45%	2.7E+16	3.26	2.24	2.54	3.81	5.42
P & B11 -> 3a	8.7E+06	45%	4.6E+12	0.0005	0.0004	0.0003	0.0006	0.0006

This is very exciting. These rates are very similar to todays' PWR reactors. Bussards' report also argued that the dpa rates would be close to current pressurized water reactor rates[28]. Does this mean a Polywell core would last as long as a typical fission core? A typical PWR core, today, can last at least 21 years. This is an open question.

E&I Guns

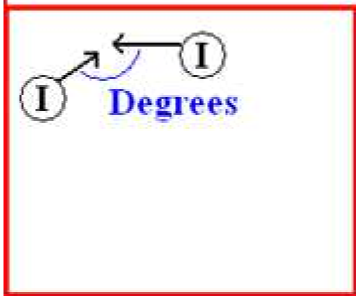
If this reactor is to work, it may be that a resonance condition is the most likely route. Someone needs to investigate this possibility and see if it fits with Nevins, Riders and Bussards' analysis. Nevins made a number of assumptions and used theory to make his argument. He had no polywell data. His model for the reactor was vague. This is good. It makes his analysis applicable for many reactor designs – which is why everyone should read his paper [52]. But, this means that Nevins may have ascribed the wrong details to the reactor. He may have used the wrong plasma cloud structure. Do electrons and ions inside the polywell form a virtual anode? Is there a diamagnetic effect increasing containment of the plasma? Do the electrons recirculate with a high efficiency? Are there edge annealing effects? Someone needs to answer these questions. Hopefully the navy team could take data in this vein. Would these things change, at all, Nevins assessment? Additionally, would his work change with different sizes, ring configurations, or injection configurations? If someone could write an in depth, understandable and fair review of Nevins' paper, that would be helpful as well.

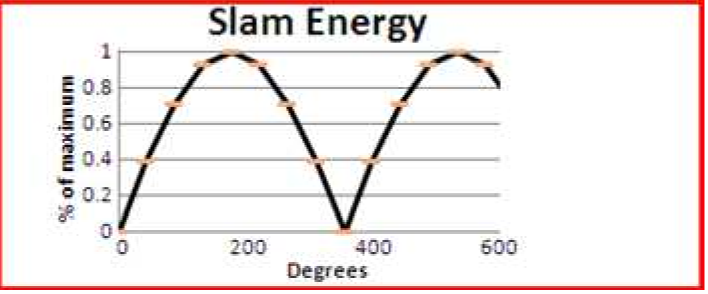
Nevins' work is significant because it touches an important question about a working polywell. Would a working polywell run continuously or would it be pulsed? I do not know the answer to that question. However, for the purposes of this analysis we assumed the reactor was pulsed for 100 microseconds, and five minutes. Choosing both extremes was the first step in trying to figure out what ions and electron guns would be needed to operate the machine. This reactor will probably need custom made ion sources – especially to increase the time the gun can fire off ions. Building off of an off-the-shelf product [53], we picked typical attributes for an ion and electron gun, these are shown below.

Example E&I Guns	D, T, Proton:	Boron:	Electrons:
Vacuum (Pascals):	1E-7 to 1E-8	same	same
Firing Time (Sec):	2E-8 to 1E-4	same	same
Firing Rate (Thing/Sec):	0 to 1.2E+15	0 to 2.5E+14	0 to 1.2E+15
Firing Energy (Joules) :	0 to 6.4E-15	0 to 3.2E-14	0 to 6.4E-15
Size (Meters):	0.8 x 0.3 x 0.6	same	same
Input Energy: (kW)	10	same	same

From these parameters, the ion guns were modeled as firing at their maximum energy and rate. They were modeled as being across from one another. A collision can be modeled using the equations shown in the diagram below. This follows a rule of engineering: start with the simplest model first. The model is grossly unrealistic - but, it gives some equations to build on. The question we want to answer is: what voltage is needed in the center to fuse a given fuel? Ideally, we want the fuel to hit each other at the correct slam energy. Our simple model says collision energy depends on three things: the angle of collision, the injection energy and the voltage drop. We set the angle at 180 degrees. The injection energy, is set by our ion guns operating a full power. We set the collisional energy equal to the slam energy and finally we have an estimate for the voltage drop in the center. This is shown below.

$$Impact\ Energy_1 = Voltage\ Drop * Charge_1 + Injection\ Energy_1$$
$$Impact\ Energy_2 = Voltage\ Drop * Charge_2 + Injection\ Energy_2$$
$$Slam\ Energy = Abs(Sine\left(\frac{degrees}{2}\right))*(Impact\ Energy_1 + Impact\ Energy_2)$$





	Joules		Coulomb	Joules	Kilovolts	
Reaction:	Injection:	Angle:	D,T Charge:	Slam Energy:	Well Voltage:	
D & T -> a + n	6.40E-16	180	1.60E-19	1.0254E-14	28	
D & D -> T + p	6.40E-15	180	1.60E-19	2.0027E-13	585	
D & D -> He3 + n	6.40E-15	180	1.60E-19	2.8038E-13	835	
						Kilovolts
Reaction:	P Injection:	B Injection:	B Charge:	P Charge:	Slam Energy:	Well Voltage:
P & B11 -> 3a	6.40E-15	3.20E-14	8.0105E-19	1.602E-19	8.8116E-14	52

Rider, using a much more sophisticated model estimated wells of 60, 300 and 900 kilovolts for DT, DD and PB11, respectively [17]. We will also use his numbers. We leave this analysis open for your additions, criticism and comments.

Vignette: Problems with Ion Injection:

A note on ion injection is appropriate here. We purposed on this blog that: ion losses most likely happens right after an ion is injected. This is because the energies to inject and escape the well, are most likely close in value. Rider raised the issue of ion injection in his 1994 paper, here is an excerpt:

> "...It may not even be possible to inject ions that deeply into the well with any accuracy, and it would be still more difficult to inject them more deeply to try to reduce the upscattering losses. Even if ions could be injected more deeply, for the ions to have the same energy the well depth would have to be increased by a corresponding amount. This increased well depth would in turn increase the power loss due to electrons escaping the system…"

This needs to be addressed. It certainly could make the reactor unworkable. It could make the idea a dud. We need data. The counter argument would be that the plasma inside the center forms some kind of structure. Wither the plasma experiences a diamagnetic whiffle ball, or a space charged limited virtual anode, or highly efficient electron recirculation or some edge annealing effect – the plasma is somehow more ordered. Being more ordered, or better confined, or less prone to electron loss, the reactor would then have a deeper well with less input energy. A deeper well would allow for deeper ion injection. If this is, in fact happening would it be enough to overcome Riders objections? Until we have published, credible data, we cannot tell how credible this counter argument is.

Electron Guns Needed:

From the voltage drop and gausses law, we can get a rough estimate how many electrons are needed in the center. At some high number of electrons the Brillouin limit starts become important. As we currently understand it, this limits how much plasma can be fit in a given space. We admit however, that the Brillouin limit is very poorly understood by us. This would have implications on the overall size of the machine. At the limit, more electrons and ions would need more space. Someone needs to investigate this question. From the number of electrons, the pulse time, the fuel burn rate of a kilogram an hour, we can get a rough estimate of how many electron guns would be needed. We assumed the ions and electrons were injected at a ratio of 1:2. We also assumed that the reactor had three electron guns. Below is an example calculation of this, using gauss's law.

$$\oint_{\text{A Closed Surface}} \text{Electric Field}\, d\overline{\text{Aera}} = 28{,}000\ \text{volts} = \frac{\text{Net Number of Electrons} * 1.602E - 19\ \text{Columbs}}{8.854\text{E-}12 \, \frac{\text{Columbs}^2}{\text{Newtons} * \text{Meter}}}$$

$$\boldsymbol{Voltage\ for\ DD\ [28{,}000\ Volts]} = \frac{(\boldsymbol{\#of\ electrons}[\mathbf{3.0E12}] - \boldsymbol{\#of\ ions}\ [\mathbf{1.5E12}]) * \boldsymbol{elem\ charge}[\mathbf{1.6E-19\ C}]}{\mathbf{8.854}\boldsymbol{E} - \mathbf{12}\, \frac{\boldsymbol{Columbs^2}}{\boldsymbol{Newtons * Meter}}}$$

$$\boldsymbol{Firing\ Time} = \frac{\boldsymbol{\#\ of\ electrons}}{\boldsymbol{Number\ of\ guns * electron\ firing\ rate}} \rightarrow \boldsymbol{\#\ of\ pulses} = \frac{\boldsymbol{Firing\ time}}{\boldsymbol{Max\ Pulse\ Time}}$$

	kilovolts	1 ion : 2 electrons		Three: 200 mAmp e-guns		Two: Ion 200 mAmp Guns	
Reaction:	Net Voltage:	# of Electrons:	# of Ions:	Electron Fill up (sec):	Pulses:	ion fill up (sec)	Pulses:
D & T -> a + n	28	3.09E+12	1.55E+12	0.001	8	0.001	6

D & D -> T + p	585	6.47E+13	3.23E+13	0.017	173	0.013	129
D & D -> He3 + n	835	9.23E+13	4.61E+13	0.025	246	0.018	185
P & B11 -> 3a	52	5.72E+12	2.86E+12	0.002	15	0.01	57
Rider - DT	60	6.63E+12	3.32E+12	0.002	18	0.001	13
Rider - DD	300	3.32E+13	1.66E+13	0.009	89	0.007	66
Rider - PB11	900	9.95E+13	4.97E+13	0.027	266	0.10	996

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