Explaining the Counter Argument

Hello Polywell Fans,

I have been working steadily since May of 2010 on explaining "A general critique of internal-electrostatic confinement fusion systems". This paper was published in 1995 and was written by Dr. Todd Rider. It is this document, as well as Riders' thesis, which represent the largest theoretical arguments against the polywell working. My goal is to explain this paper to you. We need to see if Riders' arguments and Bussards' statements about the Polywell agree or disagree.

So far I have explained 70% of Rider's paper. Though my work is not yet finished, I feel comfortable releasing the first portion, here on the internet. It is included below.

Sincerely,
The Polywell Guy.
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Explanation of "a general critique of internal-electrostatic confinement fusion systems"

Science is a conversation. One researcher stands up and says: "this is the way it is." They do this by writing a paper, filled with evidence which backs up their argument. A few years and sometimes decades go by and, someone else stands up and responds: "No. This is the way it is." and so on. We are in just such a conversation about the polywell; the very early stages. The first statement - I would call the opening argument - was "The Polywell: A spherically Convergent Ion Focus Concept" published by Nicholas Krall, with assistance from Robert Bussard in 1992. In that paper, Krall explains the idea of the polywell, and gives an overview of its basic strengths and weaknesses. This caused a rumbling in the physics community and three years later an answer was advanced. This came from Dr. Todd Rider, whose 1995 paper: "A general critique of internal-electrostatic confinement fusion systems" gave theoretical reasons against the polywell working. This paper, combined with Rider's masters and doctoral theses were often pointed too as the reason the polywell would not work. Eleven years went by. In 2006 Robert Bussard responded, in his "should Google Go Nuclear" speech and subsequent "The advent of clean nuclear fusion: super performance space power and propulsion" paper. The highlights of Bussards retort? Plasma inside the device behaves differently then expected. Phenomena such as the Whiffle ball and the virtual anode break Riders' old assumptions. There must be something to Bussards' response, because the Navy gave the team 7.8 million dollars.

I got a hold of Rider's '95 paper. It presents a maze of theoretical assumptions and mathematical argument against the polywell. Rider tackles - one by one - phenomena inside the polywell. He steals formulas from other situations and applies them to the polywell. This is about the best one could expect; the polywell was very new idea in 1995. He makes order of magnitude arguments which both show you how many ways the polywell can fail and, how many ways Rider could have gotten it wrong. The more I dove into the paper, the more respect I had for Rider. For one man to tackle such a problem is audacious and the work is certainly scholarly. However, the topic is so complicated it is hard to imagine the work did not miss something. For most papers in science, this may not be such an issue. However the polywell could be a major invention for mankind. A way to produce cheap clean abundant electricity is not a trivial matter. In this situation, it is my stance that raw data is needed to verify these claims. I do not care if the data indicates this idea is a flop. It is too important to leave up to theory.

My favorite part of Rider's paper, is the mass and energy balances. Rider analyzed energy flow within the reactor; quantifying the amount coming in, going out, and being exchanged between the ions and electrons. He tried to estimate how fast these energy transfers would happen. He compared these rates, to the rates of fusion. The paper also looked at the flow of mass. How many ions and electrons were entering and leaving the system. He attempted to quantify ion-ion collision time, calculate how fast ions were lost and how fast the polywell thermalized. This offers us an interesting and new perspective on the polywell.

What follows is my attempt to explain this paper. It is very complex - like navigating a maze. It is not perfect, I am sure I made mistakes. What you are reading is the result of several months of volunteer work. What have I learned? Rider made lots of assumptions. His work is not solid. The topic is maddeningly complex – and there is a good chance the analysis is flawed. It is hard to see how any one man could have account for all the factors in play inside the polywell. It makes one want to just build the thing and see what kind of results you would get.

If the polywell works, it would be a major invention, akin to the automobile or the computer. A cheap, clean way to produce abundant electricity; it would help stop global warming, help stop the energy crisis and make some people very rich. Not to mention, getting the US out of recession. This is not something we can afford to leave up to theory alone. The stakes are too high. We need data, not complex estimations. I do not care if the data indicates that the idea is a failure. I will accept that. We need to know. Riders' paper cannot be taken as a definitive no on this idea, as you will see, he makes many estimations and approximations, stealing formulas from other fusion devices. It should make you realize how badly testing of this idea is needed. We need to know for sure. As the famous physicist Richard Feynman said: "It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." Please enjoy this unraveling of Riders paper.

Synopsis of "A general critique of internal-electrostatic confinement fusion systems"
Author: Dr. Todd Rider, MIT
Published: Plasma Physics, June 1995

Rider opens his paper with a description of electrostatic confinement devices. These devices make deep electrostatic wells. Ions are shot into the center of these wells. The ions fall down the well. They build up speed and smash together in the center. They can hit hard enough to fuse. Here is a graphic of this from Mr. Kralls' paper:

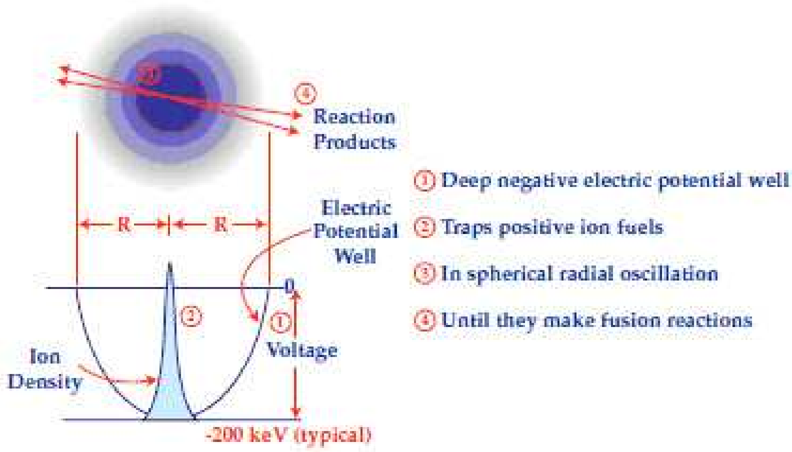
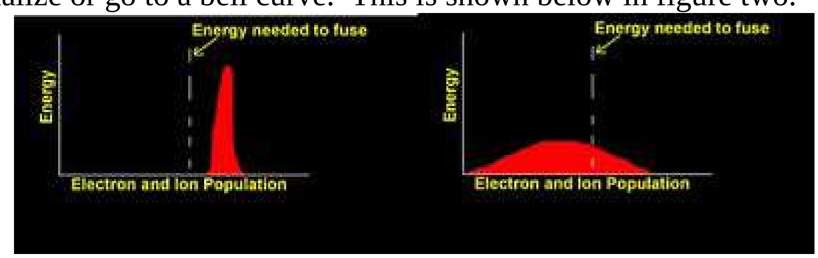


Figure 1: Mr. Kralls' diagram describing the polywell.

Mr. Kralls' paper also suggests that you could "squeeze" the plasma using sound waves. The idea is by blasting microwaves into the center the plasma would squeeze together. Riders' paper will look at both normal Polywells and these, microwave enhanced Polywells. There are two important polywell properties that Krall and Bussard suggested:

1. That the material inside the polywell could maintain a sharp energy distribution[1,2]. The ions would not thermalize or go to a bell curve. This is shown below in figure two.



The Polywell will do this. The Polywell will not do this.

Figure 2: A comparison of a non-thermalized and thermalized polywell.

2. That polywell could maintain two different ion temperatures[2]. For example, if we were fusing deuterium and deuterium -the second easiest fusion reaction- one group of ions could be cold, one group could be hot. These temperature differences could be maintained.

Rider is going to look at both these claims. First, can the material inside the polywell not go to a bell curve? This is very important. On this point, there is agreement from Rider, Ligon, Bussard and Krall. If the material goes to a bell curve, if the polywell thermalizes, it will fail. Rider starts by figuring out where to look for thermalization: in the center. Rider models the ions inside the Polywell into three parts: the core, the mantle and the edge. A picture of this model is below in figure three. Rider showed that collisional effects were about 100 times less in the edges, then in the dense central core.

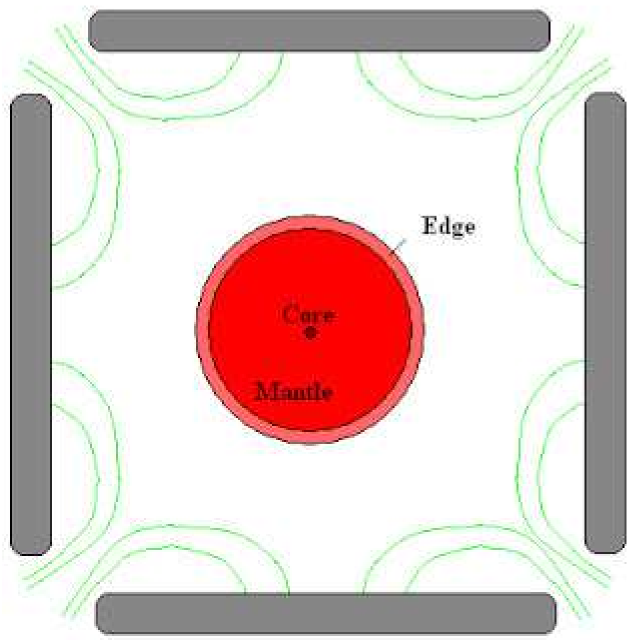


Figure 3: This is a rough sketch of ion distributions inside the Polywell, as modeled by Rider (not to scale). Some magnetic field lines are shown in green, the magnetics are shown in gray. Ion density gets higher as you get closer to the center. Rider broke up the ion concentrations in three zones, the core, the mantle and the edge. He even assigned rough radiuses to these sizes. The core radius was about 1unit, the mantle radius was between 50 and 80 units, while the edge was about 100 units out.

<u>Assumptions' Rider Makes:</u>

These collisional effects lead to the focused ion ball in the center to spread out. This is degradation of focusing and, is a problem Rider states he will ignore for this paper. There is good reason to believe that core convergence will rapidly degrade. By not assuming any degradation of focusing, Rider is assuming that the picture above remains constant throughout all of the Polywell's operation; a core, a mantle and an edge. Rider then looks at various effects inside the polywell and notes how some depend on where you are relative to the center, and some depend on the plasma volume and density.

1/Radius Dependent Effects (outside core)	Effects Independent of Plasma Volume, Density (everywhere)
1. Fusion	1. Fusion
2. X-ray cooling	2. X-ray cooling
3. Ion and Electron Energy Exchange	3. Scattering
4. Thermalization	

Table 1: This is effects and their dependence on radius, volume and density inside the polywell (for good converged systems).

This means that the size of the core will only slightly change fusion, x-ray cooling, thermalization and ion to electron energy exchange. This also means it is safe for Rider to compare fusion, x-ray cooling and scattering effects without having to worry about the specific volume or density of the polywell. I want to point out that these assumptions - are just that - assumptions, not absolute truths. In reality, fusion rate, x-ray cooling, energy exchange, thermalization and scattering are not absolutely radially dependent nor are they independent of volume and density.

Rider is going to assume the core as uniform in all directions, with the same energy amounts and temperatures inside the core. Rider assumes that the fusion fuel is uniformly mixed everywhere with any significant density. He also assumes the plasma is quasineutral. Quasineutral means that there is no net charge in volume, the density of negative electrons and the density of positive ions cancel out. This is shown mathematically below.

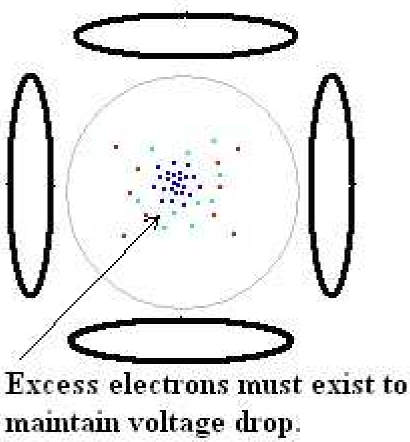
$$\text{Density}_{\text{electrons}} = \text{Density}_{\text{Fuel1}} * \text{Charge}_{\text{Fuel1}} + \text{Density}_{\text{Fuel2}} * \text{Charge}_{\text{Fuel2}} \quad (1)$$

The quasineutral assumption stated mathematically: the density of the electric charge equals the density of the ion charge.

This seems to be one of the most questionable assumptions. It is a clear fact that to maintain a potential well, there needs to be more electrons than ions inside the polywell. The polywell cannot work any other way. If there are more electrons, then only under specific conditions would their densities work out, such that the above expression would hold. Conditions where the electrons occupied a different volume, the charges worked out or the assumption was for a local volume, not the entire reactor. Furthermore, if the Whiffle ball and the virtual anode do exist, then there will be regions of the center with excess ions and excess electrons. There, quasineutrality may not hold. Below is an example explaining quasineutrality, using DT fuel.

$$\frac{\text{Electrons}}{\text{Volume}} = \frac{\text{Deuterium Ions}}{\text{Volume}} * \text{Charge On Dueterium} + \frac{\text{Tritium Ions}}{\text{Volume}} * \text{Charge On Tritium} \rightarrow$$

$$\frac{25}{10} \neq \frac{10}{10} * 1 + \frac{10}{10} * 1$$



Example 1: working out what the quasineutrality assumption would be for an example polywell reactor.

A. Calculating The Fusion Power Density:

It makes sense to start by calculating how fast you expect to get energy out of this device. That way, you can compare this rate to the rates of all these other effects.

$$\frac{\text{FusionPower}}{\text{Volume}} = \langle \text{CrossSection} * \text{velocity} \rangle * \text{EnergyReleased} * n_{\text{fuel1}} * n_{\text{fuel3}} \quad (2)$$

Equation two is the fusion power per volume. The cross section is the measure of the "fusibility" of two atoms when they smash into one another at some velocity. Rider applies the quasineutral assumption to this equation, changes the units to cgs -except for energy (eV)- and, rearranges the equation. Looking at the case of deuterium, deuterium fusion, where the fuel densities are the same for all the deuterium ions, Rider can make the following approximation:

$$\frac{\text{FusionPower}}{\text{Volume}} \approx \langle \text{CrossSection} * \text{velocity} \rangle * \text{EnergyReleased} * \frac{\text{ElectronDensity}^2}{2 * \text{ChargeOnIons}^2} \quad (3)$$

Rider now has the equation in the form he wanted all along; one independent of fuel density. The above expression estimates the rate of fusion power coming off the reactor in a given volume.

B. Calculating An Ion Lifetime In Device:

Based on this equation above, Rider figures that the time it would take an ion entering the system and getting fused would be.

$$\text{Time To Fusion} = \frac{1}{\text{Effective Density Of Ions} * < \text{CrossSection} * \text{Velocity} >} \quad (4)$$

This equation works for dissimilar ion fusion (aka A+B fusion) in the case of A + A fusion you divide the above equation by two.

C. Rate of Energy Transfer Between Two Groups of Ions:

We have an equation for how energy is transferred from two different clouds of ions. The guy who figured this out was Lyman J Spitzer, a physics professor at Princeton, back in the '50s and '60s. If you are just looking at ion cloud Two being heated by ion cloud One, here is the equation:

$$\frac{\text{Energy Transferred To Ion 2}}{\text{Volume}} = \frac{3}{2} * \text{Density Ion 2} * \frac{d(\text{Temperature Of Ion 2})}{d\,\text{time}} \quad (5)$$

D. Can you keep ions at 2 different temperatures? Case 1

Rider wants to use equation five above to answer a very important question: can you keep two ion clouds at two different temperatures? This is a really important question to answer. Lets' assume inside the polywell we have cold ions and hot ions. First looking at the cold ions; we are injecting cold ions and as they get fused they leave. Also the cold ions pick up energy from the hot ions also flying around in the center. Given this, Rider gives us the following energy balance:

$$\text{Energy Of Cold Ions} = \text{Energy Of Cold Ions Injected} - \text{Energy Of Fused Ions Leaving} + \text{Energy From Hot Ions} \quad (6)$$

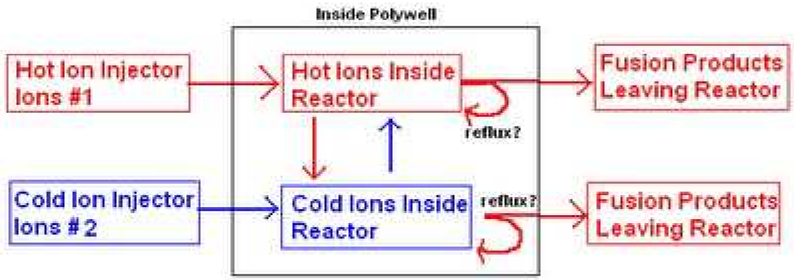


Figure 4: Schematic of some of the energy flows analyzed in section D, by no means a complete picture of the energy flows inside the polywell.

This energy balance, equation six, is also shown schematically in figure four, which shows the flow of energy inside just the ion cloud. I have a few questions here. I can think of a few other sources of heat, I do not know if Rider did not include them because they are insignificant, or if they cannot be a mechanism for heating. Some suggestions would be: heat transfer from the electron cloud, annealing from the potential well, radiation from the walls, and x-ray heating from within the cloud. Electron heating of the ion cloud is an easy thing to ignore; an electron is about 1,836 times less massive then an ion. Also the fusion products leaving have lots of energy, and they will re-heat material as they bump into ions on their flight out (for DD fusion this is about 3.64 MeV, loads of energy). Incidentally, they will probably not incite other fusion reactions, though the products of DD fusion can, in theory, undergo a cascade of other fusion reactions. Rider now works out two equations: the ion to ion heating rate, and the ion cooling rate. The ion cooling rate is *solely* due to the replacement of hot fused ions with cold ions coming in from outside.

$$\frac{\text{Ion}_1\ \text{To Ion}_2\ \text{Heating}}{\text{Volume}} = \frac{3}{2} * \text{Density}_{\text{ion2}} * \frac{d(\text{Temp}_{\text{ion2}})}{d\text{Time}}$$

$$\frac{\text{Ion Cooling Rate}}{\text{Volume}} = \frac{3}{2} * \text{Temperature}_{\text{ion2}} * \text{Density}_{\text{ion1}} * \text{Density}_{\text{ion2}} \langle \text{CrossSection} * \text{Velocity} \rangle \quad (7,8)$$

He is looking specifically at the ion two, population. He balances the two expressions and integrates over space and density, coming to this expression for the cold ion's temperature.

$$T_2 = T_1 \left[1 + \frac{7.4E-6 * \langle \text{CrossSection} * \text{Vel} \rangle * (\#\text{ofProtons}_2 * T_2 + \#\text{ofProtons}_1 * T_1)^{3/2}}{\sqrt{\#\text{ofProtons}_1 * \#\text{ofProtons}_2} * Z_2^{\,2} * Z_1^{\,2} \text{Ln}[\Lambda_{1-2}]} \right]^{-1} \quad (9)$$

Where the Ln() term is the Coulomb logarithm. The Coulomb logarithm is a way to find the mean free path for an ion in a big cloud of ions. Lets say you have a cloud of ions. You know the density, the charge, the temperature of this cloud. You throw in a test ion. The coulomb logarithm is a way to tell how for that test ion could go without smacking into other ions. The Z is the atomic number it would be 1 for deuterium and 1 for tritium. By including Z, Rider has made his nice equation work for lots of fuel combinations. *From this Rider calculates that the cold ion temperature would <u>be within 5% of the hot</u> <u>ion temperature.</u>* If that were true, then Rider argues you could only keep the two cloud temperature separated by a maximum of 5%.

<u>D. Can you keep ions at 2 different temperatures? Case II</u>

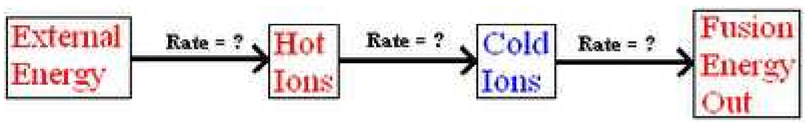
Rider looks at another method of maintaining two different temperatures, a hypothetical case. Assume you keep the cold ions cold, artificially; how much cooling would you need to pull this off? To figure this out, Rider needs to know the velocity of the collisions between the ions. He assumes all collision velocities are

$$\text{Velocity of ion 1} \approx \sqrt{\frac{3 * \text{Temperature}_{\text{Ion1}}}{\text{Mass}_{\text{Ion1}}}} \qquad \text{Velocity of Ion 2} = 0 \tag{10}$$

This is an estimation based on the statistics for such a case. There will certainly be collisions at much higher and lower energies. If this is true then all the energy transferred from the really hot ions to the really cold ions will be via collisions. Rider can then use his ion to ion heating equation, equation seven. Is Rider missing any energy flows? I do not know. Rider divides the energy transfer rate by the fusion power rate to arrive at equation 11.

$$\frac{\text{EnergyTransferTo"Hot"Ion2}}{\text{FusionPower}} = 1.2E-13 * \frac{\text{Mass}_C}{\text{Mass}_H} * \frac{Z_C^{\,2} * Z_H^{\,2} * Ln(\Lambda_{\text{Hh-Cld}})}{\text{CrossSection} * \text{EnergyReleased} * \text{Temp}_H} \tag{11}$$

What Rider is actually doing by this is comparing how fast we can fusion energy out, to how fast energy would transfer from one cloud to the other. The idea is, if one cloud can be heated, would it lose energy to the cold cloud faster, than fusion energy comes out of the reactor? In addition, there is another rate to consider: the rate it takes to heat the hot cloud in the first place.



It is important to point out that Rider's analysis do contain some simplifications. First of all, there are the assumptions on collision velocity and his estimation on the Columbic logarithm value. These are somewhat reasonable. Next, Rider is only looking at two rates, *ion to ion* energy transfer and fusion rate. There are, electron to ion energy transfers (albeit small), x-ray heating and cooling, ion annealing, Cyclotron radiation and fusion products reheating the cloud; just to name a few other phenomena which could effect ion temperature.

Rider is correct that if one could maintain a temperature difference this would vastly improve Polywell performance. For instance, in the P-B11 reaction, the reaction everyone wants to do, it is helpful if we keep the borons cold and the protons hot. Ideally we would maintain this temperature difference and run the reaction at 620,000 eV - to take advantage of the peak cross section for the reaction. I have read[5] that the optimum voltage for pB11 was 550,000 eV; this needs to be figured out. Rider plugs in the numbers for this situation, into his equation and comes up with this comparison.

$$\frac{\text{Energy Transfer To "Hot" Ion2}}{\text{Fusion Power}} \approx 1.4 \tag{12}$$

This argument makes a Polywell operating like this: an energy loser. What he is saying is: in this case you would always need to put in energy faster then you can get it out. This is, of course, a hypothetical case. *Based on these calculations Rider will, from now on, <u>assume all clouds of ions have the same average temperature</u>.* Rider accurately points out that even if you had a big cloud of ions in the center, in which each individual ion was at the same temperature, not all the ions would collide correctly. It is these kinds of calculations that make me want actual, real, data about polywell operation.