The World's Simplest Fusion Reactor Revisited

Or

The Not-Quite-So-Simple Fusion Reactor, and How They Made It Work

Tom Ligon
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Analog published my fact article "The World's Simplest Fusion Reactor, and How to Make It Work" in the December 1998 issue[1]. Those of you who read it probably wonder if anything became of the technology and project I described. Alas, for many years, requirements for confidentiality prevented me from saying any more about it. But things have changed, and I can now tell you the good news.

I'll save the best news for later, and just start you out with the *very* good news.

To bring you newer readers up to speed, the article described a method for making hot fusion that was championed by Philo T. Farnsworth, one of the inventors of television, back in the 1950's and 60's. The device, the fusor, which he invented and Dr. Robert Hirsch improved upon, was an electrostatic particle accelerator that converged fusion fuel ions at the center of a spherical vacuum chamber, where they tended to collide head-on. While this little reactor had shortcomings that prevented it from ever reaching breakeven, it nonetheless showed how easy fusion is once you stop thinking *thermo*nuclear and realize that it is particle velocity, not heat, that triggers fusion. The article went on to describe how easy these things are to build, and suggested they might even make good high school science projects.

Finally, I described the new and improved version of this scheme that Dr. Robert W. Bussard was attempting to build, one that might lead to working power reactors, including powerplants suitable for spacecraft. And one of the most intriguing things about Dr. Bussard's device, is it would be able to burn a much more desirable fuel, $p\text{-}B^{11}$.

A few months before the article was submitted, I built a crude version of a Hirsch-Farnsworth fusor, which I took to a Tesla Coil Builders of Richmond party put on at the home of noted coil builder Richard Hull. I also carried copies of a draft of the article. While I was standing there in awe of Richard's mighty Tesla coil, the other attendees were falling madly in love with the idea of building their own tabletop hot fusion reactors.

Richard had his first model up and running in a matter of weeks, and several other members of the group were close behind. By the time the article was in print, there was already a small core of amateur fusor builders chatting away on the internet.   They were soon joined by a cadre of new blood inspired by the *Analog* article. And that included some high school students.

One of those students, Michael Li, helped by Richard and his friends, won second prize (and a $75,000 scholarship) in the Intel Science Talent Search in 2003 for his work on the fusor. It is *the* big U.S. science fair. As this is written, at least eight high school students have made measurable fusion using fusors, and two more are getting close.

The amateur effort has now evolved into a powerhouse of talent, centered on a website called fusor.net. And *Analog* can take a lot of the credit for getting the ball rolling. That article reached tens of thousands of science-minded subscribers. Some of you picked up the ball and ran with it. I'm mighty proud of you!   And enough of you thought highly enough of the article that you voted for it in AnaLab, and it won fact article of the year in the 1999 poll.

The Great News, the Bad News, and the Good News

But that is old news. You want to know where Dr. Bussard's project has led. And that's the great news. In the fall of 2005, he finally worked the bugs out of the little proof of concept devices we had been working on, and got one to do some serious fusion[2]. And then there's the bad news. He did that on the last of his research funds, and then had to close the lab. He is presently seeking funds to get the program started again. But the good news in that is, without the previous sources of funds telling us to stay quiet, we can now tell the world.

How Was it Done?

Ah, you notice I'm using the pronoun "we"? Yes, yours truly was right in the thick of it. So let me take you back to 1995, and how I met Dr. Robert. W. Bussard. Imagine, you're a science fiction author, discouraged with your old job and about to quit and start a consulting business. You get wind of the fact that there's someone in the area working with high vacuum equipment, whose last name is Bussard. So you think, Bussard, vacuum, space, fusion, interstellar ramjets? The inventor of the gizmo behind science fiction classics like *Tau Zero*, the *Ringworld* stories, and many others? Could it be *that* Bussard? So I found the address, dropped by with my newsletter, résumé, and an introductory letter, and knocked on the door of the little office two miles from my home. Nobody was there, but the sign by the door declared that it was the Energy/Matter Conversion Corporation. I slipped my propaganda under the door, smiling as I got the connection to Einstein's famous formula.

Some moments you just never forget. A few weeks later I was sitting at my computer, when my business phone rang. I answered eagerly (that thing didn't ring much). The voice on the other end called himself R.W. Bussard, and wondered if Tom Ligon was available. "I certainly am," I said, "but I just have to know if this is *the* Robert. W. Bussard, as in interstellar ramjets?"

"I guess I'll never live that down," he admitted, and then he invited me in for an interview.

We hit it off smashingly, and I instantly recognized that his scheme was a superior version of something I had dreamed up while studying health physics, but never pursued. I went to work for him as soon as he got a little dribble of funding to start back up. I felt like I'd just gotten the opportunity of a thousand lifetimes. If you can only afford one lab rat for your project, I'm the jack-of-all-technical-trades you want, and the company could only afford one lab rat at that time. I worked on the project for about five and a half years. By that time, the project had gotten more funding, and moved out to San Diego. I agreed to move out there for a year or two to help him get the bigger lab going.

So, what was it like to work at EMC^2? The small hand-selected technical staff was composed of amazingly talented people, highly motivated by a desire to make fusion, a true dream team. The lab ran on physics and passion. Dr. Bussard is awesome. His career stems from a very early and intense desire to make spaceflight practical, and, with R. D. DeLauer, he literally "wrote the book" on nuclear rocket propulsion. His first degree was as an engineer, and only after developing the first working fission rocket engine did he head off to Princeton to earn his PhD in physics. While he is a first-rate physicist, he still has the heart of an engineer and inventor. It was always great fun to watch him at a blackboard, *NRL Plasma Formulary* in one hand, chalk in the other, working problems faster than I could follow them with a calculator.

I should mention a few of the others in this effort. Dr. Nicholas A. Krall is one of the best theoretical plasma physicists ever, and has collaborated on this project from the start. Lorin Jameson is a computer whiz and physicist that put the math of Bussard and Krall into functioning computer programs like EIXL, to analyze the data from the experimental runs and predict performance of larger systems. Later on, Mike Wray, Mike Skillicorn, Ray Hulsman, and Noli Casama were the ones who made the machine that finally worked. And none of this would have happened without EMC^2 president, Dolly Gray, the only person on Earth who can make R. W. Bussard do what he needs to do when he doesn't want to.

Two and a half years after the move to San Diego, he had hired enough talent that I started to feel like excess baggage, so we parted company and I came back to Virginia and found another amazing job. But we stayed in touch, I remain a true believer in the project, and wonder if I'll ever again have a chance to literally save the world. Maybe this article will help.

Basic Principles

Let's review the idea of Inertial Electrostatic Fusion. A little earlier I described a device called a Hirsch-Farnsworth fusor. This remarkably simple device consists of an outer vacuum container (typically spherical, but any shape will work) and a spherical inner grid (Figure 1). This device is the descendent of a spherical vacuum tube designed by Langmuir and Blodgette in 1924[3]. If you pump the chamber down to a vacuum, backfill with a trace of deuterium gas, and apply high negative voltage to the inner grid, at the right combination of pressure and voltage, a glow discharge will light off. A glow discharge, also called a Paschen discharge or Paschen arc, is what occurs in a neon sign. Near the low-pressure end of this glow discharge region, with voltages of ten kilovolts or higher, a distinct bright spot can be seen in the center of the fusor's inner grid, and deuterium-deuterium fusion starts to occur. Deuterium ions (deuterons, the + marks) formed near the outer grid or chamber walls are attracted to the inner grid by the high negative voltage. They accelerate toward the grid, which is very open, and most pass on to the center, where density rises rapidly and the chance for fusion goes up with it. That's just how simple fusion is. The fusion reaction is driven by particle velocity, not heat. You don't need to "heat" the fuel by applying a hundred million degree Kelvin torch the way tokamaks or laser fusion approaches run. Plain old high voltage acceleration works fine. In fact, because it is not random, but instead both directed and monoenergetic, it works a lot better than Maxwellian heat.

Alas, the simple machine shown in Figure 1 is flawed. Not every deuteron that shoots into the center of the device manages to collide sufficiently head-on with another deuteron to produce fusion. Some hit and bounce off, and most just miss. In fact, only a few ions produce fusion on any pass. But, if you could build the machine so that the ions conserve energy and can make many passes thru the machine, that wouldn't matter. Eventually they would fuse. But those darned grids are the problem. It just isn't practical to make them more than about 98% transparent, and the usual figures are more like 90-95%. On every pass, 2% or more of the deuterons will hit a grid wire and be lost, and that's too many to make a breakeven reactor, by a very wide margin.

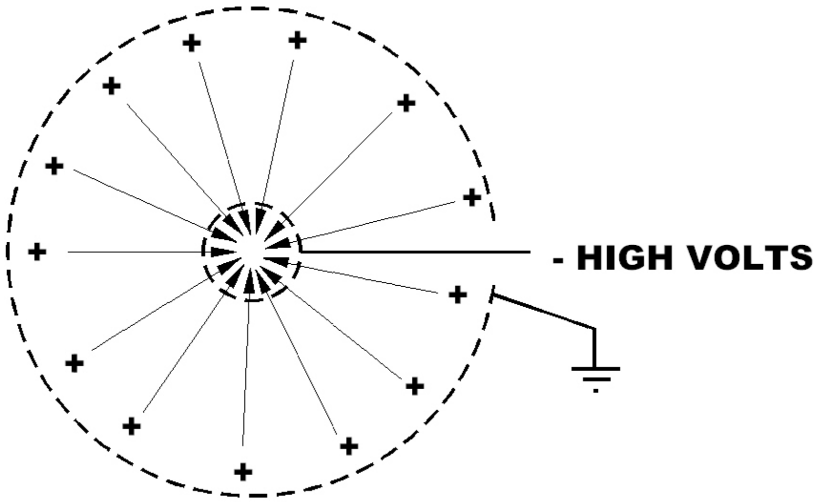

Figure 1. A Hirsch-Farnsworth "fusor" ion accelerator.

So that brings us to Figure 2. The Elmore-Tuck-Watson machine[4] is the reverse of a Hirsch Farnsworth machine. The inner grid is positively charged instead of negatively charged, so it attracts electrons instead of ions. Electrons pass thru the inner grid and converge on the center, pass out the other side, then come back for another pass. The result, at sufficiently high current and voltage, is a very dense region of negative charge in the center of the machine. This is really what you want instead of the negatively-charged grid in the Hirsch-Farnsworth machine. If you generate deuterons just inside the inner grid of an Elmore-Tuck-Watson machine, they'll oscillate happily thru that cloud of electrons for a very long time. The electrons and ions are at such high energy that they essentially can't recombine to any significant degree, so, in principle, the ions might make enough passes thru that central region to produce meaningful fusion.

Ah, but what about the electrons? Of course, the machine still has grids, and they still will have about the same limits of transparency, and about 2% or more of the electrons will be lost on every pass. That loss kills this machine as a power reactor.

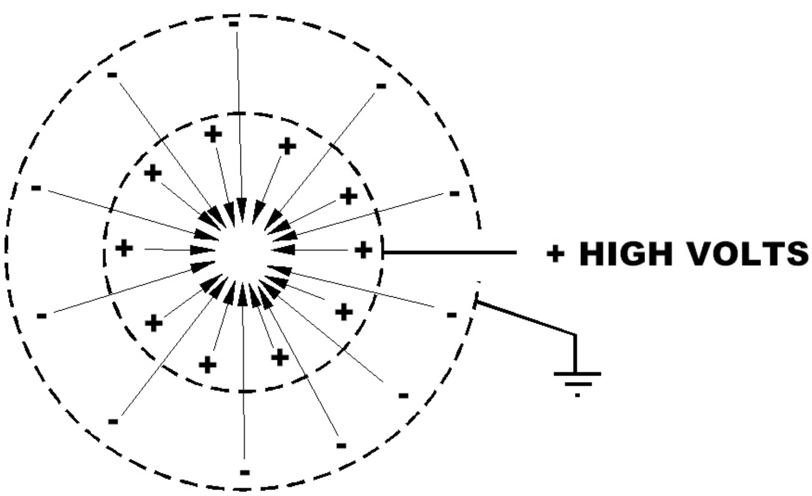

Figure 2. An Elmore-Tuck-Watson electron accelerator with ion-accelerating central potential well.

Dr. Bussard once designed a small tokamak called the "Riggatron" (described in "World's Simplest"). Although he maintains to this day that it would have worked, he was unable to secure sufficient funds to actually build it. Perhaps that was just as well, for it got Dr. Bussard thinking about how to get around the problems plaguing tokamaks.

Tokamaks work by employing intense magnetic fields around a toroidial vacuum vessel. The idea is that ions will spiral around the resulting "lines" of magnetic force that the magnets produce that parallel the inside surface of the torus. Deuterium and tritium ions are thousands of times as massive as electrons, and it takes a really intense magnetic field to make them stay on a line. If you run their density and energy up enough to make fusion, they tend to hop from line to line with each collision until they hit the wall and are lost. The bottom line is that's why we've been messing with tokamaks for all these decades and we're still not using them to light our homes. The most optimistic estimates say they may be working by 2040, but a more realistic estimate might be post-2100. The Electric Power Research Institute fears they'll never make power economically due to high capital costs and short life.

The New and Improved Elmore-Tuck-Watson Machine

As Dr. Bussard thought about this, he had the thought that it was a shame ions are so much more massive than electrons, because a tokamak would be able to confine electrons at high density far more easily than it would ions of fusion fuel. And then he thought about Hirsch and Farnsworth and the idea that Elmore, Tuck, and Watson had, and a little light went on in his head. He began to wonder if an Elmore-Tuck-Watson machine might actually work if the accelerating grid could be magnetically insulated. And so was born the notion of building a "quasi-spherical" device into which one could inject high-energy electrons. He realized if he took certain geometries, including an equilateral pyramid, a cube, or a dodecahedron, and placed a circular solenoid electromagnet on each face, each pointing with the same pole inward, a suitable electron containment might be achieved. All of these devices are described as Polywell™ designs.

Please understand that this is not a *thermo*nuclear approach to fusion. It does not confine a Maxwellianized plasma in order to produce fusion. The "confinement" principle for the fuel ions here is purely due to their attraction to the electric field produced by the electrons. What that gives us is an ideal form of the Farnsworth fusor, with no grids, within the confines of the magnetic grid. The fusion is more straightforward because the fuel ions converge to a region of high density with the same kinetic energy, sufficient to trigger fusion, rather than depending on some tiny tail of a Boltzmann distribution of energies. Ions not producing fusion have an excellent chance of circulating in and out of this potential well for many passes until they do fuse. The magnets are there strictly for the electrons.

The underlying principle driving the concept is the electron potential well. In order to achieve the desired well depths for D-D fusion, excess electron densities on the order of a million electrons per cubic centimeter are required. It is very important to realize that this is not a multiplier. You *don't* need a *million times more* electrons than ions in the center of the machine, you only need *a million more electrons per cc* than ions. If there are 1.000000×10^{12} ions per cubic centimeter, then 1.000001×10^{12} electrons are sufficient to maintain the well. That suggested a certain robustness of the machine to allow manipulation of ion densities to achieve fusion conditions. The plasma does not need to be overwhelmingly negative, it can, in fact, be *almost* neutral, and the higher the ion density, the closer the plasma is to neutral.

Another important principle is that the potential well is not some static thing. The electrons forming it are in constant, and very vigorous, motion. They pass in and out of the well continuously, as do the ions. While the inner grid of a fusor might classify its driving force as "electrostatic", Dr. Bussard's concept (and for that matter the Elmore-Tuck-Watson machine) are more properly considered "electrodynamic".

Several devices have been built according to one version of this scheme, in which the magnets are mounted on the outside surfaces of a vacuum chamber of the shape described. The first was HEPS, a very large pulsed machine built in the 1980's. I personally assembled and ran PXL1, a miniature of HEPS that could be run for many seconds at a time. Finally WB-5, a scaled-up and improved version of PXL-1, was built and run. None of these were successful fusion machines, but all were quite capable of trapping a lot of electrons, and provided important insights into the trapping mechanism. I won't go into them here because they were not found to be the right approach for making fusion, but the interested reader will find references at the end of the article if they wish to explore these further. Their fundamental flaw is that they cannot recirculate electrons *around* the magnets.

The machines that can produce useful fusion use magnets that operate in the geometries described, located inside the vacuum chamber, and covered with metal shells that tightly conform to the magnets. The faces and corners are open. These are magnetic grids, or magrids, and they are charged to a high positive voltage. They serve the exact same function as the inner electron accelerating grid of the Elmore-Tuck-Watson machine, except that magnetic fields are used to keep the electrons from being able to actually *hit* the grid. But the magnetic field also turned out to have an additional effect.

When I arrived at EMC2, WB-1 and WB-2 had already been built and tested. The designation WB describes the shape of the magnetic field inside a Polywell as it "inflates" with large populations of trapped electrons. The resulting field looks just like the plastic toy Wiffle Ball™ on the computer models, the holes corresponding to cusps going thru the magnets' central holes and corners. The toy-ball phenomenon tends to make the population of electrons, and consequently ions, much higher inside the magrid than outside. A high trapping factor is very helpful in achieving fusion conditions inside the magrid without having excessive densities of charged species outside the magrid. Ball formation can be visualized by imagining that the magnetic fields' graceful convex hyperbolic arches penetrating into the volume within the magrid are made of foam rubber. High electron populations act more or less like a balloon, and push back the fields, producing a nearly spherical volume, and squeeze the cusp holes to a very small effective diameter. Figure 3 illustrates the nominal magrid field condition and what happens when it operates with a large population of energetic electrons.

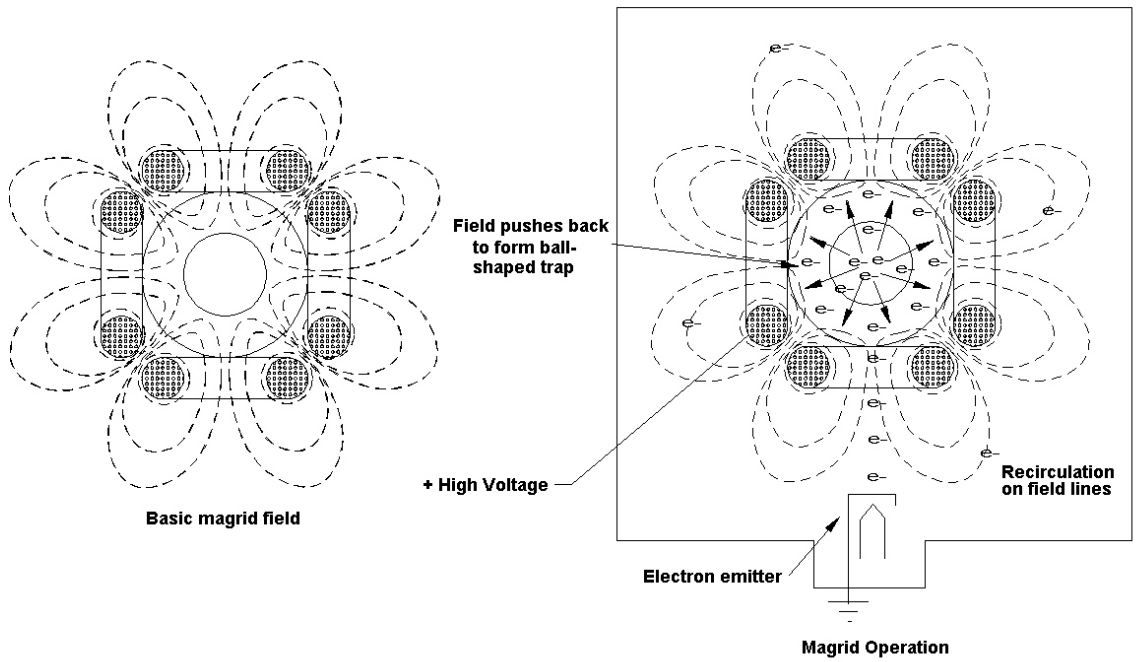

Figure 3. Magrid operation and formation of the diamagnetic trap "ball".

WB-1 was made with ceramic donut magnets, the kind used to make audio speakers. These were crudely encased in stainless steel shells, assembled into a cube, and used as a magrid. The best thing about this device was that it was really cheap and simple. The machine did show some electron trapping, and made some pretty glows, but suffered high electron losses due to the fact that magnets of this type have lines of flux going into their faces. This property will affect all permanent magnets and all iron core magnets. The first thing that pops into everybody's mind when they start trying to understand a magrid is that permanent or iron-core magnets might work, but all such devices have cusp-lines going into faces, and are unusable. But this machine would be almost as easy to build as a fusor, and I'll be disappointed if I don't see them start to show up at science fairs.

WB-2, on the other hand, was built of six copper-wire electromagnets, on square cross-section spools welded together at the corners to make a square box. Although small, WB-2 was the right general idea, and it turned out to be a vigorous electron trap. I did a large number of test runs with it, as we tried to increase both drive voltage and magnetic field strength. We even tried it with deuterium gas to see if it could be coaxed to make a little fusion. Per G. Harry Stine's axiom that the tests are not over until the prototype is destroyed, WB-2 blew a coil when we pushed it to about 4.5 kilovolts and a couple of kilogauss. It was a brave little machine, but it was too small for fusion (proving that at least that much of the mathematical models were correct).

Next we built WB-3, which was simply WB-2 scaled up to double the magnet diameters. While it did show signs of trapping electrons aggressively, and lit off all the spectacular effects seen in WB2, it just never seemed to want to "clean up". Every time we cranked up the voltage past about half the potential needed to make deuterium fusion, it seemed to generate huge quantities of hydrogen gas, swamped out the potential well, and lit off the whole interior of the machine with a bright glow. WB-3 did serve as a good platform for testing several new instruments and ionization methods. And, had we run it with deuterium-tritium, it very likely would have made measurable fusion. WB-3 was capable of running at about half the voltage needed for D-D fusion for a fairly long time before the big glow set in, and is one of the reasons I'm sure these machines are capable of running steady-state.

I left the company just as the finishing touches were being put on WB-4, a very nicely put-together machine about 50% larger than WB-3, made with water-cooled coils, and with elegantly fabricated magnet shells that were sealed up so that outgassing from the insulated copper coils was no longer a problem. They had high hopes for WB-4, and they were, in fact, able to coax some fusion from it, although at far lower levels than hoped for. It shared some of the problems with WB-2 and WB-3. It lost more electrons than it was supposed to, and tended to generate excessive gas when run hard. That excessive gas, in turn, often triggered a Paschen discharge between the magrid and the outer Faraday cage and chamber walls, that same bright discharge the earlier machines tended to generate. A Paschen discharge is what makes most amateur-built fusors run, but in a magrid machine, it shorts out the high voltage supply driving the electrons, so it must be avoided.

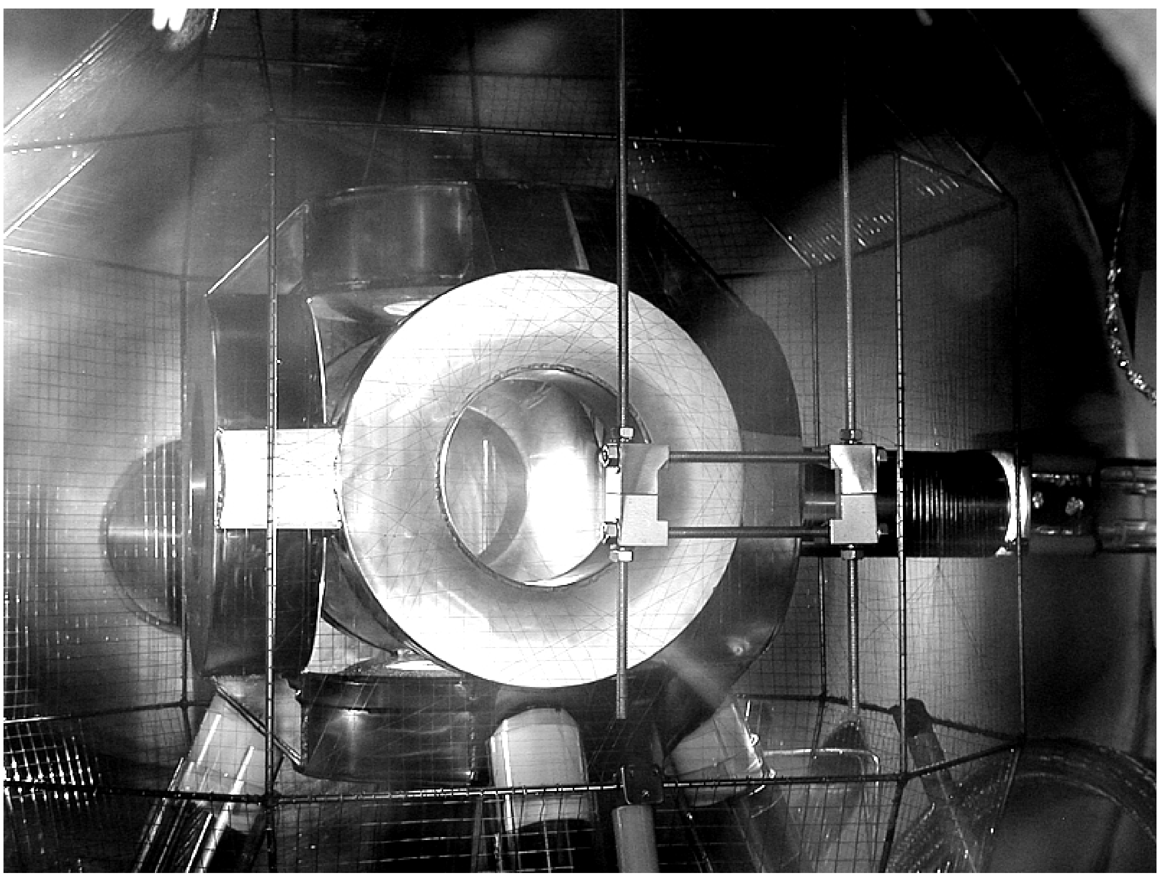

Figure 4. WB-4 in operation.

At several points in the development of these machines, Dr. Bussard described to me a problem he suspected might be plaguing them. WB-2, -3, and -4 were all assembled from six magnets whose cases were welded at four spots on each case to form a rigid cube. Each point where they touched was something he called a “funny cusp”. In principle, we knew that magnetic field lines penetrated these points, much like the lines that entered the faces on the solid-state magnets of WB-1. However, the hope was that, since this phenomenon really was just a short line, and since lines have no area, it really was not important. Also, with two magnets touching, those points had the highest magnetic field strengths in the machine, which was hoped to make them more prone to act as magnetic mirrors, which also insulate. But what these three machines had been whispering in our ears was that the funny cusp might not be so trivial after all. The other thing these machines had in common was that their magnets were made on square cross-section spools. The magnetic fields produced by the magnets were not square, though, so that meant lines of magnetic force tended to cut across the corners, making another loss path.

Alas, it was finally concluded that the maximum field strength WB-4 could produce running continuously and cooled, about 3 kilogauss, was not good enough, and it was not going to be possible to push any harder with cooled magnets of the sizes possible at that facility. The scaling law said the effectiveness of the machine should scale as B^4R^3 (magnetic field strength to the 4^{th} power, times radius cubed), and at the higher field that was needed, even pumping ice-water under pressure into the coil was going to produce steam in short order. That would stop the water flow. At that point, it became obvious that making serious fusion with the little machines required very short pulsed operation of the magnets. There was no question that cooled magnets would work with larger machines, with radii on the order of 1.5 meters, but those were not going to fit in the vacuum chambers available, much less operate with the limited power available.

They even contacted the best superconducting magnet maker in the world, to see what it would take to build a superconducting magrid. It turned out, for the little machines with a diameter of under half a meter, it just was not practical. The structure of magnet required would have an inner superconducting core soaked in liquid helium, a vacuum jacket around that, a jacket of liquid nitrogen encasing that, and another vacuum jacket around that, all with a well-thought-out structure to minimize thermal leaks while maintaining strength against the enormous mutual repulsive forces of the magnets. At a larger scale, he saw no problems, but he could not do it as small as was needed.

Simultaneously with the tests of WB-3 and WB-4, two other machines were run with a configuration we called MPG. The simplest to describe is MPG-1. This machine was formed from a length of copper tubing bent so that it formed a single-turn magnetic structure approximating the WB-3 size and form, a truncated cube (a cube with the corners cut off). MPG-1 was limited to fairly low magnetic field strength, but that was partly offset by the fact that the magrid it formed didn’t have much area to start with. Furthermore, the conductor was round and so the magnetic field it produced circled it cleanly. And finally, the conductor was spaced so that it never touched itself, and the result was that it had no funny cusps.

And be darned if that simple piece of hardware store tubing didn’t manage to make a little fusion!

It turned out that the electron losses and the mysterious generation of hydrogen gas were of the same cause. In an ultra-high-vacuum chamber, it barely takes a trace of gas to raise the pressure by a factor of a thousand or more. Electrons bombarding the magrid case corners and funny cusps were not only being lost, they were digging out hydrogen buried in the metal. That hydrogen diluted the fusion fuel, sometimes so greatly that they couldn't produce fusion even when they had a good potential well depth. The abrupt increase in neutral gas flooded the area between the magrid and the chamber walls, and produced Paschen discharge, effectively shorting out the power supply driving the electron acceleration to the magrid.

Dr. Bussard had resisted building pulsed machines, knowing that what we really wanted was machines that could run continuously, or at least for seconds at a time, but finally gave in when the limits of magnet cooling at the available size was apparent. As a result, WB-4 finally produced neutrons at a rate of about a million per second when run at higher fields for very short times, in a pulsed mode. But it was still plagued by excessive electron losses and all of the problems that caused.

And Finally, The Solution!

At last, he realized that they had to build a machine that had the right structure, even if the size and budget requirements meant it must be uncooled and intended only for pulsed operation right from the start. Time was running out. The stubborn loss mechanisms had dragged the program out longer than intended, and the source of funding was about to be shut off. They finally realized the right way to build a magrid, but had to do it in haste. The result was a design called WB-6, and it was one gorgeous magrid. One day that thing should be set up with spotlights on it at the entrance to a fusion museum. It is that pretty, and it is that important. The magnet cases are circular crossection toroids. Instead of touching, they are spaced apart by a few electron gyroradii. Electrons don't actually follow magnetic field lines, they spiral around them, at a radius determined by the field strength and their kinetic energy. By spacing the coils apart to clear this spiral, the funny cusp is eliminated, and the electrons slip past the grid instead of impacting it. This was, at last, a magrid of the proper form. Figure 5 is a photograph of the finished magrid before installation, and figure 6 illustrates the critical difference between this machine and the earlier magrids.

Figure 5. WB-6, the gorgeous piece of hardware that finally did the trick.

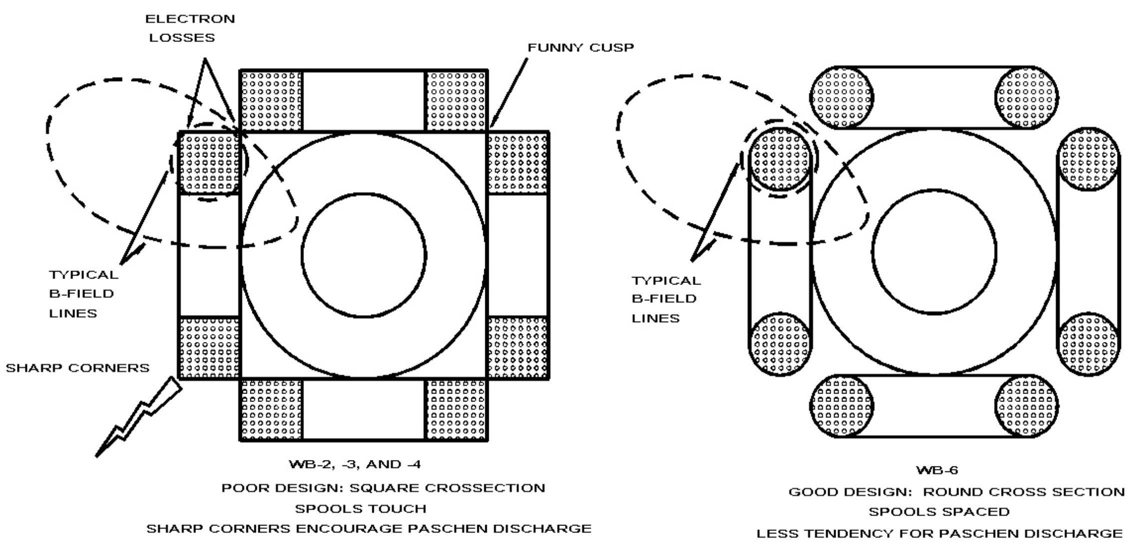

Figure 6. The flawed design of WB2, 3, and 4 was replaced by the good design of WB-6, shown on the right. This greatly reduced electron losses, and allowed the machine to validate the concept.

Pretty though it was, it had limitations. The coils were wound from plain varnish-insulated magnet wire, with no cooling mechanism. Like WB-2 and WB-3, the wire was going to get very hot, very fast. The tests would have to be quite short. Also, realize that the configuration of coils on any Polywell produces mutual repulsion. The coils experience high forces as they press against their containers attempting to get away from each other, and the individual windings also tend to mutually repel. The WB-6 magrid, built from wire meant for more ordinary applications, was destined for abuse. Both of the previous magnet-wire machines had reached end of life due to coil blowouts, and this one was going to be hammered even harder.

Another limitation was apparent. Scaling information generated by the other machines revealed that the drive power requirements for this device exceeded the power available to the little light industrial bay that housed the lab. The previous experiments had been bumping up against this limit all along. Typically, we had to use huge battery banks to operate the magnets as we didn't have the power to run the magnets and high voltage supplies simultaneously. But WB-6 was going to require more electron beam power than the building could provide. It would have to be driven from a large capacitor bank. The capacitor bank could only deliver current for a very short time, with no current regulation in case of Paschen breakdown.

One final problem limited this machine. With so much effort needing to go to perfecting the basic magrid electron trapping performance, carefully metered ion production was beyond the scope of the program. A practical fusion machine is going to need something akin to a carburetor to produce ions, with no neutrals, in the right quantity and location. Fuel to WB-6 was metered by what amounts to an eye-dropper, a "puff-gas" system, which delivered a pulse of neutral deuterium to the inside of the magrid. Ion formation in this device was not produced in as well-controlled a manner as might be desired, although it did work well enough for the purposes at hand. A byproduct of this method of introducing fuel was that Paschen discharge tended to occur between the magrid and the outside walls about 0.5 to 2 milliseconds after the pulse, the time it took any un-ionized gas to migrate to the area outside the magrid. Had this particular puff-gas system been capable of turning off after the initial pulse, this could have been avoided, but the machine had to be built with what was already on-hand. Once the puff was started, gas would continue to flow into the machine until the small reservoir was exhausted.

Following a number of preliminary non-fusion runs at reduced power to characterize the machine's electron trapping properties, four tests of this machine were run in early November 2005 in an attempt to produce fusion. The drive voltage was approximately 12.5 kV in most of the runs, with a resulting expected potential well depth of about 10 kV. The tests were actually run several days after the lab had officially closed, and produced a few neutron counts each. One additional test threw caution to the wind, hammering the device harder than ever before, and that ended the predictably short career of WB-6. This magrid, too, satisfied G. Harry Stine's axiom. The last test pushed it too far, and blew a coil. And so they sadly closed down the lab, before even having a chance to analyze the data.

A month later, the data were finally analyzed, and they discovered that the relatively few neutron counts produced, corrected for the counting efficiency and the geometry of the test (13,000 neutrons per count), and the fact that there are two fusions for every neutron in the D-D reaction, showed that nearly a hundred thousand fusions were produced in about a quarter of a millisecond! That's a rate of roughly half a billion fusions per second. The low count meant that the number could not be stated with precision, but it was certainly statistically significant enough to establish the order of magnitude. And the burst of neutrons repeated on each of the four tests, right where the potential well was right for fusion.

One of the things that amazed me when I learned it, was WB-6 actually ran at a considerably lower magnetic field strength than WB-4, and yet still out-performed the more robust machine by orders of magnitude. The improvement was not due to boosting the magnetic field strength. The improvement was due to the subtly-improved geometry. The other thing that amazed me was the low drive voltage.

By comparison, a Hirsch-Farnsworth fusor running straight deuterium at ten kilovolts produces neutrons, but at a level so low as to be barely above background. My own fusor (presented at the PhilCon and LepreCon science fiction conventions circa 1998-1999), which I ran with EMC^2's neutron counters, produced around 3000 fusions per second at 18 kV, and I was hard pressed to count anything above background at 10-13 kV.

Robert Hirsch reportedly managed about a billion fusions per second once[5], but that required pushing his fusor to 150 kV. And for a rate that high, he used deuterium and tritium, a much easier fuel mix for producing fusion. In spite of the relatively few counts, crude deuterium metering, unregulated pulsed power, and small size, WB-6 was making fusions like crazy.

So what does that prove? Did WB-6 reach breakeven? No. But it demonstrated that, once the configuration of the machine was correct, it does, indeed, produce fusion at a rate in line with the models. The data said the machine was, at last, working properly, around three orders of magnitude better than WB-4. The fundamental problem was fixed.

And the models say that the reactor output will scale as B^4R^3. Power gain scales as B^4R. If the magnetic field can be made stronger in proportion to machine radius, that would mean output increases as the 7th power of radius, and power output with the 5th power of radius. If this is even vaguely close to being correct, then at some modestly larger scale, this type of reactor is *virtually assured* to produce net power. And Dr. Bussard says the results of the tests of WB-6 put that point at a radius of about 1.5 meters for a deuterium machine, and 2 meters for $p\text{-}B^{11}$.

At a radius of 1.5 meters, cooled copper magnets of the required field strength and capable of continuous operation are practical. It is also at about that size that superconducting magnets become practical for building magrids, and superconducting magnets make possible much stronger magnetic fields, which the model says tremendously improve performance. While one could imagine spending some years sneaking up on a net power version of this technology, it is apparent that very little is to be gained by doing so. Machines much smaller than 1.5 meters will still have to be run for very short durations, not the continuous operation needed for a working technology. And the size described for net power is not an extraordinary effort. Dr. Bussard estimates about $150 million for a D-D machine, and $200 million for a $p\text{-}B^{11}$ machine. Now, we all know that estimates are estimates, and going over-budget is a long-standing tradition in technical projects, so let's just suppose for a minute that Dr. Bussard is wrong by a factor of 5. That would put a $p\text{-}B^{11}$ demo reactor at a billion dollars, to demonstrate a technology to save the world. And let's say he is low by a whopping and exceptionally unlikely factor of 50. That would put the program at $10 billion. That would still be a fraction of what has been spent over the last few decades on mainstream fusion research.

The problem is *not* that too much money has been spent on fusion efforts to date. The world spends something like *five trillion* dollars a year on energy, and an R&D effort of a couple of billion dollars a year on a better alternative, over a decade or so, is hardly an unreasonable expenditure if the probability of success is high. If anything, fusion is under-funded. So under-funded, in fact, that existing programs jealously guard their budgets, and the result is some very ugly politics that make it difficult for competing ideas to get a fair chance.

I admit that I think the present tokamak program is a dead end, and Dr. Bussard does not make a secret of the fact he also believes it. The majority of the public probably thinks the same thing, after decades of promises that always seem to be 30 years or more away from bearing fruit. But, in fact, tokamak research has developed or proven most of the technologies needed to build electrodynamic fusion machines, and has even explored tapping some fusion power using direct conversion from charged particles. Remember, Dr. Bussard's concept springs from the realization that a tokamak would easily confine electrons. The proposed reactors would be a small fraction of the physical size of the ITER tokamak, and the technology to build them should be far less challenging. Cost of machines like this tend to scale with size, and comparing the size of Dr. Bussard's proposed machines to the cost and size of ITER suggests that his cost estimates should be pretty good. Nothing entirely new and mysterious needs to be done, we just need to decide to put the pieces together and *do* it. At this point, the challenge is engineering.

And this little fusion program knows where to go. The intent is clearly not to sneak up on fusion a little at a time over many decades, the intent is to target a breakeven demonstrator on the first shot, which could be built in a decade, or even far less if it had the right commitment. When that reactor is built, we'll quickly know if it is a success, a very near miss that needs one more attempt, or hopeless.

What Is This Pie-In-The-Sky p-Whatever?

Let's examine p-B^{11} fusion fuel. What is it, and how realistic is it?

Most fusion efforts expect to burn a mix of deuterium and tritium. The reaction produces most of its energy from neutron emissions, which tend to limit life of the reactor and render the whole structure radioactive. This might be worthwhile if nothing better can be found, compared to the adverse environmental problems of burning fossil fuels, but it is hardly ideal. It is the fusion fuel you usually hear about because it is, by far, the easiest reaction to produce, and it is the only fuel system with any chance at all of making net power from tokamaks, laser fusion, and the like. One look at the reaction cross-section versus initiating energy graphs will show you why they don't consider p-B^{11} for tokamaks. The "temperature" it would take to trigger the p-B^{11} reaction in a system operating on Maxwellian heat is vastly higher than for D-T. Expressed in Kelvins, the "temperature" required would be nearly 6 *billion* degrees!

Nevertheless, the p-B^{11} reaction is, and has been for decades, on the "short list" of fusion fuels. Why, if it is so much harder to burn? For one thing, it is remarkably clean. The reaction results in three alpha particles, which, recombined with electrons, are plain old helium. Breathe the waste product of this reactor, and the worst that happens is you talk like a duck for a few seconds. The reaction produces almost no neutrons. Natural boron is 80% B^{11}, it is abundant, and is somewhat toxic. This reaction turns a toxin into an inert gas.

The way the energy comes off has always been attractive. Alpha particles have a charge of +2. The first particle carries 43% of the reaction energy, and comes off at 3.76

million electron volts. The other two alphas come off at around 2.46 million electron volts each (skewed somewhat by the velocity of the intermediate particle). If you wanted to make an alpha with 3.76 MeV of energy, you would knock both electrons off a helium atom, and accelerate it with an electric field of 3.76/2 = 1.88 million volts. To get that energy back, simply decelerate that alpha against a 1.88 million volt field, let it kiss gently into a metal plate as it comes to a stop, and it will produce two electrons of current at that voltage. This has been done on a small scale using radioisotopes, and it is very simple to do. Since virtually all of the energy from this reaction comes off as alphas, and since their energies are relatively close together, it should be possible to devise a method of doing the same thing with the products of the p-B^{11} reaction. The principles are straightforward, although one can bet the engineering will not be trivial. But the benefits of doing it this way are enormous. Even the klutziest approach, setting the decelerating potential at 2.46/2 = 1.23 million volts, would presumably recover something like 85% of the energy. Considering that any nuclear reactor that generates its power as heat will wind up running steam turbines that waste 2/3 of the energy, this is a stunning technology. The environmental benefit of avoiding all that waste heat, the economic benefits of avoiding large cooling towers, and implications for lightweight space propulsion systems all make this efficiency highly desirable.

If this works, it has got to be the greenest technology to come along since photosynthesis.

But can an electrodynamic fusion reactor burn boron? If the models are right, yes, and surprisingly easily. Boron has five electrons. Knock them all off, and the nucleus has a charge of +5. That means an electrostatic or electrodynamic acceleration system will work 5 times as hard on that nucleus as it would on a proton of charge +1. The net result is that one only needs a potential well depth something like 100-150 kilovolts. So, build the machine a little larger and run it at higher voltage, and it should be straightforward.

But is that "should be" a risk? Well, let's say we build a machine to try the p-B^{11} reaction, and find out the estimate is off and it won't hit breakeven. Well, you've just built a machine that should burn D-T or D-D with ease. If it were my choice, with the cost of the demo boron-burning reactor only about 1/3 higher, I'd design for p-B^{11} without a second thought.

Saving the World

Energy touches almost every facet of civilized life. In the final analysis, energy, raw materials, and human talent are the foundations of prosperity. We receive frequent little reminders of this every time fuel prices spike, conflict breaks out in an oil-rich area, or new environmental news makes the headlines.

Global warming is a hot topic these days, and it should be obvious that p-B^{11} fusion would be an elegant solution. This sort of power source would make hydrogen a practical fuel for transportation. Other issues are pollution from burning fossil fuels, oil as a catalyst for war, Iran enriching uranium for "peaceful" purposes, North Korea breeding plutonium for bombs, struggling economies around the world, and the whole question of what the heck do we do when oil gets scarce, not too far in the future? And how many of you *Analog* readers would like to see fusion-powered spacecraft?

The world needs a technology that can be brought on line in the next few decades (preferably a lot sooner), compatible with existing power grids, affordable, compact, non-polluting, incapable of making nuclear weapons, and able to be used world-wide. If p-B^{11} fusion can be made to work, I cannot imagine a better overall solution to the world's energy problems.

Unfortunately, Dr. Bussard is no spring chicken, and he has reached a point in his life where he really needs to turn this over to someone else. He is willing to help where he can, but this project needs young blood. Young, *passionate* blood.

It is my hope that, by the time this article is in print, a deal will already be in effect to get the program back underway in earnest. For the interim, Dr. Bussard has set up a non-profit organization called EMC2 Fusion Development Corporation, under the New Mexico Community Foundation (NMCF), at 343 E. Alameda, Santa Fe, NM 87501.

But who will pick up the full program? The United States government could easily fund it. But are they the most logical to run it? The Department of Energy is running a tokamak agenda, and has a vested interest in continued funding of that program over long careers. A number of people it that field would love nothing better than to be put in charge of electrodynamic fusion to prove it won't work.

A company with the resources, knowledge, and desire to pull this off might be better than a government agency. Perhaps this would be with government funding, or perhaps just as a private investment. The sum of money involved is well within the capabilities of good old-fashioned private enterprise. For that matter, there are probably a few hundred individuals in the country who could fund it if they so chose, perhaps sacrificing an especially nice yacht.

Do I expect somebody to read this article and just pull out their checkbook? That would be nice, but I don't think this should be undertaken by an idiot. After all the decades of fusion promises, skepticism is a sensible reaction. What I hope this article does is to make a few of the right people curious enough to really get down and look at the data. They'll want to know just why a handful of neutron counts from a few short tests are so significant. They'll need to see the math codes, and understand if that B^4R^3 scaling is really solid. They'll want to meet Dr. Bussard and find out for themselves if he's a scammer or the real deal. They'll need to do their homework.

They'll want to consult some experts. And there will be no shortage of experts who will tell them it can't be done. And there will be a few who will tell them why it *can*.

And if they come and talk to me, I'd tell them if I had two hundred million bucks lying around, this project would be funded already.

Postscript – April 28, 2008

Robert W. Bussard obtained funding in August 2007 for continued work on a small-scale Polywell, similar in size and configuration to WB6. The purpose of this device is to confirm the results of WB6, hopefully allowing peer review of the test setup and results. Successful replication of the results would hopefully justify the proposed larger-scale tests.

After a lengthy battle with cancer, Dr. Bussard passed away on October 6, 2007. Knowing his condition, he enlisted two noted physicists from Los Alamos National Laboratory, Rick Nebel and Jaeyoung Park, to head the new work. Joining them were *three talents from the WB6 work, mechanical engineer par excellence Mike Skillicorn, and brothers Mike and Kevin Wray. Working with incredible efficiency, they had WB7 basically up and running in January of 2008, announcing "first plasma". This first step is far from full operation, and as of this posting Dr. Nebel has reported they are awaiting equipment to allow full power operation.*

Dr. Bussard's dream is still alive, and will have a chance to prove it will work.

Readers are also referred to:

"Should Google Go Nuclear?" Transcript of a talk by R. W. Bussard, by Mark Duncan http://www.askmar.com/ConferenceNotes/Should%20Google%20Go%20Nuclear.pdf

"Should Google Go Nuclear? Clean, cheap nuclear power (no, really)." Google Tech Talks, November 9, 2006. On-line video lecture by R. W. Bussard. http://video.google.com/videoplay?docid=1996321846673788606

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[1] Tom Ligon, "The World's Simplest Fusion Reactor", *Analog Science Fiction and Fact*, Dec 1998. Updated copy available online at http://fusor.net/newbie/Ligon-QED-IE.pdf

[2] "The Advent of Clean Nuclear Fusion: Superperformance Space Power and Propulsion", Robert W. Bussard, Ph.D., 57th International Astronautical Congress, Valencia, Spain, October 2-6, 2006. http://www.askmar.com/ConferenceNotes/2006-9%20IAC%20Paper.pdf

[3] Irving Langmuir and Katharine B. Blodgett, "Currents Limited by Space Charge Between Concentric Spheres", *Phys. Rev.*, 23, pps 49-59, 1924.

[4] "On the Inertial-Electrostatic Confinement of a Plasma", William C. Elmore, James L. Tuck, Kenneth M. Watson, *The Physics of Fluids*, v. 2, no. 3, May-June 1959.

[5] "Inertial-Electrostatic Confinement of Ionized Fusion Gases", Robert L. Hirsch, *Journal of Applied Physics*, v. 38, no. 11, October 1967.