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The World's Simplest Fusion Reactor,

And How to Make It Work

by Tom Ligon

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Although edited slightly for reprints in Infinite Energy *and for posting on fusor.net, it was intended for a fairly broad audience, especially high school science students. Fusor.net has my permission to post this article.*

A really distressing trend has been developing for some time among scientifically knowledgeable people I've met. A lot of you are growing quite pessimistic about the prospects for practical fusion power in general, and fusion-powered space travel in particular. The roots of this disillusionment are not hard to find.

Fusion, for those of you who slept through high-school physics, is the process of squashing two atomic nuclei together to produce a new element. Many light-weight nuclei give off copious energy when this happens. In the Sun, hydrogen nuclei fuse (we pretend we know the mechanisms) to form helium. A tiny fraction of the original mass is converted to energy according to $E = mc^2$. The process occurs deep in the Sun's core, at mind-boggling temperatures that cause the nuclei to move rapidly, where similarly mind-boggling pressure keeps the nuclei in close proximity, and sheer bulk prevents rapid heat escape. The physics community often calls these "thermonuclear reactions" because of the high temperatures driving them in the Sun, or triggering them in "hydrogen" bombs. *IE* readers may have some differing opinions as to the exact mechanism, but in any event the Sun's process involves some temperature and density conditions difficult to sustain on Earth. The Sun is a *gravitational spherical confinement device*, something not even the contributors to *IE* seem to have in their labs.

When I was studying Health Physics in the mid-70's, the nation was well into a program to develop "practical, clean thermonuclear fusion power". This was universally acknowledged to be a considerable technical challenge, but we were told to expect results in, say, twenty-five to thirty years. Well, twenty-five years have come and gone, along with twelve-plus billion fusion research dollars (over the past 45+ years), and those researchers have announced that they have made a great deal of progress. They say if we will only fork over the money (another ten to twelve billion) for the next stage of R&D, they think they might be able to build a net power demonstration reactor in another twenty years. This should lead to a workable fusion powerplant in about forty or fifty years, for *another* $25 billion. Present indications are that the resulting powerplant would not be able to run competitively with any current powerplant technology. The power industry doesn't see much value in reactors which cost billions each and have a life expectancy of only a couple of years.

The focus of most of the present Department of Energy (DOE) research is large tokamaks. How large? The ITER machine was planned, with the supporting equipment and structure, to be about the volume and mass of an aircraft carrier. If it is ever built, it will use gigantic toroidial superconducting magnets, storing magnetic energy equivalent to 1/40 of a Hiroshima bomb, which would be released suddenly if the liquid helium cooling system were ever breached and any one of the magnets warmed above the critical superconducting temperature. Surrounding the machine is a blanket of molten lithium one to two meters thick, not nice stuff to spread about the countryside if the magnets blow. The core of the machine is a torus (donut) sixteen meters high and twenty-two meters across with a crossection diameter of five meters, whose structural material will become radioactive as the machine runs. This beast might actually hit breakeven occasionally (i.e produce as much power as it consumes), with a little luck. Presuming working power plants would be even larger and heavier, the system does *not* look promising for strapping on the back of a rocket!

Additional work continues on laser- and particle beam-fired fusion. The reaction vessels proposed for this program are considerably smaller, however the lasers or beam guns and power systems to run them are even larger and more massive than those of the tokamaks, making them prohibitive for space propulsion use, too.

Both systems struggle to overcome the three competing factors which have so far made thermonuclear fusion such a formidable challenge. The goal is to slam fuel nuclei together hard enough to make them stick and form new elements. Nuclei carry a positive charge, and like charges repel, and they do so more vigorously the closer they approach. This "Coulomb barrier" is the force which must be overcome to cause "hot" fusion. ("Cold fusion" approaches, i.e. proton or deuteron interactions with heavier nuclei in solid state, occur in a sea of electrons which drastically reduce the range of the Coulomb barrier.) To make a useful hot fusion power reactor, you must have particle velocity, density, and confinement time sufficient to produce enough reactions to generate more power than is required to drive the reaction.

The formula for fusion rate per unit volume is

$$n_1 \, n_2 \, \sigma_F \, v$$

where

n_1 and n_2 are the densities of the two colliding fuel species
(n^2 is substituted if only one species is present, as in DD)
σ_F is the fusion crossection at the velocity or particle energy
v is the particle velocity

This equation, with different crossections, is used in chemical kinetics as well as other nuclear applications, and would also work for calculating hits of anti-aircraft shells on a swarm of aircraft. You will kindly notice that *nowhere in the above equation will you see temperature, T!* You can calculate a spread of velocity v in a population of particles from temperature, but velocity is the actual parameter required. The value v is generally frame-shifted to assume one particle is moving and the other stationary, since the crossections were measured in that manner in linear accelerators. The value σ_F is a function of v, and is generally tiny for low values of v, starts becoming useful at velocities corresponding to temperatures of a hundred million Kelvins or more, and peaks out at some much higher velocity. Crossections are in units of area. Achieving useful fusion requires some balance of high density and velocity, and if the resulting fusion rate is low, high confinement time with no additional expenditure of energy can potentially make up for it.

Tokamaks use magnetic confinement, and inject energy into the confined plasma (typically by huge current discharges or bursts of microwave energy) to heat the plasma to temperatures which raise the velocity of the nuclei to overcome the Coulomb barrier. The powerful magnets surrounding the reactor force the plasma ions (ions are atoms missing some or all of their electrons) to follow tight circular paths within the machine, isolating the plasma from the walls and giving high confinement time, thus opportunity to react. However, there are practical limits to magnetic field strength, and those limits are felt most severely under just the conditions where trapping is most needed. The fast-moving ions needed to cause fusion make larger orbits than slower, cooler ions, and thus temperature and density are in constant conflict. There is also an inherent stability problem in these machines: when ions collide *without* causing fusion (which is most collisions in a thermal system), they tend to “jump to new field lines.” Just a few collisions will likely make them jump to the wall of the machine. The net result is that while large tokamaks using superconducting magnets placed outside the torus and lithium blanket can confine hot ions for long times at low density, or cold ions for long times at higher density, you must build very large machines in order to achieve sufficiently high temperature (high ion velocity) and high density at the same time.

Small copper-coiled machines with the coils *inside* the lithium blanket, such as R. W. Bussard's "Riggatron", can achieve the required field strength at much lower cost, but would have an operating life of around 30 days due to neutron damage to the magnets.

Laser- and particle beam-fired approaches (called Inertial Confinement Fusion, or ICF) use small pellets or capsules of fusion fuel flash-heated by extremely powerful lasers or particle beam pulses. The fuel is usually liquid or even solid, so initial density is already high. The capsule is not just a fuel container, it serves to absorb the laser or beam energy, compress the fuel as the capsule explodes, and provides mass (and inertia) to confine the fuel. The challenges in ICF stem from the fact that high temperature causes rapid expansion of the capsule and fuel: temperature and confinement time are in conflict. ICF machines also have their own instability problem: once you compress the fuel pellet to a small fraction of its normal size, it will find any little gap in what you are compressing it with, and try to squirt out. So far these problems have frustrated attempts to produce useful ICF fusion.

Both of these methods have achieved some limited success, that is, they have produced some fusion, and one tokamak has even reported "breakeven" (in a research sense, but far from that needed to totally power itself). However, both use heat as the means of raising the velocity of the ions, what physicists call "Maxwellian" (randomly oriented and distributed) velocity. Stephen L. Gillette would use the term "Promethean"[1], for Prometheus, the bringer of fire. Both approaches rely on the principle that a heated plasma contains a wide distribution of particle velocities. "Temperature," in the sense of gas and plasma physics, is the average kinetic energy of the particles involved, and kinetic energy is proportional to particle mass and the square of the velocity.

The trouble is, neither approach brings the *average* ion kinetic energy up high enough to cause fusion. Only the fastest few percent of ions reach the energy needed to overcome the mutual repulsion of the Coulomb barrier. Furthermore, the heated ions move randomly in all directions, thus collisions are at random angles which usually do not produce fusion. What they need is particles hitting head-on at fusion velocities, but what goes on in thermal systems, at the particle level, is virtually uncontrolled chaos: fast and slow particles colliding like bumper cars at all angles.

Finally, while these heat-based methods *do* produce *some* fusion, they do so *only* with the easiest of fuels: deuterium ("heavy hydrogen", with a nucleus of one proton and one neutron), tritium (one proton with two neutrons), and helium-3 (two protons and one neutron). Thermonuclear fusion has been pushed on the public as "clean", i.e. not producing nuclear waste. This turns out not to be the case. Reactions between two deuterium nuclei (DD), or deuterium and tritium (DT) produce neutrons. Most of the useable energy in the favored DT systems comes from the neutrons, and the only way to exploit it is to slow them down in a blanket of absorbing fluid (usually liquid lithium) which is then used to make steam to run a turbine (more Promethean technology). In fact, the DT systems *depend* on neutrons reacting with the lithium to produce more tritium fuel, for tritium is a fast-decaying radioactive isotope not found in nature. The neutron-lithium reaction also breeds helium-3.

From time to time you may hear about this miraculous nuclear fuel, helium-3, which supposedly can be mined from the lunar surface (actually, the Jovian atmosphere is probably a *far* better source). The claim often heard is that the reaction between deuterium and helium-3 produces no neutrons. While this is true, any such reactor will also produce deuterium-deuterium reactions, which *will* produce neutrons. While it is a substantial improvement over tritium, it is far from aneutronic. If a DT reactor could kill you in one second, a DHe^3 reactor would require about *thirty* seconds to kill you. Besides, as mentioned above, that lithium blanket has a purpose: it reacts with the neutrons to produce tritium and helium-3! The aneutronic reaction can't breed its own fuel, but the neutron-producers can.

While the neutrons produced by these reactions can be harnessed to make heat and more fuel, they have very undesirable side effects. They render many engineering materials radioactive, transmute their elements, and produce metallurgical damage. Thus, after a few years of operation, the inside of the reactor becomes weakened and possibly even deformed. Repairs and disposal of the damaged material are greatly complicated because it is radioactive.

Fusion the Easy Way - Using Vacuum Tube Technology

There are a variety of other potential fusion fuels for which the necessary temperatures for fusion are simply too high to be achieved by the *thermonuclear* technologies DOE is currently pursuing. How do we know about these reactions? We have been doing them since 1928, using extremely simple devices called linear accelerators[2]. Charged particles can be made to accelerate to enormous velocities and energies by means of simple electric fields. By charging a grid to a few hundred thousand volts, you can accelerate protons or other light nuclei fast enough to fuse with almost any element in the periodic table. True, it takes far more energy to run such a device than it produces, but the equipment is extremely simple, and the "temperatures" achieved are easily sufficient to produce most transmutation reactions between nuclei.

Let's bury this "temperature" nonsense right here and now. While you may have heard a figure of something like fifty or a hundred million degrees being required to produce fusion, in fact few researchers use those numbers except to impress the public. The units of temperature they use are "electron volts", which are easily understood in terms of linear accelerator operation. For every electron's worth of charge on a particle, multiply by the volts on the accelerating grid to get electron-volts of energy. For purposes of impressing your friends, for each electron volt, multiply by 11,604 to get degrees Kelvin. You may be amused to know the electrons hitting the screen of the typical television set are around 200 million degrees according to this scheme, and 50 million degrees is a paltry 4300 electron volts.

At about the same time linear accelerators were first being developed, development of vacuum tubes, or electron valves, was being refined. Vacuum tubes use the principle that a very hot metal surface will emit a cloud of electrons, which can be caused to cross a gap in a vacuum to a positively charged "anode". In simple diode vacuum tubes, a hot tungsten filament or heated thin cylindrical surface (the "cathode") is surrounded by a cylindrical anode (also called the "plate") and electrons will flow from cathode to the anode, but not from the anode to the cathode.

One of the best-known researchers in the field was Irving Langmuir, who had developed theories and confirmed by experiments the principles of "space charge limitation" between tube elements composed of concentric cylinders. In 1924, Langmuir and Katharine Blodgett[3] investigated the case of concentric *spheres* as a vacuum tube configuration. While the device worked well, the normal configuration was concentric cylinders, which were much easier to manufacture and also worked well, so there was no widespread use made of this development at the time. Limited use of the spherical configuration includes some "multipactor" tubes and certain specialized light sources.

In the mid-1950's, P. T. Farnsworth (one of the inventors of television) pondered the bright visible convergent focus glow that forms in the center of spherical multipactor tubes, and came up with the idea of using a spherical diode as a fusion machine. Called the "Fusor", the device, later patented[4], would cause ions of fusion fuel to speed to the center of the machine. As they converged on the central focus region, their density would increase rapidly, making collisions more likely.

Farnsworth’s original machines used a spherical array of ion guns and were treated as though the ions got only one pass through the center. Later machines, especially “Hirsch/Farnsworth” machines, used very open spherical wire grids to accelerate the ions, and achieved considerable ion recirculation. Ions which did not collide would decelerate out the other side, stop, and accelerate back to the center for another try, conserving energy. The class of machines based on this principle are "spherical convergent focus electrostatic ion accelerators", with the abbreviation IXL to remind us that they use the grids to accelerate *ions* (see figure 1). Because they use simple electrostatic forces to accelerate and confine ions, and rely on the inertia of the ions to store energy for collisions, the term Inertial Electrostatic Confinement (IEC) is used for machines of this type. Be careful not to confuse it with ICF, or laser/particle beam fusion.

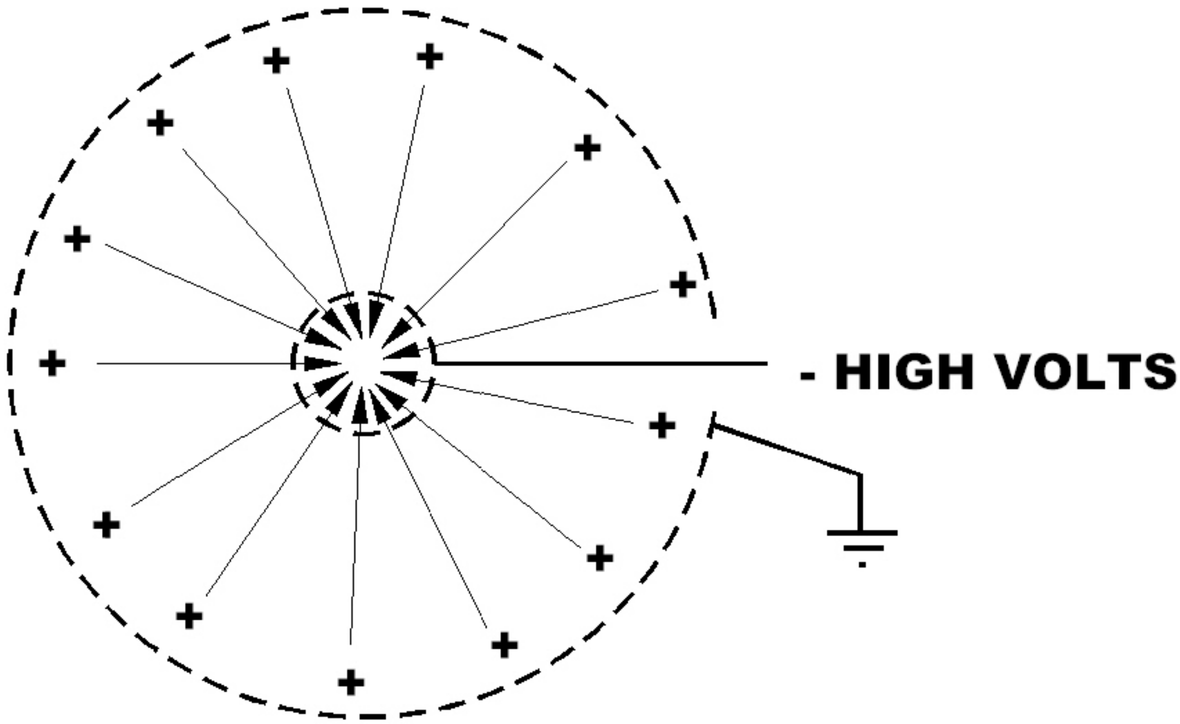

Figure 1. A Hirsch-Farnsworth machine.

By 1959, Elmore, Tuck and Watson[5] explored the idea of using Farnsworth's gizmo backwards to accelerate *electrons* from the outer sphere (a cathode) to the inner sphere (an anode). The inner sphere of such a machine is a grid, which forms a geodesic "potential surface" which the electrons aim for as if it were solid. However, when they get there, most pass right through and coast in a straight line, converging from all sides to the center, then they pass out the other side. What results is region at the center of the inner sphere with a very high density of negative charge, called a "virtual cathode". This region will attract positively-charged ions, which will tend to oscillate back and forth through the central region. Provided more electrons are force-fed into the system than ions, a "potential well" is formed in which the ions are trapped by excess negative charge. Interestingly, an ion oscillating entirely inside the inner grid will be trapped almost indefinitely and will conserve its initial kinetic energy remarkably well, thus theory predicted this device might be a surprisingly efficient ion trap. However, the electrons had to pass through the grid, which meant eventually most of them would *hit* the grid. Depending on the grid's "transparency", an electron might make 10 to 50 passes before being lost, requiring another electron and the power to fire it into the system. Because the electrons had to outnumber the ions by a significant margin, the researchers expected this device could be harnessed to produce only tiny amounts of fusion, and decided it could never make a workable power reactor. The Elmore, Tuck, Watson concept is an electron accelerator, or EXL machine (see figure 2).

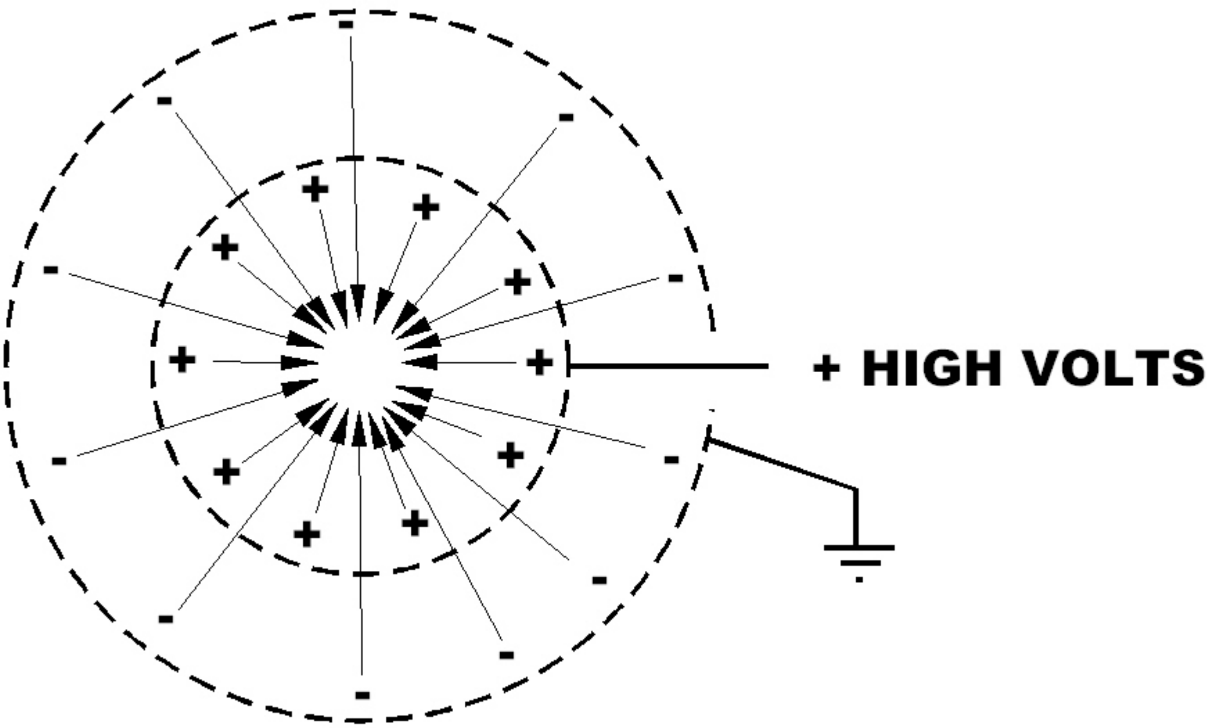

Figure 2. An Elmore-Tuck-Watson machine.

In 1967, Robert L. Hirsch published a paper describing a concentric sphere device which produced "copious neutron emission"[6]. Hirsch (working at the ITT/Farnsworth Lab under Farnsworth's enthusiastic encouragement) primarily worked with the IXL configuration, with the cathode (negative grid) in the center and the anode (positive) to the outside. His machine was a spherical version of a linear accelerator: positive ions formed at the anode accelerated toward the central cathode grid (i.e. IXL and EXL machines are similar but of opposite polarity). Again, the accelerated particles usually miss the inner grid, continuing on to the center of the device. There they stood a fair chance of collision, and very importantly, all of the particles were *at the same energy*, which was sufficiently high for fusion to occur. If they missed or collided without producing fusion, they could travel out the other side, conserving their energy for another pass through the middle. Although not all collisions were head-on, particles which did not fuse rebounded with most of their original energy. It did not matter to which direction they rebounded, as all directions were "uphill" against the potential gradient, so they slowed down, and came rushing back "downhill" for another try. Like the Elmore, Tuck, Watson design, the losses due to grid collisions prevented breakeven, but a lot of fusion was possible, nonetheless.

Dr. Hirsch operated his machine at up to -150,000 volts on the inner grid, at currents up to 60 milliamps. Using DD and DT, the machine produced abundant fusion, but far below breakeven. The neutron emissions he achieved (published results on the order of a billion neutrons per second, and unpublished results of around a *trillion* per second!) would be considered dangerous today. Hirsch also built an Elmore-Tuck-Watson EXL machine, and verified it would produce a deep potential well.

What Hirsch's machine demonstrated was that, contrary to popular belief, fusion is actually quite easy to produce, once the *thermo* mindset is shed. The problem is to come up with a configuration that does not waste the drive energy.

The Nuclear Reactor High-School Science Project

I notice a few of you have gone glassy-eyed on me. Trust me, this is *easy*. A Hirsch-Farnsworth machine is so simple it could be built as a high-school science project (though I caution anyone without the necessary skills to seek knowledgeable advisors, and good safety practices *must* be followed). You will need to borrow, buy, or build some vacuum equipment, obtain a small supply of deuterium, and figure out some instruments so you can tell if it is working, but the actual reactor components are *trivially* simple to build, and will cost only a few cents!

WARNING

The apparatus described in this article uses high voltages at potentially lethal currents. High vacuum apparatus and compressed gasses may also be dangerous if improperly used. This device may produce ultraviolet radiation and soft x-rays. Do not attempt to build or operate such a device unless you have been trained in high voltage safety, and safe use of compressed gas cylinders and vacuum equipment, and can verify that no unsafe radiation exposure occurs.

Regarding the presumed danger of building a nuclear reactor, the simple fact is that the proposed machine would run at the very bottom end of the voltage required for fusion, and it will take some skill and effort to even detect the neutron output. The *real* danger is in the potentially lethal high voltages used, and some lesser concerns for safe handling of compressed flammable gas and operation of vacuum equipment. A metal vacuum vessel will stop virtually all of the weak x-rays which may be produced (a little tamer than those produced by a television), and a thick glass window will stop most ultraviolet radiation produced. The voltages involved are somewhat lower than those present in an ordinary television set, which also has a large, fragile, glass vacuum vessel, and I would characterize the project as about as dangerous as television repair. They still teach television repair in high school technical education programs, don't they? But make no mistake, the insides of a television set can kill you in a heartbeat.

While you will wish to rig a method for detecting and quantifying neutron production (that being your proof you are making fusion), the levels produced by the machine described below should be so low you would have to stand a meter away from the machine for twelve days of continuous operation before you got a 100 mrem dose of neutrons (and that is a *small* dose). Most likely, the device will be run only for a few minutes at a time at actual fusion conditions. Still, if for no other reasons than the educational benefits and common sense, I would advise the experiment be done with due consideration to nuclear safety. For those wusses who don't wish to "go nuclear", or who cannot find qualified advisors, you can still demonstrate the visible glow by using a non-nuclear gas (the residual air in the vacuum chamber will do) running at below fusion voltages. In fact, even without producing fusion, you can do a lot of interesting and useful science with these devices. (*IE* readers may be fascinated to know that a pesky effect which occurs during cleanup of a new grid fits the definition of "pulsed anomolous glow discharge.")

The expensive component is the vacuum system, which may have to be borrowed or scrounged. The pressure required can be achieved by a simple mechanical rotary-vane roughing pump (a two-stage "micron" pump used for refrigeration repair will do) if the system is compact and tight, although it would be preferable to have a higher-performance system. Such a pump, used, can cost around $750 (a lucky scrounger I know has stumbled on to several for $150 or less), so a borrowed pump will be a real advantage if you are as broke as I chronically was in high school. A vacuum chamber and some high-voltage and conventional electrical feedthrus will be needed. A metal vacuum chamber with a thick glass viewport is far preferable. I have built a small demonstrator device in a $90 plastic desiccator chamber, but it did not achieve good enough conditions for fusion, finally failed due to a stray electron beam heating the walls, and provided little protection against x-rays or ultraviolet light. Glass vacuum containers such as bell jars are fragile and consequently dangerous, and must be used with guards, face protection, and with great care. Spark plugs will do as high voltage feedthrus, and spark plug wire for high voltage cable, for researchers who are "cash challenged". Home-made vacuum instruments can be made from light bulbs or old vacuum tubes.[7]

I have achieved the blue glow of convergent ion focus using a furnace ignition transformer and a pair of high-voltage diodes. This will produce close to five thousand volts, and ignition transformers are usually current-limited to a level that *probably* won't stop a healthy teenage heart. Such a transformer will not produce significant fusion, but makes a pretty glow which will demonstrate the convergence effect.

Higher voltage and power can be obtained using a 15,000 volt (7500 volt RMS centertapped) neon sign transformer with two high voltage diodes, which can produce over 10,000 peak volts DC, and considerably more current than the ignition transformers. I have successfully pushed such a transformer to 13,000 volts. This power source *can* produce measurable fusion. Before buying one, check with an electrical contractor who remodels commercial property, as they frequently dispose of such transformers from old neon signs. You want at least the higher-current 60 mA variety if you can get it, or several 30 mA transformers in parallel, or, better yet, three 60 ma transformers on a 3-phase power source. *This type of transformer can kill, particularly if you use a capacitor on it to filter the AC ripple.*

Deuterium gas is not radioactive, and can be purchased without special license through many gas suppliers, sometimes even through welding suppliers. A lecture bottle should cost under three hundred dollars, and you will also need a suitable regulator, which you may be able to borrow, or at least re-sell after you are done with it.

The reactor grids themselves will cost a few cents and take about an hour to build, if you have access to a small spotwelder. What, no spotwelder?!! Build one yourself with common parts from an electronics store[7]. Each grid can be formed from six rings of stainless steel welding wire. I have used 0.025 inch diameter wire, which is cheap and easy to work. Buy it from any welding supply dealer. The dimensions can be adjusted to fit your apparatus. Typically the outer grid is somewhere between the size of a basketball down to the size of a volleyball, and the inner grid is about the size of a ping-pong ball. You may gather from this that precision in diameter is not an issue. It also is surprisingly unimportant that the grids be perfectly spherical or mathematically precise, although the best machines are built with precision. This edition of this article is edited for fusor.net, and that forum will have a wealth of information on grid designs, so no figure is included here.

I've deleted my original description of poor-boy neutron detectors, as the *IE* crowd is rife with CF researchers, experts at hunting tiny neutron fluxes, and many folks on fusor.net are more expert on the subject than I am. I will mention that proton-recoil scintillation counters are one of the more intriguing options, among the many in the literature. BiCron 720 is specifically intended for fast neutron detection, and is ideal for DD and DT fusion neutrons. BF3 and He3 detectors are also good choices, although they are notoriously sensitive to electric arcs and must be well shielded. For high neutron fluxes, neutron activation of indium provides absolute proof of neutron production.

A professional lab could probably manage to sink $50,000 in equipment for such a project. My own personal machine, built of about 50% used equipment, cost about $3000. I suspect a particularly talented scrounge/beggar could get by for around $500 out of pocket, which I estimate could be raised in under a month of flipping burgers, or a couple of days of computer consulting.

At higher pressures (about one one-hundred-thousandth of atmospheric pressure), the system will work in "glow discharge mode", the way a neon sign works. This is the easy way to go, as it requires no fancy electron guns, ion guns, or extra power supplies. Those of you with access to higher performance vacuum systems may wish to venture to lower pressures, where the ion recirculation becomes far more efficient. There are a number of ways to do this, but they are too involved for this article. These methods are described in the referenced papers, and can also be accomplished with cheap and available odds and ends.

If you jack the inner grid voltage on this simple little machine up to 10,000 volts or more, and feed deuterium to the system at a pressure a little under 10 microns (1×10^{-2} torr), it should produce fusion, evidenced by neutrons. I have seen a 17-year-old build a grid that produced 300,000 neutrons a second at 13,000 volts.

So you see, you *can* build a fusion reactor with parts from an electronics store, auto parts store, welding shop, refrigeration supplier, hardware store, and craft store, perhaps with a bit of dumpster-diving on the side, and creative use of big, sad, pleading eyes. It really *doesn't* take tens of billions of dollars!

These hints should be enough to get you started. I don't want to describe the apparatus *too* completely, because hitting the books and figuring this out is how you earn that science fair prize dancing before your eyes right now. There are a number of people on the internet who are doing this very thing right now (a search for “Farnsworth fusor” will be a great start). Chief among them is Tesla-coil guru Richard Hull, who was literally enthralled by a machine I showed him a few years ago.

Can The Problems Be Overcome?

While machines based on Farnsworth's Fusor are indeed easy to build, and worked better than any thermonuclear fusion machines until quite recently, it was immediately apparent to the researchers that they could never reach breakeven. The reason, quite simply, was that either configuration required grids, and grids simply could not be built more than about 98% transparent and be expected to support their own weight, especially as they typically run red hot when fusion conditions are achieved. The machines seemed doomed to operate at no more than 0.01% of breakeven. A few researchers struggle on, tantalized by the fact that the machines seem to have modes of operation which are better than theory predicted. Dr. George Miley of the University of Illinois has shown that a "star mode" develops in which recirculation passes primarily through the grid openings, reducing grid losses (his group’s “Fusion-Star” design, developed with Daimler-Chrysler, is commercially available for use as a neutron source). There also appears to be considerable fusion occurring immediately outside the convergent focus region, where head-on collisions dominate, which was neglected in early analysis. Still, these improvements fall far short of what is needed for a power reactor.

Basically, the grids had to disappear!

A way may be forthcoming. The actual inventor of the scheme below asked me to drop my original glowing testimonial. He is entirely too modest, if you ask me, but I understand his motives. Still, he isn't getting off without his name being mentioned here, and at least a few of his extensive accomplishments. You may have heard of him as the inventor of the interstellar ramjet concept featured in *Tau Zero* and many other science fiction stories: Dr. Robert W. Bussard. In the 1950's, he proposed and designed a workable nuclear fission rocket engine, KIWI-A, the first predecessor of NERVA. KIWI-A was ready to test *before Sputnik was launched*.

Dr. Bussard also worked with Dr. Hirsch in the thermonuclear fusion program at the old Atomic Energy Commission, predecessor of the DOE. Both of them recognized the finer points of the IEC machines, and wondered if a way could be found to get around the grid problem.

When life hands you a lemon, it has been said, you should make lemonade. Dr. Bussard was struggling with another of his inventions, a small tokamak called the Riggatron, which looked marginally workable, but had turned out to be far too expensive to build with the available money. The enormous energy required to bring the magnets up to a field strength that would trap the plasma would require a monster flywheel-generator that was simply way over budget. The problem with tokamaks, he realized, was that ions are so damnably hard to trap with magnetic fields, particularly under fusion conditions. Yes, using superconductors, or by putting copper coils very close to the plasma and pushing them to their limits, it was possible to trap light ions like deuterium and tritium, but as soon as they collided they would tend to jump field lines, unless the fields were especially powerful. Achieving that field strength was turning out to be a killer problem, especially if you lacked the financial resources of a major government.

It was a pity, Bussard thought, that ions are not as simple to trap with magnetic fields as are electrons. Because electrons are thousands of times lighter than fusion fuel ions, they are deflected easily by much weaker magnetic fields. If the little tokamak contained only electrons, they could be held at high energy and density quite efficiently. And then an epiphany struck.

It might just be possible to build an EXL machine with magnetically insulated grids. The magnetized grids[8] would accelerate electrons just as well as wire grids, but it would be next to impossible for the electrons to actually *hit* the grid. Ions formed just inside the grid would be drawn into the potential well and oscillate until they collided, totally unimpeded by grids, and trapped by the *one* thing (other than the gravity of a star) that holds them vigorously -- an electrostatic potential. From time to time, theory seemed to pose a fatal obstacle, but each time a closer analysis of the obstacle revealed a solution that made the theory work even better.

Funding was found to build a large-scale (1-meter radius) machine, which demonstrated that the system could produce a deep potential well. Further small-scale work showed successful magnetic trapping of dense electron clouds. Theory and computer simulation seem to support the models and experiments, with no roadblock problems found, yet.

The theory and preliminary lab studies look good. A few million dollars would fund a working prototype, and if that doesn't work, indications are that scaling up a factor of ten in volume almost certainly would. While not cheap for most of us, compared to the DOE budget for the last 20 years it is practically petty cash. Will it succeed? At this point, only time will tell. (Note: As of the fall of 2005, this has been done, and Dr. Bussard reports a machine called WB6 produced copious neutrons and validated the concept. He now believes the concept is ready to be scaled up to a sized predicted to produce net power, at a cost estimated at $200 million).

The Possibilities

If successful, the impact of this type of reactor would be enormous. I need not describe the overall economic consequences in too great a detail to this audience: science fiction is chock-full of stories in which we developed cheap, clean fusion to replace petrochemical fuels and to power our spacecraft, *IE* is premised on the notion of the need for potent alternative energy sources, and a lot of *IE's* readers also subscribe to *The Electric Spacecraft Journal*. However, Bussard's magnetic-grid EXL version of the Fusor shows promise as a power source that sounds like science fiction. One reason is that it doesn't have to run on nasty neutron-producing fuels like deuterium and tritium.

As mentioned earlier, there are many nuclei which can produce net fusion energy besides deuterium, tritium, and helium-3. Most of them are not commonly discussed, because they require far higher collision energies than DT reactions. Since DT reaction conditions themselves are a formidable challenge for *thermo*-nuclear approaches, the other fuels are simply out of the question for tokamaks or ICF systems. These limitations become almost trivial in IEC devices, however. By simply jacking the voltage up to a couple of hundred kilovolts, the electrons can be made to produce a deeper potential well, and the ions race to the focus region faster. This requires scaling up the hardware, but does not appear to require any great leaps of technology.

Among the fusion fuels is a favorite of Dr. Bussard: the reaction between ordinary hydrogen nuclei (protons) and boron-11. Boron can be mined as borax or other minerals, and is readily extracted from seawater. About 80% of natural boron is the boron-11 isotope. The fuel is plentiful.

The p-B^{11} reaction is ideal: when the two nuclei fuse, they form *excited* carbon-12, which is unstable and almost immediately begins to fly apart. In two rapid stages, it casts off an energetic alpha particle (a helium nucleus), then the remaining nucleus splits into a *pair* of alpha particles. The first particle carries 43% of the reaction energy, and comes off at precisely 3.76 million electron volts, which turns out to be very handy. The other two alphas come off at an average of 2.46 million electron volts each, over a spread of energies. Finally, the reaction produces no neutrons or high-energy gamma rays. There is a little bremsstrahlung radiation (basically x-rays) from collisions associated with the reaction, easily shielded. Alpha particles are dangerous if produced in your body, but can be stopped by the thinnest of shields, and are essentially harmless in a reactor vessel. Once they pick up two electrons, alpha particles become helium, a harmless inert gas. There is no radioactive waste produced in this reaction!

Lithium can also undergo similar reactions, producing charged particles, and is an alternative fuel for such a reactor.

Most nuclear power generation systems produce heat by one mechanism or another, which is in turn used to heat a "working fluid" to run turbines or otherwise do mechanical work. The process of converting heat to mechanical energy by such means is inherently inefficient. Rarely does more than about a third of the energy end up in useable electrical or mechanical form, and the theoretical limit is around 40% for most practical fluids, engine materials, and operating temperatures. This fact has depressed thermodynamics students for the last century or so, but there appears to be no getting around it using primitive "Promethean" technology.

While you *could* simply allow the alpha particles from the p-B^{11} reaction to slam into the reactor walls producing heat, there turns out to be a much better way to extract their energy. Alpha particles, which are helium atoms stripped of their two electrons, have a charge of +2. Each of the particles produced by this reaction has a kinetic energy of around 3 million electron volts. An electron volt is the energy a particle of charge 1 will pick up when accelerated through a field of 1 volt. The reverse is true, too. To slow down a 3 MeV particle with a charge of +2, simply decelerate it with a +1.5 million volt electric field. The particle will just kiss into the charged surface, and draw two electrons from it, producing current at high voltage. This method has been used to extract small amounts of power from alpha-emitting radioactive substances, and should also work for a large reactor of the correct configuration. The correct configuration is a spherical vacuum chamber (which this reactor just happens to be) with several charged grids to pick off the lower energy alphas, and the outer walls charged to catch the high energy alpha. It should be possible to approach 95% conversion of fusion energy to electricity with such a system (the rest being lost as bremsstrahlung radiation and a few other minor mechanisms). This is quite remarkable -- a nuclear reaction which allows almost all of the energy produced to be *directly converted* to high-grade electrical power!

You might think that if nuclear energy is so cheap, efficiency would not be a problem. For powerplants, particularly large ones, waste heat release can cause local environmental changes, either by heating a body of cooling water, or causing local weather changes when water-mist cooling towers are used. The cooling apparatus is generally massive, and can easily cost more than the actual power-generating equipment!

Waste heat in spacecraft is even more serious. Any nuclear-electric powerplant using gas turbines or similar equipment *must* get rid of the excess heat in order to operate. Since there is no air or water in space to conduct away the heat, it must be radiated. For a thermal-cycle reactor of sufficient power to operate even a modest manned spacecraft, the radiators will be on the order of the size of football fields. They end up being a huge portion of the dry mass of the spacecraft, and simply *ruin* the performance. Thus, a reactor that can produce electrical power directly, at 95%

efficiency, has a *tremendous* performance advantage over its thermal/mechanical/electric counterpart.

Dr. Bussard has done some preliminary design studies on spacecraft that could realistically be built around p-B^{11} reactors. Most use a large and very powerful reactor of close to 10 billion watts capacity, typically with two reactors for redundancy. While fairly bulky, with a diameter of around 5 meters, the reactor is mostly empty vacuum, with only the MaGrid™ and a few electron and ion guns in it. It is thus exceptionally light for the power produced. Supporting cryogenic and power conversion equipment should also be practical space hardware, and not especially massive.

Because the reactor produces no radioactive waste and only a trace of radiation, it will be safe to operate in the atmosphere. Using high-voltage electron beams to superheat gas, one could build either an air-breathing jet or a rocket (relying on on-board reaction mass). In space, the rocket configuration will be used. Because the reactor can work only if there are far more electrons in it than fuel ions, it is also “intrinsically safe”: if you feed it too much fuel, it just chokes off.

There are many ways of exploiting the EXL reactor output to produce rocket thrust, but the fact that the p-B11 powerplant produces high voltage electricity makes it particularly suited for arc-jet propulsion's meaner big brother. In a million-volt-plus electron beam the electrons are pushing lightspeed, so the term relativistic electron beam (REB) is used. With some heavy-duty R&D, it is expected that REB-heating can be made quite efficient, and should be able to impart high velocity to the reaction mass. Water would be a perfectly suitable reaction mass, as would almost any other handy and abundant material. REBs are not picky about what they blast to plasma. Dr. Bussard calls the REB-heated systems “QED” (Quiet Electric Discharge) engines.

For longer-range missions, where quick acceleration is less important, a more efficient rocket which uses the fusion exhaust directly, with some reaction mass added, could be built. This would be the system of choice for trips to the outer planets, or even out to the Oort cloud. Dr. Bussard calls these more efficient systems “DFP” (Diluted Fusion Product) engines.

What kind of performance could realistically be achieved? Try these figures from some of Dr. Bussard's papers[9,10,11]!

> Low Earth Orbit (LEO) to Mars: 33 days, more or less, for high performance designs, or 6 weeks for economical freight-hauling variations. The craft are single-stage, with a 15-20% payload fraction.
>
> LEO to Saturn's Moons: as low as two months, with a short coasting period. Again, the craft is single-stage, and has a 14% payload fraction

How would such a rocket affect the economics of space exploitation? Most estimates you have heard in the past were for single-use multistaged chemically-propelled rockets, which can barely achieve Earth orbit, the upper stage of which must limp to the planets along painfully slow Hohmann ellipse orbits. Chemical rockets are almost all fuel and barely any payload. While rocket fuel is fairly cheap, rockets are not, and each flight has a high operating cost in labor and hardware. Dividing the cost of a large rocket by a payload mass somewhere just above zero gives a really depressing cost per kilogram. Efficient fusion-powered rockets, reusable for many flights, fast enough to make many flights before becoming obsolete, and with a high payload for each mission, can improve economics by several powers of ten. Consider the following colonization figures extracted from a more recent paper by Dr. Bussard[12], and I recommend you read these sitting down:

> Cost to LEO: $27/kg (a price that compares favorably to the cost of riding the Concorde across the Atlantic).
>
> 4000 people on Earth's moon, each person with 25 metric tonnes of equipment, and each person receiving an annual visit back to Earth: $12 billion over 10 years.
>
> 1200 people on Mars, each with 50 tonnes of equipment, and an annual visit back to Earth: $16 billion over 10 years.
>
> 400 people on Titan, each with 60 tonnes of equipment, and an annual visit back to Earth. $16 billion over 10 years.

I leave you to ponder these figures, particularly in light of the projected costs of sending a few people to explore Mars with chemical rockets, typically estimated on the order of a hundred billion dollars per trip. In particular, consider what these numbers would mean to your personal chances of living and working in space.

This article won the 1999 Analab award for best science fact article in Analog *magazine in 1998. Tom Ligon is an engineering technologist and science fiction writer. His name also crops up in these pages occasionally in connection with the Marinov Motor.*

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(OK, I need to figure out where the darned references went!)

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