Inertial Electrodynamic Fusion

Is this the answer to interplanetary space travel?

Tom Ligon, Member SFWA SIGMAForum.org
Unofficial cheerleader for EMC2Fusion.org
Robert W. Bussard, 1928-2007
Bussard Factoids

- Bussard Ramjet, circa 1960. “I guess I’ll never live that down.”
- Proposed Rover nuclear rocket, 1953. Built, tested, worked!
- An architect of the US fusion research program: “It was a scam.”
- “Nuclear weapons are addictive. Once you set one off, you feel like a god, and you want to do it again.”
- Space enthusiast from early childhood, believed we must go to space for our continued survival.
- Watch “The Google Talk” to see his personality.

Askmar.com/fusion.html
IEC Background

- Fusion reactions were discovered using electrostatic particle accelerators.
- P. T. Farnsworth conceived of spherical accelerators as practical fusion reactors.
- Robert Hirsch, working for Farnsworth, demonstrated practical devices in the 1960’s.
- DOE never funded the research.
This is a “Hot Fusion” Technology

- Actually, temperature is not the important factor, and temperature does not appear in the fusion rate equation
  \[ = n_1 n_2 \sigma_f v \]
- Achieve velocity by electrostatic acceleration. All particles reach center at fusion energy instead of a Maxwellian mix.
- May calculate temperature: 11604 Kelvins per electron volt

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Hirsch/Farnsworth Fusor

Dog and Pony II

- D&P I was built in a plastic desiccator and only lasted 2 weeks, but launched the amateur fusion movement.
- D&P II has actually made sustained DD fusion (3000 fusions/second at 18 kV for up to 45 minutes at a time), but was badly beat up from many road trips.
D&P II before rebuild
D&P II Old Grids
(suffers from inner grid ED)
New Outer Grid Construction
Spot Welding is Fun!
Lots of fun!
Coming together ...
An outer grid is done!
Inner Grid Construction
Going Back Together
Back in Operation
1030 mtorr, 400 V
500 mtorr
300 mtorr
75 mtorr
50 mtorr
25 mtorr
16 mtorr
10 mtorr
8 mtorr
7 mtorr, High Voltage
Extinguished
Fusors Cannot Make Net Power

- By a very large margin!
- Great educational tools
- Useful as neutron sources
- Easy: many high school students have built them.
- North Korea claims to have a fusion reactor ... maybe they are catching up with Free World high school students?
ETW is the opposite of a Fusor

- Grid polarity reversed.
- Accelerate electrons to the center.
- Use the electrons (negative charge) instead of a negative grid to trap ions.
- Hopeless electron losses for a net energy machine, but they would make some fusion.
Potential well

Just Electrons

Electron potential well

Electron Well with Converging Ions

Electron potential well
Bussard’s IEF Approach

- Electron grid of ETW machine replaced with magnetically-insulated “magrid”
- Electrons several thousand times lighter than fusion fuel ions ... fields that can’t hold ions easily confine or repel electrons.
- Remember, this is *dynamic* confinement, and both electrons and ions are in constant, vigorous motion.
WB6 Schematic

Basic MaGrid Field

Wiffle-Ball Trapping

High Voltage

Recirculation on field lines

Electron Emitter

MaGrid in Operation
Energy/Matter Conversion Corp’s Main Players, San Diego, WB-6

- Dolly Gray, President
- Dr. Robert W. Bussard
- Dr. Nicholas A Krall
- Lorin Jameson
- Michael Wray
- WB6 Construction Team: Mike Skillicorn, Ray Hulsman, Noli Casama
WB-6: Proof of Concept?

- November 2005: successful fusion tests
- Subscale device, not a net power demo
- Four test runs replicated the fusion rate
- Runs agreed with rate predicted by theory
- Theory projects a very strong scaling with increased size ($B^4R^3 \approx R^7$)
- Net power predicted at 1.5 to 2 m radius

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This is the device that finally worked

- Truncated cube (6 magnets, open faces and corners)
- Magnets spaced slightly apart to avoid “funny cusp” losses.
- Magnets are simple copper solenoid coils, all with the same pole pointed in.
- Wiffleball trapping plus MaGrid factor gives electron lifetimes of around 100,000 transits.

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What did WB6 accomplish?

- Finally confined electrons as the computer models said it should.
- Demonstrated the importance of two fine details of magrid constructions that prior devices had ignored.
- Worked about a thousand times better than previous models.
- Four replicate fusion runs before it fried
WB6 Operation

- Pulsed due primarily to limitations of available power supplies. Ran on capacitors for high voltage.
- The fusion was produced in sub millisecond bursts just when a deep potential well was present.
- Deuterium, 2-3 neutrons counted per test, $1.3 \times 10^4$ neutrons/count, 2 fusions per neutron.
- Resulting rate between $1 \times 10^8$ and $1 \times 10^9$ fusions per second ... at a potential well depth of only 10 kV!

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Hirsch achieved such reaction rates with DT running at 150 kV.
DD fusors have gotten close to this at 120 kV and above.
But a fusor at 10 kV barely makes detectable fusion. WB6 was *screaming*, running at a very high rate for such a low voltage.
What terminated the runs?

- Pulse ended with a Paschen discharge (neon sign glow discharge) that drained the capacitors. This was due to excess gas, not some intrinsic limit of the concept.
- This does demonstrate what happens if excess fuel is introduced: the machine will “choke”. This is an intrinsic safety feature.
- Further work should incorporate an improved ion source.

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Piston Engine Analogy

- Early engine with eye-dropper fuel metering rather than a carburetor
- Would a few cycles of firing just be a noisy waste of good booze?
- Would a cracked piston after four tests mean the technology was doomed?
- Or would you build an improved engine with fuel metering, cooling, oil system?
Main Players, Santa Fe, WB-7

- Rick Nebel (Theory)
- Jaeyoung Park (Lab work)
- Both “on loan” from Los Alamos, very experienced in IEC fusion research
- Mike & Kevin Wray (Computer/Physics)
- Mike Skillicorn (Mech. Design)
WB-7: Confirming Study

- Runs consistently and reliably “Like a watch”
- “Produces results we like”
  - (The results are, however, “nuanced”)
- Results have been peer reviewed.
- But project back under *%$ embargo
WB7.1 under construction

- Larger scale, less than a net power size
- Attempt to burn p-B11?
- Funding around $8M?
Proposal for full-sized WB-D reactor

- Highly speculative at this point, beyond the scope of funded work
- EMC2FDC soliciting donations to pursue preliminary design work
And then ….

- OK, let’s suppose they build a p-B11 net power reactor ….
- …. And then save the planet with cheap, clean power ….
- …. And make a lot of money so we can do what we really want to do ….
p-B$^{11}$

- Can’t be run in a tokamak … initiation energy far too high, bremsstrahlung losses excessive.
- Relatively easy in an electrodynamic machine … circa 100 kV potential well depth
- Almost all reaction energy comes off in 3 alpha particles. No neutrons, no radioactive byproducts, allows direct conversion
- Brem losses mitigated by restricting the central virtual anode height (keep electron energy low) and running hydrogen-rich (keep average Z low)
Fusion Cross Sections

Direct Conversion

- Possible when reaction energy is kinetic energy of charged particles, especially when energies closely grouped
- The opposite of putting kinetic energy in with electric fields.
- Decelerate against electric fields to make high voltage DC.
- $p\text{--}B^{11}$ may allow 85 - 95% recovery

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Terrestrial Power

- High efficiency means less cooling requirements, reduces costs
- HV-DC output converts to AC using existing technology
- A p-B\(^{11}\) system has no radioactive waste, fuel abundant and cheap
- By 2015, world installed generating capacity projected at over 5000 gigawatts, so a nice market exists

Applications to Spaceflight

- This technology projects reactors of multiple gigawatts.
- The intended fuel, p-B11, allows direct conversion of fusion energy to high voltage DC.
- Lightweight, high density electrical source for various electric thrusters.

Find papers at Askmar.com
Space Power

- NSTAR/DS1: 2.3 kW, 93 mN, $I_{sp}$ 2000-3000 sec
- ESEX 27 kW arcjet, $I_{sp}$ 500-1200 sec
- 180 HP light aircraft: 134 kW
- SSMEs: 18 GW, 1.7 MN, $I_{sp}$ 460 sec
Dr. Bussard’s Propulsion Systems

- **QED**: Quiet Electric Discharge. Typically use relativistic electron beam heating of reaction mass (the arcjet from hell). Lower $I_{sp}$, higher thrust, for shorter missions.

- **DFP**: Diluted Fusion Product. Some inert reaction mass added to fusion product directly from reactor. Very high $I_{sp}$, lower thrust, for long-range missions.

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Tokamak vs QED Radiators

- Compact DD, D³He tokamak
- CSR/QED p¹¹B
- ARC/QED p¹¹B
- ARC/QED LH₂
- ARC/QED H₂O
- MIN ARC/QED SCALE

1000 feet
QED Engine Variants

- **QED/ARC: All Regenerative Cooling.** Reaction mass used as the coolant, so fairly high flows required. Low $I_{sp}$, high thrust. Good for launches, landers, short missions.

- **CSR: Controlled Space Radiation.** Radiators required. Higher $I_{sp}$, but less thrust and more “junk in the trunk”.

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QED/CSR Types

- **CSR-A**: Limited regenerative cooling, REB heating of reaction mass, typically water. Smaller radiators than CSR-B, but lower $I_{sp}$ and higher thrust.

- **CSR-B**: Very low reaction mass flow, so larger heat radiators required. High $I_{sp}$, low thrust. Expected to use an ion accelerator rather than REB heating.
For the outer solar system …

“Diluted Fusion Product” (DFP)

- Low thrust, high $i_{sp}$: 50,000 sec to $> 10^6$ sec
- Radiators required
Spacecraft Based on These Systems

- SSTO
- Landers
- Short range
- Intermediate range
- Long range
SSTO: Air-Breathing!

- QED/ARC
- Air-breathing at low altitude (like scramjet)
- Hydrogen reaction mass at high altitude
- $I_{sp}$ 1538-3062 sec
- Thrust 208.6-83.2 T
- Wet 250 T, Dry 155 T
- Payload 35 T
- $27$/kg to LEO

See Askmar.com for paper
LEO to Luna Transport/Lander

- QED/ARC, water reaction mass
- $I_{sp}$ 1590-2760 sec
- Thrust 75.5-43.5 T
- 250 T wet, 105 T dry
- Payload 35 T
- $\Delta V$ 15.8 km/sec
- $\$24.20/kg$

Figure: an RWB original!

System Technical and Economic Features of QED-Engine-Driven Space Transportation, Robert W. Bussard

33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
Mars: LEO to LMO

- QED/CSR-A preferred (ARC will work)
- Water reaction mass
- Lander similar to lunar transport/lander
- $I_{sp}$ 7800 sec
- Wet 500 T, dry 171 T
- Payload 78 T
- $\Delta V$ 59 km/sec
- $\$232.60/kg$

See Askmar.com for paper
LEO to Titan

- DFP preferred, CSR-B usable
- $I_{sp}$ 70,000 sec (almost continuous thrust)
- Wet 400T, Dry 148 T
- Payload 45 T
- $\Delta V$ 354.5 km/sec
- $\$331.20/kg$

See Askmar.com for paper


System Technical and Economic Features of QED-Engine-Driven Space Transportation, Robert W. Bussard

33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
Colonizing the System

- Estimates include transportation costs of the people, a generous allowance of equipment and supplies for each, and regular trips home.
- Estimates do not include the cost of the equipment and supplies, just the transport thereof.
- Estimates expect 10 years, many trips.
- Spacecraft development costs not included, but life cycle costs included.
- Estimates made in 1997
Lunar Colony

- 4000 people
- 25 tons of stuff each
- $12.48 B

See Askmar.com for paper

Mars Colony

- 1200 people
- 50 tons stuff each
- $15.64 B


See Askmar.com for paper
Titan Colony

- 400 people
- 60 tons stuff each
- 16.21 B

See Askmar.com for paper

1200 people on Mars for the cost of a few Apollo landings?!!

- Economics driven by exceptional performance
- High payload fractions
- Low trip times, so many flights
- Craft highly reusable
- Fuel cheap and light
- Reaction mass from native materials wherever possible
- Each part of the system improves the economics of the rest.
References

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- Open-Source discussions: talk-polywell.org
- Valencia report
  - Many earlier papers referenced, available at Askmar
- Google Talk
- Fusor.net (original Analog article, many refs)
- en.wikipedia.org/wiki/Polywell
- cosmiclog.msnbc.msn.com/ (news updates)
- Handout available after the talk