OutPost on the Endless Frontier©

EPRI e-News on Recent Key Developments in Energy Science and Technology
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Return to Death Valley Days

Trivial Pursuit question. What's the 6th most abundant chemical element in the earth's crust? Answer: boron, element number five in the Periodic Table. In fact, California's southern deserts contain vast amounts of borax, or $Na_2B_4O_7{:}10H_2O$ (remember the radio-TV series, *Death Valley Days*, sponsored by 20 Mule Team Borax and hosted briefly in the mid-1960s by a B-movie actor who later got himself real day jobs in Sacramento and Washington?). You're probably wondering what possible connection could there be between a cleaning compound commonly used in your grandmother's era and energy (aside from that needed to apply elbow grease!). Actually, boron has a myriad of uses, ranging from antifreeze to solder flux to glass to semiconductors, and, it may turn out, as a potential source of electric power as well.

About 80% of boron atoms found in nature contain five protons and six neutrons in their nucleus, the rest five-and-five. The two isotopes, designated as ^{11}B and ^{10}B, respectively, have identical chemical properties (their soaps and bleaches behave the same), but undergo quite different nuclear reactions. The rarer isotope, boron-10, is an absorber of neutrons and is sometimes used as such in nuclear power reactors. Boron-11, however, may prove to be a new nuclear fuel.

But first, we have to make a rather lengthy, but necessary, digression on the history and physics of nuclear-derived electricity, both existing and to-be-hoped-for. Sorry about that.

We all know conventional nuclear plants are powered by the chain reaction fission of certain actinide isotopes, like uranium and plutonium, under bombardment by "surplus" neutrons provided by spontaneous fission of these elements themselves. Uranium-235, for example, splits into strontium and xenon when struck by a neutron of appropriate energy, releasing then two more neutrons to sustain and multiply the next reaction. The masses of the resulting strontium, xenon and two neutrons add up to just slightly less than that of the original U-235. This "lost mass" appears both as kinetic energy of the fragments and as radiative gamma-ray energy via Einstein's relation, $\Delta E = \Delta mc^2$, which is then absorbed and turned into "hot water and steam" in the usual pressurized water or boiling water reaction designs. The neat thing about fission reactions is that they can be "throttled," as discovered by Enrico Fermi in the famous 1942 experiment under Soldier's Field in Chicago, by the insertion of an appropriate amount of material, e.g., cadmium, to absorb a given amount of secondary neutrons…or none at all, in which case we have a bomb! Fortunately for the city of Chicago, Fermi's slide rule got the required amount of moderator right.

Fusion is a different beast. Pioneering studies in the 1930s by George Gamow and Hans Bethe on energy production in stars (Bethe won the Nobel Prize in Physics in 1966 for his contribution) uncovered several reactions whereby light atomic nuclei combined, or "fused," resulting in differential mass loss, or excess energy, again via Einstein's relation, which produced large amounts of heat. An example of one such reaction is the fusing of two isotopes of hydrogen -- deuterium (one proton, one neutron) and tritium (one proton, two neutrons) -- yielding helium (two protons, two neutrons) plus a very energetic neutron (about 14 million electron-volts, a neutron with a velocity close to the speed of light). The appropriate "nuclear chemistry" equation is the so-called "D-T" reaction, $^{2}H^{+} + {}^{3}H^{+} \rightarrow {}^{4}He^{2+}$ (3.6 MeV) + n (14.1 MeV),. Unlike nuclear fission, which can occur more or less "cold," fusion reactions require extremely high temperatures and pressures to overcome the repulsive force which would normally keep the deuterium and tritium ions well apart. Everything is ionized at the temperatures required for fusion -- several million degrees (hey, the units don't matter when it's that hot inside) -- and the electrons have been long separated from their parent atoms.[1] It was realized by Edward Teller and other members of the World War II "Manhatten District Project" that just such temperatures and pressures could be realized within the explosion of the fission-ignited atomic bomb then under development.[2] Thus was born the concept of the hydrogen bomb, and subsequently the dream of harnessing this form of atomic energy for electric power generation.

However, unlike fission, fusion is not easily controllable (I'm often amused by the use of "controllable" as a euphemism for "please avoid blowing up nearby human beings or their belongings." Certainly fusion is "under control" within the sun…just don't get too close!). Most attempts to produce non-violent terrestrial fusion reactions involve creating a plasma -- a gas of isotopic hydrogen ions, usually deuterium and tritium, with the electrons stripped from them by an applied electric field -- and then squeezing them in a very large magnetic field which results in an enormously high density and temperature in a microscopic volume in the hope they fuse. Therein lies the difficulty. Designing a magnetic field configuration to confine a plasma without its leaking brings new meaning to the expression "corralling the cats" as slang for disorganization. Another visualization is to imagine yourself trying to squeeze a ball of jello without some of it oozing between your fingers. This problem was in large part solved by the invention of the "tokomak," a Russian acronym which means "torroidal magnetic chamber," invented in the 1970s in the former USSR (a tokomak sort of looks like DNA torturously twisted into a ring shape). This particular approach became the major focus of attention and funding (billions of dollars internationally) and has remained so until very recently. It has been estimated that the primary energy gain, Q, that is, energy out over energy in, of a D-T reaction in a tokomak could be as high as 30 - 50.[3] As yet sustainable ignition of a fusion reaction remains to be attained, although most researchers feel this will be accomplished should the International Thermonuclear Experimental Reactor (ITER -- a tokomak) be completed. In any event, a great deal of excellent plasma physics research has resulted over the years chasing the dream of fusion generated electricity, but the dream is not without some upsetting nightmares, perhaps serious enough to wake us up permanently.[4]

The advocates of hydrogen isotope fusion make essentially two principal claims -- that the fuel is abundant, and the reaction produces no radioactive waste. All in all, the energy deliverance of mankind is at hand -- at least that is what we have been told every ten years or so![5] Well, as the currently running Hertz TV advert puts it, "not exactly."

Although deuterium appears naturally in about every 6000 water molecules (doesn't sound like much, but it is), tritium is extremely rare, because its "half-life" is about twelve years (63% of a given amount decays after 12 years). Tritium's primary application is for thermonuclear weapons and it thus has to be continuously produced and replaced in warheads. There are two primary methods of manufacturing tritium. One is to use a large proton accelerator -- very expensive. The other is to produce tritium as a byproduct of neutron bombardment of lithium metal used as a moderator in a fission reactor. The latter, of course, requires the construction and maintenance of just the kind of nuclear power source with its attendant waste that fusion is supposed to supplant. As the reader is probably well aware, the creation and maintenance of such plants for weapons tritium is one of current hot political debate.

Regarding the presence or absence of nuclear waste produced by fusion reactions, the picture is by no means clear. As already stated, the energy released by D-T fusion is primarily in the form of high-velocity neutrons. Since neutrons are not charged, they're almost impossible to confine and the container walls of any envisionable reactor will undergo intense bombardment resulting in both highly radioactive material and material degradation, requiring the replacement and disposal of this component every five years or so.[6]

But perhaps the greatest challenge D-T fusion faces is the essential difficulty of effectively "boiling water" with neutrons on any practical economic scale. Early studies[7] by EPRI in the 1970s on the thermal transfer of fusion-derived energy into steam to spin the rotor of a turbine generator indicated any fusion reaction (there are several others besides D-T) which involved neutrons would have this problem, and concluded by the end of the decade that fusion power was so far in the future that it no longer justified more than a monitoring activity on behalf of our members.

Thus fusion electricity faces a engineering challenge, not just one of physics. Nonetheless, in the years following the mid-1970s, the plasma physics discipline has received between $200-300 M/yr in pursuit of "endless power to the people." The continuation of this "energy entitlement program" was called into question once again recently by three "blue ribbon" scientists -- W. E. Parkins (formerly of Rockwell International), J. A. Krumhansl (widely renowned and respected condensed matter physicist from Cornell) and C. Starr (yep, that's our Chauncey, founder of EPRI) -- in separate letters-to-the-editor of Physics Today published in its March 1997 issue.[8] All stress the improbability of neutron-based fusion energy in the foreseeable future. The response of the fusion energy community followed several issues later. Read the arguments pro and con, and then judge for yourself.

Are there alternatives? Of course. Are they more practical than D-T? Well, that remains to be seen. So now back to boron.

A well-studied reaction, reviewed in the EPRI report of Ref. 7, is the fusion of protons with boron-11, given by the equation $^{1}H^{+} + {}^{11}B^{5+} \rightarrow 3He^{2+}$ (8.7 MeV) (this sort of reaction is sometimes called "light fission," since the reaction is really one of proton capture followed by fission of the resulting unstable and excited ^{12}C nucleus). Note there are *no* neutrons emitted, only three charged helium ions, or "alpha-particles." Thus, we can keep via an appropriate magnetic field all reaction products away from vessel walls, and, moreover, subsequently channel the 8.7 MeV He ions into a microwave cavity to produce radio-frequency (rf) energy which can be reconverted directly into consumable electric power, either low frequency ac or simply dc. No thermal plant involved.

The only problem is that, due to the low average collision probability of protons and boron-11 ions confined in a plasma, the estimated Q is 1.1…not much wiggle room for errors in practical physics or engineering realization. For this reason, the p-^{11}B reaction historically has not been thought a plausible alternative to D-T for fusion power. Until recently.

Just about a year ago, in the 21 November 1997 issue of the journal *Science*, a paper[9] entitled, "Colliding Beam Fusion Reactor," was published by N. Rostoker (University of California, Irvine), M. W. Bindebauer (also UC-Irvine) and H. J. Monkhorst (University of Florida). These researchers proposed a "work-around" for the normally low reaction efficiency using a "colliding beam" arrangement, somewhat similar in design to those giant particle colliders employed by high energy physicists, instead of just a plasma. For most reactions of a quantum nature, atomic or nuclear, there is a relative energy difference between colliding particles which is optimum for their interaction, called the "resonance cross-sectional energy." For example, if two hydrogen atoms hit each other with an energy difference of around 13 eV, it is highly likely an ultraviolet light photon will be emitted. For an optimal p-^{11}B reaction, this energy is 580 keV. The colliding beam fusion reactor of Rostoker, et al., is designed to do just that, thus raising Q to as high as 4.5 as calculated by the authors. The *Science* article attracted some attention from the wire services and was the subject of a column in the British magazine, *The Economist*.[10] The authors have formed a corporation, *CBFR*, and are now seeking $15 M funding to construct a test facility.[11] Their proposal projects a $3,500/kW cost for a 100 MVA plant, a figure one would expect to decrease with increasing scale. Not too bad for starters, especially in a potential geopolitical scenario which may prevent exploiting remaining fossil reserves. Has our "clean energy" salvation finally arrived? As always, the devil is in the details.

The Rostoker, et al., paper took over a year to clear peer review, an obvious indication that there was significant disagreement among the referees. This was confirmed several issues later with the publication of three letters-to-the-editor of *Science* taking strong exception to the paper's conclusions (*OutPost* has obtained copies of two more dissenting letters not yet published). Each letter raises several different objections, but they all make one point in common: the physics of a confined gas of charged particles of differing energies will drive it rapidly toward thermal equilibrium. This means that the 580 keV energy difference between the protons and boron ions cannot be maintained long enough to sustain a significant resonance reaction unless enough external energy is continually supplied. The opponents maintain the energy required will result in $Q < 1$, and we already have plenty of technologies like that on the customer side of our wires.

Plasma physics is one of the most difficult and arcane branches of the profession. The differential equations that govern plasmas contain many parameters and are hugely non-linear, especially far from equilibrium. As some readers may know, a non-linear partial differential equation has no general solution…that's why it took many years to find magnetic field configurations, like those produced by a tokomak, that were stable For colliding beams far from equilibrium, the situation could be even worse.[12]

These elegant issues are not going to be solved in a hurry, but we can get started. With the consent of the Executive Committee of the Division of Plasma Physics (DPP) of the American Physical Society, and the help of Dr. William Nevins of the Lawrence Livermore National Laboratory, *OutPost* has organized a special "Mini-Conference on Advanced Fuels for Fusion," to be held on 19 November next at the DPP Annual General Meeting in New Orleans.[13] It will include not only a discussion of the p-^{11}B reaction and its role in the Rostoker, et al., proposal, but other non-tokomak approaches as well. *OutPost* believes this mini-conference may prove to be a watershed event -- the first shot in a re-examination of other options to D-T and tokomaks.[14] In the words immortalized on the silver screen by the once and sometimes host of *Death Valley Days*, we are asking the plasma physics community to turn their attention to some alternative paths to fusion energy and "go in there with all they've got and win just one for The Gipper."

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[1]Under *very unique* conditions, a certain kind of "cold fusion" can occur. Muons are fundamental particles very much like electrons except they are much heavier. When a proton captures a muon, a sort of proto-hydrogen atom is formed. The large mass of the muon makes its single negative charge state very effective in "screening" the normally repulsive force between positively charged protons so that an extremely small probability for "muon-induced fusion" is created, an event far too small to be practical. Regarding the fiasco promulgated by Pons and Fleischman in 1989, forget it. Those interested in this fascinating event in pseudo-science are encouraged to read *Bad Science: The Short Life and Weird Times of Cold Fusion,* by Gary Taubes, ISBN 0394584662 (Random House, 1993) and keep in mind a portion of Abe Lincoln's admonition, "You can fool some of the people all of the time,…"

[2]*The Making of the Atomic Bomb,* by Richard Rhodes, ISBN 0684813785 (Touchstone Books, 1995); *Dark Sun: The Making of the Hydrogen Bomb,* by Richard Rhodes, ISBN

0684824140 (Touchstone Books, 1996). The initial chapters of *The Making of the Atomic Bomb* contain the finest and most fascinating presentation of the history of modern physics from 1890 to 1940, both technically and from a human perspective, that your correspondent has ever read. Five stars.

[3]To put "Q" in a little more perspective, the energy required, or "hotel bill," to run a large coal-fired plant or nuke is about 10% of its output, yielding a Q around 10. Note this is *not* the same as fuel-use efficiency which is an entirely different matter.

[4]For more information on plasma physics and its relevance to fusion power, we recommend the following URLs: Princeton Plasma Physics Laboratory, *www.pppl.gov;* the *Energy Fact Sheet* of the Energy Educators of Ontario, *www.iclei.org/efacts/fusion.htm;* the home page of the International Thermonuclear Experimental Reactor (ITER), *www.iter.org*, and links to other sites contained therein.

[5]Your correspondent was recently present at a seminar delivered by the chief of Japan's MagLev train program (a superfast train floating on a magnetic field produced by superconducting magnets, under development in Japan for thirty years with construction now beginning on a test line between Tokyo and Osaka). A question came from the audience as to the expected date of a positive revenue return from this technology. The speaker replied, "We tell the politicians ten years from now. We learned that response to be very effective from experience with our fusion energy program." Considerable chuckling ensued.

[6]Materials scientists consulted by *OutPost* know of no compound robust enough to withstand such intense neutron bombardment without amorphizing and eventually becoming brittle and crumbling. Silicon carbide (SiC) is sometimes mentioned as a far-out candidate. Testing of candidate materials is complicated by the lack of terrestrial sources of 14 MeV neutrons of sufficient intensity until we actually possess a fusion reactor. One friend of your correspondent ironically remarked, "Perhaps what should be done is to coat a space probe with all prospective compounds and send it off to the nearest star with the appropriate neutron spectrum and flux (unfortunately, the sun doesn't possess such). By the time we get the data back, the tokomakers may have achieved ignition!"

[7]EPRI Report ER-429-SR (1977).

[8]See Physics Today **50**, No. 3 (March, 1997), beginning page 15, and the response collection in the issue Physics Today **50**, No. 5 (May, 1997), beginning page 11. Adobe pdf format reprints of this letters exchange are available by e-mail from *OutPost* on individual request.

[9]N. Rostoker, M. W. Bindebauer and H. J. Monkhorst, Science **278**, 1419 (1997).

[10]*The Economist*, 22 November 1997, p.98.

[11]A copy of the business plan can be obtained from David G. Schetter, UC-Irvine, schetter@uci.edu.

[12]One section of the PhD thesis of Todd Rider, a recent MIT plasma physics graduate who studied the kind of system proposed by Rostoker, et al., contains an eight-page expansion of the Fokker-Planck equation, the general stochastic expression for plasmas, as applied to ion beams not in equilibrium. Rider is one of those who believes the CBFR scheme will fail due to inevitable thermalization of the ion beams.

[13]For general information about the DPP General Meeting the week of 16-20 November 1998, visit *www.aps.org/meet/DPP98/*. For mini-conference abstracts and speakers, visit *www.aps.org/BAPSDPP98/abs/S6900.html#SR8M3.001*. More from *OutPost* after the mini-conference.

Note added 6/23/2010...Correct URL is now: http://flux.aps.org/meetings/YR98/BAPSDPP98/abs/S6900.html#SR8M3.001

[14]The timing of the DPP 98 mini-conference coincides with an important directive recently issued by the House-Senate Conference on the FY99 DOE budget on Fusion Energy Sciences. As mentioned previously, plasma physics research has received consistent support throughout the years in the amount roughly between $200-300 M/yr (this does not include about $500 M/yr which goes to DOE's Defense Programs). Much of this money has gone to support tokomak centers and related magnetic confinement research. Last month the H/S conferees pointedly urged DOE to "place special emphasis on funding…proposed alternative concept experiments at the proof-of-principle level…" Quite a sea change.