20120 Wells Drive
Woodland Hils, CA 91364
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James Krumhansl
142 Kendell at Hannover
80 Lyme Road
Hannover, NH 03755

Dear Jim,

It was great to be able to talk to you again! Somehow we are both surviving and at least our brains still seem to be intact. I called Gene Crittenden after we finished our conversation on Sunday. He was pleased to learn of your whereabouts, and may have called you by this time. I gave Gene your address and phone number.

I am pleased you are willing to contact Sherwood Boehlert to make sure he understands the uselessness of the fusion program and the ITER in particular. He is in a powerful position now as Chairman of the House Science Committee. Enclosed are a couple of pages from a 1996 booklet on the Congress. Note that Walker was replaced by Sensenbrenner, who in turn was replaced by Boehlert.

By now you have probably seen the article on pages 28 and 29 of the November PHYSICS TODAY. The fusion proponents are pushing for more money again and are using the ITER project as a driving wedge. Unfortunately that is backed by Ray Orbach and Anne Davies of the DOE. There are, nevertheless, some skeptics as is mentioned near the end of the article.

The other article that disturbed me, and to which I plan to send in a letter of comment, is the one beginning on page 981 of the November 1 SCIENCE. It contains a long diatribe on the promise of fusion and fusion-fission hybrids, which is a disservice and can only further confuse the public as to what may be the real alternatives for dealing with the CO_2 pollution problem. They reject fission reactors and the breeder for the wrong reasons, and then make the amazing statement in comparing fission and fusion at the bottom of the first column on page 985, "Despite enormous hurdles, the most promising long-term nuclear power source is still fusion."

As long as such an opinion pervades political thinking, the country is in great trouble. That same point is emphasized in Chauncey's letter when we published our three in 1997. Note the last sentence in the next to last paragraph of Chauncey's letter. As requested, I am also enclosing a copy of those three letters for your use in dealing with your friend Boehlert.

As you of course know, there are many huge problems facing ever achieving practical power generation from any fusion reactor plant. These are pointed out in our three earlier letters. But a convincing case is difficult to make for the single most serious obstacle. It is clearly pointed out in the beginning of my letter, but it has been unappreciated and still is ignored by the fusion community and all other proponents. That obstacle is the effect of the heat removal constraint in forcing the capital cost of any fusion plant into a totally unacceptable range, independent of the method of confinement, the fusion fuel used, and any success that fusion reactor physics may achieve. This argument would also be a difficult one to make with Boehlert, but somehow that fundamental and over-riding disadvantage of the fusion concept must be understood.

For whatever help it might be, I am enclosing a four page write-up that attempts to show the cost impact of the heat removal constraint by dealing only with the blanket and shield of a fusion reactor using the D-T reaction. And this is a most favorable case since 80% of the thermal power (MWt) is carried into the blanket by fast neutrons, where heat removal is more easily accomplished than at the reactor vessel wall.

Also enclosed is a single page that gives comparative heat removal rates for proposed fusion reactors and for fission reactors. The Aries I design was an all-out attempt to boost heat removal in a D-T fusion reactor, but it was based on a totally unrealistic design. For example, the gigantic toroidal vessel was fabricated from silicon carbide.

Jim, let me know if I can be of any further help. And good luck in beating back the vandals at the gate!

Sincerely,

Bill

CENTRAL STATION POWER GENERATION BY FUSION REACTORS IS MADE HOPELESS BY A FUNDAMENTAL HEAT REMOVAL CONSTRAINT

Any nuclear reactor based on the fusion principle is faced with the inherent fundamental engineering disadvantage that heat cannot be extracted from within the reacting plasma. The physical installation required to remove the heat generated from outside of the plasma is necessarily so large and expensive that the electric power produced will be unacceptable on the basis of cost alone.

This can be illustrated with the example of a hypothetical fusion reactor design using magnetic confinement with the Tokamak configuration and employing the deuterium-tritium thermonuclear reaction. The excessive cost of the power produced will be shown based on the required capital cost of a single component, the neutron blanket and radiation shield combination that surrounds the vacuum vessel (or "first wall").

The following terminology will be used:

H = Average heat transfer rate at the first wall in MWt/m^2

t = Average total thickness of blanket and shield in meters

d = Average density (specific gravity) of blanket and shield

C = Average cost of blanket and shield, engineered and field installed to nuclear specifications in \$/kg

R = Charge levied against each kWhr generated due to the annual charges against capital investment, expressed in cents/kWhr for every \$1000 of capital investment per kWe of design rated plant electrical output

Now proceed to determine the cost contribution to each kWhr generated due to the capital cost of the blanket and shield:

Average heat flux removed at the first wall equals H MW/m^2.

Total thermal power of the plant per unit of area of first wall equals $5H$ MW/m^2.

It will be assumed that whatever power might be removed at the divertor (and thereby reduce the heat load at the first wall) is compensated for by heat generation within the first wall caused by the fast neutrons (thereby increasing the heat load there).

The factor of 5 results from the fact that 80% of the energy released in the deuterium-tritium reaction is carried away by the fast neutrons, which give up most all of that energy in the blanket and shield.

Design rated plant electrical output per unit area of first wall equals 5/3 H MWe/m^2.

This simply assumes the plant net power conversion efficiency from heat to electricity will be 1/3. The net conversion efficiency is made lower by the high station load required for coolant pumping.

The cost of each unit area of blanket and shield per unit of plant rated electrical output is 3000tdC/5H in $/MWe, The multiplying factor of 1000 converts m^3 to liters.

The charge levied against each kWhr generated due to the capital cost of the blanket and shield combination equals 3000tdCR/5x10^6 H in cents/kWhr.
The dividing factor of 10^6 accounts for the conversion of dollars into 1000's of dollars of capital investment and of megawatts of plant output into kilowatts.

Now consider a realistic fusion reactor plant design case to estimate this last quantity of cents levied against each kWhr generated due solely the charges on the capital investment in the blanket and shield.

H will be taken to equal 0.3 MWt/m^2.

The best choice of coolant for the first wall is pressurized helium. Liquid mentals cannot be used in the strong magnetic field and all non-corrosive liquid coolants contain hydrogen, making them ineligible because of potential contamination of the plasma from normal hydrogen released through decomposition of the coolant by radiation. No other gaseous coolant is superior to helium in its heat transfer capability and other required properties.

The average heat transfer rate of 0.3 MWt/m^2 should be considered a practical maximum when using pressurized helium. This value is 50% higher than that used in helium cooled fission reactors, and it is about half of that used in water cooled fission reactors.

It should be noted that the average heat transfer rate is always made lower than the peak considered possible for two reasons. There will be a peak-to-average ratio between 1.5 and 2 caused by known design differences in coolant flow rates, by the fact that the coolant will be at different temperatures compared to the mixed-mean temperature at the inlet to the power conversion heat exchangers, and because of other considerations. The second reason concerns "hot channel factors". These are factors less than one which are multipliers of the idealized heat transfer rate that are required to ensure engineering conservatism. They account for possible departures from the ideal condition because of variations in manufacturing tolerances, heat transfer reductions caused by deposited films, approximations inherent in calculated heat transfer rates, and other factors. It is necessary to ensure adequate heat transfer under all conceivable adverse conditions in order to avoid excessive heating at any location.

The product of t and d will be about 6.

Two illustrations of this are a blanket and shield average thickness of 2 meters with an average density of 3, and an average thickness of 1.5 meters with an average density of 4. These illustrations correspond approximately to those engineered and optimized for the UWMAK-I and UWMAK-III plant designs.

C will be taken to be $175/kg.

This figure is made high by the large contribution of the cost of labor for the field fabrication and erection of the blanket and shield combination. The design will be a complex layered structure wrapped around a toroidal geometry and comprised of a variety of expensive materials. The installation will have to conform to established nuclear standards.

Indirect as well as direct costs are included, as well as amounts for interest during construction and a contingency. The plant is assumed to be "first generation" but not a first-of-kind constructed.

R will be taken to be 2.4¢ per $1000 of capital investment per kWe of plant rated electrical output.

This figure simply assumes a plant factor of 0.8 and total annual charges against the capital investment of 17%.

Now to calculate the cost of generating each kWhr due solely to the annual charges on the investment made in the blanket and shield combination, based on the above assumptions:

As stated before, this contribution to the cost of each kWhr of output equals $3000\ tdCR/5\times10^6\ H$.

Substituting gives $(3000)(6)(175)(2.4)/5\times10^6(0.3)$ ¢/kWhr. Which calculates to be 5.0 ¢/kWhr as the amount the capital cost of the blanket and shield combination contributes to the generation of each kWhr.

The total capital charges levied against each kWhr generated must include, in addition, amounts due to the capital investment in such items as the following:

- Vacuum vessel with connections to ancillary systems
- Superconducting magnetic field coils and associated cryogenic system
- Systems for vacuum pumping, coolant pumping, plasma heating, plasma fueling, "ash" removal, divertor cooling, hydrogen isotope separation, etc.
- Heat exchangers, turbine-generator and complete plant power conversion installation
- Land, foundations, supporting structures, and housing
- Containmnt building and its associated systems

Total capital cost will be many times that of the blanket and shield. The cost of operation and maintenance, including the cost of replacements for the vacuum vessel and other components, then must be added to the total capital charges to determine the net cost of each kWhr generated. The result is certain to be an appreciable fraction of a dollar per kWhr. This is well outside the range of the cost of power generation by traditional methods, and would be unacceptable to electric utility companies and to the public consumer.

The inherent fundamental heat transfer constraint of the fusion concept, wherein heat cannot be extracted from within the reacting plasma, prevents ever bringing the cost of central station power generation by a fusion reactor plant into a competitive range with other available means of generation. This will be true regardless of the method of plasma confinement employed and the choice of thermonuclear reaction.

Comparison of Average Heat Transfer Rates and Power Densities in Fusion and Fission Reactors

Name of Plant	Average Heat Transfer Rate at First Wall or at Fuel Cladding (MWt/m^2)	Thermal Power Per Unit of Reactor Vessel Volume (MWt/m^3)	Thermal Power Per Unit of Core Volume, Fission Only (MW/m^3)
UWMAK-I	0.25	0.65	
UWMAK-II	0.08	0.65	
UWMAK-III	0.85	1.6	
UWMAK Cost Example	0.62	1.6	
Princeton Design	0.60	1.4	
Aries-I	1.3	5.1	
HTGR Fulton	0.20	0.45	8.4
PWR Calvert Cliffs	0.70	13.	79.
BWR Douglas Point	0.50	5.7	57.
LMFBR Near Commercial Breeder	1.8	8.2	380.