Fusion Power: I Think We're Lost

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How to Tell People Things They Don't Want to Hear?

- **First, Some Physics**
- **Second, Some Engineering**
- **Third, Some Market Realities**
- **Tokamaks vs Fission Reactors**
- **How This Unfortunate Situation Happened**
- **Conclusions &Recommendation**

Key References:

1. **Hirsch, R.L., Kulcinski, G., Shanny, R. *FUSION RESEARCH WITH A FUTURE*. Issues in Science and Technology. Summer 1997 & fall 1999.**

2. **Kaslow, J., et al. *CRITERIA FOR PRACTICAL FUSION POWER SYSTEMS.* EPRI. Spring 1994.**

3. **Perkins, L.J., et al. *FUSION- THE COMPETITION AND THE NEED FOR ADVANCED CONCEPTS*. LLNL. Sept. 22, 1993 & March 30, 1994.**

4. **National Research Council. *ENERGY RESEARCH AT DOE – WAS IT WORTH IT?* National Academy Press. 2001.**

5. **Hirsch, R.L. *ENERGY FUTURES – FACTORS TO CONSIDER.* NAE Regional Conference. Univ. of Wisconsin. March 18, 2002**

FIRST, SOME PHYSICS

- **Net fusion power from diffusion dominated plasmas requires large plasma volume.**
- **DT fusion produces high-energy (fast) neutrons.**
- **Slow neutrons are more easily absorbed than fast neutrons.**
- **Fast neutrons require large volumes of materials to slow down.**
- **Neutrons induce radioactivity when absorbed by most materials.**
- **Neutrons damage materials, limiting their useful life.**
- **Many but not all fusion reactions give rise to neutrons.**

SECOND, SOME ENGINEERING

- **In general, the more materials in a piece of equipment, the more expensive it will be.**

- **In general, the more complex a piece of equipment, the more expensive it is.**

- **Competition between technologies is a matter of dealing with moving targets.**

- **Time-value-of-money penalizes high capital cost technologies.**

THIRD, SOME MARKET REALITIES.

The1994 EPRI Fusion Report

- **"…tomorrow will be different - social, regulatory, and energy issues will pose moving targets."**

- **"To compensate for the higher economic risk associated with new technologies, fusion plants must have lower life-cycle costs…"**

- **"…these criteria are likely to remain crucial… a reality checklist.."**

  - **ECONOMICS**
  - **PUBLIC ACCEPTANCE**
  - **REGULATORY SIMPLICITY**

- **Later: Costs must be 10-20% better than the competition.**

Since the EPRI report and the ISSUES article, deregulation of electric power generation has begun in earnest…

- **Economics is even more important (cost advantage over the competition).**
- **High initial capital cost represents an even bigger disadvantage.**
- **It is even clearer that the competition (other electric power generators) is a moving target.**

"Economic value … must be estimated on the basis of comparison with the next best alternative…" NRC 2001.

TOKAMAK VS FISSION REACTOR CORE COSTS

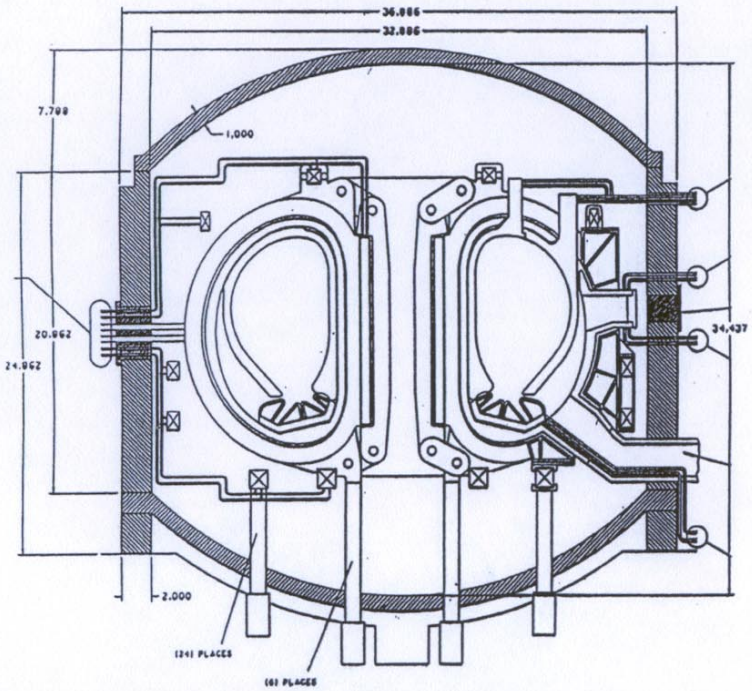
Perkins, et al.

- **1994 comparison of the then existing ITER core design (real!) to the AP 600 Advanced Light Water Reactor.**

- **Not a comparison with the "next best alternative" – A comparison with the closest relative.**

  - **Both ~1.5 gigawatts thermal**
  - **ITER was without tritium breeding: COST ↑**
  - **ITER was / is first of a kind: COST ↓**

- **COST DIFFERENCE: FACTOR OF 30!**



Volume:	25,600m^3	-v-	167m^3	*(factor of 154)*
Mass:	40,560tn	-v-	630tn	*(factor of 64)*
Cost:	$3137M	-v-	$53M w/o fuel	*(factor of 59)*
			$108M, w/ fuel	*(factor of 29)*

International Thermonuclear Experimental Reactor (ITER):
A Prototype Fusion Reactor Core

Westinghouse AP-600:
Advanced, Passively-Safe, LWR

ITER IS A START. IS IT THE BEST THAT FUSION CAN OFFER?

L.J. Perkins, D.E. Baldwin, J.H. Hammer, Lawrence Livermore National Laboratory, March 1994

The Indisputable Factors at Work

- **Net fusion power from diffusion dominated plasmas requires large plasma volume.**
- **DT fusion produces high-energy (fast) neutrons.**
- **Fast neutrons require large volumes of materials to slow down for easy absorption.**
- **In general, the more materials in a piece of equipment, the more expensive it will be.**
- **It's a huge, hollow torus vs a comparatively small cylinder.**

OTHER POINTS FROM THE ISSUES ARTICLES

Hirsch, et al.

- **Because of such high neutron fluxes, "large amounts of …radioactivity."**
- **Embrittlement requires replacement of blanket materials "every few years." "…interior…rebuilt by remote controlled robots."**
- **Radiation damaged materials disposal "at great expense."**
- **Volume of radioactive stainless steel produced is ~10x fission.**

SOME UPDATES

- **Current favored lower activation material: FERRITIC STEEL.**
  - **Initially, roughly the same curries / watt as fission products.**
  - **Must be carefully handled and regulated.**
  - **Levels drop to ~1/100 fission at 10,000 years—STILL NOT ZERO.**
- **DT tokamaks consume large amounts of blanket structural materials.**
  - **Effectively "fueled" by blanket structural material.**
  - **Sustainablity?**
- **The future of fission reactors isn't clear.**

Where Things Went Astray - Remember Fission

- **Once upon a time in fission there many interesting concepts:**
  - **Organic moderated reactors**
  - **Sodium-graphite reactors**
  - **Homogeneous reactors**
  - **Gas cooled reactors**
  - **All with lots of R & D funding & lots of dedicated, bright people.**

- **Then "a tough navy engineer" wanted nuclear powered submarines.**
  - **He needed something that would work reliably.**
  - **His choices: Pressurized & Boiling Water Reactors.**

- **What's in the market today? Products of pragmatic, tough engineering!**
- **Fusion has not benefited from competition-hardened engineers.**

SOME FINAL THOUGHTS

- **What's the definition of success in fusion research?**
  - **To some – We've demonstrated net power. "Build it and they will come."**
  - **To Policy-Makers: We've developed a cost-effective, clean source of electric power.**

- **Winning a big-time competition that has clear rules requires people trained and experienced in that game.**
  - **Physicists in fusion are "necessary but not sufficient."**

Conclusions & Recommendations

- **The arguments against the commercial viability of DT tokamaks are strong and compelling.**

- **Then why spend money and time on a huge, expensive DT burning plasma experiment?**

- **Needed - a careful review by a panel of pragmatic, commercial world engineers.**

Where else? The National Academies, but on the engineering side of the house.

Post Script

- **Fusion - a rich array of mostly unexplored possibilities & one of the few alternatives for a sustainable future.**
  - **Other fusion concepts conceivable**
  - **Other fuel cycles**
  - **Other physics**
- **Let's take advantage of all that has been learned and search for a concept or concepts that stand a chance in the commercial market.**
- **Let's be sure that commercial engineers watch over the program, providing guidance & stopping dead-end concepts at the right time.**

I believe that we can make fusion happen.