his liquid-film reactor concept. Many man-years of engineering calculations are required to assess even the conceptual feasibility of a particular reactor design. These studies, usually performed by interdisciplinary teams from national laboratories, universities, and industry, are widely circulated and criticized. Old ideas often reemerge in new clothes. In the future we shall endeavor to cite both the inspiration and the perspiration.

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SOME THOUGHTS ON THE ENGINEERING PROBLEMS OF FUSION RESEARCH

The following facts and thoughts were brought to my attention in relation to the "Workshop on the Engineering Aspects of Fusion Ignition Experiments," which was held at Chicago during October 29-30, 1981 (see p. 433) in conjunction with the 9th Symposium on the Engineering Problems of Fusion Research. I would emphasize that these views are not my own nor represent any organizations that I might represent. They are published as a note that, I think, impacts on the fusion community. But for convenience, I have used a singular person, "I," in the following comments.

If you look at the costs of electric power from fusion, most of the costs by far come from amortization of the capital investment; fuel costs are negligible, as Dick Post pointed out eons ago. Therefore, it is most important to keep our capital costs down. (As a matter of fact, I have to keep track of all new energy forms, and one almost always finds that capital costs are of dominant significance.)

So what contributes to high capital costs?

1. *Lots of power*. Power plants in the 100- to 1000-MW(electric) range seem most acceptable to the power industry. The lower range is of most interest abroad; the higher range in the United States. Regardless of the unit cost of power, one is often concerned with whether or not a utility can afford to buy any power plant at all. The only real reason for building large power plants is economics of scale. I do not accurately know present costs of transmission of electricity, but I think it is somewhere between 25 and 50%. Thus, if one had a lot of little plants scattered around, one could save at least some of these transmission costs and have a more reliable system, *assuming* that we could get people to accept such plants in their midst, which means a small amount of radioactivity, and *assuming* that there were not large economies of scale. Thus, I find some of the field-reversed mirror ideas we discussed at the workshop quite interesting. Further, utilities *do not* want more than 10% of the power capability of the grid to come from any one source for reliability reasons. (By the way, the cost of a nuclear steam supply system is only ~13% of the total cost of a power plant.)

2. *Large amounts of recirculating power*. However, I feel one does not really need to go so far as ignition to reduce circulating power, but only to get one's Q up to something reasonable, since in any event one has to supply power to pumps, lights, control systems, communications, and God knows what else. Thus, it makes economic sense to push Q only to the point where the power recycled to the reactor itself for reactor purposes is comparable to the power required anyway to supply overhead (on the order of 10 to 15% of the total).

3. *Physically large, intense magnetic fields*. Thus, high-beta machines are much preferred to low-beta ones. Machines having relatively simple coils to make are much preferred to those having complicated ones.

4. *Fast pulsed magnetic fields*. These are costly because of the huge number of wires needed to keep the inductance down and because it is devilishly hard and costly to design and construct a blanket for a fast-pulsed machine, despite Bob Krakowski's cleverness. Where do the magnets go? Where does the shielding go? Eddy currents, heat dumped into superconducting (S/C) magnets, and all that.

5. *Pulsed operation*. This type of operation requires energy storage devices. Further, one must design components to endure the stress cycling that takes place. Steady-state operation greatly reduces the engineering problems connected with eddy currents in S/C magnets.

6. *Need for divertors and limiters*. As you know, divertors are not easy to build into a system and make it much more complex, more costly, and larger. Magnetic limiters and magnetic configurations that automatically have some field lines leading to the outside world for impurity removal are, I feel, to be preferred, simply because one will not have the high Z contamination, the limited life that goes with limiters, and the constructional disadvantages that go with divertors. Of course, it would be pleasant to discover a way of running with dirty plasmas, but that is not in the cards, I think, simply because of the radiation and charge exchange losses that necessarily follow.

7. *Large machines for a given amount of power*. It is extremely desirable to achieve a high power density in our fusion machines in order to reduce their capital cost. This statement implies a very high flux through the first wall. I believe this goal can be achieved for the reasons outlined below. It is probably a mistake to design our first walls to last more than a year or two, and as a consequence, we can use much higher fluxes through this wall than is often contemplated now. The first wall will have to be changed annually, but that is all right *provided* it is easy to change. This statement implies modularity of the magnets and

probably a generally cylindrical design for the fusion chamber, instead of a torus, which is a topologically miserable thing, especially when all sorts of coils are interlocked together. Thus, the type of machine most preferred is in part determined by this matter.

The flux we can send through the first wall is determined in part by the following utility practices.

1. The heavy loads on utilities occur in the summer because of air conditioning and in the winter because of lighting.

2. Although it used to cost about $500 000 per day for a nuclear reactor to be down when it is needed to carry the load, it costs nothing, in one sense, to have it down if it is not needed.

3. Therefore, utilities schedule fuel changes in the spring or fall about once a year for fission reactors.

4. A fission reactor could probably be refueled in as short a time as nine days. However, the shutdown is always taken as an opportunity to get other work and repairs done. Therefore, a four- or five-week shutdown is normal, i.e., the work proceeds at a more leisurely pace. Thus, one could easily expect to have a month to change the first wall in a fusion machine; further, I think it reasonable to do this if the right type of machine is selected and if one plans all this ahead of time. Hopefully, little Maxwell demons will not be needed to weld and unweld the vacuum chamber from the inside, but they could be used if and as necessary.

Next, note that it is really unreasonable to apply the same standard to the first wall of a fusion machine as those applied to a fission reactor fuel element for the following reasons.

1. The reliability required of a fission reactor fuel element is very much higher than that required of a vacuum wall for a fusion machine because the radioactivity in the fuel element is very much higher than that in a fusion machine. A wall leak in a fusion machine means that you have to shut down; the newspapers will make big, nasty headlines of it, and there will be a little tritium here and there. And, of course, Nader, various movie stars, other purveyors of pornography, and self-styled nuclear "experts" will enjoy saying many misleading and false things, and the environmentalists will have a really good time pointing fingers. The utilities and their investors will be unhappy, but you will not be banished to Antarctica.

2. The mechanical tolerances in a breeder and in a fusion machine can be orders of magnitude different. In a fission breeder, the fuel pins bend and tend to shut off the flow of coolant (liquid sodium). This leads to a hot spot that aggravates the situation. The spacing between pins is on the order of 2 mm or so, so if the pins bend by something on this order, as a result of irradiation or otherwise, you are in trouble. In contrast, the vacuum chamber of a fusion machine is measured in metres. So who cares if the wall grows a few millimetres or a few centimetres for that matter, just as long as the vacuum integrity is maintained.

The conclusion then is to irradiate the walls like crazy, reduce the size of the vacuum chamber as much as possible to reduce the capital costs, design the wall so it can be easily changed, and change it every year during the scheduled shutdown for maintenance.

Next, the matter of load following has not yet been touched on by the fusion community, although for the first time people seem to be concerned about thermal stability in tokamaks. (Of course, Princeton Plasma Physics Laboratory did worry about this in connection with their cathedral tokamak design and threw in argon to regulate the temperature of the plasma.) The following data are presented concerning load following.

1. Weekends: 100 to 35% in 4 h, 35 to 100% in 2 h.
2. Normal line flutter: ±10% instantaneously, namely, in ~0.5 s.
3. Off peak day: 75%.
4. Loss of load: 100 to 10 or 15%, which represents the house load. Steam dumping is permitted. Must be able to recover. Loss is instantaneous. Economics determines the time steam may be dumped. It is very improtant to recover quickly.

In a driven machine that does not ignite, there should be no problem, just regulate the source. In an ignited machine, one could dump in impurities, move the plasma nearer the coils to spoil the confinement, or purposely add ripple.

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