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# The Potential Economics of Magnetic Fusion

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JOHN SHEFFIELD

Speaker: The next talk will be given by John Sheffield, the Associate Director for the Fusion Energy Division at the Oak Ridge National Laboratory.

I'm going to talk about what we call generic magnetic fusion reactors. Generic calls to mind going to a local supermarket and being confronted with something in a brown paper package, which they charge you less for, instead of a gaudily packaged named product. You still go and buy the named product because your perception is, owing to the pretty picture on the front, that it is better. What I'm going to discuss is the reverse of this. That there are a number of perceptions of fusion as being unsatisfactory and use a generic model to try to deal with some of these questions, particularly relating to things like Larry Lidsky's comments, for example.

Of course, on packages in supermarkets, you get other comments like the Surgeon General's comments that, "smoking can be hazardous to your health," and on the packaging of fusion we have the equivalent which is, "fusion can be hazardous to your wealth." What I want to show is that most of the perceptions are a little unfair. They can't be proved, though as many people including Larry have indicated there are some real issues and we have to develop better devices than the ones we are studying today. That appears to be quite possible.

Others who have worked with me include Jerry Delene, Bob Dory and Steve Cohn from Oak Ridge National Lab; Wayne Reiersen, who was in the Design Center for a

couple of years as a Grumman Employee, he now works at Princeton; and Dave Ashby who came over from Culham and worked with us at the beginning of the study.

To understand the comments I'm trying to give answers to or to clarify, let me just remind you of some of the words of wisdom from various experts. Lidsky, "Even if the fusion program produces a reactor, no one will want it." Walter Marshall, Head of the CEGB in Britain, "Subject with infinite possibilities but zero chance for success." Bob Carruthers and John Mitchell at Culham who are competent people, I think, have genuine and reasonable concerns about complacency and lack of realism in some of the overly optimistic views of fusion. Karl Schmitter, who is Head of Engineering at Garching, decided that the thing to do to stir people up was just to compare a tokamak reactor to a PWR pressure vessel. And, Bob Krakowski and Ron Miller at Los Alamos have commented on the very obvious difference in tons per megawatt thermal of the fusion nuclear island compared to say a PWR pressure vessel, and have suggested that one possible route is ultra-compact reactors, not using superconducting coils. That's an interesting idea and I'm not going to really comment much on that because I'm only going to consider systems with superconducting coils and try and understand are we really in such bad shape.

The conclusion, to give it to you up front, is that generically, DT burning magnetic fusion reactor models show that within constraints set by generic limitations, (and I'll explain what I mean by that) it is possible for magnetic fusion to be a competitive source of electricity in the 21st Century. I'm not going to try and prove to you that magnetic fusion is cheaper than fission in the future. I thinks that's a fruitless exercise. All we have to do, I think, at this state of the game, tens of years away from commercial deployment, is to

show that the thing has reasonable potential. It is one of the few inexhaustible sources of energy, and we just simply can't afford to ignore it. The fact that we may or may not see, each one of us, how to make an attractive commercial reactor today, really isn't something we ought to take too seriously. The question is as follows, "is it clear or not clear that from fundamental first principles you can prove it won't work?" My answer is, you cannot prove that from first principles.

What we do in assessing the viability of magnetic fusion as an economic source of electricity is to separate out two limitations: those set by today's state-of-the-art and those generic limitations such as cross sections. We've made a lot of progress, but today's reactor designs, as Gerry Kulcinski correctly pointed out, are not blueprints for a future commercial reactor but are simply to help guide us. In addition, today's technology is changing at an incredible rate for the better, and today's views of reliability are based upon present research devices in which totally inadequate money is spent on making them reliable. We're rushing to get something built to get some quick results and so on.

It is important to separate these perceptions from generic limitations such as cross sections which are more or less immutable. Occasionally someone comes up with something like polarization which offers a genuine improvement to a cross section and even in materials properties, one can probably do some clever things, but there are limits. There is no miraculum. So, you need to sort of make sure that you're not putting in something which is just plain silly because it's asking for miraculum or maintaining a cross section that doesn't exist. We do this in our study by using the generic limitations as the main constraints.

We use technology which either exists or is a modest improvement over the present state, as suggested by studies people have done for say TFCX or INTOR. We use, by the standards of many, conservative costings: I don't want to be accused of having got the results simply because I charged half the price anybody could believe for every component and put indirect costs at some ridiculously low level. At the same time, what we're going to do is allow for moderate improvements in reactor design.

I want to decouple it too from people's perspectives that they like or don't like a Tokamak or a Stellarator or Reversed Field Pinch or a Tandem Mirror, and so we don't actually use any one of them.

In order to get a generic reactor, what we do is to start with representative parameters from existing reactor studies to get a feel for what are credible assumptions in designs engineered at least to some level. I'll just give a short list in Table 1 of some representative reactor parameters: STARFIRE, MSR-IIB, EBT-R from Los Alamos, the MARS Reactor. For the basic study we consider something right about 4,000 megawatts thermal, producing 1,200 megawatt electric net. I'm going to assume a certain amount of recirculating power. This can vary, but I'm going to take about 14 percent. I'm going to assume a certain electrical efficiency, 36 percent. Now one of the key parameters is the ratio of the field in the plasma to the field on the coil. This is sort of a characteristic of all these reactors and if I ignore the Reverse Field Pinch where the field in the plasma can be higher than the field on the coil so I am not discussing the Reversed Field Pinch in this, then it's an interesting fact that for tokamaks, EBT's, stellarators and so on, this ratio is typically not more than 0.6. So if you have a 10 Tesla coil, you have up to 6 Tesla in the

plasma. In the case of the Tandem Mirror here, I'm only discussing the center cell: The reason for pointing this out is, that even in a linear system, because of access requirements, you don't have a densely packed superconducting coil, you have access regions between magnets, and you end up with typically <0.60, a value we use in this study (Note, more recent tandem mirror reactor designs have about 0.80). It's important because when we discuss beta it is normalized to that field. I'm going to assume there is a scrape off layer which is 10 percent of the minor plasma radius. I'm going to assume there is 100 megawatts of auxiliary electrical power going to the plasma and I'll show you what the sensitivity to that is. We charge $2.00 a watt direct cost for it. Then, for the blanket and shield and gaps for maintenance, I've taken a consensus of these studies and I am going to have two thicknesses. I'm going to have a thin bit of blanket and shield, 1.3 meters thick which is underneath the coil and then in between the coils I'm going to have something 2 meters thick. These values are typical of every study I've seen. I'm going to assume that one-third is thin and two-thirds is thick.

As far as the coil system is concerned, I'm going to have a primary coil which is a simple toroidal coil set. In addition there is a secondary coil, and I'm going to assume that the secondary coil weighs 25 percent of the weight of the primary coil. Now that again is typical of these studies, in STARFIRE it is 40 percent, the stellarator has 10 percent, EBT 26 percent, MARS is 27 percent. So you can view this 25 percent as representing the end cells of a Tandem Mirror or the twisty bit of a helical coil plus the poloidal coils in the stellarator or the poloidal coils in the tokamak, or the aspect ratio enhancement coils on an EBT.

What I want to find out is how does cost vary with the weight, how does it vary with beta, does aspect ratio matter, what kind of wall loadings do I have to go to, and what do I have to do to get the cost of electricity down to the ball park of fission? So, to summarize then, the key simple assumptions in this study, based upon existing reactor designs are electrical efficiency of 36 percent, a field ratio not more than 60 percent, 10 percent scrape off layer, 100 megawatts electric auxiliary power to the plasma, 14 percent neutron gain in the blanket, 2 regions of blanket and shield, (1.3 meters and 2 meters respectively), ratio of secondary to primary coil set weight of 25 percent and the volume of additional structure to that which is already included in the coils, at 50 percent of the total coil volume. We include 20 percent redundancy in each coil in order to ensure a reasonable availability. Then I use the existing reactor studies mainly STARFIRE and MARS to establish the balance of plant requirements and costs. My costing is taken as a consensus of the costings used in the Los Alamos studies, in the STARFIRE studies, in the Wisconsin studies, plus more recent information from studies done for INTOR, and TFCX which possibly put a slightly more sober view of say the cost of coils than some of the earlier studies.

The totality of the system as shown in Figure 1 is a non-circular plasma with scrape-off layer, blanket gap shield, dewar, primary coil, secondary coil set which I just show schematically as poloidal, it doesn't have to be, and then all the balance of plant as you have in say the STARFIRE and MARS studies, cryogenic systems, magnet systems, heating systems, pumping, turbines and all the rest of that kind of stuff, buildings and what have you, waste disposal, remote handling, I&C and so on.

For the plasma, we assume a simple pressure profile, with a relatively flat density, peaky sort of temperature, and then we assume $T_e$ is equal to $T_i$, we assume a certain fraction of the ions are DT, and the temperature is ≥ 10 keV and we calculate the fusion power output as a function of the pressure, and this we can then relate to beta (the ratio of plasma pressure to magnetic pressure).

The magnets are superconducting. Their performance is based upon recent developments and on studies that have been done for TFCX and INTOR. The winding pack current density used is shown in Figure 2. The algorithm relating current density to maximum field on the coil is relatively conservative, e.g., the EBT coil, designed at Oak Ridge and built by General Dynamics for EBT-P, runs at approximately 10 kiloamps per square centimeter at 7.5 Tesla. We add structure inside the coil at a level based upon studies done for INTOR, in which typically the structure volume equals the winding pack volume at 12 Tesla.

So now lets come to the question of how does one calculate the cost of electricity? It is shown in Table 2. Well, you calculate first of all the direct capital costs and add a contingency, say 15 percent. Then on top of that you have indirect charges. The numbers I have are very similar to the ones John Nuckolls showed. I'm taking 50 percent indirect charges on top of which there are interest charges. The calculation is in constant dollars with an eight year construction. You say, how can you only have 10 percent interest? The answer is, because it is adjusted both for tax write-offs and it's adjusted by backing out inflation. You then take the total capital cost and then you multiply it by a cost recovery factor, which is your mortgage. You borrowed all this money and now you've got to pay a mortgage over 30 years. It's typically 10 percent of the capital cost per annum, in constant dollars. In the fuel costs, $C_F$, I do

something different from the other studies. It's normally stated that the fuel cost for fusion is zero. That is a little misleading. Lithium is one of the fuels, and the cost of recycling the blanket in and out isn't zero. So I take the entire blanket system plus all those things involved in the energy gain that are regularly replaced and that are peculiar to fusion, like limiters, targets, rf launching structure, and I cycle these through and work out an annualized fuel cost. It is not so small. The deuterium is trivial, but those other things aren't. We choose to treat these items as a fuel cost rather than as a capital cost because we want to show that it is very insensitive to reactor power density at constant power output. That is an interesting result.

For operations and maintenance, we take note of the fact that there are typically 430 people to run a fission plant, of which 98 are security guards, and 40 are quality assurance. We look at fusion and say, well maybe we get away with less security guards but they don't need cryogenics experts, RF experts, and diagnosticians, etc. We conclude that we're likely to have as many people but for different reasons. So in fact we have over 400 people to run this fusion plant. Anybody who thinks you need less should look at the personnel needed to run TFTR, MFTF-B and other machines. It's better than putting down 50 people which nobody's going to believe. So, we took a relatively sober view of the operations and maintenance. Interestingly, it really isn't a big cost driver. For availability at full power, I'm assuming 65 percent; that, is of course, as big an assumption as everything else put together.

As an example, consider a 1.22 gigawatt electric plant, let the capital cost direct be 1.3 billion, with the indirects it goes up to $2.5 billion, 10 percent fixed charged rate means that it is necessary to raise in revenue $250 million a

year and then we have $68 million fuel charge, and $46 million operations and maintenance. The cost of electricity will be 52 mills per kilowatt hour, which compares reasonable to present fossil and fission reactor costs, which on the same basis run around 40→45+ mills/kWh.

As far as costs are concerned, I use costs which are somewhat higher than the STARFIRE study and are more in line with the more recent Los Alamos studies. I would like to draw your attention to the coils. For the magnets, I take a $80.00 a kilogram, including structure with indirect costs and contingency, that comes up to $150.00 a kilogram. This is a little lower than present coils, but present coils tend to be one of a kind and in 50 years, maybe we can do a little bit better than we presently do.

In calculating fuel cycle costs we assume a 20 MW.y $m^{-2}$ neutron fluence limit on the first wall and change out the blanket and first wall every time it reaches this limit, typically every five years For the targets and limiters we set a similar but more stringent limit and replace them regularly, typically every year or less.

Now lets have a look at some of the data from this calculation; see Figure 3. The first question is: does the cost of electricity depend strongly upon aspect ratio and what is it? And how does it depend upon beta? This is cost of electricity for a generic system, 1.22 gigawatts electric, non-circular, field limited by 9 Tesla coils, 100 megawatts electric auxiliary plasma power.

It is easy to see why designs are floating up from 5 percent towards near a 10 percent beta. It is because there is a cost advantage of something like 20

percent that we really can't ignore. On the other hand, going much above 10 percent beta at this field, doesn't really gain you an awful lot, because the rate of change of cost is getting very small, because so little of the cost is in the fusion island. At the higher betas, ≥ 10 percent, we could use the opportunity to drop the magnetic field. And that might, ultimately, as pointed out by Los Alamos through the Reverse Field Pinch studies allow one to go water cooled copper coils.

The COE is remarkably insensitive to aspect ratio over a wide range, therefore there is no need to restrict ourselves, say, to tokamaks. Simple tokamaks tend to be at low aspect ratio and there may be attractive possibilities at larger aspect ratios with the RFP's, stellarators, EBT's or Tandem Mirrors. There is a price to pay as the aspect ratio is increased in that you have to have better physics. So there should be good cause to believe that you can get both the high beta and the better physics before you move in that direction.

To minimize the COE it is necessary to reduce the weight of the fusion island; see Figure 4. It is interesting that much of the cost is independent of the weight of the fusion island and therefore with superconducting coils there is little point in working to reduce the weight below about 10,000 tonnes. What price do you have to pay? Well, the prices you have to pay are the following: As you lower the weight, and this is more or less independent of aspect ratio, you tend to have to go to higher beta and you may have to put up with a higher wall loading if you operate at fixed field. However, if you could get higher beta, you might be entitled to drop the field and the saving from doing that might, in fact, allow you to make a slightly bigger machine and still stay at relatively moderate wall loadings. So in going from, say, somewhere

around MARS and STARFIRE weights which are about 20,000 to 25,000 tonnes down to say 10,000 tonnes, you do need to do slightly better in physics, but you can probably trade down in field to compensate the increased wall loading.

In Figure 5, the sensitivity of the COE to various fusion parameters is indicated and a COE range for optimized fusion systems is compared to the typical range of fission costs.

The fission range is similar to that shown by John Nuckolls and in fact, fossil power is in a similar cost range. You can see that on this simple model, if we can build fusion reactors weighing about 10,000 tonnes with superconducting coil they are in the same ball park. Then I think the choice depends upon other criteria as to whether somebody is going to buy them or not. But basically as far as I can tell, there are perfectly reasonable generic fusion reactors sitting in the same region as fission and coal in the future. I believe that at this stage it's not worth trying to prove more than that. They are somewhat smaller than the present design such as MARS and STARFIRE, and I assume they can be smaller because I assume we're going to advance fusion over the next years. Inventiveness has been shown in all these areas, and we'll come up with somewhat better configurations. It's not asking for a fantastic improvement.

Just to illustrate the kind of point and very schematically, let me take a European conceptual fusion reactor. Here is the Culham Mark II-B and I haven't made a mistake and drawn the edge of this wrong. This is actually an iron core and the reactor weighs 25,000 tons. It has these enormous coils which are partly for access but also partly because of perspectives about the effects of

magnetic ripple on plasma losses. Interestingly, we have costed it, applying our costing code, and we get somewhat higher costs than the designers.

On the other hand, as shown in Figure 6 there could be a toroidal device (it is not necessarily a tokamak), with the same plasma and the same blanket and shield thickness, but in fact it is an improved configuration where the coils are allowed to be closer to the plasma. It is a slightly bigger aspect ratio so it is not scrunched up in the middle and the system weighs 10,000 tons and costs somewhat less. You could view this as a tandem mirror center cell with improved performance and improved end cells or as an improved toroidal device, simply because we have a better engineered system.

Let me make a few final points on this study. The effect on cost electricity of changing construction time is shown in Figure 7. The effect of changing additional power is shown in Figure 5. We assumed eight year construction time, had it been seven we would have chopped a few percent off the cost of electricity. If the auxiliary plasma power were only 50 megawatts, we would have saved a couple of mills per kilowatt hour. Auxiliary plasma power is an enormous cost driver. That enters not only into the cost of that system, it enters into the reliability, and it also enters into the recirculating power which impacts the total cost of the system.

The cost of electricity for a simple case, is shown in Figure 8 with fixed beta, fixed field ratio, fixed aspect ratio and assuming that the auxiliary power is proportional to the fusion power. An important result, shown in Figure 5 is that with the chosen algorithm for the superconducting coils, you don't want to work at 12 Tesla, you don't gain anything by it. The increased field on the

coil is compensated by the increase in the amount of coil volume and this is seen in many studies. If, however, in the future improved 12 T coils are made then a lower beta level would be acceptable.

Let's just have a look then at the question of the unit size. There is a cost penalty, as shown in Figure 8, of about 20% in going from 1200-600 $MW_e$. However, the wall loading in the 600 $MW_e$ case is lower and the cost could be decreased by going to higher beta or higher field, with improved coils. The price to pay would be the achievement of a lower $\chi_E$. Another important point is that this is a similar situation to that found in fission and what I would do if I had 600 megawatt units, would be to build a couple of them rather than one, in which case the cost differential from a 1200 $MW_e$ unit is similar to that for fission.

Let me give you my conclusions from the generic studies. Do generic limitations eliminate fusion? The answer is no. Within the constraints set by the cross sections and so on, it seems possible for magnetic fusion to be competitive in the 21st Century. We obviously have to do a lot of things we haven't presently done. Desirable features are steady state operation (you really don't want pulsed if you can avoid it), moderate to low additional power and recirculating power, as pointed out by John Nuckolls (it's difficult to afford hundreds of megawatts recirculating because of reliability issues as much as anything else, not to mention cost), beta, I think, most people agree nowadays 4-5 percent beta isn't going to make it, (you want 8 percent or more), and a system with a good field ratio because it's the coupling of these two together that determines what pressure you can support.

So the generic toroidal studies were started at Oak Ridge about two years ago because of concern about some assessments of magnetic fusion viability. They have evolved to meet the goals of defining satisfactory products and to determining self-consistent/component requirements of the system. We think a moderate scale reactor 10 or 15,000 tons will be fine. Component requirements appear to be no different from those that people have studied and it appears, quite interestingly to me, that one could reasonably make moderate size electric plants maybe even smaller than 600 megawatts electric.

Table 1. Representative Parameters from D-T Reactor Studies

| Parameter | Units | Starfire | MSR-IIB | EBT-R | MARS | Generic Reference |
|---|---|---|---|---|---|---|
| $P_{th}$ | MW | 4000 | 4000 | 4030 | 4060[d] | 3750 |
| $P_e$(net) | $MW_e$ | 1200 | 1300 | 1200 | 1360(1570) | |
| $P_{er}/P_{eg}$ | – | 0.167 | 0.07 | 0.16 | 0.29(0.20) | |
| $\eta_e$ | % | 0.357 | 0.350 | 0.355 | 0.386(0.436) | 0.36 |
| R | m | 7.0 | 23.0 | 36.0 | 24.0 | – |
| $\bar{a}$ | m | 2.45 | 0.81 | 1.0 | 0.43 | – |
| $R/\bar{a}$ | – | 2.86 | 28.4 | 36.0 | 55.8 | – |
| $B_o$ | T | 5.8 | 6.56 | 3.64 | 4.7 | – |
| $B_o/B_m$ | – | 0.523 | 0.566 | 0.375 | 0.635 | ≤0.60[e] |
| $\bar{a}_w/a$ | – | 1.10 | 1.41 | 1.10 | 1.40 | 1.10 |
| $P_{aux}$ DC | MW | 153 | – | 105 | 354 | 100 |
| $P_{aux}$ Pulse | MW | 12 | – | 100 | – | – |
| $g_n$ | – | 1.14 | 1.10 | 1.50 | 1.16 | 1.14 |
| $\Delta b$[a] | m | 0.37 0.90 | 0.41 1.07 | 0.37 0.55 | 0.38 1.13 | 0.45 0.90 |
| $\Delta g$ | m | 0.04 1.00 | 0 0 | 0.02 0.07 | 0.14 0.38 | 0.10 0.30 |
| $\Delta s$ | m | 0.64 1.10 | 0.60 1.00 | 0.67 0.63 | 0.84 0.45 | 0.75 0.80 |
| $\sum\Delta$ | m | 1.05 3.10 | 1.01 2.07 | 1.06 1.25 | 1.36 1.96 | 1.30 2.00 |
| $W_b$ | tonnes | 1550 | 2060 | 4120 | 3220 | – |
| $W_s$ | tonnes | 13400 | 10280 | 13110 | 5930[f] | – |
| $W_{cp}$ | tonnes | 5310 | 12860 | 20230 | 9600[f] | – |
| $V_{ct}$[b] | $m^3$ | 950 | – | – | – | – |
| $f_{cs}$[c] | – | 0.41 | 0.10 | 0.26 | 0.27 | 0.25 |
| $V_{st}/V_{ct}$ | $m^3$ | 0.5 | – | – | – | 0.5 |
| $\sum W$ | tonnes | 25,280 | 26,490 | 43,360 | 21,340 | – |

Table 1. Representative Parameters from D-T Reactor Studies (Cont'd)

(a) The two sets of numbers for the radial build of blanket and shield refer generally to values under and between coils, respectively. For the generic studies the coil radius will be determined by the smaller value. The volume of blanket and shield will be based upon assuming that 1/3 of the blanket and shield have the smaller radial build, and therefore, 2/3 the larger build.

(b) $V_{ct}$ is the total coil volume.

(c) $f_{cs}$ represents the mass (volume) of coils normalized to those coils (or parts of coils) which give the toroidal field. In the case of MARS, it is the ratio of end cell to central cell magnets.

(d) The numbers in brackets are for an improved barrier system which requires less power. The high efficiency ($\eta_e$) is a result of the use of a direct recovery system for the plasma thermal power.

(e) It is assumed for the generic toroidal system that $B_o/B_m$ has the value for a simple toroidal coil set. The constraint to $B_o/B_m \leq 0.60$ reflects the fact that large aspect ratio is generally associated with with configurations which do not have at the inner bore of the torus a continuous toroidal magnet.

(f) Solid breeder blanket, includes central cell support structure.

Table 2. Cost of Electricity (COE) Formula Definitions

The Cost of Electricity (COE) is given by

$$COE = \frac{(C_C F_{CRO} + C_F + C_{om})}{(P_e \times hr \times f_{av})} \text{ mills/kW.h}$$

- The costs are in constant 1983 dollars, 1 mill = $10^{-3}$ \$. $P_e$ is taken to be the maximum net electric power (MW).hr = $8.76 \times 10^3$ is the number of hours in a year.
- $f_{av}$ = 0.65 is taken to be the plant availability at maximum power. This level corresponds to good power plant experience.

  The capital cost is

$$C_C = C_{DO} \times (1 + f_{con}) \times f_{IND} \times f_{IDC}$$

- $C_{DO}$ is the direct capital cost of the plant $f_{con}$ = 0.15 is the contingency.
- $f_{IND}$ = 1.50 are the indirect charges for an 8 year construction period (Y = 8). These are taken to be typical of the better fission plant experience. They are slightly higher than for fossil plants to take account of the somewhat higher technological complexity. For varying the construction time we assume that

$$f_{IND} = \left(1 + 0.5 \frac{Y}{8}\right)$$

where $6 \leq Y \leq 12$.

Table 2. The Cost of Electricity (COE) Formula Definitions (Cont'd)

Indirect charges consist of

| | |
|---|---|
| Construction facilities, equipment and services | 15% |
| Engineering and management services | 25% |
| Owners costs | 10% |

- $f_{IDC} = 1.10$ is the accumulated interest charges over an 8 year construction period. For a variable construction period $f_{IDC} = (1.011)^{(Y + 0.61)}$, $4 \leq Y \leq 12$.
- $F_{CRO}$ is the fixed charge rate in constant dollars. It is similar to the annual payment for a mortgage. For a nominal plant lifetime of 30 years, $F_{CRO} = 0.1$.
- $C_F$ is the equivalent of the annual fuel costs for fission and fossil plants. In those systems it includes the cost of the uranium and coal. In past fusion reactor studies items such as the initial blanket costs have been put under the direct costs. This makes harder the assessment of the effects of varying, say, power density since it is the replaceable items which are affected and hiding part of their cost in the initial capital cost confuses the picture. The system used here is to assign all items which involve continuing replacement and which relate to the "fuel" or "energy gain" cycle to this account. This procedure does not alter the total COE. The items are the first wall and blanket, limiters/targets and the expendable components of additional heating which are used in the power producing phase.
- $C_{om}$ represents the annual running costs beyond those included in $C_F$.

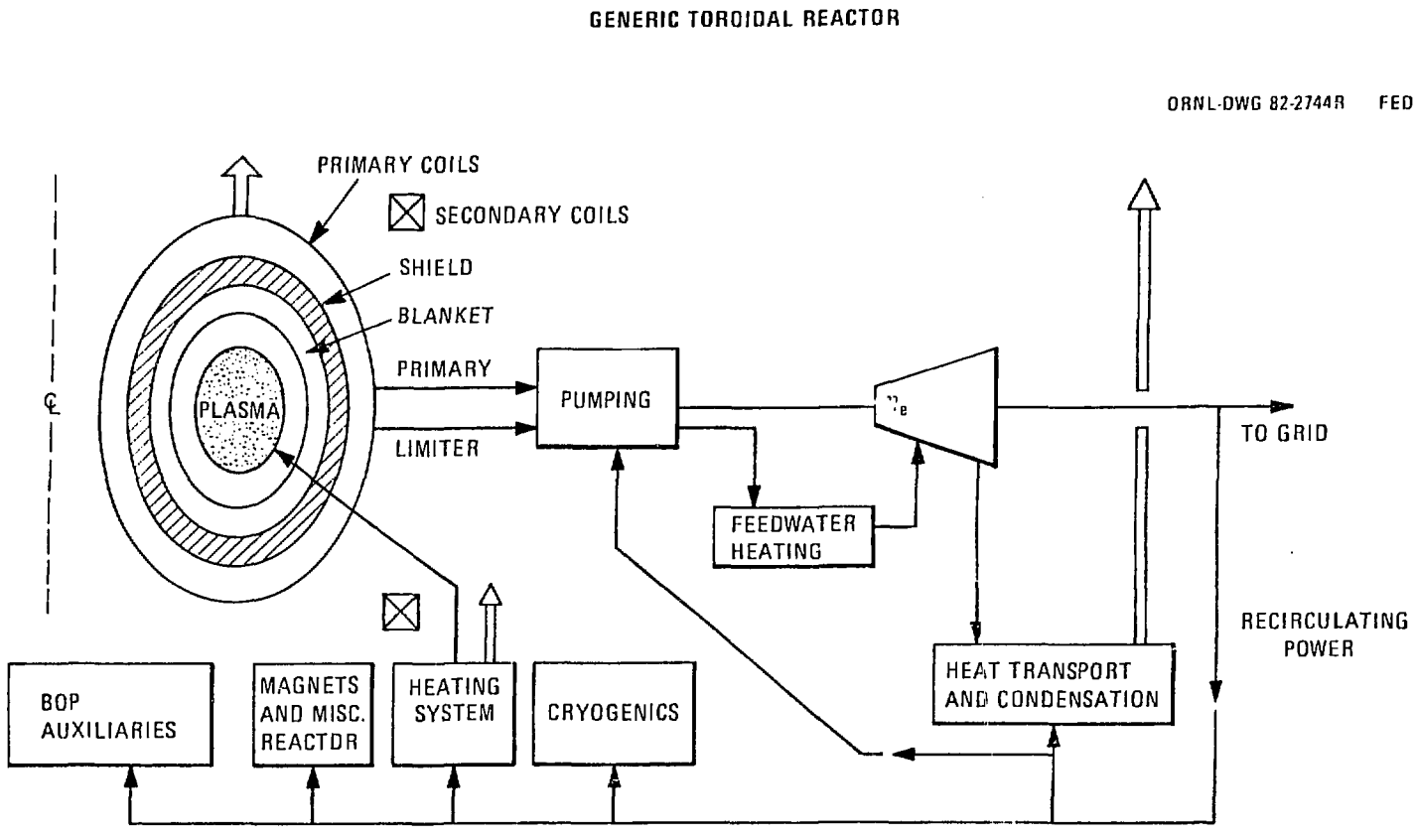


Fig. 1. Schematic diagram of generic fusion reactor.

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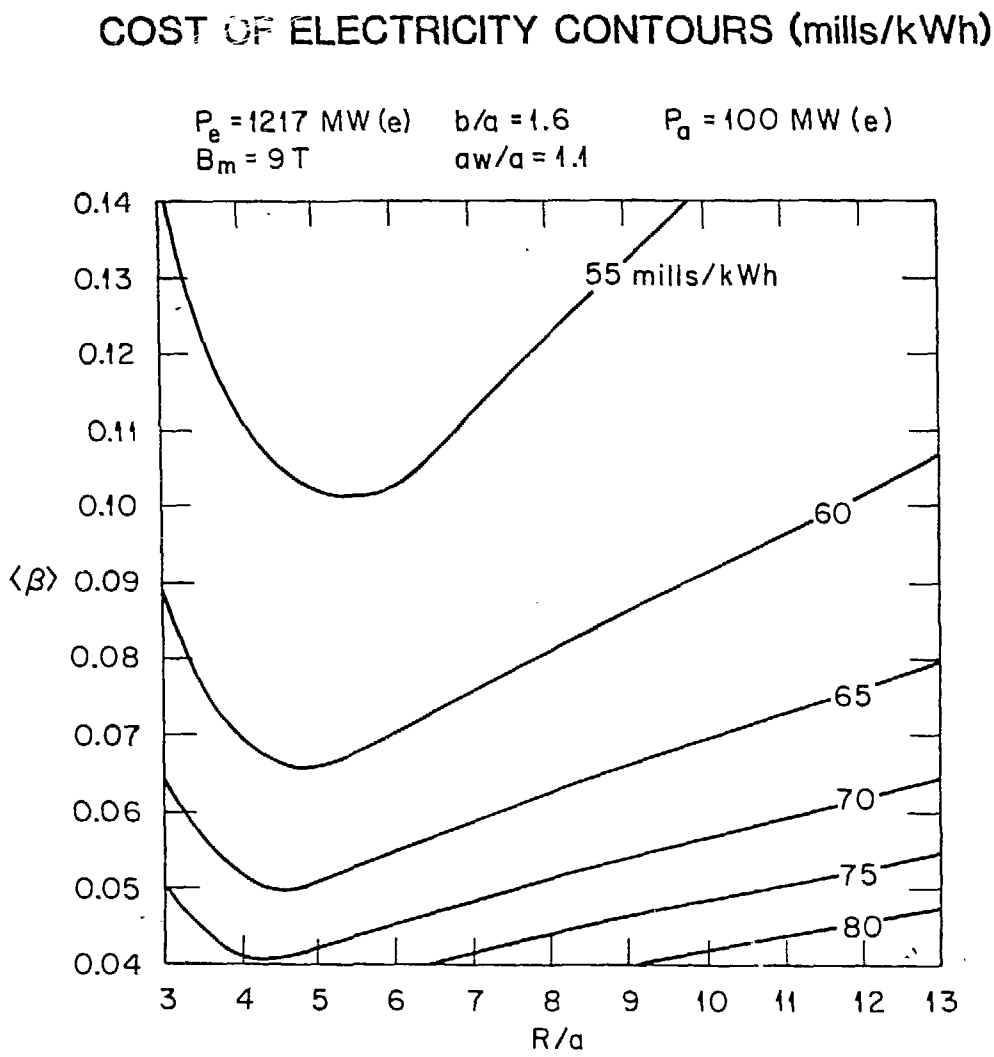


Fig. 3. Variation of the COE with volume average beta (⟨β⟩) and aspect ratio (R/a).

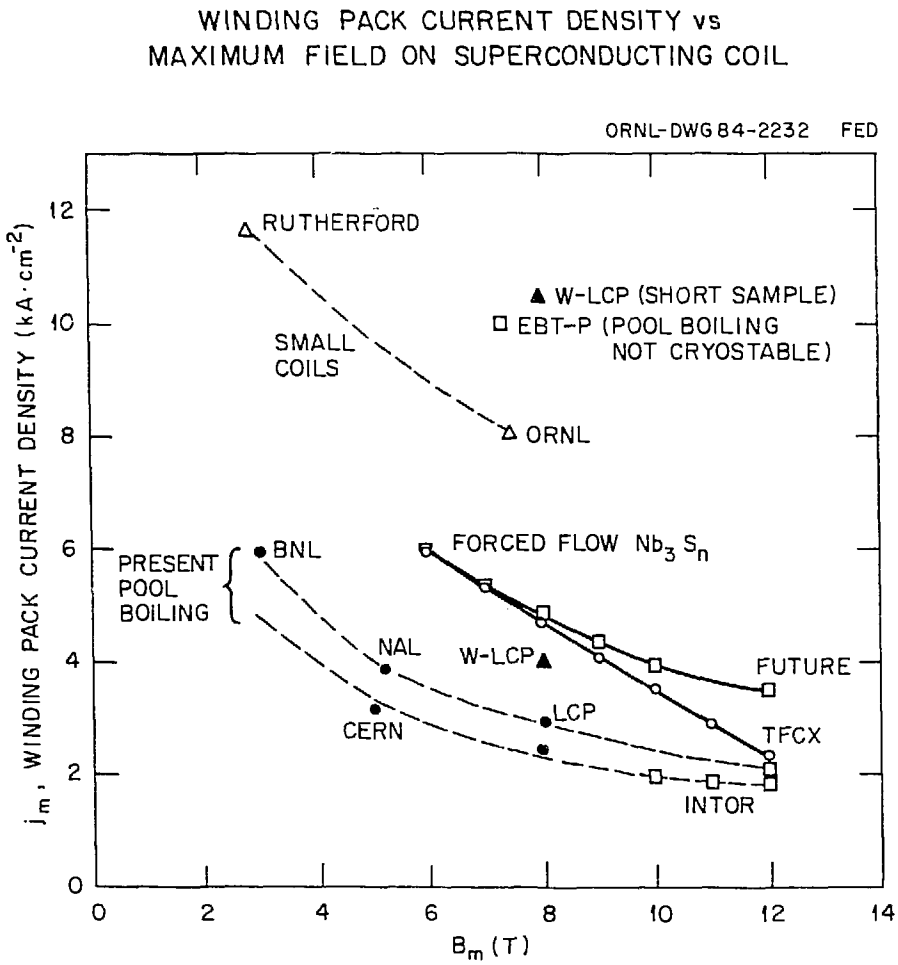


Fig. 2. Values of the maximum field $B_m$ and winding pack current density $j_m$ for existing and future superconducting coils.

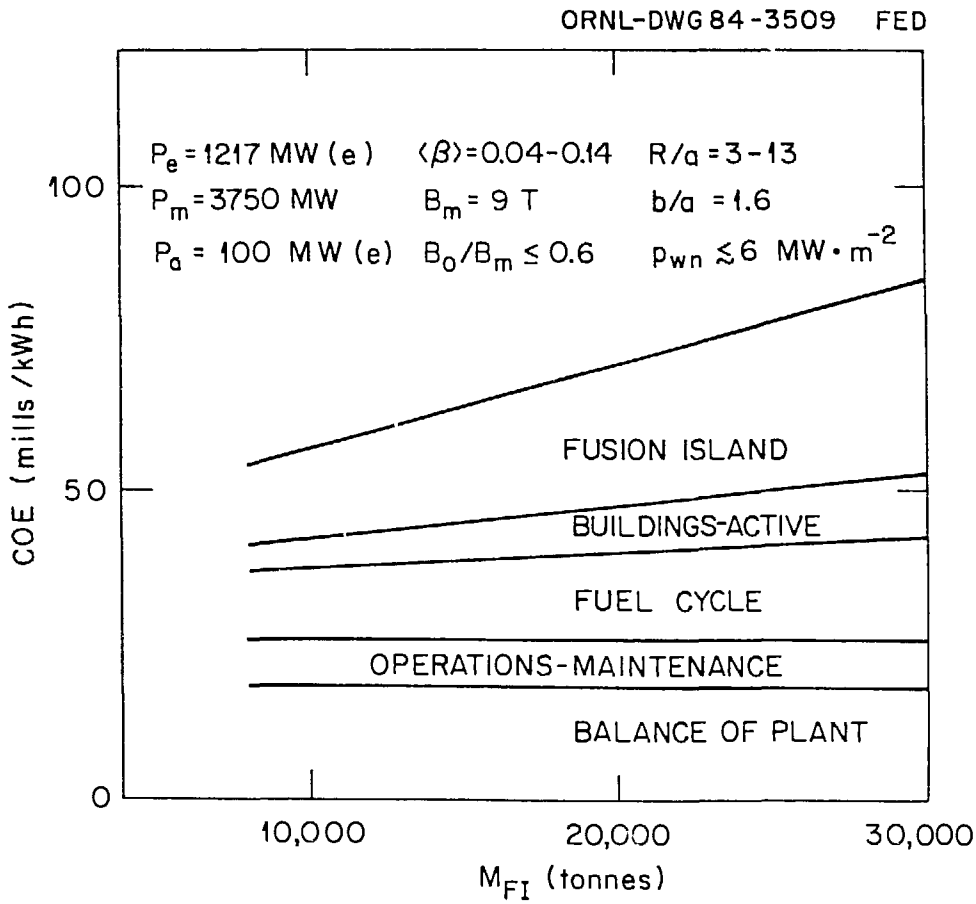


Fig. 4. The COE decreases as the mass of the fusion island ($M_{FI}$) decreases.

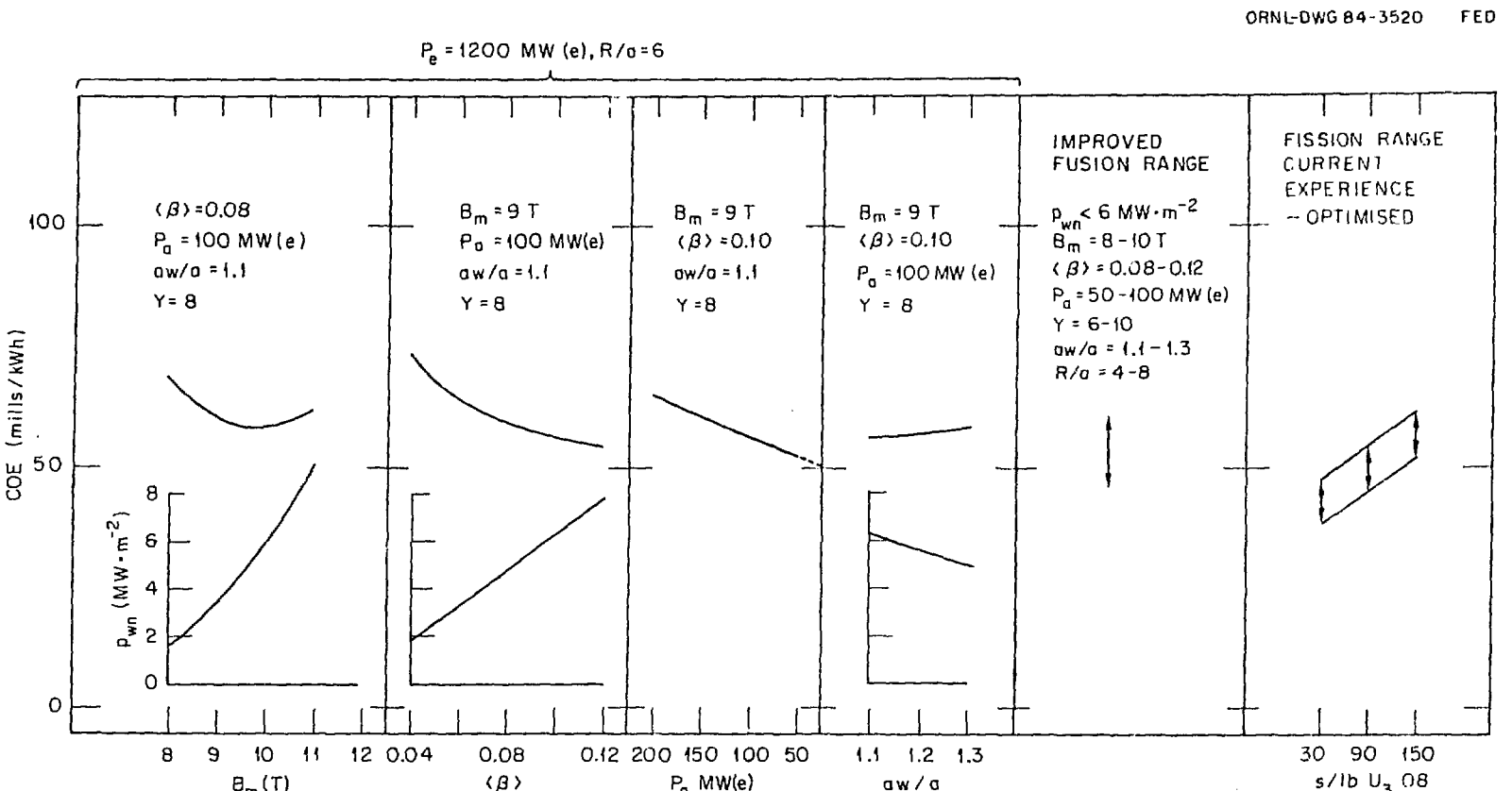


Fig. 5. (a) Dependence of COE and $p_{wn}$ on $B_m$ at fixed $\langle\beta\rangle$, $\frac{a_w}{a}$, $P_a$.

(b) Dependence of COE on $\langle\beta\rangle$, $p_{wn}$ at fixed $B_m$, $\frac{a_w}{a}$, $P_a$.

(c) Dependence of COE on $P_a$, at fixed $\langle\beta\rangle$, $p_{wn}$, $B_m$, $\frac{a_w}{a}$.

(d) Dependence of COE and $p_{wn}$ on $\frac{a_w}{a}$ at fixed $\langle\beta\rangle$, $B_m$, $P_a$.

(e) Range of COE for ranges of $B_m$, $\langle\beta\rangle$, $p_{wn}$, $P_a$, $\frac{a_w}{a}$, Y and R/a.

(f) Range of COE for a fission reactor as a function of the price of $U_3O_8$

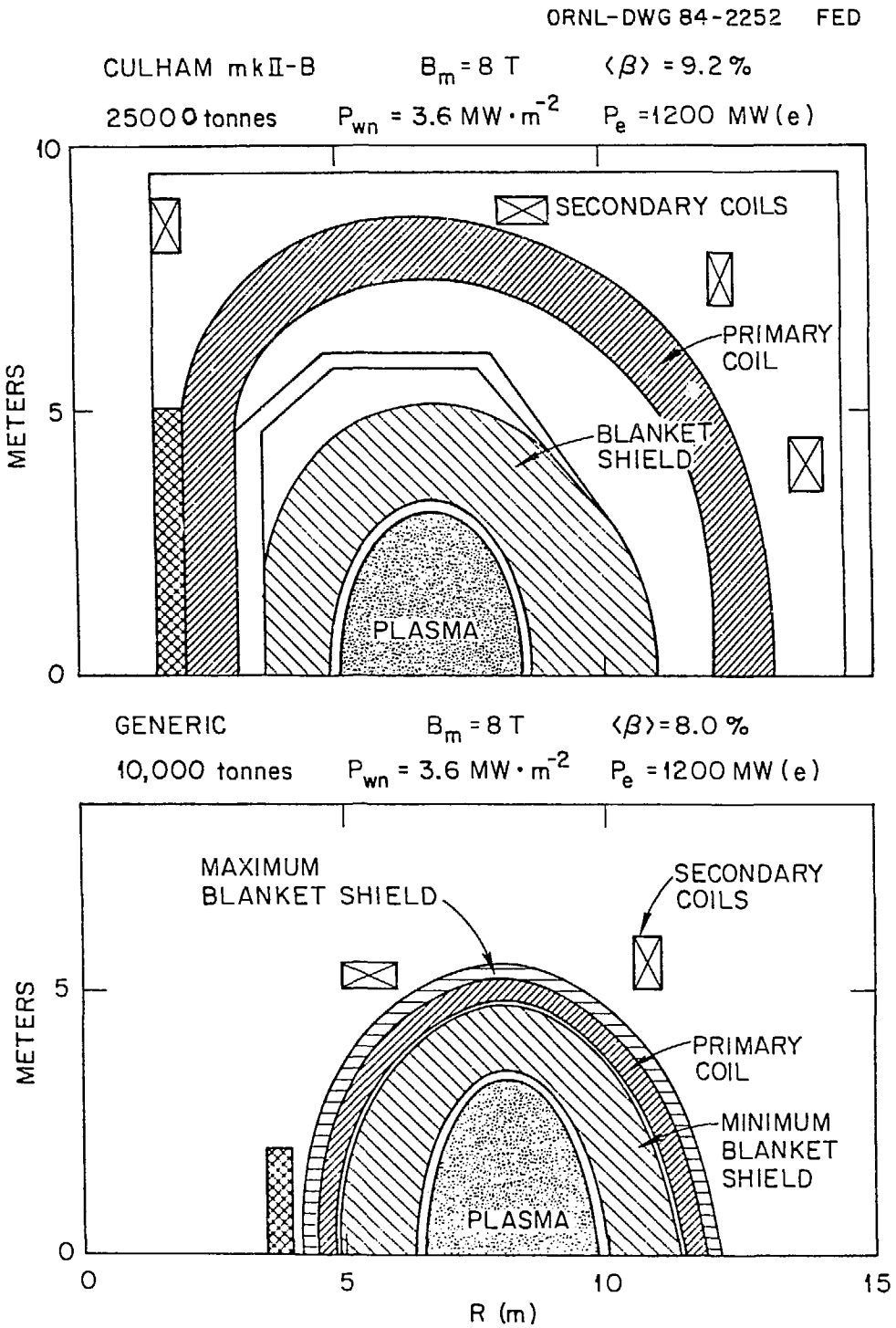
ORNL-DWG 84-2252 FED
CULHAM mkII-B
$B_m$ = 8 T
⟨β⟩ = 9.2 %
25000 tonnes
$P_{wn}$ = 3.6 MW · $m^{-2}$
$P_e$ = 1200 MW (e)
SECONDARY COILS
PRIMARY COIL
BLANKET SHIELD
PLASMA
METERS
10
5
0
GENERIC
$B_m$ = 8 T
⟨β⟩ = 8.0 %
10,000 tonnes
$P_{wn}$ = 3.6 MW · $m^{-2}$
$P_e$ = 1200 MW (e)
MAXIMUM BLANKET SHIELD
SECONDARY COILS
PRIMARY COIL
MINIMUM BLANKET SHIELD
PLASMA
METERS
5
0
0
5
10
15
R (m)

Fig. 6.

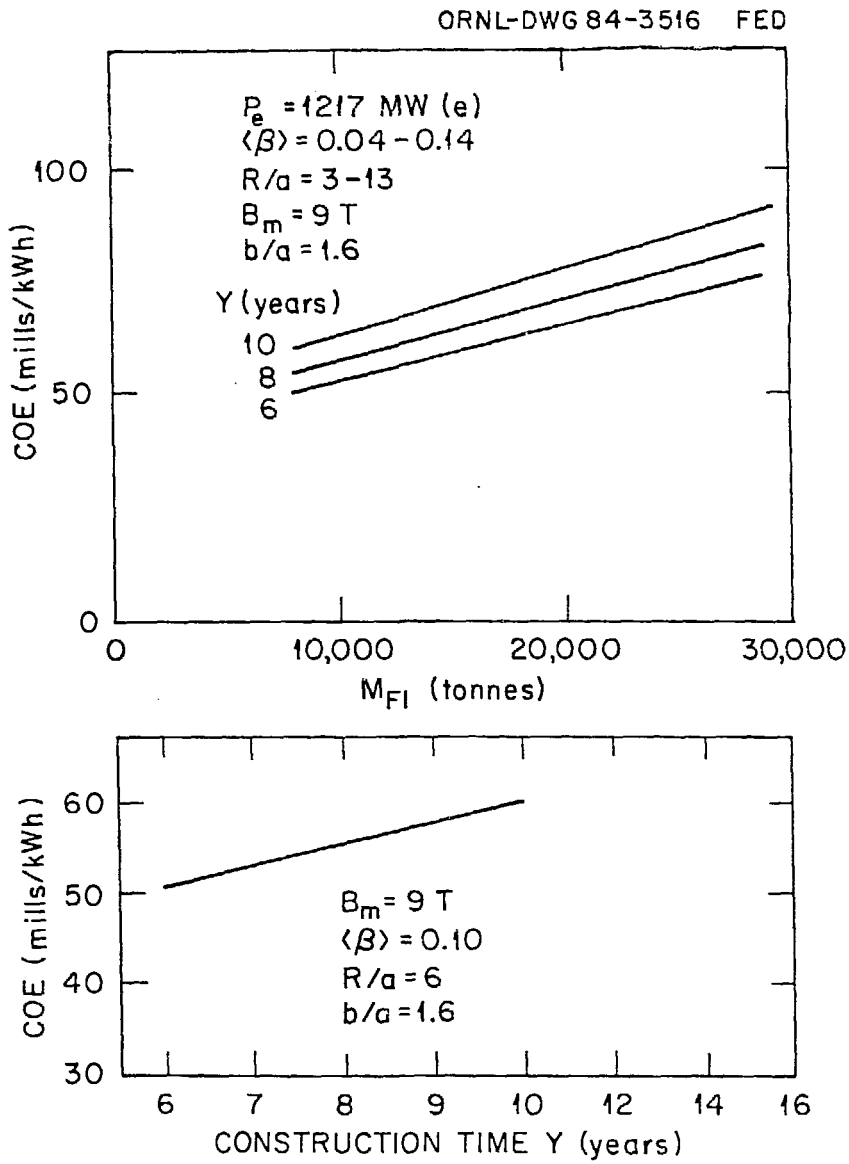


Fig. 7. Dependence of the COE on Y at fixed ⟨β⟩. (a) Dependence of the COE on the construction time (Y) as a function of $M_{FI}$.

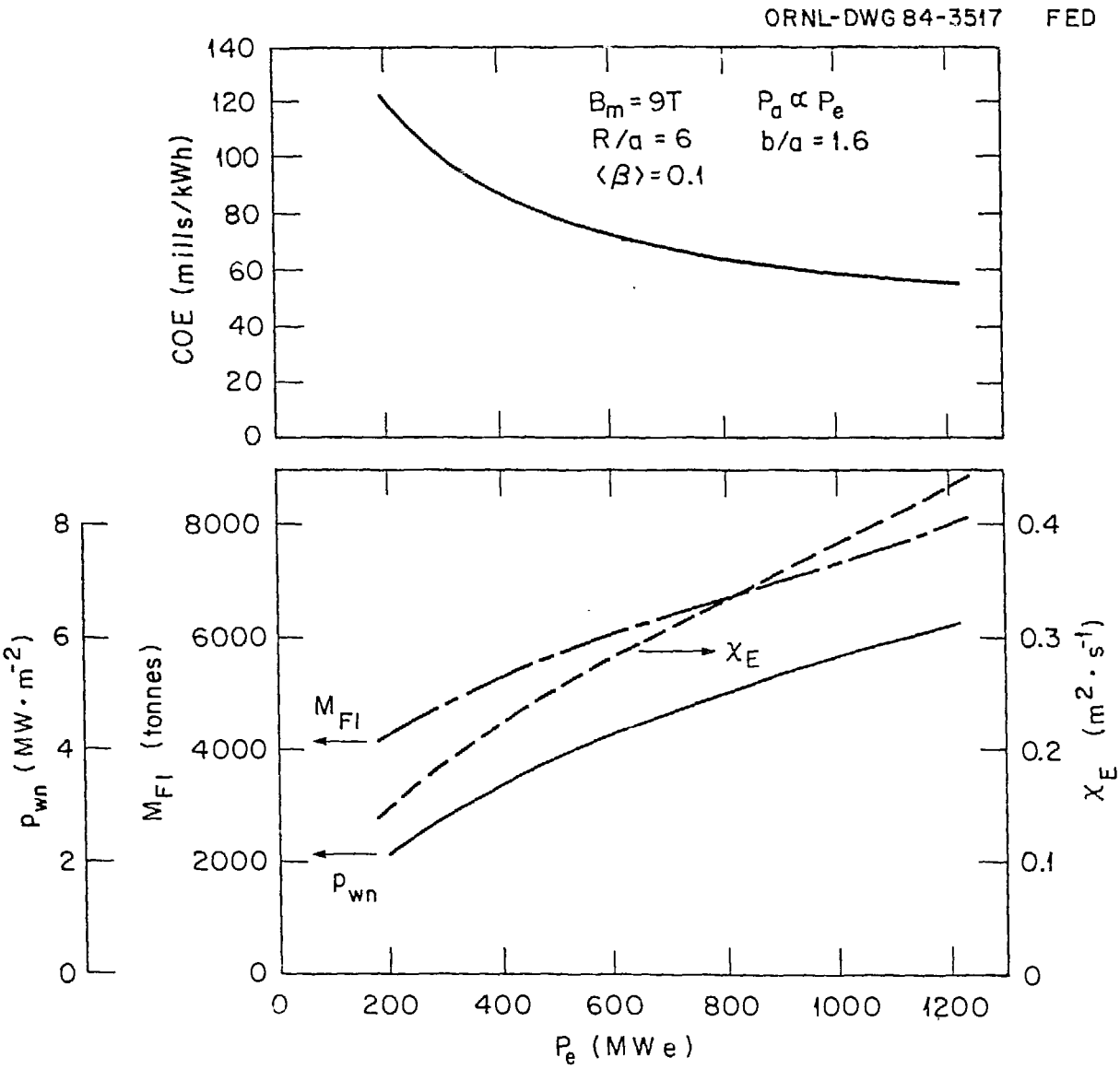


Fig. 8. (a) Dependence of the COE on the net electric power of the reactor ($P_e$).

(b) Dependence of $M_{FI}$, $p_{wn}$, $\chi_E$ on $P_e$.