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IMPACT OF TECHNOLOGY AND MAINTAINABILITY ON ECONOMIC ASPECTS OF TOKAMAK POWER PLANTS

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Abstract

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Results of system studies on the primary energy conversion, energy storage and transfer, tritium and vacuum subsystems of a tokamak reactor are presented. These results quantify the impact of technology choices and maintainability on the economics of tokamak power plants. It is found that the expensive refractory alloys must offer a factor of three or greater advantage in lifetime compared to stainless steel in order that their costly development should have a reasonable benefit-to-cost ratio. Five reactor concepts are analysed in terms of their scheduled maintenance requirements for replacing the first wall and blanket. The total downtime is found to vary from ~100 days to 500 days for a single replacement of the entire first wall and blanket. Substantial reduction in the power supply requirements and costs over previous estimates seems possible. The emergency air detritiation system is found to be a major cost item.

1. INTRODUCTION

The successful development of a new energy source depends on the effort and time required for new technology developments and the economics of the commercial units. In the case of fusion energy, even for a single confinement approach such as the tokamak, there are a variety of design concepts and a wide range of potential choices for the major features of a power reactor.

TABLE I. REFERENCE REACTOR PARAMETERS

Thermal power, MW	4950
Neutron wall load, MW/m^2	4
Major radius, m	7.3
Maximum toroidal field, T	9
$\bar{\beta}_t$, %	8
Inner blanket/shield thickness, m	1
Outer blanket/shield thickness, m	1.3

TABLE II. REFERENCE PARAMETERS FOR THE HEAT TRANSFER AND TRANSPORT SYSTEM

Structure Material in the Blanket and Primary Loop	Stainless Steel	Vanadium Alloy
Primary coolant	Lithium	Lithium
Intermediate/cycle	Na/steam	Na/steam
Maximum structure temperature, °C	500	620
Steam temperature, °C	292	442
Thermodynamic efficiency, %	30.1	34.4
Net electric power, MW	1420	1630
Blanket structure, vol.%	10	8
Number of coolant loops	4	4
Unit cost for first wall and blanket structure, $/kg	30	440
Cost of first wall and blanket structure, M$	16	138
Cost of the primary loop:		
Pumps and pump drives, M$	43	3 × 43
IHX, M$	34	3 × 34
Pipes (installed), M$	17	3 × 17

Systems studies provide a means to help resolve some of these choices. The purposes of this paper are: 1) to describe some important results from an integrated systems studies effort at Argonne National Laboratory [1]; and 2) to describe the results of a comparison study on developing maintainability in fusion power systems performed at McDonnell Douglas Astronautics Company [2]. The paper is limited to the work on tokamak power plants.

2. FIRST WALL AND BLANKET SYSTEM

The maintainability of the first wall/blanket is a critical factor in determining the economics of the power reactor. A successful design and technology development strategy must focus on the goal of reducing the economics impact and requirements of the maintainability for the first wall/blanket. The most effective means to achieve this goal are: 1) to reduce the frequency of required replacement, i.e. by increasing the lifetime of the structural material; and 2) to reduce the downtime and cost associated with the first wall/blanket replacement. These two means are discussed, respectively, in Sections 2.1 and 2.2 below.

2.1. Selection and Development of the Structural Material

The only suitable structural material with an existing qualified industry is stainless steel. Recent studies [3,4] indicate that the first-wall life for stainless steel may be limited to an integral wall loading of ∿ 3-5 $MW\cdot yr/m^2$ at a maximum operating temperature of ∿ 500°C. It is therefore necessary to explore the possibility of developing advanced structural materials with better material properties. The refractory alloys offer a good potential. A major disadvantage of the refractory alloys is a high material plus fabrication cost compared with stainless steel. Therefore, a fundamental question that needs to be resolved is whether the costly development of refractory alloys will result in a pay-off in terms of lower cost of energy. This study attempts to answer this question by comparing the economics of stainless steel and the refractory alloys as structural materials in tokamak reactors.

A reference lithium-cooled reactor whose major parameters are shown in Table I was selected. Two cases were considered. The first employs stainless steel as the structural material with conventional materials throughout the heat transfer and transport system. In the second case, a vanadium alloy is employed in the first wall, blanket structure, and primary coolant loop piping and pumping. "Switching" of materials from vanadium to conventional materials is made in the intermediate heat exchanger (IHX) such that the primary coolant is always in contact only with the refractory alloy. The intermediate coolant loop, steam generators, and turbines are built with conventional, relatively inexpensive materials. The reference parameters for the two cases are shown in Table II.

A meaningful comparison of stainless steel and refractory alloys must carefully consider several key variables. The first is the lifetime of the structure. Our analysis shows that the lifetime of stainless steel for the operating conditions discussed here is ∿ 3 $MW\cdot yr/m^2$. The lifetime of the vanadium alloy is longer but it cannot be predicted with good accuracy and is parameterized in this study. The second key variable is the total downtime required to replace the first wall and blanket structure. This downtime is essentially a weighting function for the importance of the longevity of the structural material. The magnitude of the downtime is extremely design-dependent. Table III shows the estimated downtime for replacement of the first wall and blanket in several conceptual designs. This downtime exceeds 100 days and can be as long as 500 days. Another key variable is the cost of the structural material. Table II shows the cost assumptions used in this study. The cost data for stainless steel were derived from the detailed work of the Prototype Large Breeder Reactor (PLBR). We have chosen the highest estimate projected for the cost of the vanadium alloy.

TABLE III. ESTIMATED DOWNTIME REQUIRED FOR REPLACEMENT OF THE FIRST WALL AND BLANKET IN SEVERAL CONCEPTUAL DESIGNS

Module Concept/Design	Downtime (days)
Large Module Concept	
UWMAK-I (remote maintenance)	354
CULHAM (remote maintenance)	128
Intermediate Module Concept	
UWMAK-III (remote maintenance)	112
UWMAK-III (partially contact operations)	111
Small Module Concept	
GA-DPR (remote maintenance)	558
GA-DPR (partially contact operations)	544
ORNL-DPR (remote maintenance)	131

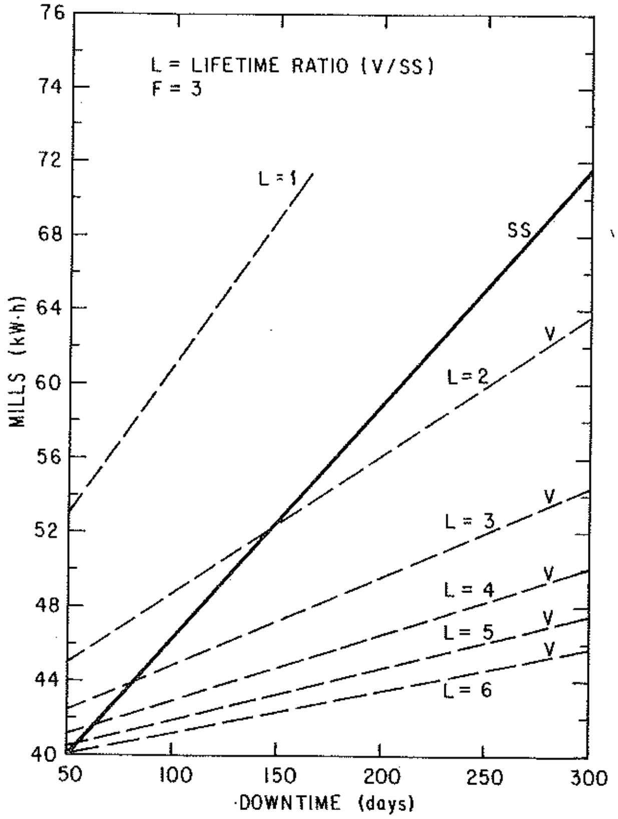

FIG.1. Dependence of the cost of energy on the downtime for stainless steel structure and vanadium structure with lifetime ratio in the range 1–6.

Figure 1 shows the cost of energy as a function of downtime for the reference reactor with the above assumptions for stainless steel and vanadium alloy. The cost of energy for the vanadium case is shown for several values of L, the ratio of the lifetime of the vanadium alloy to that of stainless steel. The results in this figure show that: a) If the downtime is short, 50 days or less, the vanadium alloy is required to offer a factor of six or greater better life in order to be economically competitive with stainless steel. Therefore, the benefits of using a refractory alloy in this case will depend mainly on the lifetime advantage in excess of 20 MW•yr/m^2. Since lifetimes much longer than 20 MW•yr/m^2 cannot be assured prior to an extensive and costly experimental irradiation program, these short downtimes - if achievable - may render the development program for the expensive refractory alloys unwarranted. b) If the downtime is long, > 100 days, a significant saving in the cost of energy can be achieved by using the vanadium alloy provided that it offers a factor of 2.5 or more improvement in the lifetime of the first wall and blanket structure compared to stainless steel.

Table III shows that the downtime in tokamak reactors is most likely to greatly exceed 100 days. Furthermore, the available data [5] for vanadium and other refractory alloys, albeit limited, suggest strongly that these alloys are very likely to have a lifetime much greater than three times that of stainless steel. In addition, this study analysed the worst case for the refractory alloys in terms of the cost associated with their use. Therefore, one can conclude from this analysis that the benefit-to-cost ratio of a vanadium alloy, or a similar structural material, development program is high.

2.2. Scheduled Maintenance Requirements

In a recent maintainability analysis [2] of tokamak reactor concepts, the cost of scheduled maintenance for the first wall/blanket was assessed for both completely remote operations and partially contact (hands-on) operations. Existing conceptual designs were selected for analysis. These consisted of three baseline designs: large module concept - UWMAK-I; intermediate module concept - UWMAK-III; and small module concept - General Atomic Demonstration Power Reactor (DPR). Two alternate designs were also chosen. These are: the alternate large module - Culham Mark II concept; and the alternate small module - Oak Ridge Cassette concept. Major differences exist in the techniques required for accessing the first wall/blanket modules for the five concepts. In addition, the concepts, as defined in this study, employ different approaches to controlling plasma impurities.

In order to compare the impact of scheduled maintenance activities, candidate reactor designs were normalized to the same thermal power level, 5000 MW. The integral neutron wall load limit was set at 5 MW•yr/m^2. Downtimes were estimated for each concept as a function of the fraction of the first wall/blanket modules replaced per outage. Plant availability was estimated based on the scheduled first wall/blanket replacement downtimes plus an allowance for balance-of-plant scheduled shutdowns (28 days per year) and for all plant unscheduled shutdowns (65 days per operating year). These availability data are presented in Fig. 2. In some designs, a number of the accessing activities are of the same duration independent of the number of modules removed. For these designs, as the wall fraction replaced approaches 1.0, the relative effect of accessing time diminishes, resulting in the hyperbolic shape to the curves.

Of the five reactor candidates, the Culham concept possesses the highest availability, 74%, achieved with a replacement wall fraction per outage of 1/3.

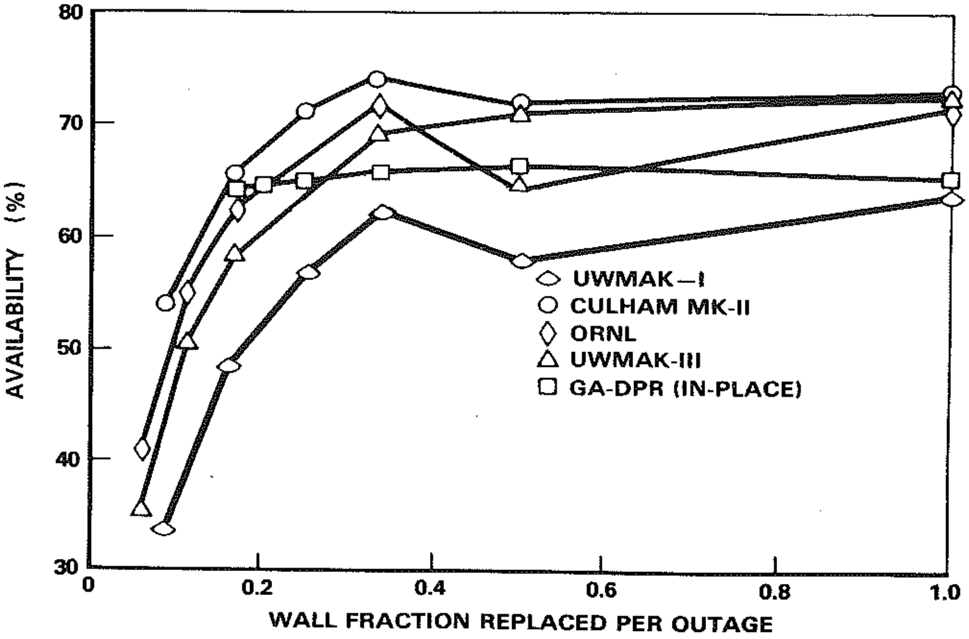

FIG.2. Plant availability factor as a function of wall fraction replaced per outage.

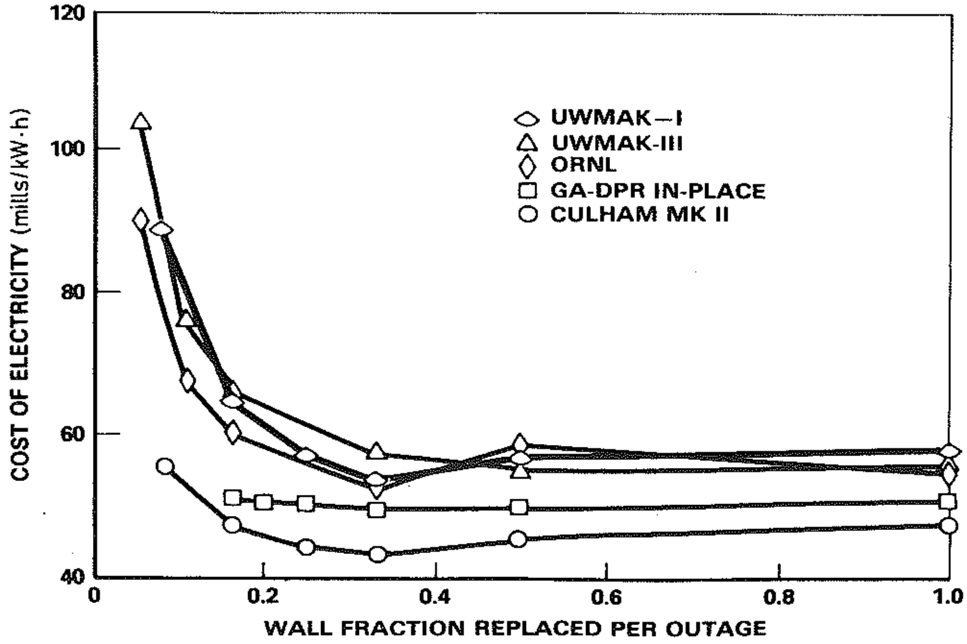

FIG.3. Cost of electricity as a function of wall fraction replaced per outage.

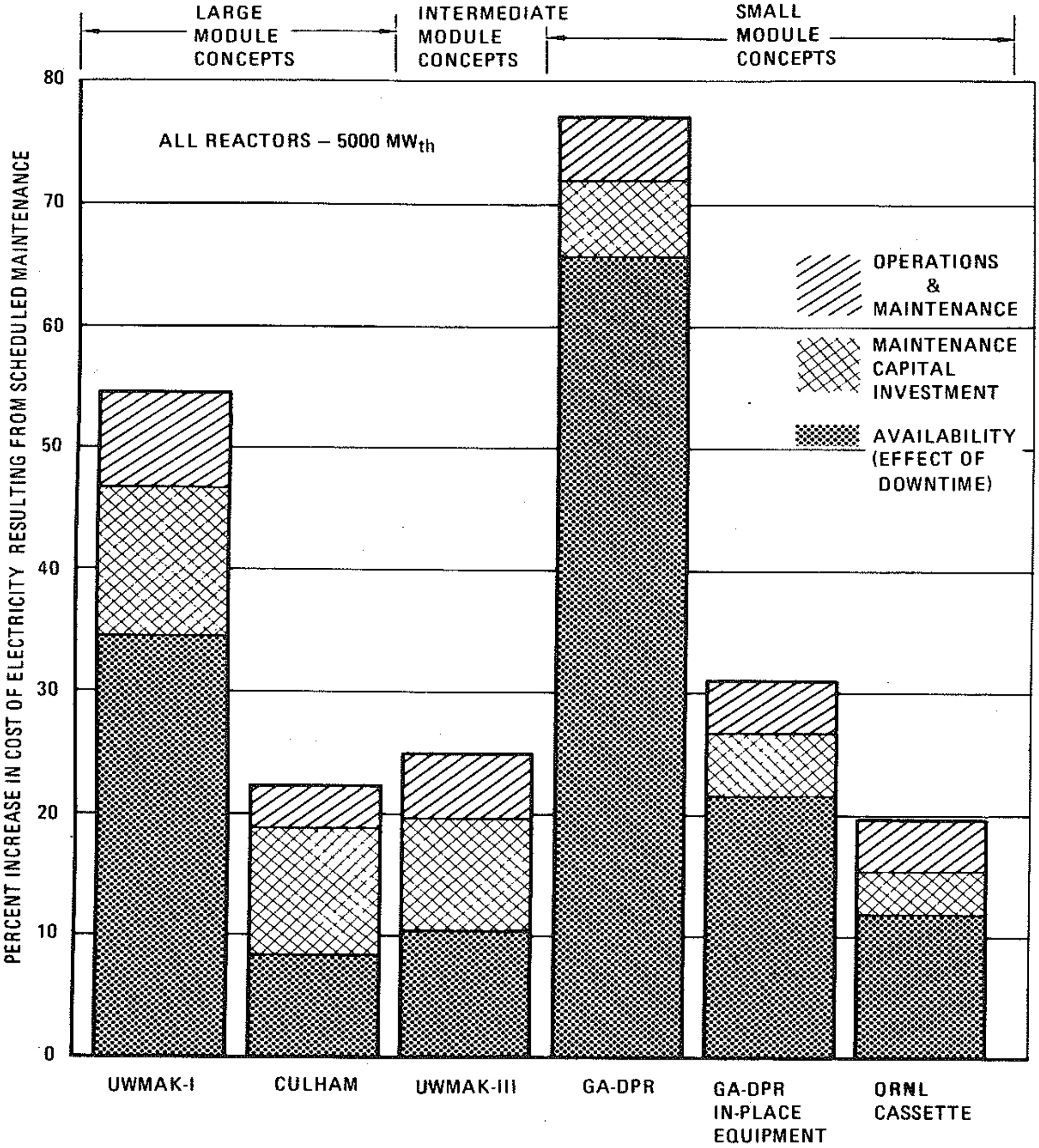

FIG.4. Impact of scheduled maintenance on cost of electricity (comparison of normalized reactors).

The impact of scheduled maintenance requirements on the cost of electricity is shown in Fig. 3. The elements affecting the cost of electricity are: maintenance equipment cost, maintenance facility cost, initial spares cost, labor and materials for replacement and refurbishment and plant availability. These data illustrate the dominant effect of availability.

The impact of scheduled maintenance for each of the five concepts is shown in Fig. 4. The impact is shown as a percentage increase to the cost of electricity relative to a plant designed for no reactor scheduled maintenance.

The total impact is made up of the annual operations and maintenance costs, the maintenance capital investment and the effect of availability. The wall fraction replaced per outage employed in this comparison is that fraction which results in the minimum cost of electricity for a particular concept. Availability is the dominant factor in all but the cases of Culham Mk-II and UWMAK-III. Examples of all three first-wall blanket module size categories - large, intermediate and small - have maintenance impacts in the 19-31% range. Three of these are below 26%.

The conclusions from this maintainability study can be summarized as follows: a) First-wall/blanket replaceable module size is not a discriminator in terms of minimizing the effect of scheduled maintenance on the cost of electricity; b) the wall fraction replaced per outage should be 1/3 or greater to minimize the effect of scheduled maintenance on the cost of electricity; c) the total effect of scheduled maintenance on the cost of electricity can probably be kept below 26% for commercial tokamak power systems; d) selection of design approaches for maintainability should be based on a careful evaluation of developmental and operational risks associated with the required remote maintenance equipment; and e) the use of partial contact (hands-on) techniques for scheduled maintenance operations resulted in improved availability for each of the three baseline reactor concepts. For two of the concepts, however, increased shielding costs and labor costs offset the benefit from availability. Unscheduled outage situations (reliability) should be given careful attention in ongoing tokamak power system studies.

3. POWER SUPPLY AND ENERGY STORAGE REQUIREMENTS

This section is concerned with analysing the power supply and energy storage system requirements for commercial tokamak fusion reactors. This activity is performed using an integrated systems approach whereby reactor design constraints and power supply characteristics are fully coupled to a detailed plasma burn cycle simulation code and to MHD equilibrium codes.

A conceptual design of a typical commercial tokamak reactor has been developed to serve as a test bed for the present study. This reactor has a 7-m major radius, a non-circular plasma cross-section (b/a = 1.3) and parameters of $I_p = 11.6$ MA, $B^{TFC} = 8.6$ T and $\beta = 7\%$. The thermal output of the plasma is about 2300 MW. The ohmic heating (OH) coils are solenoidal with a midpoint radius of 2.5 M. The equilibrium field (EF) coils are located outside the TF coils and are decoupled from the OH coils. All coils are superconducting.

Several types of power supply/energy storage systems were examined ranging from the conventional, presently available, to those needing development. In general, substantial reductions in the power supply requirements and costs seem possible over previous estimates [1], because of a number of cost-saving techniques made plausible by some encouraging information from present tokamak experiments. Figure 5 shows the voltage and current waveforms for a burn cycle when a conventional power supply system is used. In this example both the OH and EF coils are driven by a thyristor type rectifier/invertor power supply both operating out of a motor-generator-flywheel (MGF) set. For the case shown, the OH current is ramped up in a time "Δt_{OH}" = 8 s. Neutral beam heating (100 MW) is applied from 8-15 s to bring the plasma to an ignited equilibrium. Some beam power ($\sim$ 15 MW) is also applied during the first and last second of the cycle to overcome some of the radiation losses due to oxygen impurities. Shutdown is accomplished by first reducing the DT fuel density and the plasma temperature (not shown) and then ramping

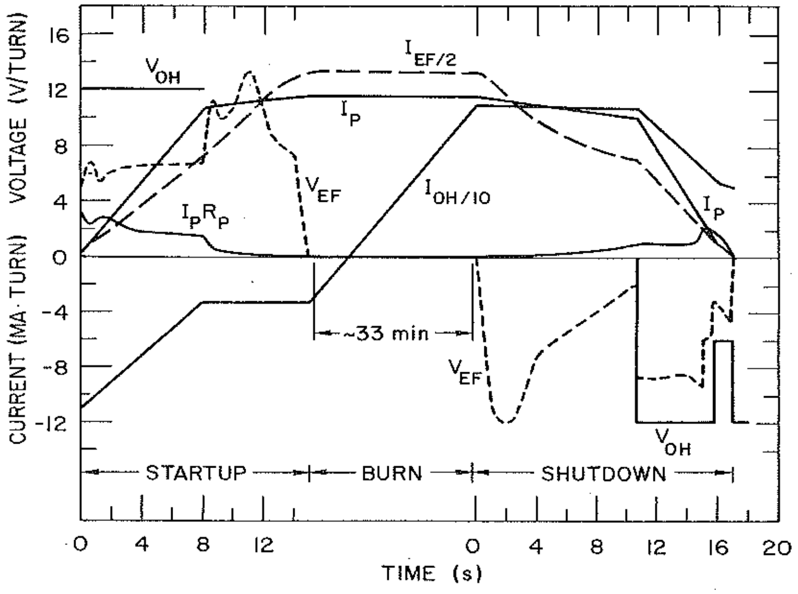

FIG.5. Voltage and current waveforms for a typical burn cycle using MGF set and thyristor OH and EF supplies.

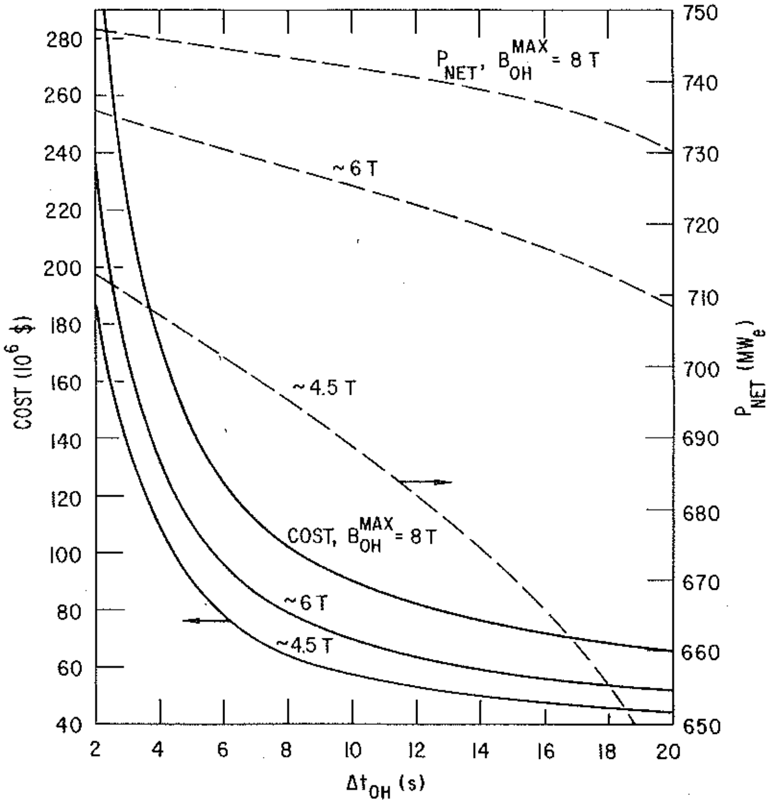

FIG.6. Power supply/energy storage system cost and net electrical power from the plant, as a function of OH startup ramp time. Δt_{OH}, and OH design field, B_{OH}^{MAX}.

down the OH current to bring down the plasma current and terminate the discharge. During the burn cycle the EF current must be adjusted in a way requiring active control of the EF voltage, as shown. For this example, the maximum power supply requirements are OH power = 1330 MVA, EF power = 351 MVA, and MGF stored energy = 12.8 GJ.

The effect of different startup densities, beam power levels, confinement scaling, impurity concentration, and several other parameters on the power supply requirements has been examined in detail. The most important single parameter has been found to be the OH startup ramp time. Figure 6 shows the cost of the power supply/energy storage system, for the conventional system described above, as a function of the ramp time, and for three assumed values of the maximum OH design field. This cost covers the MGF set and the OH and EF supplies but does not include the neutral beam supply. Figure 6 also shows the net electrical power from the reactor as a function of Δt_{OH} and B_{OH}^{MAX}. This net power takes into account the different burn times and duty factors obtainable as a function of the available OH flux swing. As shown, the cost is very sensitive to Δt_{OH} for short times. Previously, a range of Δt_{OH} = 2-4 s was considered optimum because shorter ramp times impose very high $\dot{B}$ and power levels while longer ramp times resulted in excessive resistive volt-second losses. Operation in this 2-s window tended to favor the use of a homopolar generator for the OH system because the cost of a homopolar generator is basically determined by the energy transferred and not the power level, exactly the opposite characteristic of a thyristor supply. Recent plasma physics experimental results that point to classical resistivity (no anomaly), less oxygen contamination and ease of low-density startup have now substantially extended what appears to be a feasible range of Δt_{OH}. Longer ramp times still use more resistive volt-seconds but not by an excessive amount. For these longer times, the power supply system cost is estimated in the $\sim$ 60-100 $M range.

4. TRITIUM AND VACUUM SYSTEMS

The major effects of the tritium and vacuum systems on overall plant design obtained in our study are summarized below.

Fractional burnup has a substantial effect upon tritium inventories. The total tritium inventory in a 3000 MW(th) plant is in excess of 50 kg if the fractional burnup is 1.0%. Under these conditions, a breeding ratio of 1.20 is required for a doubling time of 5 years. The inclusion of an active impurity-removal mechanism on a tokamak, such as a divertor or a gas blanket, could result in a fractional burnup of the order of 1% or less [6]. On the other hand, if the fractional burnup is 2% or higher, tritium inventories will be 35 kg or less and a breeding ratio of 1.10 is sufficient to double the inventory in five years or less.

An item of considerable significance, from the standpoint of both safety and costs, is the emergency air detritiation system (EDS). The costs of such systems are primarily due to the reactor building volume and the permissible cleanup time. Our earlier studies [7] showed that the cleanup time should be no longer than about 48 hours. The required speed to attain this is about 0.5% of the reactor building volume per minute. Further, since the unit costs are about $20 000 per m^3/min, the cost of the EDS is about $100 per m^3 of reactor building. Since this is roughly half the cost of the reactor building itself, the EDS is a significant cost driver.

Compound cryopumps are assumed to be the primary torus vacuum pumps. A significant finding was that, because of the conductance losses imposed by the cryocondensation surfaces ahead of the helium cryopumps, the required helium pump speed may be in excess of the required DT pump speed.

Neutral beams require very high pumping speeds. It was found that the neutral beam vacuum system was a high-cost item [typically, 30-50 million dollars for a 3000 MW(th) reactor]. Getter pumps cost about the same as cryopumps for this application.

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DISCUSSION

F.R. SCHWIRZKE: Could you say what processes were assumed to limit (primarily) the life-time of the first wall? Was it structural damage induced by the neutron flux, or surface damage and impurity release due to plasma-wall interactions such as sputtering, blistering and so on?

C.C. BAKER: This study assumed a separate first wall and was concerned mainly with blanket life-time, as the blanket will probably be more difficult to replace than the first wall. The effects considered in connection with blanket life-time included radiation damage and the consequences of pulsed reactor operation. First-wall life-times and plasma-wall interactions do not have any direct effect on the blanket replacement time.

R.W. CONN: The first-wall temperature in the stainless-steel cases is assumed to be 500°C. It is possible to lower the first-wall temperature to 300–400°C and thereby achieve a substantial life-time increase. The outlet temperature of the coolant at the back of the blanket, where the neutron flux is low, can still be 500°C, so that the thermal efficiency would be preserved.

What impact would this have on your conclusions regarding the potential advantages of vanadium alloys relative to steels?

C.C. BAKER: This point was not explicitly considered in your study. However, I would expect that longer stainless-steel life-times would decrease F and increase L for conditions under which refractory alloys would compare favourably with stainless steel.

R.A. KRAKOWSKI: Could you say a little bit about the possible cost advantages of concepts that are sufficiently compact and modular to permit maintenance or replacement times of the order of days rather than hundreds of days — the range you have quoted for your tokamak studies?

C.C. BAKER: First, I doubt whether any fusion reactor concept would have replacement times of the order of days. I am certainly not aware of any. Secondly, as was mentiond earlier, the increment in the cost of electricity for the maintenance activities required by tokamak reactors can probably be kept to less than 25%. Therefore, other reactor concepts would have to be within 25% of the estimated cost of tokamak reactors to be in the same cost regime.

R.S. PEASE: Can you say specifically why the vanadium alloys used for your studies are believed to be more resistant to radiation damage than stainless steel?

C.C. BAKER: Life-times are determined by several factors, including radiation damage and resistance to pulsed reactor operation. The known mechanical properties of vanadium clearly indicate that it is more resistant to pulsed wall loadings. Irradiation data are not abundant, but the information available suggests that swelling and related effects will be much slighter than in stainless steel.