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SYSTEMS STUDIES ON TECHNOLOGY AND ECONOMICS ASPECTS OF TOKAMAK POWER PLANTS*

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This paper presents the results of systems studies for the primary energy conversion, tritium and vacuum subsystems. It is shown that the refractory alloys offer significant economic advantages compared to stainless steel if the total downtime to replace the first wall and blanket structure is $\geq$150 days. For shorter downtime, the economic competitiveness of the refractory alloys depends strongly on the ratio of the lifetime of the refractory alloy to that of stainless steel. The plasma fractional burnup is shown to have a substantial effect on the tritium inventory and the tritium doubling time.

INTRODUCTION

Systems studies provide an important framework for obtaining critical information to help guide the research and development and the selection of a fruitful path to commercialization of fusion power. This paper presents results from the cur-mak power plants at Argonne National Laboratory.(1) The principal objective of these studies is to provide comparative evaluation of different design concepts and options, employing the economics, safety, and cost and timing of the required technological developments as the primary bases for comparison. The work in these studies is focused on three areas:

(1) Detailed Subsystem Analysis: This is concerned with the development of information necessary to describe the performance of each reactor component for a variety of design concepts and operating conditions.

(2) System Code Development: The subsystem models are synthesized into a computer system code that is capable of predicting the performance and economics of the entire power plant.

(3) Global Parametric Analysis: This phase of the study employs the systems code to examine in a systems context the critical issues concerning tokamak reactor development.

Studies have been carried out for the primary energy conversion, tritium, and vacuum subsystems. These studies were carried out on both the levels of detailed subsystems investigation and global parametric analysis. The following sections present some of the significant results from these studies.

PRIMARY ENERGY CONVERSION AND STRUCTURAL MATERIALS

A critical issue in the design of the energy conversion system for fusion reactors is the choice of the structural materials. The two widely recognized options are (a) stainless steel; and (b) one of the refractory alloys. The maximum operating temperature of stainless steel in the first wall and blanket is limited to $\sim$500°C.(1) The refractory alloys can be operated at much higher temperatures and therefore produce more electric power for the same thermal power. Furthermore, the refractory alloys are generally more resistant to radiation damage than stainless steel. The principal disadvantage of the refractory alloys is a very high material plus fabrication cost compared to that of stainless steel. A difficult question that needs to be resolved is whether the use of refractory metals in fusion reactors is economically favorable. The purpose of our study here is to explore the range of design paramters and operating conditions in which the refractory alloys offer

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clear economic advantages.

A key area of investigation is the extent to which the refractories are used in the power plant. There are three principal schemes:

(1) The refractories are employed in the first wall, blanket structure, primary, intermediate and power cycle coolant loops including piping, pumps, heat exchangers and turbines. Such a scheme is necessary if the peak coolant temperature out of the blanket is high (>800°C). Results from UWMAK-III(2) showed that such a scheme is economically unfavorable because of the high capital cost for the heat transfer and transport system.

(2) The use of the refractory alloys is restricted to the first wall and blanket structure. Piping and pumping materials in the rest of the primary coolant loop and the balance of heat transfer and transport system is a stainless steel or other relatively inexpensive conventional material. A fundamental drawback of such a scheme is that the coolant will transport impurities from stainless steel to the refractory alloy resulting in its embrittlement. Thus while such a scheme with severe restriction on the extent of using the refractories has clear economic merits the problem of mass transport of impurities casts serious doubts about the viability of the scheme.

(3) The refractory alloy, in this scheme, is employed in the first wall, blanket structure, and primary coolant piping and pumps. "Switching" of materials from refractory to stainless steel is accomplished in the intermediate heat exchange (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 materials and state-of-the-art technology. This scheme attempts to eliminate the disadvantages associated with the first two schemes.

In this study, we compare the performance and economics for stainless steel and a vanadium alloy as structural materials. The vanadium alloy is chosen as representative of the refractory alloys. A reference reactor whose major parameters are shown in Table I was selected. Two systems were considered. The first employs stainless steel as the structural material. The second uses a vanadium alloy in the primary loops with stainless steel employed in the balance of the heat transfer and transport system according to scheme (3) discussed above. The reference parameters for the two systems are shown in Table II. Lithium and sodium are the primary and intermediate coolants, respectively and a steam cycle is employed. A four-loop heat transport system is utilized. The maximum structural temperature in the blanket is limited to 500°C and 620°C in stainless steel and vanadium, respectively. The heat transport system for the stainless steel case is similar to that of the Prototype Large Breeder Reactor (PLBR)(3) with steam conditions of 292°C and 1100 psig. The heat transport system with a vanadium primary loop produces steam at 442°C resulting in a thermodynamic efficiency of 34.4% compared with 30.1% for the lower temperature stainless steel system.

A meaningful comparison of the economics of the stainless steel and vanadium systems has to care-

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 Paramaters 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
No. coolant loops	4	4

fully 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-yr/m^2. The lifetime of the vanadium alloy is longer but it can not be predicted with good accuracy until comprehensive irradiation data becomes available. In this study, we define the parameter L as the ratio of the lifetime for the vanadium alloy to that of stainless steel. The economics analysis is parameterized as a function of L in the range L = 1-6. The second kay 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 design dependent and may vary from about 50 to 300 days.

Another key variable is the unit cost for the structural material. Table III shows the major cost items for the structural material. The unit material plus fabrication cost for the vanadium alloy in the first wall and blanket structure is taken to be about 15 times that for stainless steel. This represents the worst case for the cost of refractories and the actual cost is believed to be at least a factor of 2 lower than what we assumed here. The cost of the primary loop, i.e. pumps and pump drives, IHX, and pipes is another key item. For the case of stainless steel, the cost data was taken from the PLBR(3) cost estimate. The cost of a vanadium primary loop is assumed to be equal to F times the cost of the stainless steel primary loop, where F is a variable greater than unity. In this study, we vary F from 1 to 4.

TABLE III. Major Cost Items Assumed for the Structural Material

Major Cost Items	Stainless Steel	Vanadium Alloy
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	F × 43*
IHX, M$	34	F × 34
Pipes (installed), M$	17	F × 17

*F is a variable in this study.

Figure 1 shows the cost of energy as a function of L at F = 1, 2, 3, and 4 and at a total downtime for replacement of the entire first wall and blanket structure of 50 days. The ratio L of the lifetime of vanadium to that of stainless steel is considered in the likely range 1-6. The cost of energy for the reference case of stainless steel is 40 mills/kWh. The figure shows that the refractory alloy cannot compete economically with stainless steel.

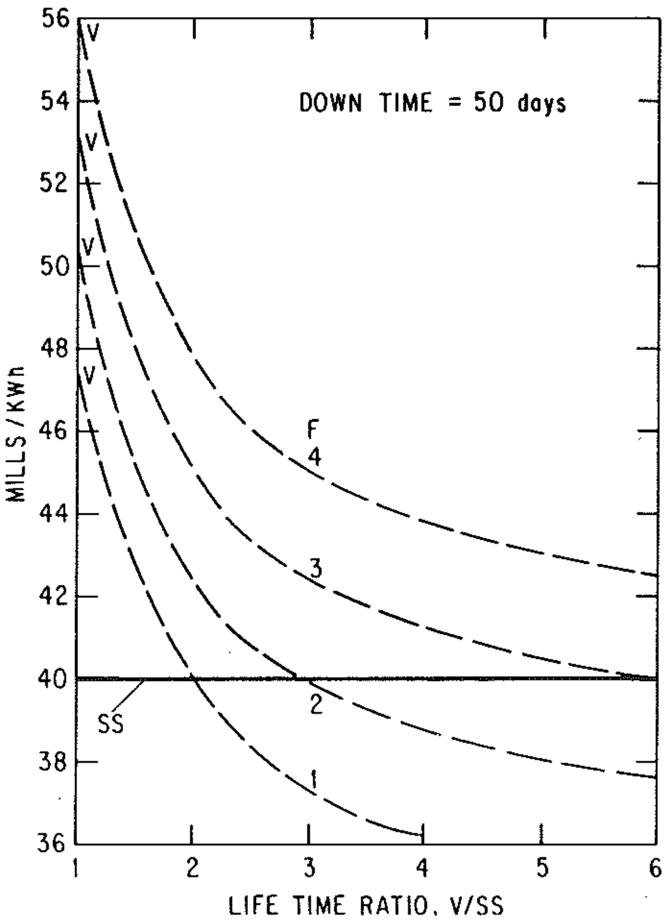

FIGURE 1. Variation of the cost of energy with the ratio of lifetime of vanadium to that of stainless steel for a short downtime of 50 days and F = 1-4.

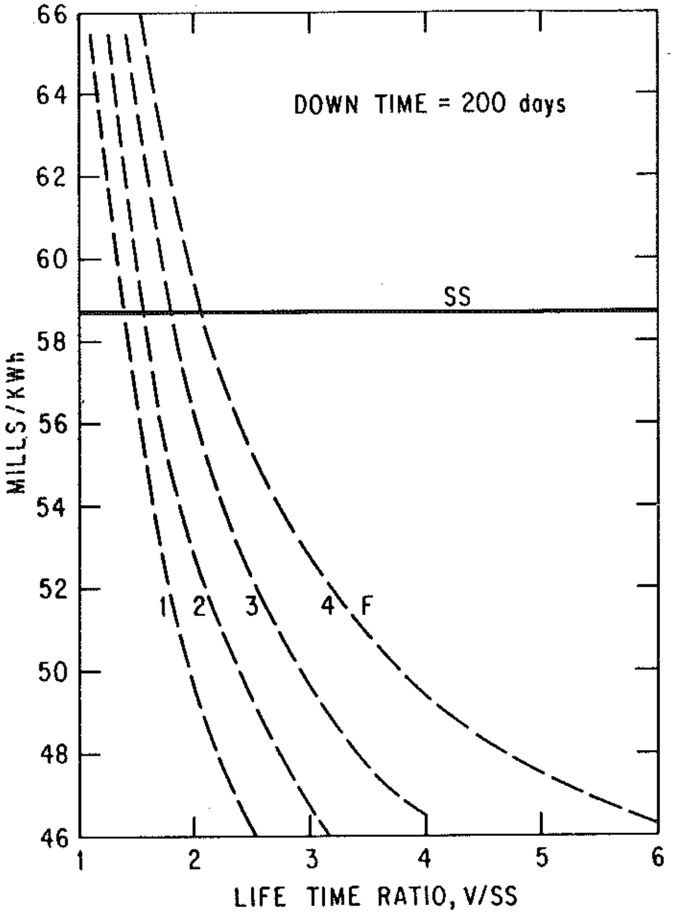

FIGURE 2. Variation of the cost of energy with the ratio of lifetime of vanadium to that of stainless steel for a long downtime of 200 days and F = 1-4.

Figure 2 is similar to Fig. 1 except that the downtime for replacement of the first wall and blanket structure is increased in Fig. 2 to 200 days. In this case, the cost of energy for the reference case of stainless steel is ∿58 mills/kWh. The cost of energy for the vanadium system is less sensitive in this case to the value of F. For ≤3, the vanadium alloy is required to offer a lifetime advantage of only a factor of 2 better than that of stainless steel in order to be economically competitive.

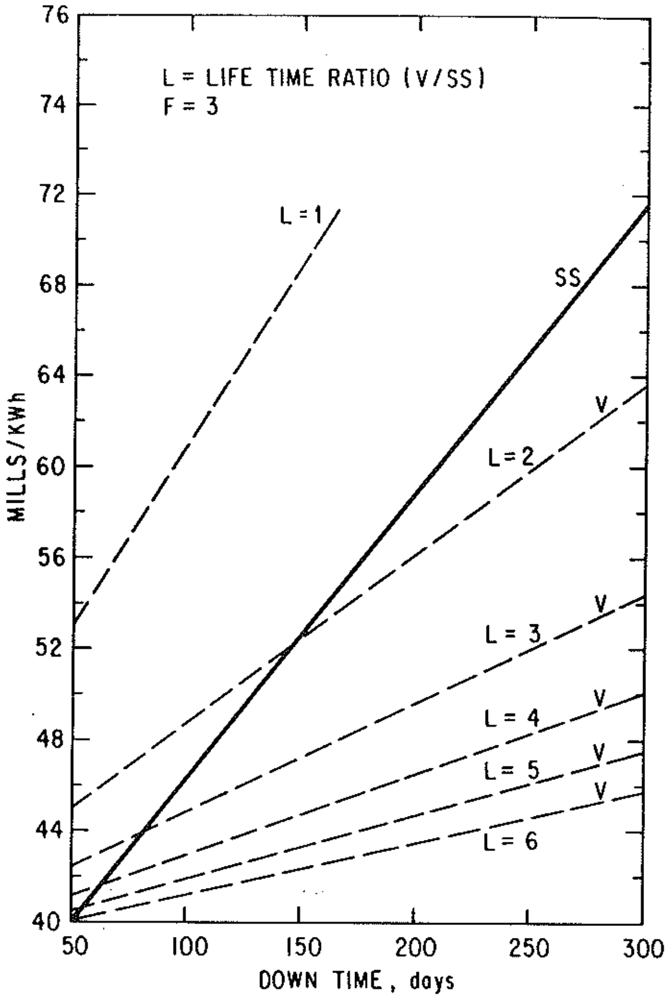

FIGURE 3. Dependence of the cost of energy on the downtime for (a) stainless steel structure; and (b) vanadium structure with lifetime ratio in the range 1-6. Results are for F = 3.

Figure 3 displays the cost of energy as a function of downtime at a lifetime ratio, L, in the range 1-6 and a fixed value of F equal to 3. The results in this figure show that: (a) if the downtime is ≥150 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 or more improvement in the lifetime of the first wall and blanket structure compared to stainless steel; (b) for downtime in the range of 100 to 150 days, a factor of 3 advantage in the longevity of the first wall and blanket structure is required in order for the vanadium alloy to offer a marked economic advantage over stainless steel; and (c) if the downtime is short, 50 days or less, the economic viability of the vanadium alloy (and similarly all refractory alloys) is not assured as it must offer a factor of 6 or greater better life than stainless steel.

TRITIUM AND VACUUM SYSTEMS

The ANL Systems Code includes TCODE,(4) a comprehensive package for analysis of tritium and vacuum systems. This routine accepts information on mass flow rates in the plasma chamber and from that calculates tritium flow rates and inventories throughout the system. The cost and size of the individual components is determined by the throughput rates. The major effects of the tritium and vacuum systems on overall plant design are summarized below.

Fractional burnup has a substantial effect upon tritium inventories. As shown in Fig. 4, the total tritium inventory in a 3000-Mw(t) 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(5) of 5 yr. 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.(2) 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.

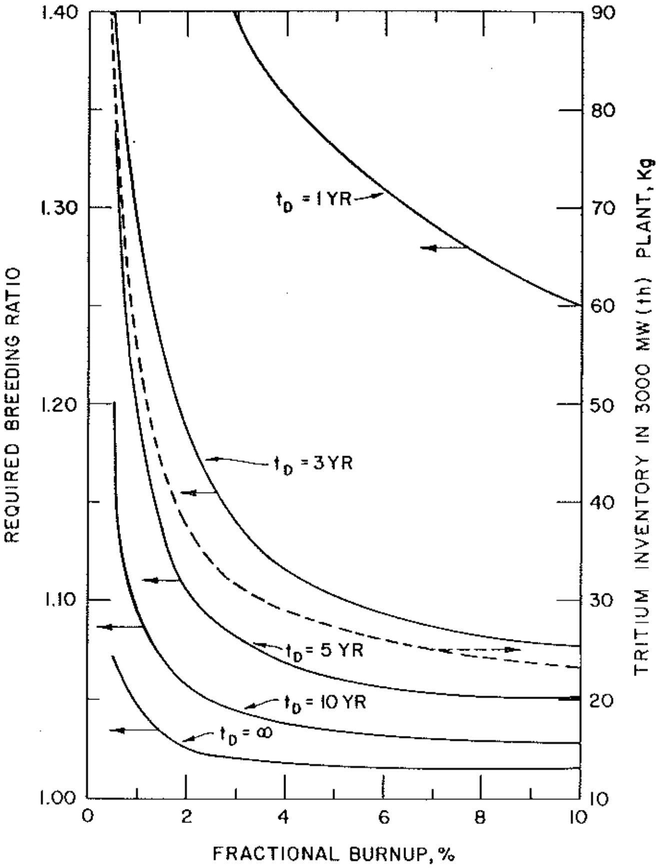

FIGURE 4. Dependence of tritium breeding ratio, doubling time, and tritium inventory on the plasma fractional burnup.

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(6) showed that the cleanup time should be no longer than about 48 hr. 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(7) 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(t) reactor]. Getter-pumps cost about the same as cryopumps for this application.

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