A COMPARATIVE STUDY OF THE PERFORMANCE AND ECONOMICS OF ADVANCED AND CONVENTIONAL STRUCTURAL MATERIALS IN FUSION SYSTEMS*

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The impact of the neutron wall load as well as the lifetime and operating temperature of the structural material on tokamak reactor economics was investigated and a comparative study of stainless steel and vanadium alloys was performed. In order to limit the fractional increase in the cost of energy due to the plant downtime, t, for replacement of the structural material to δ, the structure lifetime, T, must be greater than t/δ where T and t are in years. Economically attractive tokamak reactors produce a neutron wall load of 3-4 MW/m^2 for 3000 MW thermal power. The cost of energy is optimized by an operating temperature of the structural material in the wall/blanket in the range 475-500°C for stainless steel and 620-660°C for vanadium alloys. The gain in electric power due to higher operating temperatures is not sufficient to offset the penalty in the capital cost associated with the use of vanadium alloys as compared to stainless steel. Therefore, the vanadium alloy must exhibit a significant lifetime advantage over stainless steel to be economically competitive. The magnitude of this advantage is particularly sensitive to the plant downtime and the reference lifetime of stainless steel as well as the extent to which the refractory alloy has to be used in the heat transport system.

1. INTRODUCTION

The characteristics of the structural material strongly influence the economic potential and the environmental impact of fusion power. The cost of energy is affected by a) the contribution of the cost of the structural material plus fabrication to the capital cost, b) the reduction in the plant availability due to the plant downtime to replace the structural material, and c) the cost of replacement which consists of the costs of the new material, maintenance equipment and labor. The principal potential contributions to the environmental effects are 1) radiation exposure to the maintenance work force during replacement operations, 2) the accumulation of an inventory of used structural materials with long-term radioactivity, and 3) the depletion of material resources.

The above effects are determined largely by a) the lifetime of the structural material, and b) the downtime for replacement of the first wall and blanket. The achievable lifetime is a function of intrinsic material properties as well as the operating conditions. The neutron wall load and the operating temperature are two key operating conditions. Higher neutron wall load and operating temperature make it possible to design reactors with higher power density and smaller capital cost; but they also lead to a shorter lifetime and increased frequency of the structural material replacement.

The considerations given above indicate that the impact of the structural material on fusion reactor economics and environmental effects is not determined only by the material properties but it is also strongly influenced by a host of reactor design parameters and operating conditions. Therefore, comparative evaluations of structural materials for the purposes of making material selection and/or defining the goals for structural alloy development must cover a wide range of design parameters and a diversity of design concepts presently being proposed for future fusion reactors.

In this study, an attempt is made to compare the performance and economics of stainless steel and a vanadium-alloy as structural materials in fusion reactors. Vanadium alloys are typical of the advanced structural materials that have desirable properties but for which there is presently no qualified industry and an inadequate data base. In view of the cost and time involved in alloy development, it is important to quantify the economic and environmental benefits, if any, of using advanced materials compared to the conventional materials represented by stainless steel. The comparison presented here covers a wide range of key variables but is limited to tokamaks operated on the DT cycle. An important tool used in this study is the ANL systems analysis computer code.[1] This code is capable of predicting the performance characteristics and the economics of tokamak power plants. Presenting the results of the comparison between stainless steel and vanadium alloys is preceded by an examination of the general economic effects of the neutron wall load, the structural material lifetime and the operating temperature.

2. NEUTRON WALL LOAD

The neutron wall load, P_w, is related to the reactor thermal power, P_{th}, as

$$P_{th} = P_p V\epsilon = P_w A_w \epsilon \quad (17.6/14.1) \qquad (1)$$

where P_p is the average fusion power density in the plasma, V is the plasma volume, ϵ is the energy multiplication factor in the blanket and A_w is the surface area of the first wall. For the same power, higher P_w implies a smaller surface area, higher power density and smaller reactor volume. This underlines the motivation for developing designs with higher neutron wall load.

There are limitations, however, on the ability to generate and on the usability of high wall loads. These limits are dictated by:

a. the highest power density, P_p, achievable in the plasma. P_p is ~ $\beta_t^2 B_t^4$ where β_t is a plasma parameter limited by stability considerations and B_t is the toroidal magnetic field in the plasma center and is limited by technology constraints on the maximum toroidal field as well as reactor geometry considerations

b. limitations unique to tokamaks on the smallness of the reactor size. In order to achieve a reasonable plasma burn-time, the ohmic heating coil (central core) radius must be greater than a certain minimum. This sets a minimum size for the reactor and hence a maximum value for the wall load for a given reactor power.

c. structure cooling capability. Constraints on the maximum operating temperature and thermal stresses place an upper bound on the usable wall load.

d. structure lifetime. For a given fluence lifetime the neutron wall load has to be limited so that the frequency of structure replacement is not excessive.

Since the neutron wall load is a key parameter in defining the desirable material properties and fluence lifetime of the structural material, the system analysts are always faced with the question: What is the optimum neutron wall load? A detailed investigation has shown that the implications implicit in this question are incorrect. The neutron wall load is a dependent parameter whose value is determined by a large array of reactor variables such as those discussed in connection with Eq. 1 (e.g. reactor geometry, materials and design concept). Thus, if our interest is in quantifying the radiation environment for the purpose of defining the desirable properties of the structural material, then the appropriate question is: What is the neutron wall load expected in economically favorable fusion reactors? The answer to this question is briefly summarized below. More details are given in Ref. 1.

Investigation of a diversity of tokamak design concepts and wide range of reactor parameters shows that reactors that have favorable economics produce a neutron wall load, P_w = 3–4 MW/m^2 for a reactor thermal power, P_{th} = 3000 MW and P_w = 4–5 MW/m^2 for P_{th} = 5000 MW. A condition for the validity of these results is that the lifetime of the structural material is sufficiently long compared to the downtime for replacement of the structure so that Eq. 3 given in the next section is satisfied.

3. LIFETIME

Two important parameters are the fluence lifetime ($MW \cdot yr/m^2$) and the lifetime (years). The former is the product of the latter and the neutron wall load. The impact of the magnitude of the fluence lifetime will be addressed later in Sec. 5. We show below that the impact of and the desirable goals for the lifetime can be derived from extremely simple arguments.

One of the major effects on the reactor economics of the lifetime of the structural material being shorter than the plant lifetime is the loss of sale of energy during plant downtime. This affects the cost of energy only through the change in the plant availability factor, f. The latter can be written as

$$f = \frac{365 t_w - t_u t_w}{365 t_w + t_d} \qquad (2)$$

where t_w is the structural material lifetime in years, t_d is the total plant downtime for replacement of the structural material and t_u is the number of days of downtime per year of operation for other plant maintenance (generally, ~ 30). The cost of energy is proportional to 1/f. From these considerations, one can derive a useful relationship between the structure lifetime and the increase in the cost of energy due to plant shutdown for replacement of the structure. This relationship can be expressed as follows. In order to limit the fractional increase in the cost of energy due to the plant downtime for replacement of the structural material to δ, the structure lifetime must be sufficiently long to satisfy the following inequality

$$t_w \geq \frac{t_d}{365\ \delta} \qquad (3)$$

where t_w is in years and t_d is in days. For example, in order to limit the increase in the cost of energy to 10% (i.e. δ = 0.1) when the downtime is 125 days the structure lifetime must be greater than 3.4 years.

The advantage of Eq. (3) above is that it is based on simple basic principles independent of any particular system or structural material. Notice that the inequality in (3) gives a lower limit on the structure lifetime since in

addition to the loss of sale of energy during plant downtime, the structure replacement will also increase the cost of energy due to a) the cost of replacement materials and labor and b) the cost of the necessary increase in the utility's power generating reserve capacity.

An important conclusion can be deduced from Eq. (3). A target lifetime for the structural materials cannot be specified independent of the downtime necessary for structure replacement. The lifetime determines the frequency of replacement but the downtime is a key weighting function that determines the penalty of a replacement. The downtime is a strong function of the reactor complexity; therefore, the desirable lifetime of the structural material can vary from one design concept to another.

4. OPERATING TEMPERATURE

Operating the first wall and blanket at high temperatures results in a significant gain in the thermodynamic efficiency and a reduction in the cost per unit power. On the other hand, higher operating temperatures cause, in general a reduction in the structural material lifetime and a decrease in the plant availability. Therefore, it is of interest to find out the optimum operating temperature that results in a minimum cost of energy. We have addressed this question for stainless steel and vanadium alloys. A summary of the results is given below.

A specific tokamak reactor design whose major reference parameters are shown in Table 1

TABLE 1. Reference Reactor Parameters

Peak thermal power, MW	3000
Neutron wall load, MW/m^2	3
Major radius, m	6.5
Aspect ratio	3
Plasma elongation, (b/a)	1.3
Maximum toroidal field, T	9
β_t, %	8
Inner blanket/shield thickness, m	1.0

was selected. The simplified lifetime model of Mattas and Smith (Ref. 2) was incorporated into the ANL system code used in this study. The thermal design in all cases is such that the difference between the maximum structure temperature (in the first wall/blanket) and the steam temperature (inlet to the turbines) is 150°C. For stainless steel structure, Fig. 1 shows a) the thermodynamic efficiency, η, b) the fluence lifetime, I_w, in $MW \cdot yr/m^2$, and c)

the cost of energy as functions of the maximum operating temperature. The limiting properties for stainless steel in the specific lifetime model used in generating Fig. 1 are loss of ductility from 400 - 450°C, swelling from 450 - 550°C and loss of ductility from 550 - 650°C.
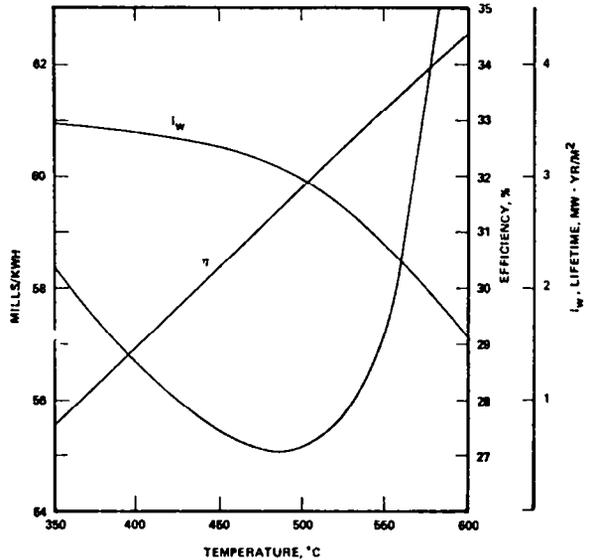

Fig. 1 Efficiency, Integral Lifetime and Cost of Energy as Functions of Operating Temperature for Stainless Steel.

The results in the figure show that the optimum operating temperature for stainless steel is - 485°C with the cost of energy exhibiting a broad minimum in the temperature range of 475 - 500°C . Figure 1 also shows that the penalty from operating at temperatures lower than the optimum is less than that resulting from operating at temperatures higher than the optimum. This is a consequence of the fact that the relative reduction in the lifetime per unit increase in the temperature is larger at higher temperatures.

Figure 2 is similar to Fig. 1 but the structural material is a vanadium alloy. Swelling, at a 4% end-of-life criterion, is the life-limiting property at 550 - 635°C. Creep, with 1% end-of-life and a design stress of 15000 psi, is the life-limiting property above 635°C. The cost of energy is minimum at 640°C with relatively small variation in the temperature range 620 - 660°C. This result suggest that the inlet temperature to the turbines need not exceed - 510°C for full utilization of the high temperature capability of vanadium alloys. Thus, conventional steam cycles are adequate with no apparent incentive for advanced power cycles.

5. CONVENTIONAL AND ADVANCED MATERIALS

One of the critical issues facing fusion reactor development is the selection of the structural material for the first wall and blanket. A key question in this issue is whether conventional materials are adequate or there is a necessary and justifiable need for the development of advanced material. A conventional material is characterized by the availability of qualified industry and a
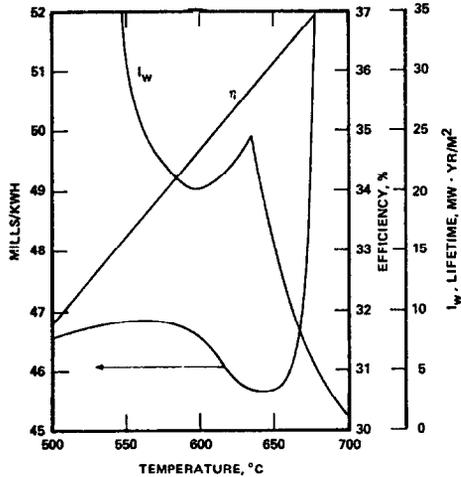
Fig. 2 Variation of Lifetime, Thermodynamic Efficiency and Cost of Energy with the Operating Temperature of a Vanadium Alloy

TABLE 2. Qualitative Comparison of Stainless Steel and Vanadium Alloys

	Stainless Steel	Vanadium Alloy
Qualified industry?	yes	no
Data base?	good	poor
Operating temperature	$500^{\circ}C$	$650^{\circ}C$
Material cost	30 \$/kg	180 \$/kg
Cost per unit power	?	?
Lifetime	short	long
Plant availability	low	high
Economics:		
Cost per unit energy	?	?
Environmental Effects		
Resources recycling	no	yes
Radwaste storage (Long-term)	large	small
Radiation exposure	large	low

sufficient information base for manufacturing and predicting the performance, particularly in radiation environment, of the material. Advanced materials have potentially better properties but they require substantial development because of the lack of an adequate data base and the absence of qualified industry. A material development and data acquisition program is costly and time consuming. Therefore, one needs to quantify the potential payoff, if any, of such program in terms of better reactor economics and/or favorable environmental impact. This section attempts to examine this question by comparing stainless steel as representative of the conventional materials and vanadium alloys which are typical of advanced materials.

Table 2 shows a qualitative comparison of stainless steel and vanadium alloys. As shown earlier in this paper, the optimum operating temperature for vanadium alloys is ~ 650°C, which is considerably higher than that for stainless steel (~ 500°C). Therefore, for the same reactor design and thermal power, the electric power output is larger with vanadium alloys. On the other hand, the material plus fabrication cost for vanadium alloys is substantially higher than that for stainless steel. One objective of this study is to determine which structural material results in a lower cost of power (\$/kWe). Another key item of comparison is the lifetime of the structural material in the fusion reactor environment. The available irradiation and material property data for vanadium indicate that its lifetime is potentially longer than that for stainless steel but the data is not sufficient to determine quantitatively the lifetime ratio for the two

materials. The decisive parameter in the economics analysis is the cost of energy which is a function of the capital cost, operating cost including the cost of structure replacement, the plant availability factor and the electrical power output. We will compare shortly the cost of energy for reactors employing stainless steel and vanadium alloys for a variety of conditions and assumptions.

As shown in Table 2, another important area of comparison between structural materials is the environmental impact. Irradiation of stainless steel results in a rapid buildup of many radioactive isotopes with very long half-lives.[3] This has two consequences: a) stainless steel structure removed from the reactor cannot be recycled in any practical period (several decades) after disposal; thus, the use of stainless steel in fusion reactors will result in a continued depletion of the resources of the elements that this alloy is composed of, and b) if fusion is to provide a significant part of all our power requirements, the use of stainless steel as a structural material will result in an accumulation of large inventories of radioactive materials for which long-term radwaste storage has to be provided.

The third environmental effect is extremely important. This is the radiation exposure[4] of the work force performing the task of replacement of the first wall and blanket. The level of radioactivity in all practical structural materials is so high for several years after shutdown that replacement of the first wall and blanket has to be carried out by remote means. However, there are many tasks associated with the first wall/blanket replacement. Some of these tasks (e.g. disconnects) may require[4] personnel access into the reactor building. Although this access can (and must) be limited to regions outside the main magnets, the presence of many major penetrations (e.g. neutral beams and vacuum pumps) causing radiation

streaming and activation of magnets and prephir-
ral equipment makes designing for a very low
biological dose in the reactor building imprac-
tical.[4] Therefore, radiation exposure to the
maintenance work force is unavoidable despite
the fact that the structural material is always
handled by remote means. The accumulated bio-
logical dose (man-rem) to the work force will
increase as the frequency of the structure re-
placement increases. Thus, structural materials
with lifetimes as short as those presently pre-
dicted for stainless steel will result in rela-
tively large levels of radiation exposure.
Notice that for a given reactor design the magni-
tude of radiation exposure is independent of the
activation level for the structural material and
depends only on the frequency of the structure
replacement as well as the length of downtime
for replacement, the size of the maintenance
work force and other reactor design features
such as those of the major penetrations and
shielding.

The environmental effects for vanadium alloys
can vary considerably from one alloy to another.
The most favorable alloys are those that consist
only of vanadium and titanium. The level of
radioactivity in these two elements decreases
so rapidly after shutdown that recycling of
vanadium-titanium alloys in 3 to 4 decades after
disposal is feasible.[3] The ability to recycle
the structural material is an important advan-
tage in that it limits the depletion of re-
sources to a fixed amount determined by the
rate of deployment for fusion reactors. Vana-
dium-titanium alloys do not require radwaste
storage for more than 3 to 4 decades. If the
lifetime of V-Ti alloys is considerably longer
than that of stainless steel this will provide
for a significant reduction in the radiation
exposure resulting from the structure replace-
ment.

In order to provide a quantitative comparison
of the performance and economics of stainless
steel and vanadium alloys as structural mate-
rials, a reference reactor whose parameters
were shown earlier in Table 1 was selected.
This reactor has a thermal power of 3000 MW and
produces a neutron wall load of 3 MW/m^2. Liquid
lithium was chosen as the primary coolant. The
performance and economics of this reactor were
compared for the two cases of structural
material: a) stainless steel and b) vanadium.
In both cases a) and b), conventional struc-
tural materials are used in an intermediate
sodium-coolant loop as well as in the steam
cycle system. Each of the structural materials
to be compared (stainless steel and vanadium
alloy) is employed in the first wall, blanket
and throughout the primary coolant loop (pipes,
pumps, etc.). In other words, material
"switching" is made at the intermediate heat
exchanger (IHX). The choice of this location
for material switching is particularly important
in the case of the refractory alloy as discussed
below.

The experience of UMAK-III[5] has shown
that using refractory alloys in the entire heat
transfer and transport system including heat
exchangers and turbines leads to unacceptably
high capital cost. Furthermore, we have shown
earlier in this paper that the optimum operating
temperature of the structural material in the
first wall and blanket is $\leq 650^{\circ}$C in the case
of vanadium alloys. Therefore, an optimized
steam cycle with conventional materials is
capable of utilizing effectively the high
temperature potential of vanadium alloys employ-
ed in the first wall and blanket. Restricting
the use of the refractory alloys to the first
wall/blanket region with material switching ac-
complished at the main headers may not be prac-
tical. The reason is the possibility that the
primary coolant will transport interstitial im-
purities from stainless steel (or alternate con-
ventional material) in pipes and pumps to the
refractory alloy in the first wall/blanket
resulting in its embrittlement. Such an inter-
stitial mass transfer, and the accompanying
embrittlement was one of the primary reasons
for rejecting vanadium alloys for LMFBR clad-
ding.[6] While oxygen appears to present no
problem with lithium coolants, the mass transfer
of nitrogen and carbon remain as a potential
problem to be resolved. Therefore, switching
materials from the refractory alloy to stainless
steel at the intermediate heat exchanger (IHX)
appears to be a reasonable compromise which is
examined in this work. In this scheme, the
primary coolant is always in contact only with
the refractory alloy while the intermediate and
the steam cycle loops are built with conven-
tional materials and state-of-the-art technology.

Table 3 shows the key reference parameters and
the major cost items for the heat transfer and
transport system for both cases of stainless
steel and vanadium alloy. The operating con-
ditions and the cost of the heat transport
system for the stainless steel system were taken
from well-studied cases for the Prototype Large
Breed Reactor (PLBR).[7] The material plus
fabrication cost of the structural material in
the first wall/blanket is taken[8] to be 30 $/kg,
and 180 $/kg for stainless steel and the vana-
dium alloy, respectively.

There are three key items of uncertainty that
strongly affect the conclusions of this compara-
tive study. One of these is the cost of liquid
metal pumps, pipes and IHX in the refractory
alloy case. Another is the lifetime of the
structural materials. Present predictions for
the lifetime of stainless steel vary consider-
ably. These variations are caused by the lack
of some important irradiation data, differences
in interpreting existing data and the absence
of well-defined end-of-life criteria. The un-
certainties in predicting the lifetime of vana-
dium alloys is even larger because the available
data base is severely limited. The third item
of uncertainty is the length of the total cumu-
lative plant downtime for replacement of the
first wall/blanket structure. For these three

TABLE 3. Reference Parameters and Cost
for the Heat Transfer and Transport System

	Stainless Steel	Vanadium Alloy
Primary coolant	Lithium	Lithium
Intermediate/cycle	Na/steam	Na/steam
No. coolant loops	4	4
Max. structure temp, C	500	650
Steam temperature, C	350	500
Thermodynamic efficiency, %	31.8	36.1
Net electric power, NW	868	986
Blanket structure, vol %	10	8
Unit cost for wall/blanket structure, $/kg	30	180
Cost of the primary loop:		
Pumps and drives, M$	30	F × 30
IHX, M$	24	F × 24
Pipes (installed), M$	13	F × 13

items a parametric study approach is utilized.

Figure 3 shows the cost of energy in mills/
KWh for the two types of structural material,
stainless steel and a vanadium alloy. The re-
sults of stainless steel system are shown
for two values of fluence lifetime, 3 and 6
MW.yr/m^2. The cost of energy for the vanadium
system is shown as a function of the fluence
lifetime of vanadium in the range of 3 to 24
MW·yr/m^2. The vanadium alloy results are dis-
played for four values of F (1,2,3 and 4), where
F is the ratio of the cost of the primary coolant
loop (including pumps and pump drives, pipes and
IHX) constructed of the vanadium alloy to that
made of stainless steel (see Table 3). The re-
sults of Fig. 3 are based on a total downtime
for replacement of the entire first wall and
blanket of 125 days. This represents the most
probable value for the downtime in the best
conceptual designs presently available as pre-
dicted by the maintainability study of Ref. 9.

The case of F = 1 in Fig. 3 assumes that
liquid metal pumps and pipes constructed with
vanadium alloy cost the same as those made of
stainless steel. This case is included as it
represents in practice a system in which mate-
rial switching from vanadium to stainless
steel is accomplished in the heat transport
system immediately outside the blanket. As
can be seen from Fig. 3, for the same lifetime
of SS and vanadium alloy (3 or 6 MW·yr/m^2),
the cost of energy for the vanadium system
with F = 1 is a few percent higher than that
for a stainless steel system. A conclusion
to be made here is that the difference in the
thermodynamic efficiency resulting from higher
temperature operation of the vanadium alloy
(650°C compared to 500°C for stainless steel)
is not sufficient to offset the increased
material plus fabrication cost (180 $/kg for V
and 30 $/kg for SS; see Table 3) for the re-
fractory alloy in the first wall and blanket.
Therefore, the vanadium alloy must offer a
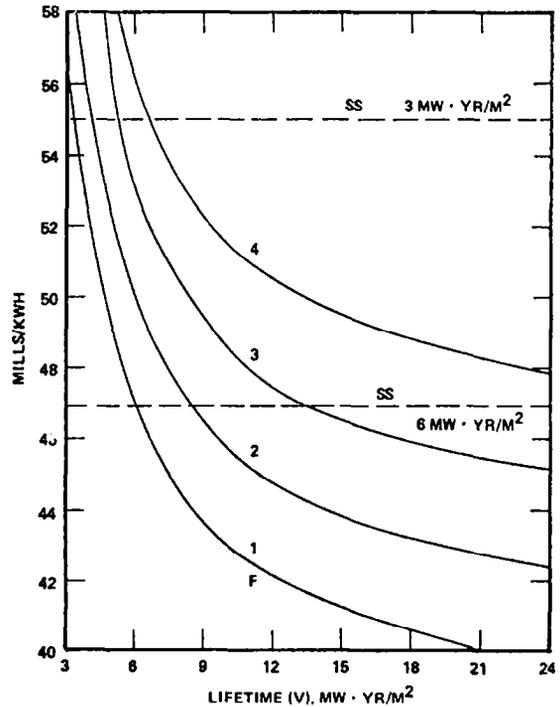lifetime advantage compared to stainless

Fig. 3 Cost of Energy as a Function of the
Vanadium Alloy Lifetime at Various Values of F.
Shown also are two reference values for stainless
steel with 3 and 6 MW·yr/m^2.

in order to be economically competitive even if
the use of the refractory alloy could be re-
stricted to the first wall/blanket region only.

The lifetime advantage that the vanadium alloy
must offer to compete economically with stainless
steel increases rapidly as the cases of switching
materials at the IHX (F = 2,3, or 4 in Fig. 3)
are considered. This lifetime advantage re-
quired for economic competitiveness increases also
rapidly as the reference lifetime of stainless
steel increases. For example, if F = 4, the re-
quired ratio of the lifetime of vanadium to that
of stainless steel increases from 2 to 5 if the
reference stainless steel lifetime is increased
from 3 to 6 MW·yr/m^2. Notice that if the number
of coolant loops is increased to more than 4 (see
Table 3) as used in the present study the capital
cost of the vanadium system increases substan-
tially and its economic competitiveness becomes
less likely.[10]   However, detailed investigations
for the fast breeder program[7] indicate that the
optimum number of coolant loops for a 3000 MW(th)
reactor is 4.

Previous experience[10] with refractory alloys
suggests that the cost of liquid metal pumps and
pipes is likely to be about three times those
constructed of stainless steel. Thus, assuming
that F = 3 is a reasonable reference value, we
show in Fig. 4 the cost of energy for both the
vanadium alloy and stainless steel systems as a
function of the total downtime for replacement

of the first wall and blanket. Several cases for vanadium system identified by the letter V and for the stainless steel system identified by the letters SS are shown in Fig. 4. The numbers
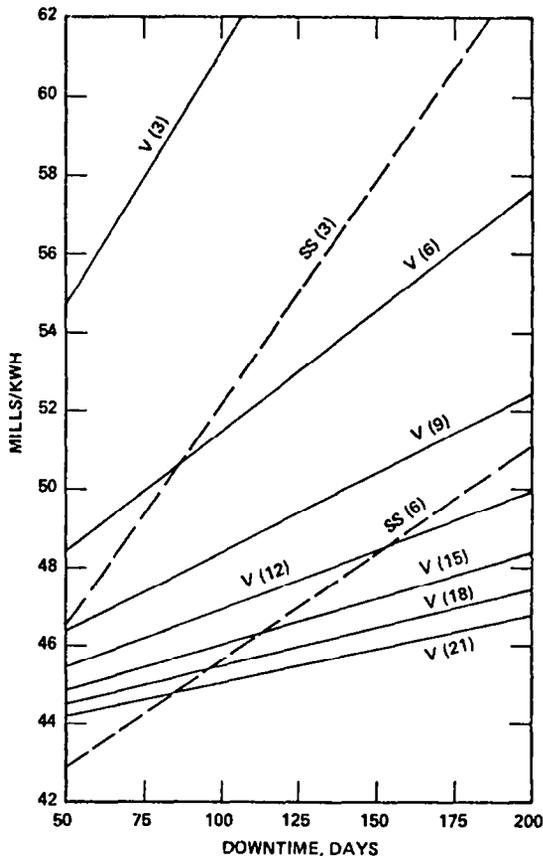

Fig. 4 Dependence of the Cost of Energy on the Total Plant Downtime for Replacement of the First Wall and Blanket Structure. Numbers in parenthesis refer to the lifetime in MW·yr/m².

in parentheses for each case represent the magnitude of the fluence lifetime in units of MW·yr/m².

The length of the total downtime for replacement of the first wall and blanket is a strong function of the reactor design and is most affected by the reactor complexity. Yet, to be resolved are many issues concerning the tokamak reactor design requirements (e.g., is a divertor necessary?) that strongly affect the reactor complexity and the magnitude of the replacement downtime. This fact in addition to the lack of specific and detailed maintenance plans for commercial fusion reactors explain the present wide variations in downtime estimates. A recent maintainability study[9] indicates that the downtime for present conceptual designs is likely to be in the range 100-300 days. In Fig. 4 we consider the range 50-200 days. As seen from Fig. 4, the cost of energy increases very rapidly as the downtime is increased. Shorter

downtime is a goal that design studies will have to vigorously pursue.

The results in Fig. 4 show that the economic competitiveness of the vanadium alloy system to that of stainless steel is strongly dependent on the magnitude of the achievable downtime. If the downtime is longer than 200 days, the use of vanadium alloys will result in significant savings in the cost of energy compared to stainless steel. On the other hand, if the downtime is very short, < 50 days, it is doubtful that any economic gain can be realized from the use of vanadium alloys unless the fluence lifetime achievable with stainless steel is very short (i.e. < 3 MW·yr/m²).

If the achievable lifetime with stainless steel is < 3 MW·yr/m² vanadium alloys become economically attractive if they offer only a factor of 2 improvement in lifetime for downtime > 85 days. For a stainless steel lifetime of 6 MW yr/m², the lifetime advantage required for economic competitiveness of the vanadium alloy depends strongly on the downtime as shown in Fig. 4.

6. SUMMARY AND CONCLUSIONS

The impact of the neutron wall load as well as the lifetime and operating temperature of the structural material on tokamak reactor economics was investigated. A comparative study of stainless steel and vanadium alloys was performed. Important conclusions from this work are summarized below.

In order to limit the fractional increase in the cost of energy due to the plant downtime for replacement of the structural material to δ, the structure lifetime must be sufficiently long so that $t_w \geq t_d/(365\ \delta)$, where t_w is the structure lifetime in years and t_d is the plant downtime for replacement of the structure in days.

Economically attractive tokamak reactors produce a neutron wall load in the range 3-4 MW/m² for 3000 MW thermal power reactors and in the range 4-5 MW/m² for 5000 MW thermal power. A condition for the validity of this result is that the structural material lifetime satisfies the condition given above.

The cost of energy is optimized by an operating temperature of the structural material in the first wall and blanket in the range 475-500⁰ C for stainless steel and 620–660°C for vanadium alloys. Conventional steam cycles are adequate for full utilization of the high temperature capability of vanadium alloys and no apparent incentive exists for advanced power cycles.

The three key environmental concerns related to structural materials are a) depletion of resources, b) long-term radwaste storage, and c) radiation exposure to the maintenance work force during the structure replacement. The environmental effects associated with vanadium-

titanium alloys are tremendously better than those for stainless steel.

The gain in the electric power obtainable by operating vanadium alloys at 650°C compared to stainless steel at 500 C is barely suf-- ficient to offset the high cost of the vana- dium alloy in the first wall and blanket structure. Furthermore, if the problem of interstitial transport cannot be resolved, the need for using the vanadium alloy throughout the primary coolant loops (pipes, pumps and IHX) will substantially increase the cost penalty associated with the use of the re- fractory alloy. In this case, the vanadium alloy must exihibit a significant lifetime advantage over stainless steel to be economi- cally competitive. The necessary magnitude of this advantage is particularly sensitive to: 1- the plant downtime for replacement of the wall/blanket structure, 2- the reference lifetime of stainless steel and 3- cost ratio of liquid metal pumps, pipes and heat exhangers constructed of the refractory alloy to those made of stainless steel. Specifically:

a. if the ratio of the downtime to the life- time of stainless steel is low, 15% or less, it is unlikely that the refractory alloys can be economically competitive as they must offer a factor of 7 or more advantage in lifetime compared to stainless steel.

b. if the ratio of the downtime to the life- time of stainless steel is high, 30% or greater, a significant saving in the cost of energy can be realized by using the refractory alloys pro- vided that they offer a factor of 2 or more improvement in lifetime compared to stainless steel.

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