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IMPACT OF MAJOR DESIGN PARAMETERS ON THE ECONOMICS OF TOKAMAK POWER PLANTS*

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ABSTRACT. A parametric systems studies program is now in an active stage at Argonne National Laboratory. This paper presents a summary of results from this systems analysis effort. The impact of major design parameters on the economics of tokamak power plants is examined. The major parameters considered are: (1) the plant power rating; (2) toroidal-field strength; (3) plasma β_t; (4) aspect ratio; (5) plasma elongation; (6) inner blanket/shield thickness; and (7) neutron wall load. The performance characteristics and economics of tokamak power plants are also compared for two structural materials (stainless steel and a vanadium alloy).

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1. INTRODUCTION

Numerous conceptual designs for tokamak power reactors [1-15] have been developed and investigated in the past several years. These design studies have elucidated many of the important features of tokamaks and have identified many technological problems that require a vigorous research and development program. These designs taken collectively demonstrate the presence of a huge space of design parameters and a diversity of design concepts. The required technological developments depend greatly on the features of the perceived commercial tokamak. Therefore, a resource-limited research and development program inevitably has to select and focus on a very limited number of paths to the commercialization of fusion power. An exceedingly important concern with this inevitable approach is the decision-making process to identify a low-risk high payoff path. One great difficulty is that much of the technical information required for scientifically evaluating the various paths is often not available. This situation is not unique to fusion research but is common to the development of most new energy sources, and is actually faced in many facets of life. There is no unique scientific formula for dealing with this situation; there are only guidelines.

Global parametric systems studies represent a useful framework for providing critical information to help guide the research and development and selection of the most fruitful path to commercialization of fusion power. In these studies, all the performance characteristics and the complex interrelations among and within the power plant components are modeled into a computer program. Trade-off studies are performed and design variables, options, and concepts are compared in a systems context. The economics, safety, and cost of required technological developments provide the primary basis for comparison. The systems approach is general and can be utilized for comparative evaluation of different plasma confinement schemes as well as comparing the different design concepts within a given confinement approach.

A parametric systems studies program is now in an active stage at Argonne National Laboratory (ANL). Up to the present, the studies have focused only on commercial power-producing tokamaks. The purpose of this paper is to present a summary of some results from these systems studies concerned with the impact of major design parameters on the economics of tokamaks. The major parameters considered are: (1) the plant power rating; (2) toroidal-field strength; (3) plasma β_t; (4) aspect ratio; (5) plasma elongation; (6) inner blanket/shield thickness; and (7) neutron wall load.

2. REACTOR THERMAL POWER RATING

The optimum values of many of the tokamak design variables depend to a great extent on the selected reactor thermal power. The desirable power rating of a power plant depends on several factors that include the relationship between the cost of electricity and the plant power rating as well as the generating capacity and the operating conditions of the utilities.

Figure 1 shows the dependence of the cost of electricity on the reactor thermal power for the design conditions specified in the figure caption. Results are shown for both cases of stainless steel and advanced vanadium alloys as the construction material for the first-wall and blanket structure. The results in Fig. 1 demonstrate the "economy of scale" for tokamak power plants with thermal power in the range of 3000 to 9000 MWt, i.e., the cost of electricity is lower for larger power plants. Therefore, there is an economics incentive to build tokamak power plants with larger capacity. Since tokamak plants represent a large capital investment and a small operating cost, they are particularly suited for a "base load" operation. The demand on the reliability is more stringent, however, for larger power base-load power plants. An important factor to the reliability of tokamaks is the structural integrity of the first-wall and energy-conversion system. The radiation environment is more severe for larger power plants as they produce higher neutron wall loads (see Fig. 1). These aspects and the comparison of stainless steel with advanced alloys will be discussed in a later section.

Despite the strong incentives of the economy of scale, the largest desirable power will be limited by many of the financial and operating considerations of the electric utilities. These considerations vary from one country to another and they differ among utilities. In the United States, nuclear power plants with capacities in the range of 1000 to 1500 MWe, i.e. 3000 to 4500 MWt, are presently under construction. Assuming only 3% growth per year in the electric generating capacity of the United States, one would expect that power plants with capacities in the range 7000 to 10,000 MWt will be in demand by some of the larger utilities by the year 2020. Most of the utilities, however, are still likely to prefer smaller power plants of approximately 3000 MWt.

3. DESIRABLE TOROIDAL-FIELD STRENGTH AND PLASMA β_t

Knowledge of the highest desirable toroidal-field (TF) strength is important because of the technology developments required for high fields. Niobium-titanium superconductors are ductile and can be designed for a high strain but the maximum practical magnetic field with niobium-titanium is limited to only $\sim$9 T. Higher fields can be produced by Nb_3Sn but its brittleness casts some doubt on its viability in large superconducting magnets. Many of the technological developments required for high-field Nb_3Sn magnets are more difficult than those for niobium-titanium. Therefore, it is essential to quantify the economic benefits, if any, associated with Nb_3Sn. We have examined this question in some detail and a summary of the results is presented below.

Consider the class of reactors with thermal power, P_{th} = 3000 MWt; aspect ratio, A = 3; plasma D-shape height-to-width ratio, κ = 1.65; a scrape-off region thickness, Δ_v = 0.2 m; and a blanket/shield thickness, Δ_{BS}^{i} = 1 m. Three major parameters remain to be determined to fully describe the basic features of a reactor. These are the major radius, R, the maximum toroidal-field strength, B_m, and the average plasma toroidal beta, β_t. Since the MHD stability limits on β_t have not been established yet, a plausible range of β_t is considered. The relationships among the three parameters are discussed in Ref. 18. The size (major radius) of the reactor decreases as B_m and/or β_t are increased since the power density in the plasma increases as $B_m^4\beta_t^2$ (for a fixed R, A, and Δ_{BS}^{i}). This underlines the often-mentioned motive for a high field capability; smaller-size reactors are generally less expensive. Figure 2 shows the cost of energy production in mills/kWh as a function of B_m and β_t for the class of reactors specified above. In these calculations, NbTi with a maximum strain of 0.2% is used for $B_m \leq 9$ T and Nb_3Sn, with a maximum strain of 0.1%, is employed at higher fields.

The results in Fig. 2 show that, in the range $0.06 \leq \beta_t \leq 0.14$ and 6 T < B_m < 9 T, larger β_t and higher toroidal-field reactors produce electricity at a cheaper cost. For $B_m \geq 10$ T, the cost of electricity increases substantially at higher fields and the benefits of high β_t are poorly utilized and turned into disadvantages. The reasons for this large increase in cost at high fields and high β_t are explained below.

The type of reactor examined in this study is based on the conventional design concept of locating the solenoid ohmic-heating (OH) coil outside the bores of the TF coils and inside the central core formed by the inner legs of these TF coils. Increasing the toroidal-field strength decreases the OH flux core area in two ways: (1) the major radius decreases; and (2) the thickness of the TF coils increases. Although the volt-second requirements to achieve a particular burn cycle decrease with a smaller major radius, the reduction in the OH flux core area is so large that the OH field increases very rapidly at higher toroidal field. In the calculations presented here, the OH field is permitted to exceed the technological limits on pulsed magnets and the cost algorithms are assumed to be extrapolatable to these very high OH fields. For the low toroidal-field ($B_m < 9$ T) cases the power supply cost is approximately 15% of the direct capital cost of the plant. For higher toroidal fields, i.e. $B_m > 9$ T, the power-supply cost increases very rapidly until it represents approximately 60 to 70%of the direct capital cost at $B_m \sim 14$ T.

From the above discussion it is clear that the difficulty with high toroidal fields is the smallness of the available OH central flux core area. Situations that might alleviate this problem can be considered. Figure 3 is similar to Fig. 2 except a larger aspect ratio, A = 4, and a lower degree of noncircularity, $\kappa = 1.3$, are considered. An additional case of low β_t ($\beta_t = 0.04$) is also included. The same trends observed earlier are once again evident in Fig. 3. For $\beta_t \geq 0.06$, the minimum cost is achievable with NbTi at 9 T. However, the rate of cost increase at higher fields is less for the larger aspect ratio lower κ cases. An important result in Fig. 3 is that for $\beta_t = 0.04$, the cost of energy continues to decrease beyond $B_m = 9$ T and has a minimum at $B_m \sim 12$ T. However, this minimum is only <1 mill/kWh lower than the cost of energy at $B_m = 9$ T. This is a marginal difference, well within design and cost uncertainties, and cannot alone justify costly and high-risk new technology development.

In the above discussions, reactors with 3000-MW thermal power were considered. Figure 4 shows the cost of energy as a function of β_t and the toroidal-field strength for larger power reactors, $P_{th} = 7000$ MW, with A = 4,

$\kappa = 1.3$, and the other parameters are the same as those used above. Other parameters being fixed, a larger power reactor has larger major radius and central flux core area. For these larger power reactors, the minimum cost is obtainable with a toroidal-field of 9 T for $\beta_t \geq 0.08$. For reactors with $\beta_t = 0.06$, the cost of energy is slightly smaller at $B_m = 12$ T than that at 9 T. The cost of energy for reactors with $\beta_t \leq 0.04$ has a markedly different behavior. In general, it decreases gradually as the toroidal-field is increased up to ∿13 T. The largest reduction in cost is accomplished by increasing B_m from 6 to 9 T. The lowest cost of energy, which occurs at 13 T, is ∿7% lower than that at 9 T. We also examined the 7000 MWt class of reactors at higher plasma elongation and lower aspect ratios. For reactors with $\kappa = 1.65$ and $A = 3$, the minimum cost occurs at 9 T for $\beta_t \geq 0.06$. For the lower β_t cases, $\beta_t = 0.04$, the cost at 12 T is insignificantly smaller than that at 9 T.

An outstanding conclusion from these results is the great dependence of cost on β_t. Reactors designed properly can always benefit from higher β_t equilibria — if achievable — by reducing the reactor size and/or by operating at a lower toroidal field. Higher β_t equilibria are likewise more tolerable to the levels of impurity buildup. However, the economic benefits of increasing β_t are smaller at high β_t. A β_t of ∿0.08 seems to achieve most of the economic potential of tokamaks.

Our analyses, a part of which has been presented above, show no economics incentive for developing magnets that can operate at fields higher than 9 T if plasma stability can be assured for $\beta_t \geq 0.06$. If the stability limit on β_t is 0.04 or lower, then tokamaks will be considerably more expensive. In this case, it might be worthwhile to develop high-field (∿12 T) magnets if the economic competitiveness with other energy sources dictate that. However, two points have to be carefully considered then:

(1) There will be very strong motives to develop other design concepts for the OH system. One such concept has been suggested [11] although its technical feasibility has not been established yet. Concurrently with this, new design concepts that permit smaller toroidal-field magnet thickness become more important.

(2) Tokamak power plants with the conventional central OH solenoid will have to be designed at large power levels ($P_{th} \gtrsim 5000$ MWt), large aspect ratios ($A \gtrsim 4$), and small elongation ($\kappa \lesssim 1.3$) to realize significant economic advantages from high toroidal fields. As discussed in the next section, there are indications that β_t will decrease significantly as the aspect ratio increases. It is unfortunate that the high-field approach dictated by low β_t has to employ a large aspect ratio and does not make a good utilization of β_t.

4. ASPECT RATIO AND PLASMA ELONGATION

It has often been stated that tokamaks are better designed at lower aspect ratios because the β_t stability limit may be higher. A similar reason has been argued for greater plasma elongation, i.e. higher κ. In addition, elongating the plasma permits a larger volume of the plasma to be positioned in the high magnetic field region. On the other hand, tokamaks with lower aspect ratio have more difficult engineering-related problems concerning accessibility, assembly, and disassembly. Highly shaped plasmas may require locating the equilibrium-field (EF) coils inside the blanket which creates the problems of maintenability and replacement in a geometrically difficult configuration and radioactive environment. All these questions are difficult to resolve at present because the quantitative dependence of β_t on κ and A is not known, and quantifying the economics of the engineering problems require considerable design details that vary from one design concept to another. In this section, we examine the possibility of the presence of economic effects for A and κ other than the β_t dependence and the engineering-related problems. In addition, we examine the sensitivity of the cost of energy to several possible scenarios for the variation of β_t with A and κ.

Figure 5 shows the cost of energy as a function of the aspect ratio for three assumed cases of the β_t dependence on A: (1) β_t is fixed and independent of A; (2) $\beta_t \sim C_1/A^2$ with C_1 in the range of 0.5 to 1.0; and (3) $\beta_t \sim C_2/A$ with C_2 varying from 0.2 to 0.3. In all cases in Fig. 5 we fix P_{th} = 3000 MWt, B_m = 9 T, κ = 1.3, and Δ^i_{BS} = 1 m. Several interesting results are noted from Fig. 5.

For a fixed value of β_t, in the range β_t = 0.04 to 0.1, the cost of energy decreases by approximately 10% as the aspect ratio is increased from 2.5 to 4. This trend of lower cost of energy at larger A was observed for other values of κ (1-2) and reactor power (3000-10,000 MWt). There are two reasons for this:

(a) Increasing the aspect ratio increases the magnetic field in the plasma region. The increase in the power density at larger A makes it possible to reduce the plasma volume and the first-wall area. This results in a reduction in the costs of the first-wall, blanket, shield, and toroidal-field coils.

(b) The cost of the poloidal coils and their power supply decreases significantly as A increases due to several factors. The central OH flux core area increases as A increases. The reduction in the plasma cross section area at larger A results in a significant decrease in the plasma current as discussed in Ref. 18. Furthermore, the equilibrium field also decreases as A increases.

Figure 5 shows that if the β_t stability limit depends strongly on A such that $\beta_t \sim C/A^2$ then the cost of energy increases at larger A. The rate of increase is less significant at larger β_t-values (i.e. larger C) and low-aspect ratio. For moderately high β_t ($\gtrsim$8% at A = 2.5), the increase in the cost of energy resulting from increasing A from 2.5 to 3 is so small that it will almost certainly be compensated for by the ease of assembly/disassembly and maintenance.

If the dependence of the β_t-stability limit on A is moderate, i.e. $\beta_t \sim C/A$, the results of Fig. 5 show that the cost of energy actually decreases as A increases for A $\gtrsim$ 3.5. Taking the engineering-related problems into consideration, it appears that A $\sim$ 3.5 is a favorable design point if $\beta_t \sim C/A$.

Figure 6 shows the cost of energy as a function of the plasma height-to-width ratio, κ. Results are shown for three scenarios of the β_t-stability limit on κ: (1) β_t is fixed and independent of κ; (2) $\beta_t \sim CS^2$ where S is the shape factor (the ratio of the plasma perimeter to the circumference of an inscribed circle); and (3) $\beta_t \sim CS$. We have chosen the D-triangularity parameter, d, to vary with κ as follows: d = 0.0 at κ = 1.0, d = 0.25 at κ = 1.3, d = 0.5 at κ = 1.65, and d = 0.75 at κ = 2. Thus, the shape factor, S, is equal to 1, 1.16, 1.36, and 1.56 at κ = 1, 1.3, 1.65, and 2, respectively. All results in Fig. 6 are for P_{th} = 3000 MW, A = 3, B_m = 9 T, and Λ_{BS}^{i} = 1 m.

A clear observation from Fig. 6 is that for a fixed β_t, the variation of the cost of energy with κ is very small with a broad minimum in the range of κ = 1.3-1.6. This weak dependence of the cost of energy on κ when β_t is fixed was also found for reactors with larger power and aspect ratio. There are several counteracting effects with increasing κ. The plasma major radius and width decrease resulting in reduction in the costs of the TF coils, the reactor containment building, and the piping for the heat transport system. On the other hand, the height of the plasma increases and the costs of the first-wall, blanket, and shield increase. Very strong effects come from large increases in the plasma current and the equilibrium-field at higher κ as is discussed in Ref. 18. Although the reduction in the area of central OH flux core is moderate, the rapid increase in the volt-second requirements result in a significant increase in the OH field. The cost of the power supply for the OH and EF coils increases significantly with κ.

If the β_t-stability limit is strongly dependent on the shape factor, i.e. $\beta_t \sim CS^2$, the results in Fig. 6 show a significant economics benefit from increasing κ. The savings from the reduction in the size of the reactor at larger κ significantly exceed the increase in the power supply cost. If the β_t stability limit depends only moderately on κ, i.e. $\beta_t \sim CS$, the cost of energy also decreases as κ is increased from 1 to 1.3 but at a much slower rate than in the previous case of $\beta_t \sim CS^2$. The cost of energy exhibits little variation as κ is increased from 1.3 to 1.65 for the case of linear dependence of β_t on κ.

5. NEUTRON WALL LOAD AND STRUCTURE LIFETIME

A major problem relating to the successful operation of tokamak power plants is the satisfactory performance of the first-wall and blanket structure. The neutron wall load is an important measure of the severity of the operational environment for the first-wall and blanket. The useful lifetime of the structural material, on the other hand, is an important indication of the performance of the first-wall and blanket. In this section, the tradeoffs concerned with the neutron wall loading and the structure lifetime are examined. The results provide a useful input to determining the desirable goals for structural alloy development.

The neutron wall loading, P_w, is strongly related to the reactor thermal power, P_{th}, the surface area of the first wall, A_w, the plasma power density, P_p, and the plasma volume. The motive for a higher P_w capability is that it makes it possible to design higher power density, smaller size, and potentially more economical reactors. However, there are upper limits, on the highest wall load that can be realized, arising from: (a) physics constraints on the power density achievable in the plasma; and (b) limitations unique to tokamaks on the smallness of the reactor size. There are also limits on the usability of high P_w dictated by the structure cooling capability and its lifetime in a harsh radiation environment.

An extensive parameter survey was made to determine the range of wall loads producible in tokamaks. For a 300-MWt reactor with $B_m = 9$ T, P_w varies from ~ 3 MW/m^2 at $\beta_t = 0.06$ to $P_w \sim 5$ MW/m^2 at $\beta_t = 0.1$. For a larger power reactor with $P_{th} = 7000$ MWt, P_w at $B_m = 9$ T varies from ~ 5 MW/m^2 at $\beta_t = 0.06$ to ~ 8 MW/m^2 at $\beta_t = 0.1$. The producible P_w is sensitive to the aspect ratio, A. For $B_m =$ 9 T, $\beta_t = 0.08$, and $\kappa = 1.3$ increasing A from 3 to 4 increases P_w from ~ 3 MW/m^2 to ~ 4 MW/m^2 for $P_{th} = 3000$ MWt. The wall load decreases slightly as the plasma elongation, κ, is increased from 1 to 1.65. P_w is particularly sensitive to β_t and P_{th}. The uncertainties in the plasma stability limit on β_t and in the projected optimum plant power rating at the time fusion is commercialized complicates the task of determining a target wall load for structural alloy development.

One technological constraint on the usability of a high wall load is the ability to cool the first-wall. This technological constraint varies with the properties of the structural material and the type of coolant. This question is examined in Ref. 22 which shows that a lithium-cooled vanadium alloy can be operated in the presence of a divertor up to $P_w \sim 8$ MW/m^2 with $B_m = 9$ T. Lower wall-load limits are derived for higher fields, no divertor, helium cooling, and/or stainless-steel structure. Provided that this cooling constraint is met, the neutron wall load affects the economics of the power plant in two ways. A higher wall load results in a lower exit temperature, a lower thermodynamic efficiency and a smaller electric power output. Furthermore, for a given fluence lifetime (MW-yr/m^2) of the structural material, a higher wall load results in a shorter calendar lifetime (years) of the structural material, a lower plant capacity factor, and a higher cost of structure replacement. All these effects are accounted for in the ANL Tokamak Systems Program which was utilized to derive the results given below.

One substantial difficulty with determining an optimum neutron wall load is the strong economic dependence on many major design parameters and options for tokamaks. For the purpose of this work, we choose a common set of parameters that generally result in favorable economic conditions. These are: $B_m = 9$ T, $\kappa = 1.65$, $A = 3$, and $\Delta^i_{BS} = 1$ m. The reactor thermal power and the plasma β_t are left as variables because of the large uncertainties in determining desirable and feasible values for them as well as their large effect on the wall load. Lithium cooling and two structural materials are considered.

Figure 7 shows the cost of energy, mills/kWh, as a function of the neutron wall load obtainable at various values of β_t and P_{th}. The lines of constant β_t and those of constant P_{th} are shown in Fig. 7. The results are for a structural material with properties and cost similar to those of an advanced vanadium alloy with a relatively long lifetime of $\sim$34 MW-yr/m^2 and a maximum operating temperature of 650°C. The total downtime, t_d, for replacement of the first wall and blanket structure is assumed to be 80 days. The results show a significant economic benefit for operating at a higher neutron wall load. Figure 7 also shows that the lines of constant β_t are much steeper than those of constant P_{th}. In other words, a more substantial cost saving is achieved at higher wall loads obtainable by increasing the reactor thermal power from 3000 to 9000 MW than by increasing β_t from 0.06 to 0.14. This difference in the cost saving is attributable to the economy of scale discussed earlier in this paper.

Figure 8 is similar to Fig. 7, except that the vanadium structure is replaced with stainless steel operating at a maximum temperature of 500°C with a predicted lifetime of 3.1 MW-yr/m^2. Figure 8 shows that under these conditions the cost of energy for any given reactor thermal power increases as the neutron wall is increased to values greater than ∿2 MW/m^2.

Therefore, structural materials with stainless steel-like properties impose a limitation on the neutron wall load and do not permit a full utilization of the economics potential of tokamaks. In contrast, structural materials with vanadium-like properties permit operation at higher wall loads at a significantly lower cost of energy. The economics benefits of advanced structural alloys compared with stainless steel are obvious in Fig. 1. With the assumption that the material plus fabrication cost is 30 $/kg for stainless steel and 440 $/kg for vanadium alloys, the capital cost of the power plant is higher with the advanced alloys. However, our trade-off studies indicate that the optimum operating temperature is 650°C for vanadium structure compared with only 500°C for stainless steel. Therefore, for the same reactor thermal power, the net electrical power output is significantly larger with the advanced alloys. The net effect is that the cost per unit power is roughly the same for power plants employing advanced alloys or stainless steel. The large saving, ∿20%, in the cost of energy obtainable with vanadium alloys is due mostly to the much longer lifetime compared with that of stainless steel.

Figure 9 shows the cost of energy as a function of the structure lifetime (MW-yr/m^2) at several values of the reactor power and a fixed β_t of 0.08. A reference set of parameters (B_m = 9 T, κ = 1.65, A = 3, and Δ_{BS}^{i} = 1 m, t_d = 160 d) is fixed as above and a structural material with properties and cost similar to vanadium alloys is employed. The neutron wall load at each reactor power is shown in the figure. These results show that the cost of energy will always decrease as the lifetime of the structure is increased. At any given reactor power and wall load, a large reduction (∿20-30%) in the cost of energy is achieved by increasing the lifetime from 5 to 12 MW-yr/m^2. The reduction in the cost of energy obtainable by further increase in the structure lifetime is smaller but is still significant.

Based on the results of this study, goals for structural alloy development can be recommended regarding the wall load capability, calendar lifetime (years), and fluence lifetime (MW-yr/m^2). The goals are classified into two categories: (a) very important (Priority 1); and (b) important (Priority 2). Achieving the goals in Priority 1 category ensures that the structural materials do not pose serious limitations on the economic competitiveness of tokamak power plants. The Priority 1 goals are 3 MW/m^2, 4 yr, and 12 MW-yr/m^2. Accomplishing the goals in the Priority 2 category will provide an important step in a comprehensive research and development program to improve the utilization of the tokamak potential as a relatively inexpensive energy source. The Priority 2 goals are 5 MW/m^2, 6 yr, and 30 MW-yr/m^2. These results are based on our present understanding of tokamaks. Future results, experience, and the burden of economic competitiveness may require appreciable modification of these goals. For example, material resources limitations, long-term radioactive inventory problems, and benefits of simpler designs obtainable with relaxation of requirements on frequency of shutdown and length of downtime may demonstrate a more pressing need for longer structure lifetime. In this regard we reached two conclusions that supplement the above goals:

(1) Remote maintenance for the first wall and blanket is necessary for all structural materials of practical interest. Therefore, the only requirement on structure activation is a low long-term radioactivity so that the structural material can be recycled after a reasonable cooldown period ($\sim$30-100 yr). This requirement satisfies two objectives: (a) a substantial reduction in the material resources required for an all fusion power economy. This is a most desirable objective to be consistent with the major advantage of fusion as an energy source with "inexhaustible" fuels; (b) reduced storage and sociopolitical costs associated with very long-term radioactivity. It is of interest to note that

vanadium-titanium alloys have the greatest potential of satisfying this requirement as they can be recycled in ∿40-70 yr.

(2) The above goals for lifetime assume that the total downtime, t_d, for replacement of the first wall and blanket structure is in the range of 80 to 160 days. Longer t_d will require longer lifetime. In order to limit the increase in the cost of energy due to downtime for replacement of the first wall and blanket rebuilding to less than 10%, the following condition must be met

$$t_d(\text{days}) < 30 \cdot t_w(\text{years})$$

where t_w is the structure lifetime.

6. SUMMARY AND CONCLUSIONS

A parametric systems studies program for simulation of the performance characteristics and economics of tokamak power plants is now in an active stage at ANL. The program has proven to be a powerful tool in addressing critical issues for tokamaks. Parametric systems studies provide a useful framework for identifying the design concepts and the region of parameter space that can make tokamaks economically attractive. The results presented in this paper represent an example of the usefulness of the parametric systems studies approach. A summary of the conclusions that can be drawn from our work is given below. One should be extremely careful, however, not to extrapolate these results far beyond the scope of work that has been defined in this paper. The reader is encouraged to consult References 16 through 26 for greater detail on each specific topic.

(1) In the entire range of variables examined, the cost of energy for tokamaks varies from ∿25-50 mills/kWh (∿1200-2500 \$/kWe). This is comparable to the present range of cost estimates for LMFBR. Cost estimates for other nuclear and coal power plants are in the range of ∿14-20 mills/kWh. Since

the fuel cost is negligible in tokamak fusion power plants the present trend of escalation in the fuel cost for other energy sources will make tokamaks competitive in ∿2-4 decades.

(2) Tokamaks exhibit an "economy of scale". Increasing the reactor thermal power from 3000 to 5000 MWt reduces the cost of energy by ∿10-15%. The saving from further increase in reactor power is smaller. The values of parameters that characterize an optimum reactor system are, in many instances, very sensitive to the design value of thermal power output. It is very desirable for the fusion community to select a "target" thermal power for design, analysis, and planning.

(3) The cost of energy is very sensitive to β_t. The choice of the best parameter space for tokamaks is strongly affected by the operating value of β_t. Determining the stability limit of β_t should be a high priority goal for the fusion program.

(4) Much of the economics advantages of tokamaks can be realized at a β_t of ∿6%. Most of the economics potential of tokamaks is achievable with $\beta_t \sim 8\%$. Higher β_t values — if achievable — are always desirable but not crucial to the prospect for economic competitiveness of commercial tokamaks.

(5) The highest desirable toroidal-field strength is ≤ 9 T, which can be achieved by NbTi, if the β_t stability limit is $\gtrsim 6\%$. If $\beta_t < 4\%$ higher fields (>9 T) would be desirable. Such high field (∿12 T) reactors have to be designed for large power and/or large aspect ratio. The necessity of large aspect ratio for high-field reactors implies poor utilization of the β_t stability limits that will further reduce their benefits if the attainable β_t is inversely proportional to the aspect ratio.

(6) The optimum aspect ratio, A, is sensitive to the variation of β_t with A. If $\beta_t \sim 1/A$, then a favorable aspect ratio is $A \sim 3.5$. If $\beta_t \sim 1/A^2$, then $A \sim 3$ results in an economically favorable design.

(7) The increase in the plasma current and the equilibrium field at larger elongation reduces the benefits of highly shaped plasmas. Assuming the equilibrium-field (EF) coils are located outside the bores of the TF coils, the following conclusions can be derived. If the β_t stability limit is independent of κ there is no motive for employing elongated plasma. If $\beta_t \sim \kappa$ there is a very shallow minimum in the cost of energy in the range $1.3 < \kappa < 1.6$. A significant economic benefit from increasing κ is obtainable if $\beta_t \sim \kappa^2$.

(8) Tokamaks with reactor thermal power in the range of ~3000-6000 MWt have favorable economic conditions with plasma major radii of ~5-8 m.

(9) With proper design concepts, the blanket/shield thickness (distance in midplane from first wall to the point inside the toroidal magnet where the maximum field occurs) can be kept as small as 1 m.

(10) Favorable economic conditions occur when the annealing of the superconducting magnets coincides with the replacement of the first wall.

(11) Experimental data on the radiation damage to organic insulators at low temperatures (~4°K) are required. There is an economic incentive to develop insulators suitable for the TF coils that can operate satisfactorily up to 10^{10}-10^{11} rad.

(12) Advanced structural alloys (e.g. vanadium alloys) offer the potential of reducing the cost of energy by ~20-25% compared with stainless steel.

(13) In order to limit the increase in the cost of energy due to the downtime associated with the replacement of the first wall to less than 10%, a long structure lifetime, t_w, and a short downtime, t_d, for replacement are required to meet the following criteria:

$$t_d(\text{days}) < 30 \cdot t_w(\text{years}) .$$

(14) The recommended highest priority goals for structural alloy development are 3 MW/m^2 eutron wall load and 4-yr lifetime. More ambitious goals that can lead to a very significant economic payoff are 5 MW/m^2 and 6 yr.

(15) Detailed engineering and structural analysis of the first wall and blanket is required to quantitatively define the end of life criteria for the structural materials.

(16) Ignoring the application of advanced power conversion cycles, there is little incentive for structural temperatures in excess of 650°C in lithium-coated reactors. Reasonable values for the maximum operating temperature of the structure is 500°C for stainless steel and 650°C for vanadium alloys.

(17) With lithium cooling and a maximum toroidal field of 8 T, the thermomechanical response of the first wall limits the maximum allowable neutron wall load, in the absence of a divertor, to $\sim$8 MW/m^2 for vanadium and 2 MW/m^2 for stainless steel. Higher fields result in a significant reduction in the allowable neutron wall load. Fields as high as 12 T may preclude the lithium cooling option.

(18) The presence of a divertor (or equivalent mechanism to reduce surface heating) can increase the maximum allowable neutron wall load by $\sim$40 to 90% with both helium and lithium coolant.

(19) For the helium coolant option, a maximum structural temperature of $\geq$600°C is necessary to assure the attainment of attractive operating conditions (i.e. reasonable thermodynamic efficiency).

(20) The power supplies for the poloidal coils represent a significant cost item. The use of a conventional motor-generator-flywheel set as a central energy storage device leads to an increase in the plant cost as large as 10%. There is a strong economic incentive for the development of homopolar generators and superconducting energy storage devices.

ACKNOWLEDGMENT

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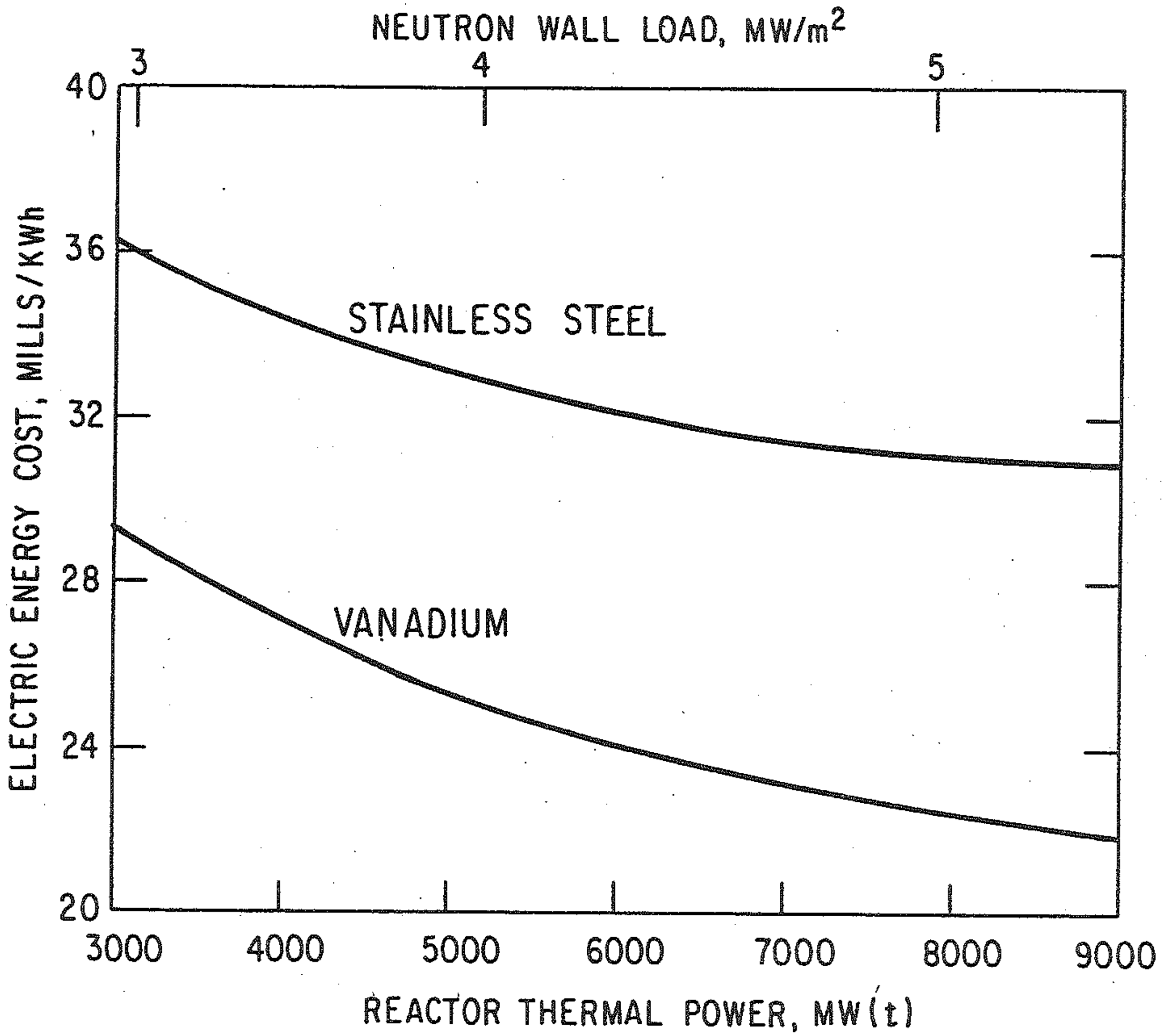

Fig. 1. Variation in the cost of energy with reactor thermal power. ($A = 3$, $\kappa = 1.65$, $q = 3$, $d = 0.5$, $\Delta^{i}_{BS} = 1$ m, $B_m = 9$ T, $t_d = 80$ d). Results are shown for both stainless steel ($T_{max} = 500°C$, lifetime ~3.1 MW-yr/m^2) and a vanadium alloy ($T_{max} = 650°C$, lifetime ~34 MW-yr/m^2) as the first wall and blanket structure.

(ANL Neg. No. 190-77-399)

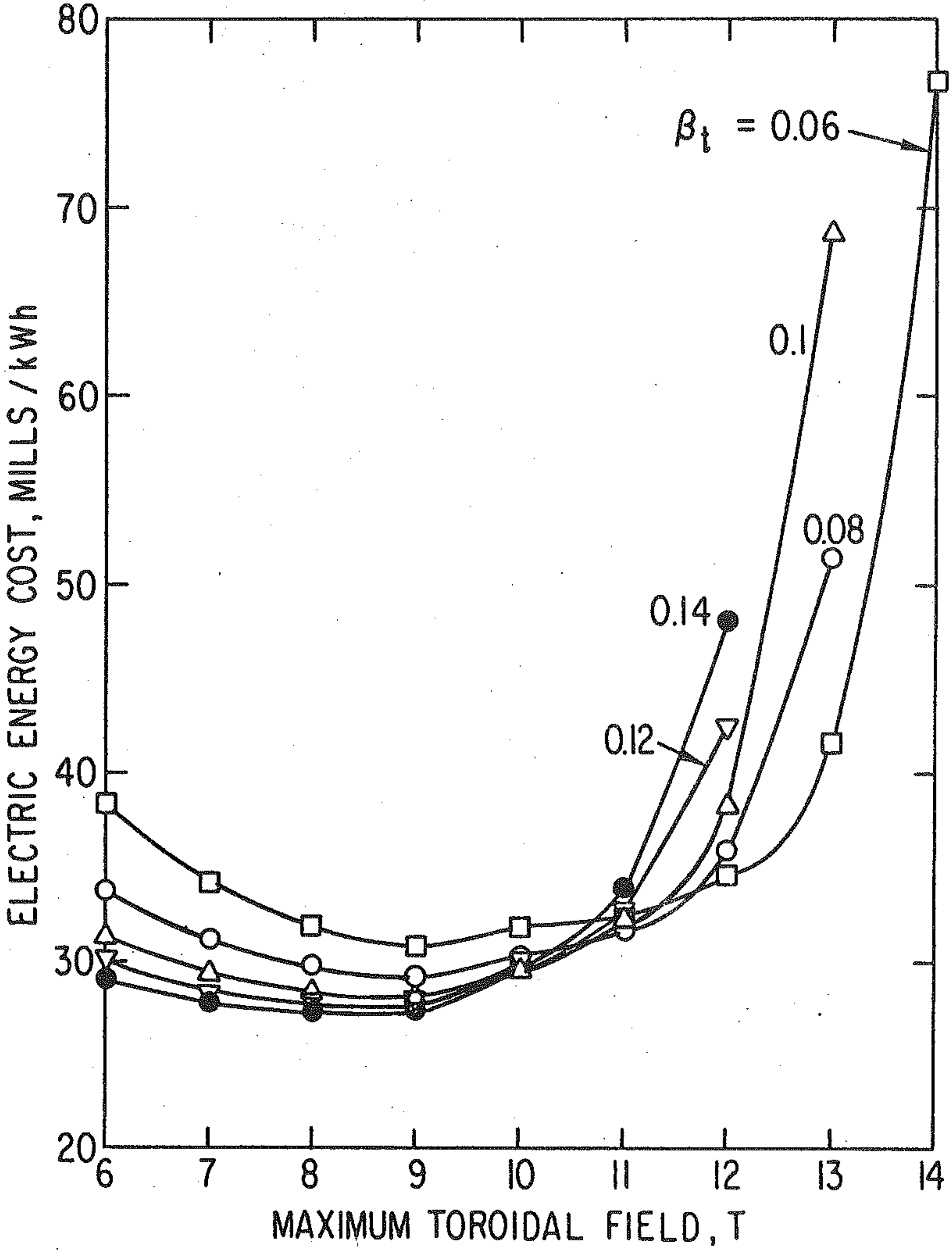

Fig. 2. Cost of energy as a function of maximum toroidal-field strength and plasma β_t for reactors with thermal power of 3000 MWt ($A = 3$, $\kappa = 1.65$, $q = 3$, $d = 0.5$, $\Delta^i_{BS} = 1$ m, $t_d = 80$ d; lithium-cooled vanadium alloy structure with $T_{max} = 650°C$ and lifetime ∿34 MW-yr/m^2).

(ANL Neg. No. 190-77-387)

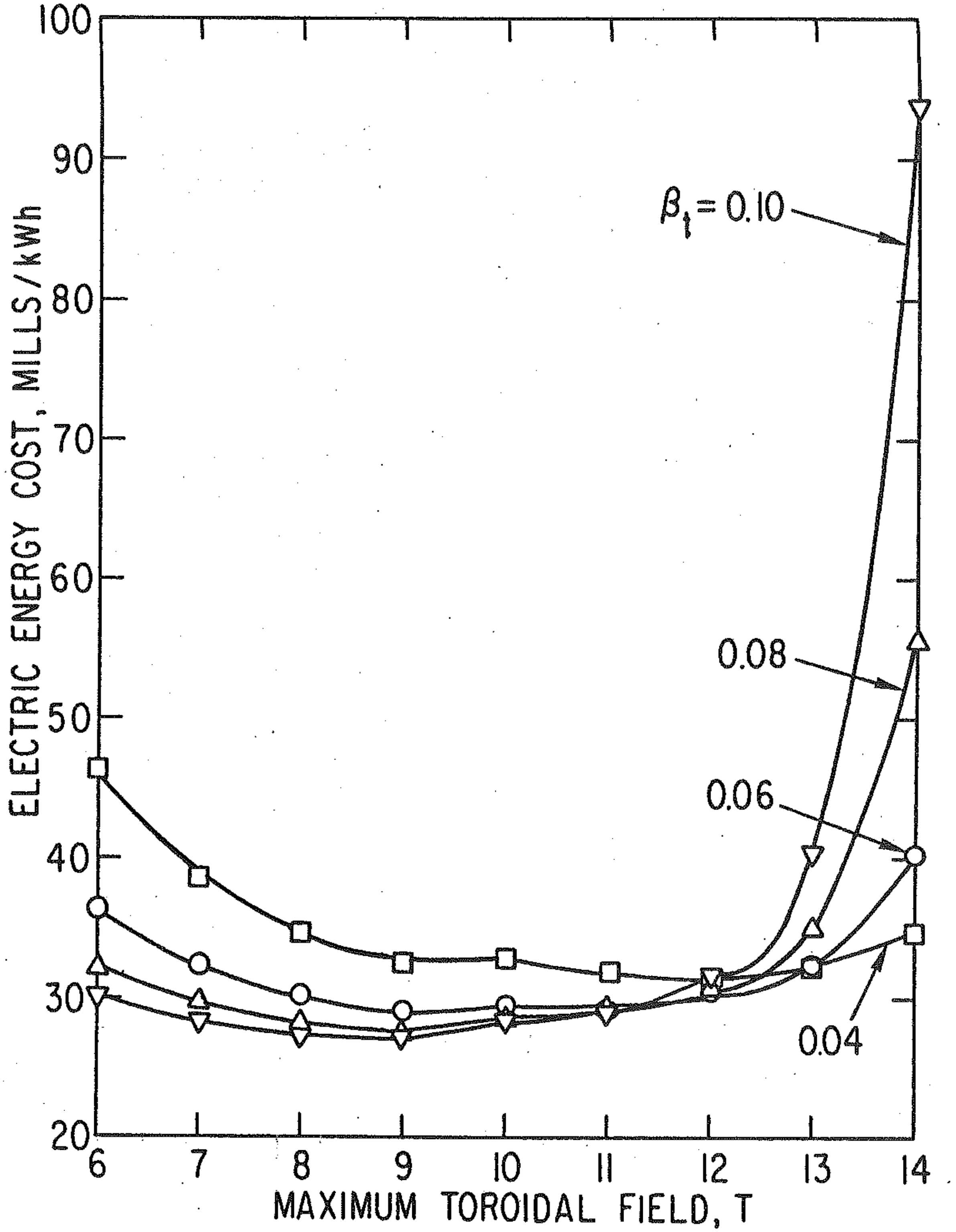

Fig. 3. Cost of energy as a function of maximum toroidal-field strength and plasma β_t for reactors with thermal power of 3000 MWt (A = 4, κ = 1.3, q = 3, d = 0.25, Δ^i_{BS} = 1 m, t_d = 80 d; lithium-cooled vanadium alloy structure with T_{max} = 650°C and lifetime ∿34 MW-yr/m^2).

(ANL Neg. No. 190-77-390)

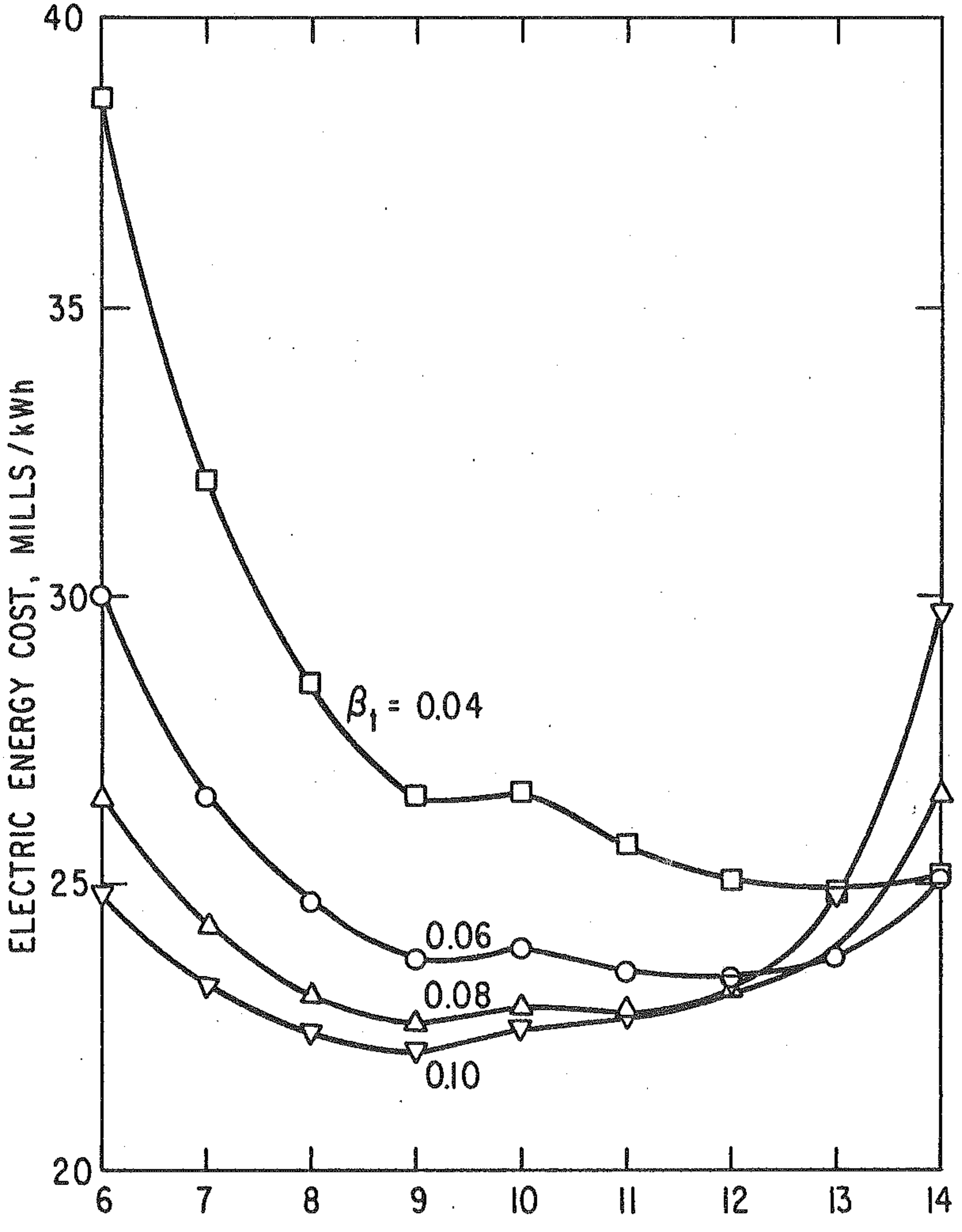

Fig. 4. Cost of energy as a function of maximum toroidal-field strength and plasma β_t for reactors with thermal power of 7000 MWt ($A = 4$, $\kappa = 1.3$, $q = 3$, $d = 0.25$, $\Delta_{BS}^{i} = 1$ m, $t_d = 80$ d; lithium-cooled vanadium alloy structure with $T_{max} = 650$°C and lifetime ∿34 MW-yr/m^2).

(ANL Neg. No. 190-77-391)

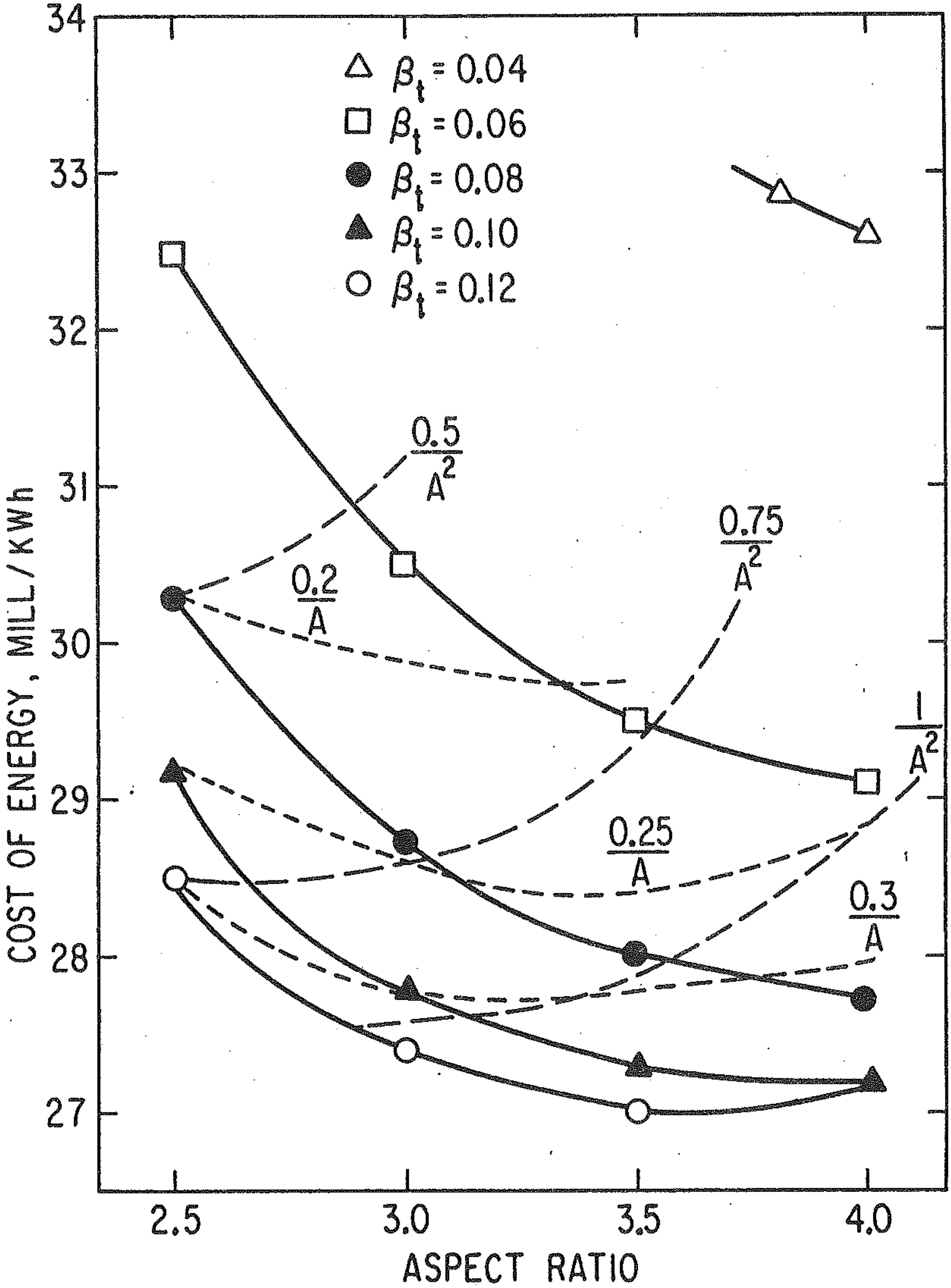

Fig. 5. Cost of energy as a function of the aspect ratio for three assumed cases of the β_t dependence on A.

(ANL Neg. No. 190-77-389)

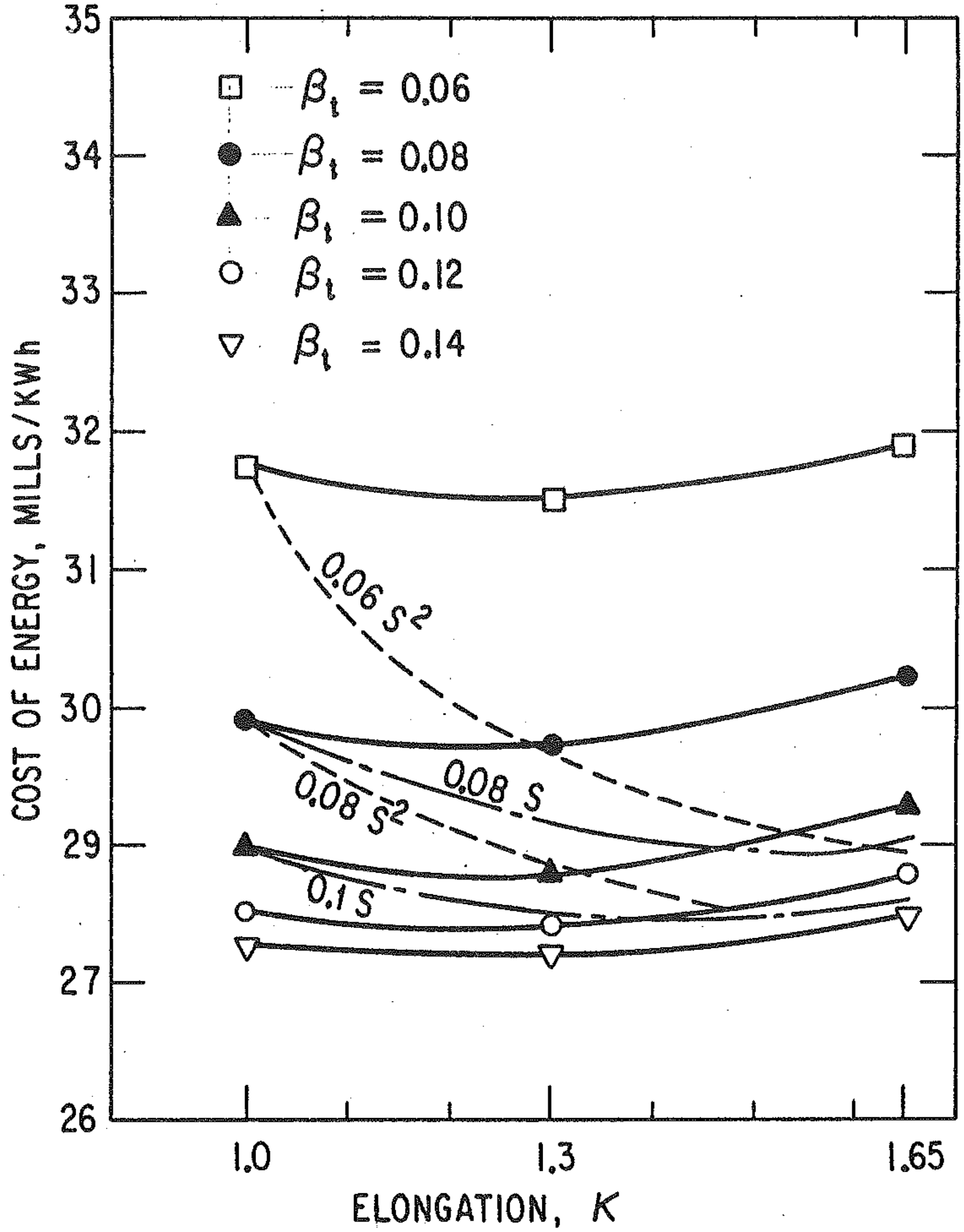

Fig. 6. Cost of energy as a function of plasma elongation, κ, for three assumed cases of the β_t dependence on κ.

(ANL Neg. No. 190-77-386)

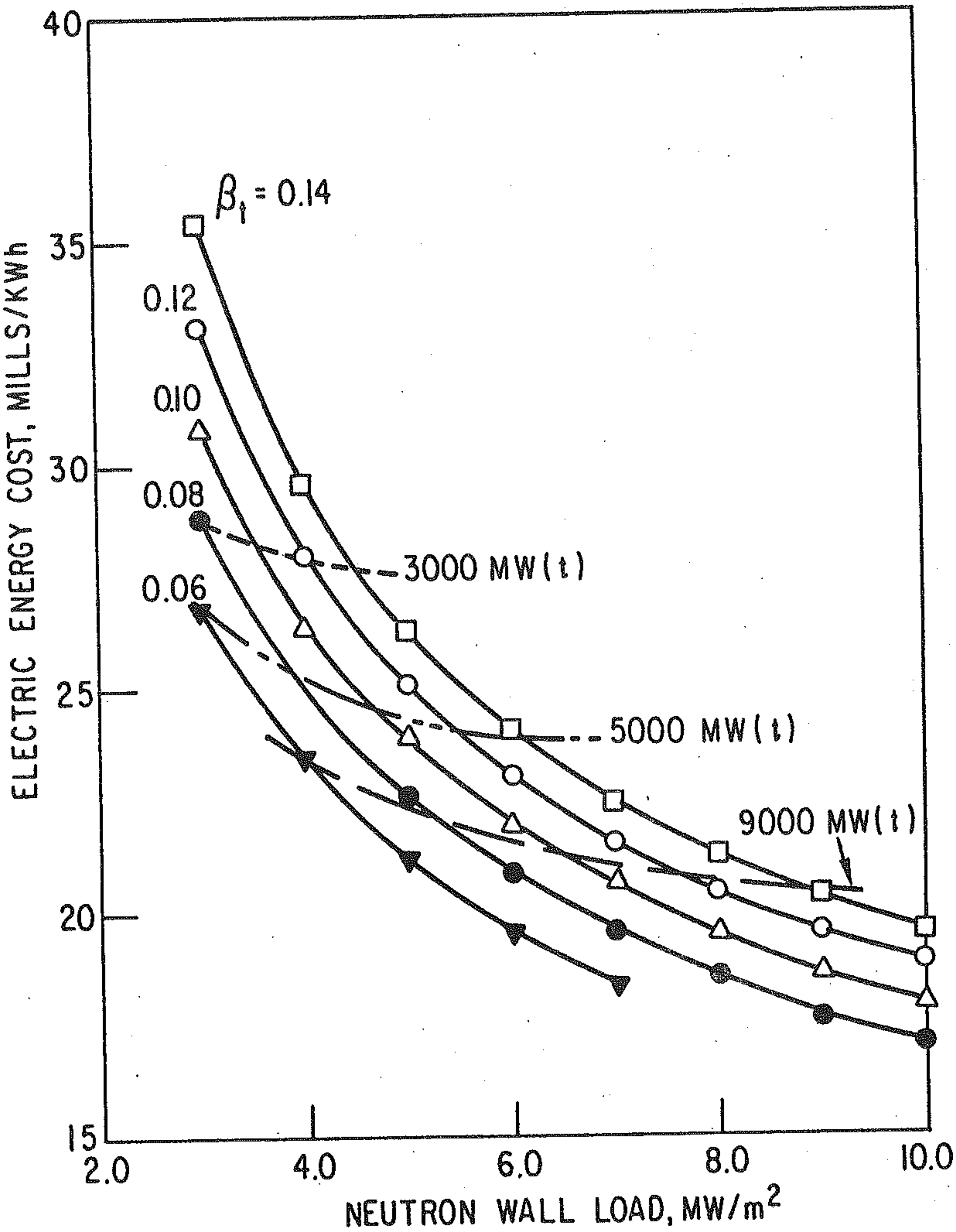

Fig. 7. Cost of energy versus neutron wall load displayed for lines of constant thermal power (variable β_t) and for lines of constant β_t (variable P_{th}). Results are for $A = 3$, $\kappa = 1.65$, $d = 0.5$, $q = 3$, $\Delta^i_{BS} = 1$ m, $B_m = 9$ T; lithium-cooled structural alloy with vanadium properties and cost, $T_{max} = 650°C$, lifetime ∿34 MW-yr/m², $t_d = 80$ d.

(ANL Neg. No. 190-77-395)

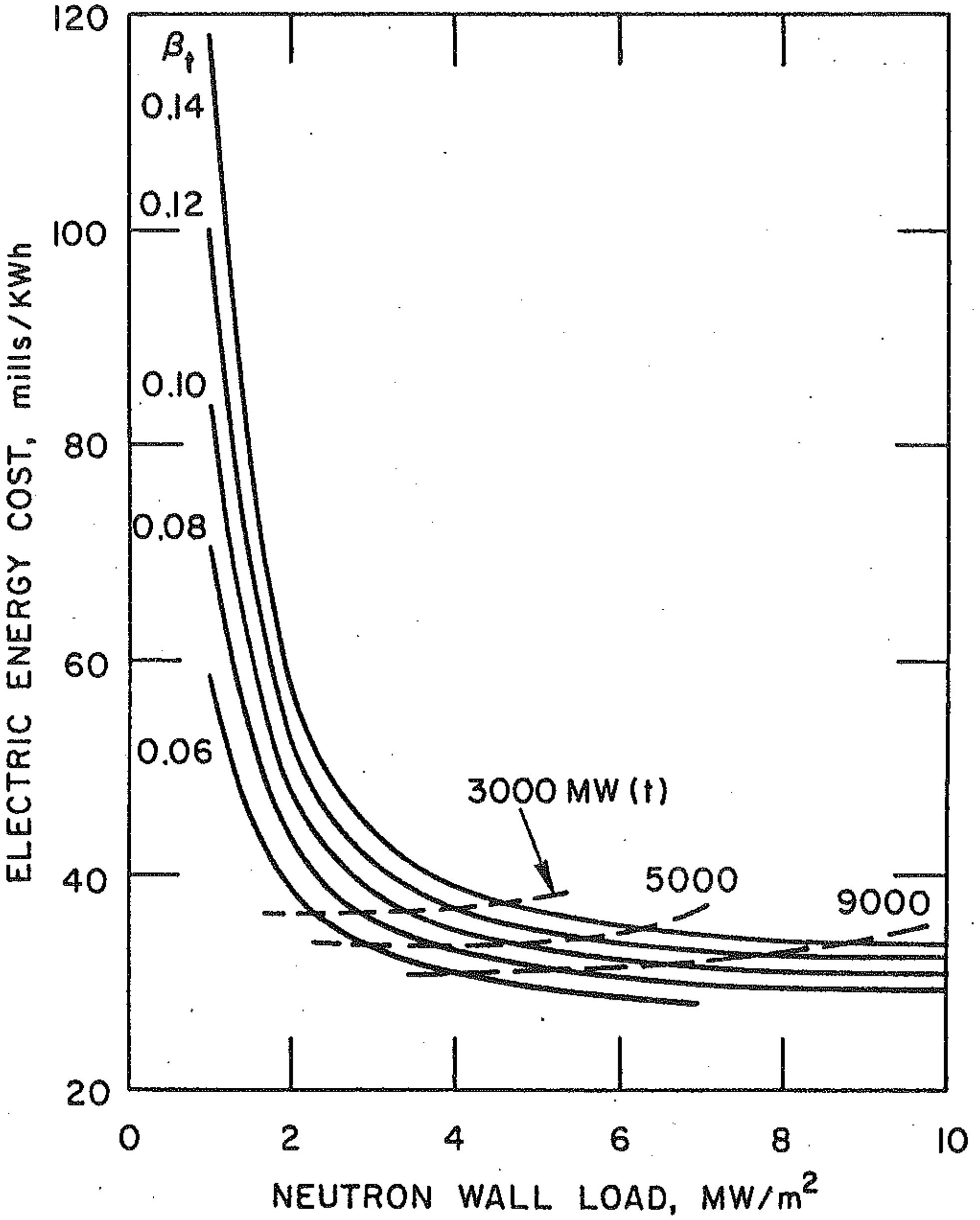

Fig. 8. Cost of energy versus neutron wall load displayed for lines of constant thermal power (variable β_t) and for lines of constant β_t (variable P_{th}). Results are for $A = 3$, $\kappa = 1.65$, $d = 0.5$, $q = 3$, $\Delta^i_{BS} = 1$ m, $B_m = 9$ T; lithium-cooled structural alloy with stainless steel properties and cost, $T_{max} = 500°C$, lifetime ∿3.1 MW-yr/m², $t_d = 80$ d.

(ANL Neg. No. 190-77-393)

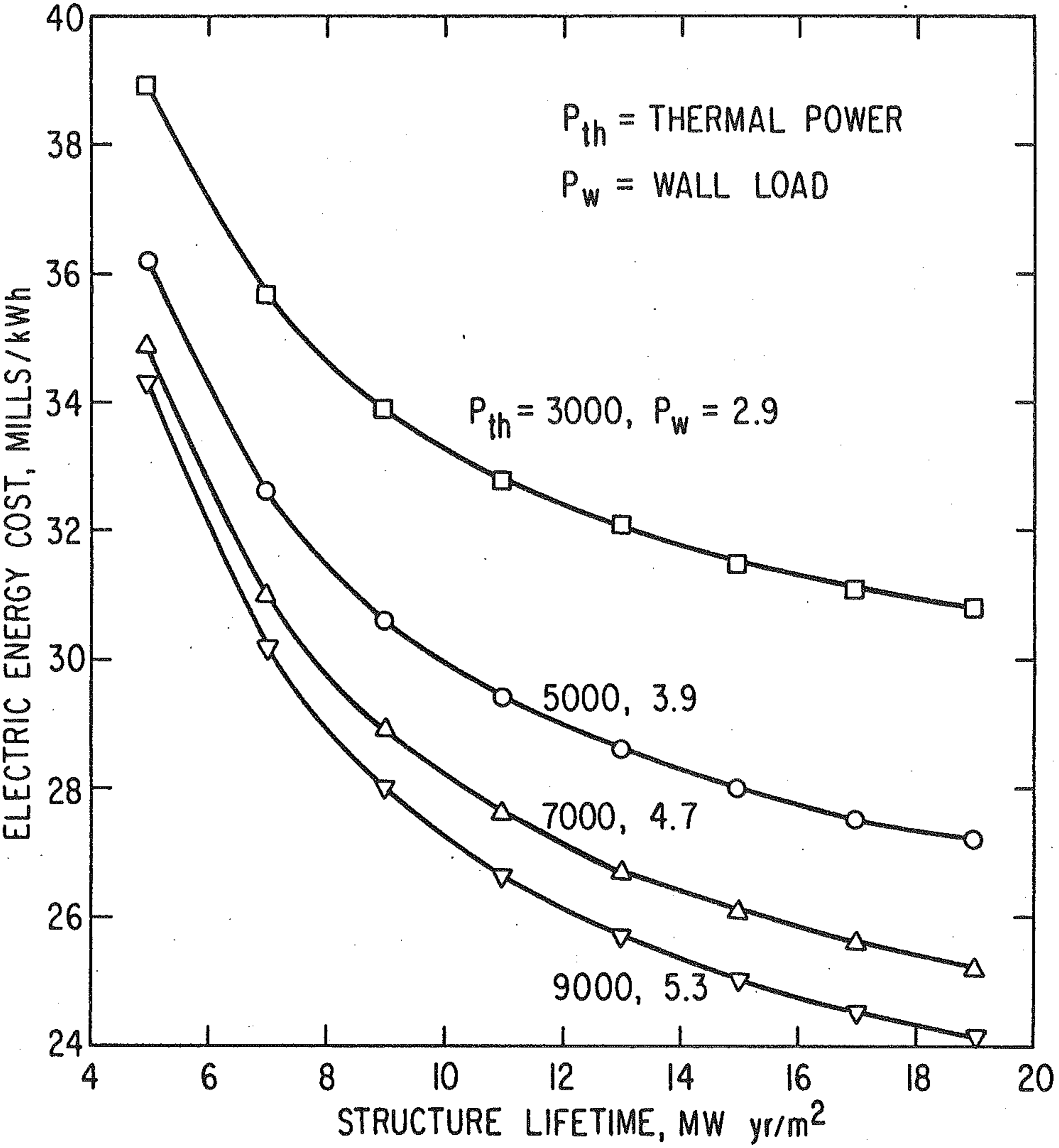

Fig. 9. Sensitivity of the cost of energy to the lifetime (integrated exposure in MW-yr/m^2) of the first wall at various reactor thermal power and neutron wall load.