COST ESTIMATION FOR A THETA-PINCH REACTOR*

by

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ABSTRACT

A simulation of a theta-pinch fusion power plant has been completed to the point where economic feasibility can be examined. A PL/I cost subprogram is presented for interfacing with the computer code TPFPP. This code is then used to obtain a first approximation of the costs for the reactor. Independent geometrical and plant design parameters are varied over a wide range, with simultaneous variation of magnetic field, minor first wall radius, and plasma maximum compression.

The study indicates that the plant energy balance must be favorable, availability must be high, and major component costs must be low to achieve economical results. Although costing uncertainties remain, it is clear that development of easy and rapid replacement methods for reactor components is essential and that new staging concepts to reduce the implosion energy requirement must be pursued.

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1. INTRODUCTION

Comparative parametric systems analysis is being conducted at ANL for various fusion reactors.[1] The reference theta-pinch (see Fig. 1), was the first to be studied,[2] and analysis has now advanced to the point where we can make reasonable estimates of the cost of electricity from such a plant.

A cost estimation has the advantage of clarifying the interrelation of subsystems, no matter how uncertain the parameters used. In the theta pinch, this interrelation is particularly difficult to appreciate otherwise. Unlike other fusion reactors, the theta-pinch has many loosely coupled systems; and although changes in one portion affect another, it is possible to grossly change one system and still retain a workable reactor.

To implement the estimation, a PL/I subprogram was written for interfacing with the computer code TPFPP that was developed earlier for a mathematical model of the theta-pinch reactor.[3] The various calculations in this cost model are discussed in Section 2. In Section 3, a first approximation of the costs for the reactor is made. Parameters are varied over a wide range, and capital costs as well as energy costs (mils per kWh) are estimated.

It must be emphasized that the cost estimates are very tenuous and are intended principally to show the effects of trade-offs in technology required for development of the fusion reactor. A search for an "optimum" design is not attempted since many of the costing input figures are uncertain and many of the constants used are crude. A prime example is the interest rate. Inflation factors, component lifetimes, escalation and interest during construction, amortization and compounding periods, etc. are generally ignored. Instead, trends and sensitivity are shown.

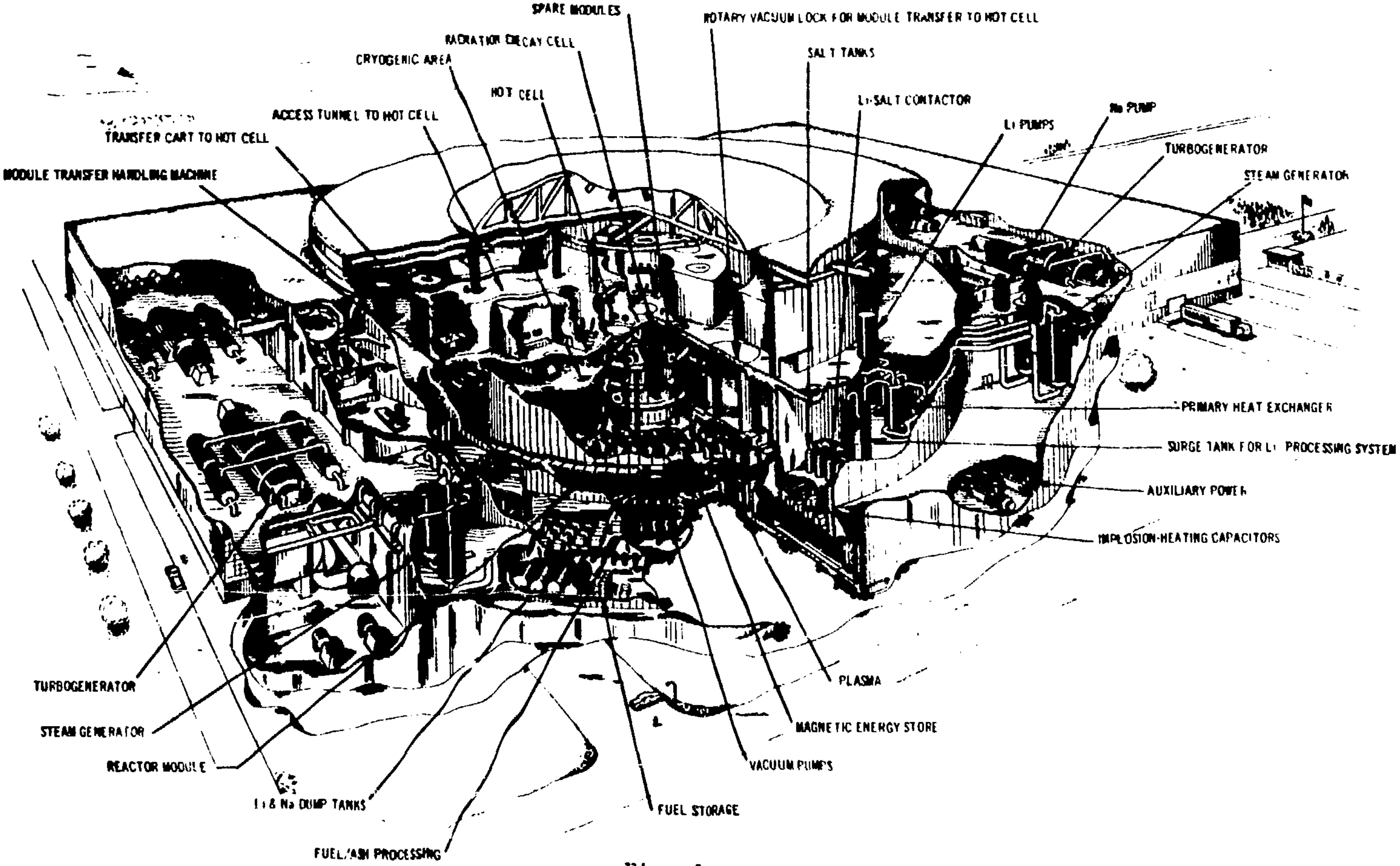
MODULE TRANSFER HANDLING MACHINE
TRANSFER CART TO HOT CELL
ACCESS TUNNEL TO HOT CELL
CRYOGENIC AREA
HOT CELL
RADIATION DECAY CELL
SPARE MODULES
ROTARY VACUUM LOCK FOR MODULE TRANSFER TO HOT CELL
SALT TANKS
Li-SALT CONTACTOR
Li PUMPS
Na PUMP
TURBOGENERATOR
STEAM GENERATOR
PRIMARY HEAT EXCHANGER
SURGE TANK FOR Li PROCESSING SYSTEM
AUXILIARY POWER
IMPLOSION-HEATING CAPACITORS
PLASMA
MAGNETIC ENERGY STORE
VACUUM PUMPS
FUEL STORAGE
FUEL/ASH PROCESSING
Li & Na DUMP TANKS
REACTOR MODULE
STEAM GENERATOR
TURBOGENERATOR

Fig. 1

2. COST MODEL CALCULATIONS

2.1 COSTING SUBPROGRAM

In the preliminary economic analysis of the theta-pinch power plant, primary attention was given to those components peculiar to the theta-pinch design, i.e., the reactor modules and the plasma confinement systems (see Fig. 2). Conventional equipment (turbines, generators, buildings, etc,; see Fig. 1) were estimated as a lump sum. For the purpose of a cost model, the costs were divided into three main categories: the energy storage devices, the module, and the "rest". The cost of the energy storage was in turn subdivided into three: the fast and slow circuits for implosion heating-energy storage, the staging fast and slow circuit for staging energy storage, and compression energy storage. The cost of the modules was subdivided into the cost of the blanket, compression coil, and titanium support ring. The cost of the "rest" was assumed to be a linear function of gross plant size and is expressed in terms of \$/kW of gross plant capacity.

2.2 CAPITAL COST

The cost of the energy storage system can be calculated, if the unit cost of energy storage and the amount of energy storage needed is known, by use of the following relation;

$$\text{COST} = \text{ENERGY} \times \text{STORE} \times 10^6, \qquad (2.2.1)$$

where the term ENERGY is the amount of energy storage in megajoules required for a given system, and STORE is the storage cost per joule.

The capital cost of the implosion heating-energy storage system is

$$\text{CAPITAL.IHES} = \text{STORE.IHES} \times 10^6 \times (\text{WIHF}/\eta_{\text{TRIHF}} + \text{WIHS}/\eta_{\text{TRIHS}}), \qquad (2.2.2)$$

where the quantity $(\text{WIHF}/\eta_{\text{TRIHF}} + \text{WIHS}/\eta_{\text{TRIHS}})$ is the actual amount of energy storage required, and η_{TRIHF} and η_{TRIHS} are the transfer efficiencies for the

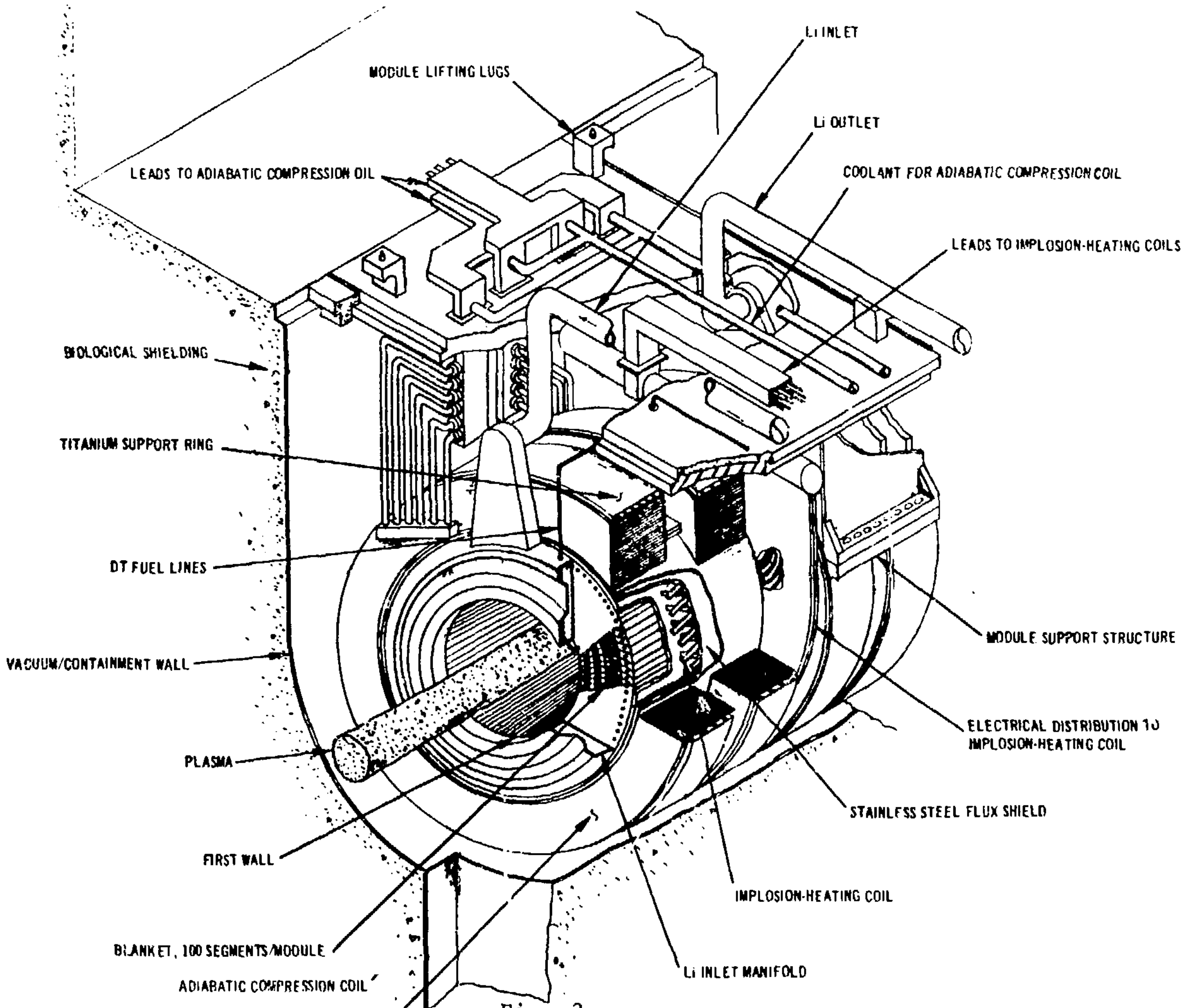

Fig. 2
Cutaway view of a 2-meter long RTPR module

fast and slow pulses respectively, which account for required excess capacity of energy storage system. The values WIHF and WIHS are calculated by an existing computer code, TPFPP, for wide ranges of plant parameters.[3,4] The energy balance is shown schematically in Fig. 3.

The capital cost of the staging energy storage system uses the same method:

$$\mathrm{CAPITAL.STES} = \mathrm{STORE.STES} \times (\mathrm{WSGF}/\eta_{\mathrm{TRSGF}} + \mathrm{WSGS}/\eta_{\mathrm{TRSGS}}) \times 10^{6}, \qquad (2.2.3)$$

where the quantity $(\mathrm{WSGF}/\eta_{\mathrm{TRSGF}} + \mathrm{WSGS}/\eta_{\mathrm{TRSGS}})$ is the amount of energy required by the staging system. The transfer efficiencies η_{TRSGF} and η_{TRSGS} for the fast and slow staging circuits are similar to those used for the IH system. Again WSGF and WSGS are from TPFPP. These and other parameters emanating from that code are listed and defined in Table I.

The capital cost for the compression energy storage system is

$$\mathrm{CAPITAL.CESC} = \mathrm{STORE.CESC} \times 10^{6} \cdot \mathrm{WB}, \qquad (2.2.4)$$

where WB is the amount of energy supplied to the compression coil.
All values herein are for one meter length around the major circumference of the plasma.

The blanket portion of the module consists of 100 segments containing layers of lithium coolant, graphite, and beryllium, encased in niobium with an electrica insulator between each segment (see Fig. 4). The capital cost of the

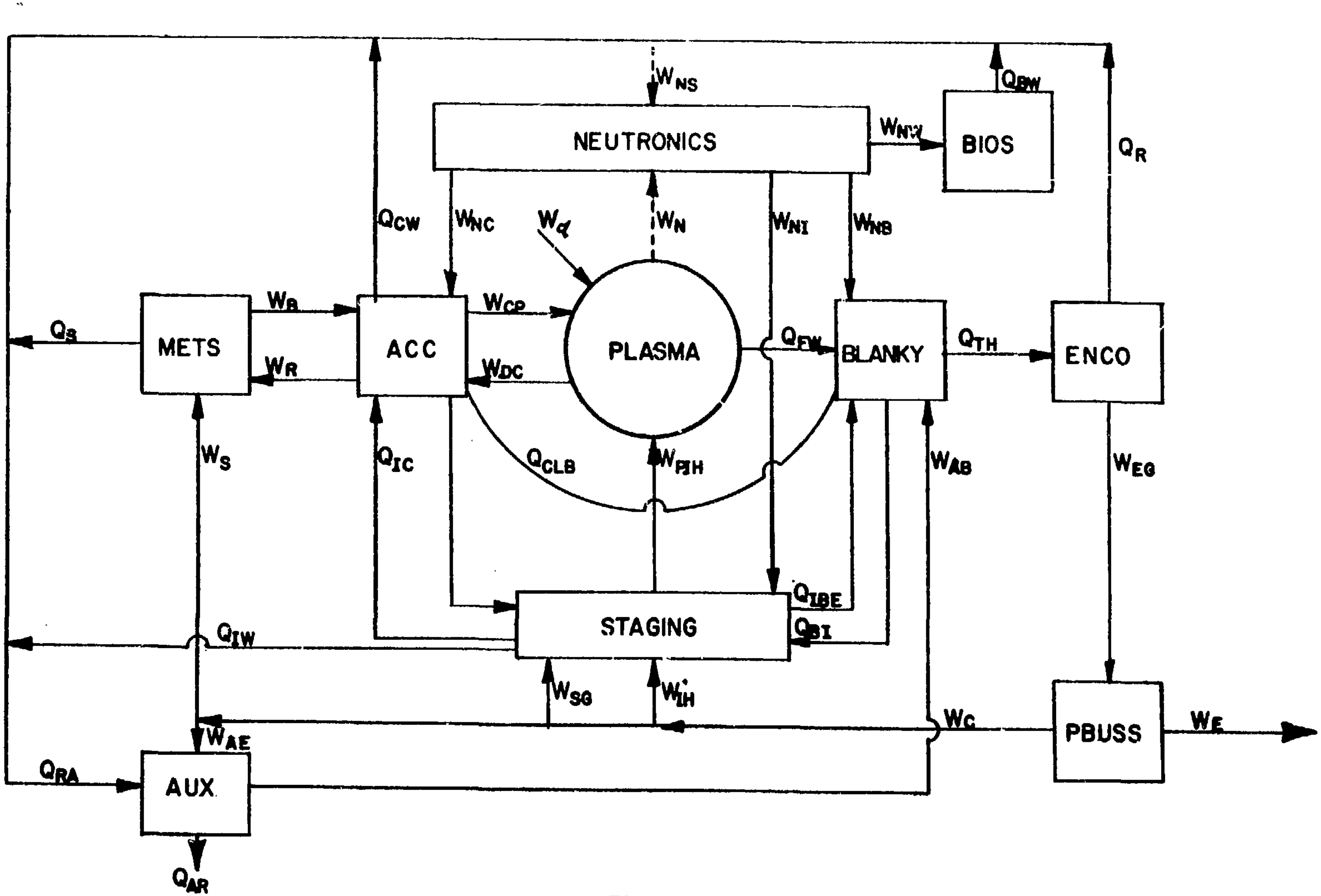

Fig. 3
Schematic showing energy balance

TABLE I. PARAMETERS FROM CODE TPFPP

Parameter	Definition
WIHF	IH energy, fast
WIHS	IH energy, slow
WSGF	Staging energy, fast
WSGS	Staging energy, slow
WB	Energy supplied to compression coil
B	First wall radius
R_{BO}	Outer radius of blanket
R_{CI}	Inner radius of compression coil
R_{CBAR}	Mean radius of the compression coil
DELRC	Thickness of compression coil
λ	Packing factor of compression coil
R_{MOD}	Radius of entire module
R_{TTR}	Radius of titanium ring
W_{EG}	Gross electrical energy produced by energy conversion system
τ_c	Time for one complete cycle
WE	Power produced per cycle
WALL-LOAD	Neutron loading on the wall
FLUENCE	Allowable time integral of neutron flux on blanket before it must be replaced

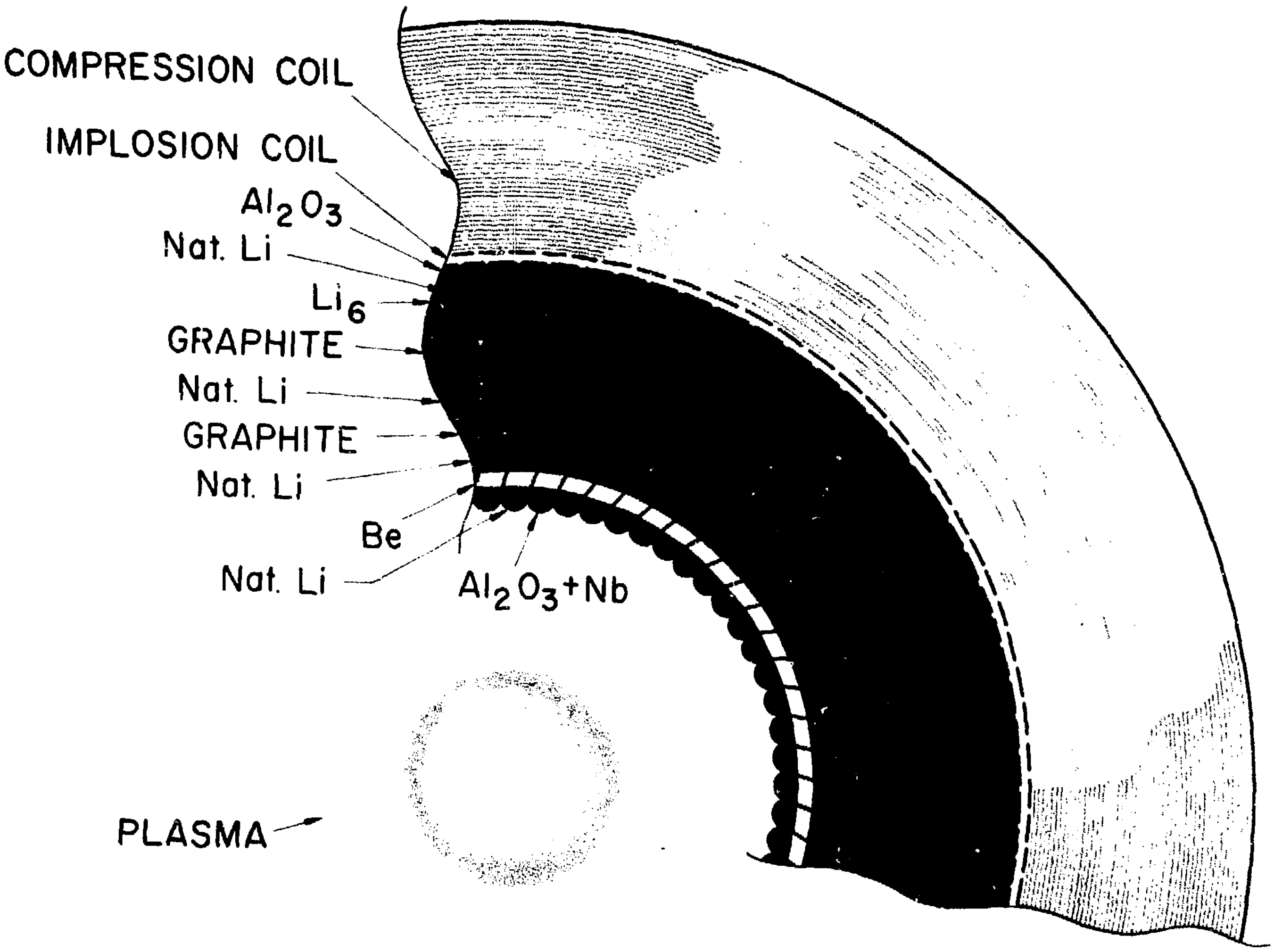

Fig. 4. Blanket portion of module

blanket can be calculated from the sum of the costs of the various materials used in it. The percentage of the total volume which a given material occupies was calculated from the data in Table B.5 in Ref. 1, reproduced here as Table II. The total cost of the blanket is a summation of the percentage - cost product for each component in RTPR times the total volume of the blanket, or

$$\mathrm{CAPITAL.BLKT} = \pi(R_{BO}^2 - B^2) \times (\mathrm{PRCNT} \times \mathrm{MATRL}) \times 100, \qquad (2.2.5)$$

where the quantity $\pi(R_{BO}^2 - B^2)$ is the volume of the blanket per unit length (one meter), including the thermal insulator between the blanket and the IH coil, PRCNT is the percent of the volume which that particular material occupies, and MATRL is the estimated fabricated cost of that material per unit volume. The 100 is used to indicate the length of blanket considered (100 cm).

The capital cost of the compression coil is

$$\mathrm{CAPITAL.CCOIL} = 2\pi\ \mathrm{RCBAR} \times \mathrm{DELRC} \times \lambda \times 100 \times \mathrm{MATRL.CCOIL}, \qquad (2.2.6)$$

where RCBAR is the mean radius of the compression coil, DELRC is the thickness of the coil, λ is the packing factor of the coil, and 100 converts centimeters to the meter length being considered.

The capital cost of the titanium ring, which supports the entire module assembly (CAPITAL.TIR), is

$$\mathrm{CAPITAL.TIR} = 100 \times \pi\ (R_{MOD}^2 - R_{TTR}^2) \times \mathrm{MATRL.TIR}, \qquad (2.2.7)$$

TABLE II. MATERIAL SUFFIXES AND COST

	% Composition in Blanket	Raw Prices $/lb	Total* Fabricated Cost	Estimated Cost $/cm^3	f. R
Al_2O_3-Aluminum Oxide	6.64	3.00	8.00	0.068	
BE -Beryllium	4.72	90.00	170.00	0.695	
G -Graphite	47.85	1.00	2.50	0.010	
CU -Copper	---	1.35	4.50	0.088	
LI -Lithium	23.14	15.00	---	0.017	
LI_6 -Enriched Lithium LI^6	14.28	450.00	---	0.52	
Nb -Niobium	3.37	60.00	100.00	1.89	
TI -Titanium	---	9.00	11.00	0.11	

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a) Information obtained from "Coors-Ceramic" approximate raw price 99.9% pure alumina, 1974.

b) "Materials Engineering" 1970 Raw Price x 1.25 escalation factor.

c) Information obtained from "Union Carbide" 74 reactor grade graphite blocks.

d) Wall Street Journal, April 1974 raw prices.

e) V. A. Maroni et al., "A Review of the Chemical, Physical and Thermal Properties of Lithium that are Related to its Use in Fusion Reactors," ANL Publication 8001, March 1973.

f) Estimated at 30 times cost of natural lithium.

* Differences between fabricated and raw material price are based on estimated complexity of machining, welding, etc. deemed necessary for fabrication and installation.

where the quantity $\pi(R_{MOD}^2 - R_{TTR}^2)$ is the volume of the titanium ring. The capital cost for the rest of the power plant is

$$\text{CAPITAL.REST} = \text{COST.KW} \times (\text{WEG}/\tau_c), \tag{2.2.8}$$

where WEG is the gross electrical energy produced by the energy conversion system and τ_c is the time for one complete cycle (see Ref. 2).

The total capital cost CAPITAL.TOTAL is the summation of the costs of the subsystem.

2.3 UNIT ENERGY COST

The actual cost of the energy must consider not only the capital cost but also the interest expenses, the depreciation during the lifetimes of the various systems, and the availability factor of the plant. For the subsystems with a long life, e.g., the staging and compression energy storage systems, the capital costs are assumed to be spread out or depreciated over a number of years; there is an associated interest expense for the money used to purchase them. The cost per year, which includes the interest expense and depreciation, is calculated from the following expression:

$$\text{INTRST(LIFE.XXXX)} = \frac{e^{iL}}{e^{iL}-1}, \tag{2.3.1}$$

which assumes that an equal number of payments are to be made over time, L, and instantaneous compounding of the interest at rate i (in this study, taken at 15 percent per year).

For the subsystems with a short life, no associated interest expense but only an operating cost was assumed, much like fuel costs in a fossil plant. The life of the implosion heating capacitors was estimated in pulses, so cost per kWh is the capital cost of the capacitors divided by the energy produced during the life of the capacitor:

$$\mathrm{KWH.IHES} = \frac{\mathrm{CAPITAL.IHES} \times 3600}{\mathrm{WE} \times \mathrm{CAPLIFE} \times 1000}, \tag{2.3.2}$$

where WE is the electrical energy produced by the plant per cycle (pulse), CAPLIFE is the life of the capacitor in pulses, and 3600/1000 is a unit conversion factor.

The life of the blanket, assumed to be short, was estimated in terms of the maximum neutron fluence which it can absorb before it must be replaced. The neutron fluence is assumed to be independent of the net energy production rate. The cost per kWh of the blanket is simply the cost of the blanket divided by the energy produced during the lifetime of the blanket.

$$\mathrm{KWH.BLKT} = \frac{\mathrm{CAPITAL.BLKT} \times \mathrm{WALL\text{-}LOAD} \times \tau_c}{\mathrm{WE} \times \mathrm{FLUENCE} \times 1000 \times 8776}, \tag{2.3.3}$$

where WALL-LOAD is the neutron loading on the wall, WE is the energy produced per cycle, and FLUENCE is the allowable time integral of the neutron flux on the blanket before it must be replaced. Wall load and fluence are expressed in terms of power per unit area of 14.1 MeV neutrons, e.g., $\mathrm{MW/m^2}$ and $\mathrm{MW\text{-}yr/m^2}$ respectively.

The availability of the theta-pinch power plant was assumed to be equal to that of a conventional power plant except for the down time required to change the blanket τ_{CHANGE}:

$$\mathrm{AVAIL} = \left[\frac{\mathrm{FLUENCE}}{\mathrm{FLUENCE} + (\tau_{\mathrm{CHANGE}})(\mathrm{WALL\text{-}LOAD})}\right] - 0.1, \tag{2.3.4}$$

where the quantity (0.1) accounts for unavailability of a conventional power plant and (WALL-LOAD)(τ_{CHANGE}) for the down time for replacing the blanket. The costs per kWh of the subsystems with long lifetimes are calculated by dividing the cost per year by the energy produced per year:

$$\text{KWH.XXXX} = \frac{\text{CAPITAL.XXXX} \times \text{INTRST} \times (\text{LIFE.XXXX})}{\text{WE} \times \text{AVAIL} \times 1000 \times 8776} \times \tau_c, \qquad (2.3.5)$$

where the quantity CAPITAL.XXXX is the cost of subsystem XXX per year and the quantity (WE × AVAIL × 1000 × 8776) is the energy produced per year.

The total cost of the energy produced, KWH.TOTAL, is the sum of the subsystems costs.

3. NUMERICAL RESULTS

3.1 ACCUMULATION OF COSTING DATA

Although the preceding sections have outlined a method for estimating electricity costs from a theta-pinch power plant, numerical results require specific values for unit costs, estimated lifetimes, interest expense, etc. At the present state of technology, these values cannot be obtained without ambiguity. Some of the components do not now exist, and considerable development work will be needed before designs are sufficiently stabilized to make a cost estimation. Other items are relatively simple modifications of existing components, but their cost is escalating so rapidly that a valid estimate today may be tens of percent low in a few weeks. Thus, the numerical values must not be considered accurate in an absolute sense; they are merely represented of the type of costs which could be experienced and are useful for trend indication.

Table III lists some values used for the first cost estimates. For items which do not deteriorate rapidly due to some unusual stress, e.g., neutron radiation damage or electrical or mechanical stresses, a lifetime of 25 years was chosen. Items such as the blanket and compression coil which are exposed to radiation damage were assigned to relatively optimistic lifetime, with the intent of investigating shorter times. Currently the extent to which the radiation damage limits the lifetime is not known. However, if some technique of mitigating the damage could be found, higher fluences could be allowed.

Another factor bearing on the lifetimes, but not yet included in the estimate, is the cost of disposal or storage of radioactive wastes. The amount of radioactive material handled will depend on the lifetime of the exposed components and could be an overwhelming factor in cost determination.

Costs of the energy storage devices have been taken from references as shown and are subject to radical changes as technology progresses. Installation costs for the components and the switches are lumped in the energy cost since it is not believed useful at this time to attempt to consider these items separately.

Aside from the energy storage systems and their associated components, the next most difficult item to cost estimate is the blanket. This is particularly true for a blanket composed of refractory and rather exotic materials usually fabricated in experimental lots and not by mass production and automated techniques. Attempts were made to break the cost of the blanket into raw material and material-forming costs (e.g., rolling, swaging, and finish machining and welding). However, so many uncertainties resulted that instead an estimate was made based on cost per fabricated pound. This was further reduced to cost per unit volume to be more convenient in the computer code. The estimated values are shown in Table II.

3.2 METHOD OF CALCULATION

The computer code TPFPP was used with this cost subprogram and the basic impact of many design parameters. It was found early that the magnetic field, minor first wall radius, and plasma maximum compression could be varied independently. Thus the results of each design variation include simultaneous variation of these three parameters. However, since visualization of graphs in more than three dimensions is extremely difficult, only illustrative results are shown. A "base" design (near the RTPR) is used, and one parameter is varied at a time to show the sensitivity of the cost to that parametric variation.

TABLE III. SUBSYSTEMS SUFFIXES FOR THETA-PINCH POWER PLANT AND ESTIMATED VALUES

		Unit Cost	Est. Life
BLKT	Blanket(fluence)	---	30Mw.yr/m^2
CCOIL	Compression Coil	---	12 yr.
CESC	Compression Energy Storage System	0.009\$/J[a]	25 yr.
IHES	Implosion Heating Energy Storage	.28\$/J[b]	3.14x10^7 pulses[b]
REST	The "Rest" of the Power Plant (cost/kW)	250/kW[c]	25 yr.
STES	Staging Energy Storage System	.10\$/J	10 yr.
TIR	Titanium Support Ring	---	25 yr.

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[a] Westinghouse Report No. EM-4620 (Ref. 7).

[b] Private communication, Paul Hoffman, Maxwell Industries, San Diego, Calif.

[c] \$250/kW approximate cost of building fossil plants without associated fuel handling and boiler costs; it also approximates cost of fission power plants without the reactor and its associated systems. This value represents 1972 costs.

4. DISCUSSION

To date, the theta-pinch fusion power plant code (TPFPP) has been used to obtain first order estimates of electricity from such a plant. It was the intent of this work to begin on a rather low level (see Ref. 3) and increase the complexity of the subsystems simulations as the need for this sophistication was determined. As a result, some of the subsystems are explored and simulated in a relatively detailed fashion, while others less critical to the plant operation or costs are studied in less detail. Consequently, the costs estimated are accurate to only one significant figure (at best), and second-order effects are ignored. Later, more detail will be added to obtain better cost estimates and determine other development objectives.

Parameter sweeps have been made so far on: magnetic field, 80 to 140 kG; minor radius, 20 to 80 cm; maximum plasma compression, 0.2 to 0.4; module change time, 8 to 80 hours; allowable fluence of 14.1 MeV neutrons, 1 to 50 MW-yr/m^2; wall load 1 to 10 MW/m^2; annulus thickness between the implosion and compression coil, 1 to 15 cm; blanket thickness, 10 to 100 cm; and plasma burn time, 40 to 160 msec. In addition to these parameter sweeps, effects of variation of constants (e.g., component lifetime, switch resistances, costs of energy storage, staging types, etc.) were also examined. Typical results obtained are illustrated in Fig. 5. Costs per kilowatt hour are given in arbitrary units. Use of cents or mils would lead to more confusion and argument than constructive criticism.

Here the cost of energy from the plant per kilowatt/hour is shown as a function of the maximum magnetic field in the cycle. This is the only parameter investigated so far which shows a minimum. The implosion energy and module costs are highest at low values of magnetic field. Thus, if the costs of implosion energy storage have been underestimated, for instance, the minimum energy costs would occur at higher magnetic field.

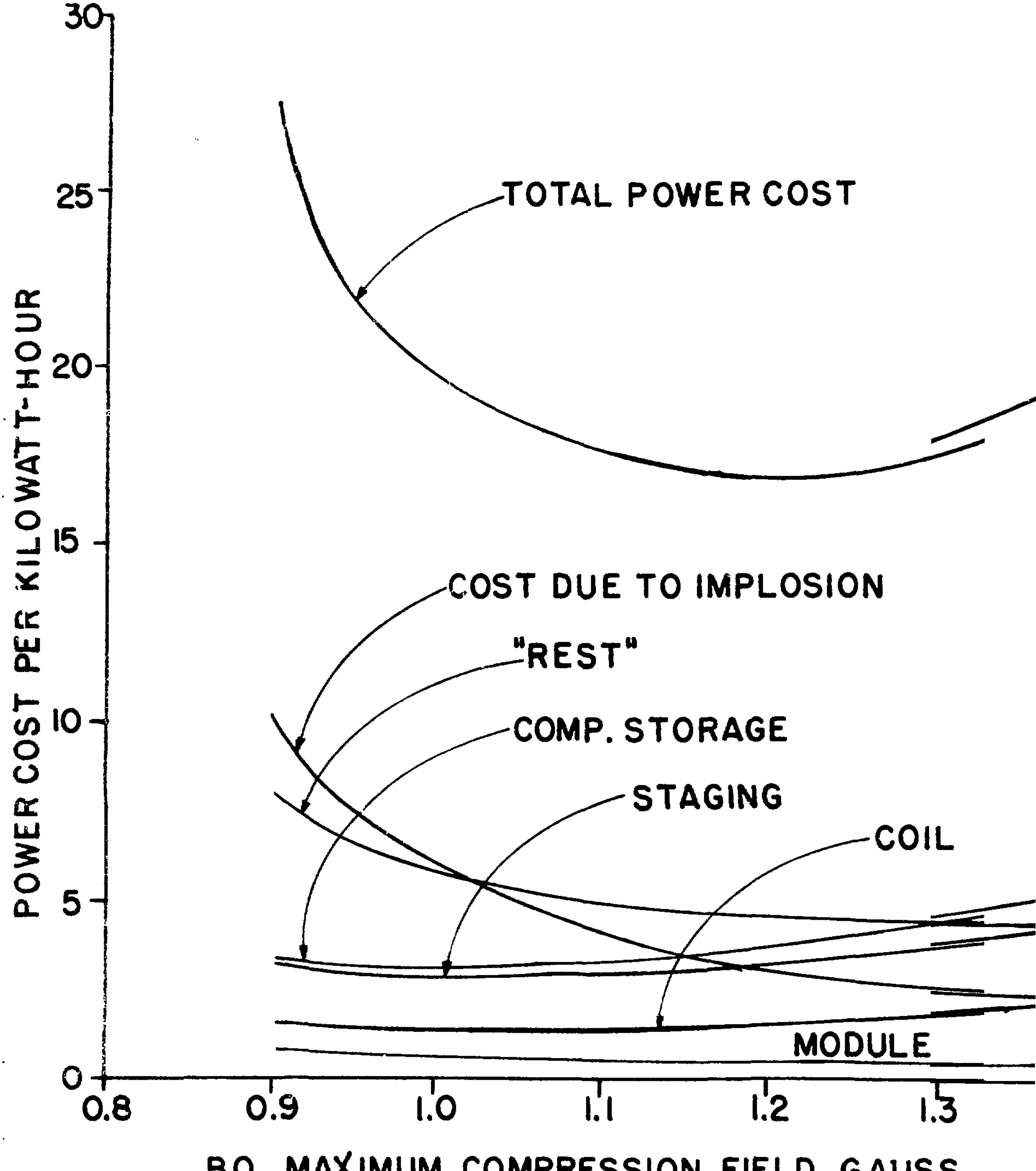

Fig. 5

Power Cost as a Function of Magnetic Field

Conversely, the highest cost vectors at high magnetic fields are the cost of compression energy storage and coil components. Thus if those costs have been underestimated, the desired field would be less. Another, perhaps even more significant observation from Fig. 5 is that there is no overwhelming cost vector. One might conclude that errors in cost estimations in a particular vector will have a small effect on the overall cost. Such a judgment may, however, prove to be premature.

5. RESULTS

5.1 EXPECTED RESULTS

From the preceding equations it can be seen at a glance that if one wishes to generate electricity economically, the net energy produced and the availability must be high. These observations are not new. For instance, it is popular to talk of "Q" of a power plant. Depending upon the definition of that "Q", it somehow involves the terms of net and gross electrical power produced. Generally, the higher the "Q", the higher the ratio of net to gross electrical power. Availability has usually been considered as a constraint. Below some arbitrary value, generally 80-90 percent, the plant is not "attractive."

At first, this study used similar "figure-of-merit" terms to ascertain the effect of various design changes and parameter values. It was determined, however, that these "figure-of-merit" definitions were not sufficiently general. This led to considering "cost per kWh." Although suffering from inaccuracy and incompleteness (externalities were not considered), it becomes a much better "figure-of-merit" than "Q," availability, recirculated power, etc.

It was found that it was very easy to pick a set of parameters leading to exorbitant electricity cost. At low (<80 kG) magnetic fields, small (<30 cm) minor radius, and short (<50 msec) burn times the plant often did not produce net energy, leading to infinite electricity cost. This effect is shown graphically in Fig. 5 as total power costs sweep up to the left. It was also found that it was quite simple to obtain unattractive power costs, even with a good energy balance. This occurs with pessimistic cost or lifetime estimates. For instance, using present day motor-generator sets for compression energy storage between reactor pulses leads to very high electricity costs because of the huge capital investment required. Similarly, if capacitor lifetime is taken at $10^3 - 10^4$ pulses (typical of Scylla capacitors), the "operating costs" for implosion heating energy supply are exorbitant. Finally, if a straightforward, "brute-force"[4] method of implosion/staging is used, the energy losses and power supply costs are very high. This occurs primarily at large values of ultimate plasma radius. At lower values used in the reference design, these losses were not unreasonable.

5.2 UNUSUAL RESULTS

The very steep dependence of implosion/staging energy requirements upon ultimate plasma compression is due to the split between implosion and compression energy. This factor is discussed in more detail in Ref. 4. Although an economic analysis is not needed to illustrate this shift of energy requirements, the parameter variation study vividly points it out.

Not totally unexpected is the effect of wall loading. The energy flux to the first wall is, of course, dependent upon the energy density in the fusion plasma and also dependent (for the theta pinch) upon the pulsing rate. Intuitively it seems that if one has an expensive plant, it is better to use it as much as possible (rapid pulsing) rather than allowing it to stand unused a large percentage of the time (slow pulsing). This intuitive feeling is borne out by the results of the economic study. The pulsing rate, and to some extent the energy density, has little influence upon "Q" or "availability," but it has a large effect upon the cost of electricity from the plant.

Lastly, it was found that fluence of 14 MeV neutrons, by itself, had little effect upon the estimated cost of power from the plant. Fluence did affect the "operating" cost of first-wall/blanket material replacement, but, as noted, the blanket replacement cost is a small portion of the total cost of electricity from the plant. The major effect of fluence was seen in the availability factor. In this case, the fluence does not enter independently but is combined with the time to change. If the ratio of fluence to tau change, i.e., the allowable accumulated first wall load in MW-yr/m^2 (fluence) divided by years to change the entire plant first wall (time to change), is less than about 16, the plant availability is so poor as to cause the cost of electricity to increase precipitously. This exact turning point depends upon the steady wall-loading of the plant, of course, and can be expressed as availability. Thus, one of the "unexpected" results is really an old constraint in disguise. For these conditions, availabilities less than about 60 percent result in expensive electricity from the plant. This result will probably also apply to fusion reactor concepts other than theta pinch. Nevertheless, it must be noted that the complex inter-relation between effects of fluence, time to change the modules, and wall load (the factors in availability) can change that acceptable availability number drastically. Thus, the conclusion that availabilities must be greater than 60 percent is not only premature but is confirmed by only one set of plant operating parameters.

6. CONS[illegible]

The value of this work is not so much in showing that the cost of electricity from a theta-pinch plant is 20 or 2 mil/kWh, for that number is subject to vast uncertainty. Instead, its value is in showing the parameters which can cause electricity costs to skyrocket. Perhaps even more important than illustrating features responsible for large costs is providing an incentive to find alternatives. A classic example is the concept of the first-wall liner: in one case (Ref. 5), to allow larger wall loads without undue thermal stress, and in another (Ref. 6), to allow higher fluences before structural materials must be replaced. Neither concept was prodded by this parametric cost estimate directly, but they illustrate how problems once illuminated can be solved, at least conceptually, by imaginative action.

This study was responsible for pointing out that if good economy and high plant availability are to be obtained, means for rapid changing of the irradiated blanket materials must be found. The numerical value for acceptable availability and acceptable replacement time is highly dependent upon other plant parameters, but the more rapid the replacement can be made, the more economical the plant will be.

Also, the interaction of allowable plasma compression and the split between compression and implosion energy is well known. As the effects of fat plasma were quantified by analysis, however, they provided impetus to finding imaginative solutions to the large implosion energy required. These solutions are discussed in Ref. 4. At least two methods seem feasible and useful for decreasing the implosion energy need.

The implosion/staging energy requirement is still high, however, if ultimate compressions of only 0.35 to 0.4 can be used, and further reductions are needed. One method would stabilize the plasma at smaller ultimate radius, on the order of 0.2 to 0.25. This is being pursued now at LASL in

7. CONCLUSIONS

The first estimated power costs using a parametric systems analysis of the theta-pinch fusion concept have been obtained. Although much work is needed to reduce the costing uncertainties, consider subsystems in more detail, and pursue other subsystem concepts, the first results have indicated that some parameters have a large influence upon the cost of the power from a fusion plant. Thus, effort has been and will be devoted to those subsystems which seem to be most important to the cost of electricity.

The results have also shown the continued need to increase plant availability, decrease recirculated energy in the plant, and find methods to allow long useful materials lifetimes in a fusion environment. They also show, however, that some problems can be circumvented by new concepts or alleviated by changes in the operating regime and various plant design details. Methods for easy and rapid replacement of reactor components should become a major development objective. Furthermore, for the theta pinch, ways must be found to stabilize the toroidal plasma, particularly at small ultimate diameter, and to implode or preheat the plasma more efficiently before final isentropic compression to ignition. Finally, continued work is required on all reactor concepts to examine initial subsystems in more detail and to explore less obviously critical ones to assure that some decisive factor has not been overlooked.

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