LA-UR 76-1203

TITLE: ENERGY STORAGE AND TRANSFER WITH HOMOPOLAR MACHINE FOR A LINEAR THETA-PINCH HYBRID REACTOR

AUTHOR(S):
H. F. Vogel
M. Brennan*
W. G. Dase*
K. M. Tolk*
W. F. Weldon*

SUBMITTED TO: 9th Symposium on Fusion Technology
Garmisch-Partenkirchen
Federal Republic of Germany
June 14-18, 1976

*University of Texas, College of Engineering, Austin, TX 78712

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

Form No. [illegible]
St. No. [illegible]
1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

F. Vogel

ENERGY STORAGE AND TRANSFER WITH HOMOPOLAR MACHINE FOR A LINEAR THETA-PINCH HYBRID REACTOR

by

H. F. Vogel
Los Alamos Scientific Laboratory, Los Alamos, NM 87545

M. Brennan, W. G. Dase, K. M. Tolk, and W. F. Weldon
University of Texas at Austin, TX 78712

ABSTRACT

This paper describes the energy storage and transfer system for the compression coils of a linear theta-pinch hybrid reactor (LTPHR). High efficiency and low cost are the principal requirements for the energy storage and transfer of 25 MJ/m or 25 GJ for a 1-km LTPHR. The circuit efficiency must be ~90%, and the cost for the circuit 5-6 ¢/J. Scaling laws and simple relationships between circuit efficiency and cost-per-unit energy as a function of the half cycle time are presented.

An important consideration concerns the pulse repetition rate of 2.25 pulses per second, 70 x 10^6 shots/yr, or 1.7 x 10^9 shots over the 25-yr plant life. Current interruption to initiate energy transfer is not feasible at this rate. We consider, therefore, a simple ringing circuit with contactors to make and break at the periodically occurring zero-current instances.

I. INTRODUCTION

Next generation large fusion devices are of such a size that new technologies are needed to meet the requirements for the delivery of pulsed energy: The ohmic heating coil of the Tokamak experimental power reactor (EPR) requires transfer of a few GJ within 0.5 to 2 s at a repetition rate of one shot every few minutes. The toroidal reference theta-pinch reactor (RTPR) requires 60 GJ delivered in 30 ms at a repetition rate of 1 shot every 10 s. A 1-km linear theta-pinch hybrid reactor (LTPHR) requires the delivery of 25 GJ in 2 to 3 ms at a repetition rate corresponding to 0.4 s per shot. Gas laser flash lamp supplies require delivery of 10 MJ in 0.2 to 1 ms at a repetition rate of 1 to 10 pulses/second.

A design study of the homopolar energy storage and transfer system (HETS) for the RTPR was completed by a group from the University of Texas at Austin, Westinghouse Electric Corp., and Los Alamos under the auspices of the Electric Power Research Institute. The conceptual design of a 1.3-GJ homopolar HETS evolved from this work.[1] The design of a scaled 10-MJ homopolar machine is presently being undertaken by that group. Construction of the 10-MJ machine at Westinghouse with delivery by mid-1979 and a test facility at Los Alamos for homopolar machines and related switchgear are planned.

The design study for the LTPHR[2] reported in this paper is based on the experience gained from the RTPR design study and from the design and construction of a 150-kJ, 1.2-ms

ABSTRACT

This paper describes the energy storage and transfer system for the compression coils of a linear theta-pinch hybrid reactor (LTPHR). High efficiency and low cost are the principal requirements for the energy storage and transfer of 25 MJ/m or 25 GJ for a 1-km LTPHR. The circuit efficiency must be ~90%, and the cost for the circuit 5-6 ¢/J. Scaling laws and simple relationships between circuit efficiency and cost-per-unit energy as a function of the half cycle time are presented.

An important consideration concerns the pulse repetition rate of 2.25 pulses per second, 70 x 10^6 shots/yr, or 1.7 x 10^9 shots over the 25-yr plant life. Current interruption to initiate energy transfer is not feasible at this rate. We consider, therefore, a simple ringing circuit with contactors to make and break at the periodically occurring zero-current instances.

. INTRODUCTION

Next generation large fusion devices are of such a size that new technologies are needed o meet the requirements for the delivery of pulsed energy: The ohmic heating coil of the okamak experimental power reactor (EPR) requires transfer of a few GJ within 0.5 to 2 s at a epetition rate of one shot every few minutes. The toroidal reference theta-pinch reactor RTPR) requires 60 GJ delivered in 30 ms at a repetition rate of 1 shot every 10 s. A 1-km inear theta-pinch hybrid reactor (LTPHR) requires the delivery of 25 GJ in 2 to 3 ms at a epetition rate corresponding to 0.4 s per shot. Gas laser flash lamp supplies require delivery of 10 MJ in 0.2 to 1 ms at a repetition rate of 1 to 10 pulses/second.

A design study of the homopolar energy storage and transfer system (HETS) for the RTPR as completed by a group from the University of Texas at Austin, Westinghouse Electric Corp., nd Los Alamos under the auspices of the Electric Power Research Institute. The conceptual esign of a 1.3-GJ homopolar HETS evolved from this work.[1] The design of a scaled 10-MJ omopolar machine is presently being undertaken by that group. Construction of the 10-MJ hine at Westinghouse with delivery by mid-1979 and a test facility at Los Alamos for homopolar machines and related switchgear are planned.

The design study for the LTPHR[2] reported in this paper is based on the experience ained from the RTPR design study and from the design and construction of a 150-kJ, 1.2-ms ischarge machine at the University of Texas at Austin.

Considerations of fundamental importance are concerned with endurance requirements, circuit efficiency, and cost. The 1.3-GJ HETS, for example, has been designed for 80 x 10^6 hots over a 25-year plant life, 95% circuit efficiency per cycle, and 1 ¢/J. The latter was ased on the premise of an existing mass production experience. The LTPHR system described in this paper requires 1.7 x 10^9 shots over a 25-year plant life, ~90% circuit efficiency per cycle, and 5.6 ¢/J. For the latter, a hundred production units of the homopolar machine are assumed.

We consider a simple ringing circuit with contactors to make and break at the periodically occurring zero-current instances. Even this simple operation will require considerable development effort for an inexpensive and reliable contactor that may be replaced during annual plant maintenance.

We consider capacitors and homopolar machines as energy storage elements with both functioning basically as capacitors. The advantage of the homopolar machine in this application is its relatively low cost, whereas that of capacitors is better efficiency.

The drum-type homopolar machine is best for endurance considerations and it was therefore chosen for the HETS and its 10-MJ scale model. These machines use spokes to support the drum from inner oil journal bearings. The spokes require considerable material development whose results will not be available for the scale model machine. The latter is designed, therefore, with disks instead of spokes. The disks unfortunately prevent convenient brush access.

For the LTPHR system with its extremely severe endurance requirement, the spokes have been eliminated in favor of outer bearings. The benefit of brush access has thus been realized. Gas is required as the bearing lubricant because of the conflicting requirements of low loss on one hand and the large diameter of the outer bearing housing accommodating the drum rotor on the other.

The severe endurance requirements result from the 1.7 x 10^9 shots over the 25-year plant life and the fast acceleration which the spokes of the 2-3 ms discharge machine would be exposed to, as compared to those of the 30-ms HETS machine.

II. EFFICIENCY AND COST REQUIREMENTS

The total plant cost is not to exceed 1000 \$/kWe. If 90% of this cost is needed for plant components other than the compression coil capacitor bank, then the capacitor bank should not exceed a cost limit per unit stored energy of 5.3 ¢/J.

These numbers may serve as guidelines, but need existed for an efficiency-vs-cost relationship useful for optimizing the overall LTPHR system. Such a relationship is given in this paper.

For the given pulse rate, we consider only the simplest type circuit requiring no current interruption which is shown in Fig. 1. With capacitors, we assume a circuit efficiency of 94% and 14 ¢/J. Overall system analysis is required to determine whether homopolar machines or capacitors best serve the requirements of the LTPHR.

III. HOMOPOLAR MACHINE OPERATING PRINCIPLE

Operation of the homopolar machines is based on the induction principle. The equivalent capacitance of the machine is given by

$$C = \Theta \left(\frac{\omega}{V_o}\right)^2 \quad , \qquad \text{eq. (1)}$$

where Θ is the moment of inertia of the rotor, ω the angular frequency, and V_o the no-load

MACHINE TOPOLOGY CONSIDERATIONS

Figure 2 illustrates the topological configurations that have been considered for fast-discharging homopolar machines. The relative merits of these topologies are discussed in Ref. 2.

The relative advantages of the spool (Fig. 2c–d) and drum (Fig. 2e–f) configurations can best be summarized as follows:

- The drum configuration has the potential of minimum internal impedance and maximum endurance strength;
- The disk and spool configurations have the potential for maximum flux linkage.

The drum type has therefore been chosen for the LTPH application.

FLUX AND EXCITATION SCALING

The proportions of coil and iron have empirically been optimized to within a few percent of an apparent optimum. The coil's inner radius was kept constant at r_6 = 118 cm, whereas the ratio of iron length to coil length and the total sector length were varied. We assumed that the coil was enclosed in a toroidal dewar with 2.5-cm wall thickness.

The optimized set of linear proportions (in cm) as shown in Fig. 3 follows.

$r_6 = 118$ $r_{7'} = 170$ $w = 18$ $\ell_7 = 109$ $\ell_6 = 113$ $\ell = 228$ $r_7 = 136$

The variable in the scaling problem for system optimization is the linear scaling factor operating on all linear dimensions.

We denote the reference dimensions by the subscript 0 and define ϕ = flux effective at collector radius, B = maximum flux density in the coil. By equating excitation ampere-turns with flux ϕ and with maximum flux density B by way of the scaling factor λ, and relating flux density B to current density J for a NbTi conductor[3] with copper area to superconductor area ratio 2.9, the following relationships are obtained.

$$\frac{B}{B_0} = 1 - \frac{\bar{B}}{B_0}\,\ln\left|\frac{1}{\lambda}\,\frac{B}{B_0}\right| \quad \text{and}$$

$$\frac{\phi}{\phi_0} = \lambda^2\,\frac{B}{B_0} \qquad \text{eq. (2)}$$

where $\bar{B}$ = 4.4T as shown in Ref. 2.

For a given scaling factor λ, the flux density B is thus uniquely determined by the first part of Eq. (2), and ϕ by the second part.

For a given scaling factor λ, the flux linked by a rotor with collector surface radius r_8 varies like $\phi \propto r_8^{2.33}$ as shown in Ref. 2.

The voltage maximum obtained when the machine operates as a capacitor equivalent in an L-C energy transfer circuit with angular rotor frequency ω and with n rotors connected in series is therefore given by

$$V_0 = n\,\frac{\omega}{2\pi}\,\lambda^2\,\phi_0\left(\frac{r_8}{\lambda r_{80}}\right)^{2.33} \qquad \text{eq. (3)}$$

where ϕ_0 = 36.3 Wb.

The circuit equations are given in Ref. 2. The voltage drop per brush is assumed to be .8 V. Ten percent was added to the compression coil inductance and resistance to account

The circuit efficiency is given by the voltage reversal rate squared. The coasting losses are to be added to the circuit loss; these consist of brush friction loss, bearing loss, refrigeration loss, and charging loss to yield the total loss per pulse cycle.

The loss equations and the electrical and mechanical design equations have been developed in Ref. 2 where they are discussed. Some of the discussions are crucial for the conceptual design of a fast-discharge machine with low loss and high endurance. These topics are concerned with

- the stresses in a drum rotor reinforced with a composite wrap;
- the losses in gas bearings of the hydrostatic and hydrodynamic types;
- the brush actuating mechanism and friction loss.

Gas bearings of the proposed type require development because no experience exists presently with hydrodynamic gas bearings operating in the turbulent flow regime (for sufficient rotor cooling) with the rotor spinning at a surface speed of approximately 280 m/s, although this operating regime and the speed are known to have been studied separately.

Economic reasons require that for short discharge times many LTPHR compression coils must be connected in parallel to a multisection homopolar machine, which may result in several megamperes of discharge current. Double compensation will then be required to limit the radial electrodynamic load between the return conductors and the drum. More than half the current will return through the inner return conductor and the balance will return through the additional coaxial path in the space between coil and drum as shown in Fig. 3.

VI. COST EQUATIONS

The following cost formula appears to be realistic for the production of a hundred homopolar machines:

$$\$_{tot} = \Big[1.2\ nM_{Fe}\ \$_{Fe} + nM_C\ \$_C + nA_B \$_B + nM_{coil}\ \$_{coil} + nV_{He}\ \$_{He} + n\ell_m (IN)\ \$_{SC} + (nP_{ref})^{0.7}\ \$_{ref} + n\lambda^2\ \$_{dewar}\Big] \quad \text{eq. (4)}$$

where

M_{Fe}	= iron weight		
M_C	= weight of drums and return conductors		
A_B	= brush-to-collector contact area		
M_{coil}	= weight of stabilized superconductor (i.e., 0.4 x coil volume x 8.9 g/cm^3)		
V_{He}	= volume of liquid helium inventory (i.e., 0.6 x coil volume)		
(IN)	= excitation ampere-turns		
ℓ_m	= mean turn length		
λ	= scaling factor		
n	= number of machine sections in series		
$\$_{Fe}$	= 1.59 $/kg	(stator iron)	
$\$_C$	= 9.0 $/kg	(return conductor and drum)	
$\$_B$	= 4.80 $/cm^2	(brush system)	

- the losses in gas bearings of the hydrostatic and hydrodynamic types,
- the brush actuating mechanism and friction loss.

Gas bearings of the proposed type require development because no experience exists presently with hydrodynamic gas bearings operating in the turbulent flow regime (for sufficient rotor cooling) with the rotor spinning at a surface speed of approximately 280 m/s, although this operating regime and the speed are known to have been studied separately.

Economic reasons require that for short discharge times many LTPHR compression coils must be connected in parallel to a multisection homopolar machine, which may result in several megamperes of discharge current. Double compensation will then be required to limit the radial electrodynamic load between the return conductors and the drum. More than half the current will return through the inner return conductor and the balance will return through the additional coaxial path in the space between coil and drum as shown in Fig. 3.

VI. COST EQUATIONS

The following cost formula appears to be realistic for the production of a hundred homopolar machines:

$$\$_{tot} = \Big[1.2\ nM_{Fe}\ \$_{Fe} + nM_C\ \$_C + nA_B \$_B + nM_{coil}\ \$_{coil} + nV_{He}\ \$_{He} + n\ell_m (IN)\ \$_{SC} + (nP_{ref})^{0.7}\ \$_{ref} + n\lambda^2\ \$_{dewar}\Big] \quad \text{eq. (4)}$$

where
- M_{Fe} = iron weight
- M_C = weight of drums and return conductors
- A_B = brush-to-collector contact area
- M_{coil} = weight of stabilized superconductor (i.e., 0.4 x coil volume x 8.9 g/cm^3)
- V_{He} = volume of liquid helium inventory (i.e., 0.6 x coil volume)
- (IN) = excitation ampere-turns
- ℓ_m = mean turn length
- λ = scaling factor
- n = number of machine sections in series
- $\$_{Fe}$ = 1.59 \$/kg (stator iron)
- $\$_C$ = 9.0 \$/kg (return conductor and drum)
- $\$_B$ = 4.80 \$/cm^2 (brush system)
- $\$_{coil}$ = 17.5 \$/kg (coil construction)
- $\$_{He}$ = 2.0 \$/ℓ (liquid helium inventory)
- $\$_{SC}$ = 0.00165 \$ $A^{-1}m^{-1}$ (0.5 mills/A-ft) (superconductor)
- $\$_{ref}$ = 8400 \$$W^{-0.7}$ (refrigerator cost)
- $\$_{dewar}$ = [illegible] \$ (dewar cost)

The factor 1.2 in Eq. (4) accounts for the assembly cost, which should be 1.25 in those cases where double compensation is required.

The refrigeration power is given elsewhere.[4] The cost rate $\$_{ref}$ is that given in Ref. 4, multiplied by a factor 1.2 for escalation.

VII. OPTIMIZATION

Figure 4 is a plot of circuit efficiency η vs cost rate c in c/J for N = 32, 36, and 40, $\tau_{\frac{1}{2}}$ = 3 ms, where the parameter n = 32 and 36. The plot shows that efficiency and cost rate increase with increasing radius.

The curves in Fig. 4 move up and to the left, indicating decreasing cost and increasing efficiency with increasing number of rotors (for a given number of parallel coils) to an optimum beyond which the trend reverses. Hence, with each N, there is associated an optimum n, and for this set of L_{coil}, R_{coil}, and I_{coil} values, the optimum $n_{opt} \approx N$.

The figure shows that a substantial number of coils must be paralleled for short discharge times, which may result in large currents requiring double compensation.

With each $\tau_{\frac{1}{2}}$ value a set (N n) is associated where $N \approx n = n_{opt}$ exists. This optimum characteristic fits within an error $a|\pm\epsilon_1| < 0.5\%$ the relationship

$$\eta = H_0 \left[1 - \exp\left(-c/K_0\right)\right] \qquad \text{eq. (5)}$$

The parameters H_0 and K_0 in Eq. (5) have been plotted in Fig. 5 for compression coils with 25 weber-turns each. The variable c is constrained to

$$1.5 \text{ to } 3.5 < c/K_0 < \sim 1.9 \text{ to } 15 \qquad \begin{array}{llll} 1.9 & \text{for } \tau_{\frac{1}{2}} = 1.5 \text{ ms} & 6 & \text{for } \tau_{\frac{1}{2}} = 5.0 \text{ ms} \\ 3 & \text{for } \tau_{\frac{1}{2}} = 2.0 \text{ ms} & 9 & \text{for } \tau_{\frac{1}{2}} = 10.0 \text{ ms} \\ 5 & \text{for } \tau_{\frac{1}{2}} = 3.0 \text{ ms} & 13 & \text{for } \tau_{\frac{1}{2}} = 30.0 \text{ ms} \end{array}$$

where the upper limit is set by the flux model. In other words, if c/K_0 increases beyond 2 to 15, then the flux density, which is scaled in accordance with the first part of Eq. (2), will exceed our arbitrary but practical limit of 8 T, as a result of $\lambda > 1.2$. The lower limit in the c/K_0 constraint corresponds to the minimum rotor radius for which structural stability in the drum-composite structure exists, with a 1.5 factor of safety. Optimization could be carried to $\lambda > 1.2$ if B is kept constant at 8 T; however, this was not done.

The loss and cost elements of one point design, i.e., one with $\ell_{cycle} = 0.9$, c = 4.84 ¢/J) are listed in Table I.

ACKNOWLEDGMENTS

Useful suggestions on the compression coil's design and structural analysis were contributed by R. Bartholomew. We had many worthwhile discussions with R. Krakowski, coordinator of the LTPHR study group, and with K. Thomassen, G. Boicourt, M. Kristiansen, F. Ribe, and H. H. Woodson. Ribe and Woodson were probably first to suggest that the compression coil energization might be possible with homopolar machines. Many contributions on gas bearings are from H. G. Rylander.

REFERENCES

[1] K. E. Thomassen, J. D. Rogers, D. M. Weldon, C. F. Swannack, H. F. Vogel, H. G. Rylander, W. F. Weldon, K. M. Tolk, M. D. Driga, W. L. Bird, Jr., H. H. Woodson, C. J. Mole, R. E. Stillwagon, "Pulsed Energy Storage in Fusion Devices," submitted to International Atomic Energy Agency (IAEA) 6th International Conference on Plasma Physics and Contr. Nucl. Fusion Res., Berchtesgaden, Federal Republic of Germany, Oct. 6-13, 1976.

[2] H. F. Vogel, M. Brennan, W. G. Dase, K. M. Tolk, and W. F. Weldon, "Energy Storage and Transfer with Homopolar Machine for a Linear Theta Pinch Hybrid Reactor," Los Alamos Scientific Laboratory Report LA-6174 (April 1976).

[3] Obtained by numerically fitting the tabulated characteristic, from Gundolf Meyer, "Supraleitende Kabel fuer Magnetspulen," Brown Boveri Mitt. No. 10/11 (Oct.-Nov. 1975), p. 491. (Engl. transl. in preparation in Brown Boveri Rev.)

[4] T. R. Strobridge, "Refrigeration for Superconducting and Cryogenic Systems," 1969 Particle Accelerator Conference, IEEE Trans. Nucl. Sci. p 1104.

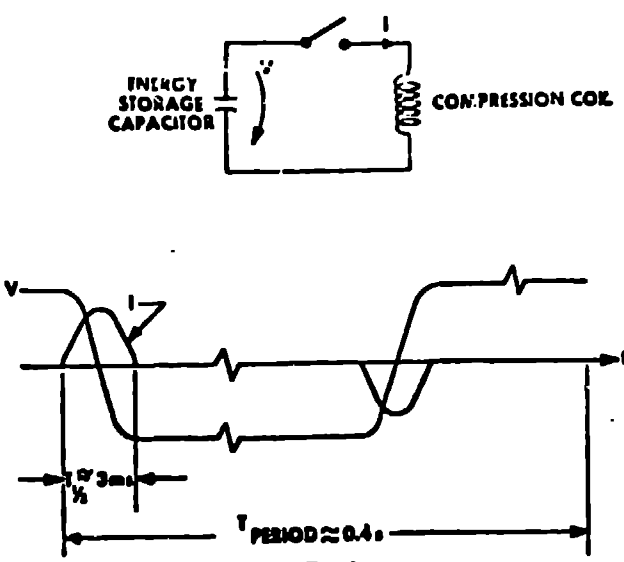

Figure 1

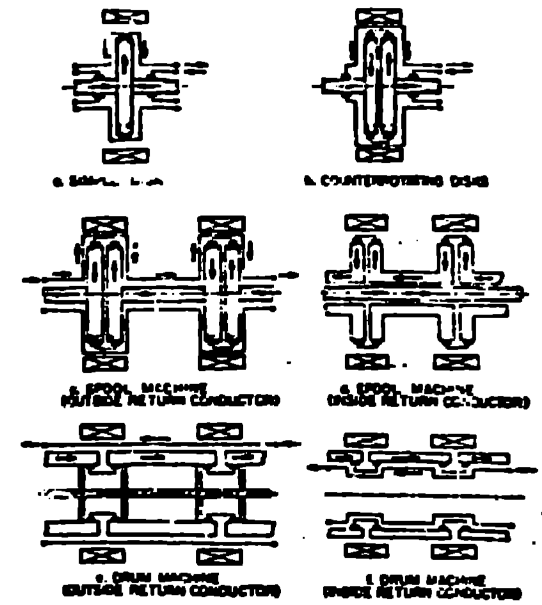

Figure 2

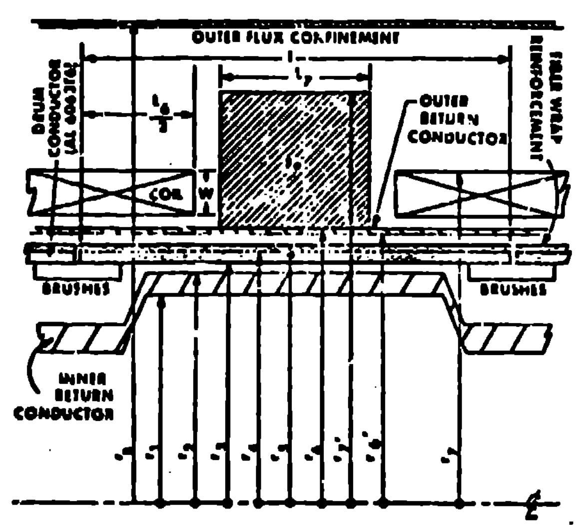

Figure 3

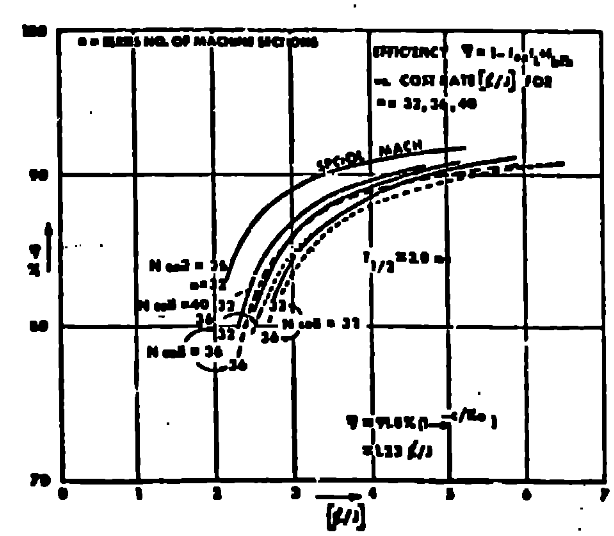

Figure 4

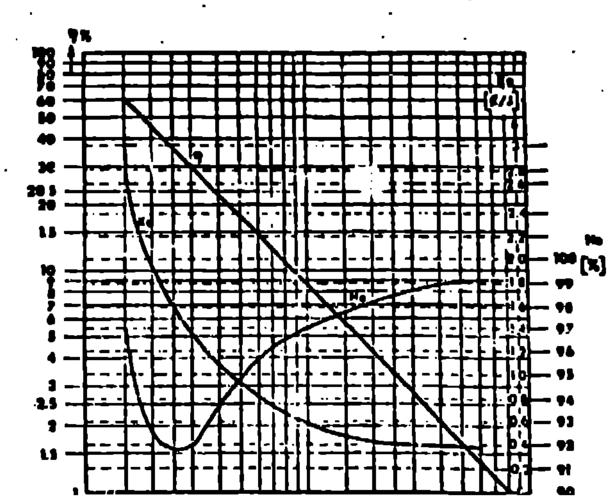

FIGURE CAPTIONS

Figure 1 Compression coil circuit

Figure 2 Alternative topological configurations for fast-discharging homopolar machines

Figure 3 Definition of dimensions for the drum-type machine with double compensation (i.e., inner and outer current return).

Figure 4 Efficiency $\eta = 1 - f_{ex} f_{L} + f_{blk}$ vs cost rate (¢/J) for number of parallel coils N = 32, 36, 40

Figure 5 Optimization characteristics

η = number of machine sections in series

H_0 = efficiency limit

K_0 = logarithmic cost decrement vs discharge time $\tau_{1/2}$

TABLE I

LOSS AND COST SUMMARY ON THE DESIGN FOR $\eta_{cycle} = 0.899$, $c = 4.84$ ¢/J,
$r_4 \approx 102.5$ cm, and $\lambda = 0.899$

Losses in Percent of $1/2\ CV_0^2$ for 0.4-s Pulse

Period	
Drum joule loss	5.8%
Return conductor joule loss	0.2
Brush joule loss (voltage drop)	0.6
Brush friction loss[a]	1.3
Bearing loss + windage loss	0.4
Refrigeration loss	0.02
Power supply loss (charging loss)	0.2
Compression coil loss	1.7
Total loss incl. compression coil	10.2%

Costs in Percent of Total Machine Cost

Iron $(nM_{Fe}\ \$_{Fe}/\$_{tot})$ =	12.3%
Supercond. coil $[n(m_{coil}\ \$_{coil} + V_{He}\ \$_{He} + \ell_m IN\$_{sc})\|\$_{tot}]$ =	44.4
Refrigeration $[(nP_{ref})^{0.7}\ \$_{ref} + n\lambda^2\$_{dewar}]\|\$_{tot}$ =	3.4
Return conductor, drum $(nM_c\ \$_c\|\$_{tot})$ =	6.2
Current collection $(nA_B\$_B\|\$_{tot})$ =	17.4
Assembly (1 - 1/1.2) =	16.4
Total machine cost $\$_{tot}$ = 12.4 M$	100%

[a]Assuming that the brushes make contact for 9 ms at an average pressure of 0.7 bar superposed with an electrodynamic load peaking at 8 bar.

ENERGY STORAGE AND TRANSFER WITH HOMOPOLAR MACHINE FOR A LINEAR THETA-PINCH HYBRID REACTOR

by

H. F. Vogel, Los Alamos Scientific Laboratory

M. Brennan, W. G. Dase, K. M. Tolk, and W. F. Weldon
University of Texas at Austin

CONTENTS

KEYWORDS

1. Large fusion devices, new technologies

2. Endurance, 1.7×10^9 pulses over 25-yr plant life

3. Drum machine, gas bearings, NbTi coils

4. Equivalent capacitance, ms-energy delivery, low loss, low cost

5. Double compensation

6. Optimization of linear proportions, stator, coil, rotor

7. Scaling laws

8. Cost equations

9. Fitting equation for 3-parameter space, cost vs. efficiency vs. energy delivery time