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Channel

An MHD Study for the ETF Conceptual Design

S. Y. Wang, P. J. Staiger,
and J. Marlin Smith
National Aeronautics and Space Administration
Lewis Research Center

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S. Y. Wang, P. J. Staiger,
and J. Marlin Smith
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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S. Y. Wang, P. J. Staiger, and J. Marlin Smith
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Cleveland, Ohio 44135

Abstract

In this paper, the procedures and computations used to identify an MHD channel for a 540 mW_T ETF-scale plant are presented. Under the assumed constraints of maximum E_x, E_y, J_y and β, our results show the best plant performance is obtained for active length, L ~ 12 M, whereas in the initial ETF studies[1,2], L ~ 16 M. As MHD channel length is reduced from 16 M, the channel enthalpy extraction falls off, slowly. This tends to reduce the MHD power output. But the shorter channels result in lower heat losses to the MHD channel cooling water which allows for the incorporation of more low pressure boiler feedwater heaters into the system and an increase in steam plant efficiency. In addition to the sensitivity of various channel parameters (B, K, L, Ma, and P_C), the trade-offs between the level of oxygen enrichment and the electrical stress on the channel are also discussed.

Background

Previous studies[3-5] have considered the optimization of channel performance in terms of the MHD power (P_{MHD}) or the net power ($P_{NET} = P_{MHD} - P_{CPR}$, where P_{CPR} denotes the MHD cycle compressor power consumption). These analyses which utilized a modified chemical equilibrium program[6] and a quasi-one-dimensional channel code[4], have been extended to identify MHD channels that result in the highest overall thermodynamic cycle efficiency of the MHD/steam plant. In addition to the normal constraints considered for determing the best channel performance, we have found that the variation of channel heat loss (Q_{MHD}) with channel length and the effects of this heat loss on the thermodynamic efficiency of the steam bottoming plant (η_S) are important in establishing the proper generator length.

The value of Q_{MHD} has a direct effect on the value of η_S because the channel is assumed to be cooled with low temperature boiler feedwater (≤290° F). The channel cooling displaces regenerative feedwater heaters (FWH) which could otherwise be used. For example, when L = 10 m and Q_{MHD} < 20 mW, two FWH can be used; when L = 12-15 m and Q_{MHD} = 20-36 mW, one FWH can still be used; but when Q_{MHD} > 40 mW for longer channels, no FWH can be effectively used. Consequently, the net result is that η_S decreases with increasing Q_{MHD}.

Constraints and Assumptions

The channel is assumed to perform under a common set of limiting design constraints[4]:

1. Axial electric field, $E_x \leq E_{x,max}$ = 2.5 kV/m
2. Transverse electrical field, $E_y \leq E_{y,max}$ = 4.0 kV/m
3. Transverse current density, $J_y \leq J_{y,max}$ = 10 kA/m²
4. Hall parameter, $\beta \leq \beta_{max}$ = 4

This choice of limiting values approximately represents the current technology[7,8] on channel hardware based on limited endurance tests. The electrical stresses due to too high a value of E_x, E_y, or J_y can cause interelectrode and/or sidewall breakdown. If β is too high, non-uniformities and current leakage paths within the MHD channel can be amplified and degrade the generator performance. In the analysis, the values are maintained within the design constraint limits by varying the B-field and load parameter axial profiles[4] along the channel. The channel is operated in the Faraday mode at nearly constant Mach number.

To obtain the channel design conditions for a prescribed channel length and an assumed diffuser pressure recovery coefficient (0.46), several iterations are required to meet the prescribed diffuser exit pressure. The correct conditions are reached by adjusting either the combustor pressure and/or the minimum load parameter (K_{min}). This gives the performance parameters required for the overall plant calculation; i.e., the total MHD power and the total channel heat loss (Q_{MHD}). Also calculated are the axial profiles of the plasma conditions and the channel loft. By assuming a polytropic efficiency (0.898) and pressure drop fraction (Δp = 0.1), the cycle compressor power consumption is calculated. Using the specific power of the air separation unit (204 kWh/equivalent ton of pure oxygen), the ASU compressor power is also computed for a fixed level of oxygen enrichment. Finally, the bottoming steam cycle efficiency (η_S) and the overall thermodynamic plant efficiency (η_{TH}) are obtained.

Inlet Conditions

The conditions used in these calculations are consistent with those designated for the ETF.[3] The plant is sited in Montana (elevation = 3300 ft, ambient pressure = 0.89 atm, and ambient temperature = 42° F). The designated fuel is Montana Rosebud coal dried to 5 percent moisture and the oxidant is oxygen-enriched air preheated to 1100° F. In this study two levels of oxygen enrichment, 30 and 35 percent by volume, were considered. The combustion gas conditions are computed for an oxygen stoichiometric ratio of 0.9, with a combustor-nozzle heat loss of 5 percent of the total thermal input. The seed is injected as K_2CO_3 with the potassium being 1 percent of the total mass flow rate.

Results

Using the abovementioned constraints, the primary operating parameters B_{max}, Ma, L, O_2 percent, P_C, and K_{min}, as well as the axial profiles of B and K that yield the highest overall performance are determined. Hundreds of calculations were performed to cover the wide variation of these parameters in order to identify the channels that will result in the best η_{TH}. Two sets of calculations were performed. In the first set, the axial profile of the magnetic field and load parameter were adjusted to keep the electrical field, current, and Hall parameter constraints within limit. From these calculations an optimum B-field profile was selected and a preliminary magnet design approximating this profile was obtained[9]. This designed B-field profile was then fixed for a second set of calculations. the results are summarized in two sets of data: thirteen "designed-B" cases and eighteen "fixed-B" cases, respectively.

"Designed-B" Cases (Computer Generated-B): Tables 1 to 3

To illustrate the sensitivity of the results about the channels that yield the highest η_{th} (case 1-1), four other sub-cases (1-2 to 1-5) are also tabulated for common L = 10 m and O_2 = 30 percent. Both the P_c and K_{min} have been varied and the optimum conditions meeting the prescribed exit pressure are shown in Fig. 1. The highest η_{TH} (41.23 percent) occurs at P_c = 4.2 atm. For the 10 M channel, P_c cannot be increased beyond 4.2 atm without causing a lowering of K_{min} below 0.677 and this in turn will cause $E_{x,max}$ to be exceeded. Typical axial profiles of B, E_x, E_y, J_y, K, β, and P_{MHD} are plotted in Figs. 2-A (L = 10 m) and 2-B (L = 15 m).

Comparing cases 1 to 3 for L = 10, 12, and 15 m with 30 percent-O_2, the 12 m channel is found to have the highest η_{TH} (41.37 percent), while for 35 percent-O_2 (cases 4 to 6) the highest η_{TH} (41.44 percent) is found for the 10 m channel. The variations of η_{TH}, η_{IS}, and η_{EN} with channel length are presented in Fig. 3 for the two levels of oxygen enrichment. For shorter channels (L < 15 m), η_{EN} is dropping slowly while η_{IS} is increasing. The effect of less channel heat loss results in the best η_{TH} at L ~ 12 m.

The dependence of η_{TH} on B_{max} and Ma is shown in Fig. 4. At B_{max} = 6 Tesla, the highest performance is obtained at a Mach number of 0.9. Lowering B_{max} lowers the overall plant efficiency and shifts the optimum Mach number to supersonic values. These results, as also illustrated in Tables 2 and 3, indicate that the final selection of the final configurations may depend upon a tradeoff study between magnet cost and system efficiency. Other factors which might result in better performance for low B-fields are variations in the gas stream velocity in the channel and the channel length which were not included in this study.

The magnet sizes (∇B^2, m^3T^2) are estimated to be 636, 764, and 968 for L = 10, 12, and 15 m respectively (O_2 = 30 percent); and be 508, 644, and 782, respectively (O_2 = 35 percent). The savings due to the reduction in length are thus significant.

"Fixed-B" Cases (National Magnet Laboratory-B): Table 4

The previous cases provided simple magnetic field profiles designed from the channel performance point of view. Together with the channel loft they provided the basic requirements for a detailed magnet design. These detailed designs were supplied by the National Magnet Lab[9] and their B-field profiles are shown in Fig. 5, for active lengths of 10, 12, and 15 m. The channel performance was then recalculated, in terms of η_{TH}, using these fixed-B profiles and oxygen enrichment levels of 30 percent (cases 14 to 22) and 35 percent (cases 23 to 31) by volume. The results are given in Table 4.

The decrease in η_{TH} as compared to the previous designed-B cases is within 0.32-0.85 of a point. The small change in η_{TH} is a result of the local optimization process which is capable of maximizing power by shifting load.

The effect of variations in $E_{x,max}$ on η_{TH} was also investigated and the results are shown in Figs. 6 and 7 for O_2 = 30 and 35 percent, respectively. From the design point of view, the 35 percent-O_2 channel is preferred over the 30 percent-O_2 channel because the best performance is obtained at lower values of $E_{x,max}$. Furthermore, the Hall electrical field does not reach the critical value until much later in the channel for the higher enrichment case, as shown in Fig. 8. This means reduced stress level for the channel. However, a larger ASU is required for the higher level O_2 case.

Concluding Remarks

The initial design parameters (B-field, Combustor Pressure, Length, Load Parameter, Mach Number, and Oxygen Enrichment) of the 540 MW_T ETF channel have been identified with respect to the overall plant efficiency. The results are:

1. The basic design conditions (B_{max} = 6 Tesla, M_a = 0.9, L = 12 m, O_2 = 30-35 percent by volume) yield an overall plant efficiency, η_{TH} ~ 41 percent.

2. Recalculation using the fixed-B profiles has shown little change in η_{TH} from the original designed-B channels.

3. Lower B_{max} results in higher M_a for the best performance, but results in lower η_{TH} for the same channel length.

4. Higher oxygen enrichment results in a shorter channel and lower $E_{x,max}$, but requires a larger air separation plant. Consequently, the selection of O_2 level still depends upon further study of the air separation plant, especially on the economy of size.

5. Results have shown that when the effect of channel heat loss on bottom cycle efficiency is taken into account, the best performance is obtained at significantly shorter channel lengths than were previously thought necessary. This is primarily due to the recovery of the MHD generator heat loss as low grade heat by the steam plant which is an important feature considered in this paper.

Nomenclature:

B	Magnetic field, tesla (or T)
E	Electric field, kV/m
J	Electrical current density, kA/m^2
K	Faraday load parameter or factor
L	Active channel length, m
Ma	Mach number
O_2	Oxygen enrichment, percent by volume
P	Electrical power, MW
p	Pressure, atm
ΔP	$(P_{CPR} - P_C)/P_{CPR}$
Q	Heat loss in the channel, MW
∇	Magnet warm bore volume, m^3
u	Velocity, km/s
β	Hall parameter
η	Efficiency, percent

Subscript:

ASU	Air separation unit
C	Combustor
CPR	MHD cycle compressor
EN	Enthalpy extraction
IS	Isentropic
MAX	Maximum; critical
MIN	Minimum
NET	Net
S	Steam thermodynamic bottoming cycle
TH	Overall cycle of MHD/steam plant
x	Axial
y	Transverse

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TABLE 1. - COMPUTER GENERATED-B CASES FOR B_{MAX} = 6 (TESLA); Ma-0.9; L = 10, 12, 15 (m); AND O_2 = 30, 35 (PERCENT-VOL)

Case no.	Vol. percent O_2	Product mass flow, kg/s	Final product mass flow, kg/s	Oxidant mass flow, kg/s	Channel length, m	Combustor pressure, atm	MHD power, MWE	Channel ht loss, MWT	Cycle compres power, MW	O_2 compres power, MW	Bottom cycle input, MWT	Stm cyc eff., percent	Stm cyc output, MWE	Cyc coal input, MWT	Gross ac power, MWE	Therm cyc eff, percent
1-1	30.0	133.0	161.10	110.50	10.090	4.2	88.21	17.34	21.21	11.62	426.55	39.40	135.21	539.81	222.5	41.23
1-2	↓	↓	↓	↓	10.010	4.1	87.64	17.32	20.82	↓	426.32	39.40	135.68	↓	222.4	41.21
1-3					10.000	4.0	87.03	17.45	20.42		426.93	39.39	136.14		222.3	41.18
1-4					10.010	3.9	86.31	17.60	20.01		427.25	39.38	136.64		222.1	41.14
1-5					10.040	3.8	85.50	17.75	19.59		427.64	39.38	137.18		221.8	41.09
2					12.050	4.7	92.53	20.58	23.05		424.07	39.23	131.69		223.3	41.37
3					15.040	5.1	95.87	25.90	24.48		422.16	38.90	128.12		223.0	41.32
4	35.0	117.5	145.57	95.37	9.970	5.8	97.50	23.28	22.93	15.37	422.86	39.07	126.90	539.19	223.4	41.44
5	35.0	117.5	145.57	95.37	12.000	6.4	100.56	28.56	24.58	15.37	421.46	38.71	123.21	539.19	222.8	41.31
6	35.0	117.5	145.57	95.37	14.030	7.3	102.69	36.48	26.75	15.37	421.49	38.08	118.19	539.19	220.1	40.81

TABLE 2. - COMPUTER GENERATED-B CASES FOR B_{MAX} = 5 (TESLA); L = 12 (m); O_2 = 30 (PERCENT-VOL); AND Ma = 0.95-1.15

Case no.	Vol. percent O_2	Product mass flow, kg/s	Final product mass flow, kg/s	Oxidant mass flow, kg/s	Channel length, m	Combustor pressure, atm	MHD power, MWE	Channel ht loss, MWT	Cycle compres power, MW	O_2 compres power, MW	Bottom cycle input, MWT	Stm cyc eff., percent	Stm cyc output, MWE	Cyc coal input, MWT	Gross ac power, MWE	Therm cyc eff, percent	Mach no.
7	30.0	133.0	161.10	110.50	11.990	4.3	83.29	21.66	21.60	11.62	431.86	39.28	136.05	539.81	218.5	40.48	0.95
8	↓	↓	↓	↓	11.990	4.3	83.54	20.13	21.60	↓	431.61	39.27	136.28	↓	219.0	40.57	1.05
9					12.040	4.3	83.21	19.15	21.60		431.94	39.32	136.61		219.0	40.57	1.10
10					12.070	4.2	81.60	18.30	21.21		433.16	39.36	137.67		218.5	40.47	1.15

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TABLE 3. - COMPUTER GENERATED-B CASES FOR B_{MAX} = 4 (TESLA); L = 12 (m); O_2 = 30 (PERCENT-VOL); AND Ma = 1.15-1.35

Case no.	Vol. percent O_2	Product mass flow, kg/s	Final product mass flow, kg/s	Oxidant mass flow, kg/s	Channel length, m	Combustor pressure, atm	MHD power, MWE	Channel ht loss, MWT	Cycle compres power, MW	O_2 compres power, MW	Bottom cycle input, MWT	Stm cyc eff., percent	Stm cyc output, MWE	Cyc coal input, MWT	Gross ac power, MWE	Therm cyc eff, percent	Mach no.
11	30.0	133.0	161.10	110.50	12.000	4.0	72.05	19.88	20.42	11.62	441.91	39.31	141.66	539.81	213.0	39.46	1.15
12	30.0	133.0	161.10	110.50	12.070	4.1	72.09	17.79	20.82	11.62	442.27	39.41	141.84	539.81	213.2	39.50	1.25
13	30.0	133.0	161.10	110.50	12.170	3.8	68.99	16.00	19.59	11.62	444.15	39.49	144.20	539.81	212.5	39.37	1.35

TABLE 4. - NATIONAL MAGNET LABORATORY-B CASES FOR B_{MAX} = 6 (TESLA); Ma = 0.9; L = 10, 12, 15 (m); AND O_2 = 30, 35 (PERCENT-VOL)

Case no.	Vol. percent O_2	Product mass flow, kg/s	Final product mass flow, kg/s	Oxidant mass flow, kg/s	Channel length, m	Combustor pressure, atm	MHD power, MWE	Channel ht loss, MWT	Cycle compres power, MW	O_2 compres power, MW	Bottom cycle input, MWT	Stm cyc eff., percent	Stm cyc output, MWE	Cyc coal input, MWT	Gross ac power, MWE	Therm cyc eff, percent	[illegible] kV/m
14	30.0	133.0	161.10	110.50	9.890	4.0	84.61	17.60	20.42	11.62	429.35	39.39	137.08	539.81	220.8	40.91	2.5
15	↓	↓	↓	↓	10.000	3.5	81.01	17.06	18.30	↓	430.84	39.42	139.91	↓	220.1	40.78	2.0
16	↓	↓	↓	↓	10.360	3.0	74.33	17.14	15.97	↓	435.18	39.42	143.98	↓	217.6	40.30	1.5
17	↓	↓	↓	↓	12.000	4.5	88.62	21.39	22.36	↓	427.28	39.20	133.51	↓	221.2	40.99	2.5
18	↓	↓	↓	↓	11.990	3.9	85.95	20.26	20.01	↓	427.61	39.26	136.23	↓	221.3	41.00	2.0
19	↓	↓	↓	↓	11.960	3.3	79.31	19.55	17.16	↓	431.40	39.30	140.75	↓	219.3	40.62	1.5
20	↓	↓	↓	↓	14.620	5.0	90.49	26.21	24.13	↓	427.19	38.90	130.43	↓	220.0	40.76	2.5
21	↓	↓	↓	↓	14.790	4.5	90.18	24.60	22.36	↓	425.72	39.00	132.05	↓	221.3	41.00	2.0
22	↓	↓	↓	↓	15.180	3.7	84.67	24.39	19.17	↓	428.05	39.02	136.23	↓	220.1	40.76	1.5
23	35.0	117.5	145.57	95.37	9.880	5.5	92.46	23.54	22.12	15.37	427.09	39.07	129.36	539.19	220.9	40.97	2.5
24	↓	↓	↓	↓	9.980	5.1	92.23	22.11	20.98	↓	426.18	39.15	130.51	↓	221.8	41.14	2.0
25	↓	↓	↓	↓	10.070	4.1	86.41	20.98	17.82	↓	426.85	39.22	135.01	↓	220.6	[illegible]	1.5
26	↓	↓	↓	↓	11.860	6.0	94.56	28.75	23.46	↓	426.33	38.72	126.26	↓	219.9	40.78	2.5
27	↓	↓	↓	↓	11.780	5.6	95.52	26.61	22.39	↓	424.30	38.86	127.13	↓	221.7	41.12	2.0
28	↓	↓	↓	↓	12.080	4.7	92.00	25.09	19.77	↓	425.20	38.97	130.54	↓	221.6	41.10	1.5
29	↓	↓	↓	↓	14.660	7.2	94.59	36.81	26.40	↓	429.24	38.11	121.81	↓	215.5	39.96	2.5
30	↓	↓	↓	↓	14.770	6.5	96.72	34.31	24.73	↓	425.44	38.31	122.86	↓	218.6	40.54	2.0
31	↓	↓	↓	↓	14.830	5.5	96.27	30.88	22.12	↓	423.28	38.56	125.71	↓	221.0	40.99	1.5

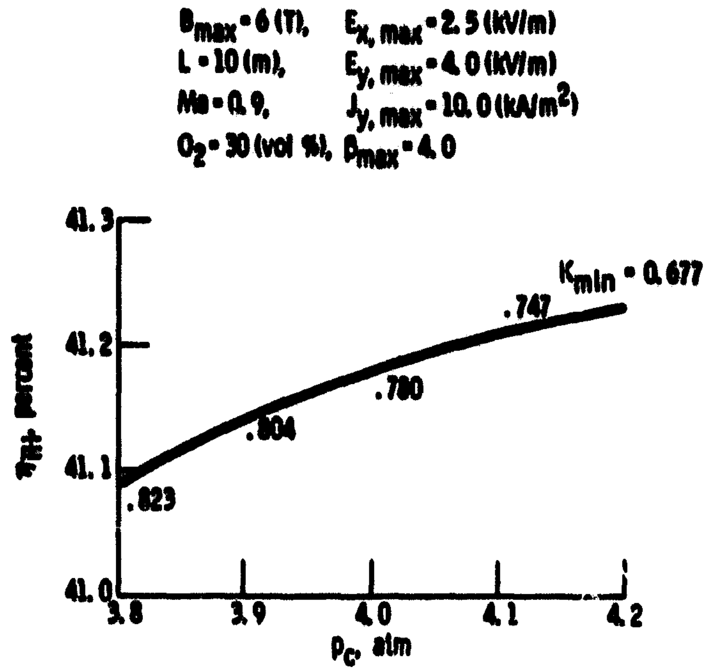

Figure 1. - Plant efficiency vs. channel inlet stagnation pressure and minimum load parameter for a 10-meter (m) channel.

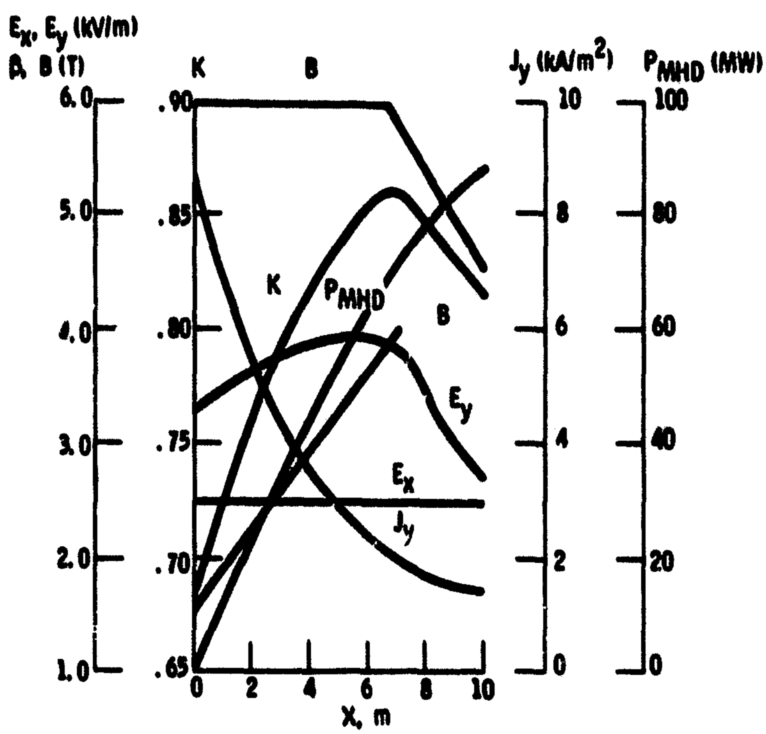

Figure 2(a). - Typical axial variations of B, K, E_x, E_y, J_y, β, and P_{MHD} of the 10-meter (m) channel (design case 1-1: O_2 = 30 %, Ma = 0.9, p_c = 4.2 atm).

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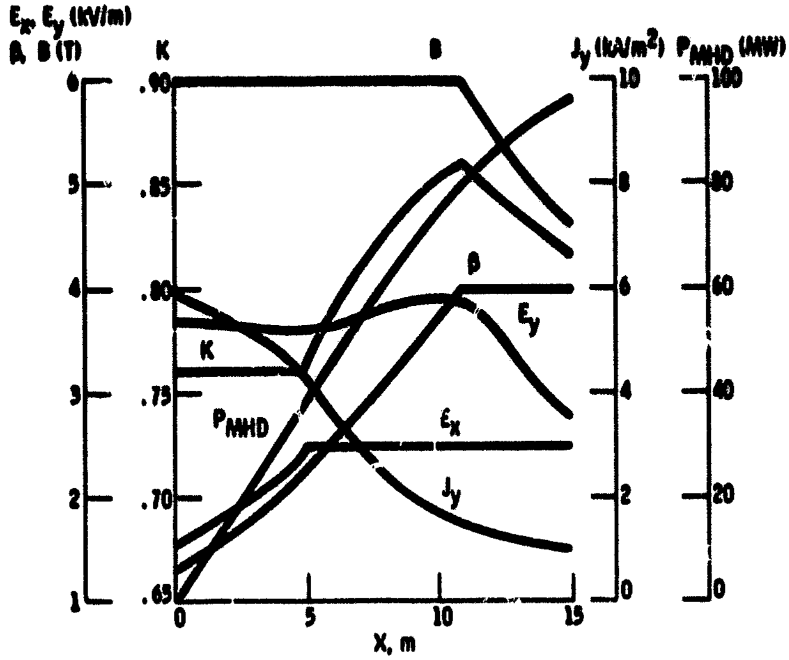

Figure 2(b). - Axial variations of B, K, E_x, E_y, J_y, β, and P_{MHD} of 15-m channel (design case 3: O_2 = 30 %, Ma = 0.9, P_c = 5.1 atm).

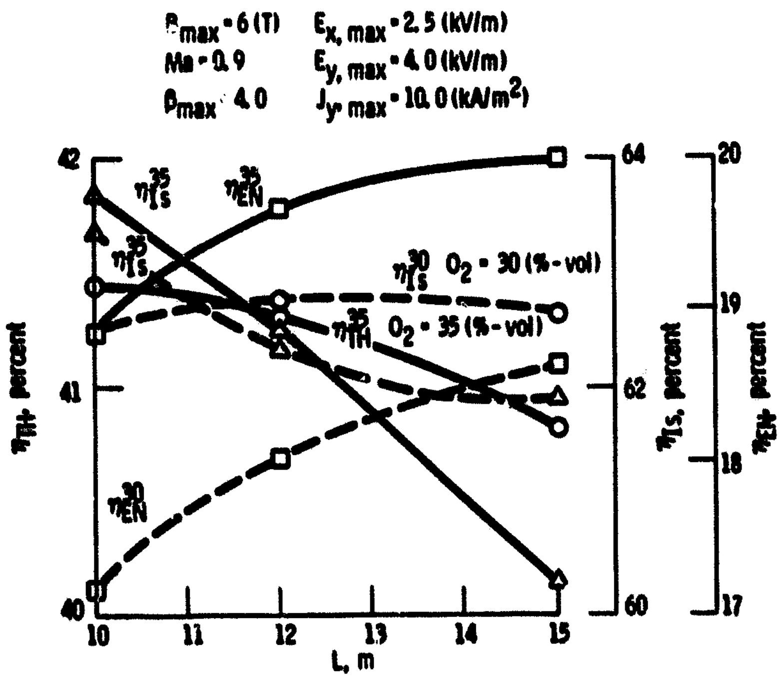

Figure 3. - η_{TH}, η_{TS}, and η_{EN} for different channel lengths and oxygen enrichments.

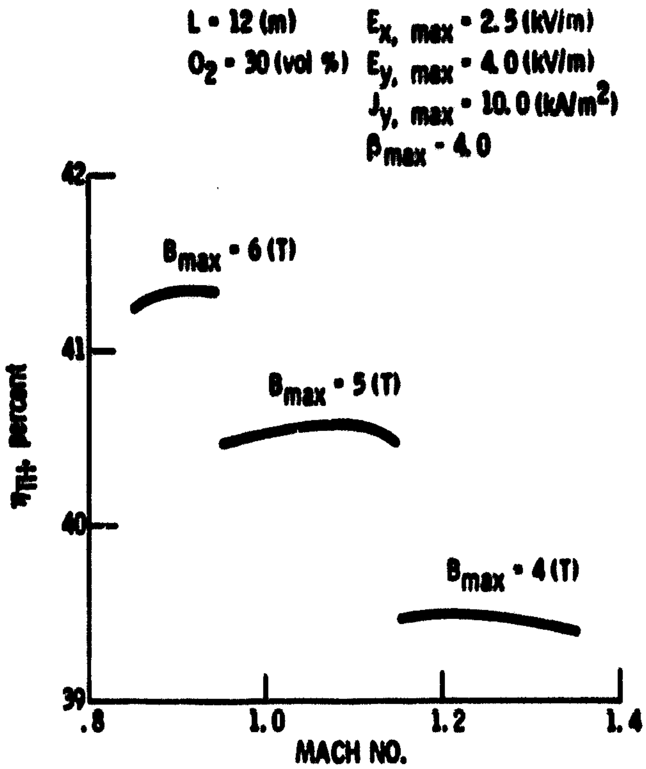

Figure 4. - Peak plant efficiency for B_{max} = 4, 5, and 6 Tesla (T) at a range of channel Mach no. under common constraints.

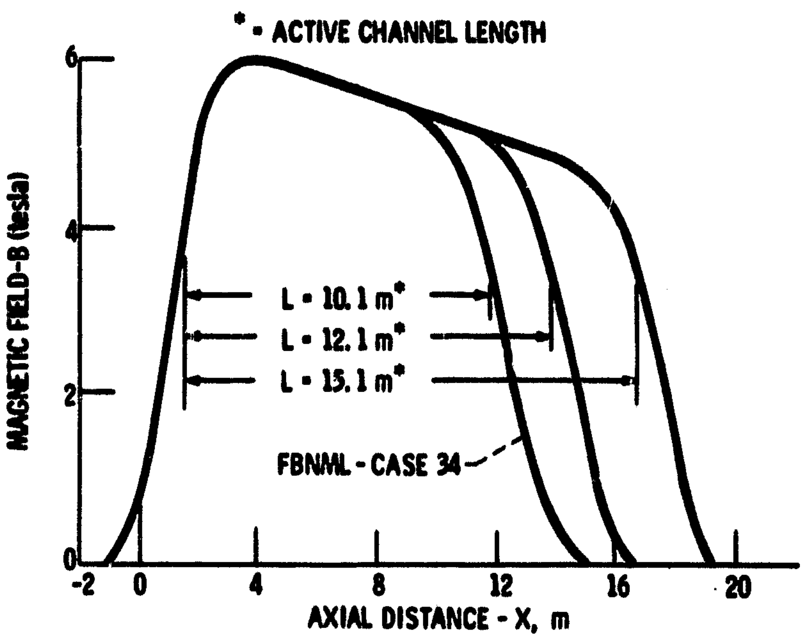

Figure 5. - National magnet laboratory axial profiles of B-field.

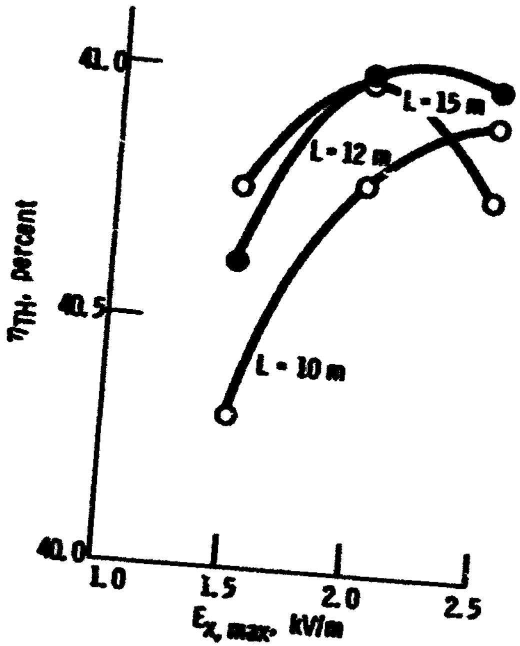

Figure 6. - National magnet laboratory-B cases for 30%-O_2 and Ma = 0.9.

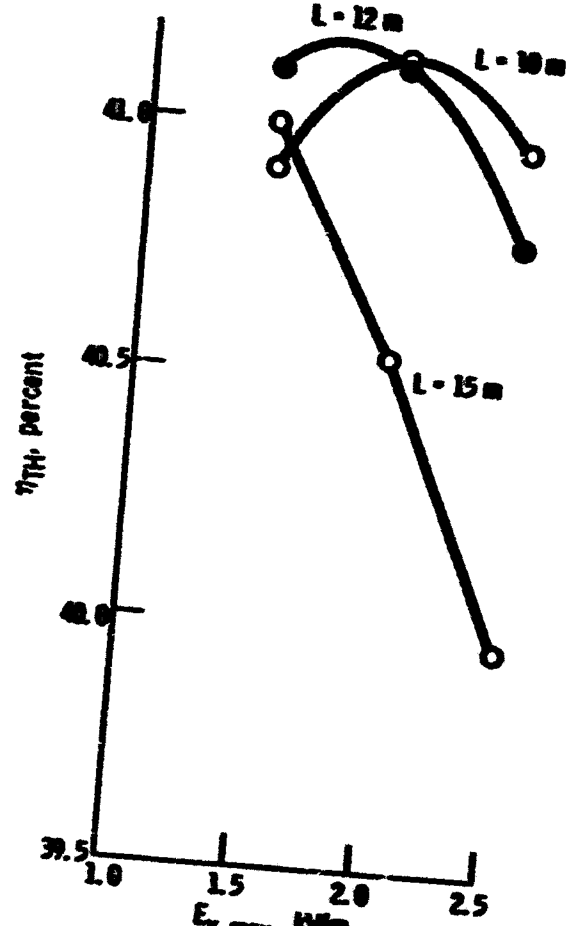

Figure 7. - National magnet laboratory-B cases for 35%-O_2 and Ma = 0.9.

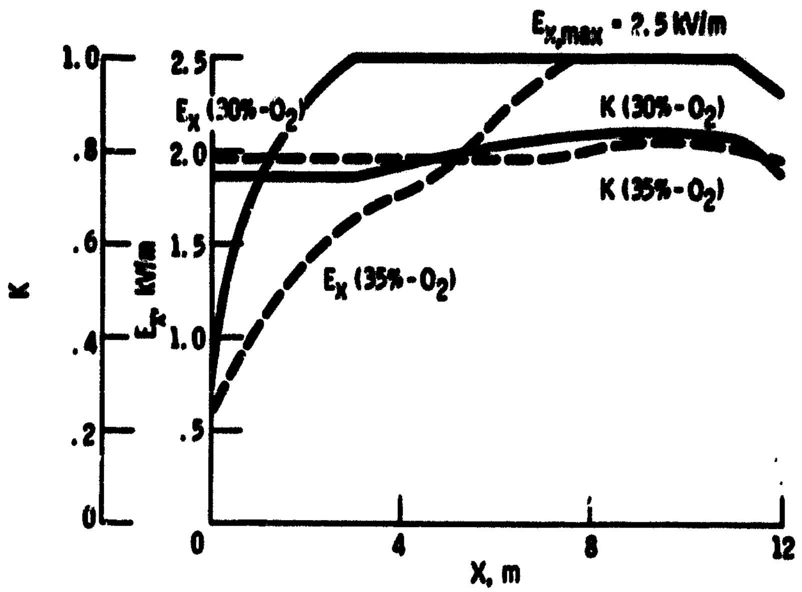

Figure 8. - Axial development of hall electric field E_x and loading K (for national magnet laboratory -B, O_2 = 30, 35%, and L = 12 m).