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MHD ETF CONCEPTUAL DESIGN

Volume V-ADDENDUM

F.D.RETALLICK
Project Manager

WESTINGHOUSE ELECTRIC CORPORATION
Advanced Energy Systems Division
P.O. Box 10864
Pittsburgh, Pennsylvania 15236

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1.0 ETF REFINED CONCEPTUAL DESIGN - PURPOSE AND APPROACH

Westinghouse studied three distinct ETF concepts during the conceptual design phase of the program. Based on this work and subsequent discussion with ETF review committees, Westinghouse suggested that the ETF-3 evolving facility concept be the basis for continued ETF conceptual design investigation.

The following discussion will describe the major changes made to the original ETF-3 concept design and state point data for the amended configuration. These changes are the result of analysis made through the conceptual design phase including a major systems iteration and, in part, reflects additional thinking regarding a multiple step facility approach. (See Section 2.1) In addition, pertinent issues raised by the DOE review committees, (see Section 3.0) and all subsequent component analysis have been factored into the refined concept definition.

Through the iteration phase of the conceptual design study, the model used in computation of the MHD generator performance has been improved. Independent comparisons have been made (see Sections 4.2 and 4.3) to substantiate the revised model. Table 1.0-1 lists the various system and component performance parameters and their updated values as used in developing the heat and mass balances and plant performance estimates for the refined ETF-3 described herein. As a result of their modifications, the resulting plant design is slightly larger than the original ETF-3 concept. In view of this, the ETF-3 plant costs were reviewed and modified to reflect the revised concept (see Section 2.5.1). In addition, specific " case studies" were made that represent major system alternatives or uncertainties in important system parameters. These are also described in Section 2.1.

TABLE 1.0-1

SUMMARY OF REVISED SYSTEM AND COMPONENT PARAMETERS FOR ETF-3 REFINED DESIGN

Item/Parameter	Revised Value(s)	Basis
1. Combustor heat loss	7% of HHV	Calculation based upon conceptual design of combustor
2. Nozzle/Diffuser heat loss	2.7 MW - Nozzle 13 MW - Diffuser	Calculation based upon conceptual design of components
3. Channel performance	a) Explicit computation of heat losses	Need for size-dependent estimation of heat losses
	b) Calculation of boundary layer development	Need to detect danger of flow separation and exit blockage
	c) Addition of internal voltage drops to power computation	Need for a more adequate estimate of electrical losses
4. Steam cycle efficiency	a) η_S = .354 for 1300 psia/950°F	Turbine-generator analysis by W Steam Turbine Div.
5. Diffuser performance	η_D = 0.58	Analysis by ANL
6. Air compressor efficiency	η_C= 0.83	Supplied by manufacturer
7. Power conditioning losses	η_I = 0.96	Conceptual design analysis of power conditioning equipment
8. Addition of seed quench tank	Configuration Design Modification	Need to protect downstream heat exchanger surfaces

The information presented in this addendum was in pursuit of the ETF reference design prior to DOE direction to investigate a smaller 150 MWt truncated system. This work, in conjunction with the previously developed component conceptual designs, had progressed sufficiently to allow a relatively complete plant definition and approximate cost. As such, this Volume V, when combined with Volume I through IV of the MHD ETF Conceptual Design Report, allows consideration of an alternative concept to the 150 MWt truncated system.

2.0 DESCRIPTION OF REFINED SYSTEM

2.1 Basis for Evolving Plant - Limiting Considerations

The basis for an MHD pilot plant which evolved to a final configuration using direct fired high temperature air heaters was developed in the earlier ETF-3 conceptual design effort. This evolution was a two step process where the initial step was an oxygen-injected system without a turbine generator and with non-integrated seed recovery/regeneration and coal drying. The second step took the plant to a complete pilot scale unit.

The large uncertainty in the high temperature air heater development, defined during the conceptual design effort, resulted in the recommendation to consider a separately fired system during the plant evolution process.

Figure 2.1-1 was used in attempting to define a refined ETF-3 facility concept which would offer the most flexibility for evaluating or incorporating the two candidate high temperature air heater systems, or utilizing oxygen injection in place of high temperature preheat.

Indicated in the upper left corner is a logical three step evolution for a direct fired system. The first step is an MHD demonstration with oxygen injection. The second step adds the steam demonstration components and proves out the seed and coal drying systems in a non-integrated fashion. The final step incorporates the direct fired high temperature air heaters and the turbine-generator, resulting in a complete pilot plant. The incorporation of the high

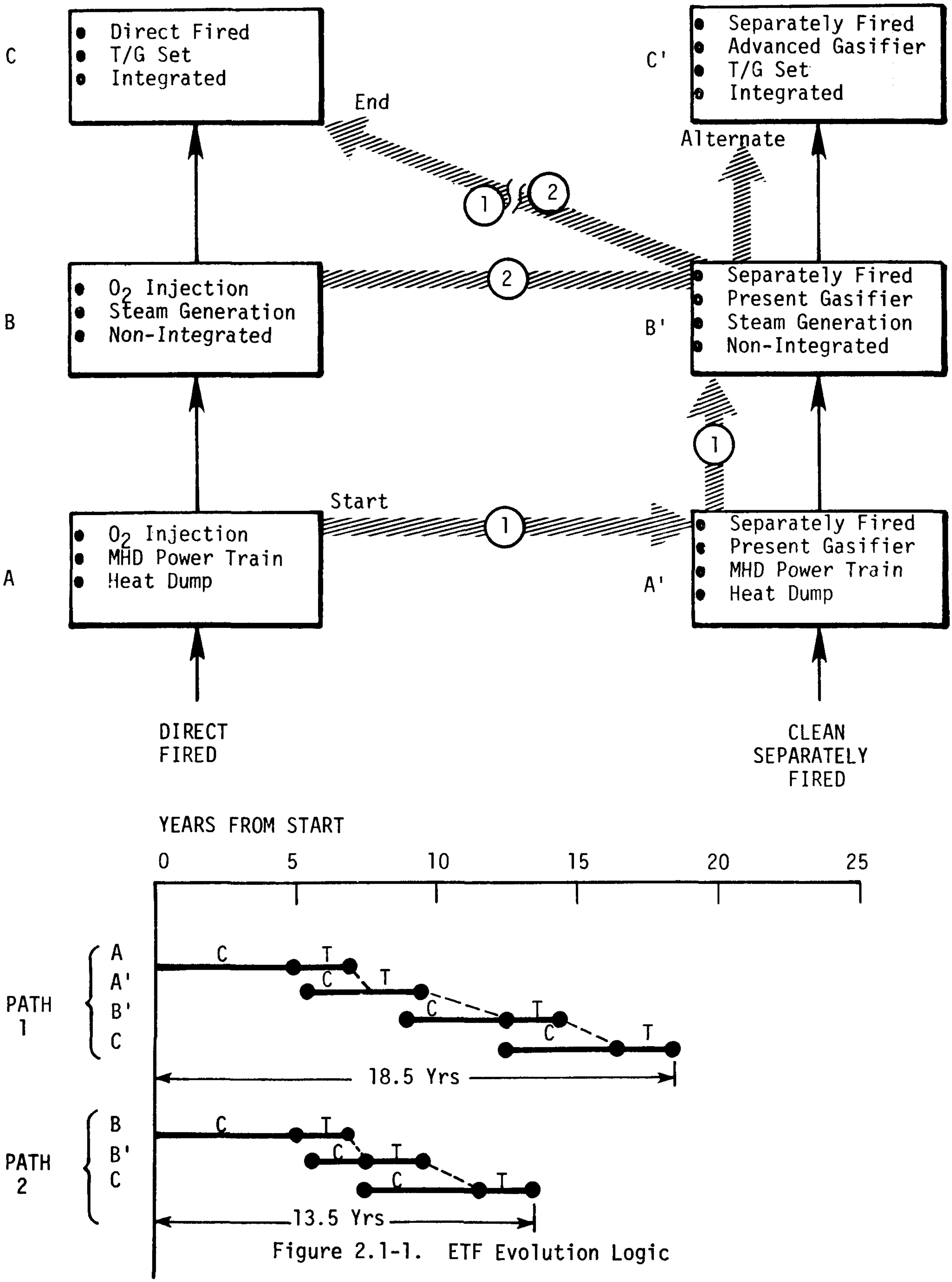


Figure 2.1-1. ETF Evolution Logic

temperature air heater is done in the third step to allow maximum development time for this critical component.

In the upper right hand corner a logical three step evolution of a separately fired system is indicated. Present day technology allows one to consider a separately fired system in the initial facility using blast furnace stoves and existing coal gasification plants with cold gas cleanup. The use of fuel other than coal in the separately fired system is deemed highly undesirable. Again the first step is an MHD demonstration. In the second step the steam generation components and the seed and coal drying systems are demonstrated in a non-integrated manner. In the final step the less efficient present technology separately fired systems are replaced with advanced units, the turbine-generator is added and the system is integrated to a complete pilot plant. The separately fired system offers a plant which can be developed without the major uncertainty posed by the direct fired high temperature air heater, but at the expense of performance, cost and system simplicity. However, it merits consideration from the standpoint that the program need not be stalemated due to development problems with the high temperature air heater.

In an attempt to develop a recommended evolutionary path for the facility, the two paths shown as ① and ② on the figure were investigated. Path ① started with the simpliest facility for MHD demonstration using oxygen. It then proceeded to add a present technology separately fired pre-heat system. Thirdly it added the steam generation and non-integrated seed and coal drying systems, and lastly it proceeded to add a direct fired pre-heat system. As an alternate to this last step it could proceed to add an advanced separately fired preheat system if development results on the direct fired system have been unsatisfactory. As a further evaluation of path ① , a cursory evaluation of total time involved in such an evolution was prepared and is shown at the bottom of the figure. On the time lines shown, C means <u>construction</u> period and T means development and demonstration <u>testing</u>. Judgement was used in overlapping construction of the subsequent configuration with the configuration under test based on the potential interfacing required. Path ① resulted in a span time of 18.5 years from start indicating the difficulty of the evolutionary approach as multiple sequential steps are introduced.

In an attempt to minimize the time span, path ② was investigated. Path ② starts with a configuration which includes demonstration of an oxygen injected MHD system and the steam generation equipment simultaneously. The second configuration incorporates the present day technology separately fired high temperature air pre-heat system and the third step incorporates the direct fired preheater. Alternately the second configuration could proceed to an advanced separately fired system.

The time line for path ②, shown at the bottom of the page, indicates a total span of 13.5 years.

The time span could have been further shortened by using a path such as B' to C or C', however the cost for the initial configuration would probably be significantly greater and it would preempt the possibility of proceeding immediately to the direct fired configuration if development in the early years shows this to be possible.

As a result of this process of evaluation it had been decided to study an ETF-3 facility along path ②. It appeared that by this means three configurations would be investigated and defined in sufficient detail to allow proper future consideration of the desired evolutionary process considering time span, cost, and development uncertainty. However, subsequent direction by DOE for a smaller reference design precluded detailed investigation of the intermediate step (separately fired) for the ETF-3 concept. Refined definitions of the first and third step for ETF-3 are given herein.

2.2 Expanded Configuration

The cycle diagram for the final evolved configuration is shown in Figure 2.2-1. The primary modification to the original conceptual design work performed on ETF-3 was to provide a means for positive seed removal capabilities in the downstream heat exchange components. Excessive carryover of seed compounds from the radiant section results, if no removal other than liquid runoff from reheater and superheater surfaces is accounted for, resulting in an extremely unfavorable environment in those components. The buildup of potassium sulfate on reheat tubing could seriously inhibit heat transfer, thus making necessary the provision of excess surface area. In the refined ETF-3 cycle, a seed quench tank is included downstream of the high temperature air heater. Recirculated gas from the exhaust of the low temperature economizer is injected into the quench tank in sufficient quantities to drop the gas temperature to 1300°K (1880°F). At this temperature any liquid K_2SO_4 that has been carried over from the high temperature air heater should be a solid and should be significantly less troublesome in the heat exchangers downstream.

The inclusion of the seed quench tank requires the rearrangement of heat exchange surfaces. The temperature drop across the tank (1445°K - 1300°K) makes it impossible to include superheat surface upstream of the low temperature air heater without raising stack temperature. The superheater has therefore been displaced to the lower end of the LTAH. The result of this rearrangement is a significant increase in the average gas temperature in the LTAH, thus improving the LMTD and making that surface more effective. For the same heating duty the LTAH effectiveness need only be 0.75 rather than the original 0.80. The superheater is, on the other hand, forced to operate across much lower temperature differences and the surface required in that component is correspondingly less effective. However, the steam/gas heat transfer is better than that expected in the LTAH, making the trade-off desirable. Although the cost of the superheater and economizer are increased, an offsetting decrease in the cost of the LTAH is realized.

The effect of the changes in the cycle configuration and in computation techniques on component designs are most immediately apparent in flow rates. Since a steam turbine-generator size of 50 MWe has been chosen to determine the minimum allowable plant thermal rating, any increase in the assumed steam plant heat rate will require larger quantities of energy transferred from the topping cycle exhaust. The steam plant efficiency for the configuration specified for the ETF-3 expanded version is 35.4%, significantly lower than the 39% value used in the original calculation. In order to attain a 50 MWe output from the turbine-generator, the thermal rating of the plant was increased from 286 MWt to 345 MWt. Flow rates through the MHD generator, radiant boiler and high temperature air heater are also higher, rising from 91.4 kg/sec to 120.1 kg.sec.

The flow rates through the low temperature heat exchanger components were increased by the recirculation of stack gas to the seed quench tank. The original flow rate was 112 kg/sec, which has been recalculated to be 152 kg/sec.

The state point and performance data for the refined ETF-3 expanded configuration is shown in Tables 2.2-1 through 2.2-4. Table 2.2-1 lists input parameter information for the steam and MHD cycles. The state point data are contained in Table 2.2-2 for both the gas and water sides. The performance summary for the entire plant, including heat loads on heat exchanger surfaces are given in Table 2.2-3. Design data and plasma conditions for the MHD generator proper are reported in Table 2.2-4.

The conceptual design and analysis of the MHD components (combustor, nozzle, channel, and diffuser) have resulted in higher heat losses to the coolant than had been initially assumed. A somewhat higher friction factor (.007 vs .005) has also been added. The drop in topping cycle efficiency (from 27.7% to 23.0%) is a result of these more pessimistic losses. Furthermore, the original channel performance analysis included no provision for boundary layer formation and voltage drops across the boundary layer. Thus, the specific power production in the original calculation was 0.76 MWe/kg/sec, whereas the upgraded calculation results in 0.66 MWe/kg/sec. These considerations have resulted in decreased plant performance. The calculated overall energy efficiency for the refined ETF-3 is 34.9%.

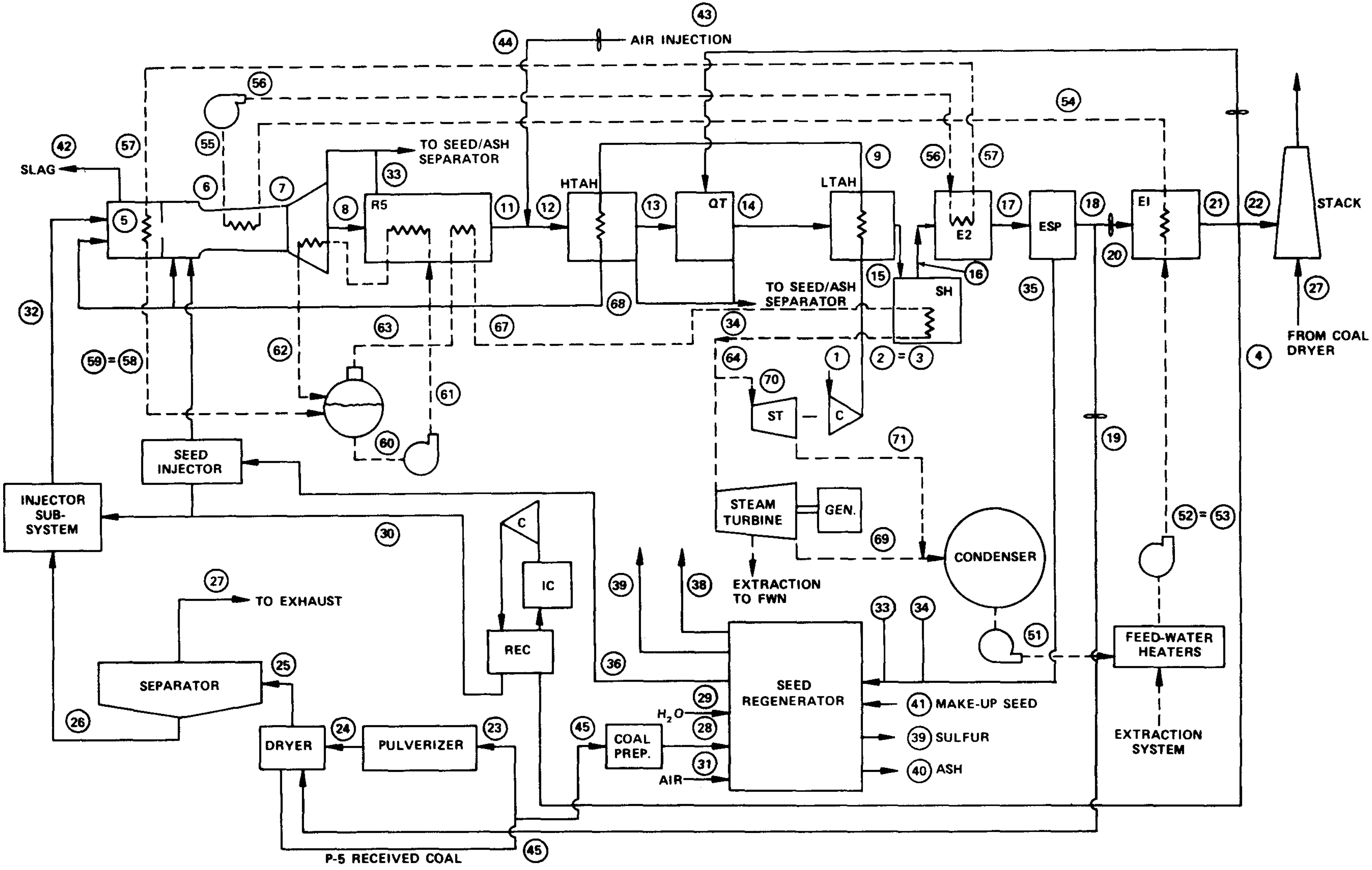


Figure 2.2-1. ETF-3 Refined Design (expanded configuration)

TABLE 2.2-1

ETF DIRECT FIRED REFERENCE DESIGN
FINAL CONFIGURATION

```
INPUT PARAMETERS

COMBUSTOR CONDITIONS : FOR AN MONTANA      COAL
  (AT  5% MOISTURE)   IN A TWO STAGE COMBUSTOR
 90% ASH REJECTION :  OVERALL PHI=    .950


PRESSURE =      4.7   ATM

TEMPERATURES

  2ND STAGE = 2727.0   DEGK


AIR PREHEAT TEMPERATURE = 1644.00  DEG K


INITIAL DUCT VELOCITY          =  825.0    M/S


FUEL/AIR RATIO (AS FIRED)    = .12594    KG/KG


STEAM PLANT  :  1300PSI /  950F


FW TEMP TO ECON AND COOLING =  345.5    DEGK



DUCT PARAMETERS

 BO= 6.00 T
 KO=  .75
  C=  .10
 DK= .0000
  F= .0070


COOLING SYSTEM HEAT TRANSFER RATES,   MW
      FROM COMBUSTOR TO COOLANT   =     21.336
      FROM NOZZLE    TO COOLANT   =      2.700
      FROM DIFFUSER  TO COOLANT   =     13.000


EFFICIENCIES

ROTATING GENERATOR              =         .9840
DC/AC INVERTER                  =         .9600
DIFFUSER                        =         .5800
AIR COMPRESSOR                  =         .8300
PUMPS                           =         .7000
BLOWER                          =         .8000
TRANSPORT GAS COMPRESSOR        =         .8300
```

TABLE 2.2-2

STATE POINT DATA
(EXPANDED CONFIGURATION)

GAS CONDITIONS

POINT	P (ATM)	T (DEG K)	H (J/KG)	W/ /AIR	FLOW (KG/SEC)
1	.7840	288.3000	15266.	1.0000	105.0124
2	5.2400	533.8982	266221.	1.0000	105.0124
3	5.2400	533.8982	266221.	1.0000	105.0124
4	.8000	425.0000	0.	.0126	1.3225
5	4.7040	2727.0080	656736.	1.1436	120.0884
6	2.7861	2575.2192	293685.	1.1436	120.0884
7	.6861	2225.3188	-459423.	1.1436	120.0884
8	.8707	2292.5109	-319212.	1.1436	120.0884
9	5.0874	1100.0000	893079.	1.0000	105.0124
10	4.9392	1644.0000	1547981.	1.0000	105.0124
11	.8446	1900.0000	-1018000.	1.1429	120.0187
12	.8404	1863.0000	-953870.	1.2482	131.0726
13	.8152	1447.3177	-1524735.	1.2344	129.6320
14	.8070	1300.0000	-1708000.	1.4521	152.4855
15	.8070	956.8336	-2139700.	1.4521	152.4855
16	.7828	710.0000	-2432580.	1.4521	152.4855
17	.7593	611.0000	-2544717.	1.4521	152.4855
18	.7480	611.0000	-2544717.	1.4482	152.0751
19	.8612	611.0000	-2544717.	.7546	79.2376
20	.8200	611.0000	-2544717.	.6936	72.8375
21	.8000	425.0000	-2747531.	.6936	72.8375
22	.8000	425.0000	-2747531.	.4634	48.6614
23	.8000	311.1111	0.	.1548	16.2534
24	.8612	311.1111	0.	.1548	16.2534
25	.8120	425.0000	0.	.9093	95.4910
26	.8000	425.0000	0.	.1259	13.2251
27	.8000	425.0000	-2747531.	.7834	82.2659
28	.8000	425.0000	0.	.0035	.3647
29	.8000	425.0000	0.	.0010	.1072
30	5.9270	500.0000	0.	.0126	1.3225
31	.8000	311.1111	0.	.0077	.8080
32	4.9392	300.0000	0.	.1385	14.5476
33	.8000	288.3000	0.	.0007	.0697
34	.8000	288.3000	0.	.0137	1.4406
35	.8000	288.3000	0.	.0039	.4104
36	.8000	288.3000	0.	.0170	1.7834
37	.8000	288.3000	0.	.0130	1.3612
38	.7840	288.3000	0.	.0032	.3388
39	.8000	288.3000	0.	.0006	.0637
40	.8000	288.3000	0.	.0013	.1394
41	.8000	300.0000	0.	.0002	.0185
42	.8000	288.3000	0.	.0120	1.2550
43	.8000	287.0300	13985.	.1053	11.0539
44	.8446	422.2200	151077.	.1053	11.0539
45	.8000	288.3000	0.	.1586	16.6497
46	.8000	288.3000	0.	.0038	.3964

STEAM CONDITIONS

POINT	P (ATM)	T (DEG K)	H (J/KG)	W/ /AIR	FLOW (KG/SEC)
51	62.5850	345.5000	307169.	.6630	69.6274
52	62.5850	345.5000	307169.	.6630	69.6274
53	62.5850	345.5201	307169.	.6630	69.6274
54	58.5034	396.0719	519339.	.6630	69.6274
55	55.1020	458.1939	786763.	.6630	69.6274
56	115.3061	460.0665	798045.	.6630	69.6274
57	111.2245	514.4067	1043627.	.6630	69.6274
58	107.8231	574.7110	1350059.	.6630	69.6274
59	104.4218	581.2913	1388837.	.6630	69.6274
60	104.4218	588.4909	1433030.	3.4878	366.2663
61	115.9864	589.2291	1435196.	3.4878	366.2663
62	104.4218	588.4909	1689854.	3.4878	366.2663
63	104.4218	588.4909	2717151.	.6630	69.6274
64	89.4558	783.3333	3410897.	.6630	69.6274
67	99.6599	591.9030	2769483.	.6630	69.6274

MAIN COMBUSTION AIR FLOW = 105.01 KG/SEC

GENERATOR MASS FLOW = 120.09 KG/SEC

STEAM FLOW AT THROTTLE = 69.63 KG/SEC

TABLE 2.2-3

PERFORMANCE SUMMARY
(EXPANDED CONFIGURATION)

```
      HEAT TRANSFER
      Q TO STEAM IN RADIANT BOILER =      .745535+06   J/KG AIR
      SUPERHEAT IN  RADIANT BOILER =      .535735+05   J/KG AIR
      Q TO STEAM IN REHEATER       =      .000000      J/KG AIR
      Q TO STEAM IN SUPERHEATER    =      .425283+06   J/KG AIR
      Q TO STEAM IN ECONOMIZER #1  =      .140274+06   J/KG AIR
      Q TO STEAM IN ECONOMIZER #2  =      .162631+06   J/KG AIR
      Q TO STEAM IN COOLING LOOPS  =      .406205+06   J/KG AIR
         TOTAL HEAT TO STEAM       =      .205790+07   J/KG AIR

      Q TO AIR IN HI TEMP PREHEATER=      .654902+06   J/KG AIR
      Q TO AIR IN LO TEMP PREHEATER=      .626659+06   J/KG AIR
      Q TO COAL IN CRUSHER/DRYER   =      .153035+06   J/KG AIR


          TOTAL HEAT TRANSFERRED   =      .336690+07   J/KG AIR



       HEAT LOST IN HTAH VALVES =    .576314+05J/KG AIR


      POWER GENERATION

      MHD POWER                   =   79.56  MW
      TURB GEN POWER              =   50.15  MW
      COMPRESSOR DRIVE            =   26.35  MW
      GROSS POWER OUT             =  156.07  MW


      POWER CONSUMPTION

      COMPRESSOR POWER            =   26.35  MW
      RECIRC PUMP POWER           =    2.22  MW
      TRANSPORT GAS COMPRESSOR=         .00  MW
      AIR INJECTION BLOWER        =    -.02  MW
      FORCED DRAFT FANS           =    4.01  MW
      ELECTRO. PRECIP. POWER      =     .07  MW
      AIR HTR VALVE ACTUATORS     =     .00  MW
      COOLING TWR CIRC. PMP       =     .91  MW
      COAL PULVERIZERS            =    1.49  MW
      MHD MAGNET POWER            =     .08  MW
      RAW MATERIALS HANDLING      =     .50  MW
      SEED TREATMENT SYSTEM       =     .00  MW
      MISC. STATION AUX. PWR      =     .00  MW
      TOTAL POWER CONSUMPTION =        35.62  MW


      NET POWER OUT               =  120.45  MW


      POWER SPLIT
      MHD (TOPPING)    =   51.0  PER CENT
      STEAM (SUBPOSED)=    49.0  PER CENT


       ENTHALPY EXTRACTION =     19.638%
      COAL FEED RATE     =  16.25  KG/SEC TO COMBUSTOR

      COAL FEED RATE     =    .36  KG/SEC TO GASIFIER

      FUEL FEED RATE     =    .00  KG/SEC TO DRYER

      TOTAL HEAT IN      =      345.  MW

      MHD EFFICIENCY     = .2304

      STEAM EFFICIENCY   = .3540

      OVERALL EFFICIENCY= .3487

      PLANT HEAT RATE    =     .979449+04  BTU/KW-HR
```

TABLE 2.2-4

MHD GENERATOR DESIGN DATA
(EXPANDED CONFIGURATION)

```
                        GENERATOR DESIGN

  POINT  LENGTH   D/D4     P      T     SIGMA        H       RHO      U        MU       S        N      MU*B     K      B
   600    .000   1.000  2.766  2575.   6.310    293685.   .3892   825.0   .2967   9191.8   .6517  1.7803   .750   6.00
   601    .239   1.020  2.666  2564.   6.140    268602.   .3771   818.0   .3079   9204.0   .6536  1.8475   .750   6.00
   602    .465   1.040  2.566  2553.   5.978    243576.   .3647   814.5   .3196   9205.3   .6545  1.9175   .750   6.00
   603    .699   1.060  2.486  2542.   5.816    218328.   .3523   810.8   .3317   9206.7   .6556  1.9901   .750   6.00
   604    .942   1.082  2.386  2531.   5.657    192669.   .3396   807.0   .3442   9208.2   .6568  2.0652   .750   6.00
   605   1.194   1.105  2.266  2520.   5.494    166467.   .3272   803.2   .3571   9209.6   .6582  2.1427   .750   6.00
   606   1.456   1.130  2.166  2508.   5.330    139611.   .3145   799.3   .3704   9211.3   .6597  2.2225   .750   6.00
   607   1.727   1.157  2.066  2496.   5.158    111989.   .3016   795.4   .3841   9212.8   .6613  2.3046   .750   6.00
   608   2.011   1.185  1.966  2483.   4.972     83503.   .2889   791.3   .3976   9214.3   .6629  2.3974   .750   6.00
   609   2.313   1.216  1.866  2469.   4.823     54177.   .2761   786.2   .4254   9218.3   .6651  2.5526   .750   6.00
   610   2.628   1.250  1.766  2455.   4.670     23794.   .2631   780.8   .4536   9222.7   .6675  2.7214   .750   6.00
   611   2.957   1.287  1.686  2440.   4.514     -7790.   .2500   775.2   .4839   9227.3   .6700  2.9035   .750   6.00
   612   3.302   1.328  1.586  2425.   4.353    -40746.   .2368   769.3   .5164   9232.1   .6727  3.0983   .750   6.00
   613   3.672   1.372  1.466  2409.   4.187    -75525.   .2235   763.2   .5509   9237.0   .6725  3.2232   .750   5.85
   614   4.061   1.421  1.366  2392.   4.000   -111931.   .2101   756.8   .5873   9241.8   .6724  3.3428   .750   5.69
   615   4.539   1.476  1.266  2373.   3.778   -150636.   .1966   750.2   .6254   9246.2   .6723  3.4654   .750   5.54
   616   5.056   1.537  1.166  2354.   3.539   -191979.   .1829   743.3   .6651   9250.1   .6725  3.5904   .750   5.40
   617   5.642   1.606  1.066  2333.   3.286   -236401.   .1691   736.1   .7061   9253.4   .6730  3.7171   .750   5.26
   618   6.313   1.665   .966  2310.   3.022   -284460.   .1552   728.7   .7461   9255.9   .6739  3.8447   .750   5.14
   619   7.067   1.776   .866  2285.   2.724   -336921.   .1411   721.0   .7906   9256.9   .6749  3.9723   .750   5.02
   620   8.001   1.884   .766  2257.   2.388   -394799.   .1269   713.1   .8339   9255.9   .6758  4.0989   .750   4.92
     7   9.105   2.013   .666  2225.   2.045   -459423.   .1124   704.9   .8764   9252.4   .6772  4.2230   .750   4.82


  POINT  LENGTH   CURRENT   VOLTAGE  VOLTAGE    HALL     MACH      POWER     VOLT
                  DENSITY            (O.C.)     FIELD     NO.                DROP
   600    .000    7717.2    3173.1   4230.7    2177.3   .91615      .000    50.000
   601    .239    7437.7    3206.6   4275.5    2237.9   .91055     2.490    55.342
   602    .465    7195.2    3247.4   4326.5    2307.8   .90870     2.352    65.199
   603    .699    6957.5    3289.5   4386.0    2380.0   .90675     2.435    74.311
   604    .942    6722.0    3338.0   4448.0    2455.2   .90473     2.523    83.127
   605   1.194    6488.0    3386.2   4514.9    2530.2   .90265     2.617    91.630
   606   1.456    6255.2    3440.5   4567.4    2606.1   .90055     2.719    99.807
   607   1.727    6015.0    3499.5   4666.0    2687.6   .89844     2.827   107.605
   608   2.011    5762.1    3563.1   4750.8    2778.3   .89616     2.953   114.944
   609   2.313    5547.2    3629.9   4839.8    2930.2   .89295     3.151   122.131
   610   2.628    5330.0    3702.2   4936.3    3106.1   .88949     3.313   129.262
   611   2.957    5110.3    3781.2   5041.6    3267.4   .88579     3.490   135.995
   612   3.302    4868.2    3868.0   5157.3    3479.2   .88190     3.685   142.296
   613   3.672    4543.9    3865.4   5151.3    3498.1   .87769     3.793   147.014
   614   4.061    4186.1    3858.3   5144.4    3498.1   .87372     3.995   149.832
   615   4.539    3614.0    3864.6   5152.0    3498.1   .86940     4.220   151.722
   616   5.056    3448.3    3884.7   5179.6    3498.2   .86487     4.508   152.781
   617   5.642    3092.1    3921.3   5228.4    3498.3   .86019     4.832   153.206
   618   6.313    2749.8    3977.9   5303.9    3498.4   .85544     5.215   153.013
   619   7.067    2399.2    4059.1   5412.1    3498.5   .85069     5.645   151.765
   620   8.001    2038.1    4171.6   5562.2    3498.6   .84590     6.152   148.754
     7   9.105    1694.4    4326.5   5768.6    3498.8   .84109     6.614   144.176


  MHD DUCT DIMENSIONS           CORE  CHANNEL          CORE  CHANNEL
                                 ELECTRODE           INSULATOR

  DUCT WIDTH AT INLET (M ) =  .865   .865             .432   .432

  DUCT  AREA AT INLET (M2) =  .374   .374

  DUCT WIDTH AT EXIT  (M ) = 1.741  1.647             .870   .977

  DUCT  AREA AT EXIT  (M2) = 1.515  1.604

  DUCT  TOTAL LENGTH  (M ) = 9.105  DUCT BLOCKAGE (%) =   16.03


   AVE. HYD. DIA =   .868  AVE. LENGTH/DIA. =  10.489
   ASPECT RATIO = 2.000
```

2.3 Cycle Description - Refined ETF-3 Initial Configuration

A revised heat balance has also been performed for the oxygen-enriched initial configuration of the ETF-3 shown schematically in Figure 2.3-1. The logic for the expansion from initial to final configuration in this case is essentially unchanged from that reported in the original conceptual design report for ETF-3. As in the expanded plant, the major change has been the addition of the seed quench tank and the consequent rearrangement of superheat and LTAH surfaces. This rearrangement should permit more flexibility in the control of the waste heat recovery systems temperatures than was previously achieved in ETF-3. By controlling the amount of recirculated stack gas flow, the temperatures into the heat recovery units can be altered. Further control can also be obtained by altering the dump heat exchanger dump heat rate for elevated temperature conditions.

It should be noted once more that the heat transfer components are designed to final configuration specifications and that the energy balances reported here reflect the performance expected from those components at the off-design flow conditions arising out of oxygen-enriched operation. The results of the Refined ETF-3 (initial) analysis are documented in Tables 2.3-1 through 2.3-4. The input parameter list for the oxygen-enriched case is shown in Table 2.3-7. In Table 2.3-2, state point data is reported for the gas and water-side of the initial configuration, based upon assumptions for component performance discussed above. The performance and heat transfer summary is given in Table 2.3-3. Data on channel performance, design, and pertinent plasma properties are documented in Table 2.3-4.

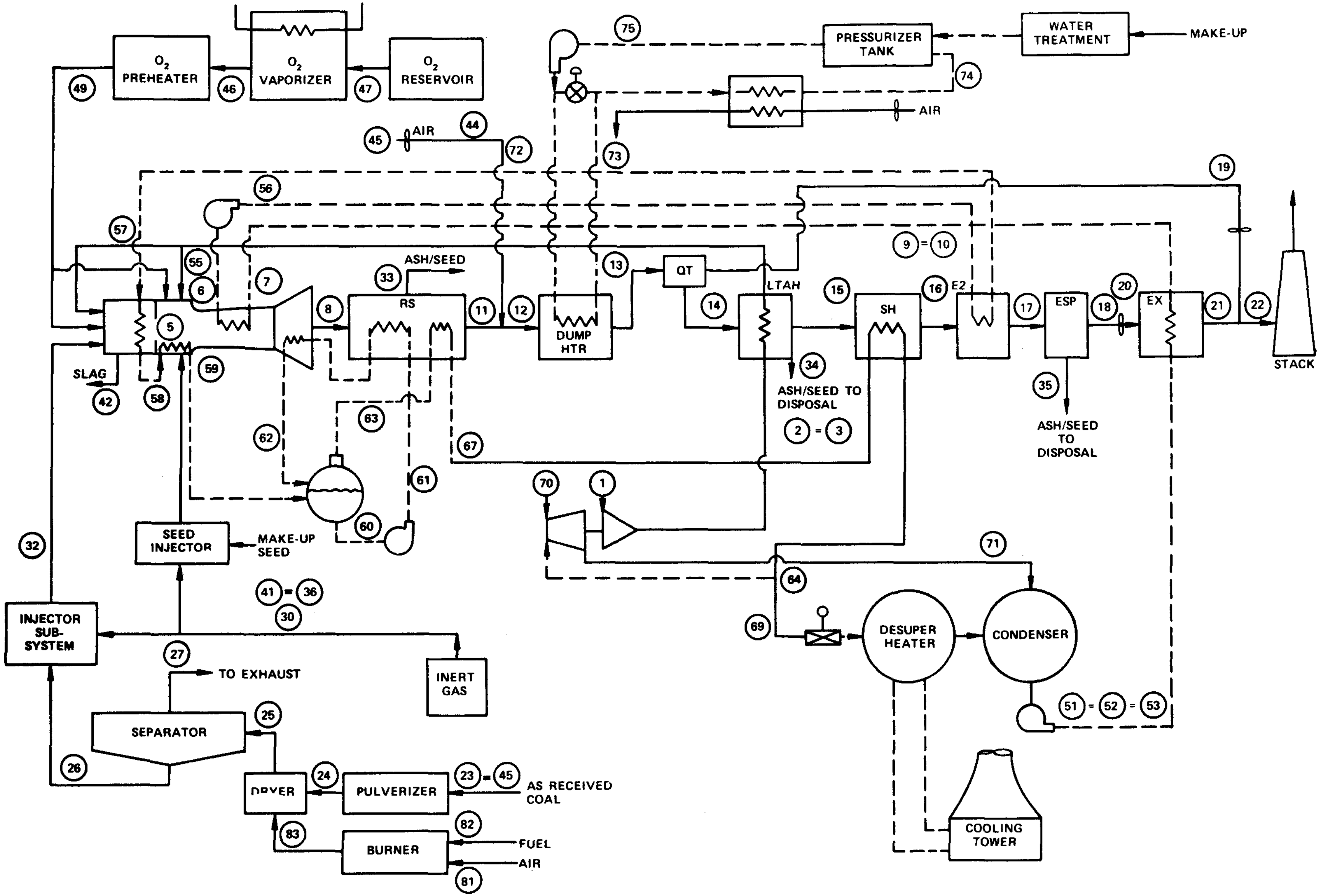


Figure 2.3-1. ETF-3 Refined Design (Initial Configuration)

TABLE 2.3-1

INPUT PARAMETER DATA
(INITIAL CONFIGURATION)

```
INPUT PARAMETERS

COMBUSTOR CONDITIONS : FOR AN MONTANA     COAL
  (AT  6% MOISTURE)   IN A TWO STAGE COMBUSTOR
 90% ASH REJECTION :  OVERALL PHI=    .950


PRESSURE =     4.7  ATM

TEMPERATURES

  2ND STAGE = 2728     DEGK


AIR PREHEAT TEMPERATURE = 1100.00  DEG K


INITIAL DUCT VELOCITY        =  825.0    M/S


FUEL/AIR RATIO (AS FIRED)    =  .2078    KG/KG


STEAM PLANT  :  1300PSI /  950F  (Hypothetical)


FW TEMP TO ECON AND COOLING =  345.5    DEGK



DUCT PARAMETERS

 B0=  6.00  T
 K0=   .75
  C=   .10
 DK=  .0000
  F=  .0070


COOLING SYSTEM HEAT TRANSFER RATES,   MW
     FROM COMBUSTOR TO COOLANT  =     21.3
     FROM NOZZLE    TO COOLANT  =      2.700
     FROM DIFFUSER  TO COOLANT  =     13.000



EFFICIENCIES

ROTATING GENERATOR            =       .9840
DC/AC INVERTER                =       .9600
DIFFUSER                      =       .5800
AIR COMPRESSOR                =       .8300
PUMPS                         =       .7000
BLOWER                        =       .8000
TRANSPORT GAS COMPRESSOR      =       .8300
```

LTAH EFFECTIVENESS = 0.750

TABLE 2.3-2

STATE POINT DATA
(INITIAL CONFIGURATION)

State Point	Pressure		Temperature		Enthalpy		Flow	
	atm	psia	°K	°F	joule/Kg	B/lb	Kg/Sec	(Lb/Sec)
1	.784	(11.52)	288.	(58.4)	15266.	6.56	63.6	(104.2)
2	5.0874	(74.78)	528.	(490.5)	261042.	112.2	63.6	(140.2)
3	5.0871	(74.78)	528.	(490.5)	261042.	112.2	63.6	(140.2)
4								
5	4.704	(69.15)	2728.	(4450.)	-208935.	-89.	86.5	(190.7)
6	2.6794	(39.38)	2583.	(4649.)	-580531.	-247.	86.5	(190.7)
7	.6794	(9.99)	2259.	(3603.)	-1343409.	-573.	86.5	(190.7)
8	.8707	(12.8)	2304.	(3687.)	-1244181.	-530.	86.5	(190.7)
9	4.9345	(72.54)	1100.	(1520.)	893079.	-381.	63.6	(140.2)
10	4.9345	(72.54)	1100.	(1520.)	893079.	-381.	63.6	(140.2)
11	.8446	(12.42)	1829.	(2832.)	-2155139.	-92.7	86.5	(190.7)
12	.8440	(12.40)	1823.	(2820.)	-2161000.	-840.45	93.0	(205.0)
13	.8404	(12.40)	1357.	(1982.6)	-2576900.	-1107.87	99.8	(220.)
14	.8404	(12.4)	1300.	(1880.)	-2651000.	-1139.73	99.8	(220.0)
15	.832	(12.23)	990.	(1322.)	-3049400.	-1311.	99.8	(220.0)
16	.8070	(11.86)	695.	(791.)	-3320100.	-1428.	99.8	(220.0)
17	.7828	(11.5)	588.	(598.)	-3434025.	-1477.	99.8	(220.0)
18	.7711	(11.34)	588.	(598.)	-3434025.	-1477.	99.8	(220.0)
19								
20	.820	(12.05)	588.	(598.)	-3434025.	-1477.	99.8	(220.0)
21	.800	(11.76)	520.	(476.)	-3552260.	-1528.	99.8	
52	62.5	(918.)	345.5	(151.9)	307170.	(132.)	67.3	148.4
53	62.5	(918.)	345.5		307170		67.3	148.4
54	58.5	(860.)	393.	(248.)	497031.	(214.)	67.3	148.4
55	55.1	(810.)	459.	(366.)	781200.	(336.)	67.3	148.4
56	115.0	(1690.)	459.	(366.)	781200.	(336.)	67.3	148.4
57	111.0	(1632.)	494.	(430.)	950590.	(409.)	67.3	148.4
58	107.8	(1585.)	554.	(537.)	1267080.	(544.)	67.3	148.4
59	103.5	(1521.)	570.	(565.)	1307199.	(563.)	67.3	148.4
60	103.5	(1521.)	587.9	(598.2)	1428200.	(614.)	350.	771.75
61	115.9	(1704.)	587.9	(598.2)	1435196.	(617.)	350.	771.75
62	103.5	(1521.)	587.9	(599.)	1678541.	(722.)	350	771.75
63	103.5	(1521.)	587.9	(599.)	2718800.	(1169.)	67.3	148.4
64	80.0	(1176.)	705.	(810.)	3226710.	(1387.)	67.3	148.4
65								
66								
67	85.	(1250.)	597.	(615.)	2823244.	1214.	67.3	148.4
72	2.36	(35.)	311.	(99.8)	158371.	68.	916.4	2020.
73	1.0	(14.7)	325.	(125.)	216299.	93.	916.4	2020.

TABLE 2.3-3

PERFORMANCE SUMMARY
(INITIAL CONFIGURATION)

Heat Transfer	
Q to Steam in Radiant Boiler	73.98 MW
Q to Steam in Radiant Superheater	4.82 MW
Q to Steam in Superheater	27.2 MW
Q to Steam in Economizer No. 2	11.4 MW
Q to Steam in Economizer No. 1	12.8 MW
Q to Steam in Cooling Loops	59.4 MW
Total Heat to Steam	189.6 MW
Q to Water in Dump Exchanger	53.09 MW
Q to Air in Low Temperature Air Heater	40.19 MW
Total Heat Transferred	282.88 MW
Power Generation	
MHD Power	54.6 MW
Compressor Drive	15.64 MW
Gross Power Out	70.24 MW
Power Consumption	
Compressor Power	15.64 MW
Pump Power	2.35 MW
Draft Fans	1.63 MW
Cooling Tower Pumps	.89 MW
Coal Pulverizers	.90 MW
Raw Material Handling	.50 MW
ESP	.07 MW
MHD Magnet	.05 MW
Total Power Consumption	22.03 MW
Net Power Out	48.21 MW
Heat Rejected in Desuperheater Condenser	147. MW
Heat Rejected in Dump Exchanger	53.09 MW
Coal Feed Rate	13.2 kg/sec
Total Heat In	354. MW
MHD Efficiency	15.4 %
Plant Efficiency	13.62%
Heat Rate	37118 Btu/KW hr

TABLE 2.3-4

MHD GENERATOR DESIGN DATA
(INITIAL CONFIGURATION)

```
                GENERATOR DESIGN

POINT  LENGTH   D/D4     P      T    SIGMA      H        RHO      U      MU       S       N     MU*B     K     B
 600    .000   1.000  2.692  2583.  5.703   -580531.   .3820   820.0   .2778  9220.1  .6301  1.6667  .750  6.00
 601    .266   1.022  2.592  2572.  5.548   -608742.   .3696   816.6   .2882  9235.6  .6327  1.7293  .750  6.00
 602    .510   1.042  2.492  2561.  5.403   -636421.   .3571   812.9   .2990  9235.9  .6340  1.7942  .750  6.00
 603    .763   1.063  2.392  2550.  5.259   -664230.   .3445   809.2   .3102  9236.4  .6357  1.8614  .750  6.00
 604   1.025   1.086  2.292  2539.  5.116   -692403.   .3317   805.3   .3218  9237.0  .6375  1.9308  .750  6.00
 605   1.298   1.110  2.192  2528.  4.971   -721100.   .3189   801.4   .3337  9237.6  .6395  2.0022  .750  6.00
 606   1.581   1.136  2.092  2516.  4.825   -750423.   .3060   797.4   .3459  9238.3  .6417  2.0756  .750  6.00
 607   1.876   1.165  1.992  2504.  4.681   -780515.   .2929   793.3   .3592  9239.1  .6441  2.1553  .750  6.00
 608   2.167   1.195  1.892  2491.  4.562   -811396.   .2799   788.3   .3824  9242.4  .6471  2.2941  .750  6.00
 609   2.511   1.228  1.792  2477.  4.433   -843261.   .2667   783.1   .4075  9245.8  .6501  2.4451  .750  6.00
 610   2.850   1.265  1.692  2463.  4.298   -876252.   .2534   777.5   .4347  9249.5  .6533  2.6080  .750  6.00
 611   3.204   1.304  1.592  2448.  4.159   -910540.   .2401   771.6   .4637  9253.5  .6567  2.7824  .750  6.00
 612   3.576   1.348  1.492  2433.  4.013   -946326.   .2266   765.5   .4946  9257.5  .6602  2.9678  .750  6.00
 613   3.966   1.396  1.392  2417.  3.842   -983847.   .2130   759.1   .5273  9261.7  .6639  3.1636  .750  6.00
 614   4.385   1.450  1.292  2400.  3.707  -1023285.   .1992   752.6   .5615  9265.8  .6646  3.2840  .750  5.85
 615   4.852   1.510  1.192  2381.  3.502  -1065372.   .1854   745.8   .5972  9269.1  .6651  3.4022  .750  5.70
 616   5.379   1.578  1.092  2362.  3.279  -1110537.   .1714   738.7   .6340  9271.7  .6661  3.5223  .750  5.56
 617   5.977   1.655   .992  2341.  3.041  -1159339.   .1573   731.2   .6719  9273.4  .6675  3.6436  .750  5.42
 618   6.660   1.745   .892  2318.  2.793  -1212495.   .1430   723.5   .7104  9274.0  .6695  3.7651  .750  5.30
 619   7.448   1.851   .792  2292.  2.525  -1270992.   .1285   715.7   .7493  9272.9  .6720  3.8856  .750  5.19
 620   8.377   1.978   .692  2263.  2.198  -1336299.   .1139   707.6   .7879  9268.7  .6741  4.0039  .750  5.08
 7     8.485   1.992   .682  2260.  2.164  -1343409.   .1124   706.5   .7918  9268.2  .6747  4.0162  .750  5.07


POINT  LENGTH  CURRENT  VOLTAGE  VOLTAGE    HALL     MACH     POWER     VOLT
               DENSITY           (O.C.)     FIELD    NO.                DROP
 600    .000   6961.7   2712.5   3616.7    2034.7   .91451     .000    50.000
 601    .266   6674.0   2739.7   3653.0    2086.5   .90733    1.824    55.352
 602    .510   6474.5   2774.5   3699.3    2150.1   .90543    1.674    65.057
 603    .763   6260.3   2812.5   3750.0    2215.7   .90340    1.737    73.694
 604   1.025   6048.5   2853.7   3804.9    2282.9   .90128    1.804    82.457
 605   1.298   5838.3   2898.3   3864.4    2351.7   .89909    1.877    90.730
 606   1.581   5629.9   2946.9   3929.1    2421.9   .89687    1.955    98.699
 607   1.876   5426.5   2999.7   3999.6    2498.4   .89458    2.044   106.375
 608   2.187   5248.3   3055.1   4073.5    2639.0   .89143    2.180   113.968
 609   2.511   5059.0   3115.3   4153.7    2790.5   .88804    2.293   121.426
 610   2.850   4865.7   3181.0   4241.4    2952.2   .88437    2.421   128.480
 611   3.204   4668.1   3253.3   4337.8    3123.2   .88044    2.561   135.137
 612   3.576   4466.2   3333.3   4444.4    3302.6   .87630    2.716   141.348
 613   3.966   4260.7   3422.5   4563.4    3489.8   .87200    2.888   147.072
 614   4.385   3948.2   3431.8   4575.7    3498.0   .86761    2.997   151.112
 615   4.852   3600.1   3449.4   4599.3    3497.9   .86314    3.179   152.849
 616   5.379   3256.0   3481.8   4642.4    3498.0   .85843    3.414   153.469
 617   5.977   2919.2   3531.8   4709.1    3498.1   .85353    3.691   153.436
 618   6.660   2594.9   3603.8   4805.0    3498.2   .84857    4.022   152.760
 619   7.448   2273.7   3703.6   4938.1    3498.4   .84371    4.417   151.308
 620   8.377   1920.5   3840.0   5120.0    3498.6   .83893    4.861   147.900
 7     8.485   1885.3   3858.3   5144.4    3499.8   .83814     .577   144.660


MHD DUCT DIMENSIONS                CORE  CHANNEL          CORE  CHANNEL
                                    ELECTRODE           INSULATOR

DUCT WIDTH AT INLET (M ) =  .741    .741             .370   .370

DUCT  AREA AT INLET (M2) =  .274    .274

DUCT WIDTH AT EXIT  (M ) = 1.476   1.596             .738   .858

DUCT  AREA AT EXIT  (M2) = 1.089   1.370

DUCT  TOTAL LENGTH  (M ) = 8.485  DUCT BLOCKAGE (%) =   20.50


 AVE. HYD. DIA =   .739  AVE. LENGTH/DIA. =  11.484
 ASPECT RATIO = 2.000
```

2.4 Discussion of Candidate Methods for Seed Quench

Seed/ash handling in the main gas stream where temperatures are between 1445°K and 1300°K presents a problem due to the phase change in K_2SO_4 at $\approx$ 1342°K. In this region, the viscosity of the molten seed begins to increase so that it becomes harder to remove the seed and ash as a slag. Furthermore, if the seed/ash mixture is not properly removed, a buildup of material could occur on any surfaces which are exposed to the gas, causing an increase in pressure drop and unacceptable corrosion of any duct surfaces.

Four options were considered for removing the seed from the duct gas or for solidifying the seed in the gas stream. These options are presented in Table 2.4-1 and include cold gas injection, removal using a pebble bed, cooling tubes, and cold gas injection (or cooling tubes) followed by a cyclone. Table 2.4-1 also presents the advantages and disadvantages of each option.

The pebble bed and cyclone options were discarded due to their high capital costs and pressure drop as compared to the cold gas injection and cooling tubes options. Although the first two options will cause a high solids loading in the steam generation equipment downstream, proper design and the use of traditional soot blower equipment should remove the light dust which results from fume production in the gas stream (1).

The technical feasibility of either the cold gas or cold tube method is uncertain but some test data for the cold tube approach exists. These experimental data and analytical studies (presented by Heywood and Womack (2)) show fume loading in the gas accounts for >90% of the K_2SO_4 in the MHD duct between the temperatures of 1450°K and 1300°K. This work was based on maintaining a temperature difference between the gas and the tube surface of at least 150°K. Furthermore, the K_2SO_4 which precipitated on the tubes was found to be a very powdery material, which should be easily removed by conventional soot blowing equipment.

---

(1) International Symposium on Magnetohydrodynamics Electrical Power Generation, Paris, July 6-11, 1964. Vol. 3., "Some Factors in Seed Recovery", A. B. Hart et al., pg 1349-1364.

(2) J. B. Heywood and G. J. Womack, Open-Cycle MHD Power Generation, pg 699-701.

TABLE 2.4-1

SEED REMOVAL OR SOLIDIFICATION OPTIONS

Option	Advantages	Disadvantages
Cold gas injection	Simple system Low capital investment (blower may be required) Low pressure drop	Loss of temperature potential Fume in duct Soot blower and rapper system required in steam plant
Cooling tubes	Lower total capital cost than cold gas injection Simple system Low pressure drop	Loss of temperature potential Fume in duct Soot blower and rapper system required in steam plant
Pebble bed	Clean gas after pebble bed system Removal of seed at one location Decreased electrostatic precipitator loading	Pressure drop up to 10 in. H_2O High capital cost Energy and temperature potential loss Pebble handling problem
Cyclone after fume production	Clean gas after cyclone Removal of seed at one location Decreased electrostatic precipitator loading	High capital cost High pressure drop due to fine particles

The choice between cold gas injection or the cooling tubes method should be based on capital cost as well as technical feasibility. The use of cooling tubes would not require more than rearrangement of the currently used heating surfaces to insure that the tube surface temperatures are at least 150°K less than the gas temperature (2). The cold gas injection, however, would involve the addition of a blower and recycle piping.

In view of the technical uncertainties involved in the seed precipitation systems, an approach was taken in the refined ETF-3 which would allow either the cold gas recycle, tube cooling, or a combination of these methods. In the heat balances contained herein, the quench tank was assumed to be adiabatic. However, in the actual design a portion of the superheater surface could be moved upstream of the LTAH and introduced into the quench tanks in order to assess the seed recovery capabilities of either approach.

2.5 Discussion of Results

2.5.1 Impact of Refined Design on Plant Costs

The two step iterative procedure used to define the ETF-3 expandable facility conceptual design and subsequently the refined design results in somewhat modified system characteristics. Overall energy efficiency is lower, thermal rating of the power plant higher, and therefore larger combustion products mass flow rates exist. Table 2.5-1, below, compares these parameters for the two cases.

TABLE 2.5-1. ETF-3 ORIGINAL AND REVISED PERFORMANCE

Parameter	Original ETF-3 (Concept Design)	Revised ETF-3 (Concept Design)
η Overall	42%	34.9 %
Thermal Rating	280 MW	345 MW
Generator Mass Flow	104 kg/s	120.1 kg/s

The ETF-3 power plant conceptual costing was based on the 280 MWt system. The following discussions summarize the procedure that was used for adjusting these costs to the 345 MWt refined ETF-3.

Cost scaling relationships were obtained based on the detailed cost data developed in the ETF-1, ETF-2, and ETF-3 original concept designs. This was done for each major ETF cost account. Specific scaling factors were based on gas mass flows, thermal plant rating or gross electrical power output depending on the account and equipment involved. Some exceptions were made. Notably, the magnet and steam bottom plant equipment. The magnet costs are not affected since channel length has not been significantly changed. Also, the same turbine-generator set is used and therefore its costs and the costs of associated auxiliaries are unaltered.

The adjusted plant costs for the refined ETF-3 are given in Table 2.5-1 which lists each major cost account, the basis used in scaling, and the revised costs. Also included are the indirects, engineering fee, construction equipment, and contingency costs which are taken as percentages of the direct capital equipment as reported in Volume I of the W ETF Conceptual Design Report.

TABLE 2.5-2

COST ESTIMATE FOR REFINED ETF-3 CONCEPTUAL DESIGN

Major Cost Account	Basis for Scaling	Scaling Exponent n	Revised Cost $\$ \times 10^6$
Account 21	Directly Applicable	N.A.	6.11
Account 22	Mass Flow	0.61	89.24
Account 23	Mass Flow	0.46	8.99
Account 24	Mass Flow	0.35	30.59
Account 25	Directly Applicable	N.A.	21.90
Account 26	Directly Applicable	N.A.	1.02
Account 27	Thermal Rating	0.115	4.42
Account 30	Power Output $/kw	N.A.	47.12

Total Direct Costs	209.39
Indirects	31.40
Const. Equipment & Supplies	20.7
Subtotal	261.44
Fee	15.69
Engineering	16.63
Contingency	19.55
Total Cost *	$\$313.3 \times 10^6$

* Does not include IDC, EDC

The total direct capital equipment costs (installed) for the revised ETF-3 expanded facility (final configuration) is 209.4 million dollars. This compares to the 203.6 million originally costed for ETF-3.

2.5.2 System Parametrics and Sensitivities

The following paragraphs review and summarize the results obtained in conducting a parametric study of key system parameters. These studies were, in part, direct results of issues raised by the ETF review committee and, in part, motivated by the lack of design precedence of certain specific components.

The studies, in general, were performed around the ETF-3 conceptual design but the specific set of parameters used may vary slightly from the ETF-3 conceptual design or the refined ETF-3 described above. However, for any given set of parametrics, a single consistant set of system parameters are employed.

2.5.2.1 Electric Motor Compressor Drives - ETF-3 Case Study

The W ETF conceptual designs assumed steam turbine drives for the air compressors. For the ETF-1 concept, steam for the turbine drive was taken at the hot-reheat line. Subsequent analysis by the Westinghouse Steam Turbine Division of this turbine generator set indicated this arrangement results in unfavorably loading the back-end blading of the low pressure steam turbine.

In the ETF-3 concept which used a non-reheat turbine generator set, steam for the compressor drive turbine is taken at the superheat line at throttle conditions. These conditions are relatively severe for commercially available variable speed drives.

In both ETF concepts 1 and 3, since steam turbine drives are used, the heat content of the combustion gas products must be sufficient to raise the steam required to drive the two compressors. Compressor power is a large fraction of the total power generated and thereby increases significantly the flow rate of the combustion gas products (plant thermal rating). Eliminating the steam turbine compressor drive and substituting an electric motor drive would alleviate the potential problems of integrating a steam turbine drive with the turbine generator set as well as reduce the overall plant size.

As part of the refined conceptual design effort, a preliminary assessment was made of using electric motor drives on the ETF-3 system. This work included developing the overall heat and mass balance and plant performance characteristics for this design as well as estimating the impact on plant capital costs. Results from the study are summarized in Tables 2.5-3 and 2.5-4. Table 2.5-3 compare the overall plant performance for the two cases. As indicated, with motor drives the plant thermal rating is reduced by nearly a third, even though both designs use the same 50 MW 1300 psi/950 turbine-generator set. Accompanying this size reduction is a marked reduction in MHD power output and therefore a smaller, less efficient channel. Overall system efficiency is also slightly lower.

The effect of eliminating the turbine drive on plant costs is shown in Table 2.5-4 The basis for costing is as described previously in Section 2.5.1. Cost scaling relationships were developed based on the ETF-1 and ETF-3 plant conceptual designs. The specific scaling factors were listed previously in Table 2.5-2.

The total direct costs for the ETF-3 that uses all electric motor compressor drives is estimated at 184.1 million dollars. This compares to the 206.4 million dollars determined for the revised ETF-3 design. Thus, a potential 22.3 million dollars savings in direct costs appear possible. The addition of indirects, fee contingency, etc., raise this to about a 33 million dollar savings, or about 10%. This savings, however, must be weighed against:

1. The power plant efficiency.
2. The inherent uncoupling of bottom plant from topping cycle which does not allow for demonstrating plant integrated control (as envisioned for commercial sized MHD steam power plants).

2.5.2.2 Combustor Heat Loss

MHD combustor designs and their requirements are not understood or developed to the extent that their performance can be calculated with great confidence. Because of this, it is important to show the impact of combustor performance on system performance in a parametric fashion. In this way, also, requirements for combustor design and performance can be better understood.

TABLE 2.5-3

COMPARISON OF PLANT CHARACTERISTICS
ETF-3 WITH/WITHOUT ELECTRIC MOTOR
COMPRESSOR DRIVES

Parameter	ETF-3 With Electric Motor Compressor Drives	Refined ETF-3 With Steam Turbine Compressor Drives
Plant Thermal Rating MW	220	345
Steam Plant Output MWe	50	50
MHD Channel Output MWe	46	79.6
Auxiliary Power Req. MW	21.8	35.6
Net Power MWe	74.3	120.5
Overall Energy Efficiency	33.8	34.9

TABLE 2.5-4

SUMMARY OF COST ESTIMATES FOR ETF-3 USING ELECTRIC MOTOR COMPRESSOR DRIVES

Account 21	\$ 5.56 x 10^6
Account 22	74.0 x 10^6
Account 23	7.28 x 10^6
Account 24	26.0 x 10^6
Account 25	21.90 x 10^6
Account 26	1.02 x 10^6
Account 27	4.16 x 10^6
Account 30	44.2 x 10^6
Total Direct Costs	\$184.12 x 10^6
Indirects	27.62 x 10^6
Const. Equip. & Supplies	18.4 x 10^6
Subtotal	\$230.14 x 10^6
Fee at 6%	13.81 x 10^6
Engineering	14.73 x 10^6
Contingency	17.46 x 10^6
Total Cost (1977 \$)	\$276.14 x 10^6

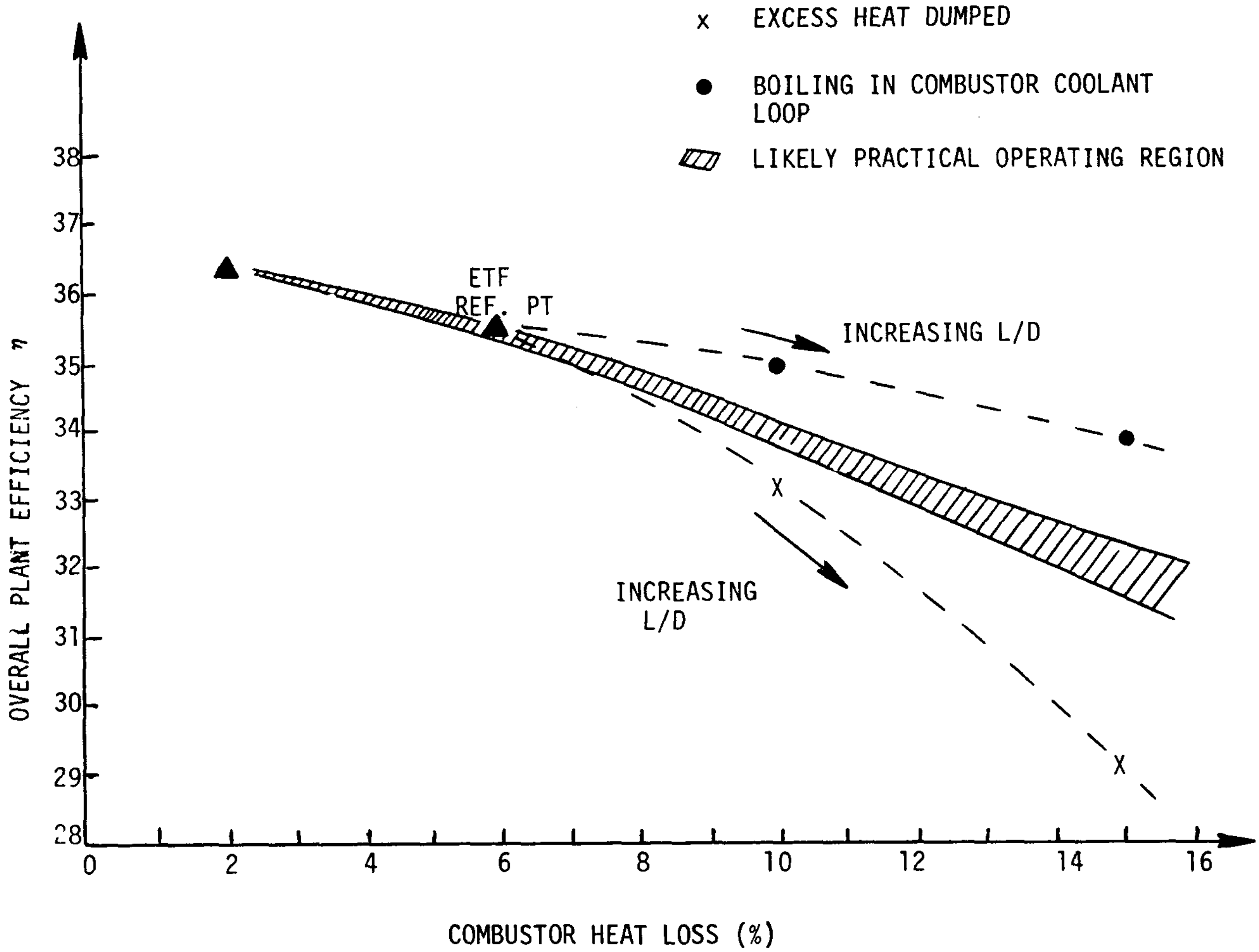
A series of system computations were made based on the ETF-3 system to determine how MHD channel and system performance are affected by combustor performance. Ten computer computations were made that utilized a common basis for calculation and systems modeling. With this basis, and to show the impact of combustor performance, selected combustor and system parameters were varied. These were:

- Combustor heat loss,
- System pressure ratio, and
- Assumptions concerning utilization of the combustor heat loss.

Results from this system study are shown in Figure 2.5-1 and tabulated in Table 2.5-5. Figure 2.5-1 shows the plot of overall plant efficiency as a function of combustor heat loss (as percent of the HHV of the coal input) for the different cases studied. The reference point is taken at 6% combustor heat loss. The particular system parameters corresponding to this point are listed. Note that this case and all the parametrics shown on the figure are based on the ETF-3 type direct fired, fully integrated power plant that uses a small 50 MWe non-reheat turbine generator set. In addition, these cases were computed for the ETF-3 case that assumes electric motor drives for the air compressor.

Referring to Figure 2.5-1, the two dotted lines show the effect of combustor heat loss under two different assumptions concerning the utilization of this heat in the steam bottom plant. The lower dotted curve assumes that only that fraction of the combustor heat loss that completes steam plant feedwater heating is utilized. That is, no steam generation is permitted in the combustor component cooling loops. Any excess heat from the combustor is therefore dumped to the cooling towers. For this case, as combustor heat loss is increased, it is seen that overall plant energy efficiency is significantly decreased.

The top dashed curve shows the counter example of utilizing all the combustor heat loss in the steam plant regardless of design implications. In this case, as the curve indicates, the overall energy efficiency decreases with increased combustor heat losses, but the overall impact is not as significant.



REF. POINT CONDITIONS

- DIRECT FIRED (2500°F)
- PR = 6
- COMBUSTOR PRESSURE - 4.7 ATM
- COMBUSTOR TEMPERATURE - 2750°K
- MHD POWER OUTPUT - 47 MW
- STEAM PLANT OUTPUT - 50 MW
- TOTAL HEAT IN (COAL) - 210 MWt

Figure 2.5-1. Summary of Impact of Combustor Performance on System Performance

TABLE 2.5-5

SUMMARY OF COMBUSTOR PERFORMANCE PARAMETRICS

- LARGE COMBUSTOR HEAT LOSSES DEGRADE SYSTEM PERFORMANCE
  - LOWER ATTAINABLE TEMPERATURE AND PLASMA CONDUCTIVITY
  - FORCES LOWER OPERATING PRESSURE RATIOS
- COMPLICATES COMPONENT COOLING DESIGN AND STEAM PLANT INTEGRATION

CASE	HEAT LOSS %	PRESSURE RATIO	FLAME TEMP. °K	σ CHANNEL MHO/M	POWER SPLIT MWe	CHANNEL LENGTH M	COMMENT
▲	6	6	2750	6.9	47/50	8	ETF Ref. Pt.
▲	2	6	2787	8.3	50/50	7	Low Combustor Loss
X	10	6	2711	5.6	48/50	10	- Heat Dumped
	15	6	2660	4.2	55/50	13	- L/D - Large
●	10	6	2711	5.6	44/50	10	- All Heat Utilized
	15	6	2660	4.2	39/50	13	- L/D - Large
	10	5	2700	6.2	39/50	7	
	15	5	2649	4.7	36/50	9	- Low Pressures
	15	4	2638	5.2	31/50	6	- Heat Utilized
	10	4	2687	6.8	33/50	5	- L/D Reasonable

combustor heat losses, but the overall impact is not as significant.

An important result that occurs in both cases is that as combustor heat loss is increased, the required MHD channel L/D also increases (for the given pressure ratio) leading to excessive channel lengths. The combustor flame temperature and plasma electrical conductivity are lowered as heat loss increases. To compensate for this effect, the channel length must be increased since it must still be sized to produce a power level that is determined by the overall system heat and mass balance. This balance is specifically constrained by the turbine-generator power output and by how the overall system is configured.

In these cases, to achieve practical generator lengths, one is then forced to reduce combustor pressure ratio. Several such reduced pressure cases were computed and are also shown in Figure 2.5-1 and listed in Table 2.5-5. Because of the reduced pressures, system performance decreases even though all the combustor heat loss is assumed to be utilized in the steam bottom plant. The shaded area in the figure represents those operating points where channel lengths are not excessive. Table 15 shows the pressure ratio values and respective channel characteristics that were used in computing this map.

This study shows that combustor performance (heat loss) can significantly affect the ETF-3 system performance. Therefore, combustor design requirements for heat loss should be set at such a level that system performance is not unduly sacrificed.

It should be emphasized that system performance with combustor heat loss would be system size dependent. With larger plant sizes, the same overall trend would still be predicted but the sensitivity of performance to combustor heat loss is not expected to be quite as large. Thus, the specific results presented herein must be interpreted only as applicable to the size system studied.

2.5.2.3 Channel Heat Loss

During the iterative study phase of the ETF-3 conceptual design an evaulation was made of the MHD channel heat loss effects. This has included, as described in Section 2.2, updating the Westinghouse Systems Codes to allow an explicit calculation (using standard turbulent flow modeling correlations) of the MHD channel heat flow. This model has now provided the means to evaluate in a systematic fashion the impact of the type of channel wall construction (hot, warm, or cold) on overall system performance. As a part of the conceptual design effort, such an analysis was conducted for the refined ETF-3 direct fired plant. Channel and system performance were calculated using the same overall plant configuration and set of downstream component performance constraints. Three channel wall temperature levels were considered; 2200°K, 1800°K (reference point), and 1000°K, roughly corresponding to hot wall, slag and cold wall construction.

In conducting such an analysis, various bases for comparison could be postulated. For this limited study, however, the basis chosen was to compare system performance for "equivalent" channels. This "equivalency" is established by requiring comparable channel L/D, boundary layer shape factor, and channel exit boundary layer blockage. This required each case to be computed using different channel pressure ratios. Furthermore, the computation assumes that a practical channel cooling system can be designed where all the heat loss through the channel walls is recovered and utilized in the steam bottom plant.

Results from the three study cases are tabulated in Table 2.5-6. As explained, the three cases were computed based on three different system pressure ratios (different combustor pressures - same diffuser exit pressure) to achieve approximately "equivalent" channel hydrodynamic characteristics. Results show, as expected, that the high channel wall temperature gives lowest heat loss. This was 10.9 MW or about 14% of the channel power output. The 1000°K cold wall shows nearly three times the heat loss or about 46% of its channel output. The reference 1800°K point gives 18.3 MW heat loss or about 26% of its channel power output.

In spite of these large differences, the overall energy efficiencies of each plant are not substantially different, there being about a 1/2 efficiency point difference between the high and low temperature case. Thus, for small, relatively

TABLE 2.5-6

SUMMARY OF CHANNEL HEAT LOSS EFFECTS - ETF-3 CASE STUDY

Case	T Wall (°K)	Channel Wall Heat Loss (MW)	Pressure Ratio	Channel L/D	Channel Length (M)	Channel Exit Blockage %	Boundary Layer Shape Factor	Channel Power Output (MWe)	Channel Mass Flow Kg/S	Overall Energy Efficiency %
1	2200	10.9	6.3	11.0	9.4	19.2	.78	75.3	116	36.7
2	1800	18.3	6.0	10.6	9.3	16.8	.77	70.7	112.3	36.6
3	1000	29.0	5.5	10.9	9.0	16.4	.77	63.4	106.5	36.2

low efficiency OCMHD power plants like ETF-3, it would appear that the channel heat loss does not greatly impact overall plant efficiency under the assumptions made in this study which include being able to effectively use all of the heat lost in producing steam for the bottoming plant.

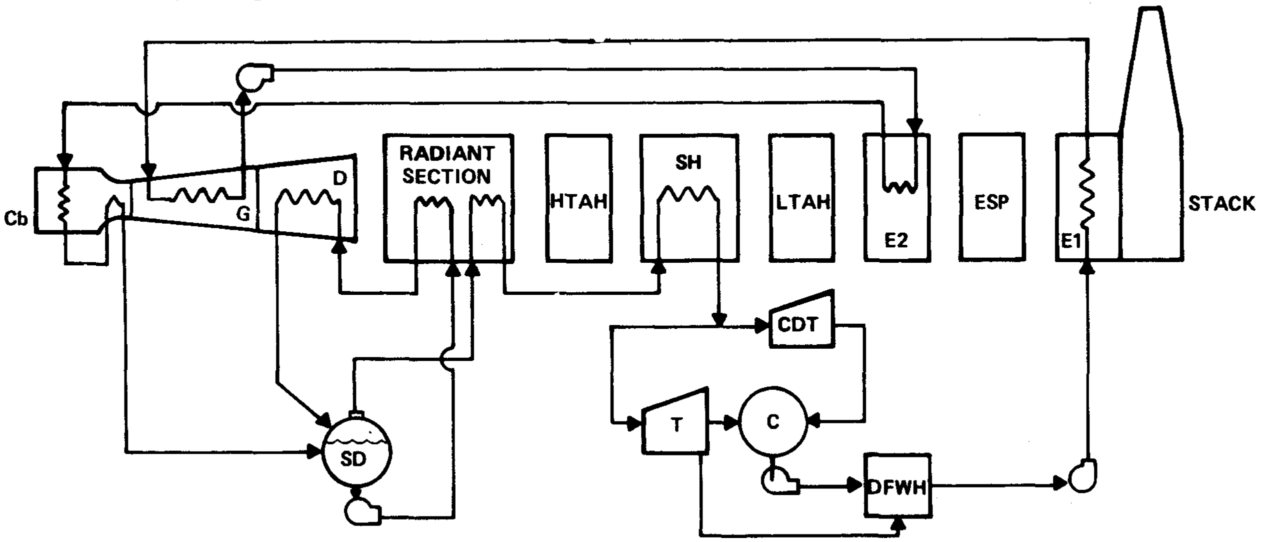
2.5.2.4 Turbine Extraction Versus No Extraction

In the conceptual designs for ETF-1 and ETF-3 which incorporate steam bottoming plants, the abundance of waste heat and the design advantages realized by cooling MHD components with sub-cooled water made a sufficiently strong case for the elimination of all but one stage of the turbine-generator extractive feedwater heating. Recognizing, however, that such actions increase the heat rate of the bottoming plant and could be detrimental to the overall power plant performance, a case was analyzed whereby the amount of extraction heating could be increased without necessitating a rise in stack temperature.

The steam-side circuitry for ETF-3 was amended as shown in Figure 2.5-2. A set of extractive feedwater heaters was interposed between the low temperature economizer and the channel coolant circuits. To eliminate two phase flow in the feedwater line due to this additional heat addition, the combustor coolant circuit was taken out of the feedwater train and placed in series with the boiling surfaces in the diffuser and radiant section. This action is only possible, it should be noted, if electrical isolation of high temperature water lines to the combustor can be effectively accomplished and if a practical cooling system for the combustor can be designed.

Heat rate calculations for the specified 1300 psig/950°F non-reheat steam turbine generator set were performed by Westinghouse Steam Turbine Division for a number of extraction cases. The variable parameter for these calculations was the exit enthalpy from the economizer interposed in the feedwater heater train. The three heat rates at constant steam throttle flow of 327,037 lb/hr for h_{out} = 250, 270, and 300 Btu/lb, were then used to establish the heat rate for the specific ETF-3 heat balance. In order to provide a common basis for comparison of extraction vs. non-extraction, the steam throttle flow for the ETF-3 concept was held constant at 55.92 kg/sec (442,886 lb/hr), sufficient to provide the

NON-EXTRACTION CASE



EXTRACTION CASE

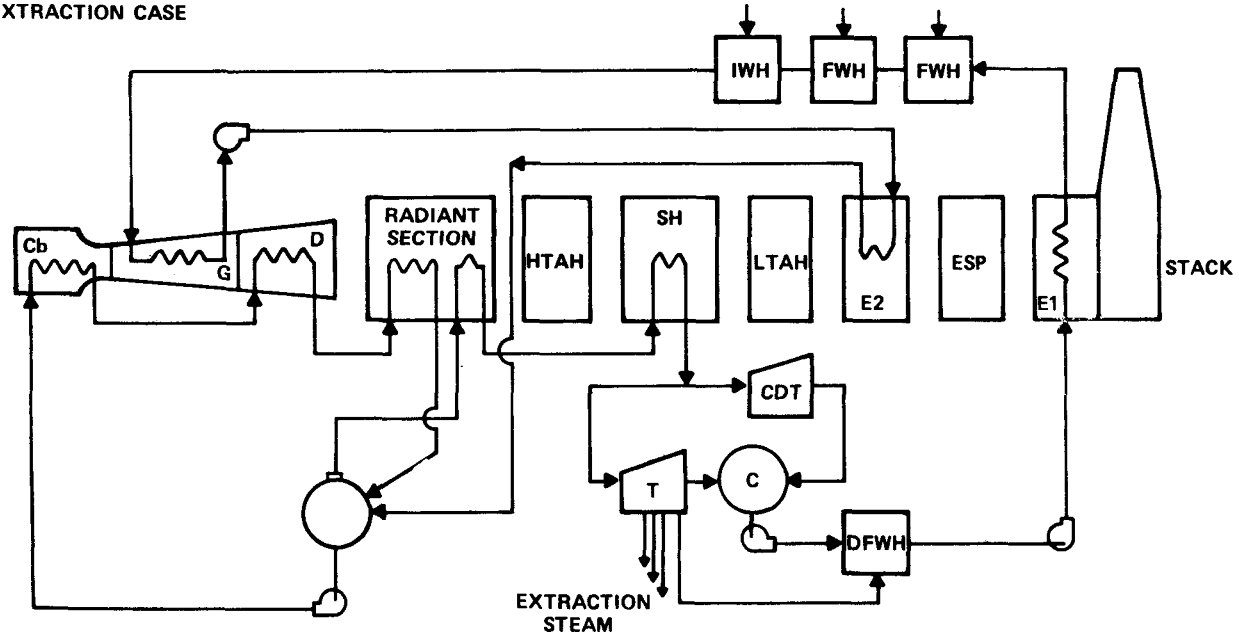


Figure 2.5-2. Steam-Side Circuitry for Extraction and Non-Extraction Configurations

the main steam turbine with 327,037 lb/hr and also power the compressor drive turbine. For an identical throttle-flow, of course, the heat required per unit steam flow from sources external to the steam plant are higher for the non-extraction case. Likewise, the power produced per unit steam flow is also higher for the non-extraction case. Thus, as a comparison of Tables 2.5-7 and 2.5-8 will bear out, the sum of the turbine-generator and compressor drive turbine power output is 61.7 MWe for a plant thermal rating of 273 MWt, while the extraction case provided a smaller plant rated at 238 MWt producing only 55.9 MWe. The overall plant efficiency is slightly better for the extraction case (35.72% or 9563 Btu/kw hr) as compared with the non-extraction plant (35.5% or 9625 Btu/kw hr). This is true notwithstanding a slight improvement in MHD duct performance (η = 23.04% compared to η = 22.4%) for the larger plant of the non-extraction concept due to lower heat losses.

Thus, for a turbine-generator operating at a constant throttle flow under an MHD topping plant designed to raise that fixed quantity of steam, extraction heating above the stack temperature permits a slight increase in overall plant efficiency while dropping the overall plant size. This configuration is only feasible, it should be noted, where any problems associated with high temperature, two-phase flow in the combustor coolant circuits and the feedlines required for electrical isolation can be overcome.

As reported in the attached memo, heat balances around the turbine-generator set were also performed for extraction cases at a constant turbine generator output of 50 MWe, varying the throttle flow rate. This would be an alternate basis for comparison to the constant flow case described above. However, no full MHD/steam cycle heat balance was performed using the constant power hypothesis.

For the constant power case, two different "last row" blades were investigated. Comparing heat rates (uncorrected) shows that different values are obtained as the extraction heating is increased (as measured by decreasing values for the "enthalpy LV, Economizer"). The trend, in fact, is opposite to that for the constant flow cases which showed lowest plant heat rate for highest extraction.

TABLE 2.5-7

ETF-3 HEAT BALANCE WITH NO EXTRACTIVE FEEDWATER HEATING

```
HEAT TRANSFER
Q TO STEAM IN RADIANT BOILER =         .651786+06   J/KG AIR
SUPERHEAT IN  RADIANT BOILER =         .149165+06   J/KG AIR
Q TO STEAM IN REHEATER       =         .000000      J/KG AIR
Q TO STEAM IN SUPERHEATER    =         .318325+06   J/KG AIR
Q TO STEAM IN ECONOMIZER #1  =         .158866+06   J/KG AIR
Q TO STEAM IN ECONOMIZER #2  =         .313927+06   J/KG AIR
Q TO STEAM IN COMBUSTOR      =         .203177+06   J/KG AIR
Q TO STEAM IN NOZZLE COOLANT =         .325009+05   J/KG AIR
Q TO STEAM IN CHANNEL        =         .107256+06   J/KG AIR
Q TO STEAM IN DIFFUSER       =         .156466+06   J/KG AIR
   TOTAL HEAT TO STEAM       =         .209149+07   J/KG AIR

Q TO AIR IN HI TEMP PREHEATER=         .654902+06   J/KG AIR
Q TO AIR IN LO TEMP PREHEATER=         .626859+06   J/KG AIR
Q TO COAL IN CRUSHER/DRYER   =         .153035+06   J/KG AIR


    TOTAL HEAT TRANSFERRED   =         .352628+07   J/KG AIR


  Steam Flow = 55.92 kg/sec
 HEAT LOST IN HTAH VALVES =     .576314+05J/KG AIR


POWER GENERATION

MHD POWER                     =   62.95   MW
TURB GEN POWER                =   50.00   MW
COMPRESSOR DRIVE              =   11.65   MW
GROSS POWER OUT               =  124.60   MW


POWER CONSUMPTION

COMPRESSOR POWER              =   20.85   MW
RECIRC PUMP POWER             =    1.72   MW
TRANSPORT GAS COMPRESSOR=           .00   MW
AIR INJECTION BLOWER          =    -.01   MW
FORCED DRAFT FANS             =    2.66   MW
ELECTRO. PRECIP. POWER        =     .05   MW
AIR HTR VALVE ACTUATORS       =     .00   MW
COOLING TWR CIRC. PMP         =     .72   MW
COAL PULVERIZERS              =    1.18   MW
MHD MAGNET POWER              =     .06   MW
RAW MATERIALS HANDLING        =     .40   MW
SEED TREATMENT SYSTEM         =     .00   MW
MISC. STATION AUX. PWR        =     .00   MW
TOTAL POWER CONSUMPTION       =   27.63   MW

NET POWER OUT                 =   96.97   MW


POWER SPLIT
MHD (TOPPING)     =    50.5   PER CENT
STEAM (SUBPOSED)=      49.5   PER CENT


COAL FEED RATE    =   12.66   KG/SEC TO COMBUSTOR

COAL FEED RATE    =     .29   KG/SEC TO GASIFIER

FUEL FEED RATE    =     .00   KG/SEC TO DRYER

TOTAL HEAT IN     =     273.   MW

MHD EFFICIENCY     = .2304

STEAM EFFICIENCY   = .3548

OVERALL EFFICIENCY= .3549

PLANT HEAT RATE    =     .962464+04  BTU/KW-HR
```

TABLE 2.5-8

ETF-3 HEAT BALANCE WITH EXTRACTIVE FEEDWATER HEATING

```
HEAT TRANSFER
Q TO STEAM IN RADIANT BOILER =        .461911+06   J/KG AIR
SUPERHEAT IN  RADIANT BOILER =        .218416+06   J/KG AIR
Q TO STEAM IN REHEATER       =        .000000      J/KG AIR
Q TO STEAM IN SUPERHEATER    =        .318325+06   J/KG AIR
Q TO STEAM IN ECONOMIZER #1  =        .158868+06   J/KG AIR
Q TO STEAM IN ECONOMIZER #2  =        .313927+06   J/KG AIR
Q TO STEAM IN COMBUSTOR      =        .203177+06   J/KG AIR
Q TO STEAM IN NOZZLE COOLANT =        .373532+05   J/KG AIR
Q TO STEAM IN CHANNEL        =        .219824+06   J/KG AIR
Q TO STEAM IN DIFFUSER       =        .179849+06   J/KG AIR
Q TO STEAM IN EXTR. HTR.     =        .289659+06   J/KG AIR
   TOTAL HEAT TO STEAM       =        .240131+07   J/KG AIR

Q TO AIR IN HI TEMP PREHEATER=        .654902+06   J/KG AIR
Q TO AIR IN LO TEMP PREHEATER=        .626859+06   J/KG AIR
Q TO COAL IN CRUSHER/DRYER   =        .153035+06   J/KG AIR


    TOTAL HEAT TRANSFERRED   =        .354645+07   J/KG AIR

←Steam Flow = 55.92 kg/sec

 HEAT LOST IN HTAH VALVES =     .576314+05J/KG AIR


POWER GENERATION

MHD POWER                   =    53.35   MW
TURB GEN POWER              =    37.72   MW
COMPRESSOR DRIVE            =    18.14   MW
GROSS POWER OUT             =   109.21   MW


POWER CONSUMPTION

COMPRESSOR POWER            =    18.14   MW
RECIRC PUMP POWER           =     1.66   MW
TRANSPORT GAS COMPRESSOR=          .00   MW
AIR INJECTION BLOWER        =     -.01   MW
FORCED DRAFT FANS           =     2.32   MW
ELECTRO. PRECIP. POWER      =      .05   MW
AIR HTR VALVE ACTUATORS     =      .00   MW
COOLING TWR CIRC. PMP       =      .71   MW
COAL PULVERIZERS            =     1.02   MW
MHD MAGNET POWER            =      .05   MW
RAW MATERIALS HANDLING      =      .35   MW
SEED TREATMENT SYSTEM       =      .00   MW
MISC. STATION AUX. PWR      =      .00   MW
TOTAL POWER CONSUMPTION     =    24.29   MW

NET POWER OUT               =    84.91   MW


POWER SPLIT
MHD (TOPPING)     =    48.8  PER CENT
STEAM (SUBPOSED)=      51.2  PER CENT


COAL FEED RATE      =  11.19  KG/SEC TO COMBUSTOR

COAL FEED RATE      =    .25  KG/SEC TO GASIFIER

FUEL FEED RATE      =    .00  KG/SEC TO DRYER

TOTAL HEAT IN       =     238.   MW

MHD EFFICIENCY      = .2244

STEAM EFFICIENCY    = .3660

OVERALL EFFICIENCY= .3572


PLANT HEAT RATE     =     .956315+04  BTU/KW-HR
```

These data demonstrate that the question of extraction feedwater heating as it relates to combined cycle plant optimization requires detailed analysis considering multiple operating points and specific design alternatives.

3.0 SUMMARY OF DOE REVIEW COMMITTEE MEETINGS AND ACTIONS

During the December - January time period, a series of design meetings were held with DOE appointed committees to review the various ETF-component and subsystem designs.

The purpose of this section is to summarize the major material covered in their presentations and to provide documentation of the important issues raised by the review committee and any subsequent action taken by Westinghouse. In preparation of the presentations most of the material that was covered was extracted from the Westinghouse MHD-ETF Conceptual Design report.

The copies of visuals used in the presentation and attached herein represent information not specifically included in the Conceptual Design Report. Other material used was extracted directly from the report.

The summary reported herein is divided into the following sections, corresponding to the specific committee meetings.

- Systems Analysis and MHD Components (Channel/Magnet/Power Conditioning)
- Downstream Heat Exchangers
- High Temperature Air Preheater
- MHD Combustor
- Seed Processing

3.1 SYSTEMS ANALYSIS AND MHD COMPONENTS

A meeting was held on December 14th and 15th, 1977 with DOE-ETF review committee to discuss the Westinghouse-ETF Systems Analysis and MHD Channel/Magnet/Power Conditioning facilities for the ETF conceptual designs.

The attached copies of visuals used represent information not included in the design report. The most significant of these is the table and chart which shows the effect on plant performance of "iterating" the conceptual design by providing up-dated steam plant and diffuser performance values. The table also shows the impact of key channel design assumptions.

The Westinghouse approach to channel design was one of facility requirements. That is to provide sufficient flexibility and a structural design and assembly that would allow for easy channel replacement and/or repair. The types of channel or specific channel performance is viewed as a development issue to be resolved in the CDIF or equivalent facility.

Pertinent points raised by the committee during these meetings were:

- The use of electric motor drives for the air compressor would reduce the plant thermal rating for the given turbine-generator set. [This approach has been subsequently studied by Westinghouse - See Section 2.4.3.]
- The committee felt that alternate system concepts could be defined using more "off-the-shelf" components such as a current technology gasifier that would be amendable to later incorporation of a more advanced technology gasifier, etc.
- Why did W stop at 1400°F in the LTAH for the separately fired case? Why not take more heat out; say down to 1000°F on the hot side. [This suggestion is reasonable from a technology standpoint in that it will reduce the difficulty of the LTAH - but it could require more energy into the separately fired leg to avoid pinch point problems.]
- Committee questioned the 4-1/2 percent combustor heat loss assumption! [See Section 2.4.3.]
- The committee questions any ETF concept (like ETF-2) that does not provide the full set of downstream heat exchangers and which does not demonstrate with steam generating components the needed NO_x control.

- The committee expressed concern for results of fixing the ETF-3 concept to a direct fired final configuration (high uncertainty in technology) and sees this as constraining any flexibility in using the add-on system. They see no freedom once design is fixed for later variation. Suggest Westinghouse check-out some "what-if" conditions to see if such flexibility does exist.

- The committee was skeptical of the 1 to 2 percent efficiency difference calculated in plant performance between ETF-1 and ETF-3. Also they questioned the calculated low 40 percent values. They feel it may be more like 30 percent. What should the ETF efficiency goals be? What would be the impact (response) if ETF were <30 percent. [Recalculated performance values for each of the Westinghouse-ETF concept designs have been completed as part of the reference design effort.]

3.1.1

VISUALS UTILIZED

SYSTEMS ANALYSIS AND MHD

ETF SYSTEM OPTIONS

- MHD HOT TRAIN ONLY WITH SIMULATED BOTTOMING SYSTEM
- SMALL INTEGRATED SYSTEM - NON-COMMERCIAL PERFORMANCE
- ADD-ON TOPPING TO EXISTING "BOTTOMING" SYSTEMS (FACILITY)
- EXPANDABLE - MHD HOT TRAIN TO INTEGRATED SYSTEMS

MAJOR ISSUES

- MHD PERFORMANCE DEMONSTRATION (OUTPUT AND ENDURANCE)
- INTEGRATED SYSTEM COMPATIBILITIES - PROBLEMS?
- SCHEDULING AND COST

GUIDELINE MODIFICATIONS

1. CONSIDERATION SHOULD BE GIVEN TO INCLUDING OR MAKING PROVISION FOR TURBINE GENERATOR INCLUSION.

2. LONG ENDURANCE OPERATION WITH CLEAN FUEL IN A SEPARATELY FIRED PRE-HEATER IS UNREALISTIC FOR ETF.

CONCEPTUAL DESIGN STUDY APPROACH

1. DEFINE THE CYCLES AND ARRIVE AT STATE POINT CONDITIONS
2. DEFINE PROCESS DIAGRAMS, AND INVESTIGATE SUBSYSTEM PER-
3. DEFINE HARDWARE - VENDOR IF AVAILABLE OR THROUGH CONCEPTUAL DESIGN
4. ESTIMATE COSTS FROM VENDOR OR FROM INTERNAL ESTIMATES ON CONCEPTUAL EQUIPMENT
5. INTEGRATE PLANT AND PERFORM TOTAL FACILITY COST ESTIMATING

1. INVESTIGATE SCALING CONSIDERATIONS AND DRAW CONCLUSIONS
2. OUTLINE PRELIMINARY TEST PLAN INCLUDING DEVELOPMENT LOGIC
3. OUTLINE PRELIMINARY SCHEDULES INCLUDING DEVELOPMENT PROGRAM
4. ESTIMATE DEVELOPMENT PROGRAM COSTS

CONCLUDE:
1. CONCEPT ALTERNATIVES
2. SYSTEM DESIGN AND INTEGRATION
3. COMPONENT DESIGN
4. COST AND SCHEDULE

RECOMMEND:
1. REFERENCE DESIGN DIRECTION

RECOMMENDATIONS FOR REFERENCE DESIGN

PROGRAM

- MINIMUM SUBSYSTEMS FOR SINGLE PARTY RESPONSIBILITY
    - MHD SYSTEM
    - SEED SYSTEM
- UTILIZE EVOLVING CONCEPT TO CONTROL RATE OF EXPENDITURE AND TO ASSURE FLEXIBILITY AND PROGRESSION CONSISTENT WITH DEVELOPMENT.
- MUST ESTABLISH ETF CONCEPT AS QUICKLY AS POSSILBE TO MAKE MEANINGFUL DEVELOPMENT PROGRESS. MUST ORIENT DEVELOPMENT GOALS TO ENDURANCE AT SPECIFIED PERFORMANCES.

DESIGN

- UTILIZE AN EVOLVING PLANT DESIGN WITH SMALLEST NON REHEAT TURBINE.
- UTILIZE A FLEXIBLE APPROACH TO HTAH TO PREVENT DELAY OR STAGNATION OF ETF EFFORT.
    - OIL FIRED FOR EARLY SHORT DURATION OPERATION
    - DEVELOPMENT AND EVOLUTION TO DIRECT FIRED
    - ALTERNATE EFFORT ON COAL FUEL BASED SEPARATELY FIRED
- DEFINE A SERIES OF EVOLUTIONARY STEPS, PROBABLY BEYOND TWO, INTEGRATED WITH A BASE DEVELOPMENT PROGRAM. MINIMUM CONFIGURATION SHOULD INCLUDE COMBUSTOR, NOZZLE CHANNEL, MAGNET AND POWER CONDITIONING WITH POWER TO GRID.
- RIGOUROUS DEFINITION OF DESIGN GOALS FOR MHD TRAIN.
- PROVIDE FOR POSITIVE SEED CONDENSATION.

COMPONENT SCALING CONSIDERATIONS

KEY QUESTIONS ADDRESSED:

- WHAT ARE PRINCIPAL COMPONENT PARAMETERS THAT SHOULD BE DEMONSTRATED?
- WHAT ARE SCALING IMPLICATIONS AND "FIRST PRINCIPLE" CONSTRAINTS?
- IS CURRENT TECHNOLOGY ADEQUATE?
- IS THERE A MINIMAL CONDITION (SIZE) NEEDED TO MEET ETF OBJECTIVES?

OBJECTIVE

DETERMINE THE MINIMUM SIZE SYSTEM FOR THE ETF TO ASSURE ACCEPTABLE UNCERTAINTY IN SCALING TO COMMERCIAL SIZE

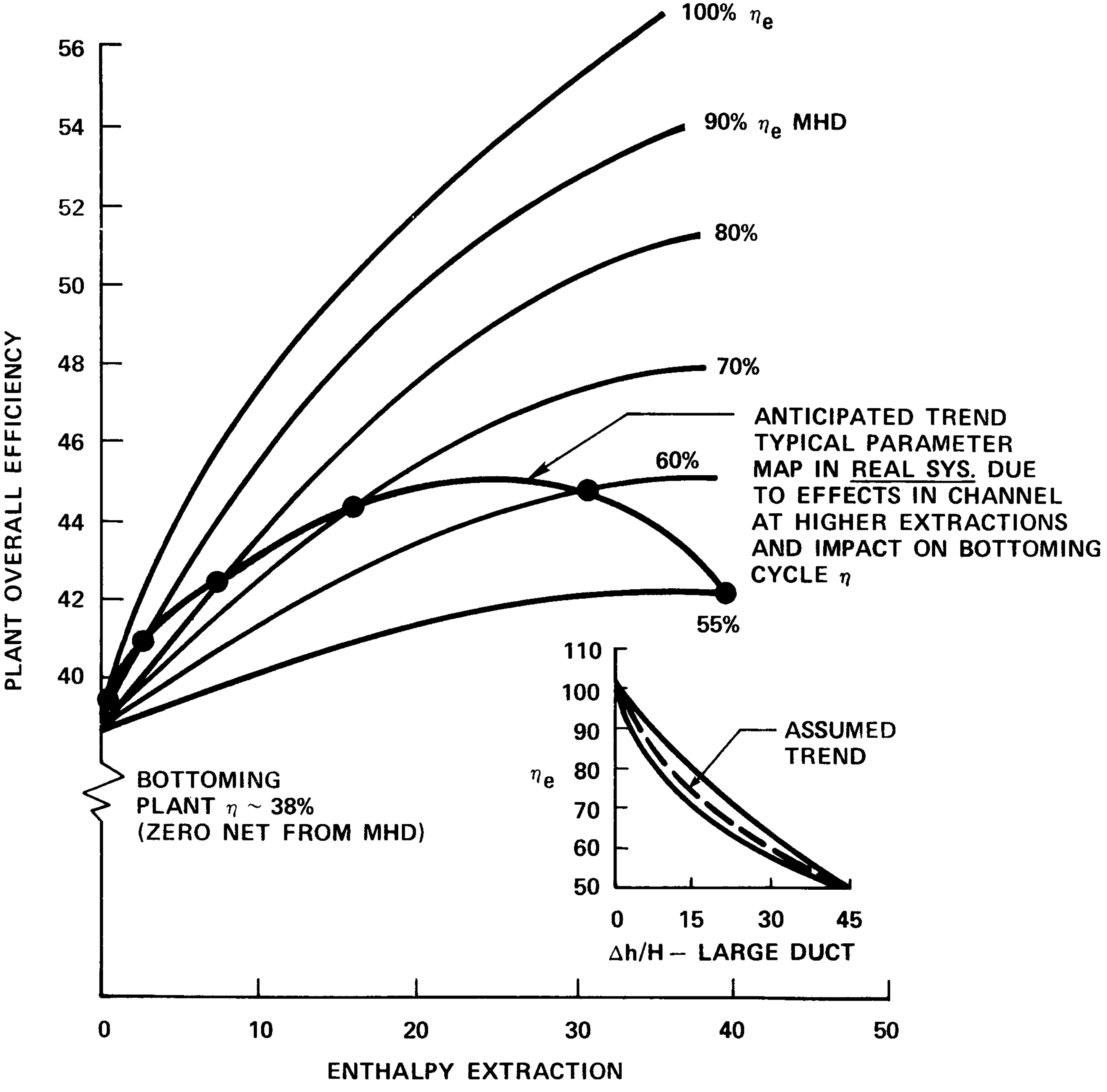
SPECIFIC CONSIDERATIONS WERE:

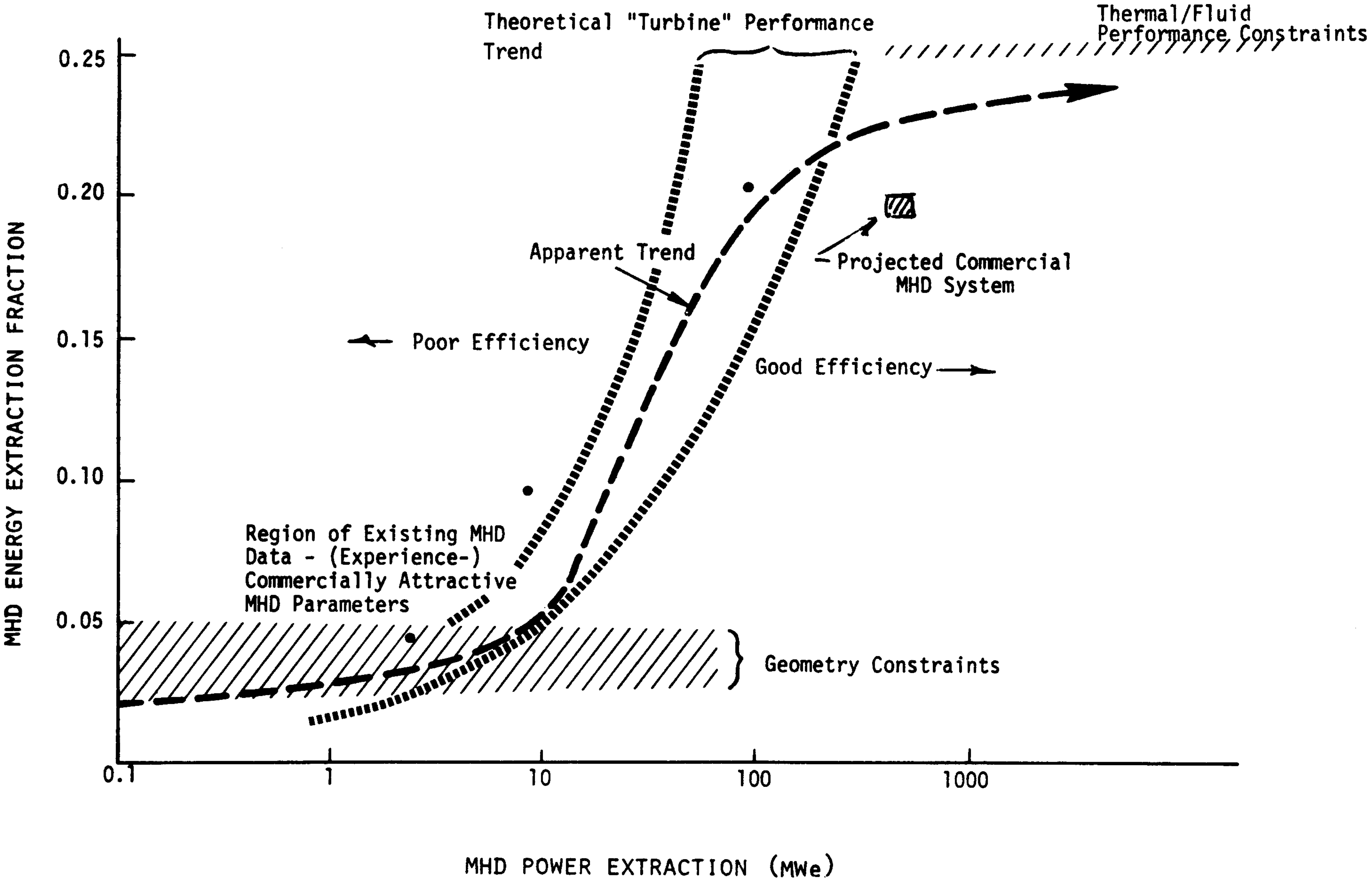
- DEFINITION OF COMPONENTS COMPRISING THE MHD SYSTEM WHICH POSE SCALING CONCERNS
- ESTABLISHING THE RANGE OF OPERATING CONDITIONS REQUIRED FOR DESIGN PURPOSES
- DETERMINE PRESENT TECHNOLOGY STATUS
- DETERMINE MINIMUM ACCEPTABLE SIZE OF MAJOR COMPONENTS FOR CONFIDENT SCALING TO COMMERCIAL SIZE

MAJOR SCALING CONSTRAINTS IDENTIFIED

- MINIMUM SIZE FOR NEEDED MHD ENTHALPY EXTRACTION DUE TO IMPACT ON PLANT DESIGN
- MAXIMUM THERMAL CAPACITY OF COMBUSTOR DUE TO TECHNOLOGY AND DESIGN PRECEDENCE

ESTIMATED PERFORMANCE TREND – MHD BINARY





Theoretical "Turbine" Performance Trend
Thermal/Fluid Performance Constraints
Apparent Trend
Projected Commercial MHD System
Poor Efficiency
Good Efficiency
Region of Existing MHD Data - (Experience-)
Commercially Attractive MHD Parameters
Geometry Constraints
MHD ENERGY EXTRACTION FRACTION
0.25
0.20
0.15
0.10
0.05
0.1
1
10
100
1000
MHD POWER EXTRACTION (MWe)

ESTIMATED PLANT CAPITAL INVESTMENT SUMMARY

Direct Costs:				
Non-Depreciating Assets				
Land and Land Rights	$ 5,866	$ 3,860	$ 4,497	$ 6,109
Depreciating Assets				
Special Materials	265,056	124,664	153,138	196,223
Physical Plant				
SUBTOTAL	$270,922	$128,524	$157,635	$202,332
Engineering (a)				
Construction Contingency				
Fee	136,240	64,141	78,828	101,486
Indirect Costs				
TOTAL CAPITAL	$407,162	$192,665	$236,463	$303,818
Escalation (@40%)(b)	162,865	77,066	94,585	121,527
Interest During Construction (@20%)(c)	114,005	53,946	66,210	85,069
TOTAL PLANT INVESTMENT	$684,032	$323,677	$397,258	$510,414

(a) From Table 3.2-8 consistent with current power plant costing experience based on A&E estimate.

(b) Based on 6.5%/yr for 5-1/2 years to time of procurement and construction (complete acquisition of major cost items).

(c) Based on 8%/yr on 63% of escalated capital cost for 3-1/2 years procurement period [as assessed from expenditure (cash flow "S" curve) from ECAS study].

COSTING FACTORS IMPACTING RESULTS

- Very high cost MHD system components have not been optimized. A large variation exists in acceptable parameter ranges, which should be optimized (e.g., trade-off of size versus performance efficiency).

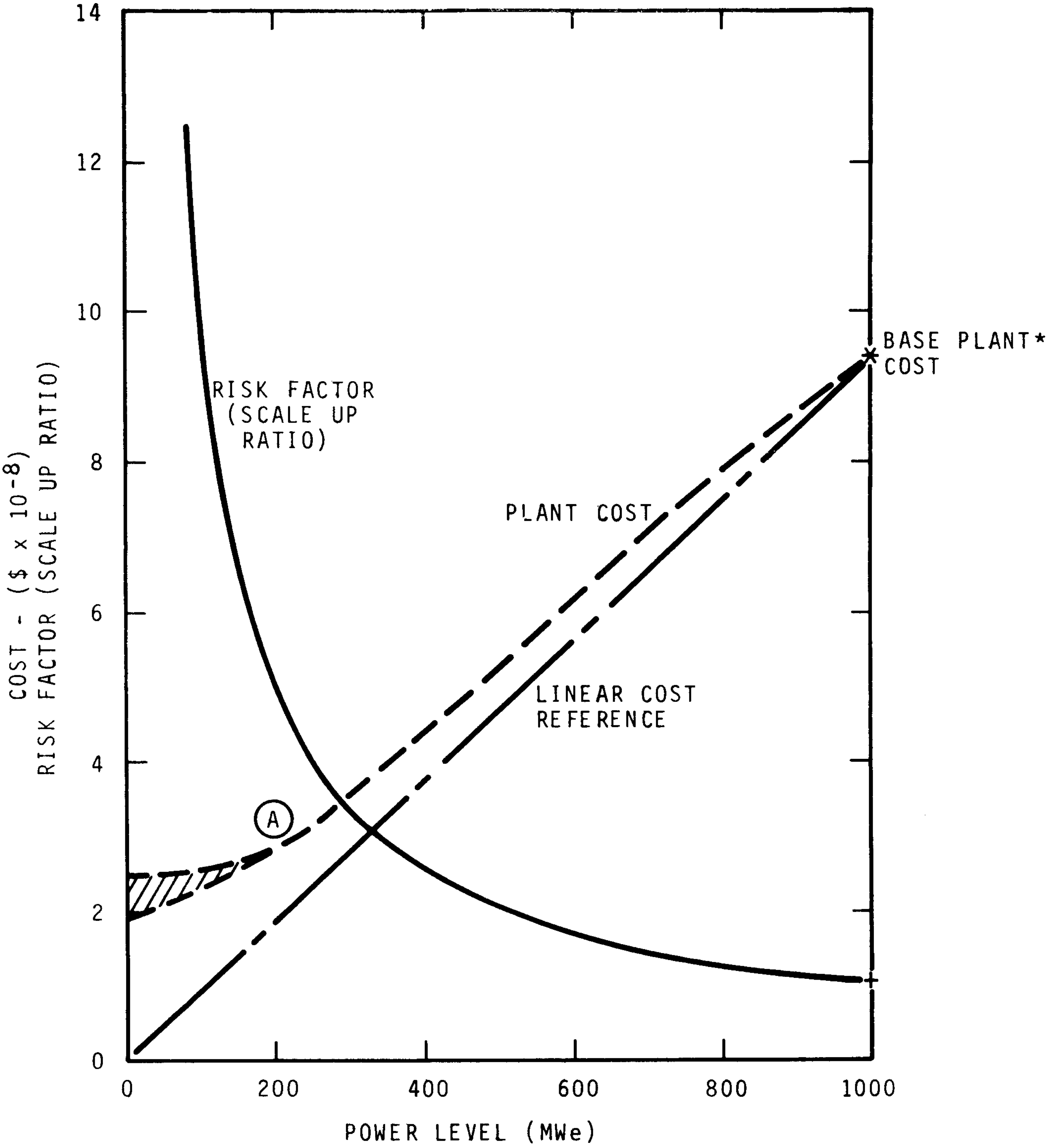
- Direct design experience/precedence with seed/slag conditions in some components is lacking, although of a similar concept to conventional units.

- Large MHD system and component performance involves some degree of uncertainty, because of the lack of both operating experience and design precedence. (It is, in fact, the purpose of the ETF to develop experience in both areas.)

- Currently, there is wide variation in vendor quotes and cost estimates for similar materials and equipment, as well as uncertainty in economy and inflationary effects on item cost estimates due to schedules.

- Comparative specific cost factors are lacking due to the state of cost data. (Costs included here are for as-delivered items with varying degree of accuracy in fabrication, field assembly, and erection costs.)

- Lack of sufficient component design detail to allow credible costing of detailing and tooling costs.



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*BASED ON STANDARD COAL FIRED STEAM PLANT COST AT $720/kWe - REF. 19, AND MINIMAL 30% ADDITION FOR EXCESS TOPPING CYCLE IMPACT - MHD SYSTEM

Simplified Cost/Risk Factor Trade-Off Comparison

PARAMETERS SPECIFIED FOR CYCLE ANALYSIS

- SITE AMBIENT CONDITIONS
- BOTTOM PLANT
  - ETF-1 - 1800 PSI/950°F
  - o ETF-2 - NONE
  - ETF-3 - 1300 PSI/950°F
- COAL MOISTURE AND TRANSPORT REQUIREMENTS
- o SEEDING LEVEL
- RADIANT BOILER RESIDENCE TIME AND EXIT GAS TEMPERATURE
- PLANT DRAFT
- TUBE METAL TEMPERATURES/FEEDWATER TEMPERATURE
- BOILER DRUM CONDITIONS - FEEDWATER SUBCOOLING
- COMBUSTOR STOICHIOMETRY/OVERALL STOICHOMETRY
- COMBUSTOR PRESSURE LEVEL
- CHANNEL PARAMETERS

  TYPE OF FLOW
  HALL FIELD LIMITATIONS
  PEAK MAGNETIC FIELD
  HEAT LOSS REQUIREMENTS
- HIGH TEMPERATURE AIR PREHEATER
  - DIRECT FIRED
  - SEPARATELY FIRED
- LOW TEMPERATURE AIR HEATER
- O_2 ENRICHMENT

	SYSTEM PARAMETERS						CHANNEL PARAMETERS						SYSTEM OUTPUT					
CASE NO.	η_{St}	η_{COMP}	η_{DIFF}	η_{PC}	$\lambda_{\%}$	Pcomb	Type		λ_2	Δ	K	$\frac{du}{dx}$	η_{cr}	Power MHD (MWe)	$\dot{M}$ (kg/g)	L (M)	SUB (°F)	T_z (°K)
1 - ETF-1	0.39	0.9	0.8	0.985	4.5	5.11	FAR.	0.005	0.10	0.	0.75	-	43.53	152.	187.	9.86	61.	2259
2								0.010					42.82	143.	182.	9.01	69.	2272
3									0.15				43.48	151.	186.6	10.35	37.	2242
4								0.010	0.15	200.			42.0	133.	177.	8.69		
5											0.70		42.43	138.	180.	8.69	74	2282
6									0.20				43.41	150.	186.	10.86	15.	2225
7												+	41.90	131.	176.	9.65	80.	2225
8 - ETF-1 REV	0.379	0.83	0.58	0.96									41.89	156.	197.	9.38	62.	2269
9	0.379	0.83	0.58	0.96				0.010	0.15	200.			40.42	136.	187.	8.77	55.	2284
10	0.379	0.83	0.58	0.96	10.0								40.97	145.	192.	12.4	BOIL	2212
11	0.379	0.83	0.58	0.96					0.40				41.45	148.	193.	12.5	BOIL	2173
12	0.379	0.83	0.58	0.96				0.010	0.40	200			40.04	130.	184.	10.6	BOIL	2213
13							DIAG.	0.007	0.75	180		-		120.	187.	11.0		2355
14	0.379	0.83	0.58	0.96				0.010	0.40	200		+	88.25	109.	173.	9.74	BOIL	2195

RECOMMENDED SYSTEM MODIFICATIONS FOR REFERENCE DESIGN STUDY

- SCALE ETF-3 CONCEPTUAL DESIGN WHERE APPLICABLE
- UPDATE MAJOR SYSTEM PARAMETERS BASED ON CONCEPTUAL DESIGN STUDY
    - CORRECTED STEAM PLANT EFFICIENCY
    - REVISED COMPRESSOR, DIFFUSER AND POWER CONDITIONING EFFICIENCIES
    - REVISED VALUES FOR COMPONENT HEAT LOSS
- UTILIZE UPDATED CHANNEL PERFORMANCE CODE
- DEVELOP A ETF RD INTERIM CONFIGURATION THAT UTILIZES SEPARATELY FIRED AIR PREHEATERS WITH COMMERCIAL GASIFIER
- MODIFY SYSTEM DESIGN IN THE FOLLOWING AREAS;
    - REMOVE COMPRESSOR DRIVE FROM STEAM PLANT TURBINE GENERATOR REHEAT CROSSOVER LINE
    - INTERPOSE SEPARATE COMPONENT COOLING SYSTEM BETWEEN THE COMBUSTOR, CHANNEL AND THE STEAM PLANT FEEDWATER
    - ESTABLISH FEEDWATER TEMPERATURE CONDITIONS COMPATIBLE WITH PRACTICAL COMPONENT DESIGNS THAT WILL ACCOMMODATE ELECTRICAL ISOLATION LIMITATIONS

CHANNEL DESIGN PHILOSOPHY AND APPROACH

- OBJECTIVE IN ETF CONCEPTUAL STUDY IS TO DEVELOP THE MHD CHANNEL DESIGN FROM AN OVERALL SYSTEM REQUIREMENT. DESIRABLE TO HAVE CAPABILITY TO INTERCHANGE CHANNELS.

- SELECTED SEGMENTED FARADAY CHANNEL FOR PURPOSES OF SIZING, COSTING AND SYSTEM INTEGRATION.

- SPECIFIED FOLLOWING PARAMETERS FOR CHANNEL CALCULATIONS

  FRICTION FACTOR
  HEAT LOSS FACTOR
  LOADING PARAMETER
  VELOCITY DECREMENT
  PEAK MAGNET FIELD
  HALL FIELD LIMITATION

- SPECIFIED FOLLOWING PARAMETERS FOR CHANNEL AND POWER CONDITIONING DESIGN

  - ELECTRODE PITCH
  - ASPECT RATIO
  - SEGMENTATION FACTOR

SUMMARY OF CHANNEL PARAMETERS FOR ETF

CHANNEL PARAMETER	ETF-1	ETF-2	ETF-3
FRICTION FACTOR*	.005	.005	.005
HEAT LOSS FACTOR*	0.10	0.10	0.10
LOADING PARAMETER*	0.75	0.75	0.75
VELOCITY DECREMENT*	0.10	0.10	0.10
PEAK MAGNET FIELD	6T	6T	6T
HALL FIELD LIMITATION	3500	3500	3500
ELECTRODE PITCH	1 CM	1 CM	3 CM
ASPECT RATIO			
INLET	2:1	2:1	2:1
OUTLET	1:1	1:1	1:1
SEGMENTATION FACTOR	101	40	25

* VARIED IN PARAMETRIC STUDY (NOT INCLUDED IN ETF CONCEPTUAL DESIGN)

SUMMARY

Ⓦ DEVELOPMENT

- GENERALIZED CHEMICAL EQUILIBRIUM COMPUTER PROGRAM
  - (1) MULTICOMPONENT, MULTIPHASE SYSTEMS
  - (2) (P,T), (V,T), (ρ,T)
  - (3) P_I, ρ_I, N_I
  - (4) H, S, ρ, M_W, C_p, C_V, V
  - (5) FAST COMPUTATION TIME
- LARGE DATA BASE
  - (1) OVER 2400 CHEMICAL SPECIES
  - (2) OPTION TO INPUT DATA VIA CARDS
  - (3) CONTINUOUS UPDATE OF DATA BASE
- GENERALIZED TRANSPORT PROPERTY COMPUTER PROGRAM
  - (1) K, η, σ
  - (2) CHAPMAN ENSKOG THEORY (K, η)
  - (3) MOBILITY INTEGRAL (σ)
- RESULTS TESTED
  - (1) N_2, H_2, O_2, SF_6, AIR, HG, AR, NA, HG-I, HG-NA, HG-SC-NA-I

GENERATOR MATERIALS

COLD WALL

ELECTRODES - COPPER - WITH AND WITHOUT COATINGS

INSULATORS - Al_2O_3, BN

SEMI-HOT WALL

ELECTRODES - $MgCr_2O_4$, $3MgAl_2O_4 \cdot 1\ Fe_3O_4$, Mo_2Si, Fe

INSULATORS - $MgAl_2O_4$, MgO

HOT WALL

ELECTRODES - ZrO_2 OR HfO_2 BASE, PEROVSKITES

INSULATORS $MgAl_2O_4$, MgO

3.2 DOWNSTREAM HEAT EXCHANGERS

A meeting was held on January 18, 1978 with the DOE-ETF review committee to discuss the ETF-downstream heat exchangers. Tables of some of the pertinent parameters relating to each heat transfer component were presented. (See Copies of attached visuals.) The purpose of these arrays of numbers was to permit a comparison of designs between the ETF systems although the ETF-2 should not be compared with ETF-1 or ETF-3 except for the low temperature heater and the economizers.

The heat transfer flux in the radiant boiler is noted to be lower than current practice. This results from the higher slag wall temperatures assumed in the study along with the requirement that seed would not precipitate on the surface.

In reviewing the tabulated parameters and sketches of each component, which were used to show size and tube spacing, it was questioned whether the free space between the tubes in the reheaters and superheaters was sufficient to prevent bridging where seed would build up on the tubes. This observation had been further reinforced through conversations with Babcock & Wilcox relating to Kraft System Black Liquor Recovery Boilers. It was also pointed out that fouling factors developed through experience at B&W were about 1/2 of the allowance applied to these designs.

Subsequent to this review, the reheater and superheater designs were modified to reflect these issues by reducing the number of parallel circuits which opens up the space between tubes and also reduces the effective length of each circuit to achieve a 33% reduction in surface without increasing pressure drop on the steam side. The secondary combustor air heater was also redesigned after the design review to reduce size and cost.

3.2.1

VISUALS UTILIZED

DOWNSTREAM HEAT EXCHANGERS

DOWNSTREAM HEAT EXCHANGERS

DESIGNS ARE WHOLLY DEPENDENT ON MAINTAINABILITY OF HEAT EXCHANGER SURFACE.

CONCEPTUAL DESIGNS

USEFUL TO:

- COMPARE RELATIVE SIZE AND COST OF COMPONENTS BETWEEN DIFFERENT CYCLES OR SYSTEMS IN A NON-OPTIMIZED WAY.
- PROVIDE A BASE FOR CRITICAL REVIEW.
- FOCUS ON AREAS OF UNCERTAINTY.

CONVECTIVE HEAT EXCHANGERS

SURFACE REQUIREMENTS:

- HEAT TRANSFER PARAMETERS ARE BASED ON CLEAN SURFACES DETERMINED BY METHODS GIVEN IN "STEAM, ITS GENERATION AND USE", B&W, 38TH EDITION.
- GROSS FOULING FACTORS APPLIED TO CLEAN SURFACE WHERE APPROPRIATE (SUPERHEATERS, REHEATERS AND LOW TEMPERATURE AIR HEATERS).

MECHANICAL ARRANGEMENT

- ALL DESIGNS ARE ILLUSTRATED AS VERTICAL PENDANT TYPE EXCHANGERS SUPPORTED FROM TOP LOCATED HEATERS.
- ALTERNATE DESIGNS COULD HAVE HORIZONTAL TUBES WHICH WOULD DRAIN BETTER, OR IN CLEAN AREAS BE BUILT "UPSIDE DOWN" WITH HEATERS ON BOTTOM.
- INSULATING REFRACTORY BLOCK ASSUMED INERT TO SEED.
- CONVENTIONAL TUBE SPACING: $G \leq 3000$ #/HR·FT IN HIGHER TEMPERATURE EXCHANGERS TO $G \leq 6000$ #/HR·FT IN COOLER EXCHANGERS.
- IN TEMPERATURE ZONES OF THE EXCHANGER WHERE LIQUID SEED IS PRESENT, IT IS ASSUMED THAT THERE WILL BE A SOLID SEED LAYER BETWEEN LIQUID SEED AND METAL SURFACE TO LIMIT ATTACK.
- METAL TEMPERATURES IN LOW TEMPERATURE ECONOMIZERS ALWAYS ABOVE WATER DEW POINT.

DOWNSTREAM HEAT EXCHANGERS (CONTD.)

RADIATION HEAT EXCHANGERS

SURFACE REQUIREMENTS:

- OVERALL HEAT TRANSFER COEFFICIENTS ESTIMATED USING METHODS GIVEN IN HEAT TRANSMISSION, MCADAMS, CHAPTER 4, 3RD EDITION.
- REFRACTORY SURFACE ASSUMED TO BE AT 2650°F.
- NO_x DECOMPOSITION RATE DETERMINED MINIMUM VESSEL VOLUME WHICH SET MINIMUM BASED ON NO_x DECOMPOSITION RATES.
- CHROMOXIDE ASSUMED SUITABLE FOR REFRACTORY COVERING OF WATER COOLED WALLS.

MECHANICAL ARRANGEMENT

- CYLINDRICAL SHAPES FOR MORE EFFECTIVE USE OF MATERIAL.
- RADIANT BOILER SUPPORTED FROM A PLANE NEAR TOP OF STRUCTURE.

AREAS OF UNCERTAINTY

- SEED ATTACK OF TUBING SURFACES
- SEED ATTACK OF REFRACTORIES
- SOOT BLOWING OF HIGH PRESSURE AIR BLOWING FOR SEED COATING REMOVAL FROM SURFACES.

HEAT EXCHANGER PARAMETERS - RADIANT BOILER

	ETF-1	ETF-2	ETF-3
HEAT TRANSFER			
Q, BTU/HR x 10^6	557	100	325
ΔT, °F	727	740	793
U, BTU/HR·FT^2·°F	39	32	37
A, $FT^2 \times 10^{-3}$	19.64	4.21	11.0
WATER SIDE EVAPORATOR			
$\dot{M}$, #/HR x 10^{-6}	3.568	2.55	2.56
T_{in}, °F	378	150	568
T_{out}, °F	639	200	600
A_{flow}, FT^2	11.93	1.695	7.95
G, #/HR·$FT^2 \times 10^{-5}$	2.99	15.04	3.22
R_e, x 10^{-5}	3.2	3.09	3.06
ΔP, psi	<10[3)]	<10	<10
N, NO PARALLEL CIRCUITS	582	51	388
ℓ, LENGTH PARALLEL CIRCUIT, FT	76	196	60
PIPE SIZE	2" SCH 80	2-1/2" SCH 40	2" SCH 80
STEAM SIDE "SUPERHEATER"			
$\mathring{M}$, #/HR x 10^{-6}	.726	-	.466
T_{in}, °F	639	-	600
T_{out}, °F	805	-	667
A_{flow}, FT^2	11.93	-	7.95
ΔP, psi	<1	-	<1

HEAT EXCHANGER PARAMETERS RADIANT BOILER

	ETF1	ETF 2	ETF3
<u>Gas Side</u>			
m, #/hr x 10^{-6}	1.48	0.29	0.825
T_{in}, °F	3794	3893	3824
T_{out}, °F	2960	2960	2960
A_{flow}, ft^2	942	330	658
G, #/hr·ft^2	1573 1) min	880	1250 2) min
Residence Time, sec	2.37	2.55	2.4
Volume, ft^3 x 10^{-3}	100	22.11	56.5

1) 4719 #/hr·ft^2 in manifolds

2) 2494 #/hr·ft^2 in manifolds

2 - 10" SCH 80 Down Comers

3) Natural circulation heat available = 11 psi

HEAT EXCHANGER PARAMETERS

REHEATER

	ETF1	EFT2	ETF3
Heat Transfer		(HX - 2)	
A, Btu/hr x 10^{-6}	134	77.8	(None)
$\overline{\Delta T}$, °F clean	1215	1718	
U, Btu/hr·ft^2·°F	13 clean/9.33 ave	10/5	
A, ft^2 x 10^{-3}	13.3/40	4.5/9.0	
Steam Side		Water	
$\dot{m}$, #/hr x 10^{-6}	.726	1.55	
T_{in}, °F	620	150	
T_{out}, °F	950	200	
A_{flow}, ft^2	1.66	1.462	
G, #/hr·ft^2 x 10^{-5}	2.72	10.8	
Re, x 10^{-5}	7.5	2.18	
ΔP, psi	<40	<6	
Pipe Size	2-1/2 SCH 40	2-1/2 SCH 40	
N, No Parallel Circuits	80	94	
ℓ, Length Parallel Circuit, ft	413	274	
Gas Side			
$\dot{m}$, #/hr x 10^{-6}	1.6	.516	
T_{in}, °F	2141	2285	
T_{out}, °F	1861	1546	
G, #/hr·ft^2	415/	3030	

HEAT EXCHANGER PARAMETERS
SUPERHEATER

	ETF1	ETF2	ETF3
Heat Transfer		(HX - 1)	
Q, Btu/hr x 10^{-6}	78	42.9	95.4
ΔT, °F	904	905	1153
U, Btu/hr·ft^2 °F (clean)		31/15	17 clean/5.67 ave
A, ft^2 x 10^{-3}	5075	1528/3500	4807/14421
Steam Side		Water	
m, #/hr x 10^{-6}	0.726	0.856	0.465
T_{in}, °F	805	150	668
T_{out}, °F	950	200	950
A_{flow}, ft^2	0.964	1.26	0.6379
G, #/hr·ft^2 x 10^{-5}	7.525	6.775	6.8
Re, x 10^{-5}	14	1.74	9.1
ΔP, psi	<40	<4	<100
Pipe Size	2" SCH 160	2-1/2" SCH 40	2" SCH 160
N, No of Parallel Circuits	62	38	41
ℓ, Length of Circuit, ft	145	196	564
Gas Side			
m, #/hr x 10^{-6}	1.6	0.29	0.889
T_{in}, °F	1861	2900	2141
T_{out}, °F	1702	2510	1784
G, #/hr·ft^2	5026	880	3747

HEAT EXCHANGER PARAMETERS
LTAH

	ETF1	ETF2	ETF3
Heat Transfer			
Q, Btu/hr x 10^{-6}	356	56.16	201.8
ΔT, °F	298	320	390
U, Btu/hr·ft^2·°F (clean)	7.5	8.5	7.5
A, ft^2 x 10^{-3}	159.2	27	67.4
Air Side			
m, #/hr x 10^{-6}	1.3	0.255	0.724
T_{in}, °F	489	586	467
T_{out}, °F	1520	1400	1520
A_{flow}, ft^2	55.68	14.9	33.50
G, #/hr·ft^2 x 10^{-5}	0.233	0.17	0.216
Re, x 10^{-5}	0.502	0.391	0.50
ΔP, psi	1	2	2
Pipe Size	2-1/2" SCH 80	2-1/2" SCH 40	2-1/2" SCH 40
N, No Parallel Circuits	1892	448	1008
ℓ, Length of Circuit, ft	112	80	89
Gas Side			
m, #ℓ hr x 10^{-6}	1.6	0.516	0.889
T_{in}, °F	1702	1548	0.784
T_{out}, °F	946	1177	1018
G, #/hr·ft^2	4138	3540	3661

HEAT EXCHANGER PARAMETERS
ECONOMIZER #1

	ETF1	ETF2	ETF3
Heat Transfer			
Q, Btu/hr x 10^{-6}	58.0	(None)	32.1
$\overline{\Delta T}$, °F	254		253.12
U, Btu/hr·ft^2·°F	10		10
A, ft^2 x 10^{-3}	22.8		12.68
Water Side			
Mass Flow #/hr x 10^{-6}	.726		.465
T_{in}, °F	158		162.3
T_{out}, °F	237.3		231.0
A_{flow}, ft^2	1.23		.7175
G, #/hr·ft^2 x 10^{-5}	5.91		6.48
Re, x 10^{-5}	3.19		3
ΔP, psi	5		6
Pipe Size	2" SCH 80		2" SCH 80
N, No. Parallel Circuits	60		35
ℓ, Length of Circuit, ft	612		582
Gas Side			
Mass Flow, #/hr x 10^{-6}	.663		.367
T_{in}, °F	640		640
T_{out}, °F	305.4		305.4
G, #/hr·ft^2	2967		3706

HEAT EXCHANGER PARAMETERS
ECONOMIZER #2

	ETF1	ETF2	ETF3
Heat Transfer		(HX3)	
Q, Btu/hr x 10^{-6}	134	112	92.7
$\overline{\Delta T}$, °F	390	353	436.5
U, Btu/hr·ft^2·°F	10	10	10
A, ft^2 x 10^{-3}	39.4	31.7	22.7
Water Side			
$\dot{m}$, #/hr x 10^{-6}	.726	2.24	.465
T_{in}, °F	312.3	150	292
T_{out}, °F	486	200	479
A_{flow}, ft^2	1.23	2.395	.861
G, #/hr·ft^2 x 10^{-5}	5.91	9.35	5.4
Re, x 10^{-5}	3.19	2.4	2.49
ΔP, psi	8	10	7
Pipe Size	2" SCH 80	2-1/2 SCH 40	2" SCH 80
N, No Paralle Circuits	60	72	42
ℓ, Length of Circuit, ft	921	585	870
Gas Side			
$\dot{m}$, #/hr x 10^{-6}	1.6	.5148	.889
T_{in}, °F	946	.873	1018
T_{out}, °F	640	305	640
G, #/hr·ft^2	4877	5340	6152

HEAT EXCHANGER PARAMETERS
SCAH

	ETF2		
Heat Transfer			
Q, Btu/hr x 10^{-6}	44.4		
$\overline{\Delta T}$, °F	632		
U, Btu/hr·ft^2·°F	5.92		
A, ft^2 x 10^{-3}	11.87		
Air Side			
$\dot{m}$, #/hr x 10^{-6}	.204		
T_{in}, °F	66.5		
T_{out}, °F	691.5		
A, ft^2	32.30		
G, #/hr·ft^2	6315		
Re, x 10^{-5}	.1746		
ΔP, psi	<0.1		
No Parallel Circuits, N	1273		
Length Parallel Circuit, ft	15		
Pipe Size	2" SCH 10		
Gas Side			
$\dot{m}$, #/hr x 10^{-6}	.516		
T_{in}, °F	1176		
T_{out}, °F	873		
G, #/hr·ft^2	4162		

3.3 HIGH TEMPERATURE AIR PREHEATER

A committee meeting on the high temperature air preheater was not held. A list of questions was submitted by J. Winter of NASA LRC. A copy of the question and answers is attached.

QUESTION 1: FluiDyne/EPRI Contract 640-1 Report available?

RESPONSE: Copy of the report is attached.

QUESTION 2: Guideline of oil-fired air heaters inappropriate?

RESPONSE: In the context of a pilot scale plant with the potential for demonstrating long endurance operation as required in a utility environment, oil firing is considered inappropriate. The utility industry is being forced to consider only coal and nuclear fuel for base load plants of the future and ETF should recognize this.

QUESTION 3: How was L/D ratio of air heaters arrived at?

RESPONSE: The conceptual designs of the ETF HTAH's were scaled from the EPRI configuration to maintain the thermal-flow conditions of the FluiDyne analyses (maintain Δp's and Δt's, ratio diameter to mass flow). In this manner, the same number of units and the same operating cycles as the FluiDyne analysis were maintained.

QUESTION 4: What are heat balance values for the HTAH's?

RESPONSE: The heat balance values for the HTAH's are given in Section 1.3 "Cycle Descriptions and Heat Balances" of Volume III - "Definition of Concepts" of the MHD ETF Conceptual Design Report. For example, for ETF-1 the gas and air circuit schematic is shown on Figure 1.3-1 Page 1.3-2. For the HTAH, state point 12 is the combustion gas inlet, state point 13 is the combustion slag bleed to the seed regeneration and ash removal, state point 9 is the air inlet from the LTAH and state point 10 is the air exit to the combustor. The corresponding gas and air state point conditions are given in Tables 1.3-5 and 1.3-6, Pages 1.3-10 and 1.3-11. Table 1.3-9 on Page 1.3-14 summarizes the system heat balance where 104.22 MW are transferred to the air in the HTAH and 9.48 MW are lost in the HTAH valves. The same can be determined for the other ETF concepts.

QUESTION 5: **WHAT ARE COST VALUES FOR THE HTAH SYSTEM?**

RESPONSE: The summary cost estimates of the HTAH's for the ETF concepts are:

	ETF-1	ETF-2	ETF-3
High Temp. Preheater (16)	$ 8,800,000	$ 1,760,000	$ 5,460,000
Valves (16 each of 4 sizes)	14,700,000	6,400,000	10,250,000
Manifolds	2,154,000	685,000	1,424,000
	$25,654,000	$ 8,845,730	$17,134,280

The high temperature pre-heater and manifold costs were determined by Westinghouse after review of the methods and assumptions used in ECAS and EPRI studies. The valve costs were obtained based on a vendor estimate. The higher temperatures, slag environment, and duty requirements over blast furnace experience, undoubtedly resulted in extremely conservative valve costs. Compared to estimating procedures used in ECAS and EPRI work they are 2.5-3.0 times higher. Thus the valve costs can probably be interpreted to include a significant amount of the development effort required whereas the heaters and manifold do not. We had intended to refine costs of the reference design, (ETF-3) to extract this valve development effort.

QUESTION 6: **WHAT TOTAL WEIGHTS OF CERAMICS AND METALLIC COMPONENTS ARE ESTIMATED TO BE REQUIRED FOR THE HTAH SYSTEM?**

RESPONSE: The summary weight estimates of the ceramic and metallic components are:

		ETF-1	ETF-2	ETF-3
Metal	Vessels (16)	1,514,480 lbs.	308,304 lbs.	924,608 lbs.
	Manifolds	423,737	97,293	284,986
	Valves (16 each)	400,000	113,000	255,000
	Total Metal Wt.	2,338,217 lbs.	518,597 lbs.	1,464,594 lbs.
Ceramic	Vessels	8,532,416	1,725,792	5,359,568
	Manifolds	2,313,000	907,053	1,553,418
	Valves	400,000	113,000	255,000
	Total Ceramic Wt.	11,245,416 lbs.	2,745,845 lbs.	7,167,986 lbs.

QUESTION 7: WHY WERE 16 HEATERS REQUIRED?

RESPONSE: Sixteen heaters were utilized because the design of the FluiDyne system was scaled to the ETF conceptual designs. This preserved the thermal-flow and cyclic operating conditions. Sixteen heaters may be an optimum number for a commercial size power plant system but requires additional evaluation in the reference design study phase for ETF.

QUESTION 8: HAS THE HOT GAS MANIFOLD AND ITS INFLUENCE ON THE HTAH ASSEMBLY BEEN ANALYZED WITH RESPECT TO THE LARGE DISTANCE BETWEEN THE MANIFOLD AND THE SUPPORT POINTS?

RESPONSE: For the ETF conceptual designs, no detail analyses were performed. Each manifold increment is supported between two of the HTAH's. The manifold pipes themselves are large diameter and stiff relative to the distance between the supports of each increment.

QUESTION 9: HOW WILL BOTTOM SUPPORTS FOR HEATERS BE DESIGNED TO SURVIVE AT 1700 OR 2100°F? ALL EXITS IN EACH CHECKER? IT LOOKS AS IF FLOW BLOCKAGE IS A PROBLEM.

RESPONSE: The checker stack is supported on a refractory floor with refractory insulation underneath it. As pointed out in the FluiDyne Report (p.6), the HTAH's are designed for maximum web thermal stress equal to 1/2 the modulus of rupture (MDR) of the bed material which is current blast furnace practice consistent with anticipated operating lifetimes and maintenance schedules (see p. 13-14) of commercial devices.

Ample provisions are made within the design for unobstructed gas entrance and exit from the checkers. At the top, the checker ends are exposed directly to the upper cavity of the insulated HTAH. At the bottom, channels as shown in Figure 2.4-24 (p. 2.4-73) are provided to permit cross flow to all checkers and to minimize the effect on performance due to possible accumulations of seed and slag components. In the FluiDyne design, accumulations are anticipated and provided for by allowing for one of the sixteen HTAH's to be on clean out at all times (see discussion p. 3 of FluiDyne Report).

QUESTION 10: WHAT EFFICIENCY IS EXPECTED (HEAT INPUT/HEAT OUTPUT) FOR THE HTAH SYSTEM?

RESPONSE: The performance of the ETF concepts HTAH's was determined by scaling the performance of the FluiDyne design. For the FluiDyne design, system heat losses for the HTAH vessel and valves amounted to 8.8% of the heat which was transferred to the air in the process of heating it to the required 2500°F. For the ETF concepts, a fixed 8.8% of the heat transferred to the air was assumed for the thermal losses from the HTAH's and is listed in the system heat balance (e.g. Table 1.3-9, p. 1.3-14) as heat loss in the high temperature heater valves. On this basis, the HTAH has an efficiency of 91.2%.

For the overall performance of the scaled HTAH's for the ETF conceptual designs, the state point performance as described in response to Question 4 should be utilized.

Approximately 80% of the heat loss is in valve cooling and future studies should address the problem of reducing this loss.

QUESTION 11: WHAT IS THE EFFECT OF 31 MICRON COAL PARTICLES FROM ETF-2 COMBUSTOR ON HTAH?

RESPONSE: In conventional blast stoves, gas clean-up prior to entry into the blast stove combustion chamber is utilized to prevent particle accumulation in the checker work. However, in the ETF-2 concept, the secondary combustor of the directly-fired HTAH has an 80% ash rejection, with 20% carryover to the HTAH. This is addressed as a concern in the FluiDyne design (see p. 3) and accounted for in the overall configuration. Particles affecting performance must be removed periodically by heating the ceramic bed above the slag melting point at a frequency and duration not yet established but accounted for by allowing one unit to be on clean-out at all times.

The publication by J. B. Heywood and G. J. Womack, "Open Cycle MHD Power Generation," Pergamon Press, 1969, extensively treats the subject of directly-fired air heaters and the considerations of seed/slag effects on heat and mass transfer as well as atomization, transportation and transfer of granular particles. In general, the particle size treated was that of 0.5mm and above, which is considerably larger than the 31 micron size questioned. The wall collisions of the particles (causing a buildup of particles on the walls) is dependent upon the flow distribution. And like the FluiDyne Report, this publication indicates that there is a good possibility of buildup of particles on the walls to upset the flow through the channels, particularly in a full-scale device.

QUESTION I2: WHAT IS THE LONGEST RUN TIME WHERE SPECIFIED CERAMIC BRICKS HAVE BEEN TESTED AT THE TEMPERATURES AND ENVIRONMENTS OF ETF-1 AND ETF-2 (SEED/SLAG)?

RESPONSE: FluiDyne is conducting tests of 100 hr. duration and longer at seed/slag conditions approaching the temperatures of ETF. Results obtained so far are mixed (inconclusive) so that additional tests and investigations must be performed to determine potential development needs.

Martin and Pagenstecher Gmb H, Cologne, Germany, the licensor of ANDCO Inc., Buffalo, N. Y., has performed extensive testing of blast stove materials and configurations with maximum straight line hot blast temperatures of 2550°F considered state-of-the-art with normal maintenance and lifetimes approaching commercial applications. Gas conditions are those of blast stoves where the gas has been cleaned and particulates removed prior to entry into the air heater.

QUESTION I3: WHAT ARE CHECKER DIMENSIONS INCLUDING HOLE SIZE AND WEB THICKNESS - HOW WERE THESE ARRIVED AT?

RESPONSE: The FluiDyne Report gives the checker dimensions and arrangement for the HTAH design. The design process is described in the report.

QUESTION I4: IF OIL-FIRED HTAH'S ARE USED, WHAT IS THE MINIMUM NUMBER REQUIRED AND WHY WAS THE 200-HOUR RUN LIMIT SELECTED? WHERE IS THE COST ESTIMATE FOR THE RECOMMENDED OPTION?

RESPONSE: Based on present blast furnace practice, this is expected to be approximately 10-11 units if a reasonable temperature ripple and cycling time are maintained. Four units on blast, four on heat-up, one on depressurization, one on standby, and perhaps one on maintenance would be required.

The 200-hour run limit was specified on the basis that the facility becomes a major oil user for long endurance runs and contradicts the basic objective of MHD to use coal. The cost estimate for the recommended option was to be performed in the subsequent reference design effort as stated in the Program Work plan.

QUESTION 15: ARE THERE COMPARISON TABLES ON ETF-1,-2 AND -3 FOR THE HTAH AS SHOWN FOR DOWNSTREAM COMPONENTS? WHAT I AM LOOKING FOR IS MORE DETAIL ON THE HTAH'S.

RESPONSE: Tables of direct comparison of the ETF-1,-2 and -3 HTAH's have not been prepared. However, a comparison of performance and specifications can be conveniently made from the Preliminary Component Design Specifications 01-55-007, 02-55-007 and 03-55-007 (pp 2.4-76 to 2.4-87 of Volume III) for the ETF-1,-2 and -3 HTAH's.

QUESTION 16: CAN YOU GIVE ME SOME MORE DETAILS ON WHAT THE 46 AND 41 MILLION R & D COSTS FOR HTAH'S WOULD BE USED FOR?

RESPONSE: The development program for the directly-fired HTAH consisted of four elements: (1) a small scale bed materials test program; (2) a 5MW single bed test program including a facility; (3) a 25MW multiple bed with valves test program and facility; and (4) a valve development program. (See Figure 3.2-1, p. 3.2-2 of Volume 1.) The cost of facilities, facilities operation, engineering, materials and hardware and ETF conceptual design for this program was estimated at the 41 million quoted.

For the indirectly-fired system, an additional 5 million was included for the combustor development, which was assumed to be coal fired per the ETF-2 configuration. The indirect-fired unit, because of its extreme temperature, was deemed equivalent in development required to the lower temperature direct fired unit.

3.4 MHD COMBUSTOR

On February 28, 1978, a meeting was held at PERC to review the Westinghouse-ETF combustor conceptual designs. A brief review is made herein of content of the meeting including copies of pertinent viewgraphs used. Concept drawings that are included in the design report are not attached herein even though they may have been used in the presentation.

The ETF coal combustors were designed for ETF to achieve a flame temperature of 2850°K while minimizing heat losses (∿5%) maximizing ash rejection (∿90%) and no carbon loss in the slag. To achieve these conditions, a two stage combustor concept was used which would operate at an oxygen equivalence ratio of 0.50 and 0.95 in the first and second stages, respectively. While the fuel rich conditions are desirable to minimize NO_2 formation, corrosive molten iron formation is likely in the area of the slag tap. This problem was addressed by providing a relatively steep cone angle (45°) to reduce the residence time, and thus time for the reaction, and to locate tuyereo at the slag tap for oxygen injection to provide an atmosphere and to burn the fuel rich gases to keep the slag tap running freely. The coal is premixed in the combustion air stream in the injectors which fire scantialy along the length of the first stage. Proper air-fuel mixing allows for particle burnout in the gas stream and also avoid particle agglomeration which would lead to carbon loss in the slag. An equilibrium thermodynamic program was used to determine flame temperatures, combustion gas properties, and specie concentration when burning Montana Rosebud coal with five percent moisture and ten percent of each ash constituent passing through the combustor in vapor form. Sizing of the combustor was based on standard cyclone technology for a loading value of 15 MW/m^2 - atm and a L/D ratio of 1.5. Heat transfer rates were based on particle emissivity of 0.8 and a wall temperature of 1670°K (slag viscosity equals 250 poise) in the first stage and gas emissivity of 0.4 and either a wall temperature of 2073°K for magnesium aluminate spinel brick or 2273°K for zirconium brick. The calculated heat loss for ETF-1, 2, and 3 were then compared to other design calculations and heat loss measurements from operational coal combustors. The heat loss versus combustor diameter was plotted (See Figure 3) along with two design curves — the solid curve generated using average conservative values for the design parameters and the dashed curve generated from Argonne National Laboratories one-dimensional coal combustor model.

The second stage of the combustor was designed so as to provide a uniformly seeded high temperature plasma at the exhaust. Seed material is premixed with the combustion air in the same manner as coal is mixed in the first stage. The injection angle of the combustion air is far greater than the first stage (See Figure 2) so as to penetrate the high temperature swirling jet from the first stage and provide the necessary air/fuel mixing to minimize required residence time and avoid stratification of the hot first stage combustion products and relatively cold combustion air.

The design procedure and data base for the slag system was extrapolated from existing practice. The slag layer thickness, loading, and viscosity were calculated and 0.1 percent flow of gas through the port was used to reduce the possibility of plugging. The slag tank was designed so as to provide a continuous transport system while maintaining the electrical isolation of the system (See Figure 1). The hot gas and slag are chilled with water jets which quench the slag and cause it to shatter. The slag drops into a crusher which reduces the size of the slag particles to a transportable size. The water/slag mixture is depressurized through proper design of a rubber lined carbon steel drain pipe designed to provide a high pressure drop in a reasonable length (for 380 MW, the requirement is 1.6 in I.D. 19 ft. long).

Pertinent questions and answers during the meeting were as follows:

- Loading is based on 15 MW/m^2 - atm — standard cyclone practice. This is for fuel lean conditions and may be too high.

  ANS: This value was taken from values calculated from operational coal combustors and design programs developed by others as well as standard cyclone practice. For lack of a better data and design base, this value was used.

- How was a 45° slope on the bottom of the combustor chosen?

  ANS: Compromise between slag combustor residence time (low value desired to avoid iron formation) and surface area/heat loss considerations.

- Second Stage Air/Fuel - mixing may be poor.

  ANS: It is felt that secant firing to penetrate the first stage jet will provide the required mixing. The drawing of the combustor arrangement is misleading and will be changed. Flow modeling needs to be done but was not included in the scope of this contract.

- How was residence time chosen in the second stage?

  ANS: A conservative value of 15 MW/m^2 - atm was chosen for loading. With flow modeling resulting in proper mixing, this value could be doubled. Assigning a L/D of 1.5, the residence time is determined.

- Why was a mixer included in ETF-1?

  ANS: To remove the swirling component of flow to help provide one-dimensional flow through the channel. This concept was chosen only for ETF-1 to show what a multiple combustor arrangement would be like in a large power plant (>1,000 MW).

3.4.1

VISUALS UTILIZED

COMBUSTOR

COMBUSTOR DESIGN REQUIREMENTS

- ACHIEVE ACCEPTABLE FLAME TEMPERATURES
- OBTAIN HIGH COMBUSTION EFFICIENCY
- MINIMIZE HEAT LOSSES
- ACHIEVE HIGH ASH REJECTION
- MINIMIZE NO_x FORMATION
- AVOID IRON ATTACK
- ELECTRICALLY ISOLATE SYSTEM
- PROVIDE UNIFORMLY SEEDED PLASMA
- PROVIDE LONG TERM RELIABILITY

MAJOR ASSUMPTIONS

- EQUILIBRIUM THERMODYNAMICS
- PROPERTIES OF COMBUSTION PRODUCTS DETERMINED FOR 10% ASH CARRYOVER
- COMBUSTOR LOADING OF 15 MW/M_{ca}^{2}-ATM for L/D = 1.5
- PARTICLE BURNOUT ACHIEVED IN COMBUSTOR RESIDENCE TIME
- HEAT TRANSFER CALCULATIONS BASED ON:
    - FIRST STAGE Tw = 1670 K $\varepsilon_g = 0.8$
    - SECOND STAGE Tw = 2073 K $\varepsilon_g = 0.4$

CONTRACTOR/ BUILDER	DESIGN OR OPERATE	THERMAL INPUT MW	STAGES	ASH REJ (%)	OXY CONC. (% by Wt)	PRES. (ATM)	HEAT LOSS (%)	COMB. DIA. (M)	OXID. PREH. (°K)	FLAME TEMP. (°K)
TRW	D	25	2	90	23	8	5	0.71	1866	3000
ROCKETDYNE	D	25	2	90	23	8	5/8	0.38	1866	3028
AVCO	D	25	2	70-90	23	3-10	5/10	0.53	1866	3000
UNIV. OF NUCLEAR RESEARCH SWIERK, POLAND	O	4.5	1	70-75	44	3.5	16[1]	0.40	1473	2773
BCURA	O	3.8	2	60-82	33	5	18	.45	1470	2640
PERC	O	5	2	50-80	23	6.5	10	0.30	1800	2850
POLISH	D	50-60	1	70-75	44	3.5	4-5	-	1473	2773
BCURA	D	73	2	-	29	5	10	0.90	1470	2690
(W) - ETF-3	D	286	2	85-90	33/0	5	6	1.60	1644	2752

Curve 694338-A

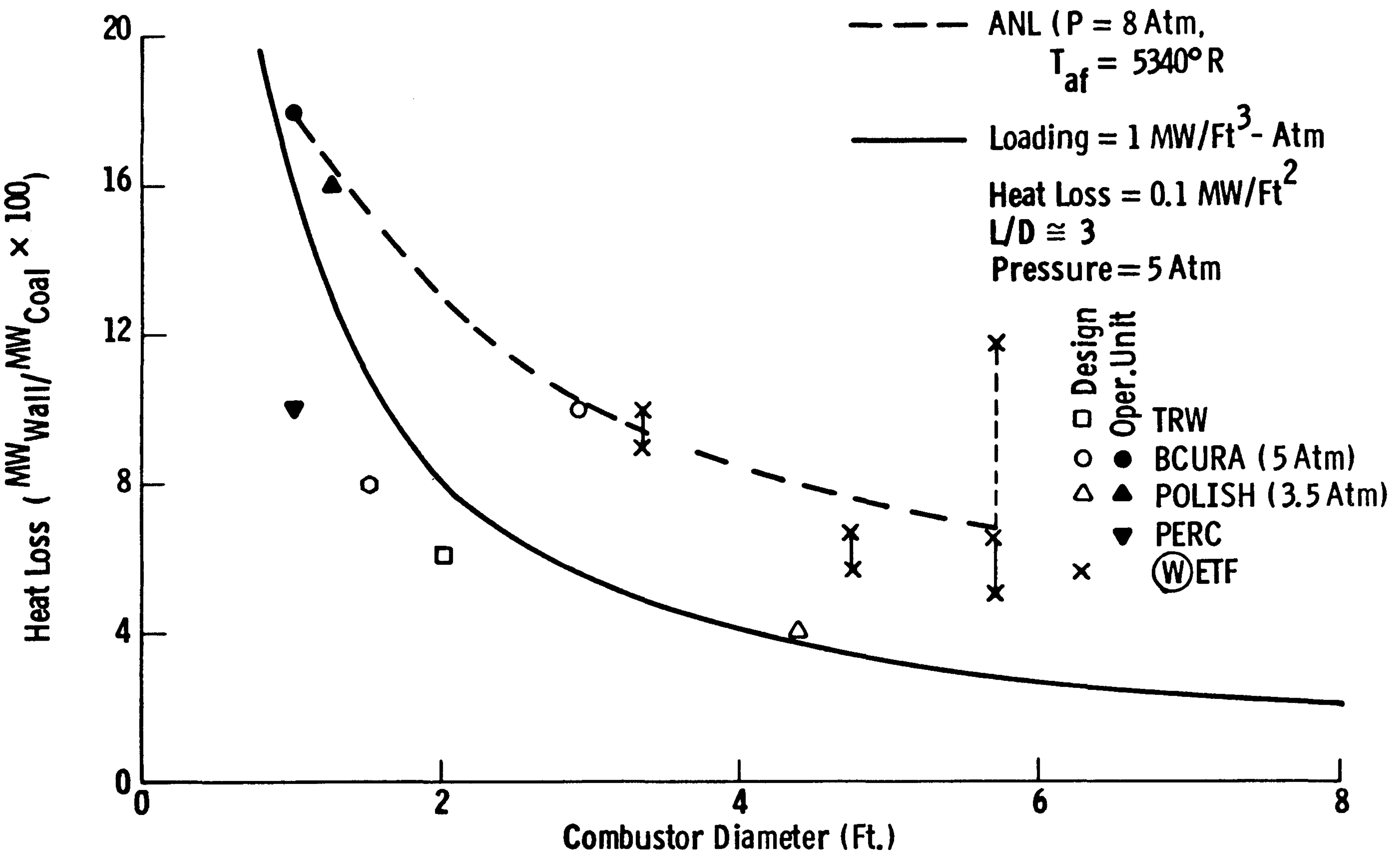

Fig. — Heat loss vs combustor diameter for MHD coal combustors

DESIGN FEATURES

- BASIC CYCLONE DESIGN
- COMBUSTION AIR/COAL PREMIXING
- MULTI-FEED POINTS ALONG LENGTH
- SLAG TAP BLEED
- TWO STAGE - FUEL RICH

PROBLEM AREAS

- ACHIEVE HIGH ASH REJECTION (90%)
- MINIMIZE HEAT LOSSES (<5%)
- ELECTRICAL ISOLATION (~30 KV)
- MATERIAL DURABILITY IN THE PRESENCE OF SEED/SLAG

SLAG SYSTEMS REQUIREMENTS

COMBUSTOR: 1ST STAGE

- HIGH SLAG REJECTION RATE (UP TO 90%)
- SLAG LAYER MUST PROTECT COMBUSTOR WALL (1ST STAGE)
- MINIMIZE MOLTEN IRON ATTACK
- LOW CARBON LOSS

SLAG QUENCH TANK

- SLAG MUST BE QUENCHED FOR HANDLING
- SLAG SHOULD BE OF EASILY TRANSPORTABLE SIZE
- MAINTAIN ELECTRICAL ISOLATION

SLAG SYSTEMS (CTD)

DESIGN APPROACH

COMBUSTOR: 1ST STAGE

- TWO STAGE APPROACH. FIRST STAGE SET A $\phi = 0.5$: LIMITS TEMPERATURE AND VAPORIZATION
- HEAT LOSS ACROSS SLAG LAYER TO WALL SET BY WALL DESIGN TO MAINTAIN MINIMUM VISCOSITY (i.e., LIMITS SLAG VELOCITY ON WALL)
- DIMENSIONING OF COMBUSTOR AND CHEMISTRY SETS SLAG LOAD (LB SLAG/FT PERIMETER)
- SHAPE OF COMBUSTOR LOWER END (CONICAL) CONVERTS THIN SLAG LAYER TO ANNULUS
- A SMALL GAS FLOW KEEPS SLAG PORT OPEN
- SMALL AIR ADDITION REGULATES SLAG PORT TEMPERATURE

SLAG QUENCH TANK

AVOID MECHANICAL DEVICES (LOCK HOPPERS, STARWHEELS, ETC.), USE CONTINUOUS TRANSPORT SYSTEMS

SLAG SYSTEMS (CTD)

DESIGN SOLUTIONS

COMBUSTOR: 1ST STAGE

- DESIGN PROCEDURE AND DATA BASE EXTRAPOLATED FROM EXISTING PRACTICE AND CDIF DESIGN STUDIES.
- SLAG LAYER CHARACTERISTICS ON THE WALL OBTAINED, BASED ON

  SILICA RATIO OF ASH
  GAS TEMPERATURE IN COMBUSTOR
  SLAG LOADING (MASSFLOW/PERIMETER)
  REFRACTORY THICKNESS
  SLAG VISCOSITY AT SOLID/LIQUID INTERFACE

- GAS BLEED AT SLAG PORT USED TO KEEP FROM PLUGGING (FLOW CAN CARRY 0.3 IN. DIAMETER SLAG PARTICLES; NOT MORE THAN 0.1% OF TOTAL GAS FLOW USED.)
- BECAUSE OF REDUCING ATMOSPHERE ($\phi = 0.5$) TUYERES CAN CREATE LOCAL FLAME TO CONTROL VISCOSITY AT SLAG PORT.

QUENCH TANK

STEPS OF SLAG REMOVAL FROM UNDER PRESSURE

1. PRECOOL CARRIER GAS WITH ATOMIZED WATER
2. EXHAUST GAS AND VAPOR MIXTURE
3. PROTECT CRUSHER UNDERNEATH COMBUSTOR
4. CHILL SLAG WITH WATER JETS
5. CRUSH SLAG IN WATER COOLED CRUSHER (EXTERNAL DRIVE)
6. QUENCH SLAG IN WATER
7. DEPRESSURIZE WATER/SLAG MIXTURE THROUGH, E.G., 19 FT LONG, 1.6 IN I.D. PIPE MATERIAL: CARBON STEEL, PROTECTED BY SUITABLE LINING, (RUBBER OR EQUIVALENT)

SLAG MANAGEMENT

SUMMARY OF DESIGN DATA

	ETF-3
GAS TEMPERATURE, FIRST STAGE °C	1835
SLAG SURFACE TEMPERATURE °C	1700
SLAG VISCOSITY, NOMINAL ON THE VERTICAL COMBUSTOR WALL, POISE	50-60
SLAG LAYER THICKNESS ON THE VERTICAL COMBUSTOR WALL, IN.	0.15
SLAG VELOCITY ON THE VERTICAL WALL, FT/MIN	3.0
HEAT LOSS FROM SLAG FLOW % OF COAL HEAT INPUT TO COMBUSTOR (MAIN COMB.)	0.9
HEAT LOSS FROM GAS FLOW AT SLAG PORT, % OF COAL HEAT INP.	0.3
SLAG TRANSPORT WATER FLOW LB/SEC COAL	1.2
TRANSPORT WATER TEMPERATURE, DISCHARGE, °F	180

3.5 SEED PROCESSING

A meeting was held on January 17, 1978 to review the Westinghouse-ETF Seed Processing systems.

Material presented at this review was extracted from the conceptual design report. The attached tables were presented and represent a compiling of information not reported. Also, attached are the pertinent comments and questions raised by the committee. Based on these, additional (preliminary) studies were done to clarify specific issues. These centered around two additional processes not previously considered by Westinghouse. Findings from these further studes are summarized.

A summary of the capital costs for the seed systems was presented for each of the ETF designs. The three major subsystem (in terms of capital cost) are the seed regeneration (∿40%), seed recycle (∿30%), and seed recovery (∿28%). The attached tables present the annual opera-ting costs, energy requirements, and seed loss for each ETF. Fixed operating costs vary from \$2.75/yr/kW to \$4.46/yr/kW while variable operating and maintenance costs are 1.34, 2.63, and 1.44 mils/kWh for ETFs 1, 2, and 3 respectively (compared with fuel costs of 12 mils/kWh for ETFs 1 and 3, and 26 mils/kWh for ETF 2).

Disucssion and questions as a result of the meeting are presented below:

- What are the reasons for using the Stretford process in the final design and Clauss process in the comparison?

  ANS: A simplification of the process was achieved using the Stretford process. Also, there was some doubt as to whether or not the Clauss process could operate with the high moisture content of the gas stream.

- In Appendix I, while comparing seed regeneration processes with throw-away processes, credit was not taken for K_2SO_4. What would the cost reduction be if credit were taken?

  ANS: Costs would be reduced about 25%. There would be no difference in the conclusions.

- Do you think the PERC process on a large scale will be able to handle higher conversion of seed materials?

  RES: Yes. More K_2SO_4 material would be sent throught the conversion process.

- What kind of reactor design will be used for seed regeneration? What kind of gas utilization have you allowed for?

  ANS: The seed regeneration reactor is a fixed bed reactor with free board of 33%. Holding time is 5 hours (about twice what the PERC data indicates is necessary). Gas utilization is 18% for H_2 and 24% for CO in the reduction step, and 63% for CO_2 and 31% for H_2 in the oxidation step.

- Have you considered other seed regeneration processes such as formate, Engle - Precht, Tanpella, etc?

  ANS: The Tanpella process was reviewed and found to offer no advantages over the oxidation step of the PERC process. The formate process would require more energy and higher capital cost than the PERC process and still produce a $CaSO_4$ sludge (see below).

- In Appendix 14, the gas composition from the gasifier is based on what coal?

  ANS: A western sub-bituminous similar to the Montana coal. Gas compositions were supplied by ATC/Wellman of Houston, Texas.

- How strong will the K_2SO_4 pellets be?

  ANS: This is unknown and will have to be determined experimentally.

- When carbonation of K_2S is going on, usually reduction of the K_2SO_4 is also taking place. Will these two reactions nullify each other?

  ANS: Based on the PERC data, if the carbonation of the K_2S is carried on at around 500°C, the rate of reduction reaction is negligible. Also, there will not be any reducing gas in the oxidation gas. Likewise, in the reduction section, if the reaction is run around 800°C, little oxidation should occur. Again, the reducing species will be in excess.

- In Appendix XIV, was the variation of the heat of reaction with temperature accounted for?

  ANS: No.

Alternate Processes: Preliminary Review

Two alternate processes were considered: 1) the Tanpella process; and 2) the formate process.

The PERC process is currently the best process based on the following guidelines.

1) minimum water recycle with regenerated seed
2) minimum energy requirements
3) minimum capital requirements

If the constraint on minimum water recycle is relaxed, and problems surface in the oxidation step of the PERC process, the Tanpella process could be considered. However, the use of the Tanpella process would increase both the energy and capital requirements of the seed regeneration system. The formate process might be competitive with the PERC process in terms of energy use and capital requirements, provided that the minimum water recycle requirement is relaxed and a $CaSO_4$ sludge is acceptable. In order to provide a definitive estimate of the applicability of these alternate processes, a detailed design, sizing, and costing exercise would be necessary.

3.5.1

VISUALS UTILIZED

SEED PROCESSING

SEED PROCESSING SYSTEMS

- SEED/ASH QUENCH
- SEED/ASH TRANSPORT FROM MHD TO PROCESSING
- SEED RECOVERY/RECYCLE
- SEED REGENERATION
- SEED CONTROL AND TRANSPORT TO MHD COMBUSTOR

DISTRIBUTION OF CAPITAL COSTS - SEED SYSTEM

SUBSYSTEM	ETF-1		ETF-2		ETF-3			
	$	(% of Total)		(% of Total)	$ Initial	(% of Total)	$ Final	(% of Total)
SEED RECOVERY	6.7×10^6	(28)	2.4×10^6	(26)	4.96×10^6	(50)	5.8×10^6	(33)
● QUENCH	2.0×10^6	(8)	0.14×10^6	(1.5)	0.32×10^6	(3)	1.4×10^6	(8)
● ESP	4.7×10^6	(20)	2.24×10^6	24.5)	4.4×10^6	(47)	4.4×10^6	(25)
SEED RECYCLE	6.3×10^6	(27)	3.5×10^6	(39)	3.9×10^6	(41)	3.9×10^6	(22)
SEED REGENERATION	9.2×10^6	(39)	2.5×10^6	(28)	NA		7.3×10^6	(41)
SEED TRANSPORT/ STORAGE/FEED	1.3×10^6	(6)	0.66×10^6	(7)	0.82×10^6	(9)	0.82×10^6	(4)

SEED SYSTEM - SUMMARY

ETF-CONCEPT	SEED PROCESSING CONCEPT	CAPITAL COST INSTALLED	TOTAL ANNUAL OPERATING COST		TOTAL ENERGY REQUIREMENT	SEED LOSS
			FOM \$/YR/Kw	VOM M/Kwh		$\left(\frac{\text{LOSS}}{\text{TOTAL}} \times 100\right)$
ETF-1	FULLY INTEGRATED	$\$23.5 \times 10^6$	2.75	1.34	15 MW	7.5%
223 MW_e		$\$102.2$ ($\$/Kw_e$)	3.25×10^6 \$/YR			
		$3.66 \left(\frac{\$}{10^6 \frac{LBS}{SEC}}\right)$				
ETF-2	OFF-LINE, SUBSCALE (1/10)	$\$9.11 \times 10^6$	12.61	2.63	5 MW	13%
			1.18×10^6			
34 MW_e						
			INITIAL			
ETF-3	EVOLVING TO FULLY INTEGRATED	$\$9.44 \times 10^6$ (PARTIAL)	1.23	2.43	11 MW	14%
121 MW_e			2.35×10^6			
			FINAL			
		$\$17.85 \times 10^6$ FULLY INTEG.	4.46	1.44		4.7%
		147 ($/Kw)	2.06×10^6 \$/YR			
		$5.22 \left(\frac{\$}{10^6 \frac{LBS}{SEC}}\right)$				

CAPITAL COST SCALE TO APPROXIMATELY 0.6 POWER

VOM INCLUDES SEED MAKE-UP AND COAL TO GASIFIER

4.0 SYSTEM COMPARISONS

4.1 ANL-ETF-1 System Comparative Study

Background

The availability of the ANL systems code for an MHD topping cycle suggested the desirability of comparing performance and statepoint data calculated by W for its initial ETF -1 concept. This was done with the objective of providing verification of the overall system performance estimates and comparison of the simplified sub-system models to permit better assessment of the key component calculational models and assumptions for those areas where adequacy of W one-dimensional models was in question.

The effort was initiated with the transfer of preliminary ETF-1 concept statepoint data as suggested by Dr. Marshal Sluyter of DOE.
These data are presented in Volume III, Section 1.3.1, Tables 1.3-1 through 1.3-10 of this report.

Discussion

The ANL systems code was exercised using preliminary W ETF-1 input data. The resulting system performance comparison data for the steady-state design point were developed by Dr. John Patton, ANL. General conclusions from this comparison are as discussed below.

Significant variations existed in the systems model approach utilized by ANL, compared to the W model. Specifically the W systems model was constrained to match a given steam bottoming plant steam flow rate and feedwater system and fixed fluid conditions (P,T) and utilized simplified one-dimensional calculation models in its initial form for the MHD train components including the MHD channel. This required the assumption of heat losses and fluid boundary conditions. The ANL program was designed to calculate progressively the downstream statepoint conditions entering and leaving each component after having established the inlet conditions at the combustor. No iterations on the MHD system to match a bottoming system were made. Some of the other assumptions which impacted the conclusions to a lesser extent included:

- ANL utilized the NASA properties code for developing the plasma properties. (W) utilized their own properties code.
- The ANL model did not include the additional injection of air downstream of the radiant boiler as used by W to increase the stoichiometry to 1.05.
- The ANL MHD component cooling conditions were treated directly without invoking the constraints of the actual feedwater conditions.
- ANL did not have the specific W enthalpy data permitting definition of stack heat losses or condenser heat losses and assumed these based on statepoint temperatures.
- ANL's code was based upon the exit pressure level of 1 standard 1 atm rather than the 0.8 standard atm at the Montana site assumed by (W).
- Power requirements for the seed processing removal and coal drying were not implicitly part of the ANL code.

The impact of the differences in the system model analytical approaches taken by W and ANL noted above, although significant, were principally seen in physical size and flow rate magntidue and not in thermodynamic state conditions. Therefore, most statepoint thermodynamic results and conditions compare, and the system calculations are found substantially in agreement. Other than flow rates and MHD power, other parameters were also in good agreement.

On the other hand, the impact of heat loss assumptions is significant. Calculating MHD power extraction and establishing the energy balance with low heat losses results in a shift in the power extraction distribution and, therefore, flow rates, component sizes, and steam plant arrangement. The overall efficiency will be affected to a secondary extent as long as the steam plant conversion efficiency is high and all lost heat from the topping system is utilized.

The apparent paradox of a significant variation in MHD power output and flow rate resulting from the change in heat loss without significant effect regarding overall plant power production and efficiency is due to two factors: 1) the assumption of the heat loss as simply a bypass of the topping cycle and recovered in the bottoming cycle conversion system and 2) the assumption of no impact of this higher heat load on the steam thermodynamic plant conversion performance. These assumptions are correct as long as the steam plant feedwater cycle and steam extraction for compressor drives is not significantly effected. Also, this results in a reduced mass flow rate in the topping cycle, as noted above, due to the higher heat transfer to the bottoming cycle capacity.

A review of the preliminary results showed good cycle thermodynamic agreement and indicated reasonable W system model performance. These key parametric data are summarized in Table 4.1-1 and compared to an updated W system analysis incorporating revised assumptions of heat loss and component performance as discussed in Volume III, Section 1.0 of this report.

Conclusions

Based upon the conditions calculated by the ANL code, the combustor and generator heat losses were significantly greater than the losses assumed by W. This resulted in a larger heat dump to the bottoming cycle and a lower power output from the MHD generator. Since the ANL code did not re-size the system to correspond to this thermal power split, the MHD generator was sized differently than resulting from the W calculations which adjust the flow to compensate for the steam bottoming plant requirements. Therefore the flow rates that were established by the ANL code to match a given plant output were noticeably lower than those that were calculated by W with the lower topping cycle heat losses.

However, the thermodynamic cycle including all of the key component statepoints that were calculated by ANL were essentially the same as those calculated by W. No noticeable discrepancy in the system model could be detected. A re-calculation by W of the system allowing for higher heat losses in the MHD generator and combustor did result in an adjustment of the flow rate in the W model that would bring the flow rates into better agreement.

Summary

- The ANL model is based on a natural calculational philosophy that establishes the inlet condition at the initial upstream component (combustor) and the system model progressively developes the inlet and exit conditions of each downstream component without iterating (to meet any fixed condition downstream) except for matching exit ambient conditions.

- The W program forces a match with a steam plant and re-sizes the MHD train components for this constraining condition.

- The lower assumed heat losses in the W combustor and MHD generator resulted in a higher percentage of power produced by the MHD train in the W calculations than that developed by the ANL calculations. Although the contribution to total power from the MHD system was sizably reduced in the ANL calculations, the overall system efficiency was not significantly affected.

- The W system model performance is good and with corrected assumptions for heat losses in the topping cycle, would be in close agreement with the ANL model.

TABLE 4.1-1

ETF-1 SYSTEM PERFORMANCE COMPARISON

	Westinghouse	ANL
Energy to Combustor (MW)	504	512.7
Heat Transferred to Steam (MW)		
Cooling Loops	39.06	66.0
Radiant Boiler	162.0	131.5
Steam Generator	61.9	45.1
Economizer #1	16.9	146.8
Economizer #2	39.2	
(Coal Drying)	23.0	---
Heat Transferred to Air (MW)		
High Temperature Preheater	107	85.3
Low Temperature Preheater	104	89.0
Stack (MW)	N.R.	39
Power Generated (MW)		
MHD	152.0	111.13
Steam Turbine	124.9	149.7
Power Consumption (MW)		
Compressor	-40.18 (P_0 = 5.7)	-26.54 (P_0 = 5.1)
Auxiliary	13.76	13.76
Condenser	N.R.	241.9
Net Power (MW)	224.0	221.3
Power Split		
MHD	54.9	42.6
Steam	45.1	57.3
Overall Cycle Efficiency	44.4%	43.1%

4.2 ANL MHD CHANNEL COMPARISON - W REFERENCE DESIGN MODEL

Background

The availability of sophisticated two-dimensional MHD channel codes at GAI and ANL suggested the desirability of making a comparison with the W systems model. At the suggestion of DOE and in accordance with Dr. Sluyter's instructions, both Gilbert Associates, Inc. and ANL have conducted calculations using their MHD generator two-dimensional codes with input data from the revised W reference design. The specific data utilized are presented in Table 4.2.1. Corresponding performance data and results of W calculations are found in Volume V, Section 2.0 of this report. The ANL comparison results are discussed in the following.

Discussion

Data from the revised ETF-3 reference design were transmitted to Dr. E. Doss of ANL for two-dimensional model calculation comparisons to assess the MHD performance developed in the W systems code. These data were for the revised reference ETF-3 concept and from a system calculation which included an updated MHD generator model.

Pertinent factors involved in the calculation of the W reference design by ANL include:

- ANL used the NASA properties code in developing the plasma properties. (W) utilized their own properties code.
- Channel flow conditions and diffuser exit conditions were assumed at the (W) value.
- Specific channel design data as presented in the W inputs were rigorously maintained by ANL.

- Channel wall conditions were assumed as slag surface with equivalent roughness elements of 2.5 mm height.

The axial variation of selected gasdynamic and electrical variables shown in Tables 4.2.2 and 4.2.3 were obtained by the ANL two-dimensional channel code

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utilizing the above data and assumptions. Table 4.2-4 shows a comparison between the ANL and W results for the important parameters at the channel inlet and exit.

The total power output and heat losses agree very well. Several of these parameters are compared directly in Figures 4.2-1 through 4.2-3. Figure 4.2-1 gives the axial distribution of the gas static temperature and pressure along the channel. Figure 4.2-2 gives the axial variation of the electrical conductivity and Hall parameter. Figure 4.2-3 gives the axial variation of the axial Hall field (Ex) and the current density Jy. The analysis shows that the axial Hall field (Ex) is much larger than Westinghouse results indicated near the exit of the channel. This difference does not appreciably effect the overall channel performance results but is a design concern. The difference appears to be due to the sophistication needed to properly calculate the voltage loss that is incorporated in the ANL two-dimensional code, but is more simply developed in the W model.

The voltage drop predicted in ANL analysis is about 400 volts at the entrance of the channel and about 1400 volts near the exit. As noted, the W calculation showed only approximately 200 volts at the exit of the channel. However, the reason for the variation in the axial Hall field and the current density is not readily apparent even though calculated boundary conditions in the code and voltage drop conditions may account for this difference.

As shown in Table 4.2-4 the blockage at the channel exit is about 15.5%. For such large blockage, the diffuser recovery coefficient will probably be less than $c_p = 0.58$ which is specified in the input data. However, the results are not expected to change much if, for example the diffuser recovery coefficient is reduced from 0.58 to 0.48, a more probable value considering the results of previous ANL diffuser assessments.

Conclusions

The results obtained by ANL utilizing a two-dimensional MHD channel code substantially agree with the W predictions. Electrical power output and heat transfer rates are in close agreement. Generally speaking similar trends are found in the distribution of the other variables along the channel however the ANL analysis showed that the axial Hall field in the last three meters of the channel exceeded the upper limit of 3500 V/m specified by W. ANL did not exercise the option of varying the magnetic field or otherwise tailoring parameters in an attempt to get agreement. In other words, no attempt was made to re-design the channel to agree with the W results.

The analysis developed by ANL suggested that the trends and specific data points calculated in the W code are in reasonable agreement with their two-dimensional model. Small variances in inlet pressure assumptions or variances in the channel geometry would permit bracketing the W data. As found in the ANL calculations the electrical conductivity appears to start at a lower value than in the W model, but tends to agree with the W model approaching the exit of the channel. Again power output, heat losses and overall performance is in good agreement.

Summary

The updated W MHD generator code appears to compare well with the two-dimensional analyses as developed by ANL. The overall performance and thermodynamic data are in very good agreement. However some variance in the downstream conditions related to voltage drop and boundary layer suggest that there are some effects that would impact design. The difference in calculating geometric data in the systems code is not a problem. However, it would be desirable to identify the reason for the discrepancy to assure full understanding of the calculational model. For the purposes of conceptual design and sizing of an MHD topping cycle these differences are of no consequence since it would be unlikely that the systems code would be exercised for the component design calculations.

TABLE 4.2-1

INPUT DATA - WESTINGHOUSE ETF CONCEPT REFERENCE DESIGN DATA

Coal Type - Montana Rosebud

Coal Feed Rate = 14.81 kg/S to combustor
= 0.33 kg/S to gasifier

Preheat to Air = 1644 K

Seed Rate = 7.0 kg(K) to 1000 kg product

Mass Flow Rate = 114.5 kg/S to MHD system

Combustor Exit Pressure = 4.704 atm (total)

Combustor Exit Temperature = 2743 K (total)

Nozzle Exit Mach No. = 0.9125

Channel Geometry

Height = 0.417 m

Width = 0.833 m

Length = 7.82 m

Channel Conditions (Segmented Faraday)

Wall Temperature - 1800 K (slag surface)

Load Factor = 0.75

Magnetic Field = 6T inlet to 4.79 T at exit (profiled to meet Hall Parameter per Generator Design Table, last column)

Hall Field Maximum = 3500 V/m

Velocity Profile = 825 m/s inlet to 703 m/s exit (profile per column 9 Generator Design Table)

Diffusion Conditions

Outlet Pressure = 0.8707 atm (total)

Recovery Factor = 0.58

TABLE 4.2-2

Axial Variation of the Gasdynamic Performance Parameters

X	VEL	TEMP	PRESS	RHO	MACH	HS	HTOT	PTOT	REN.NO.	BLOCK	P REC
0.0	816.2	2594.0	2.9900	0.4121	0.8866	3.534	3.867	4.643	221.10	0.0	0.0
0.200	790.4	2595.6	2.9872	0.4114	0.8583	3.539	3.852	4.515	299.15	0.0313	0.0
0.400	772.5	2594.7	2.9580	0.4076	0.8390	3.538	3.836	4.392	372.44	0.0416	0.0
0.600	767.0	2589.9	2.8889	0.3989	0.8340	3.526	3.821	4.269	442.90	0.0486	0.0
0.800	752.4	2587.7	2.8469	0.3935	0.8185	3.522	3.805	4.149	506.79	0.0594	0.0
1.000	741.2	2584.4	2.7943	0.3867	0.8069	3.514	3.789	4.030	566.67	0.0681	0.0
1.200	723.2	2583.0	2.7599	0.3822	0.7877	3.512	3.773	3.913	619.57	0.0802	0.0
1.400	720.4	2577.0	2.6833	0.3726	0.7856	3.498	3.757	3.798	673.42	0.0822	0.0
1.600	711.1	2572.8	2.6242	0.3650	0.7762	3.488	3.741	3.684	720.61	0.0915	0.0
1.800	700.3	2568.9	2.5677	0.3577	0.7652	3.480	3.725	3.571	762.72	0.0998	0.0
2.000	694.8	2563.4	2.4979	0.3489	0.7601	3.467	3.708	3.459	803.26	0.1069	0.0
2.200	686.8	2558.3	2.4334	0.3406	0.7522	3.456	3.692	3.348	838.40	0.1152	0.0
2.400	680.7	2552.6	2.3642	0.3317	0.7464	3.443	3.675	3.237	870.54	0.1236	0.0
2.600	674.9	2546.6	2.2936	0.3227	0.7411	3.430	3.657	3.126	898.97	0.1312	0.0
2.800	669.6	2540.1	2.2213	0.3134	0.7364	3.415	3.640	3.016	923.81	0.1383	0.0
3.000	665.1	2533.3	2.1471	0.3038	0.7324	3.400	3.622	2.906	945.20	0.1457	0.0
3.200	661.0	2526.1	2.0716	0.2940	0.7290	3.385	3.603	2.796	963.07	0.1519	0.0
3.400	656.9	2518.7	1.9977	0.2844	0.7256	3.369	3.585	2.689	977.86	0.1583	0.0
3.600	653.0	2511.2	1.9257	0.2751	0.7225	3.353	3.566	2.586	990.42	0.1639	0.0
3.800	649.7	2503.8	1.8565	0.2661	0.7199	3.337	3.548	2.488	******	0.1695	0.0
4.000	646.2	2496.4	1.7908	0.2575	0.7171	3.322	3.531	2.395	******	0.1749	0.0
4.200	643.4	2488.8	1.7263	0.2490	0.7151	3.306	3.513	2.305	******	0.1796	0.0
4.400	640.9	2481.2	1.6633	0.2407	0.7134	3.290	3.496	2.218	******	0.1839	0.0
4.600	638.9	2473.3	1.6012	0.2325	0.7123	3.274	3.478	2.133	******	0.1875	0.0
4.800	637.0	2465.4	1.5406	0.2245	0.7113	3.258	3.461	2.051	******	0.1906	0.0
5.000	636.1	2457.0	1.4799	0.2165	0.7114	3.241	3.443	1.971	******	0.1939	0.0
5.200	638.0	2447.7	1.4171	0.2081	0.7148	3.222	3.425	1.893	******	0.1932	0.0
5.400	643.6	2437.2	1.3503	0.1992	0.7225	3.200	3.407	1.815	******	0.1888	0.0
5.600	651.9	2425.4	1.2810	0.1900	0.7335	3.176	3.388	1.737	******	0.1850	0.0
5.800	661.0	2413.1	1.2120	0.1808	0.7455	3.150	3.369	1.660	******	0.1788	0.0
6.000	657.8	2404.1	1.1587	0.1735	0.7431	3.132	3.349	1.584	******	0.1831	0.0
6.200	651.9	2396.0	1.1105	0.1669	0.7375	3.116	3.329	1.512	******	0.1904	0.0
6.400	648.5	2387.1	1.0615	0.1602	0.7349	3.099	3.309	1.442	998.27	0.1943	0.0
6.600	646.8	2377.6	1.0124	0.1534	0.7343	3.080	3.289	1.375	984.09	0.1959	0.0
6.800	645.7	2367.8	0.9644	0.1468	0.7344	3.060	3.268	1.310	969.25	0.1965	0.0
7.000	646.2	2357.4	0.9168	0.1402	0.7363	3.039	3.248	1.248	954.73	0.1962	0.0
7.200	657.0	2343.7	0.8620	0.1326	0.7505	3.011	3.227	1.188	946.66	0.1870	0.0
7.400	669.8	2329.1	0.8074	0.1251	0.7671	2.981	3.205	1.129	937.80	0.1775	0.0
7.600	685.4	2313.2	0.7525	0.1174	0.7874	2.948	3.182	1.071	928.30	0.1670	0.0
7.800	705.0	2295.4	0.6967	0.1096	0.8124	2.911	3.159	1.014	918.17	0.1555	0.0
7.820	707.1	2293.6	0.6911	0.1088	0.8152	2.907	3.157	1.009	917.06	0.1541	0.0

TABLE 4.2-3

Axial Variation of the Elctrical Performance Parameters

X	BF	PARM1	PARM2	POWER	PLUC	JX	JY	EX	EY	EXINT	VF	VD	SIGMA	BETA	CONV	TUT	K	KAVG
0.0	6.0000	0.75	0.8	0.0	21.63	-264.	-7327.	-2146.	3673.	0.	-2459.	600.	5.64	1.61	60.87	0.0	0.75	0.60
0.200	6.0000	0.75	0.8	1.57	21.65	-333.	-7278.	-2129.	3557.	-428.	-2531.	495.	5.68	1.62	63.61	0.36	0.75	0.63
0.400	6.0000	0.75	0.8	3.13	20.61	-389.	-7231.	-2140.	3476.	-854.	-2474.	543.	5.69	1.63	63.36	0.72	0.75	0.62
0.600	6.0000	0.75	0.8	4.72	20.09	-438.	-7217.	-2205.	3451.	-1290.	-2464.	591.	5.64	1.66	63.02	1.08	0.75	0.60
0.800	6.0000	0.75	0.8	6.30	19.12	-490.	-7171.	-2231.	3386.	-1734.	-2407.	650.	5.62	1.68	62.57	1.45	0.75	0.59
1.000	6.0000	0.75	0.8	7.88	18.40	-536.	-7135.	-2273.	3335.	-2185.	-2376.	697.	5.59	1.71	62.09	1.81	0.75	0.58
1.200	6.0000	0.75	0.8	9.44	17.44	-580.	-7085.	-2289.	3254.	-2640.	-2314.	746.	5.60	1.73	61.59	2.17	0.75	0.57
1.400	6.0000	0.75	0.8	11.05	17.29	-618.	-7066.	-2368.	3242.	-3109.	-2349.	762.	5.53	1.77	61.21	2.54	0.75	0.57
1.600	6.0000	0.75	0.8	12.66	16.71	-659.	-7043.	-2427.	3200.	-3586.	-2325.	811.	5.49	1.80	60.77	2.91	0.75	0.56
1.800	6.0000	0.75	0.8	14.29	15.98	-706.	-7025.	-2487.	3152.	-4078.	-2275.	877.	5.46	1.83	60.34	3.28	0.75	0.54
2.000	6.0000	0.75	0.8	15.93	15.58	-744.	-7025.	-2574.	3127.	-4584.	-2265.	927.	5.40	1.87	59.87	3.66	0.75	0.53
2.200	6.0000	0.75	0.8	17.59	15.04	-783.	-7018.	-2655.	3091.	-5107.	-2235.	989.	5.36	1.92	59.38	4.04	0.75	0.52
2.400	6.0000	0.75	0.8	19.27	14.60	-818.	-7021.	-2752.	3063.	-5647.	-2218.	1049.	5.30	1.96	58.87	4.42	0.75	0.51
2.600	6.0000	0.75	0.8	20.97	14.23	-849.	-7029.	-2858.	3037.	-6208.	-2205.	1104.	5.25	2.01	58.35	4.82	0.75	0.50
2.800	6.0000	0.75	0.8	22.72	13.87	-876.	-7033.	-2972.	3013.	-6790.	-2198.	1159.	5.20	2.07	57.84	5.22	0.75	0.49
3.000	6.0000	0.75	0.8	24.50	13.59	-899.	-7046.	-3100.	2993.	-7398.	-2197.	1213.	5.14	2.13	57.33	5.63	0.75	0.48
3.200	5.9768	0.75	0.8	26.33	13.28	-908.	-7015.	-3209.	2964.	-8031.	-2205.	1248.	5.08	2.20	56.84	6.05	0.75	0.48
3.400	5.9091	0.75	0.8	28.18	12.76	-900.	-6901.	-3257.	2911.	-8677.	-2203.	1267.	5.03	2.24	56.40	6.47	0.75	0.48
3.600	5.8025	0.75	0.8	30.04	12.10	-873.	-6704.	-3245.	2842.	-9329.	-2199.	1264.	4.98	2.28	56.02	6.90	0.75	0.48
3.800	5.6815	0.75	0.8	31.88	11.43	-842.	-6490.	-3213.	2769.	-9475.	-2194.	1255.	4.93	2.31	55.70	7.32	0.75	0.48
4.000	5.5979	0.75	0.8	33.70	10.91	-820.	-6357.	-3236.	2713.	-10620.	-2184.	1269.	4.88	2.35	55.42	7.74	0.75	0.47
4.200	5.5157	0.75	0.8	35.52	10.44	-808.	-6227.	-3264.	2662.	-11269.	-2180.	1279.	4.83	2.40	55.16	8.16	0.75	0.47
4.400	5.4502	0.75	0.8	37.35	10.05	-793.	-6128.	-3319.	2620.	-11927.	-2178.	1298.	4.78	2.46	54.92	8.58	0.75	0.47
4.600	5.3845	0.75	0.8	39.19	9.71	-778.	-6039.	-3382.	2580.	-12597.	-2177.	1317.	4.74	2.52	54.69	9.00	0.75	0.47
4.800	5.3256	0.75	0.8	41.04	9.39	-761.	-5954.	-3454.	2544.	-13280.	-2180.	1337.	4.69	2.59	54.48	9.43	0.75	0.46
5.000	5.2672	0.75	0.8	42.91	9.14	-739.	-5862.	-3530.	2513.	-13979.	-2198.	1346.	4.64	2.67	54.28	9.86	0.75	0.47
5.200	5.2227	0.75	0.8	44.81	8.14	-725.	-5627.	-3671.	2499.	-14696.	-2004.	1581.	4.59	2.77	54.08	10.29	0.75	0.42
5.400	5.1904	0.75	0.8	46.62	8.47	-695.	-5778.	-3843.	2505.	-15446.	-2133.	1512.	4.52	2.89	53.75	10.71	0.75	0.44
5.600	5.1581	0.75	0.8	48.44	8.13	-666.	-5751.	-4068.	2522.	-16238.	-2085.	1636.	4.44	3.02	53.38	11.13	0.75	0.42
5.800	5.1258	0.75	0.8	50.34	8.38	-634.	-5700.	-4305.	2541.	-17075.	-2199.	1603.	4.35	3.18	53.05	11.56	0.75	0.43
6.000	5.0733	0.75	0.8	52.31	7.97	-599.	-5567.	-4393.	2503.	-17948.	-2196.	1645.	4.31	3.29	52.76	12.01	0.75	0.43
6.200	5.0162	0.75	0.8	54.27	7.54	-562.	-5402.	-4432.	2452.	-18831.	-2201.	1666.	4.27	3.40	52.48	12.46	0.75	0.43
6.400	4.9780	0.75	0.8	56.24	7.27	-524.	-5257.	-4521.	2421.	-19724.	-2227.	1671.	4.22	3.53	52.23	12.92	0.75	0.43
6.600	4.9473	0.75	0.8	58.25	7.08	-483.	-5105.	-4628.	2400.	-20639.	-2275.	1660.	4.16	3.68	52.01	13.38	0.75	0.43
6.800	4.9166	0.75	0.8	60.31	6.91	-442.	-4949.	-4740.	2381.	-21576.	-2330.	1644.	4.10	3.84	51.83	13.85	0.75	0.44
7.000	4.8865	0.75	0.8	62.41	6.78	-402.	-4787.	-4865.	2368.	-22535.	-2406.	1617.	4.02	4.01	51.69	14.33	0.75	0.45
7.200	4.8632	0.75	0.8	64.61	7.04	-358.	-4638.	-5110.	2396.	-23532.	-2624.	1518.	3.91	4.23	51.63	14.84	0.75	0.48
7.400	4.8396	0.75	0.8	66.94	7.18	-322.	-4500.	-5416.	2431.	-24583.	-2806.	1469.	3.78	4.47	51.64	15.37	0.75	0.49
7.600	4.8160	0.75	0.8	69.38	7.32	-286.	-4350.	-5775.	2476.	-25701.	-3009.	1419.	3.63	4.75	51.70	15.93	0.75	0.51
7.800	4.7924	0.75	0.8	71.93	7.46	-259.	-4221.	-6264.	2534.	-26901.	-3214.	1394.	3.45	5.05	51.81	16.52	0.75	0.52
7.820	4.7900	0.75	0.8	72.19	7.47	-256.	-4205.	-6315.	2540.	-27027.	-3236.	1390.	3.43	5.09	51.82	16.58	0.75	0.52

TABLE 4.2-4

INLET AND EXIT PREDICTED OPERATING CONDITIONS FOR W REFERENCE DESIGN FOR THE ETF MHD CHANNEL

	Westinghouse	ANL
Inlet Conditions		
P, atm	2.888	2.99
T, K	2594	2594
U, m/s	825	816
M	0.912	0.884
σ, mho/m	6.72	5.64
β	1.72	1.61
Jy, A/cm^2	0.82	0.73
Ex, Vm	2100	2146
Exit Conditions		
P, atm	0.688	0.691
T, K	2269	2294
U, m/s	703	707
M	0.833	0.815
σ, mho/m	2.71	3.43
β	4.27	5.10
Jy, A/cm^2	0.222	0.421
Ex, V/cm	3499	6315
Power output, MW	70	72.2
Total heat loss, MW	19.34	18.58
Flow Blockage at Exit of Channel (%)	--	15.5

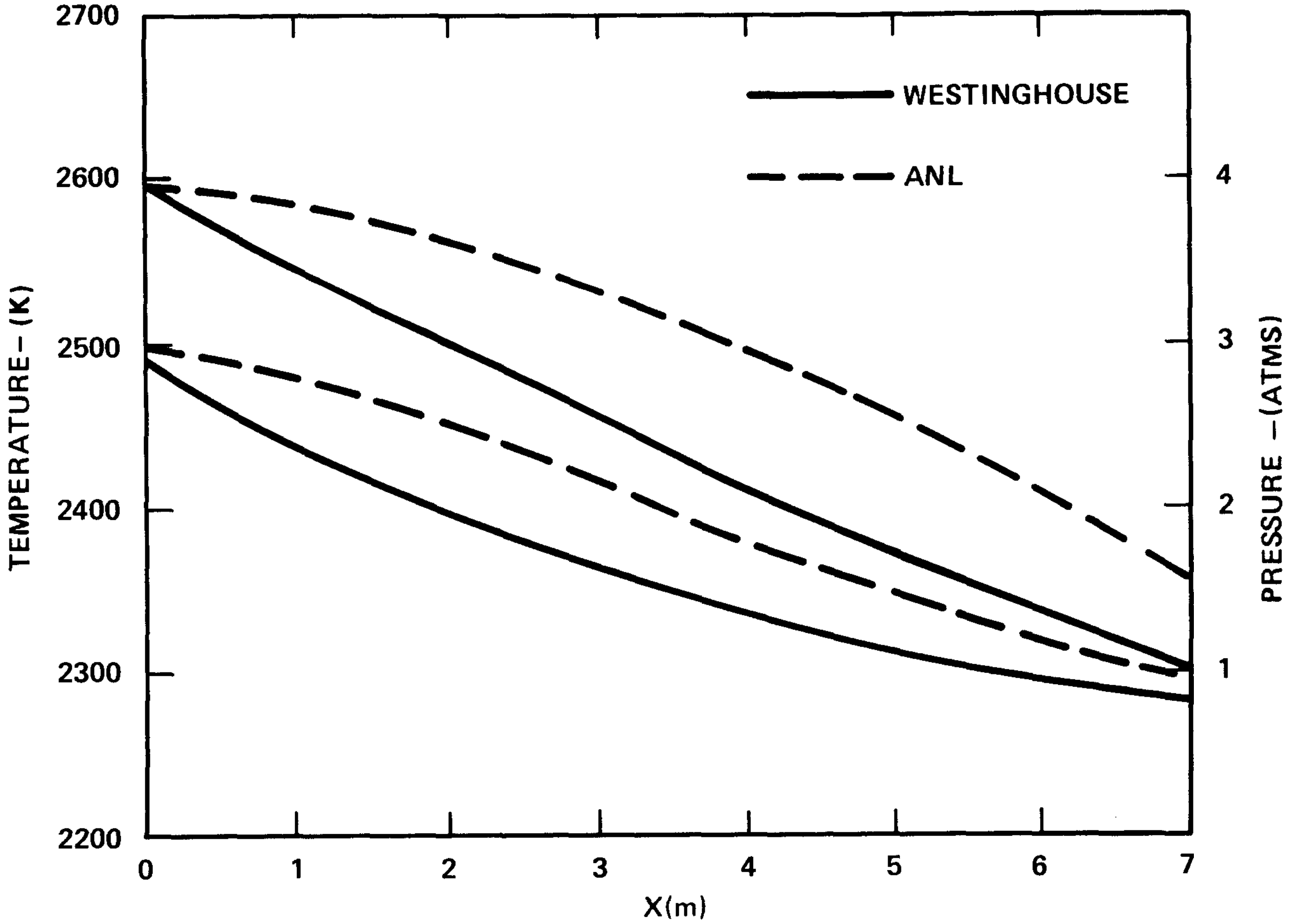

Figure 4.2-1 Axial Distribution of the Static Pressure and Temperature Along the Channel

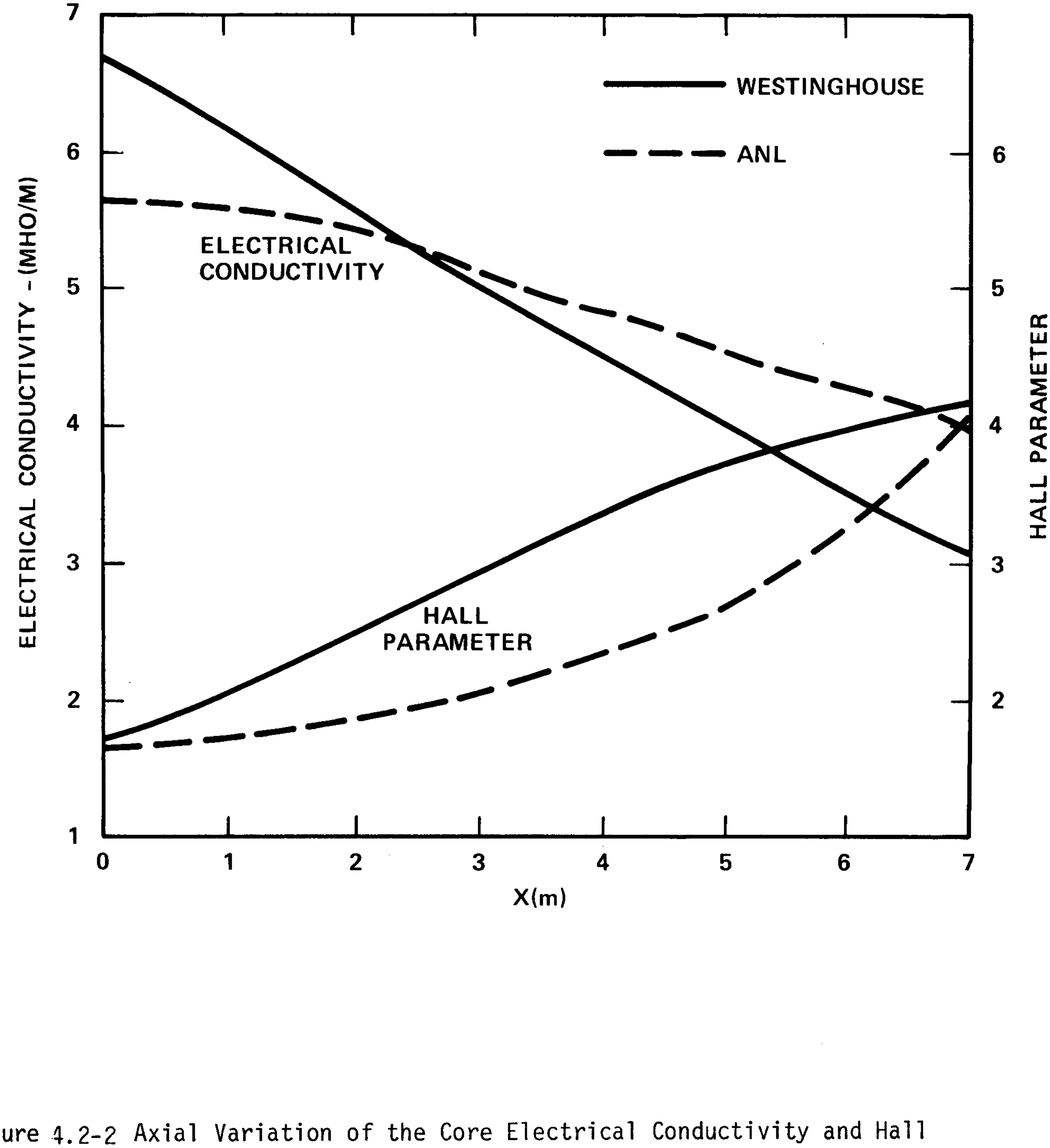

Figure 4.2-2 Axial Variation of the Core Electrical Conductivity and Hall Parameter Along the Channel

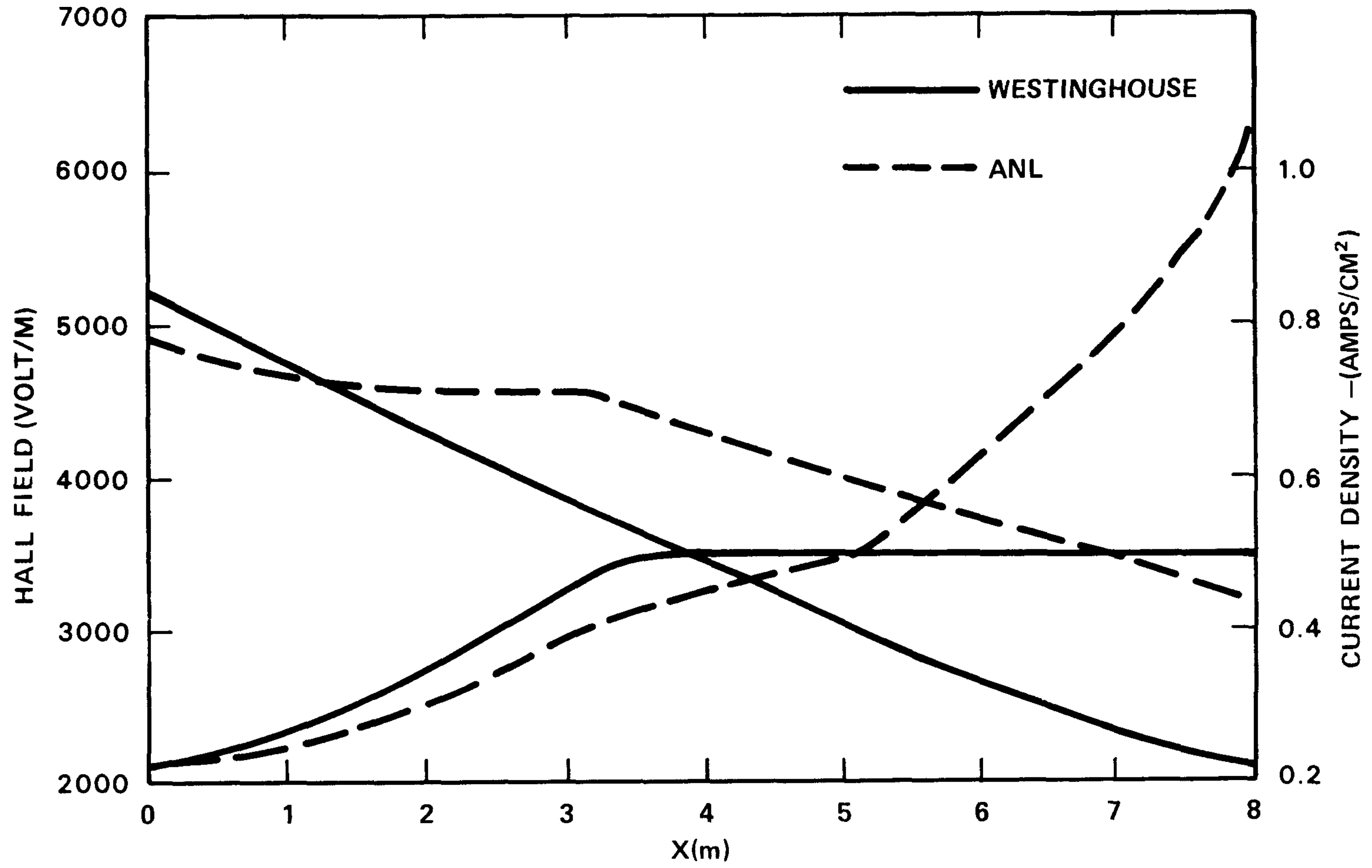

Figure 4.2-3 Axial Variation of the Current Density and the Hall Field Along the Channel

4.3 GAI/MHD CHANNEL COMPARISON - W REFERENCE DESIGN MODEL

Background

In accordance with Dr. M. Sluyter's instructions, Gilbert Associates, Inc., have conducted comparative calculations using their two-dimensional MHD channel codes and input from the (W) ETF Design. The same channel input data as transmitted to ANL and disucssed in the previous paragraph, were also transmitted. There data were obtained with the revised ETF-3 system model including an updated MHD channel calculation model.

The following general discussion is based on the results obtained:

Discussion

Pertinent factors involved in the calculation of the W reference design by GAI included:

- GAI used their modified NASA properties code for assessing plasma properties data. (W) utilized their own properites code.
- GAI initiated calculations at the channel inlet with the channel inlet conditions as presented in the W input data.
- For the base case, GAI operated its two-dimensional channel design code to calculate the channel conditions from assumed inlet conditions as a function of the channel length.

  (This differs from the ANL approach of maintaining channel geometry and calculating conditions.)
- GAI assumed input conditions are shown in Table 4.3.-1.

The specific case data utilized by GAI are presented in Table 4.3.-2 and 4.4.-3 for the three cases evaluated. Comparative curves of the (W) and GAI results are shown in Figures 4.3-1 through 4.3-7.

The principal channel parameter differences noted between the (W) and GAI results were in the electrical conductivity determined for the channel inlet as noted in

TABLE 4.3-1

WESTINGHOUSE ETF
MHD CHANNEL ASSUMPTIONS

(IDENTICAL FOR GAI & WESTINGHOUSE)

Wall Temperature (K)	1800
Loading Factor	0.75
Maximum Magnetic Field (TESLA)	6.0
Maximum Hall Field (V/M)	3500
Pressure Recovery Factor	0.58
Flow Rate (kg/s)	114.5
Initial Velocity (m/s)	825 (V = f(x))
Channel Exit Static Pressure (ATM)	0.688
Nozzle Heat Loss (MW(th))	2.7

TABLE 4.3-2

GAI CASES EVALUATED

	WESTINGHOUSE	CASE 1 GAI BASE	CASE 2 GAI EXTENDED	CASE 3 GAI REVISED INLET
		----------------GAI-----------------		
CHANNEL LENGTH - M	7.82	7.82	10.55	7.82
CHANNEL ENTRANCE				
Tstatic-K	2594	2594	2594	2584
Pstatic-ATM	2.888	2.888	2.888	2.409
CHANNEL EXIT				
Tstatic-K	2269	2296	2215	2254
Pstatic-ATM	0.688	0.976	0.688	0.688

TABLE 4.3-3

COMBUSTION COMPARISON

	WESTINGHOUSE ETF	GAI
COAL TYPE	MONTANA ROSEBUD	MONTANA ROSEBUD
COAL MOISTURE	6%	6%
AIR PREHEAT (K)	1644	1644
SEED RATE - MASS % POTASSIUM	0.7%	0.7%
COMBUSTOR EXIT PRESSURE (ATM)	4.074	(Assumed Channel Inlet Conditions and Enthalpy)
COMBUSTOR EXIT TEMPERATURE (K)	2743	

Figure 4.3-1 and the calculated pressure drop in the channel, Figure 4.3-2. The impact of these variances are noted principally in the change in area and channel geometry as indicated in Figure 4.3-3. There were no significant differences in heat loss, power output, temperature, or current density as noted in Figures 4.3-4 through 4.3-7.

GAI found that with nominal variations in assumed inlet pressure or channel length, the W conditions could be matched or bracketed. However, there is an apparent difference in the analytical model assumptions that affect the pressure loss and, therefore, the channel geometry. Again, this difference has no significant affect in the MHD overall channel thermodynamic performance calculation and would not be a problem in the system code. However, understanding the reason that the two-dimensional design calculation resulted in a lower pressure drop is needed for acceptable assurance in any design assessment. Two possible factors could account for this variance - the flow blockage and/or the plasma conductivity.
However, until some better degree of empirical understanding is developed the only conclusion that appears to be reasonable is that the variation is within the range of uncertainty.

Conclusions

The MHD channel analysis code developed by GAI has been exercised to calculate the performance of the W ETF design MHD channel for comparison of the channel models. The GAI results suggest that the trends and specific data points calculated by the W systems code are in reasonable agreement with their channel model. Small variances in inlet conditions and plasma properties would easily account for the differences and changing the channel length and/or inlet pressure by reasonable amounts permitted bracketing the W data readily.

As found by the ANL analysis, the GAI calculated electrical conductivity appears to start at a slightly lower value but tends to agree with the W model quite early in the channel and approaching the exit. Again, power output, heat losses, statepoints, and overall performance calculations appeared to be in good agreement.

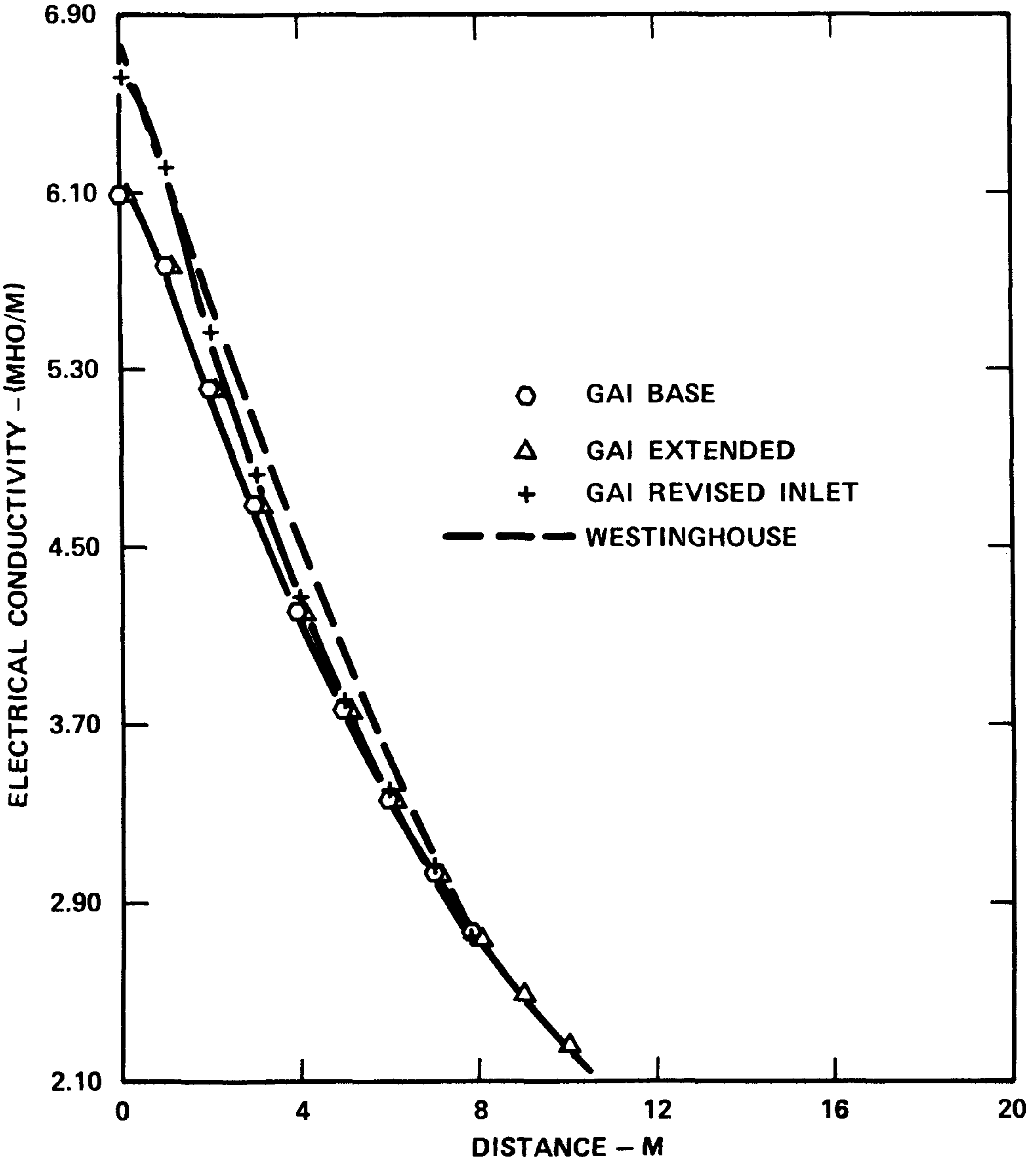

Figure 4.3-1 Electrical Conductivity vs. Channel Length

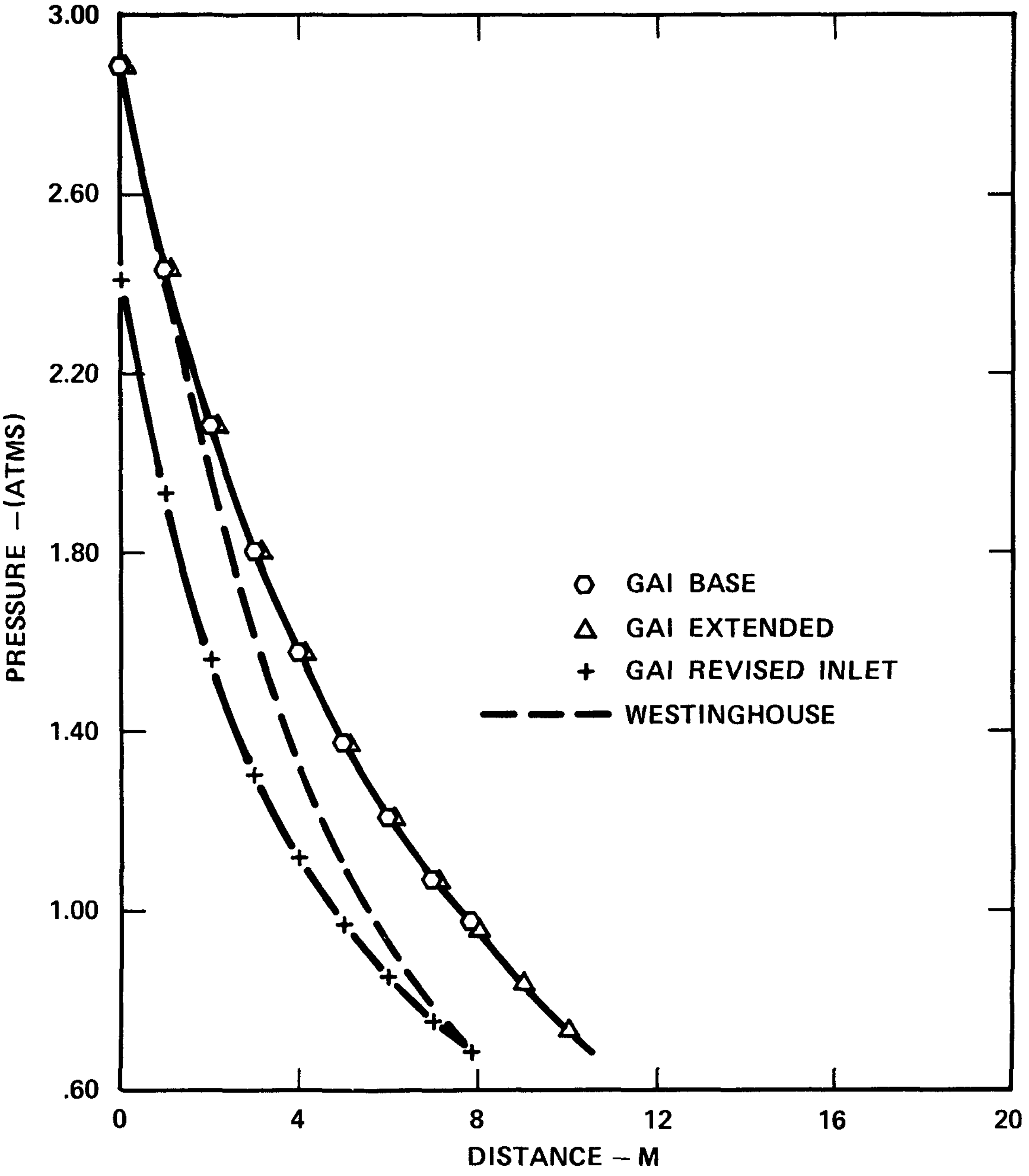

Figure 4.3-2 Pressure vs. Channel Length

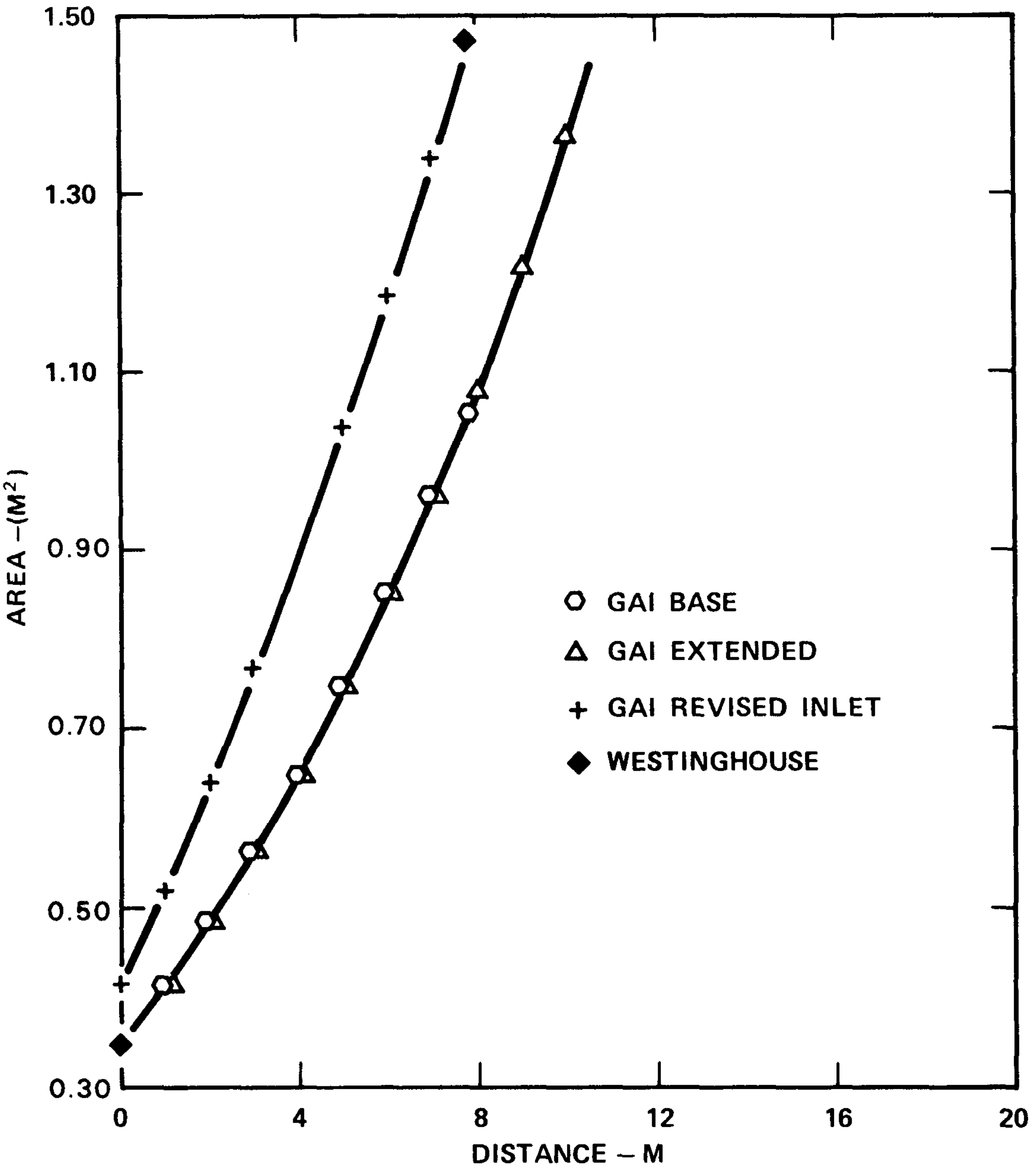

Figure 4.3-3 Area vs. Channel Length

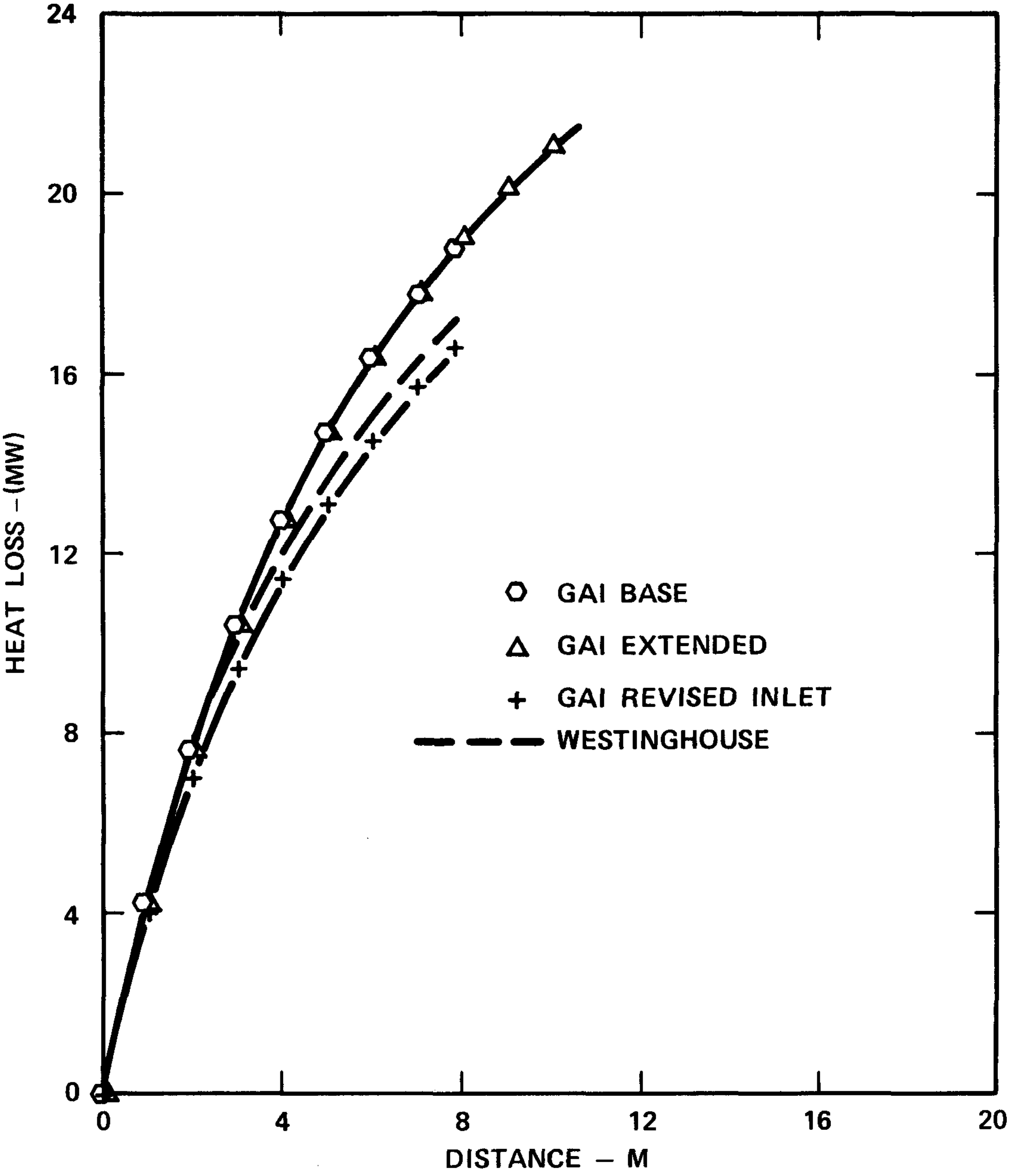

Figure 4.3-4 Heat Loss vs. Channel Length

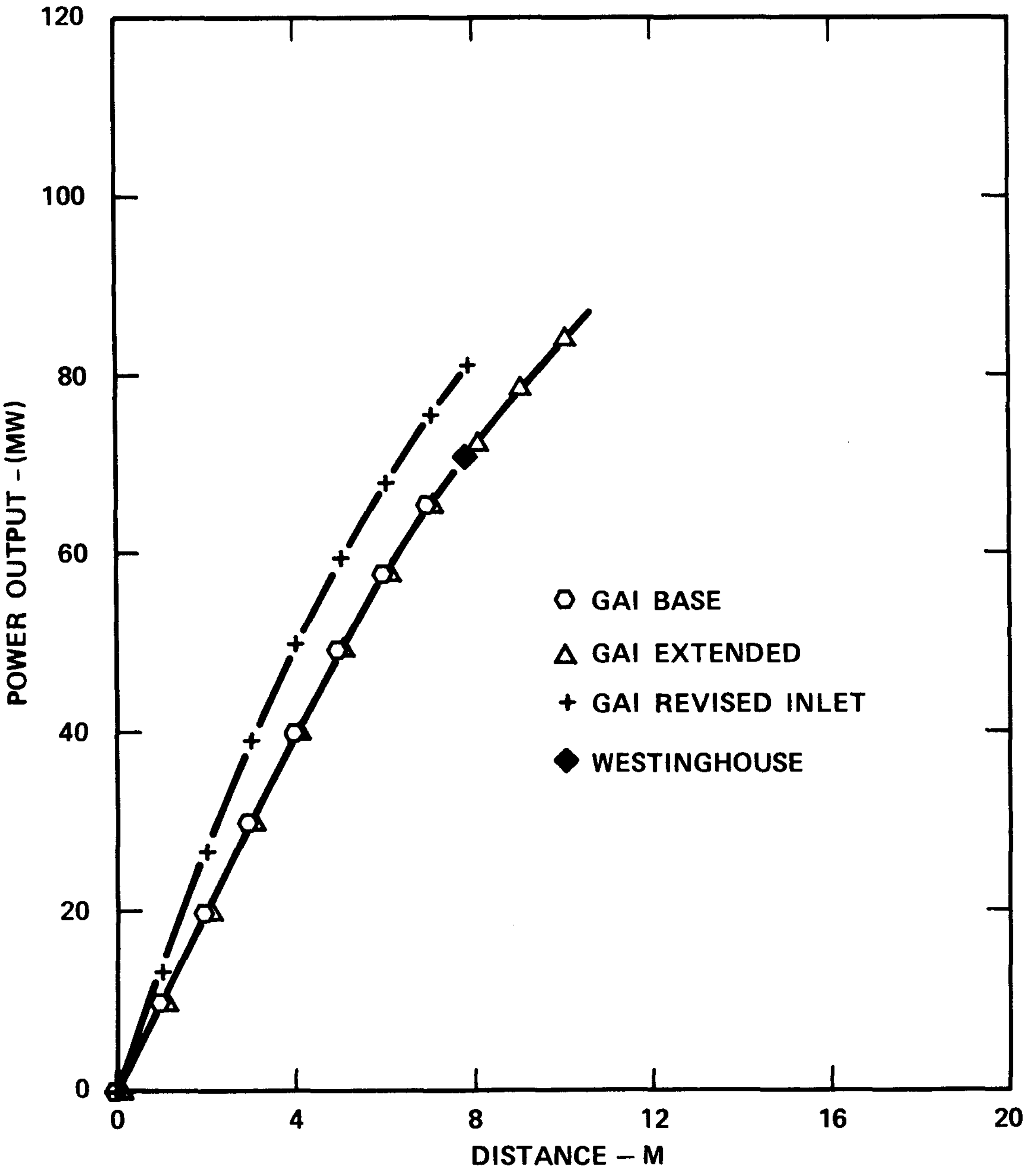

Figure 4.3-5 Power Output vs. Channel Length

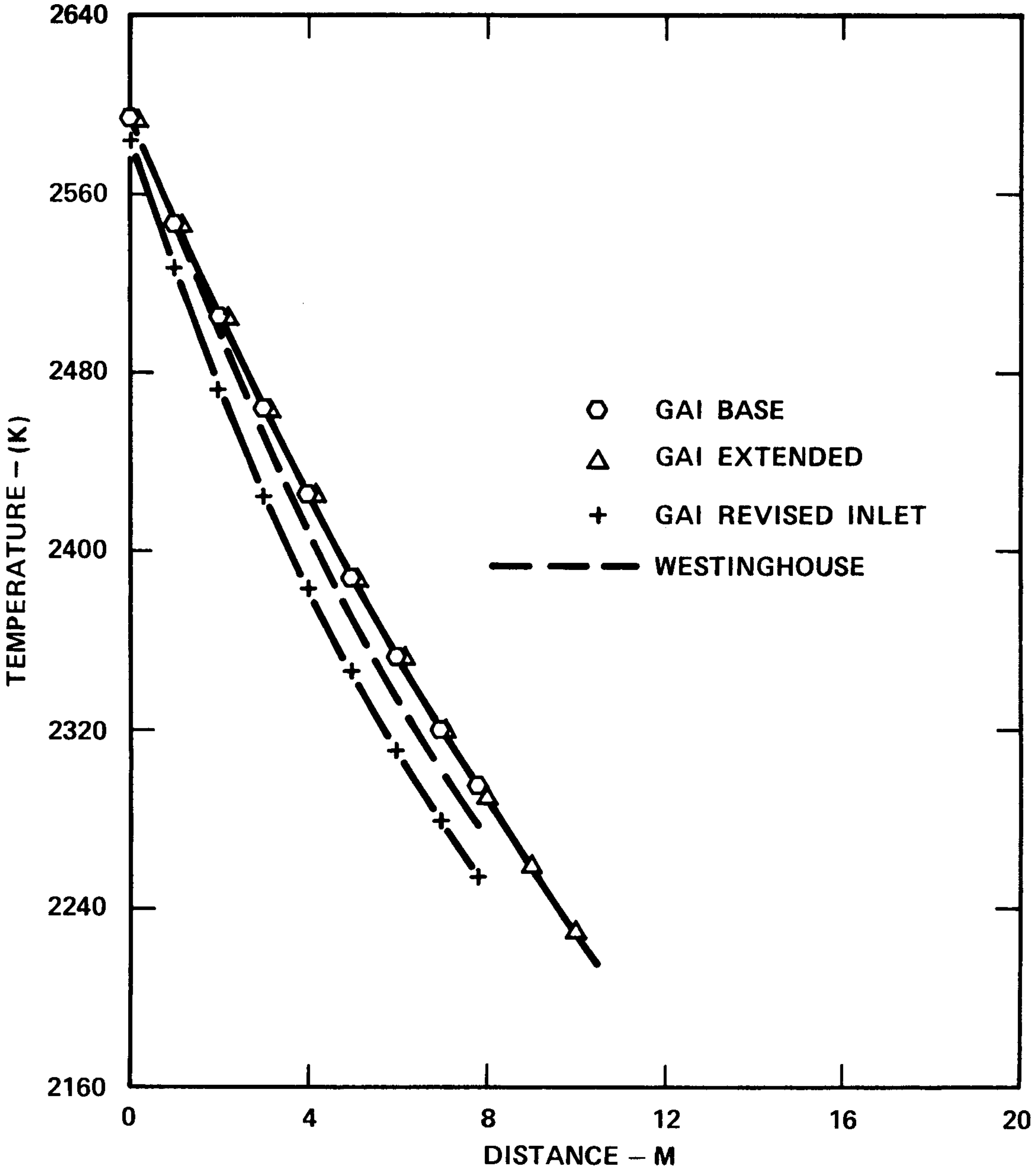

Figure 4.3-6 Temperature vs. Channel Length

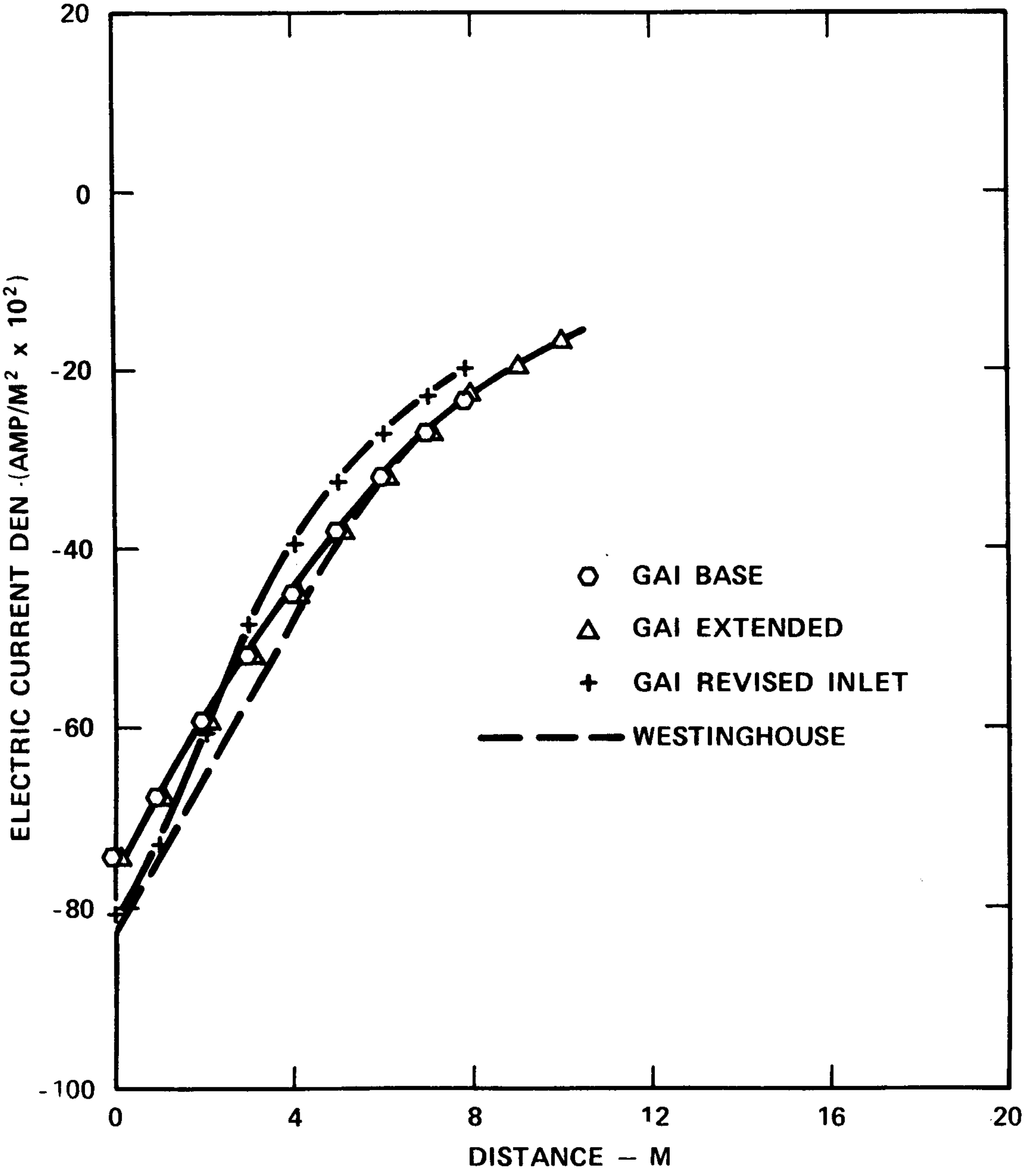

Figure 4.3-7 Electric Current Density vs. Channel Length

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