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POWER GENERATOR DESIGN FOR THE BILLINGS MHD DEMONSTRATION PROJECT

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ABSTRACT

The proposed design of the MHD power generator for the Billings MHD Demonstration Project is presented. The Billings MHD Demonstration Project, proposed by the MHD Development Corporation (MDC) for the U.S. Department of Energy's Clean Coal Technology V Program, will demonstrate the significant environmental advantages and efficiency potential of MHD electric power generation.

A diagonally-loaded, supersonic MHD generator channel is proposed. The generator channel has a thermal input of 250 MW, is 11 meters long and produces 28.5 MW gross power output at the nominal design operating condition. The gasdynamic, gas-side, and mechanical designs of the proposed generator are derived from the design of the 50 MW_t proof-of-concept MHD generator, currently undergoing long duration testing at the CDIF test facility. The design and operation of the proposed generator will be typical of those anticipated in future commercial MHD generator channels.

INTRODUCTION

The proposed design of the MHD power generator for the Billings MHD Demonstration Project is presented herein.

The Billings MHD Demonstration Project, proposed by the MHD Development Corporation (MDC) for the U.S. Department of Energy's Clean Coal Technology V Program, will demonstrate the significant environmental advantages and efficiency potential of MHD electric power generation. The Billings MHD project will consist of the design, construction, testing, and operation of a completely integrated, stand-alone, 250 MW_t MHD/steam combined cycle power plant located in Billings, Montana, at a site owned by the Montana Power Company. The MHD power plant will be built and operated by the MDC, acting as an independent power producer. Textron Defense Systems (TDS) is a team member on the Demonstration Project and will be responsible for the design and fabrication of the MHD generator system, which includes the nozzle, channel, diffuser, and current control devices.

The detailed technical description of the project, the teaming arrangement, a plan for commercialization of the MHD technology, and the financial and business plan for the project will be presented by other team members at this Symposium. The present paper summarizes the proposed designs for the MHD power generator components.

The proposed MHD generator design is based on an extensive data base, obtained through testing under operating conditions that nearly duplicate those projected for the Demonstration power plant. The geometric and mechanical designs of the generator channel are based on the 50 MW_t proof-of-concept (POC) generator currently being tested at the DOE Component Development and Integration Facility (CDIF). These well-proven, low-risk designs are the culmination of many experimental development programs and system studies. See Figure 1.

The basic criteria for the design of the Demonstration plant generator channel are that it meets performance requirements of 10 percent enthalpy extraction, 40 percent isentropic efficiency, and reliability requirements of 2,000 hours operation between scheduled maintenance. Meeting these requirements is quite feasible, based on the current state of MHD technology. The performance requirements can be satisfied as has been demonstrated by the results from the High Performance Demonstration Experiment (HPDE) generator channel,[1] which operated with a thermal input (300 MW) and electrical output (35 MW) comparable to the Demonstration plant generator channel. With respect to reliability, 500 hours of complete channel operation and 1,300 hours of electrode operation have been demonstrated with simulated coal firing at 20 MW_t scale.[2,3] Actual coal-fired testing at 50 MW_t scale, with a generator channel designed for 2,000 hours of operation, is currently in progress. The results of these tests imply that, along with the implementation of a scheduled maintenance concept during power plant operation, the component mean time between failures (MTBF) projections can be extended in excess of the required 8,000 hours.[4,5]

Several MHD channels equal in size to the proposed Demonstration channel have been built to date (e.g., HPDE and Russian U-25 channels), and therefore no difficulties are expected in the actual construction of the Demonstration MHD channel.

PROPOSED DESIGN DESCRIPTIONS

The designs of the MHD generator components for the Billings MHD Demonstration Project are based on experimentally proven designs. Testing to date on subscale prototypic components has verified the necessary performance and lifetime characteristics of these components. These experimental results provide confidence in the readiness of the MHD technology for the Demonstration plant.

The major design requirements of the inlet nozzle, generator channel, and diffuser are listed in Tables 1 through 3, respectively.

MHD Generator Performance and Geometric Design

Preliminary MHD generator performance and design analyses have been carried out for the proposed Billings MHD Demonstration plant and are presented below. Results from these calculations were utilized in estimates of overall plant efficiency and costs.

A diagonally-loaded MHD generator channel is proposed. The generator channel is 11 meters long and produces 28.5 MW gross power output at the nominal design operating condition. The overall dimensions of the generator channel are shown in Figure 2. The channel operates in the supersonic mode with an inlet Mach number of 1.2; the peak magnetic field is 4.5 tesla. The selection of supersonic channel operation, along with the use of moderate magnetic field strengths was based on results from previous MHD power plant systems studies,[4,5] which showed that this combination offers the lowest risk approach for early commercial MHD plants. Table 4 summarizes the Demonstration MHD generator performance and the associated gasdynamic and electrical characteristics.

The Demonstration MHD generator channel design was selected by maximizing topping cycle performance, while limiting internal electrical stresses to reasonable values. To help with this selection, parametric generator design and performance calculations were carried out. A range of magnetic field intensities and oxygen enrichment levels were evaluated in order to study their effects on generator power output and internal electrical stresses. The results of these calculations, plotted as a function of maximum current density (J_y) and axial electric field (E_x), are shown in Figure 3. Also shown in Figure 3 are the electrical stress constraints for state-of-the-art generator channels. Duration testing at Textron has shown that exceeding these constraints results in increased channel wear. Variations in net topping cycle power output for the same parametric calculations above are plotted in Figure 4, where net power output is defined as the gross MHD generator power minus the work required for the cycle compressor and for the air separation unit. At the nominal operating condition of the proposed Demonstration generator, the electrical stress constraints are satisfied and the net power is maximized.

It is important for the proposed MHD generator to verify that the channel design demonstrates reliable performance and duration at the projected baseload electrical and gasdynamic operating conditions. It is also important that the Demonstration generator be designed such that it operates within the range of experience gained to date. MHD generator operating parameters and stress levels are compared in Table 5 for the proposed generator, the baseload MHD generators, and the various subscale generators.

Generator Gas-Side Element Designs

The gas-side (internal) designs of the Demonstration generator channel are taken directly from the POC generator design. The gas-side design of an MHD generator channel, i.e., the selection of materials, electrode pitch, cooling, etc., are dictated by the generator's operating parameters, not its size. A small coal-fired generator channel designed to operate at the same thermal and electrical stress conditions as those in a large baseload MHD generator must have the same gas-side design for equal channel life. Using this rationale, the POC generator development has been conducted by testing at coal-fired operating conditions and channel wall stress conditions similar to those in the Demonstration MHD plant and also at those conditions projected for commercial MHD plants.

The surface protections for the cathode, anode, and sidewall elements are different from each other because different corrosion mechanisms occur on the various walls. These gas-side designs and material selections were based on the results of duration and engineering support tests in Textron's MHD test facilities and coal-fired confirmation tests at the CDIF.[6,7]

The Demonstration generator cathode wall elements will be constructed of copper bars capped with tungsten tiles, similar in design to the POC cathode elements shown in Figure 5. Tungsten resists both arc erosion, caused by slag-induced shorting of cathode wall electrodes, and electrochemical corrosion, due to ionic current leakage in the cathode slag layer.[6] Grooves are machined into the surface of the tungsten pieces to facilitate slag attachment.

The anode wall elements will be constructed of copper bases with brazed on platinum-on-tungsten caps to provide oxidation and sulfidation resistance. They will be similar in design to the POC anodes, one of which is shown in Figure 6. The primary gas-side protection is provided by the platinum top and leading edge caps. The upstream gas-side corner of the electrode, where transverse currents tend to concentrate due to the Hall effect, will be reinforced with square strips of platinum. The tungsten serves as backup protection for the platinum primary cap. The anode wall slag coating is obtained by recessing the interanode insulators at the gas surface to provide a foothold for slag attachment. Similar anodes have previously been tested for over 1,300 hours.[3,8]

The majority of the sidewall elements will be made of water-cooled tungsten-copper alloy (W-Cu) bars. This sidebar design is reliable and simple to fabricate since it requires no cap brazing. The W-Cu sidebars adjacent to the cathode wall, however, will be capped with tungsten tiles to enhance corrosion resistance. The material wear mechanisms in this sidewall region are the same as those described previously for cathodes, hence the use of tungsten capping materials in both cases. In the channel inlet region, where the wall heat fluxes from the plasma are the highest, tungsten-capped copper-based sidebars will be used. All of the sidebars will be surface grooved for slag retention. The Demonstration generator sidewalls will look similar to the POC sidewalls, shown in Figure 7, except that the Demonstration sidewalls will be larger and have a different sidebar incline angle.

Hot pressed boron nitride (BN) will be used for the interelectrode and intersidebar insulating material. BN is cooled by contact with the adjacent metallic elements. These insulators span the full height of the wall elements (from the fiberglass back wall to the gas surface), except on the anode wall where, as mentioned previously, the BN is recessed for slag retention. Aluminum nitride insulating tiles will also be used in the electrode wall/sidewall corner joint regions for reinforcement against electrical breakdowns.[9]

Mechanical Design of Nozzle, Generator Channel, and Diffuser

The Demonstration MHD power train will have the same basic design as the POC MHD power train. A layout of the Demonstration plant nozzle/generator channel/diffuser is shown in Figure 8.

The Demonstration MHD nozzle will be a scaled-up version of the POC nozzle, shown in Figure 9. Basic similarities between the two nozzle designs are: constant-height sidewalls, two-dimensional flow nozzle, electrically-segmented gas-side designs, and slagging features that minimize wear and heat losses.

An exterior view of the Demonstration MHD generator is shown in Figure 10. The generator channel will be constructed of four separable fiberglass walls, which are bolted and sealed at the corners to form a rectangular cross-sectioned duct. The channel is 11 m long and is fabricated from two 5.5 m sections joined at a mid-channel flange. The boxed walls function as the structural shell and as the pressure vessel for the channel. Electrodes and sidewall bar elements are mounted directly onto the fiberglass backing walls. Also shown in Figure 10 are the channel inlet and exit flanges, the structural support trusses, and the mid-channel flanges. Water coolant manifolds are also shown on the back section of the channel.

A constant-height, segmented-bar sidewall design, shown earlier in Figure 7, was chosen for the Demonstration generator channel. This design has excellent hydraulic and structural reliability, and is easily scaled to larger channels. Sidewalls of this design are also easy to fabricate and assemble. The sidewall element rows are arranged in a "Z" pattern to align them with the internal plasma equipotential distribution, thus minimizing electrical stresses between adjacent elements and prolonging their lifetimes.[10]

The total weight of the proposed channel is estimated to be about 20,000 kg. To accommodate this weight and the forces on the channel walls, an external structural support system will be required. The support structure, shown in Figure 10, will be placed at intervals along the channel to resist the bending loads and to provide an appropriate margin of safety to the flexural strength of the fiberglass walls. These support structures will also provide attachment points for the generator wiring conduits and coolant manifolds. Rollers will be placed on these trusses to allow axial movement of the channel for installation and maintenance and also to ensure even distribution of its weight along the rail system in the magnet bore. Figure 11 shows a typical cross-section of the generator channel installed in the magnet bore. The final arrangement of wires and manifolds will require detailed generator/magnet integration studies to maximize the utilization of the warm bore volume and to minimize the magnet cost.

The Demonstration plant MHD diffuser decelerates the supersonic flow exiting the generator channel prior to its entrance into the radiant boiler. A schematic representation of the diffuser is shown in Figure 12. The forward portion of the diffuser is a constant area duct that decelerates the flow from supersonic to sonic conditions. The diverging portion of the diffuser further decelerates the flow to a velocity acceptable for the radiant boiler.

The first supersonic diffuser section, situated immediately downstream of the power channel, will be constructed like the generator channel, with four separable fiberglass walls onto which are mounted the diffuser wall elements. These elements will be both transversely and axially segmented to prevent the generation of circulating currents by the fringe field of the magnet. Such circulating currents have led to localized corrosion of diffusers with an unsegmented construction.

Both the second supersonic diffuser section and the subsonic sections will have gas-side wall surfaces cooled by boiler tube wall designs. The aerodynamic aspects of their design will be specified by Textron, while the mechanical and heat transfer aspects of the design will be completed by the boiler designer.

Current Control Devices

The current control circuits will be installed in each of the external diagonal connections of the Demonstration generator to protect the anodes from slag-induced cathode wall voltage nonuniformities. The design of these current control devices is based on those presently being used at the CDIF for the POC program (Figure 10).[11] The circuits are passive, adjust themselves automatically and instantaneously to any electrode current delivered by the generator (through the magnetic flux linkage), and have no startup and shut-down transients. The current controls for the Demonstration generator will have slightly higher current and power handling capacities than those already built and extensively tested at the Textron and CDIF MHD facilities. Additionally, their topology will be simplified because of the availability of newly developed power semiconductor switches. These changes represent a refinement of the basic circuits that have operated reliably for hundreds of hours without failure.

Reliability, Availability, and Maintainability Considerations

An important part of the proposed Billings Demonstration Project is to provide sound evidence that commercial MHD power plants will satisfy utility requirements of safe and reliable operation, attained through high operational availability and ease of maintenance. These aspects of MHD power plants are of key importance to the power industry since they have a direct impact on the cost of electricity generated. The following discusses the reliability, availability, and maintainability of the MHD generator channel, upstream nozzle, and downstream diffuser.

Redundancy and spare components are used to maximize component reliability and availability based on analyses of conceptual early commercial MHD power plants.[4,5] A scheduled maintenance concept is used to extend the component MTBF's. This concept calls for two complete MHD generator channels (including nozzle and diffuser components) to be in routine alternating service. When one channel is taken out of service to be inspected and refurbished as necessary, the second channel is placed in service with minimum plant outage. The only channel refurbishment expected would be replacing selected elements of the electrode and sidewalls located in the generator's high transverse current density and high electric field regions. Exchange of channels every 2,000 hours of equivalent full-load operation is contemplated. This is considered a conservative estimate. The inlet nozzle and the diffuser are not expected to be replaced and refurbished each time the channel is replaced. However, if required, this can be done in parallel with channel changeout. Conservative estimates call for the planned replacements of the nozzle and diffuser after every 8,000 hours of operation. The actual component exchange schedules will be defined based on operating experience. Timely channel replacement and refurbishment will help to avoid forced outages and to extend the MTBF in operation.

Special features will be incorporated into the component and plant design to minimize outage time required for channel/nozzle/diffuser replacement. These include special fixtures, fittings, and connectors that will allow rapid changeover. The generator replacement procedure for the Demonstration power plant is shown in Figure 14. To remove the MHD power generating equipment, the cooling manifolds and wires are first disconnected. Then the diffuser is unbolted from the channel and rolled to one side on the rail system. Finally, the nozzle-to-combustor flange is disconnected, allowing the channel to be rolled back onto a transport platform and out of the power train area on the rail system. The process is reversed to reinstall the replacement generator channel.

A preliminary estimate of the total time required for channel replacement is 65 hours. This includes 4 hours to bring the plant down from full load to zero load, and 15 hours to return the plant to full load after the generator channel has been replaced. The generator channel replacement itself is estimated to take 31 hours, and 15 hours are added to allow for contingencies. Other planned plant maintenance work should be coordinated with channel replacement to minimize the total plant outage for maintenance.

The estimated operating availabilities of the MHD Demonstration nozzle/channel/diffuser are shown in Table 6.

SUMMARY

The proposed designs of the MHD power generator, inlet nozzle, and diffuser for the Billings MHD Demonstration Project have been presented. The overall philosophy adopted for the proposed MHD generator components is to minimize risks and uncertainties while fulfilling the objectives of the Demonstration Project.

The designs of these components are based on the 50 MW_t proof-of-concept designs, currently being tested at the DOE Component Development and Integration Facility. The proposed generator design has similar gasdynamic, gas-side, and mechanical designs as the POC MHD generator, and therefore the wall stresses (electrical and thermal) and internal flow conditions are commensurate with those anticipated in future commercial MHD generator channels.

Utility MHD power plants will require rapid power component installation and removal procedures to minimize downtime and maintain high availability. These factors have also been addressed in the design of the proposed generator channel.

ACKNOWLEDGMENTS

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TABLE 1

MAJOR DESIGN REQUIREMENTS OF THE INLET NOZZLE

- EFFICIENT ACCELERATION OF SEEDED COMBUSTION GASES TO GENERATOR ENTRANCE CONDITION.
- NORMAL AND PART-LOAD OPERATION.
- UNIFORMITY OF VELOCITY PROFILE.
- CONTOUR GEOMETRY TO MATCH CHANNEL INLET.
- ELECTRICAL ISOLATION.
- SLAGGING WALLS TO MINIMIZE HEAT LOSS AND EROSION FROM HIGH VELOCITY GAS FLOW.
- EFFECTIVE COOLING FOR WALL HEAT FLUXES AND RECOVERY OF HEAT LOSS BY BOILER FEEDWATER.
- PREVENTION OF RECIRCULATING CURRENTS FROM MAGNET FRINGE FIELD.
- DURABILITY/RELIABILITY/AVAILABILITY/MAINTAINABILITY.
- SCALABILITY.

TABLE 2

MAJOR GENERATOR CHANNEL DESIGN REQUIREMENTS

- POWER LEVEL AND THERMODYNAMIC PERFORMANCE.
- COMMERCIAL OPERATION ELECTRICAL STRESSES, FAULT POWER, AND WALL HEAT FLUXES.
- DURABLE WALL DESIGNS COMPATIBLE WITH SLAGGING OPERATION.
- AXIAL AND TRANSVERSE SEGMENTATION.
- GAS AND WATER SEAL INTEGRITY.
- DIAGONAL ELECTRICAL LOADING WITH EFFICIENT NORMAL AND PART-LOAD OPERATION.
- POWER TAKE-OFF AND ELECTRODE CONSOLIDATION.
- SEPARATE COOLANT LOOP WITH LOW PRESSURE BOILER FEED HEAT EXCHANGER.
- COORDINATION OF CHANNEL DESIGN WITH MAGNET DESIGN.
- QUALITY CONTROL OF FABRICATION AND ASSEMBLY PROCESSES.
- DURABILITY/RELIABILITY/AVAILABILITY/MAINTAINABILITY.
- SCALABILITY.
- DESIGNS ADAPTABLE TO AUTOMATED MANUFACTURING PROCEDURES.

TABLE 3

MAJOR DIFFUSER DESIGN REQUIREMENTS

- EFFICIENT PRESSURE RECOVERY AT ALL OPERATING CONDITIONS.
- EFFICIENT RECOVERY OF HEAT LOSS TO HIGH PRESSURE BOILER FEEDWATER.
- GAS EXIT CONDITIONS COMPATIBLE WITH HRSR (PRESSURE, VELOCITY).
- THERMAL EXPANSION INTERFACE OF MHD POWER TRAIN AND HRSR.
- DURABILITY/RELIABILITY/MAINTAINABILITY/AVAILABILITY.
- SCALABILITY.

TABLE 4

SUMMARY OF GENERATOR PERFORMANCE AND MAJOR ELECTRICAL AND GASDYNAMIC PARAMETERS

MHD GENERATOR CHANNEL	
THERMAL INPUT	250 MW_t
GROSS MHD POWER	28.5 MWe
CHANNEL HEAT LOSS	19 MWt
LOAD VOLTAGE	15.9 kV
LOAD CURRENT	1.8 kA
MASS FLOW RATE	49.6 kg/s
EQUIVALENCE RATIO	0.85 fuel rich
O_2 ENRICHMENT	40 %
PREHEAT	1,400 °F
INLET MACH NUMBER	1.2
MAXIMUM B-FIELD	4.5 tesla
INLET PLASMA CONDUCTIVITY	8.2 mho/m
MAXIMUM CURRENT DENSITY	1.08 A/cm^2
MAXIMUM AXIAL FIELD	2.33 kV/m
MAXIMUM HALL PARAMETER	3.3
DIFFUSER	
DIFFUSER RECOVERY COEFFICIENT	0.45
DIFFUSER EXIT PRESSURE	0.9 atm

TABLE 5

COMPARISON OF MHD GENERATOR OPERATION PARAMETERS AND STRESS LEVELS

	Designed			Achieved at Textron/Avco		Achieved at CDIF
	Demonstration MHD Generator	APT Retrofit MHD Plant(1)	Early Commercial MHD Plant(2)	MkVII 1000-hr Test(3)	MkVI 2-8 hr High Stress Tests	1A1 and/or POC Generators
Max Axial Field (kV/m)	2.3	2.4	2.6	2.1	3.0	2.6
Max Current Density (A/cm^2)	1.1	0.9	0.8	0.7	3.2	1.2
Max Hall Parameters (ß)	3.3	3.9	3.9	2.6	4.0	2.6
Max Heat Flux (W/cm^2)	250	217	210	310	500	350

(1) MHD Advanced Power Train Studies, General Electric Company, 1983
(2) Preliminary and Conceptual Studies of Potential Early Commercial MHD Power Plants (1979, 1983)
(3) Textron/Avco 1000-hr Anode Duration Test (1982)

TABLE 6

DEMONSTRATION NOZZLE/GENERATOR CHANNEL/DIFFUSER AVAILABILITY ESTIMATES

	A	MTBF Hours	MTTR Hours
Nozzle	0.997	16,000	50
Generator Channel	0.989	6,000	65
Diffuser	0.998	20,000	50

$$Availability\ A = \frac{MTBF}{MTBF + MTTR}$$

where MTBF = Mean Time Between Failures;
MTTR = Mean Time To Replace

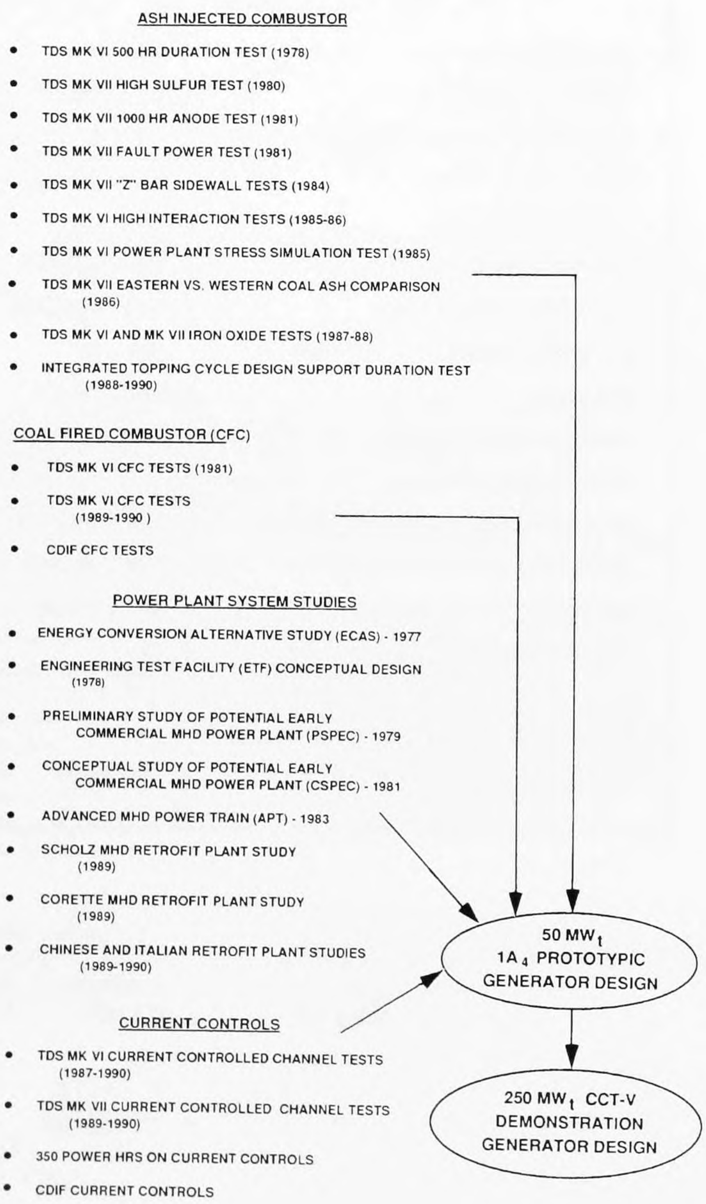

Figure 1 Database for the Demonstration MHD Generator Design

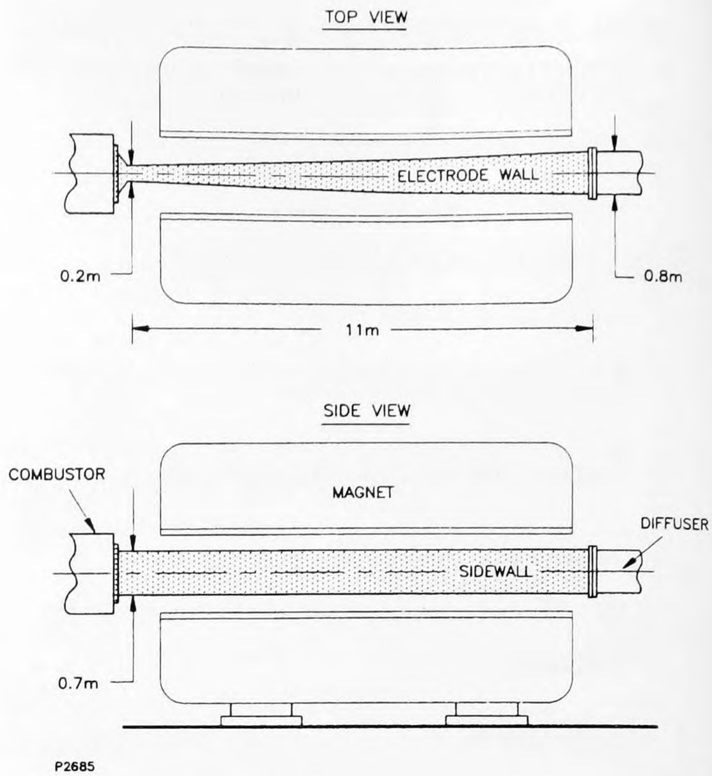

Figure 2 Overall Dimensions of the Demonstration MHD Generator Channel

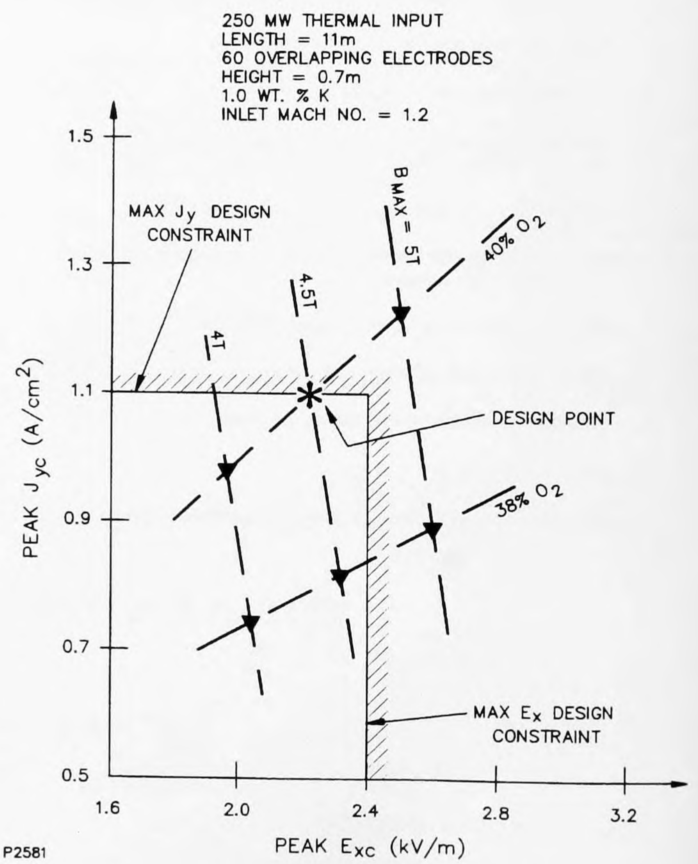

Figure 3 Demonstration MHD Generator Electrical Stress as a Function of Oxygen Enrichment and Magnetic Field Intensity

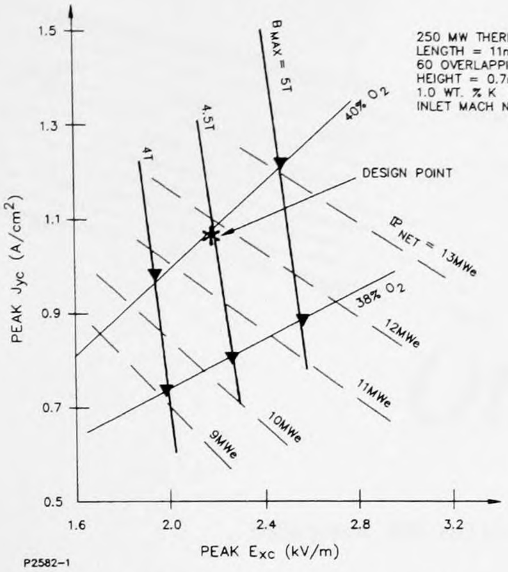

Figure 4 Net Power Output as a Function of Magnetic Field Intensity, Oxygen Enrichments and Electrical Stress Levels

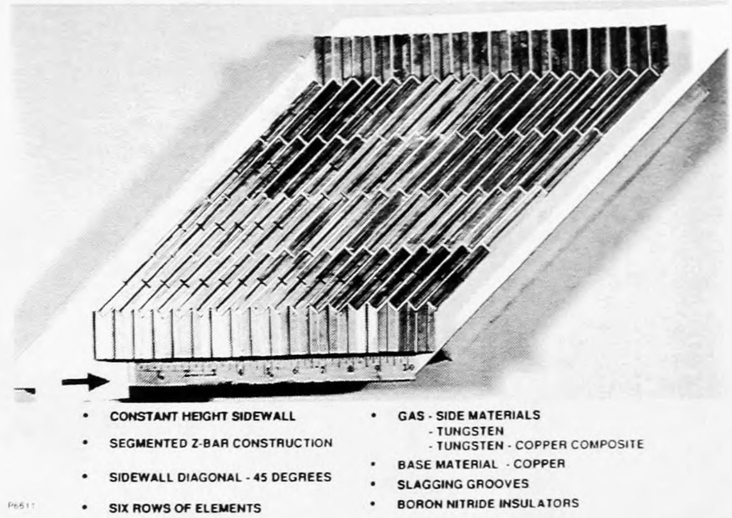

Figure 7 Prototypic Sidewall Gas-Side Design

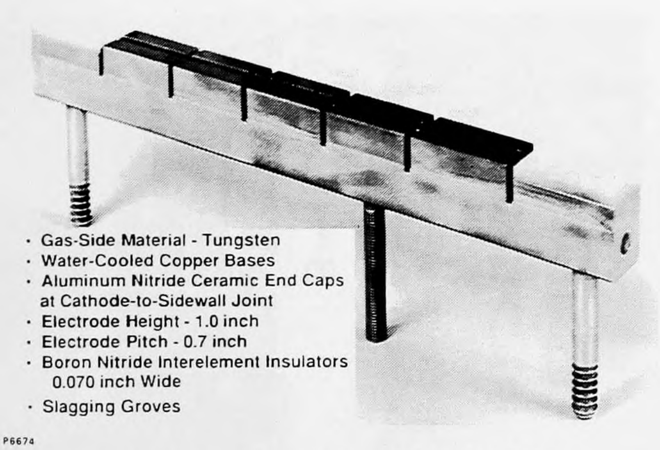

Figure 5 Cathode Gas-Side Design

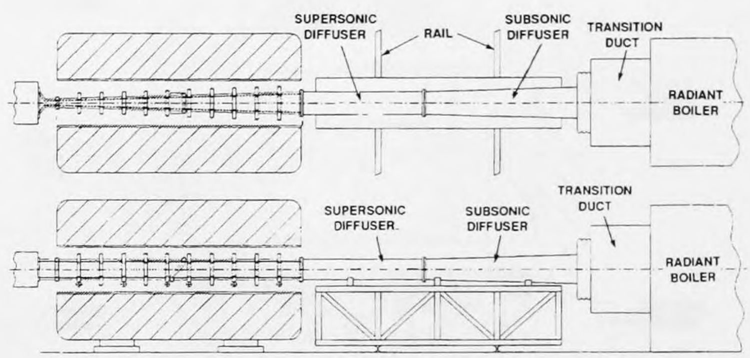

Figure 8 Layout of the Nozzle/Channel/Diffuser of the MHD Demonstration Power Plant

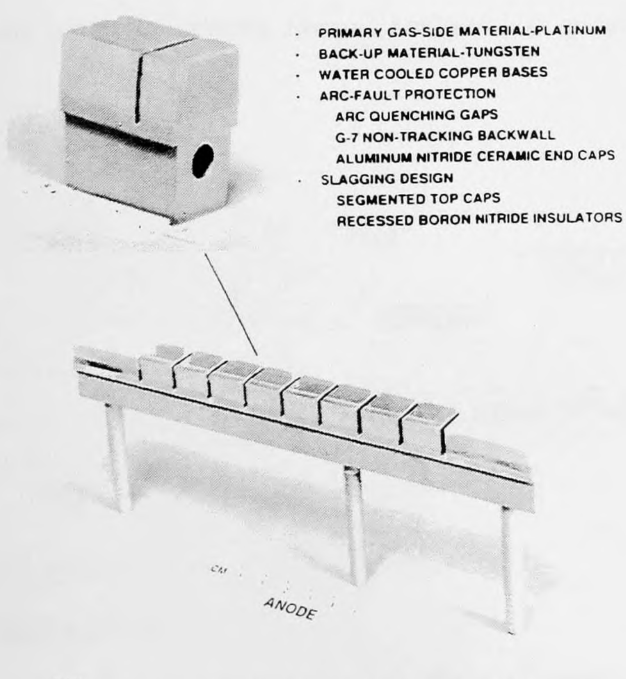

Figure 6 Anode Gas-Side Design

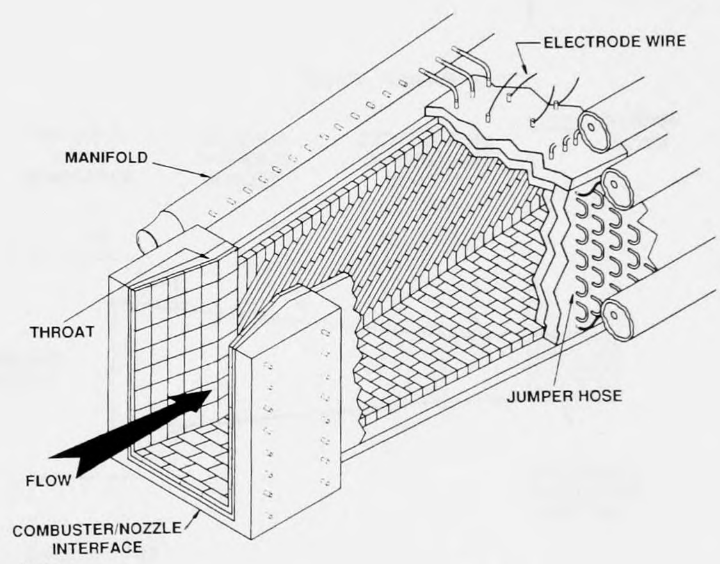

Figure 9 Inlet Nozzle Design

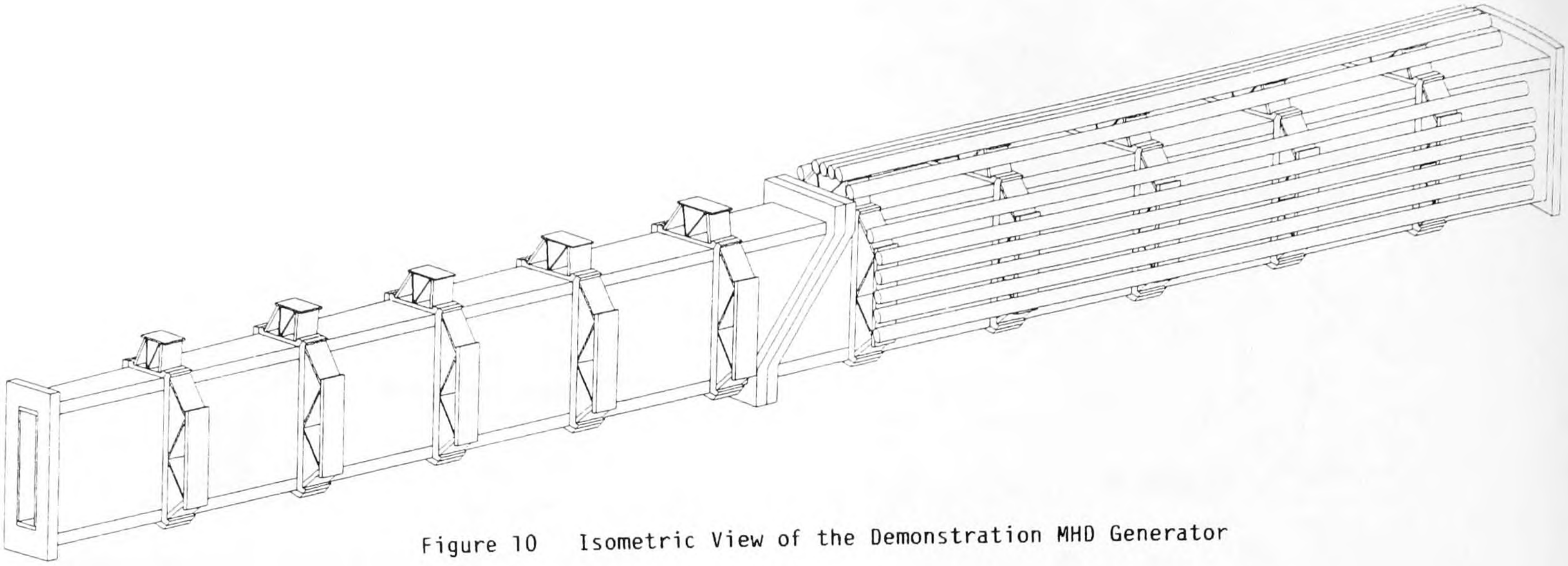

Figure 10 Isometric View of the Demonstration MHD Generator

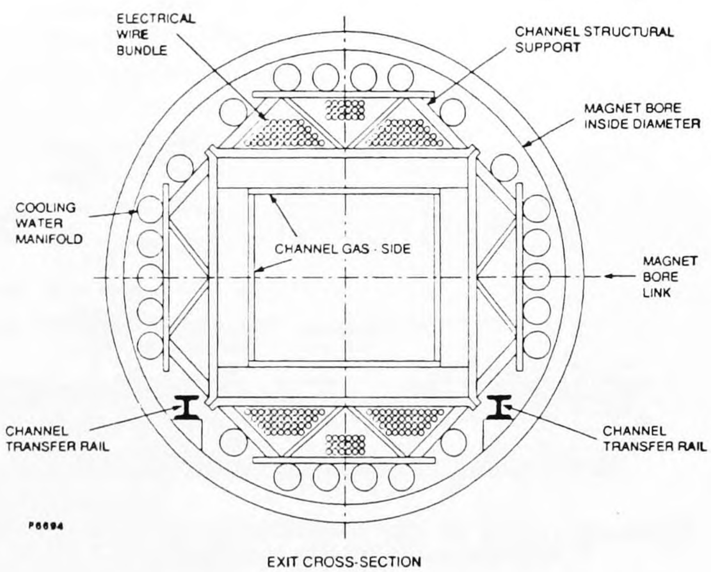

Figure 11 A Typical Cross-Section View of the Demonstration Generator Installed in the Magnet Bore

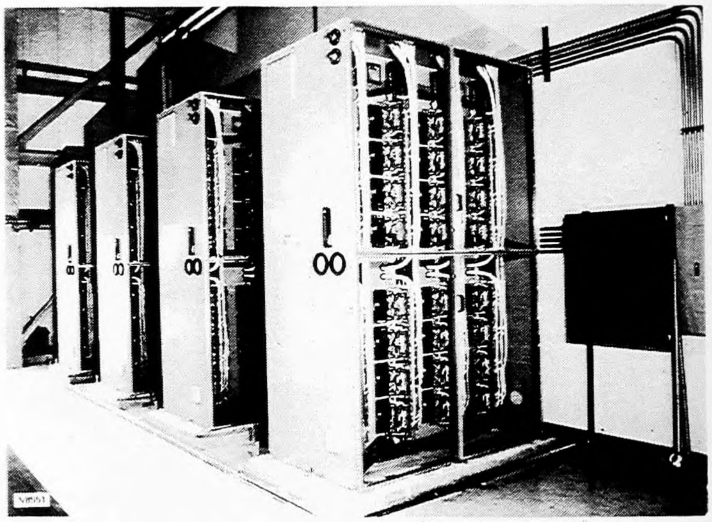

Figure 13 Textron Current Control Circuits Installed at the CDIF

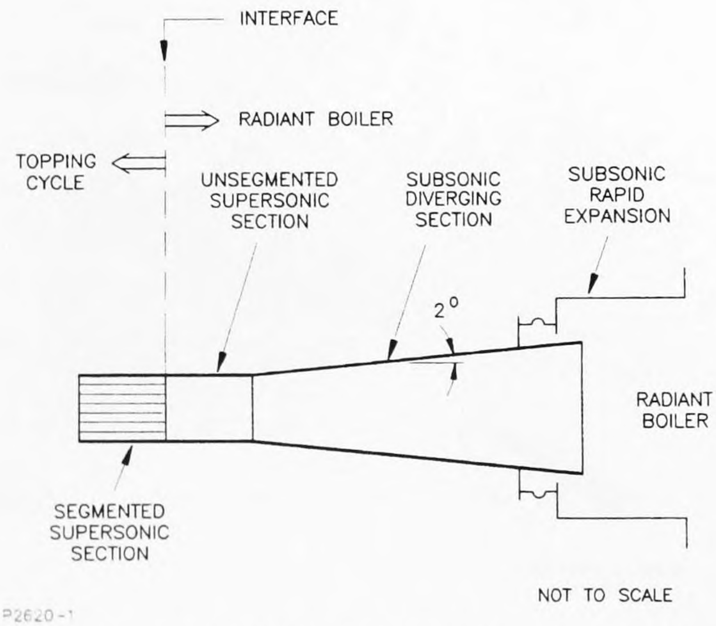

Figure 12 Schematic Diagram of Diffuser Sections

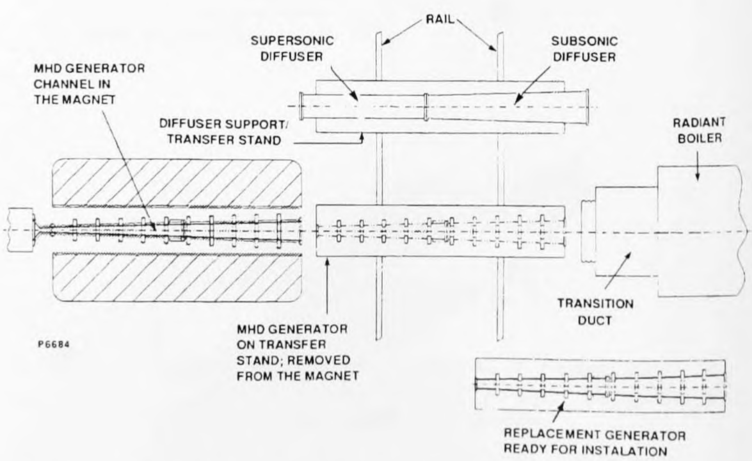

Figure 14 MHD Generator Replacement Procedure for the Demonstration Power Plant