# Overview And Progress Of The MHD Integrated Topping Cycle (Itc}Project In The Usa

Author(s): J. M. Bauer and M. P. McAllister

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# OVERVIEW AND PROGRESS OF THE MHD INTEGRATED TOPPING CYCLE (ITC) PROJECT* IN THE USA

J. Martin Bauer and Michael P. McAllister
TRW Inc.
Redondo Beach, California

## ABSTRACT

The Proof-of-Concept (POC) program in the U.S.A. involves the system development and demonstration of the topping cycle, bottoming cycle and seed regeneration components of an open cycle MHD technology. The topping cycle activities center around the MHD ITC Project and its accomplishments since the program was initiated in October 1987. The MHD ITC Project provides the design, construction, and delivery of all 50 $MW_t$ prototypical hardware necessary to conduct long duration, integrated MHD topping-cycle, proof-of-concept tests at the U.S. Department of Energy (DOE) Component Development and Integration Facility (CDIF). The integrated topping cycle power train is rated at 50 $MW_t$ and designed for a nominal operating duration of 2,000 hours and 500 thermal cycles. The prototypical power train will be tested for 1,000 hours at the CDIF during the duration test phase of the project which is scheduled for 1993. This technical paper will present an overview of the topping cycle project and will describe the accomplishments over the past four and one-half years.

The integrated topping cycle is comprised of the coal combustor, channel, nozzle, current controls and current consolidation. The magnet, inverter and facility systems are existing equipment currently in-place at the CDIF. TRW is the prime contractor of the MHD ITC Project and is responsible for the design, construction and delivery of the coal combustion subsystem. TRW is also responsible for providing the system integration of all ITC components and subsystems. Textron Defense Systems (TDS), formerly Avco Research Laboratories, is responsible for the design, construction and delivery of the channel subsystem. The channel subsystem includes the nozzle, channel, diffuser and current controls. Westinghouse Science and Technology Center is responsible for the design, construction, and delivery of the current consolidation subsystem which includes the anode and cathode current consolidation and the central control assembly.

This technical paper will provide a summary description of the design of all prototypical MHD ITC hardware that will be delivered to the CDIF in the spring of 1992. Included in the paper will be photographs of the key subsystems and components that comprise the integrated power train. The paper will also describe the design support testing that was accomplished at TRW, TDS, and Westinghouse during the design phase which formed the basis of the final prototypical designs. The design support testing included: combustor testing at TRW and TDS, channel testing at TDS, combustor spool testing at University of Tennessee Space Institute (UTSI), current consolidation testing at TDS, and extensive manufacturing development activities at TRW and TDS. The most relevant design support testing was the test activities at the CDIF with the 50 $MW_t$ workhorse power train hardware. The paper will conclude with a summary of the plans and schedules for the design verification testing and the duration test phases of the project.

## INTRODUCTION

The ITC Project will advance the state-of-the-art in MHD power systems with the design, construction, and integrated testing of 50 $MW_t$ power train components which are prototypical of the equipment that will be used in an early commercial scale MHD utility application. Figure 1 shows the relationship of the MHD ITC project within the overall MHD program that was developed by the DOE. This figure summarizes the content of the national proof-of-concept (POC) program and how it supports an eventual MHD retrofit demonstration. The shaded portions of Figure 1 are those areas represented by the MHD ITC project.

This technical paper will present an overview of the accomplishments of this project. It will cover the period from contract start (September 30, 1987) through May 1992. The project accomplishments through this period encompass completion of power train hardware designs and, in most cases, completion of the fabrication

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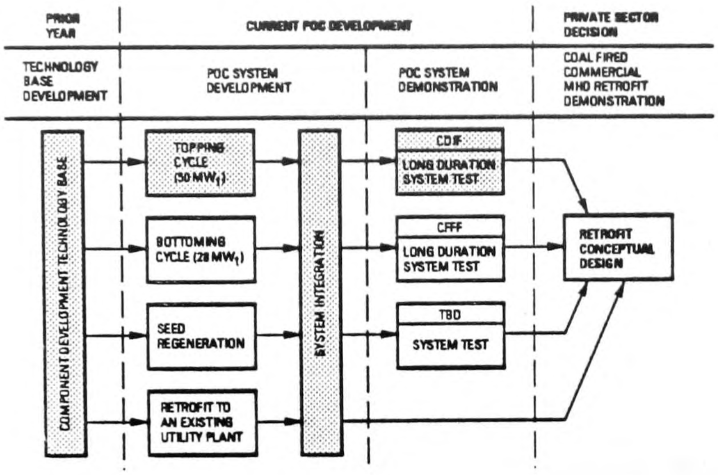

**Figure 1. National MHD Development Program**

of the prototypical hardware that will be tested at the CDIF.

## PROJECT OBJECTIVES

The overall objective of the project is to design and construct prototypical hardware for an integrated MHD topping cycle and to accumulate 1,000 hours of proof-of-concept tests of the integrated system at the U.S. DOE Component Development and Integration Facility in Butte, Montana. The results of the long duration tests will augment the existing engineering design data base on MHD power train reliability, availability, maintainability, and performance, and will serve as a basis for scaling up the topping cycle design to the next level of development, an early commercial scale integrated power plant.

The components of the MHD power train to be designed, fabricated, and tested include:

- A slagging coal combustor with a rated capacity of 50 MW thermal input, capable of operation with an Eastern (Illinois No. 6) or Western (Montana Rosebud) coal.
- A segmented supersonic nozzle.
- A supersonic MHD channel capable of generating at least 1.5 MW$_E$ of electrical power.
- A segmented supersonic diffuser section to interface the channel with existing facility quench and exhaust systems.
- A complete set of current control circuits for local diagonal current control along the channel.
- A set of current consolidation circuits to interface the channel with the existing facility inverter.

The design requirements that were specified by the DOE for the prototypical power train system are summarized in Figure 2. More comprehensive design requirements for each subsystem of the power train were specified by the DOE and the hardware developers and formed the design basis for each subsystem.

**Figure 2. System Design Requirements**

| PARAMETER | REQUIREMENT |
|---|---|
| Durability | 2,000 Hour lifetime<br>500 Startups/shutdowns |
| Scalability | Designed and implemented to allow an evaluation for scaling up to a larger MHD power plant size |
| Performance | 1.5 MW$_e$ |
| Electrical Isolation | Shall be capable of standing off 10kV; current leakage has been specified |
| Safety | Installed, tested, and operated consistent with CDIF practices and requirements |

## PROJECT SCHEDULE

The MHD ITC Project was initiated on September 30, 1987 and is currently contracted to be completed by June 30, 1993. Figure 3 is a summary of the schedule of the project and it shows the major activities, such as design support testing, hardware design, hardware manufacturing, and testing at the CDIF. This figure also shows those elements of the project that have been completed to date (the darkened bars of this figure).

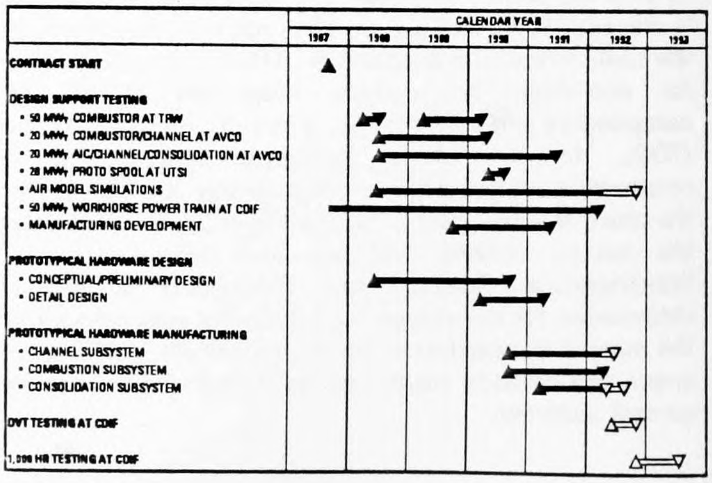

**Figure 3. Schedule Overview**

## TECHNICAL ACCOMPLISHMENTS

During the period from the initiation of the program to the present, the ITC program has advanced the state of the art in MHD combustion, channels (power generators), and power management. Figure 4 is a timeline that shows the major accomplishments to date and the schedule for the remaining milestones. The details of the design support testing will be discussed later in this paper.

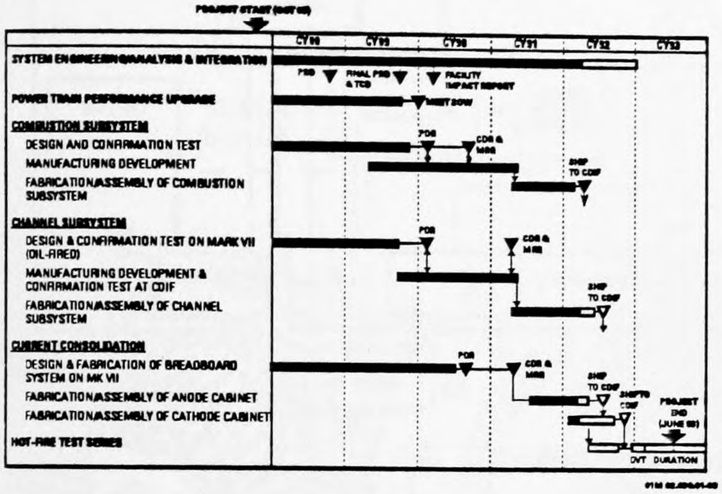

Figure 4. Project Technical Progress

## POWER TRAIN DESIGN OVERVIEW

This section of the paper will present a brief design description of the Integrated Power Train System as well as the three subsystems: combustion, channel and current consolidation.

The design approach throughout the entire MHD ITC program has been one of conservatism. As a result of the conservative approach that has been taken, the proposed design satisfies and/or exceeds the SOW requirements of the project. The conservative design approach is shown in Figure 5. At the beginning of the ITC design phase, design priorities were established among the various requirements. In essence, this meant an ordering of the requirements so that the designers knew which ones were inviolate and in which order concessions should be made. The order chosen was to preserve lifetime first, then scalability, and finally performance. It was also obvious that even though performance was lowest on this list, it could not be sacrificed to the point of not delivering a useful product or not meeting the SOW.

The design is heavily dependent on the existing hardware experience and data base. If changes were made to incorporate prototypicality or lifetime requirements, it was mandated that these changes be hot fire tested, at the 50 $MW_t$ level, to insure that performance was not degraded. Long term reliability issues were addressed by performing materials and subcomponent bench scale testing (e.g., gas- and water-side corrosion tests).

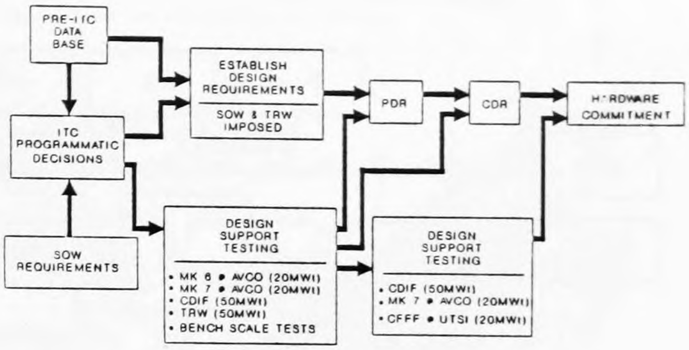

Figure 5. Conservative Design Approach

As shown in Figure 5, requirements were established at the outset of the design based on the SOW, the existing data base, and on programmatic decisions, e.g., the use of an oil fired vitiator instead of an air preheater. Based on these requirements, a design was developed and presented at the PDR where it was reviewed in light of the requirements and the results of supporting testing. Based on the PDR comments, the design was carried forward to the CDR, again heavily dependant on the test program for verification. At the conclusion of the CDR, the design was finalized and preparations made to procure hardware. During this finalization phase, design support testing was continued to ensure the success of the ITC program. Additionally, manufacturing development testing was initiated to ensure that the manufacturing processes met the requirements and were sufficient to fabricate the hardware.

### Integrated System

The MHD ITC system is comprised of three subsystems: 1) Combustion Subsystem, 2) Channel Subsystem, and 3) Current Consolidation Subsystem. The elements of each of the subsystems are shown in Figure 6. A block diagram of the integrated power train is shown in Figure

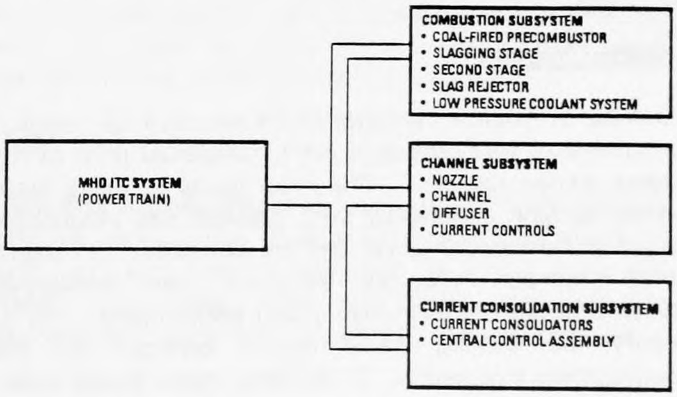

Figure 6. Elements of the Design

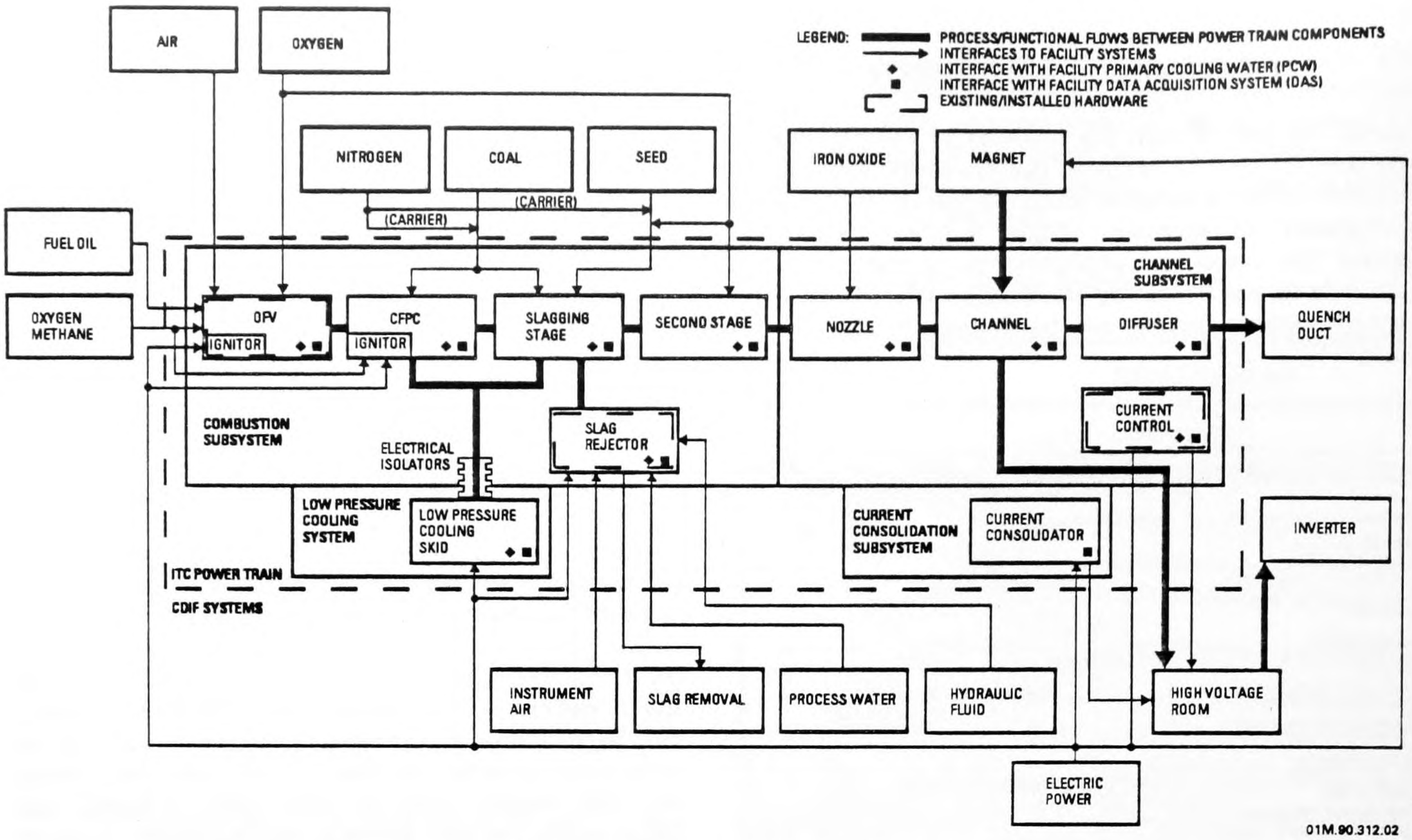

**Figure 7. Simplified Interface Block Diagram**

7. This is a simplified diagram showing the interfaces between each of the subsystems and between each of the subsystems and the facility. An electrical isolator is provided between the combustor, which operates at the Hall potential with a typical value of 6 KV, and the low pressure cooling system to allow it to operate at ground potential.

Figure 8 is an isometric view of the integrated power train that shows the precombustor, slagging stage, second stage of the combustion subsystem, the channel and the beginning of the diffuser. The combustion subsystem components are shown with the major manifolds but the cooling lines from the manifolds to the individual circuits are not shown for clarity. The channel external manifolding and electrical wiring is shown connected to the wiring panel that will sit at the end of the magnet bore.

## Support Testing

In order to confirm the basis of the prototypical designs, a number of test programs were completed prior to the detail design reviews. The main goals of these tests were: to gain experience with channel and combustor material selections under hot-fire conditions, to verify that geometry changes (different than workhorse hardware) did not adversely affect performance, and to verify the cooling panel design concept for the combustion subsystem. In addition, many bench scale tests were performed to verify the design where hot fire tests were not required. Following is a summary of the various major test facilities and the testing supported at each of them.

### TRW Capistrano Test Site (CTS)

A 50 $MW_t$ workhorse combustor was installed and tested at the CTS. This facility was mainly used to verify the second stage geometry parameters related to mixing and heat loss and to confirm first stage operating conditions.

### TDS Mark VI and Mark VII

Two separate 20 $MW_t$ facilities were used at TDS. The Mark VII facility, which is an ash injected, oil fired facility, was used exclusively for channel testing whereas the Mark VI facility, with a coal-fired combustor, was used for combustor and channel development testing. The original combustor cooling panel design verification was done in these facilities and second stage testing was also conducted here in conjunction with channel electrode and sidewall development testing. The Mark VII facility was also used for the current consolidation breadboard tests.

### CDIF

This the DOE facility utilized for MHD testing. A 50 $MW_t$ workhorse combustor and channel were installed in this

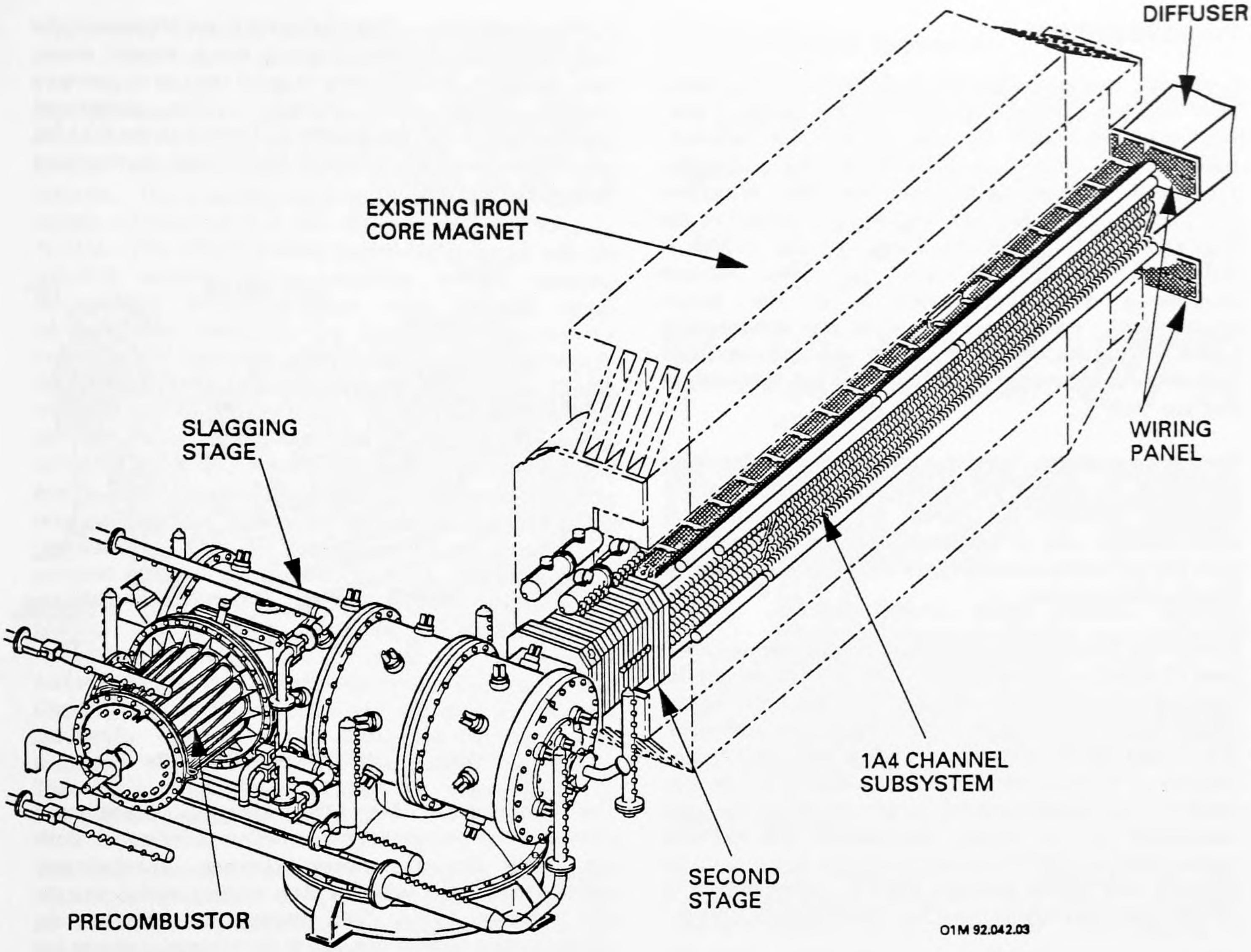

Figure 8. Power Train Isometric

facility and were used to verify all designs under actual MHD hot fire conditions. The current controls were installed in this facility where they have successfully run for approximately two years. The continuous slag rejector was also installed and tested in this facility. The prototypical hardware is presently being installed and checked out in preparation for the duration testing later this year.

### TRW Cold Flow Model

TRW has built a cold flow facility where plexiglass sub-scale models are tested to determine flow characteristics, temperature distributions, and mixing patterns. Geometry changes can be tested in this facility prior to fabricating expensive hot-fired hardware for initial verification of the concepts. Second stage geometry verification tests were conducted in this facility.

### Coal-Fired Flow Facility (CFFF) at the UTSI

The CFFF facility is primarily focused on the bottoming cycle of the MHD process. However, a test spool containing prototypical combustor cooling panels was installed in this facility and successfully operated for 250 hours in order to gain lifetime experience under conditions very similar to the topping cycle.

### Other

Many bench scale tests were conducted to verify channel element performance under prototypical heat fluxes, to verify gas side lifetime estimates, to verify water-side design parameters, and to verify manufacturing development aspects of the combustor and channel.

## System Engineering

In addition to the combustion subsystem development, TRW was the system integrator for the topping cycle. TRW was responsible for ensuring that the individual subsystems performed as a system and the successful integration of the power train into the CDIF. A system requirements document was prepared at the start of the program which formed the basis for the individual subsystem requirements and the TRW system engineering office coordinated all of the design requirements. An interface document was developed to coordinate the mechanical, electrical, and flow interfaces between the subsystems and between the subsystems and the facility.

Early in the program, many system analysis studies were completed to assess the impact of various operating scenarios, additives for channel fault control, form of seed material, and to coordinate the overall operation with the bottoming cycle program to ensure compatibility for the POC program.

One of the main tasks of the system engineering office was to ensure that the MHD power train hardware be integrated into the CDIF. A document called the Facility Impact Report was prepared which detailed the effect on the facility of installing and testing the prototypical hardware. Considerable system engineering effort was required in understanding the impact of the power train installation on the facility, coordinating the required facility changes with hardware arrival and test dates, and ensuring that facility changes could be accomplished in a time frame that would meet the overall test objectives.

As the system integrator, TRW, with inputs from TDS and Westinghouse, also prepared a Test Plan which has been iterated several times with MSE, the CDIF operators. The Test Plan documents the required facility systems and flowrates, the test setup, the documentation requirements, the objectives of each test, post test inspections, and the criteria for success. This plan forms the basis of the test directive which contains the step by step directions for each test.

Power management, which encompasses the channel power take-off region, current consolidation, and several of the CDIF systems, was another integration area in which TRW was responsible. Because many subsystems are intertwined in this area, a special task force was established to review proposed test configurations and to recommend procedures, tests, etc., to ensure the success of the testing. This task force will continue throughout the entire test series on an as-required basis.

## Combustion Subsystem Design

Figure 9 is an isometric view of the prototypical combustion subsystem which shows many of the primary cooling manifolds. The subsystem encompasses the coal-fired precombustor, slagging stage, second stage, slag rejection system (not shown) and low pressure cooling system (not shown). The operational configurationof this subsystem is identical to the 50 MW$_t$ workhorse combustor that has been under development since the mid-1980's.

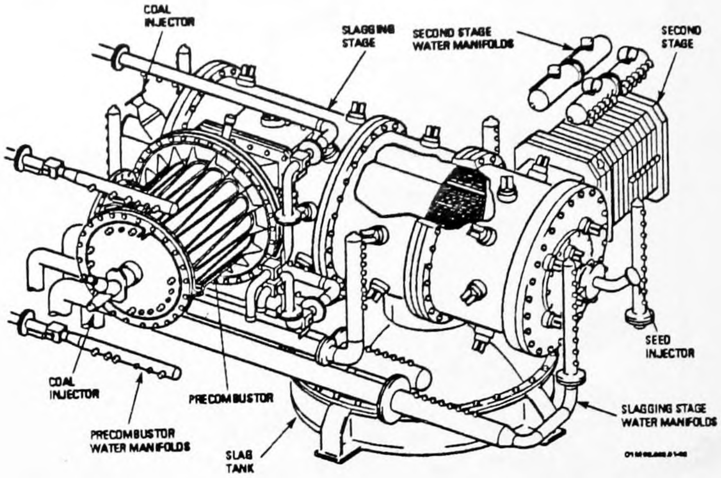

**Figure 9. Combustion Subsystem**

The prototypical 50 MW$_t$ slagging stage and precombustor use similar construction techniques. Both are made up of several flanged, spool-shaped components, each with its own cooling water circuits and pressure shell. Gas pressure is contained by stainless steel outer shells, while the internal surfaces are lined with water-cooled panels constructed with low alloy steel as shown in Figure 10. The panels mount directly to the pressure shell via welded penetrations.

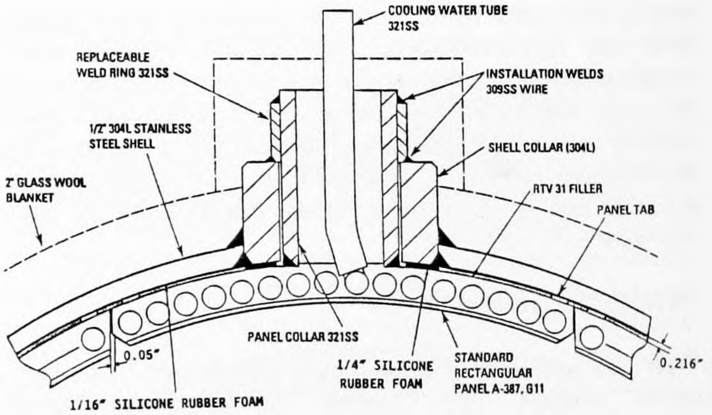

**Figure 10. Cooling Panel Design**

The design trade-off studies which led to the concept selection are described in Reference 1. From a mechanical design point of view, the concept allows unlimited scalability since the pressure containing and wall cooling functions are separated and the same size and material cooling panels can be used in larger units. The round coolant channels assure compatibility with high pressure boiler feed water. The pressure shell is made of 304L stainless steel to reduce the amount of ferretic material in the close proximity to the MHD magnet. The slagging stage and precombustor cooling panels are made of low alloy boiler steel A-387 (1¼ Cr, ½ Mo). The 450°F cooling water temperature and the gas-side surface sulfur corrosion in the reducing environment in combination with thermal stress considerations were the key factors in selecting the cooling panel materials. The main advantage of the A-387 steel relative to stainless steels or Inconels is high material thermal conductivity. The materials corrosion tests and the design trade-off studies which led to selecting the A-387 steel are described in References 2 and 3. In the slagging stage the cooling panels have slag retention grooves. In the non-slagging precombustor and the slagging stage air inlet duct, the panels are non-grooved and have Inconel 625 cladding. The Inconel 625 cladding assures that all non-slagging surfaces will operate at the same conditions as those for the workhorse hardware and protects the non-slagging surfaces from erosion. The pintle type precombustor and slagging stage coal injectors and the seed injector are practically identical to the workhorse hardware with additional provisions for improved erosion resistance. Their design has been verified by many hours of successful operation at the CDIF.

The second stage construction is similar to the present workhorse hardware. Oxygen-free copper frames with gun-drilled cooling channels are stacked to form the second stage duct. The frames' gas-side is capped with SS446 liners for erosion protection.

A significant number of bench-scale tests and hot fire tests were accomplished as part of the design support phase of the combustion subsystem design task. Summarized below are these design support activities:

**Bench-Scale Tests**

- Corrosion tests at ANL to establish permissible operating temperatures consistent with 20,000 hours mean time between failures (MTBF)
- Cyclic load test of penetration design
- RTV compliance test and RTV fill test
- Mock-ups of geometrically constrained regions to verify assembly accessibility
- Load test of welded coolant supply tubes
- Weld procedure qualification
- Braze procedure qualification
- Cold flow modeling of the second stage and precombustor

**Hot-Fire Tests**

| | |
|---|---|
| TDS: | Confirm viability of panel-in-shell concept by hot-fire test of spool piece in TRW 20 $MW_t$ combustor. |
| UTSI: | Confirm panel-in-shell manufacturing/assembly process and operational reliability by 250 hours hot-fire duration test in UTSI combustor. |
| CDIF: | Confirm changes to surface characteristics and increased metal surface temperature will <u>not</u> promote slagging of precombustor components.<br>Confirm second stage cladding material selection in terms of slagging characteristics and erosion protection. |
| TRW: | Confirm change to precombustor transition configuration will not have negative impact on performance. |

**Channel Subsystem Design**

The channel subsystem is comprised of the subsonic/supersonic nozzle, the 1A4 channel, the current controls, and the diffuser assembly. The channel is diagonally connected with a single inverter load and operates supersonically with an inlet Mach number of 1.5. It is the same length as the previous workhorse CDIF channels but has approximately 15% greater volume. The 1A4 channel employs constant height sidewalls which simplifies fabrication and allows complete interchangeability of sidewall elements front-to-rear. The inclusion of an integral nozzle and the elimination of a mid-channel flange are allowed by the selection of a stronger pressure vessel wall material for the 1A4. As with the workhorse channel, the structure is four wall construction with corner joint gas seals which allows external diagonalization, permits changes in the connection angle, and is more fault resistant than window frame construction.

The major objectives of the 1A4 design are reliability and lifetime. The 1A4 channel design is derived from the experience with the 1A1 (workhorse) channel and research in the TDS 20 $MW_t$ channel facilities. The major engineering features of the 1A4 channel aimed at the lifetime objective are: 1) noble and refractory metal capping of gas-side elements for corrosion and erosion protection, 2) ceramic corner reinforcements, 3) bar type sidewall construction for hydraulic and structural reliability, and 4) Z-bar sidewall design to minimize interbar fault power. The addition of iron oxide during operation of the channel will alleviate slag-induced shorting on the cathode wall. This will reduce the stresses on the cathode and sidewalls. Additionally, the use of current controls will protect the anodes from the slag-induced cathode shorting.

Figure 11 is an isometric view of the channel. This view shows the external packaging of the channel from the nozzle to the wiring panels that will be installed at the exit of the magnet bore. The beginning of the diffuser is shown beyond the wiring panels. The anode (top wall) wiring is shown running down the middle of the top wall between the cooling manifolds and the hoses that connect them to the individual elements and terminating at the wiring panel. This wiring panel is the interface between the channel and the facility high voltage room. The cathode (lower wall) is laid out in similar fashion. The sidewall cooling jumpers, required because each sidewall element is made up of six segments, can be seen running between the sidewall manifolds. The two sidewalls are identical.

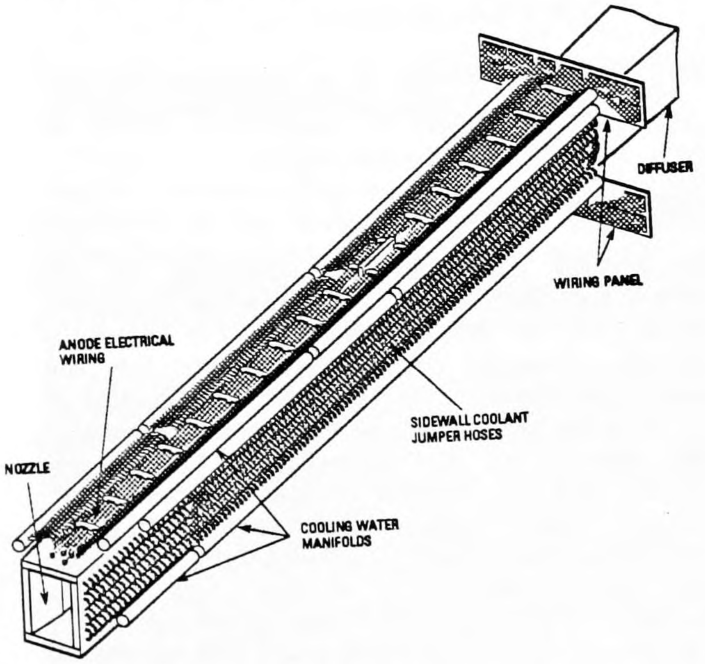

**Figure 11. Channel Subsystem**

The gas side designs of the elements are shown in Figure 12. The anode is a tungsten capped copper base with platinum capping in the high wear regions. The cathode design is tungsten capped copper with a slag retention groove in the center of each element. The sidewall design features either tungsten or tungsten-copper caps on either copper or tungsten-copper bases. The sidewall designs also incorporate a slag retention groove. The copper bases braze easily, but do not provide the best electrochemical protection against undercutting of the cap. Conversely, tungsten-copper has good resistance to electrochemical corrosion, but they are more difficult to braze and can have a water-side corrosion product build-up if the water chemistry is not controlled. All of the sidewall designs are projected to meet the lifetime requirements of the program. Because each design has different merits, all designs will be part of the DVT and duration phases of the program.

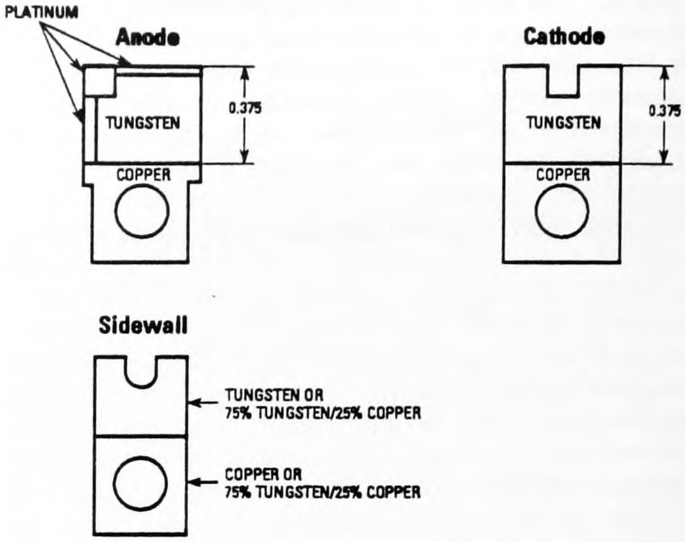

**Figure 12. Channel Gas-Side Elements**

### Current Consolidation Subsystem Design

The current consolidation subsystem operates to consolidate the electrical output of the individual electrodes in the power take-off region (PTO), which operate at different potentials, into a single pair of output terminals. Figure 13 schematically shows the connection of the current consolidation circuits to the channel power take-off electrodes. The output of the current consolidation circuits is fed to the inverter which conditions the current for distribution onto the power grid. Diode stacks will be installed between the electrodes and the current consolidation circuits which will allow the system to operate in the resistive consolidation mode. This allows the flexibility to switch to the resistive mode in the event of current consolidation failure without interrupting power train

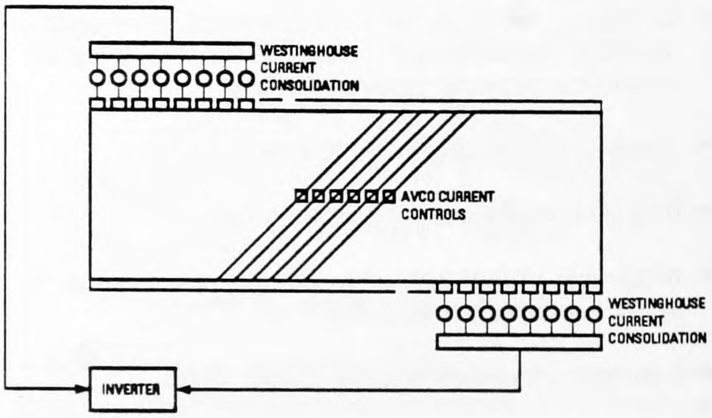

**Figure 13. Current Controls and Consolidation**

operation. Additionally, it allows a comparison of the prototypical power train operation to the workhorse power train which was run in the resistive mode.

The current consolidation is achieved by connecting each electrode to a variable dc voltage source which is connected to one of the two consolidation points. The dc voltage source applies the correct amount of balancing voltage to achieve a desired current level from the electrode to the consolidation point. A dc to ac converter is used as the variable dc voltage source. The system provides the operator with the capability to program the distribution of currents in the PTO region. It also collects data on the inter-electrode voltages and currents in the PTO region for display in the Central Control Room.

Figure 14 shows the proposed layout for the consolidation equipment at the CDIF. The anode and cathode consolidation cabinets will be located on either side of the local controls. For ease of installation, the circuit breakers and transformers for both sets of consolidators will be located in the anode side of the building. The anode consolidation circuits will be delivered several months ahead of the cathode equipment.

## POWER TRAIN MANUFACTURING OVERVIEW

### Combustion Subsystem

The fabrication and assembly of the combustion subsystem was completed in February 1992 and delivered to the CDIF on March 5, 1992. The manufacturing process used at TRW for this subsystem was to have the piece part components manufactured by local machine shop suppliers under the close supervision of TRW manufacturing engineers. The final assembly and integration of all the sub-elements and the complete subsystem was accomplished at the TRW staging area in Redondo Beach, California. All final closure welding of manifolds and coolant lines was accomplished at TRW. The water flow calibration testing, leak testing and proof testing was also done at TRW. Figures 15 and 16 show two different views of the final combustion subsystem prior to delivery to the CDIF. Figure 17 shows an earlier view of the combustion subsystem prior to the installation of the coolant manifolds and lines. Figure 18 shows the prototypical second stage assembly.

### Channel Subsystem

The fabrication and assembly of the channel subsystem is scheduled to be completed in May 1992 with delivery at the CDIF scheduled for June 1992. The manufacturing process used at TDS is very labor intensive with TDS accomplishing the brazing of the many wall elements. The machining of the individual wall elements was done by outside suppliers. The hosing and wiring materials were also supplied by outside vendors. In addition to the braze operations, the assembly of all the channel, nozzle and diffuser elements into a complete subsystem is being accomplished by TDS personnel. TDS is also responsible for all the final non-reactive testing of the channel subsystem prior to delivery to the CDIF. Figures 19, 20 and 21 show three different views of the channel walls in various degrees of completion. Figure 19 is the cathode wall, Figure 20 is the anode wall and Figure 21 is one of the side walls mounted on the cathode wall.

### Current Consolidation Subsystem

The current consolidation subsystem power circuits and control cabinets are being manufactured in two parts. The anode cabinets and the control cabinets were manu-

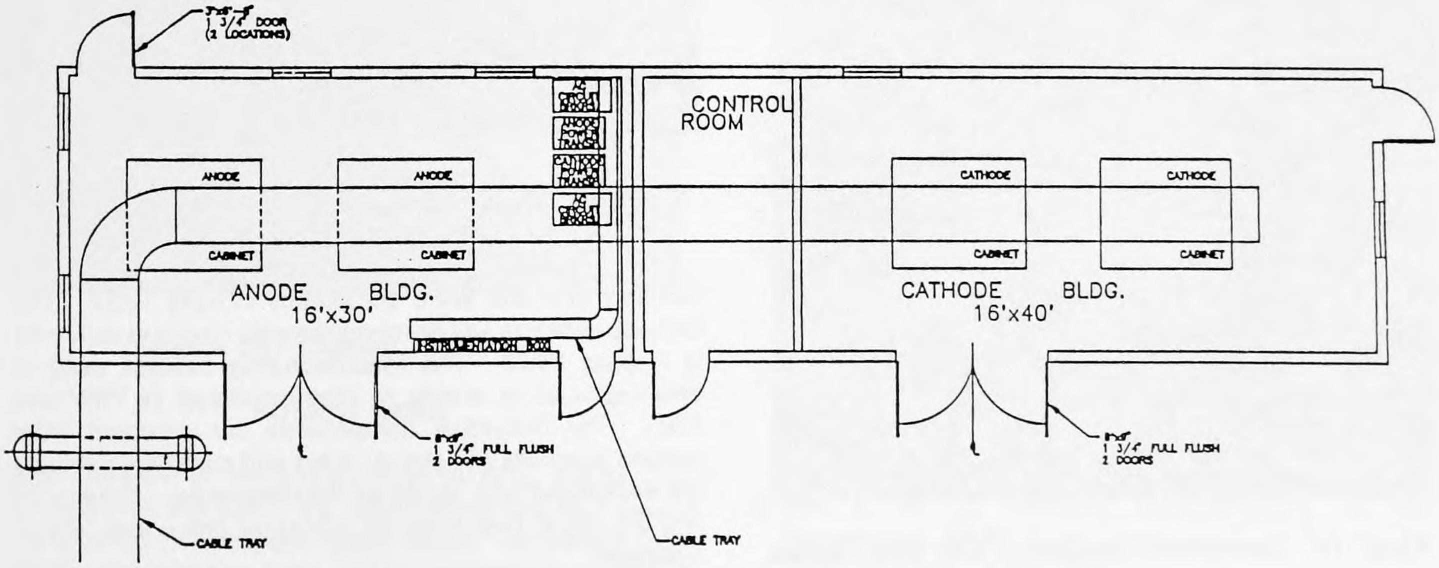

Figure 14. Consolidation Layout

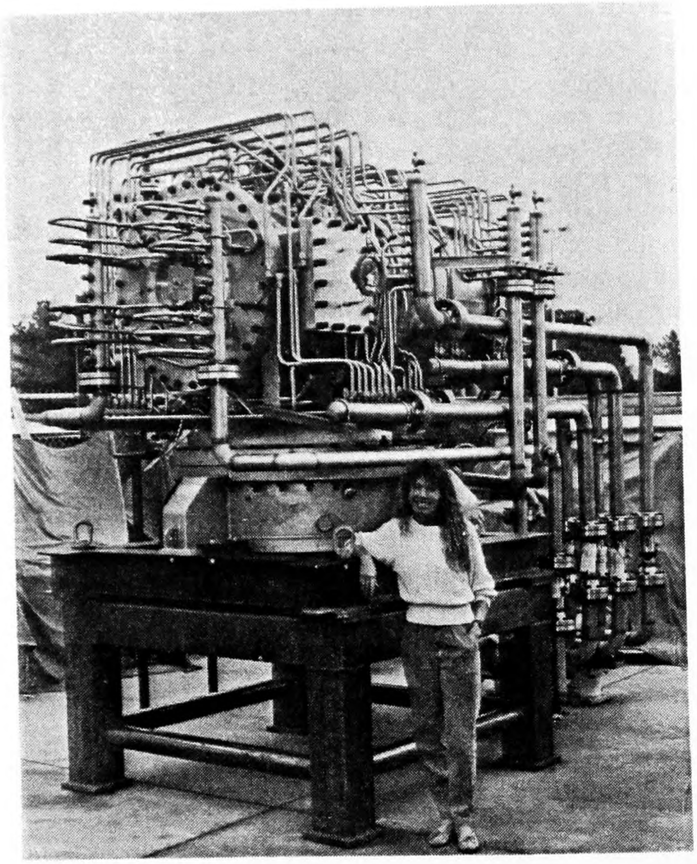

Figure 15. Prototypical Combustion Subsystem Slagging Stage

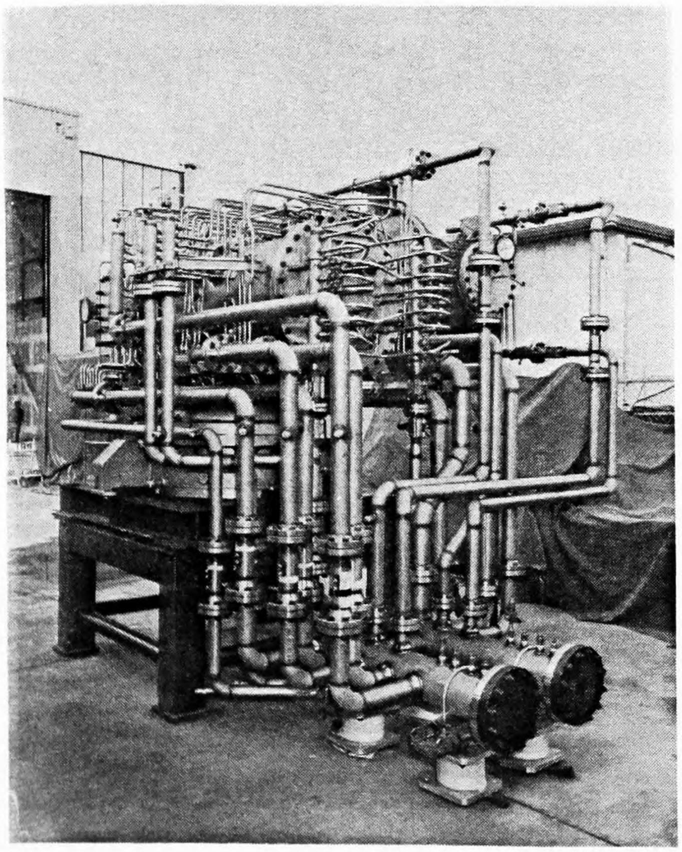

Figure 16. Combustion Subsystem with Inlet Coolant Water Lines

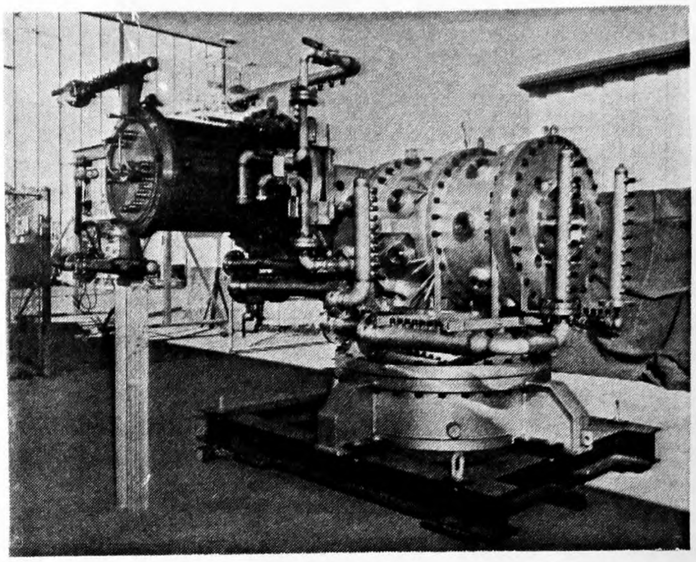

Figure 17. Combustion Subsystem Prior to Coolant Water Manifolds Installed

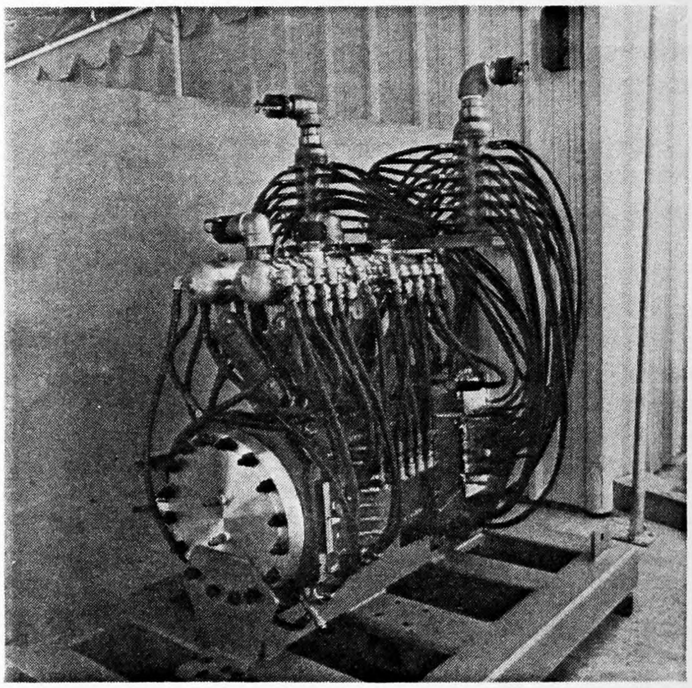

Figure 18. Second Stage of Combustion Subsystem

factured first and were completed in April 1992. The cathode cabinets will be manufactured next and delivered in August 1992. The manufacturing process used at Westinghouse is similar to that employed at TRW and TDS. The individual components are procured from outside suppliers and the modules and complete cabinets are assembled and tested at Westinghouse. Figures 22 and 23 show two different views of the anode power cabinets.

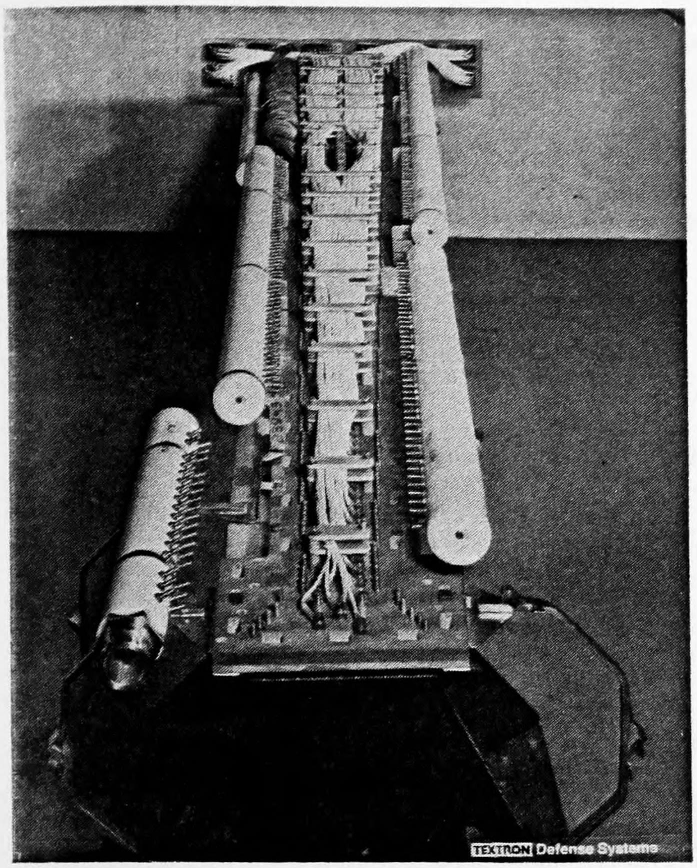

Figure 19. Channel Cathode Wall

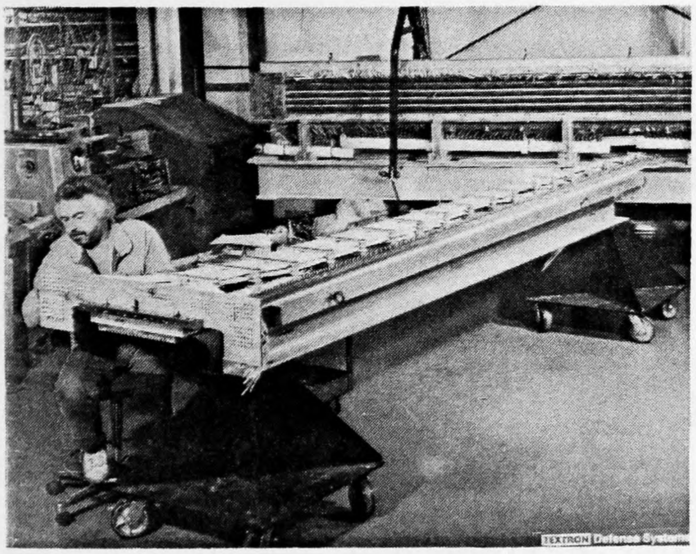

Figure 20. Channel Anode Wall

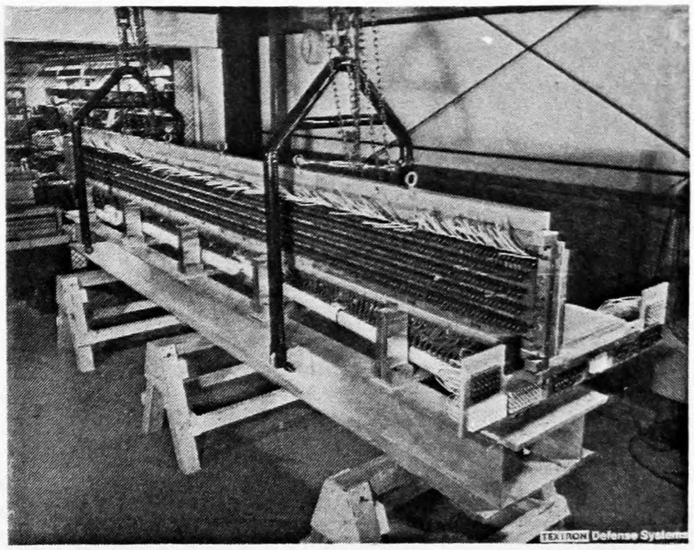

Figure 21. Channel Sidewall

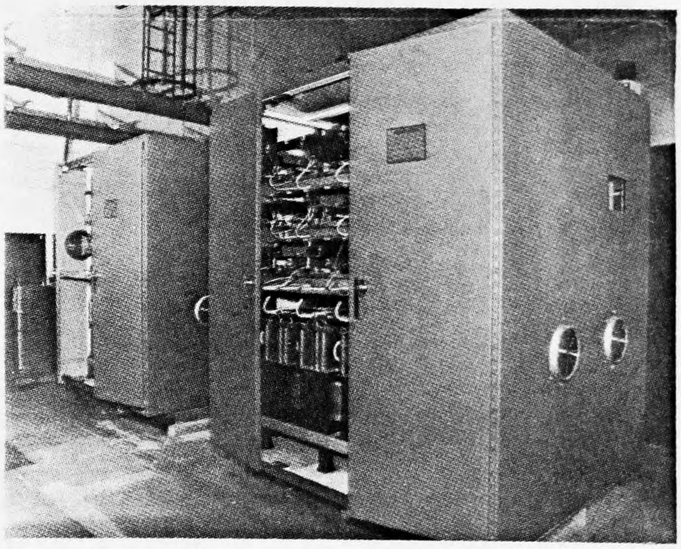

Figure 22. Anode Power Cabinets

## FUTURE WORK

After delivery of the prototypical 50 MW$_t$ power train hardware to the CDIF, the subsystems will be installed and a series of checkout tests, design verification tests (DVT), and duration tests will be accomplished. Figure 24 shows the proof-of-concept test details that are planned to complete the program. The duration phase of the program is designed to accumulate 800 hours with Western coal (Montana Rosebud) and 200 hours with Eastern coal (Illinois No. 6). The current plan is to complete this POC testing by September 1993.

## REFERENCES

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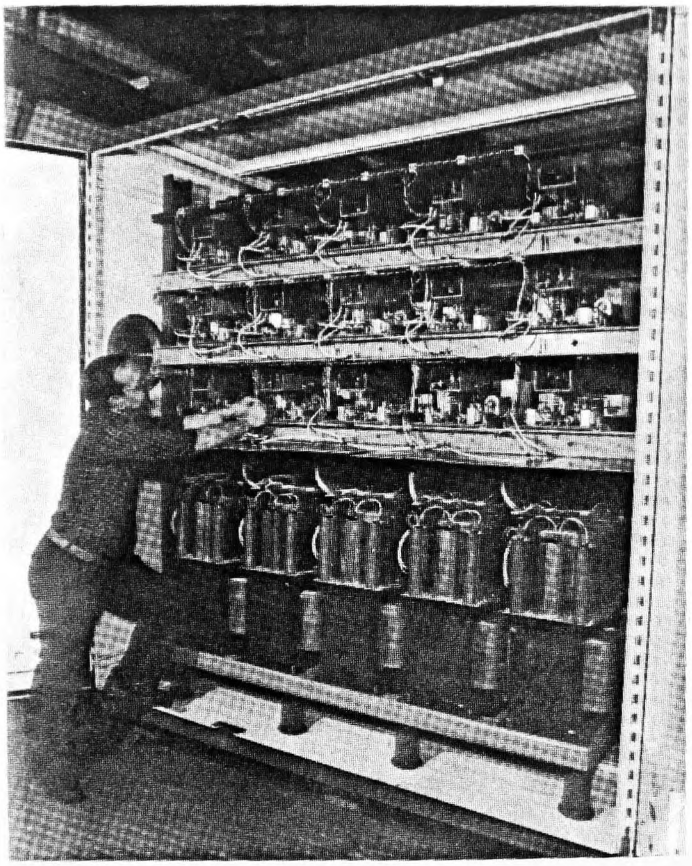

Figure 23. Anode Power Cabinet

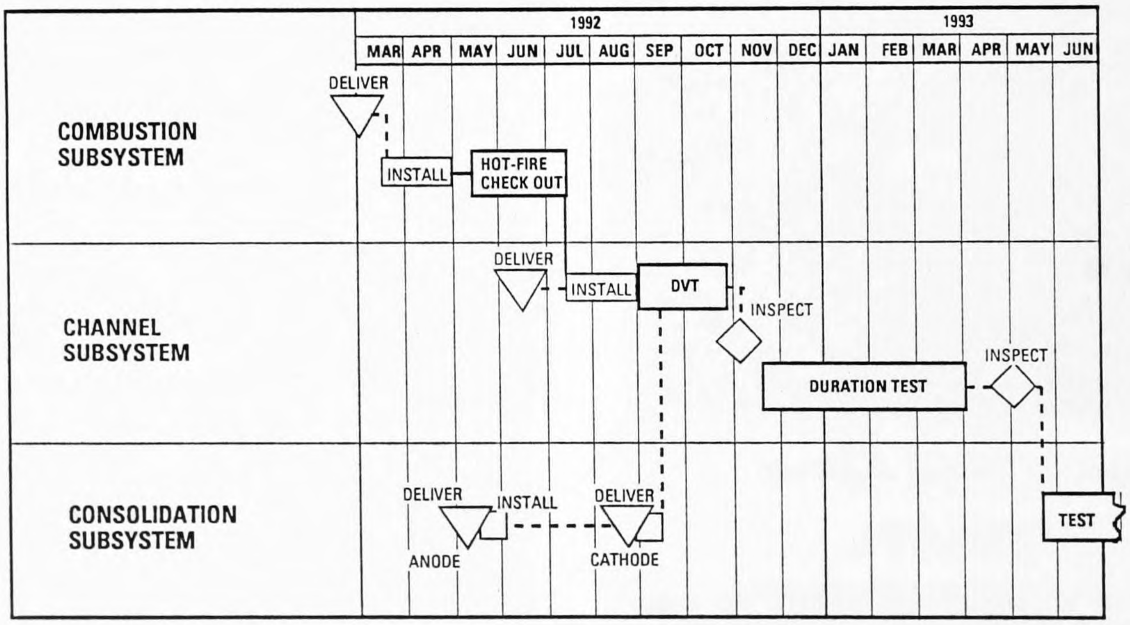

Figure 24. Remaining POC Test Program