# Proof-Of-Concept (Poc) Program Integration

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# PROOF-OF-CONCEPT (POC) PROGRAM INTEGRATION*

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## ABSTRACT

The need to focus the DOE sponsored POC programs on commercially realistic goals for the first MHD retrofit plant has led to the establishment of the POC Integration Task Force. The POC Task Force is responsible for the integration of the three program elements; topping cycle, bottoming cycle, and seed regeneration. To accomplish the POC integration charter, the existing POC data and project plans were reviewed with respect to the two retrofit conceptual designs, Corette and Scholz. From this review a Retrofit Reference Design Basis (RRDB) was formulated. It is the RRDB that provides a focal point for evaluating the testing and systems analysis for the POC programs.

Evaluation of the RRDB in relation to the POC program has identified many areas of agreement between the POC and retrofit design basis, but also a number of inconsistencies that need to be further addressed within the POC programs before advancing to the commercial retrofit scale. Each of these issues has been addressed with the objective of modifying or making additions to the POC program to improve the commercial viability of the MHD technology. Recommendations are forthcoming to the Technology Transfer and Integration Review Committee on each of these issues and other issues are being evaluated as they are identified.

## INTRODUCTION

The MHD Proof-of-Concept (POC) program is focused on the least-cost, shortest development time path to establish the MHD technology base to provide for the construction, testing and operation of a fully integrated MHD-Steam power system in a utility environment. The POC program is guided by systems engineering derived requirements and analytical modeling to support scale-up and component design. In response to environmental, economic, engineering and utility acceptance requirements, design choices and operational modes are being tested and refined to provide technical specifications for meeting commercial criteria. These engineering activities are supported by comprehensive systems analysis to establish realistic technical requirements and cost data. Trade-off studies are being carried out to direct the overall system concept toward the most advantageous designs. These system studies are essential to focus the MHD program on commercially realistic goals.

To ensure that the POC program remains focused on these commercially realistic goals for the first MHD retrofit, integration of the program elements, topping cycle, bottoming cycle, and seed regeneration is essential. To this end, the existing POC data and project plans were reviewed and integrated with the results of the two retrofit conceptual designs, Corette and Scholz. From this activity a Retrofit Reference Design Basis (RRDB) was formulated. The RRDB will provide a focal point for testing and systems analysis of the POC program.

Evaluation of the RRDB in relation to the POC program identified a number of issues that need to be further addressed at the POC level before advancing to a retrofit. These include:

- Scalability
- Performance and Reliability
- Superconducting Magnets
- Part Load Operation
- Overall MHD Combustor Stoichiometry
- Second Stage Combustor Oxidant
- Second Stage Combustor Cooling
- Seed Impurities
- Seed Regeneration Integration
- Multiple Load Operation
- Active Current Controls
- Additives
- $K_2/S$
- ESP/Baghouse Operation
- Slag Rejection
- Integrated Plant Control Strategy

This paper presents a summary of the origins and organizational structure of the POC Task Force. This is followed by the logic in which the Retrofit Reference Design Basis (RRDB) was formulated and is presented in relation with the current POC programs.

The results of the system integration process for the POC program are presented with special emphasis on open technical issues requiring further evaluation at the POC level.

## POC TASK FORCE ORGANIZATION

The POC Integration Task Force was established by the Technology Transfer and Integration Review Committee (TTIRC) and is administered by the Integrated Topping Cycle (ITC) program office. The Task Force organization, shown in Figure 1, consists of a chairperson, systems engineering personnel and two groups of technical experts. The Task Force is staffed to represent a cross-section of the three POC elements, the Integrated Topping Cycle (ITC), the Integrated Bottoming Cycle (IBC) and the Seed Regeneration Process and system engineers with extensive background in MHD and/or utility related experience. The Task Force utilizes a Technical Evaluation Team to review and respond to the Task Force's technical requirements, conclusions and recommendations. The Evaluation Team

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consists of representatives from the three POC program elements as well as the retrofit studies and the electric utility industry. This broad spectrum of participants ensures that technical issues identified by the Task Force are reviewed and analyzed both from within and outside the MHD community.

The results of the Task Force efforts are reported directly to the TTIRC Executive Committee which also serves as the final reviewing body for Task Force recommendations.

## POC PROGRAM INTEGRATION LOGIC

To ensure that the POC programs remain focused on commercially realistic goals for the first MHD retrofit plant, the Task Force utilized the following process; 1) review the existing requirements, program plans and data base for the three POC program elements and the two commercial retrofit conceptual designs. 2) integrate the results of the aforementioned review, guided by system engineering and analytical modeling studies, and establish a Retrofit Reference Design Basis (RRDB). 3) evaluate the current plans of the three POC programs in relation to the RRDB and assess program needs. 4) identify key technical issues needed to provide technical specifications for meeting commercial evaluation and make recommendations to the TTIRC Executive Committee ways to eliminate these technology gaps. The overall logic to the POC integration process is illustrated in Figure 2.

### Requirements Review

The first step in the integration of the POC program was to review the requirements imposed on the three POC programs by the DOE contractual statement–of–work, the additional requirements imposed by the respective component developers, and the requirements of the two retrofit conceptual design studies. These requirements were organized and compared to identify similarities and variances, especially with respect to the retrofit designs, which, in essence, should constitute the requirements of the POC programs. Table 1 summarizes the design basis for the major POC elements and the two retrofit conceptual designs. Some rather obvious inconsistencies between the POC programs and the conceptual designs are; scale, oxygen enrichment, seed regeneration, magnet type and field strength, component cooling and channel design. These and other discrepancies will be addressed in more detail in a later section titled, Open Technical Issues.

### Retrofit Reference Design Basis (RRDB)

To ascertain whether the POC program was focused on commercially realistic goals, a generic design basis for a retrofit plant was established and called the Retrofit Reference Design Basis (RRDB). The logic for establishing the RRDB is based on the two retrofit conceptual designs, the current POC programs and standard industry practice.

The establishment of the RRDB begins with the two retrofit conceptual designs. Where the two conceptual design studies are similar and other selection criteria such as risk, reliability and developmental maturity of the specific unit operation are satisfied, then that requirement was used for the RRDB. In situations where the two retrofit conceptual designs differed, the selection of a criteria took one of two approaches: The first path was those cases where a requirement was site specific. For this path, no specific requirement was established but a general requirement was specified that could be adapted to various sites and attempted to capitalized on established industrial practices. For other situations, where there was a basic technology difference between the two retrofit designs, the RRDB requirement was selected based on the predominant experience and/or the applicable POC test program. If, for example the POC data supports one design but not the other, then the selection of the requirement was based on POC experience. If a technology was not sufficiently developed or would not be economical at retrofit and larger commercial sizes, then that technology was not considered for the RRDB.

### Assess POC Program Needs

After a set of requirements were established for a Retrofit Reference Design Basis, the current plans of the POC program were assessed to ascertain if the requirements and the methods to meet those requirements are consistent with the goal of establishing the data base necessary to advance MHD technology to the retrofit of a utility power plant. Requirements and technical approaches for the three POC program elements were considered separately and as an integrated whole, and compared to determine consistency and system validity. The status of the POC programs in relation to the RRDB was also assessed.

### Open Technical Issues

The RRDB was evaluated by the Task Force, against the POC design basis, and a set of issues which are not being adequately addressed by the POC program where identified. These issues, along with a supporting questionnaire, were submitted to the Technical Evaluation Team, the TTIRC Executive Committee and to the DOE Technical Project Personnel for review and comments. These issues, and consensus discussions from the review members, provided the basis for a set of conclusions and recommendations which will be forwarded to the TTIRC with methods to fulfill the requirements with additions and/or amendments to the POC programs.

## RETROFIT REFERENCE DESIGN BASIS

The DOE imposed requirements on the POC program elements are very general and are not extensive enough to form a design basis. Even after the contractor imposed requirements were considered not all of the retrofit design basis needs were addressed. In addition, the two retrofit conceptual designs, Scholz and Corette, were reviewed and the design basis for each was extracted. Since many of the design basis elements are site specific, a generic design basis was prepared and called the Retrofit Reference Design Basis (RRDB). The RRDB, is based on the two retrofit conceptual designs, the current POC program and on standard industry practice. The RRDB along with the respective POC basis and a rationale for selecting the RRDB values is given in Table 2. This table was then used to make comparisons of the RRDB and POC planned activities to identify where changes or additions to the POC program would be beneficial.

## OPEN TECHNICAL ISSUES

As a result of the rigorous comparison between the RRDB and the POC programs a set of issues were established by the Task Force. While this review indicated, for the most part, that the POC programs have focused on commercially realistic goals, these identified issues must be addressed to provide technical specifications for meeting commercial criteria. These issues are discussed in the following section, their rationale for inclusion including the feedback and comments from the Technical Evaluation Team. These issues and any forthcoming recommendations that may result are based on technical rationale only; programmatic concerns such as budget or schedule were not a significant priority as part of the evaluation process. Sixteen issues were identified by the Task Force and are listed below:

- Scalability
- Performance and Reliability
- Superconducting Magnets
- Part Load Operation
- Overall MHD Combustor Stoichiometry
- Second Stage Combustor Oxidant
- Second Stage Combustor Cooling
- Seed Impurities
- Seed Regeneration Integration
- Multiple Load Operation
- Active Current Controls
- Additives
- $K_2/S$
- ESP/Baghouse Operation
- Slag Rejection
- Integrated Plant Control Strategy

**Scalability**

One obvious difference between the POC programs and the commercial retrofit demonstration is scale. The retrofit plant is envisioned between 200–300 $MW_t$ while the topping cycle, bottoming cycle, and seed regeneration POC programs are sized at 50, 28 and 5 $MW_t$, respectively. Therefore, the issue of scalability for each unit operation must be addressed. The POC programs have adopted the approach to scalability as "The Integrated MHD Programs will be designed and implemented to complement the existing engineering design data base so as to allow an evaluation of the risk and benefits of proceeding to the next development stage". This implies that, the basic design selected for testing of critical components should be capable of being scaled up and applied to full scale commercial sizes. This design approach concurs with the definition of prototypicality of design used in the ITC program. The POC Task Force, in concurrence with the Technical Evaluation Team believes it is neither necessary nor practical within the POC programs to test all of the components as unit operations directly scalable to commercial sizes.

**Performance and Reliability**

The POC test programs are prioritized with component lifetime, reliability and power train performance (power). Since the power output level of 1.5 $MW_e$ has been specified for the POC duration testing, it is impossible to simulate all other parameters that would make the test operation totally prototypical. A simple model would have the MHD combustor be the performance issue while the MHD channel is the lifetime and reliability issue. The Task Force asked the Technical Evaluation Team to prioritize specific operating parameters in order of their importance to simulate during POC testing. The result of the parameter ranking was quite varied however, three groups seemed to appear. The top priority group was related primarily to hardware lifetime and reliability (channel stresses) and were the parameters which concerned the review committee the most. The second group related mostly to performance and the third group contained parameters of lesser importance or are dependant on the other higher order parameters. Table 3 summarizes the grouping and gives the reader some insight into the parameters addressed by the Task Force.

This grouping suggests that it is more important to demonstrate lifetime and reliability of the MHD channel while operating at stress levels and conditions similar to those projected for retrofit and commercial operation than to demonstrate maximum power performance. This is necessary to begin to develop a reliability, availability and maintainability (RAM) data base for the various components.

**Superconducting Magnets**

The POC test program at CDIF will be performed with the existing iron core magnet, at a peak magnetic field of 2.93 Tesla. The retrofit and commercial MHD power plants will require superconducting magnets due to the intense magnetic fields, 4.5 to 6.0 Tesla, over large warm bore volumes and for economic reasons. Development of superconducting magnets is not part of the POC program.

Some technology for large superconducting magnets has been developed, mainly for bubble chamber and fusion reactor applications. Superconducting magnets for MHD applications have been built in Japan and United States. A magnet with a peak central field of 5 Tesla was built by Argonne National Laboratory for the U-25B facility in Moscow and has operated reliably for several years. The largest MHD superconducting magnet constructed to date was built by Argonne National Laboratory in 1981. It was successfully tested at its peak design field of 6 Tesla.

Many of the requirements for the construction of superconducting magnets for MHD power plants currently exists, or with some extrapolation, within the current state-of-the-art. The primary engineering needs are the optimization of bore utilization between the generator and magnet design and for efficient installation and maintenance of MHD components to minimize facility downtime during generator replacement, i.e., mean time to repair/replace (MTTB).

**Part Load Operation**

Current plans do not require the POC power train to address operation at part load conditions except during start-up and shutdown. Retrofit and large commercial facilities will have a requirement to operate at part electrical load; the RRDB considers operation at 50% of the nominal operating rating. To date, a strategy has not been established at the retrofit scale just how part electrical load would be achieved. In general, the Technical Evaluation Team believes that part load must be achieved through reducing thermal input and hence combustor pressure. The "trick" will be to reduce thermal input without undue restrictions on reliability and operability, without adverse effects on emissions while maintaining overall plant efficiency as high as possible. This will require an integrated control strategy which optimizes plant performance in conjunction with the simple reduction in fuel input such as channel loading, reduced magnetic field and possible recirculation of the flue gas in the heat recovery boiler. Demonstration of part load capability will not be resolved without further study, development and testing.

**Overall MHD Combustor Stoichiometry**

One of the major benefits of MHD technology is control of emissions. Control of $NO_x$ formation is achieved by two stage combustion under fuel-rich conditions in the primary combustion chamber. Secondary combustion takes place in the heat recovery boiler after appropriate cooling of the fuel-rich MHD exhaust gases in a radiant furnace. Overall stoichiometry of the

MHD combustor dictates the formation of $NO_x$ while conditions in the radiant furnace (cooling rate and residence time) allow the $NO_x$ to decompose into $N_2$ and $O_2$.

The topping cycle POC hardware has been designed at a reference design stoichiometry at the channel exit of 0.95. To effectively maintain a $NO_x$ level below current and/or future New Source Pollution Standards (NSPS), UTSI has demonstrated that a stoichiometry of 0.80–0.90 will be required. The Corette and Scholz retrofit conceptual designs studies were done at overall stoichiometries of 0.90 and 0.88, respectively. Both of these design conditions were selected to meet current NSPS standards utilizing the UTSI model. Tests conducted on the topping cycle workhorse hardware have demonstrated that the hardware can operate at lower overall stoichiometries (0.90) and still maintain acceptable combustor performance and generator output power. The Task Force believes that MHD acceptance by utilities will be based on a combination of higher system efficiency and lower environmental intrusion and we should capitalize on this synergy.

### Second Stage Oxidant

Second stage oxidant and oxygen injection methods planned for the POC testing are not representative of planned retrofit operation. 100% high pressure pure oxygen at near ambient temperature will be used during the POC testing. A retrofit facility will inject preheated (nominally 1200°F), low pressure oxygen enriched air because compression costs for high pressure injection are considered to be prohibitive. From a performance standpoint, analyses have been performed that show operation with high pressure, pure oxygen can adequately simulate commercial oxidant conditions.

Low pressure oxidant injection will present both design and engineering issues, such as injector design and mixing, that must be evaluated before scaling to a retrofit. While all low pressure oxidant injector studies have been deleted from the ITC program, it is not impractical to test the POC hardware using high pressure oxygen.

### Second Stage Cooling

The MHD second stage combustor will be cooled with low temperature process cooling water or with an intermediate temperature cooling loop using 250°F water. It is possible that the second stage of the combustor, in a retrofit application could be an extension of the nozzle/channel as far as cooling is concerned because the heat flux is in a realm closer to the channel than that of the combustor first stage. Although the RRDB calls for second stage cooling with high pressure boiler feed water, it is not an important issue for the POC testing because the choice of cooling has little impact on retrofit plant design and efficiency. The impact on large scale commercial MHD power plants may yield a differing conclusion.

### Single Load Versus Multiple Load Operation

A diagonally loaded generator has been selected for the POC testing and is envisioned for retrofit and commercial facilities. This decision was made early on in the development of MHD because a diagonally loaded generator was judged to have higher reliability, substantially greater fault tolerance, lower power conditioning losses and lower system cost than a Faraday loaded generator.

For a diagonal loaded generator, the practice proposed for utility applications in the RRDB and large scale commercial plants will be to install a limited number ( > 1) of inverters with dc terminal connections. The number of inverters and connection points along the channel will be chosen to maximize the overall reliability and performance. This implies the use of multiple load operation, where as the POC testing will be operated as a single terminal device.

There currently exists limited experience with multiple load operation also referred to as "center tapping". The experience necessary to understand the system trade–offs, reliability issues and technical challenges of multiple loaded operation can only be gained through experimental testing.

### Active Current Controls

Power conditioning devices to perform both consolidation and control functions have been built and tested by the Avco Research Laboratory. The same basic circuitry is used for both functions. The power conditioning circuitry tested to date performs the current control function by passively forcing discrete groups of generator electrodes to carry the same average current.

The POC program plans to utilize the passive current controls along the channel with an active power management system as current consolidation circuits interfacing to the DC–AC inverter. This alternative concept, which is in a less advanced stage of development, allows the current from each electrode pair to be controlled independently via external input from a remote operator or through feedback from computerized algorithms.

### Additives

Using additives, such as $Fe_2O_3$, has been demonstrated as an effective means in reducing high voltage gaps between shorted groups of cathodes. It is these high voltage gaps that are primarily responsible for accelerated material wear rates that reduce cathode and sidewall life. However, even the simple addition of iron oxide (or any additive) adds undesirable cost and complexity to the operation of a commercial facility. In addition, the effectiveness of iron oxide for reducing cathode wall slag polarization has not been demonstrated for long term operation, nor has the impact on the HRSR and the seed regeneration process been addressed. The Task Force believes that other solutions to reducing high voltage stresses which are available, (i.e., non-shorting cathodes) require evaluation.

### $K_2/S$

Potassium is added to the MHD combustion products to produce a working fluid of adequate electrical conductivity. Due to the strong chemical affinity of the potassium seed with sulfur to form potassium sulfate, control of $SO_x$ emission becomes intrinsic to the MHD process.

The $K_2/S$ issue has evolved into a high sulfur versus low sulfur coal issue. For Eastern, high sulfur, coal the $K_2/S$ ratio will be approximately one because there is sufficient sulfur in the gas to combine with all of the potassium required for ionization of the coal combustion products and the issue goes away. For Western, low sulfur, coal the amount of potassium added to the MHD combustion products for plasma ionization is significantly greater than that required to react with the coal sulfur hence the $K_2/S$ ratio exceeds one ($K_2/S$ 2-3).

For western coal a number of potential options are available each requiring a trade-off study between operating/equipment costs and equipment lifetime/reliability. Each of these options affects the topping cycle hardware (primarily channel), bottoming cycle hardware and the seed regeneration process.

If option 1 is the case where the $K_2/S >> 1$ the following issues result:

- The excess potassium carbonate in the gas affects the performance of the downstream components in the bottoming cycle
- Requires the entire spent seed mixture of $K_2CO_3/K_2SO_4$ to be processed thru the seed regeneration process unless a viable technique for partitioning the $K_2CO_3$ from the $K_2SO_4$ prior to regeneration is developed
- Removes greater than 99% of the coal sulfur thereby exceeding current NSPS
- The low sulfur levels in the gas stream increase equipment lifetimes.

The second option is to operate at a $K_2/S$ 1 by the recycle of the spent seed ($K_2SO_4$) and the following issues fallout:

- Alleviates excess potassium carbonate in the gas
- Reduces the amount of seed material required for regeneration
- Removes only 95% of the coal sulfur still exceeding current NSPS
- The higher sulfur in the gas stream will adversely affect component/material lifetimes.

There is no clear cut technical resolution for this issue, therefore to be defined it will require trade-off studies of economics, lifetime and equipment performance.

### Seed Impurities

POC testing will be performed with a commercially procured potassium carbonate seed material, primarily because of availability and to a lesser degree operating experience. Conversely, the retrofit and commercial plants will utilize a regenerated seed again because of availability (a 250 $MW_t$ plant utilized nearly all of the commercial $K_2CO_3$ production) and economics. Regenerated seed will contain impurities, primarily sodium and chlorine. The levels of impurities during steady state seed regeneration is a function of the coal chemistry and the seed regeneration plant operation.

UTSI studies have shown that increasing sodium and chlorine results in decreasing electrical conductivity of the plasma. Chlorine is also known to increase corrosion in many cases, while sodium has been associated with increased fouling and corrosion in steam bottoming cycle components.

Once the levels of impurities are known, after POC seed regeneration plant demonstration, the effects on various components must be evaluated in conjunction with methods for controlling impurity buildup to acceptable levels.

### ESP Operation

For an ESP to operate effectively the particulate resistivity should be in the range of $10^6 - 10^{10}$ ohm/cm. The resistivity is a function of the ESP inlet gas temperature and the composition of the particulate matter. The latter is affected by the coal ash chemistry and the $K_2/S$ issue discussed earlier.

### Seed Regeneration Integration

The current seed regeneration system design does not presently integrate with a total facility design. Although the actual integration of the seed regeneration process is site specific it is necessary to consolidate the POC program and RRDB requirements into an integrated seed regeneration system. This process will incorporate the impacts on the ESP, seed impurities, $K_2/S$ and slag rejection issues for an optimized plant design.

### Slag Rejection

The specific requirement for slag rejection is primarily driven by the seed recovery economics and not by power train performance. This results from the seed material being very difficult and costly to separate from the slag, while power train performance is relatively insensitive to slag carryover rates greater than that required to provide a suitable thermally insulating slag layer.

### Integrated Plant Control Strategy

The POC test program has been structured to address the operation of integrated subsystems of an MHD-steam power plant. As a result no integrated plant control strategy is addressed within the POC program.

The Task Force recognizes that all aspects of an integrated plant control strategy can only be fully addressed in a complete, integrated MHD-steam power plant of appropriate size, such as the planned MHD retrofit. However, many important aspects of an integrated control strategy can be obtained through analysis; including part load operation, start-up and shutdown.

## CONCLUSIONS

At the behest of the TTIRC Executive Committee the POC Integration Task Force was established to oversee the integration of the three POC program elements; integrated topping cycle, integrated bottoming cycle and the seed regeneration process.

The Task Force reviewed the current POC test plans and data base with respect to the two retrofit conceptual design studies. From this review a generic Reference Retrofit Design Basis (RRDB) was formulated which became the focal point for evaluating the testing and systems analyses of the POC programs. As a result of the comparison between the RRDB and the POC programs a number of issues were identified by the Task Force. While this review indicated that within the expected limitations of the POC integrated MHD subsystems, these programs have focused on commercially realistic goals, these identified issues should be addressed to provide technical specifications for meeting commercial criteria.

Table 1. POC/Retrofit Design Comparison

| Design Basis/ Requirement | POC | Corette | Scholz |
|---|---|---|---|
| **GENERAL** | | | |
| Enthalpy Extraction | NA | 11% | 13% |
| Plant Capacity Factor (design requirement) | NA | .65 | .65 |
| Operational Availability (design requirement) | NA | .85 | .85 |
| Operational Range (design requirement) | Nominal design conditions | 75 to 100% | 75 to 100% |
| **COMBUSTOR** | | | |
| Combustor Type | slagging<br>60% removal | slagging<br>70% removal | slagging<br>85% removal |
| Fuel | Rosebud and an Eastern Coal | Rosebud (Western) | Illinois No. 6 (Eastern) |
| Oxidant over all | Oxygen Enriched Air; 60% | Oxygen Enriched Air; 38%<br>6 atm | Oxygen Enriched Air; 40%<br>6 atm |
| 2nd Stage | 100% oxygen; 70°F; 225 psia | same | same |
| Preheat Temperature | 1200 to 1500°F (Vitiated) | 1200°F | 1450°F |
| Fuel Input | 40 to 60 $MW_t$ | 250 $MW_t$ | 192 $MW_t$ |
| Seed | $K_2CO_3$, dry (no regeneration) (have tested $K_2CO_3/H_2O$ solution; plan to test $KCOOH/H_2O$ solution) | $K_2CO_3$, dry (regenerated) | $K_2CO_3$, dry (regenerated) |
| Coolant | 450°F, 1200 psia | 450°F exit of combustor | 440°F inlet of combustor |
| Design Life | 2000 hrs/500 cycles | | 15 years |
| **CHANNEL** | | | |
| Channel Type | Supersonic; Cu, W, & Pt, water cooled | 1.2M inlet; Cu, W, & Pt; water cooled | 1.85M inlet; 1.0 exit; Cu, W, Mo & Pt; water cooled |
| Coolant | 70-110°F; 300 psia | 200° exit of channel | Low pressure low temperature |
| Design Life (MTBF) | 2000/500 cycles | 4000 hrs | 4000 hrs |
| Magnet | Iron Core 2.94 T | Superconducting 4.5 T | Superconducting 6 T |
| **DIFFUSER** | | | |
| Diffuser Type | Supersonic inlet;subsonic exit | Supersonic inlet;subsonic exit | Sonic inlet; sonic outlet; |
| Coolant | Low pressure low temperature | H/P Boiler Circuit Water | H/P Boiler Feed Water |
| Bottoming Cycle | Radiant Boiler, Afterburner, Convective sections, Baghouse and ESP for ash recovery | Radiant boiler, Afterburner, Secondary Superheater, Reheater primary superheater Air preheater, 2 economizers with slag & ash collection | Radiant Boiler, Afterburner; Oxidant preheater superheater, secondary air heater, economizer; slag and ash removal |
| Environmental Requirements | | NSPS | NSPS |
| Environmental Control | $SO_x$ - $K_2/S>1$<br>$NO_x$ - within limits;02 = 0.8-0.9<br>particulates - ESP & Baghouse | $SO_x$ - $K_2/S>1$<br>$NO_x$ - staged combustion<br>02 = 0.9<br>particulates - ESP | $SO_x$ - $K_2/S>1$<br>$NO_x$ - staged combustion<br>02 = 0.88<br>particulates - ESP |

**Table 2. Retrofit Reference Design Basis**

| Design Basis/ Requirement | POC | Retrofit Reference Design Basis | Rationale* |
|---|---|---|---|
| **General** | | | |
| Plant Capacity Factor | Not applicable | 0.65 min. | Goals based on existing utility operations |
| MHD Operational Availability | Not applicable | 0.85 min. | Goals based on existing utility operations |
| MHD Operational Range | 50 to 120% | 50 to 100% | Adequate for base load applications; provides adequate demo of operational aspects |
| Fuel | Rosebud and Illinois No. 6; pulverized | Western or Eastern (Site Specific) | |
| Fuel Moisture | Rosebud < 8%; Eastern coal < 4% as fired | Western < 8% as fired; Eastern < 4% as fired | Should be as dry as possible. Goals are within standard PC drying practice for these coals |
| Oxidant | | | |
| First Stage | 60% oxygen enriched air | Oxygen enriched air, 35 to 40%; | 35-40% $O_2$ is suitable for a commercial retrofit with regard to plasma temperature and conductivity |
| Second Stage | 100% oxygen @225 psia | Same | |
| Oxidant Preheat | 1200 – 1500°F | 1000 to 1500°F | Range selected to allow economic integration using a metallic recuperative heat exchanger |
| First Stage | (Vitiated) | | |
| Second Stage | None | Same | |
| MHD Thermal Input | Nominal 50 MW | Nominal design point, 200 to 300 $MW_t$ | Range selected to provide for representative topping/bottoming integration and reasonable scaling to 1000 $MW_t$ |
| Seed | 1 to 2% K | 1 to 2% K | 1 - 2% range selected based upon plasma electrical conductivity, sulfur removal and seed economics |
| Environmental | Must meet NSPS | 1/6 to 1/10 current NSPS MHD portion | Below NSPS projected to the year 2000 |

**Table 2. Retrofit Reference Design Basis (continued)**

| Design Basis/ Requirement | POC | Retrofit Reference Design Basis | Rationale* |
|---|---|---|---|
| **Combustor** | | | |
| Type | Two-stage<br>Slagging (TRW) (vitiated) | Two-stage<br>Slagging (TRW) | |
| Slag Rejection | >60% | >60% | Increased ash carryover makes seed recovery and economics problematic |
| Seed | $K_2CO_3$, 1-2% K dry (have tested $K_2CO_3/H_2O$ solution; plan to test $KCOOH/H_2O$ solution | KCOOH, molten or in solution; regenerated; $K_2/S > 1$; 1%K min | KCOOH most economic from regeneration plant; molten salt feed least complicated |
| Operational Availability | Not applicable | 0.975 | Boiler industry norm |
| Operational Range | Nominal design conditions | 50 to 100% | |
| MTBF | Not applicable | 4000 hours | |
| Useful Equipment Life | 2000 hrs; 500 cycles; design | 30 years | Utility industry norm |
| Stoichiometry<br>First Stage<br>Second Stage | <br>0.55<br>0.95 nominal (test range 0.80 to 0.95) | Overall = 0.8 to 0.9 | Necessary to satisfy projected future NOx emission limits |
| Heat Loss | 7% | 5% | |
| Operating Pressure | 6 atm | 4 to 8 atm | |
| Combustor Pressure Drop | | <4% | |
| Materials | Scalable materials and construction thermal panels/pressure shell | Based on POC | |
| Voltage Standoff | 10 kV | 20 - 30 kV | |
| Cooling<br>1st Stage<br>2nd Stage | <br>450°F/1200 psia<br>250°F/300 psia | <br>High pressure boiler feedwater<br>High pressure boiler feedwater | <br>Provides most attractive MHD process integration<br>Provides most attractive MHD process integration |
| Injectors | 70-110°F | High pressure boiler feedwater if possible | Provides most attractive MHD process integration but may be precluded by high heat fluxes |

Table 2. Retrofit Reference Design Basis (continued)

| Design Basis/ Requirement | POC | Retrofit Reference Design Basis | Rationale* |
|---|---|---|---|
| Nozzle | | | |
| Exit Velocity | Supersonic | Supersonic | Match channel design |
| Standoff Voltage | 10 kV | 30 to 30 kV | |
| Construction | Segmented to prevent current flow from fringe field | Segmented to prevent current flow from fringe field. Scalable design | |
| Coolant | PCW at 70 to 110°F, 300 psia | Low pressure cooling water | High heat flux precludes HP boiler feedwater. Nozzle likely to be integral with channel |
| MTBF | Not applicable | 4000 hours | |
| Useful Equipment Life | 2000 hours/500 cycles | 30 years | |
| Operational Availability | Not applicable | 0.99 | |

Table 2. Retrofit Reference Design Basis (continued)

| Design Basis/ Requirement | POC | Retrofit Reference Design Basis | Rationale* |
|---|---|---|---|
| **Channel** | | | |
| Enthalpy Extraction | Not applicable | > 10% | |
| Velocity | Supersonic | Supersonic | Supersonic operation selected based upon experience is less sensitive to combustion instabilities |
| Terminal Configuration | 30 anodes and 30 cathodes, diagonal, consolidated into a single load | Diagonal with multiload configuration | Diagonal loading is selected since it is more reliable, greater fault tolerance, lower power conditioning losses and lower system cost than Faraday loading. Multiload configuration is selected because it is more efficient than simple two terminal configuration |
| Isentropic Efficiency | Not applicable | > 50% | |
| Maximum Transverse Field | 2.2 - 4.8 | 4 kV/m | Similar to constraint projected for commercial MHD |
| Maximum Axial Field | 1.2 - 3.3 | 2.5 kV/m | Similar to constraint projected for commercial MHD |
| Maximum Current Density | 1.0 - 1.5 | 1 Amp/cm$^2$ | Similar to constraint projected for commercial MHD |
| Maximum Hall Voltage | 10 kV | 20 kV | Similar to constraint projected for commercial MHD |
| Maximum Hall Parameter | 2.02 | 4 | Similar to constraint projected for commercial MHD |
| Maximum Wall Heat Flux | 300 W/cm$^2$ | 300 W/cm$^2$ | Based on operating experience |
| Electrode/Insulator Design | Scalable to retrofit | Electrode/insulator wall design based on POC to provide fault, arc protection and reliability | Maximize electrode life, and reliability |
| Power Management | Active current consolidation in PTO region and current controls in remainder of channel | Based on POC | |
| External Packaging | Existing Avco state of the art | Maximize magnet bore utilization and rapid channel replacement | Minimize magnet cost and maximize plant availability |
| Cooling | PCW at 70 to 110°F, 300 psia | Low pressure cooling water | High heat flux precludes HP boiler feedwater |
| MTBF | Not applicable | 2000 hours | |
| Useful Equipment Life | 2000 hours/500 cycles; design scalable to retrofit | | |
| Operational Availability | Not applicable | 0.97 | Use of "stand-by" spare channel |

**Table 2. Retrofit Reference Design Basis (continued)**

| Design Basis/ Requirement | POC | Retrofit Reference Design Basis | Rationale* |
|---|---|---|---|
| **Inverter** | Existing single inverter | Multiple inverters to match multiload configuration | |
| Operational Availability | Not applicable | 0.998 for inversion equipment; 0.998 for electrode consol/cont | |
| MTBF | Not applicable | 1000 hours | |
| **Magnet** | | | |
| Type | Iron core | Superconducting with stabilized NbTi windings | |
| Maximum Field | 2.94 Tesla | 4.0 to 6.0 Tesla | Range is projected for early commercial MHD units |
| Operational Availability | Not applicable | 0.998 | |
| MTBF | Not applicable | 10000 hours | |
| **Diffuser** | | | |
| Operation | Slagging | Slagging | |
| Inlet Velocity | Supersonic (Mach 1.9) | Supersonic | Supersonic to match channel design |
| Exit Velocity to Boiler | | < 300 fps | Velocity selected to meet boiler requirements |
| Pressure | | | |
| Inlet | 0.4 atm | 0.7 atm | Inlet pressure selected to match channel design |
| Outlet | 1.0 atm | 1.0 atm | Outlet pressure selected to meet boiler requirements including overpressure protection |
| Coolant | PCW at 70 to 110°F, 300 psia | High pressure boiler feed water | Economic integration with boiler feedwater circuit |
| Maximum Heat Flux, $w/cm^2$ | 80 | 40 | Can use high pressure boiler feedwater |
| MTBF | Not applicable | 4000 hours | |
| Useful Equipment Life | 2000 hours/500 cycles | 30 years | |
| Availability | Not applicable | 0.99 | |

Table 2. Retrofit Reference Design Basis (continued)

| Design Basis/ Requirement | POC | Retrofit Reference Design Basis | Rationale* |
|---|---|---|---|
| **Heat Recovery** | | | |
| Radiant Boiler Residence Time | 1 - 3 seconds | 2 seconds with refractory lined radiant section | Residence time, cooling rate and lining selected for control of $NO_x$ emissions, cooldown rate based on POC program |
| Radiant Boiler Inlet Temp. | 3750 - 3800°F | 3750 - 3840°F | |
| Radiant Boiler Cooling Rate | 400 - 600°F | Minimize $NO_x$ based on POC | $NO_x$ emissions below projected future NSPS |
| Afterburner Inlet Temp. | 1900 - 2100°F | 2000°F, nominal; based on POC | Design dependent; based on above rationale |
| Afterburner Outlet Temp. | 2300 - 2400°F | 2450°F; nominal; based on POC | Design dependent; based on above rationale |
| Afterburner Outlet Stoichiometry | 1.0 - 1.3 (1.05 nominal) | 1.05 nominal; 1.00 to 1.10 control range | |
| Convective Section Inlet Temperature | 2300 - 2350°F | 2250°F, nominal; based on POC | Higher temperatures require greater surface area to compensate for fouling |
| ESP Inlet Temperature | 350 - 750°F | 350°F, nominal based on POC erosion data | |
| Materials | TS1 - 310, 316H, 253MA, 304H (inlet T=2300 - 2350°F)<br>TS2 - 321H, T22, 310, 253MA, 304H, 316H, 335P5 (inlet T=1600 - 1700°F)<br>TS3 - T22, SA - 192, T11, 335P5 (inlet T=1200°F) | | |
| Useful Equipment Life | Not applicable | 30 years | |
| MTBF | Not applicable | 8000 hours | |
| Operational Availability | Not applicable | 0.975 | |

Table 2. Retrofit Reference Design Basis (continued)

| Design Basis/ Requirement | POC | Retrofit Reference Design Basis | Rationale* |
|---|---|---|---|
| **Seed Regeneration** | | | |
| Regeneration Plant Feed | CFFF ESP and superheater spent seed/$K_2SO_4$ plus flyash | Convective boiler bottom ash and flyash | Radiant furnace slag discarded due to low K concentration and poor leaching quality |
| Product Seed Form | Potassium Formate (KCOOH) | Potassium Formate (KCOOH) | |
| Seed Loading | 1 to 2% K as $K_2CO_3$ | 1 to 2% K; seed regeneration required | All sulfur is to be captured as $K_2SO_4$; little conductivity improvement and higher cost with K > 2% |
| $K_2/SO_4$ Ratio | > 1 | > 1 | 100% sulfur removal from the gas stream |
| Product Seed Concentration | Ranging from dry anhydrous to 85% aqueous solution. | Molten potassium salt | Seed regeneration economics and generator performance |
| Impurity Levels | 2% max impurities ($K_2SO_4$, ash) chloride TBD | TBD based on elemental partitioning in ash and seed regeneration | Minimize impurities based on plasma performance, hardware corrosion, and regeneration economics |
| MTBF | Not applicable | 10000 hours | |
| Useful Equipment Life | Scalable to retrofit | 30 years | |
| Operational Availability | Not applicable | 0.996 | |
| **Feed Systems** | | | |
| Coal | Dual feed from single injection vessel using pinch valves for flow control. Measurement with load, cels, P, capacity/velocity and cariolis type devices; nitrogen carrier | Pneumatic injection. Best available technology at the time of installation | Maximize reliability, controlability and turndown |
| Seed | Basically same as coal system without the pinch valve | Formate as a liquid feed (molten or solution) | |
| Additives | $Fe_2O_3$/gear oil slurry; diaphragm type metering pump injected at nozzle entrance | Additive TBD based upon POC results | Additives if required to control cathode wall non-uniformities |

*The Rationale for selection of most parameters relates to efficiency of the integrated MHD facility.

**Balance of plant equipment including feed materials recepit, coal pulverizing, oxygen production and water treatment are not included in this table.

Table 3. General Grouping of Operating Parameters

| Lifetime/Reliability Top Priority | Performance Secondary Priority | Other |
|---|---|---|
| Transverse Current | Power | Oxygen Enrichment |
| Current Density | Conductivity | Pressure |
| Electric Fields (Ex, Ey) | Uniformity | Fault Power |
| Sulver | | Hall Parameter |
| Heat Flux | | |
| Coal/Slag | | |

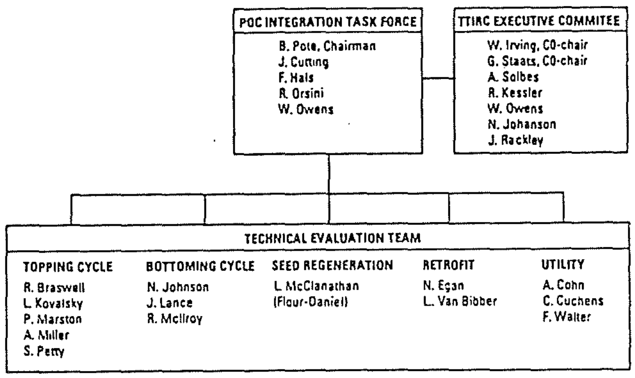


Figure 2.1 POC Task Forc Organization

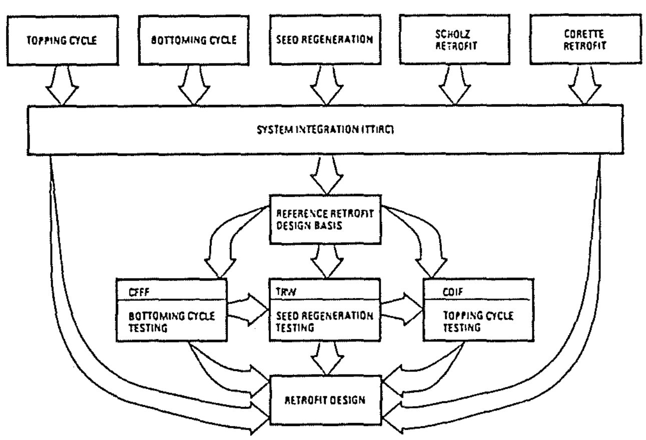


Figure 3.1 POC Integration Approach