Technology Overview for Integration of an MHD Topping Cycle with the CES Oxyfuel Combustor

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SCOPE OF WORK

Background: Clean Energy Systems (CES) have developed a combustor technology that ensures stoichiometric combustions of natural gas and oxygen at high temperature and high pressure. Water is injected into and around the combustion zone in order to minimise heat transfer to metal surfaces and ensures satisfactory thermal conditioning before the resulting drive-gas is expanded through a "near" conventional steam turbine expander.

Objective: The purpose of this Review Study is to provide an assessment of the opportunity to integrate MHD technology with the CES Gas Generator prior to expanding the drive-gas through the turbine expander. This enables additional work to be extracted from a topping cycle and significantly improve the overall cycle efficiency thereby using the CES-MHD combustor in a zero emission Oxy-MHD™ power cycle with 100% capture of CO_2 and no emissions of NO_x.

Target Audience: The Report is intended for technology personnel within the client organisation whom are located at the interface between R&D and commercial development of new game-changing technologies. The focus of the document is on describing the technology status and potential long-term benefits while presenting engineering considerations defining next-steps towards commercial development and eventual deployment of this technology.

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Dr. Carl-W. Hustad,

President & CEO, CO2-Global.

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By passing very-hot ionized combustion gas through a strong magnetic field a magneto hydrodynamic (MHD) generator can convert heat to electric power, without any rotating or moving parts. This makes it possible to reduce mechanical losses and operate at elevated temperatures using a "topping cycle" to increase the overall cycle thermal efficiency above what is possible for more conventional Brayton and Rankine cycles—thereby effectively increasing the idealised Carnot efficiency.

During the 1970's and 80's international research and development on MHD was funded in more than a dozen countries; in particular in the USSR where a 25 MW_e gas-fired MHD plant produced heat and power for residents of Moscow until the early 1990's, and there were advanced plans for a 500 MW_t commercial-size power plant. However, funding disappeared after the fall of the Berlin Wall in 1989 and ensuing demise of the Soviet Union.

In the United States extensive work was conducted by the Department of Energy (DOE) in collaboration with industry from 1987 thru to 1994 in a Proof-of-Concept (POC) Program. This included a 50 MW_t coal-fired MHD generator operating in Butte, Montana, and component tests for a coal-fired MHD bottoming (steam) cycle at University of Tennessee.

The Program received $223 million of funds from the DOE and had in principle confirmed much of the technology. However, support for full-scale demonstration projects was not forthcoming. Primarily because of competition for funding from advanced gas turbine combined-cycle power plants (CCPP) and integrated gasification combined-cycle (IGCC) technology.

Now, nearly two decades later, given technology developments and a stronger emphasis on Carbon Capture and Storage (CCS), this Review Study re-assesses integration of MHD with a stoichiometric oxy-combustor that has been developed by Clean Energy Systems (CES) Inc., based in Sacramento, California.

We describe how the CES Gas Generator (GG) enables direct combustion of either natural gas or coal-based syngas with oxygen resulting in a very-high temperature plasma. This avoids the need to pre-heat air and removal of significant volumes of ash from the coal combustor before the plasma can enter the MHD channel. Both of these were identified as outstanding issues in the POC Program before commercial deployment.

This Review Study identifies two main challenges where technology status requires further assessment. These are;

1. Improved enthalpy extraction within the MHD generator. Demonstrated performance appears to be less than 40% and should be higher for the MHD topping cycle to become thermodynamically more efficient than a super-critical Rankine bottoming cycle. This requires improvements of high-temperature electrodes, more optimal channel geometry, and a fundamental understanding of plasma dynamics.
2. Cost-effective method for plasma seeding, regeneration and recycling. Although seed material is only in the order of 1 to 2% of plasma mass flow, the POC Program estimated that this could represent as much as 20% of operating costs for a 1,000 MW_t MHD power plant.

State-of-the-art combined-cycle power plants are based on the Brayton cycle and have only recently reached 60% (LHV) efficiency. This was an increment of 2%-point achieved following one decade of development work that cost the major companies (GE, ABB and MHI) around $2 to $3 billion each. After 40-years of commercial development the combined Brayton with Rankine cycles appear to be asymptotically approaching an efficiency ceiling of ~64%.

When fully integrated with post-combustion CO_2 capture these cycles would be penalised with an estimated 8%-point while capturing ~90% of the CO_2 (and emitting NO_x). The development cost for such integration has evidently an additional $billion price tag that would at best result in a cycle efficiency of ~56%.

Given similar state-of-the-art technology for oxy-turbines the oxyfuel cycle has a targeted efficiency of ~60%. In this preliminary Study we suggest that inclusion of Oxy-MHD could further improve this efficiency by a factor of 1.15, inferring a significant commercial advantage for Oxy-MHD compared with competing zero emission cycles.

Given the revised focus on CCS and comparative levels of funding that are being proposed for technology development along different pathways, this Review Study concludes that Oxy-MHD appears to be a power generation cycle that justifiably should be assessed as a potential game-changing approach to efficient power generation using fossil fuels in a carbon constrained commercial environment.

Technical recommendations from this Review Study are as follows:

- A more thorough assessment regarding current technology status needs to be made. This is warranted because system requirements using the CES Gas Generator for MHD appear to permit some simplification compared with that identified previously for coal-fired MHD power generation.

- State-of-the-art plasma physics and dynamics should be thoroughly re-assessed because major advances have been made with development of “Tokomak” fusion reactors and the use of computational plasma-fluid dynamics.
- Detailed assessment regarding integration, size and cost of superconducting magnets with the CES Gas Generator needs to be evaluated.
- Thermodynamically the proposed cycle may offer an improvement over other CCS technology pathways. This preliminary assessment needs to be confirmed through more detailed process and cost analysis.
- Seeding, ionization and recycling are issues that remain outstanding and will need to be resolved.

Commercial recommendations are as follows:

- A Cost, Benefit and SWOT[1] analysis should be conducted (i.e. this may be a “smart mousetrap” but it also needs to be a long-term potential winner!)
- A phased Roadmap for technology commercialisation should be prepared. This should include the following;
    - Identify the stakeholders
    - Define annual funding requirements
    - Specify performance milestones and exit strategy
    - Describe commercial performance requirements.
- A technology development and funding strategy through to commercial deployment is necessary (i.e. identify who owns and supports this technology until it generates a positive cash-flow.)

It was concluded by Sens (1992) when summarising technology status on behalf of the European Commission that the MHD process opens up a temperature regime beyond that of any other process. Within that regime, it stands alone without a competitor and can provide a topping cycle for many of the competing cycles.

Typically gas turbine firing temperature limit may be extended by perhaps 200°C through special turbine blade developments which are likely to be very expensive, but it would not allow for an extra 1,500 °C as is offered by an MHD cycle with a corresponding extension of the Carnot cycle limits. Even if gas turbines offer up to 60 or more per cent in combined cycle efficiency, it is only MHD that could add another 10 to 25 per cent, quite independently, to this in practice. The extent of the improvement offered by MHD depends on the enthalpy extraction attainable. The development of high extraction generators is thus a critical issue.

[1] SWOT – Strength, Weakness, Opportunity and Threats.

1. INTRODUCTION

The phenomena of magneto hydrodynamic (MHD) electrical power generation was first recognized when Michael Faraday (1791-1867) experimented with the generation of electricity by moving a fluid electrical conductor through a stationary magnetic field[2]. However, the concept had little practical use at the time and therefore disappeared only to reappear in the patent literature from the early 1900's.

When an electrical conductor is moved and cuts lines of magnetic induction, the charged particles in the conductor experience a force in a direction mutually perpendicular to the magnetic field (**B**) and the velocity (**u**) vectors. Negative and positive charges will tend to move in opposite direction and the induced electric field provides the basis for converting mechanical energy into electrical energy.

Whereas a conventional power generator rotates a solid conductor between the poles of a magnet (see Fig. 1 A), Faraday showed that one could also employ a fluid conductor as the working substance through the interaction of a flowing, electrically conducting gas (or other fluid) and the magnetic field (see Fig. 1 B).

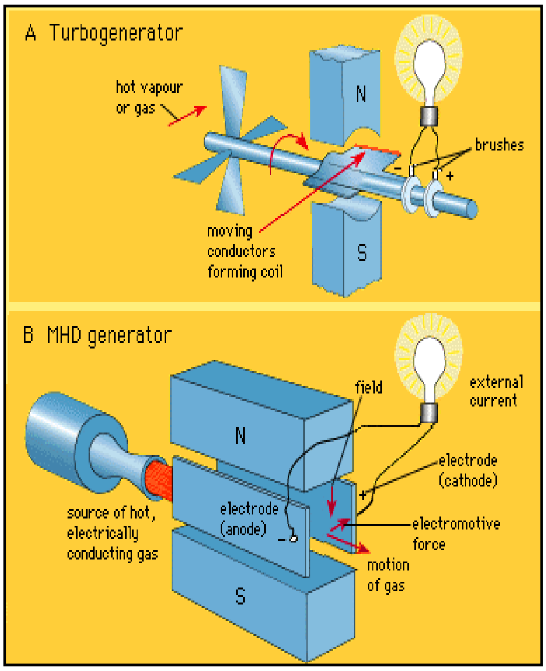

Fig. 1: Principle of operation for (A) a turbine generator, where momentum is transferred from a drive-gas to the surfaces of a rotating blade system, and (B) an MHD generator where interaction is between a gas continuum and the magnetic field through which it is passing. (Source: Encyclopedia Britannica).

The underlying principle of MHD power generation is therefore simple. Furthermore, if the conductor is an electrically conducting gas, it will expand and the MHD system constitutes a heat engine involving expansion similar to that of a gas turbine.

[2] To this end Faraday set up in January 1832 a rudimentary open-circuit MHD generator, or flow meter, on Waterloo Bridge in London. He immersed electrodes into the Thames River at either end of the bridge and connected the electrodes at mid-span through a galvanometer. He reasoned that the electrically conducting river water moving through the earth's magnetic field should produce a transverse electromotive force (emf). Small irregular deflections of the galvanometer were in fact observed. However his experiment was unsuccessful owing to the electrodes being electrochemically polarized, an effect not understood at that time.

MHD power generation was originally stimulated by the observation that the interaction of plasma with a magnetic field could occur at much higher temperatures than was possible in a rotating mechanical system where the limiting performance was based on the Carnot efficiency[3].

Already in the 1930's theoretical work on cosmic problems and projects for thermonuclear generation of energy revived interest in MHD. While approximate calculations in the 1950's and a deeper understanding in the 1960's meant that by the 1970's the technology had found niche R&D applications within diverse areas such as the U.S. space program, power generation and the defence industry.

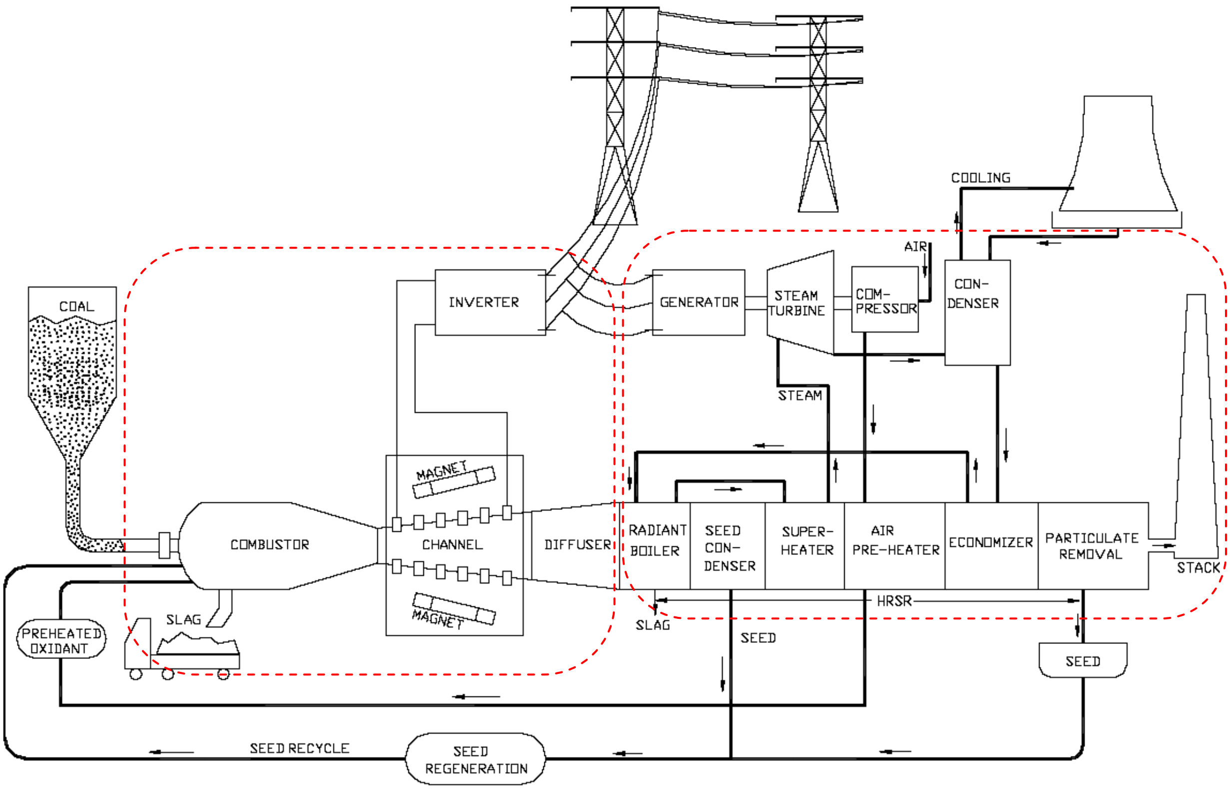

Fig. 2: Schematic for a Large Coal-Fired "Open Cycle" MHD Steam Power Plant System.

A conceptual design from this period is shown in Fig. 2 for a coal-fired MHD power plant. This comprises of a "topping" cycle centred about the MHD channel /magnets that is connected (via a diffuser) to a conventional steam bottoming cycle, as is highlighted respectively by the two dashed rectangular areas.

[3] This is obtained from the difference between the absolute hot source temperature (T_1) and the cold sink temperature (T_0) divided by T_1. With inefficiencies introduced by finite heat transfer rates and component inefficiencies in real heat engines, the effective efficiency for a state-of-the-art single-cycle gas turbine is 40 to 42%, while a modern supercritical coal-fired power plant achieves 46 to 48% and the latest gas-fired combined cycle plants manage 58 to 60%.

In the topping cycle, it was envisaged that coal and potassium seed material is fed to the combustor operating at between 5 to 10 bar and oxidised with air pre-heated to about 2,800 °F. When seeded the products of combustion produce an ionized gas (termed a "plasma") with a temperature in the range 4,600 to 4,800 °F that expands through a Laval nozzle and into a supersonic diffuser channel.

The plasma expands inside a strong magnetic field which for one-dimensional, frictionless, adiabatic flow can be described by the momentum equation as;

$$v\frac{dp}{dx} + u\frac{du}{dx} = -\sigma\, J\, B$$

With u being the axial and v the transverse velocity; while σ is the gas conductivity and B is the magnetic flux density. Furthermore, from the energy equation we have;

$$\frac{u}{v}.\frac{d(h + u^2/2)}{dx} = -\frac{JV}{h}$$

Where V is the potential difference and h the distance between the electrodes, and J is the current density given by;

$$J = \sigma\left(\frac{V}{h} - uB\right)$$

From these simplified equations (and ignoring any Hall effects) it is possible to understand some of the fundamentals of the MHD energy conversion process and deduce some useful performance criteria such as the rate that enthalpy is converted into electrical energy, the ratio of actual to isentropic enthalpy drop, and the power produced per unit volume of duct.

It can for example be shown that specific power is proportional to $\sigma\, u^2\, B^2$. Given that the peak velocity can reach Mach 1.3, and as such offsets the inherent disadvantage that σ for a seeded gas at 3,000 K is only about 100 /Ωm compared with 10^7 /Ωm for solid copper.

Considering the cycle in Fig. 2, then the incremental efficiency for the MHD topping part may be expressed simply as;

$$\Delta\eta_{MHD} = \frac{MHD\ Electrical\ Output - MHD\ Compressor\ Work}{\Delta H_o}$$

The MHD Electrical Output is the gross output less the power supplied to the electro-magnets producing the field B. The denominator ΔH_o is the enthalpy of combustion[4].

The major sources of losses are recognised as due to fluid friction, heat loss through channel walls and internal electrical resistance. Scaling is important and size is

[4] Strictly speaking the denominator should be the Gibbs function defined by $\Delta G_o = \Delta H_o - \Delta (TS)$

envisaged to be in the range of 250 to 1,000 MW_e for any larger commercial power plants; where the MHD would ideally contribute maybe one-fifth of net electrical output.

Conceptually this may be considered as a modified combined-cycle power plant (CCPP) comprising of the MHD generator in lieu of a gas turbine (Brayton cycle) combined with a super-critical Rankine bottoming cycle.

Brayton cycles have limitations determined by the turbine inlet temperature (TIT) that governs maximum efficiency. Despite advances with metallurgy, ceramic coatings and blade-cooling over the past 40 years, even the most aggressive turbine development programs do not envisage TIT above 3,200 °F (2,030 K).

For practical purposes we may assume a sink temperature (T_o) of 330 K and derive a Carnot efficiency of 84%. In reality the cycle efficiency (see footnote 3) will be around 64% suggesting that the available heat utilisation factor is roughly 0.76 (i.e. 0.64/0.84). If we include post-combustion CO_2 capture then cycle efficiency will be further reduced to around 56% and utilisation factor becomes 0.65.

By comparison the upper temperature in a combined MHD with Rankine cycle is governed by the plasma temperature which can be 3,600 K and is not constrained by turbine metallurgy. The Carnot efficiency is 91% and a significant 7%-point increase beyond what is conceivable for state-of-the-art conventional power generation[5].

Furthermore, as we also discuss in this Report there are additional reasons for reassessing the concept of zero-emission oxy-fuelled MHD power generation that should warrant further investigation beyond the scope of the present study.

[5] Invariably this assumes that the MHD generator has utilisation factor of 1.0 when extracting enthalpy and heat from the plasma working fluid.

1.1 THEORY OF OPERATION

A simplified MHD generator is shown in Fig. 3. A field of magnetic induction **B** is applied transverse to the motion of an electrically conducting gas flowing in an insulated duct with a velocity **u**. Charged particles moving with the gas will experience an induced electric field **u** × **B** which will tend to drive an electric current in the direction perpendicular to both **u** and **B**.

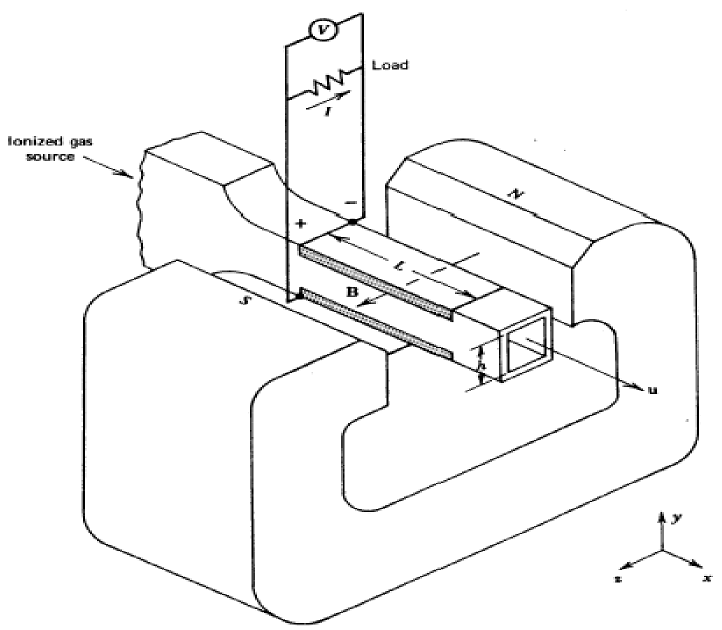

Fig. 3: A simplified Continuous electrode MHD generator.

The current is collected by a pair of electrodes on opposite sides of the duct in contact with the gas and connected externally through a load. Neglecting the Hall effect the magnitude of the current density for a weakly ionized gas is given by the generalized Ohm's law as;

$$\mathbf{J} = \sigma\,(\mathbf{E} + \mathbf{u} \times \mathbf{B}\,)$$

This is effectively the Lorentz equation that governs behaviour of charged particles under the influence of electric and magnetic fields. The conduction current density (force) **J** is given by the electric field **E**, resulting from the potential difference between the electrodes. While the particle of charge σ and velocity u by the combined electric and magnetic field **B**. For purpose of initial discussion we also assume that both **u** and σ are uniform.

In terms of the coordinate system shown in Fig. 3 we have that;

$$J_y = \sigma\,(E_y - u\,B\,)$$

At open circuit $J_y = 0$, so the open circuit electric field is $u\,B$.

For typical characteristic conditions one may assume u ~ 1,000 m/s and B ~ 2 T, the open circuit electric field is $u\,B \sim 2000$ V/m. At short circuit $E_y = 0$, and the short circuit current is; $J_y = -\,\sigma\,u\,B$.

For general load conditions, it is conventional to introduce the loading parameter;

$$K \equiv E_y\,/\,(u\,B\,)$$

where $0 \leq K \leq 1$, and write $J_y = -\,\sigma\,u\,B\,(1 - K)$. The negative sign indicates that the conventional current flows in the negative y-direction. Since the electrons flow in the opposite direction, the bottom electrode must serve as an electron emitter, or cathode, and the upper electrode is an anode.

The electrical power delivered to the load per unit volume is defined by;

$$P = -\mathbf{J} \bullet \mathbf{E}$$

For the generator shown in Fig. 3 we therefore have;

$$P = \sigma u^2 B^2 K (1 - K)$$

The power density has a maximum value $P_{\max} = \sigma u^2 B^2 / 4$ when $K = 0.5$

Furthermore, the rate at which directed energy is extracted from the gas by the electromagnetic field per unit volume is $\mathbf{u} \bullet (\mathbf{J} \times \mathbf{B})$ and we can define the electrical efficiency of a MHD generator as,

$$\eta_e = \mathbf{J} \bullet \mathbf{E} / \{\mathbf{u} \bullet (\mathbf{J} \times \mathbf{B})\}$$

The gas conductivity (σ) is proportional to the electron density and the electron mobility. Because high electron density also leads to increased recombination of free electrons with positive ions, this has a negative feedback upon conductivity and is undesirable. The aim of all MHD power generation is to achieve high electron mobility and the need for high electrical conductivity in the ionized gas is one of the key limiting factors in the energy conversion efficiency of an MHD generator.

2. HISTORICAL DEVELOPMENT OF MHD POWER GENERATION

Following Faraday's early work, MHD received little attention until B. Karlovitz, a Hungarian engineer proposed a gaseous MHD system and filed U.S. Patent No. 2,210,918, "Process for the Conversion of Energy" on August 13, 1940.

Working at the Westinghouse research laboratories he had, from 1938, conducted experiments on the products of combustion of natural gas as a working fluid using the annular Hall-type generator. By 1946 he had shown that, through seeding the working gas, small amounts of electric power could be extracted. The project however was abandoned, largely because of a lack of understanding of the conditions required to make the working gas an effective conductor (Karlovitz and Halasz, 1964).

In 1959 the American engineer Richard Rosa operated the first truly successful MHD generator producing about 10 kW of electric power. Further research by Rosa established the practicality of MHD for fossil-fuelled systems. And in 1963 the *AVCO Everett Aeronautical Research Laboratory*, under the direction of Arthur Kantrowitz, began a series of experiments culminating with a 35 MW MHD generator that used about 8 MW to power its magnet (Hals *et al.*, 1974).

For many years this remained the record power output. The assumption in the late 1960's that nuclear power would dominate commercial power generation and the failure to find applications for space missions led to a sharp curtailment of MHD research and funding.

However the energy crisis of 1973 revived the focus on more efficient coal-based systems for power generation in the United States as summarised by Pomeroy (1978) where MHD was presented as having a major impact in the United States by year 2000. A detailed historical and technical analysis of coal-fired MHD power generation was presented by Gruhl (1977) based on work sponsored by Exxon and the EPA.

In 1984, TRW, Inc. Redondo Beach, California installed the first stage of a 50 MW_t two-stage combustor at the *Component Development and Integration Facility (CDIF)* in Butte, Montana.

In September 1986 a fully integrated topping cycle was operated successfully for 8 hours continuous test and the power transmitted to the grid via an inverter supplied by *Electric Power Research Institute (EPRI)*.

2.1 DOE PROOF OF CONCEPT (POC) PROGRAM

In 1987 the Department of Energy started funding a Proof-of-Concept (POC) Program focussing on four key elements that were recognised as important for commercialisation of MHD power generation.

1. Develop technical and environment data for the integrated MHD topping cycle system through long duration (1,000 hours) testing at the 50 MW_t *Component Development and Integration Facility (CDIF)* in Butte, Montana.
2. Develop technical and environment data for the integrated MHD bottoming (steam) cycle system through long duration (4,000 hours) testing at the 28 MW_t *Coal-Fired Flow Facility (CFFF)* in Tullahoma, Tennessee.
3. Design, construct, and operate a seed-regeneration POC Facility (SRPF) capable of processing spent seed materials from the MHD bottoming cycle.
4. Prepare conceptual design for MHD-retrofit to an existing coal-fired plant.

In 1987 TRW Inc., was awarded the contract for overall management of the CDIF. While *Textron Defense Systems* (*TDS*, formerly *Avco Research Laboratory*) was in charge of development of the nozzle, channel, diffuser and the power conditioning equipment. And *Westinghouse Electric Corporation* supplied current consolidation equipment for the channel.

The topping cycle system was installed at CDIF in June 1992 and during the following 15-months over 600 hours of duration testing was accomplished while generated 1.5 MW_e as expected. However the data obtained was not considered sufficient to demonstrate the durability of the MHD generator and other critical components.

The integrated bottoming cycle program focused on the heat recovery and seed regenerative system. The *University of Tennessee Space Institute (UTSI)* was the main contractor and responsible for operating the CFFF on behalf of the DOE; with *Babcock and Wilcox Corporation* as consultants and supplemental material test data being provided by *Argonne National Laboratory*.

The CFFF had become operational already in 1982, long before the beginning of the POC Program, with efforts having focussed on assembly and testing the subsystem components such as radiant boiler, steam super-heater, and air pre-heater. Preliminary data on NO_X and SO_X control, interaction of seed with coal ash and slag products had also been undertaken so that by 1985 all major subsystems including a bag-house and electrostatic precipitator had been installed and tested.

The goal of the CFFF-POC Program was duration tests on two types of coal, Montana Rosebud, a low-sulphur western coal, and Illinois No.6, a high-sulphur eastern coal. The facility completed over 2,000 hours of testing Illinois No. 6 coal but only 1,400-hour of Montana coal because of a shortage of funds. According to Attig et al. [5], the technology of open-cycle, coal-fired MHD system demonstrated the ability to meet current contaminant emission limits and ever tighter pollution standards. The tests that were done provided extensive data on heat transfer characteristics of materials to be used in an MHD bottoming cycle facility and also provided useful data on the mechanisms for removing ash deposits and effective ways to control particulate emissions.

The seed regeneration system was awarded to TRW using their *Econoseed* process, which was based on the conversion of the recovered potassium sulphate seed to potassium formate by reaction with calcium formate.

TRW completed construction in 1991 and during the following year processed 17 tons spent seed collected by CFFF while testing Illinois No.6 high-sulphur coal. The TRW seed regeneration system performed adequately for a first-of-its-kind system, but the cost effectiveness was a major problem when considering commercial projects.

Studies also showed that retrofitting MHD to existing power plants was the most cost-effective path towards commercialization of the technology as this could make use of many existing equipment and systems including steam turbine, generator, parts of cooling system, cooling water system, waste-handling system and electrical transmission system and the site, etc.

The MHD retrofit conceptual design study was undertaken for two projects, neither of which were put into actual construction, however the studies provided valuable guidance in designing components for future scale-up to commercial size.

The first was based on *Montana Power Company Corette Plant* in Billings, Montana. This was redesigned by the *MHD Development Corporation*, Butte, Montana. The original Corette plant had a net electrical power output of 157 MW_e using Montana Rosebud coal. Plant Heat Rate was 11,010 Btu/kWh (equivalent to 31% efficiency). The MHD retrofit proposed using a 4.5 T magnet producing 98 MW_e with approximately 250 MW_t thermal input, suggesting a MHD cycle efficiency of around 38%.

The size of the proposed MHD generator represented a five-time scale up of the CDIF Test Facility and would be about half the size of an expected commercial MHD plant. The complete retrofit at Corette was budgeted to cost $329 million (in 1989) and would increase total plant capacity by 19%. The specific cost was $3,350 /kW, which was about twice the cost of a 100 MW_e commercial pulverised coal steam plant installed in 1995. While raising thermal efficiency by 10%-point. Labrie *et al.* have reported in detail on the design of this plant retrofit.

The second MHD retrofit was Gulf Power's Scholz plant located in Sneads, Florida which was designed by Westinghouse. The 50 MW_e Scholz Plant would produce net electricity of 60 MW_e after the retrofit according to Lance *et al*., [TBD]. The magnet size was here 6 T producing 25.3 MW_e based on 192 MW_t thermal input. Estimated incremental cost was $170 million.

The retrofit design parameters are shown in Table 1. The plant efficiency would increase from 28% to 31% while ensuring that the plant would meet all environmental requirements at that time.

A demonstration MHD project proposed by a consortium of private companies was not selected as one of five demonstration projects to be funded by the DOE in May 1993.

The POC Program was terminated in September 1993 with the DOE having spent $223 million in appropriated funds under the program.

Location	Sneads, Florida
Owner	Gulf Power Company
Coal	Illinois No.6
Coal Thermal Input In MW	192
Combustor Operating Pressure in bars	6.1
Oxygen Enrichment in mole %	40
Oxidant Preheat Temperature in ^{0}K	1061
Power Generation in MWe	74
MHD Generator in MWe	24
Turbine-Generator in MWe	50
Power Consumed in MWe	14
Retrofit Power Plant output in MWe	60
Existing System Power Output in MWe	49
Retrofit Plant Thermal Efficiency	31
Existing Plant Thermal Efficiency	28

Table 1: Scholz Plant MHD Retrofit.

While most of the test goals had been reached, the long-term high-temperature component reliability and durability required for commercial application remained unresolved.

2.2 INTERNATIONAL MHD TECHNOLOGY R&D

By far the largest MHD test facility in the world was operated at the High-Temperature Institute of the Russian Academy of Sciences in Moscow. The U-25 was based on natural gas and had a thermal input of 150 MW_t, while generating 25 MW_e net electrical output to the Moscow power grid for several years through into the 1990's.

Although research projects in the United States and former U.S.S.R received the most significant funding support, several other countries were also at the same time actively pursuing MHD technology development, most notably United Kingdom, Italy, Japan, China, India and Australia.

The Italian program began in 1989 with a budget of about $20 million and targeted three main development areas, i) MHD Modelling, ii) Superconducting magnets and iii) Retrofits to natural gas power plants. One was to be at the Enichem-Anic factory in Ravenna. The other was a 230 MW_t installation for a power station in Brindisi.

Since 1989 ENEA is carrying out a 5-year MHD R&D program in co-operation with Italian industries (organized in the Italian industrial MHD-forum, together with ENEL and ENI).

The principal objectives of the development program was:

1. Design and realization of a gas-fired demonstration plant as a retrofit of an existing gasfired 250 MWt power plant.

2. Design and realization of a conversion to coal of the retrofit plant.

3. R&D activities to support the design of these retrofits and to develop Italian capacities in the field of MHD power generation.

A start was made with the design and construction of a number of test facilities. One of these was to be a 20 MW_t topping cycle test facility at Brasimone, planned to come in operation in 1994. Initially this facility would be gas-fired. The magnet would be of the iron split-core type with magnetic field strength of 3 T. The emphasis was also on the development of generators with ceramic electrodes without neglecting the option of cold copper electrodes.

In China a further eleven-year program was approved in March 1994. This established centres of research at i) the Institute of Electrical Engineering in the Academy of Science, Beijing, concerned with MHD generator design, ii) the Shanghai Power Research Institute, concerned with overall system and superconducting magnet research, and iii) the Thermo-Energy Research Engineering Institute at the Nanjing's Southeast University, concerned with advanced cycle developments.

In Japan the MITI initiated in 1966 a government funded project in collaboration with industry (including MHI, Toshiba, Hitachi and Mitsubishi Electric) to develop Japanese MHD technologies.

Initially a 1 MW_e generator was achieved but overall the project was difficult when controlling the current passing through the gas solid phase, and it proved difficult to manage within the boundary layers.

The first major series of experiments was FUJI-1, a blow-down system powered from a shock tube at the Tokyo Institute of Technology. These experiments deployed a disc generator with a helium and argon carrier gas and potassium ionization seed. This extracted up to 30% of enthalpy, and achieved power densities near 100 MW/m^3.

By the late 1980’s it was becoming evident that open-cycle coal-fired MHD plants would need to be above 200 MW_e in size to be commercial. The Japanese focus moved to closed-cycle MHD because it would have higher efficiencies and be more suited to Japanese conditions.

In 1994, there were detailed plans for FUJI-2, a 5 MW_e continuous closed-cycle facility, powered by natural gas, to be built using the experience of FUJI-1. The basic MHD design was to be a system with inert gases using a disk generator. The aim was an enthalpy extraction of 30% and an MHD thermal efficiency of 60%. FUJI-2 was to be followed by a retrofit to a 300 MW_e natural gas plant.

Technology development is still on-going in Japan, but the emphasis appears to be on the research of MHD generator design and basic plasma theory.

In 1986, Professor Hugo K. Messerle at The University of Sydney researched coal-fired MHD power generation. This resulted in a 28 MW_e topping facility that was operated outside Sydney. He also wrote one of the most recent reference works, as part of a UNESCO education program. Hugo K. Messerle, *Magnetohydrodynamic Power Generation*, 1994, John Wiley, Chichester, Part of the UNESCO Energy Engineering Series.

Work on a tall-loop liquid metal MHD cycle has been concentrated in Israel, where test loops have been built to prove out the concept. These systems have the potential of 45% efficiency, but funding for further development is uncertain.

1. Tampere University, Tampere, Finland
2. ENEA, Casaccia, Italy
3. Ansaldo Ricerche, Genoa, Italy
4. British Coal, Coal Research Establishment, Stoke Orchard, UK
5. Mountain State Energy, Bozeman, USA
6. Montana Power Company, Bozeman, USA
7. Gilbert/Common Wealth Inc.
8. HMJ Corporation, Washington DC, USA
9. Department of Energy, Washington DC, USA
10. IEA - International Liason Group on MHD Power Generation
11. Pittsburgh Energy Technology Centre, Pittsburg, USA
12. AVCO Textron Everett Laboratories, Everett (Mass.), USA
13. J. Busek Company, Waban (Mass.), USA
14. University of Bologna, Italy
15. Westinghouse Advanced Energy Systems, Pittsburg, USA
16. N.V. KEMA, Arnhem, The Netherlands
17. Electricité de France
18. Unipede, Paris, France
19. Netherlands MHD Association, IJmuiden, The Netherlands
20. Technical University Eindhoven, Faculty of Electrical Engineering, The Netherlands

The above table shows list of active entities that were involved with MHD in the late 1980's.

In Russia the Pamir-3U pulsed MHD power system program was successfully completed in 1995. This was a self-contained portable power system that could be transported to various operational locations and did not require extensive support equipment. The objective was to design, fabricate, test, and deliver a 15-MW, MHD power system.

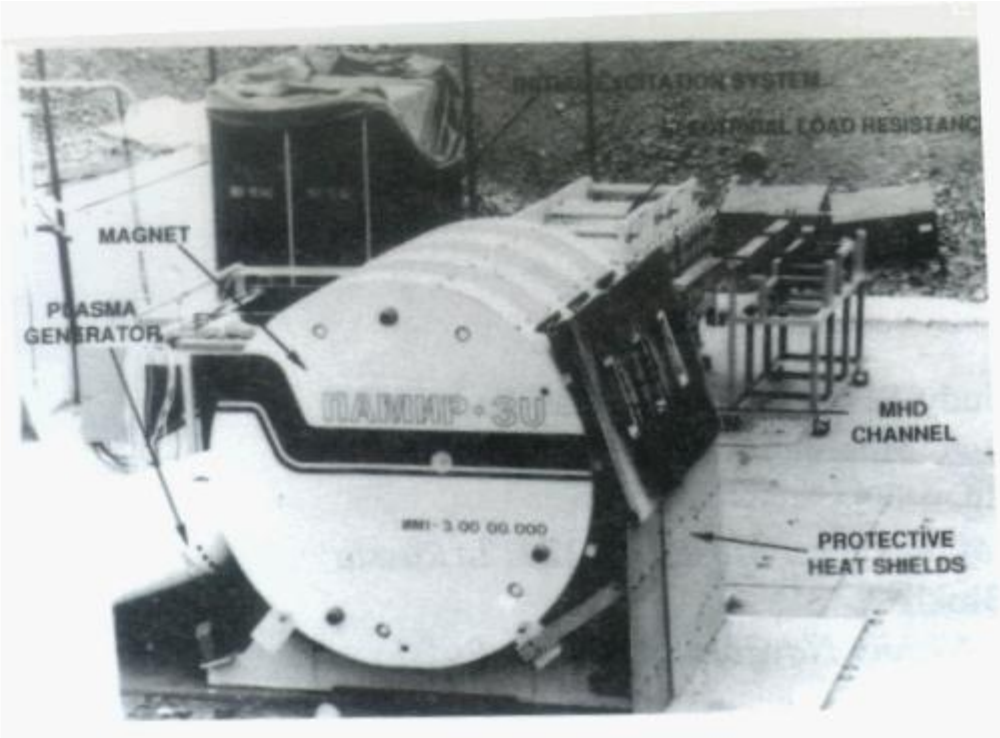

Fig. 4: The Pamir-3U Pulsed MHD Power System.

A preliminary acceptance test program, consisting of five power tests and several preliminary tests, was conducted during August 1994 at Geodesiya Research and Development Institute, Krasnoarmejsk, Russia. During this test program, net power levels as high as 15 MW were obtained. Operation of the system in various operating modes was demonstrated, and several tests were conducted where the resistance was varied during the hot-fire test run. The final Pamir-3U MHD power system acceptance test program was conducted at Aerojet Corporation, Sacramento, California, and consisted of eight hot fire tests.

Phillips Laboratory purchased the generator through a contract with Textron Defence Systems of Everett, Mass., and its subcontractor, the Institute of High Temperatures, under the Russian Academy of Sciences. The generator arrived in January at the Aerojet Propulsion Division's facilities near Sacramento, Calif. There it was prepared and tested by Russian scientists, engineers, and technicians.

This work was performed for the U.S. Air Force, Air Force Materiel Command, Phillips Laboratory, under Contract F29601-93-C-0033. The work was performed by the "IVTAN Association" of the Russian Academy of Sciences (Russia) and Textron Systems Corporation (USA). Major subcontractors that participated in this effort were the Nizhny Novgorod Machine Building Plant (Russia), the Federal Center of Dual Technologies "Soyuz" (Russia) and the Aerojet Corporation USA). Acknowledged individual participating in this work were Naufal L. Aitov, Vladimir I. Okunev, Victor A. Novikov, and Victor Yu. Rikman of the IVTAN Association of the Russian Academy of Sciences; Alexei V. Pisakin, Peter N. Egorushkin, and Boris G.Tkachenko of the Nizhny Novgorod Machine Building Plant; Reginald K. Kuzmin of the Federal Center of Dual Technologies "Soyuz"; and Alvin M. Olson, Roger E. Anderson, Mi-chael A. Fedun, and Garvin R. Hill of the Aerojet Corporation.

Since 1990 the Department of Pulsed MHD Power Systems is a part of the Institute for High Energy Densities of Associated Institute for High Temperatures of Russian Academy of Sciences.

For further information see http://www.ihed.ras.ru/mg/Pamir3U.htm

2.3 SUMMARY OF STATE-OF-THE-ART

As of 1994, the highest efficiency achieved by any MHD generator was 22% for a closed-cycle disc generator at the Tokyo Technical Institute. The peak enthalpy extraction was 30.2%. Open-cycle generators achieved a lower efficiency of 17%. This made single-cycle MHD for power generation unattractive since conventional Brayton and Rankine cycles were already targeting 40% at that time.

In June 1989 a conceptual design feasibility study for the DOE of a 1,000 MW_e Advanced Coal-Fired MHD /Steam Binary Power Plant showed that a large coal-fired MHD combined-cycle plant could attain a HHV efficiency approaching 60%. This was well in excess of other coal-fuelled technologies at that time. However the assumptions were evidently considered to be optimistic, and subsequent results from the POC Program, together with experience in other countries, showed that there remained commercial barriers to developing the MHD technology in competition with competing advanced power generation cycles.

Table 1. Thermal Efficiencies of Coal-Fired Electric Power Plants

Description	Thermal Efficiency, %
40-year old plant	30
Average of all coal-fired plants	35
Recently built plant	38
Very best, new plant	40-42
MHD-steam plant	55-60

Fig. 5: US-DOE estimate for comparative power plant efficiency as of 1989.

According to Kesseler and Hals (1992), the first generation commercial MHD plants would need to be sized between 250 to 500 MW_e power output and would be expected to attain efficiency of 40 to 42% by using oxygen-enriched air with moderate (1200 °F) pre-heat temperature for the oxidant. To achieve 55 to 60% efficiency there would need to be significant technology development regarding super-conducting magnets, materials and plasma fluid dynamics.

The recognised technical issues that remained for coal-fired MHD technology and that needed to be resolved were identified as being;

- High-temperature heat exchangers to pre-heat the combustion air to over 2,500 °F (1,370 °C).
- Cost-effective seed regeneration and recycling process.
- Durable (e.g. 8,000 hours) high-temperature electrodes for the MHD channel.
- Removal of at least 50 to 70% of the slag from the combustor in order to maintain stable power generation.
- Optimised size of plant and reduced capex with improved plant integration.

The zero emission oxygen fuelled MHD concept effectively addresses several of these issues and is discussed in the remainder of this Report.

3. THE CES COMBUSTOR TECHNOLOGY

Clean Energy Systems (CES) Inc., based in Sacramento, California has developed a stoichiometric combustor that enables combustion of gaseous fossil fuels together with oxygen at high pressure and temperature.

The Gas Generator (GG) shown in Fig. 6 has since 2004 been deployed for demonstration of oxyfuel combustion and zero emission power generation at the CES Kimberlina Power Plant, near Bakersfield, California.

Fig. 6: The 20 MW_t CES Gas Generator was installed at Kimberlina in December 2004.

The combustor design is based upon rocket technology developed within the aerospace industry during the 1960's and 70's. It was adapted for zero emission power generation by CES in the late-90's and since 2002 has been extensively demonstrated with a wide variety of fuels including NG, various low-btu syngas, MSAR (orimulsion) and glycerine.

It is also creating opportunities for transfer of existing gas and steam turbine technology into what has become known as oxy-turbines; these are scheduled for commercial deployment by 2011.

Thermodynamically such developments are important because it also permits process designers to think afresh, and potentially integrate the best features of the Brayton and Rankine cycles into what will become advanced oxy-cycles that are uniquely adapted for commercial CCS deployment. Primarily because they are 100% zero emission and, being closed-cycle, can fully utilise the higher heating value of fossil fuels. Both these attributes have a favourable impact on the techno-economics that helps counter the incremental penalty of oxygen production.

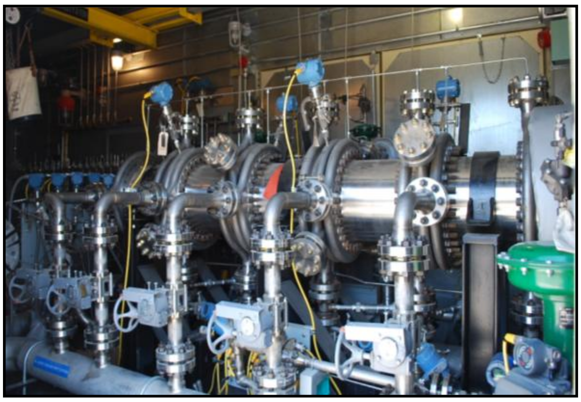

Fig. 7: The 170 MW_t CES Gas Generator is currently being deployed with a re-engineered J79 oxy-turbine expander to produce 40 MW of shaft power at the Kimberlina Power Plant.

Additionally, features of the CES combustor appear to also permit the inclusion of a MHD generator that could further improve overall cycle efficiency, while avoiding some of the issues that previously have prevented commercialisation of coal-fired MHD power generation based on the work done through into the mid-1990's.

3.1 ZERO EMISSION OXY-MHD POWER GENERATION

In Fig. 8 the CES Gas Generator is configured as a high-pressure and high temperature heat source with water-based recycle. The benefit of such a cycle is that combustion occurs without the presence of nitrogen, the working fluid is predominantly steam (with some CO_2), and thermal management is achieved with the recycle water that is readily condensed to recover pure CO_2.

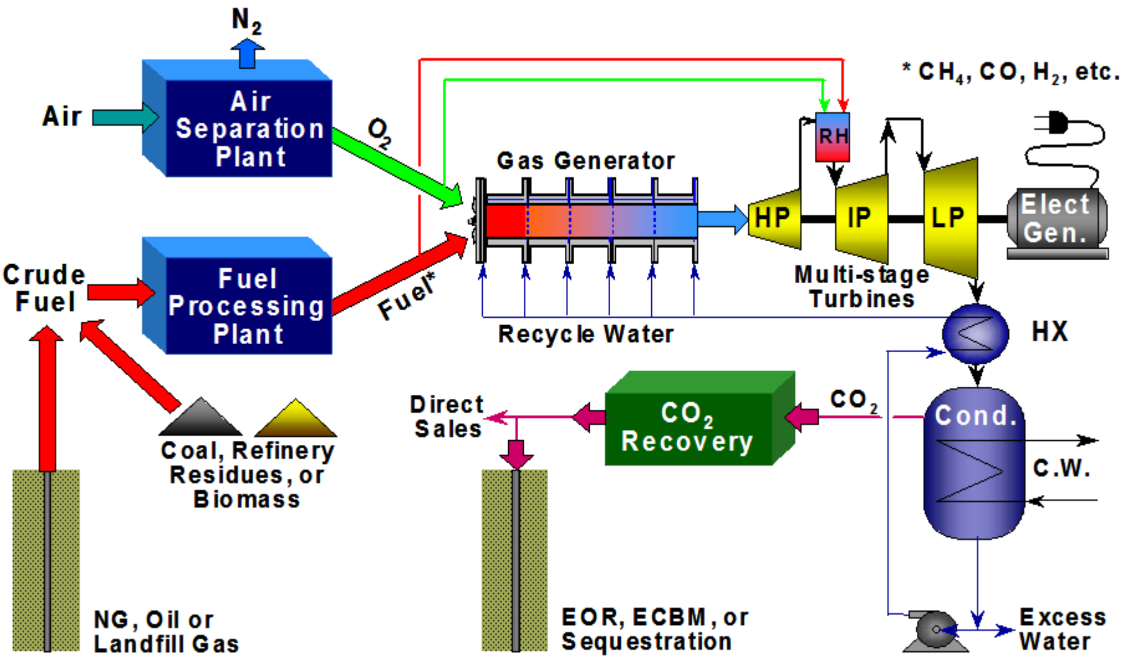

Fig. 8: Schematic of the CES Gas Generator as configured for Oxyfuel Power Generation.

One disadvantage is that the very-high temperature from stoichiometric combustion of fuel gas with oxygen is immediately quenched by injection of significant volumes of recycled water in the cool-down sections of the GG. This is necessary to pre-condition the working fluid for appropriate turbine inlet conditions. Some of the latent heat of vaporization is recovered in the condenser as latent heat of condensatio*n*—but at a much lower temperature, suggesting a significant loss in exergy (i.e. heat available for conversion to work).

To utilise these very-high temperatures Mikus (2009) has proposed integrating a MHD generator with the GG and thereby minimise the need for water quenching before the turbine inlet. Thermodynamically this implies elevating the combustion temperature to where plasma can be formed at around 6,000 °F and then cooling this by expanding through an MHD channel that would be integrated with the Gas Generator immediately after the Combustor section.

Cooling the working fluid using magneto hydrodynamics by extracting enthalpy should be more efficient than using water. Some of the issues and challenges of this are discussed in the following sub-sections.

3.2 THE COMBUSTOR DESIGN

The combustor section of the CES Gas Generator is shown in Fig. 9. It comprises of a complex injector manifold constructed using diffusion-bonded platelet technology. This precisely distributes and pre-mixes fuel, oxygen and water before injection into the combustor, where additional water quenches the combustion process to control VOC's and maintains the temperature below 3,000 °F.

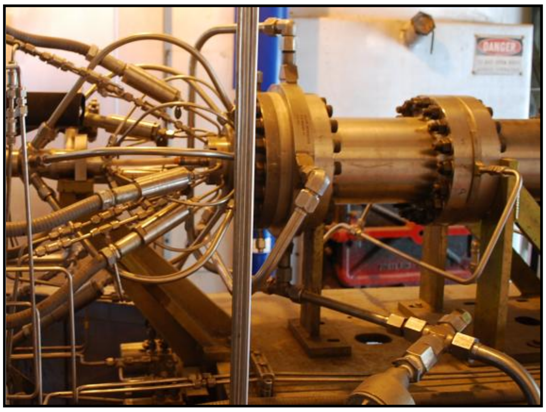

Fig. 9: The 20 MW$_t$ CES Combustor at Kimberlina shown with piping and 1st cooldown section.

Further, injection and mixing of atomised water in the cooldown sections (as sketched in Fig. 10) conditions the working fluid to be compatible with limitations governed by turbine inlet temperature (TIT). For first generation oxy-turbines this is below 1,650 °F but development work targets 3,200 °F when fully commercial.

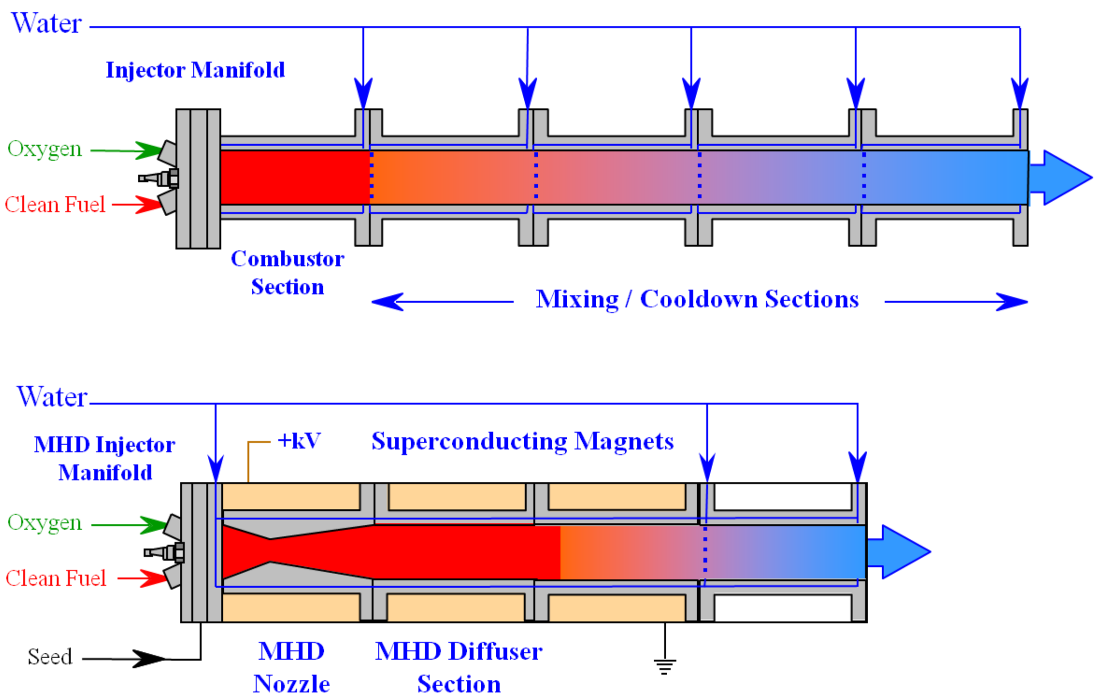

Fig. 10: Schematic of the CES Gas Generator (top) with combustor and water cooldown sections. A simplified schematic of modifications necessary for a CES-MHD Generator is shown bottom.

In the lower image the need for cooldown sections is reduced through integration and use of MHD Nozzle and Generator, with water injection only needed to complete conditioning of the working fluid before turbine expansion.

The power output of the MHD generators for every cubic metre of conductor depends directly on plasma conductivity (σ), the square of the velocity at which the plasma moves (u^2), and the square of the magnetic field through which it is passing (B^2). For satisfactory operations the electrical conductivity of the plasma must be adequate and to achieve good performance one must have reasonable physical dimensions and temperatures above 3,000 °F.

The combustor would most probably operate in the temperature range approaching 6000 °F and at a pressure approaching 100 bar in order to generate a uniform high-temperature plasma with electrical conductivity around 10 Siemens per meter. Furthermore, the combustor would also have to withstand a voltage of up to 50 kV below ground potential.

One feature of Oxy-MHD that may need to be taken into account is that the CO_2 is known to undergo substantial thermal decomposition to CO and O_2 at typical MHD temperatures. In one study, see British Coal Corporation, UK (Sens, 1992) the combustor exit conditions resulted in 18.5% of the CO_2 decomposing. However because the proposed CES-MHD generator will be operating at a much higher pressure, such dissociation may not necessarily be as extreme.

Furthermore, nearly all the energy that is not converted to electricity in the MHD generator will be available as heat for the oxy-Rankine cycle.

3.3 THE MHD CHANNEL AND DIFFUSER

The overriding challenge for any MHD generator design is determined by the extreme physical conditions it is subjected to during operation. The inner walls are exposed to high temperature, high pressure working fluid gas with a high concentration of potassium vapour from the seed material.

Electrodes either side of the channel as shown in Fig. 11 extract the electricity. These must be both conductive and heat-resistant at high temperatures.

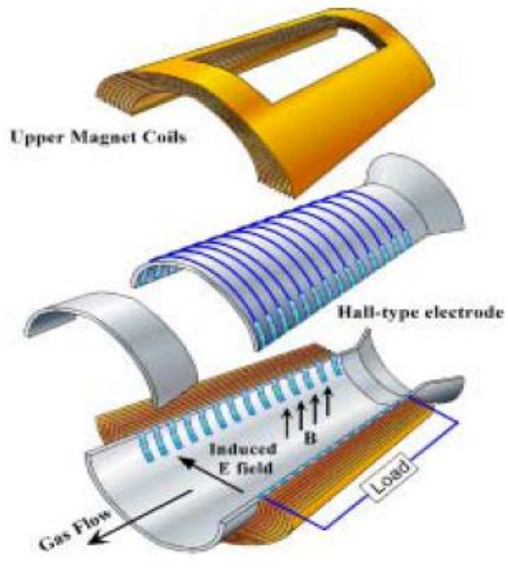

Fig. 11: Sketch of a Annular Hall-type MHD generator similar to that envisaged for integration with the CES Combustor.

The electrode walls have to carry a relatively high electric current density, and at the same time they must have good electric insulating properties in the axial direction. All walls are exposed to high heat fluxes. Therefore, the combination of high temperature, chemical attack and electric field poses a significant operational challenge with respect to materials. The development of electrode walls with a long service life and providing for high generator efficiency is one of the fundamental outstanding challenges in the design of a MHD channel. Because of the high temperatures, it has been proposed that the non-conducting walls of the channel would need to be constructed from an exceedingly heat-resistant substance, such as yttrium oxide or zirconium dioxide, in order to retard oxidation.

The plasma gas is expanded in the channel to overcome the deceleration from interaction with the magnetic field. The energy extraction causes temperature to drop and ideally the diffuser should be profiled to maintain a constant Mach Number until the temperature becomes too low to have any useful electric conductivity. Typically this might be in the range of 3,500 °F from which point the gas will be cooled with water to accommodate oxy-turbine inlet conditions.

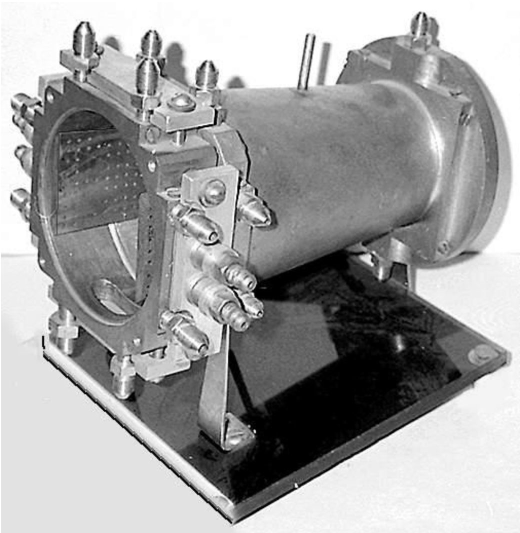

Fig. 12: Experimental Argon gas linear MHD Channel at the Department of Pulsed MHD Power Systems & Geophysics, Moscow State Aviation University.

Another important physical factors influencing the current transfer efficiency and potentially enhancing instability, is the magnetic field strength and turbulence that occurs within the "sheath" (boundary layer) of the diffuser section.

A complicating feature of a plasma MHD generator is the occurrence of a pronounced Hall effect, which results from the behaviour of electrons in the presence of both magnetic and electric fields. Electrons are accelerated in the direction of an electric field but follow a circular path around a magnetic field line (cyclotron behaviour). When these two actions are combined and the collision processes taken into account, the effect is for the electric current to flow at an angle with respect to the electric field, producing an additional field along the axis of the MHD duct. This field causes an axial current (Hall current) to flow if the electrodes are continuous. This in turn requires that either the electrode walls be constructed to support the Hall field or that the Hall field itself be used as the output to drive current through the electric circuit external to the MHD system, as shown in Fig. 11.

3.4 THE MAGNETIC FIELD

Internally-cooled cabled superconducting (ICCS) magnets are proposed for large MHD generators in order to reduce parasitic losses: once charged, these consume very little power, and can develop intense magnetic fields of 6 T and higher. The only parasitic load for these magnets is to maintain cryogenic refrigeration, and to make up the small losses for the non-supercritical connections.

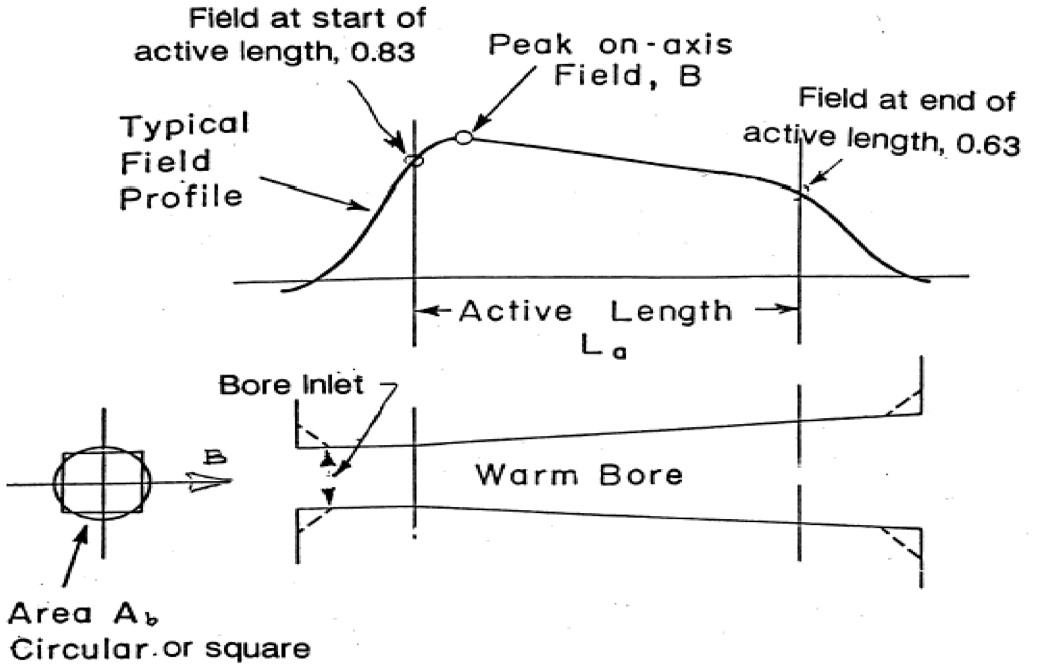

Fig. 13: Definition of magnet strength profile, length and effective volume for parameter scaling.

Characteristic volume (V) for magnets is given by the cross-sectional area (A_b) multiplied by the active length (L_a) as defined in Fig. 13 . Furthermore, a useful magnet size-parameter for initial scaling purposes is provided by VB^2 (in units of m^3T^2) where B is the peak “on-axis” field strength.

Energy extraction for large-scale MHD generators has to date has been proposed to occur over typical lengths of between 15 to 30 feet; reducing length, while increasing magnetic field intensity and plasma conductivity should be one approach to reduce specific capital investment cost by making the magnets more powerful and compact.

There were several cost analysis’s conducted for magnets between 1976 thru to 1984 as part of the MHD Magnet Technology Development Program funded by DOE. Although results varied considerably, a detailed consolidation of these was conducted by the Massachusetts Institute of Technology that included estimates for cost-escalation (MIT, 1988). For example, one result indicated that a 4.5 T magnet capable of 35 MW_e output would cost around 1,500 $/kW based on 1984 costs. Today, this provides only an order of magnitude perspective for comparative component costing. However, the methodologies for cost-breakdown that were developed at MIT remain valid once updated cost data becomes available.

3.5 PARTICLE SEEDING AND REGENERATION

Seeding is the principal source of electrons (and ions) that renders the gas conducting and thereby enables the direct conversion of electricity to occur. Typically around 1% by mass is injected into the working gas of the MHD system. The alkaline-earth and alkali metals are the most suited because of their low ionization energies. However, the readily available elements, calcium (590 kJ/mol), magnesium (738 kJ/mol) and sodium (496 kJ/mol), have considerably higher ionization energy than does potassium (419 kJ/mol). Alternatively, rubidium (403 kJ/mol) or caesium (376 kJ/mol) could further improve efficiency but these elements are scarcer and therefore more expensive.

Studies have shown that potassium carbonate (K_2CO_3) and potassium formate (KCOOH) yielded higher plasma conductivity (5 to 6 mho/m) compared with potassium sulphate (K_2SO_4). Factors affecting the conductivity of plasma were extensively investigated by Wissel (199x).

TRW, Inc.'s completed detailed design and construction in 1991 of their *Econoseed* process, which was based on the conversion of recovered potassium sulphate seed to potassium formate by reaction with calcium formate. This was tested as part of the POC Program during 1991 and 1992. According to U.S. General Accounting Office (1993) report to the sub-committee on energy, the TRW seed regeneration system performed adequately for a first-of-its-kind system, but cost-effectiveness was identified as a challenge for any commercial project.

The cost of seed-regeneration and reprocessing was also estimated by Sens (1992) on behalf of the European Commission to be 20% of the costs of the fuel, as based on 1990 prices.

3.6 THE CURRENT INVERTER

Usually, a large MHD channel will include hundreds of pair of electrodes. Each pair of electrodes has two terminal and different potential voltage output. The power conditioning system collects and consolidates (i.e. bring to one common potential) the direct currents from all terminal pairs of electrodes and transmits them to the main load inverter. The output of the inverter must be stable under the condition of fluctuation of MHD generator and change of grid load.

The inverter system, with some extensions, may also be used to control the load carried by every individual electrode. In this way the inverter system becomes a complete power control system that serves two functions: control of the power quality delivered to the grid, and at the same time controlling the power production of each, or groups of, electrodes.

3.7 CONCEPTUAL DESIGN OF OXY-MHD FOR CO2-EOR

The schematic in Fig. 14 presents a conceptual design of main components that need to be in place for a 500 MW Oxy-MHD power generation. We also assume that the CO_2 captured will deployed for enhanced oil recovery (EOR). Typically one envisages that about one-fifth of total power generation can be provided with a 100 MW_e MHD generator, while the bottoming cycle contributes 400 MW_e.

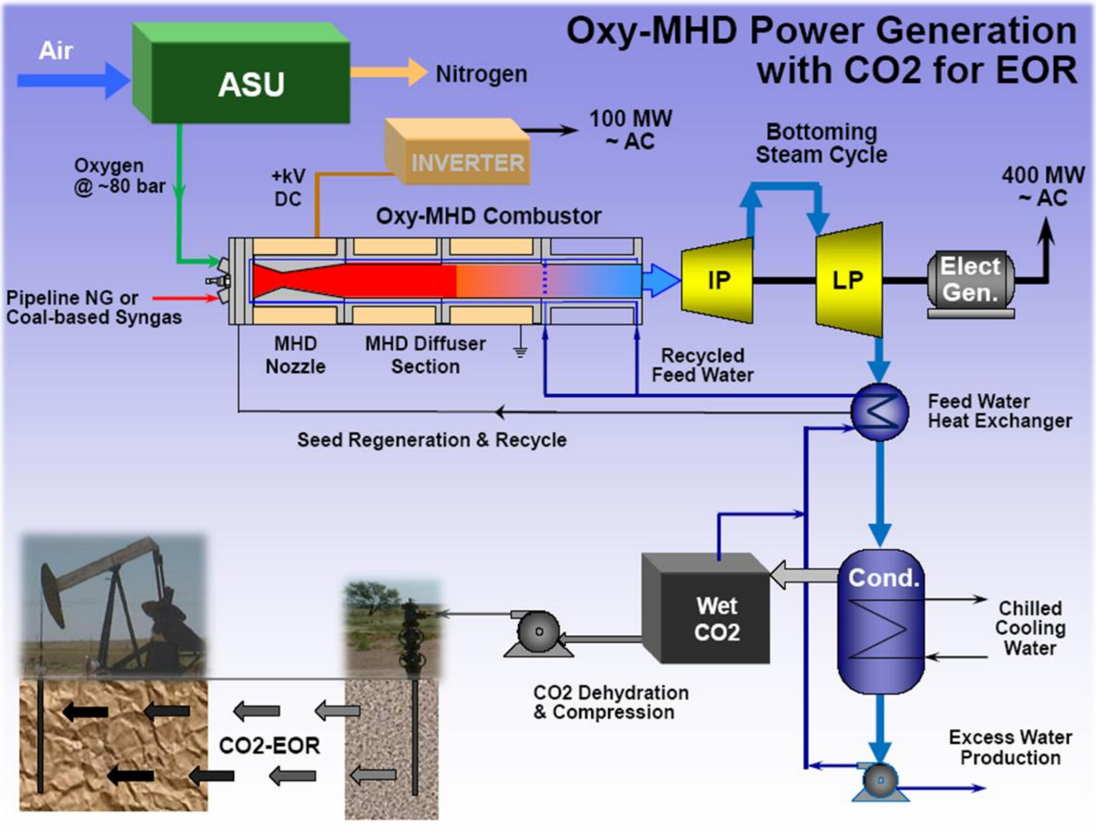

Fig. 14: Conceptual Design of Oxy-MHD Power Plant when deployed for EOR.

Preliminary economics for this concept is presented in the final section assuming a back-to-back comparison with NGCC power generation. However an additional attribute of the CES Gas Generator is that it is also capable of using low-btu fuel gas with higher CO_2 content than conventional gas turbines. When deployed for EOR, this can significantly increase potential revenue from the sale of CO_2.

• Fuel cost	$6 /MMBtu
• Discount Rate	10%
• Project Finance	100% Equity
• Project Life	25 yrs
• Construction Time	30 months
• CO2 emission cost	$20 /tonne
• CO2 sale for EOR	$20 /tonne
• CO2 EOR credit	$10 /tonne

* Commercially mature technology – assumes comparable $$ billion investment is made in R&D during period 2010 – 20 for each technology.

Some of the basic assumptions used in the economic analysis are summarised in the adjacent Table.

3.8 PRELIMINARY ECONOMIC ASSESSMENT

Economic analyses for coal-fired MHD power plants were extensively conducted during the 1980's. These were based on either retrofit to existing plants or feasibility studies for large-scale commercial units based on extrapolated cost-estimates.

An example from MIT (1988) report for a new-build coal-fired MHD power plant showed a total investment cost of $975 million (equivalent to $1,950 per installed kW). The breakdown of costs for the MHD part of the cycle is reproduced in Table 2 and was estimated to cost $625 million.

	Estimated cost[a]	Percent of total
	k-dollars	percent
Combustion Equipment	39,600	6.3
MHD Generator	14,000	2.2
Magnet system	140,000	22.4
Inverters	102,600	16.4
Preheater system	222,900	35.7
Seed system	43,700	7.0
Other	62,300	10.0
	625,100	100.0

Table 2: Cost-estimate for the MHD topping cycle of a 500 MW_e coal-fired power plant. Total plant capital investment cost was $975 million including the bottoming cycle (based on 1984-dollars).

We emphasise that there is limited scope to extrapolate past cost-estimate data to the currently proposed Oxy-MHD power plant concept. One fundamental reason for this is that there will have been relevant technology development that has occurred in the interim period, while conceptually the CES Gas Generator enables a simpler overall process design where air pre-heating and combustor equipment is either redundant or already available.

A simplified economic analysis has been conducted for back-to-back comparison of a 500 MW_e Oxy-MHD process cycle compared with a same-size state-of-the-art NG combined-cycle (NGCC) power plant having commercial post-combustion CO_2 capture plant. (For CCS the resultant cost of electricity given post-combustion or pre-combustion IGCC decarbonisation is of similar magnitude.)

Our assumptions are that the base case NGCC has specific cost $1,050 /kW and has reached an efficiency of 64% assuming certain additional advances on gas turbine technology that would enable a further increase of 200 °C firing temperature. We adopt standard economic parameters of 10% discount rate, all equity finance, 92% availability and annual operating expenses equal to 5% of the capital investment. For comparison purposes fuel cost is fixed at $6 /MMBtu, CO2-credit cost is $25 /tonne, while a market exists for enhanced oil recovery (EOR) where oil field operators are willing to pay $20 /tCO2 (equivalent to about $1.00 per Mcf) and the project is eligible for the additional $10 /tonne credit that was allocated in the U.S. in 2009 to promote use of anthropogenic CO2 for EOR.

The Base Case plant cost without CO2 capture is $525 million and at 64% LHV efficiency this result in electricity at $57 /MWh where $35 /MWh is fuel cost and $22 /MWh is capacity charge.

The post-combustion CO_2 capture plant is estimated to add an incremental 40% on plant capital investment cost raising this to $735 million while reducing efficiency 8%-point in order to achieve 85% capture of CO_2 that is sold for EOR at $30 /tonne, while having to cover remaining 15% with purchase of credits at $20 /tonne to offset emissions. The resultant cost of electricity is $65 /MWh representing a modest $7 /MWh increment. This is primarily accomplished due to the significant revenue stream from the sale for EOR[6]. It also represents an estimate that assumes significant economies due to commercialisation of the technology in the 2015-20 timeline.

The assumptions for the oxyfuel cycle are comparable and based on the fact that CES have a well defined roadmap for commercialisation of the existing Gas Generator. This involves demonstration and commercial deployment using available turbine technology while also creating the pre-requisite incentives for development of next-generation more advanced turbines, as is indicated by the red line in Fig. 15. The technology for these oxy-turbines has been proposed by the DOE turbine development program and is based on similar metallurgical and temperature requirements as those targeted for conventional advanced turbines.

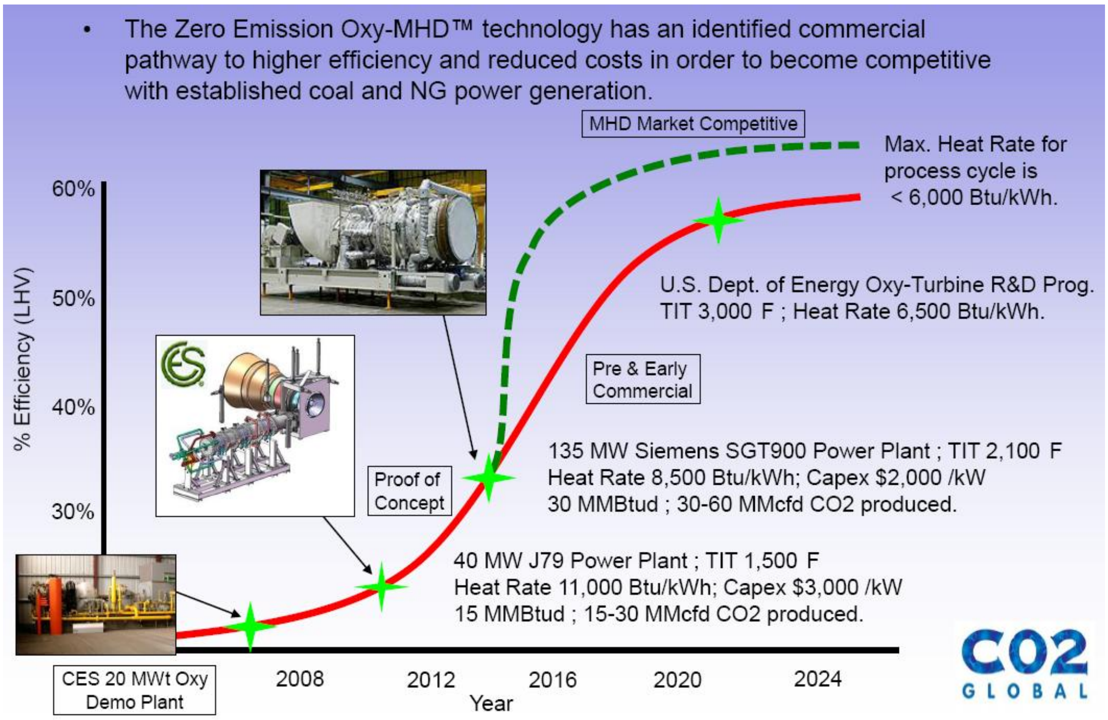

Fig. 15: Development Roadmap forCommercial Deployment of the CES and MHD Technologies. Cost-estimates are based on 2005-dollars and are presented for comparative purposes only.

[6] Without the revenue of $30 /t$CO_2$ for EOR the incremental cost of electricity would be $17 /MWh.

The dashed line shows how integration of Oxy-MHD may complement and further enhance the overall viability of this technology development pathway. Effectively the MHD topping cycle and the oxy-Rankine cycle are thermodynamically integrated and complement each other to the extent that enthalpy extraction in the MHD generator will impact heat available for conversion to work in the oxy-turbine expander. However work extraction from the plasma drive-gas in the MHD generator will thermodynamically be more efficient than from the steam and CO_2 drive-gas in the turbine expander.

Our assumption for the Base Case CES cycle is that specific-costs for rotating machinery and balance of plant will be similar to a conventional NGCC power plant at $1,050 /kW. While ASU and compression represent an increment of $450 /kW and the MHD topping cycle represents an additional $3,500 /kW deployed.

For a 500 MW_e Oxy-MHD Power Plant we assume 100 MW_e MHD generator and obtain total capital investment cost of $950 million. We assume that the topping cycle will improve plant performance by a factor of 1.15 resulting in an LHV efficiency of 69%.

Under comparable conditions as for the NGCC Power Plant we obtain a resultant cost of electricity equivalent to $55 /MWh. This represents $29 per tonne reduction in CO2-Avoidance cost compared with the post-combustion capture from the NGCC Power Plant.

We emphasise that the above analysis is based upon very superficial and preliminary assumptions. However it does indicate how the MHD route could be a game-changing contribution for CCS as technologies start evolving through to commercial deployment in the 2020 and beyond timeline.

Comparison of Results:

• NGCC - 500 MW @ 64%	$525MM	$1,050 /kW
– Cost of Electricity	$57 /MWh	Credit @ $20 /t
• NGCC + CCS - 500 MW @ 56%	$735MM	$1,470 /kW
– Cost of Electricity	$65 /MWh	
– CO2-Avoidance Cost	$22 /tonne	85% capture
• Advanced Oxy - 500 MW @ 60%	$750MM	$1,500 /kW
– Cost of Electricity	$69 /MWh	
– CO2-Avoidance Cost	$33 /tonne	100% capture
• Oxy-MHD – 400 + 100 MW @ 69%	$950MM	$1,900 /kW
– Cost of Electricity	$55 /MWh	
– CO2-Avoidance Cost	- $7 /tonne	100% capture

The main conclusion so far is that the economics for integrating MHD with the CES oxy-combustion tech-nology should warrant further, and more detailed, evaluation.

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