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COMPARISON OF LIME AND IRON OXIDE FOR HIGH TEMPERATURE SULFUR REMOVAL

Department of Civil and Mineral Engineering

Institute of Technology

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submitted
to

United States Department of Energy
Pittsburgh Energy Technology Center

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COMPARISON OF LIME AND IRON OXIDE FOR HIGH TEMPERATURE SULFUR REMOVAL

CONTENTS

ABSTRACT[1]

Slagging combustors with injected lime or limestone are being considered as replacements for conventional coal burners. They have advantages in that they can be staged to reduce NO_x and SO_x emissions. Lime and limestone are the currently preferred sorbent materials but iron oxide, as an alternative to lime or limestone may be effective not only as a desulfurizing agent, but, under the right conditions of oxygen potential, it can act as a flux to produce a glassy slag. This glassy slag should be dense and environmentally inert.

This project aimed to compare the sorption characteristic of lime and iron based sorbents in a novel double vortex combustor. The first phase of the project was the design installation and commissioning of the combustor test rig following which sorbent test work could be carried out.

Due to a variety of unknown factors in the combustor design/performance characteristics, it was not possible to complete all aspects of the sorbent test work as originally planned.

A considerable amount of experience has been gained in the operation of the combustor and in understanding the importance of key design factors. It was found that a narrow conical design for the combustor body gave significant improvement in combustion performance and in solids entrainment compared to a cylindrical form.

Tests with a glass combustor were used extensively to obtain visual insights into flame flow patterns, structural stability and general operating characteristics. The double vortex system prevents flame contact with the wall and permitted safe operation up to 1.6m Btu/hr in the glass walled combustors.

Several tests with entrainment of taconite concentrate into a double vortex flame were accomplished but only one test was carried out in a flame containing sulfur. Due to time pressure and termination of the project no material balance was possible on the final sulfur run. Visual examination of the solids product did however, indicate that surface modification of the taconite particles had occurred and that an Fe-O-S phase had formed.

The project has stimulated the interest of the local power utilities and it is planned to move the system to a local power plant for continuing test work.

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[1] Key words underlined

INTRODUCTION

Prior to the 1973 energy crisis the major portion of combustion research was directed toward high performance systems such as jet engines, turbines or internal combustion engines and relatively little attention was paid to industrial coal burning systems. In more recent times with ever increasing economic competition motivating the use of lower grade fuels and increased environmental awareness demanding increased pollution abatement there has been a renewal of interest in coal combustion technology.

Sulfur emissions from coal burning power plants are of particular concern. However, more progress has been made in flue gas desulfurization and raw coal cleaning than in sulfur removal during combustion. This latter area has the potential to permit the use of low cost high sulfur coals for which current environmental control technologies are prohibitively costly.

Aims for new combustion technology addressing these issues include:

- high specific heat conversion rates without increase in blower horsepower.
- Good mixing characteristics under both oxidizing and reducing conditions,
- Removal of slag and ash in the combustor without adversely influencing combustion efficiency.
- Capabilities of removing sulfur during combustion through suitable additives.

These objective can be sought in a variety of ways and most current research and development projects in coal combustion are based on one or more of three basic principles namely cyclonic flow, jet mixing and acoustical resonance.

Cyclonic flow is the most widely adapted approach and a strong swirling motion is used to facilitate particle disengagement by centrifugal force. Several systems use jet mixing alone or in combination with swirling flow and seek the high degree of mixing and improved combustion kinetics achieved with interacting high velocity jets. Acoustical resonance in combustion systems has been known for some time but has only recently achieved increasing attention as a potentially attractive technology to reduce both chemical and particulate emissions. There is a general lack of theoretical knowledge in these areas and most recent research has taken an empirical approach.

In the area of desulfurization the currently preferred sulfur absorbent is lime in one form or another. By direct injection of lime into the flame, under oxidizing conditions, sulfur is captured as a solid calcium compound. A recent economic analysis of sulfur sorbents is given in Table 1 and indicates that iron oxide could potentially be more cost effective than the traditional lime approach.

Table 1. Cost Comparison of Sulfur Removal by Different Reagents.

Basis: Coal Containing 3% by Weight Sulfur

Reagent	Reagent:Coal Mass Ratio	%S Removal	Unit Cost $/ton	Cost for cited % S Removal $/ton coal	Cost for 50% S Removal $/ton coal	Ref
Limestone	0.188	45	$18	$3.38	$3.80	1
Lime	0.111	62	45	5.00	4.00	1
Promoted Lime	0.083	65	50	4.16	3.20	1
Portland Cement	0.167	95	70	11.69	6.20	2
Magnetite	0.10	89	30	3.00	1.70	3

Interests in combustion technology at the Mineral Resources Research Center, University of Minnesota have evolved from a long history of iron ore research including research in the area of coal based reduction technology. For optimal use of U.S. resources an iron smelting system is required that can use fine domestic iron ore concentrates and lower grade coals than those currently required for metallurgical coke production. One approach to this problem is via flash smelting in which the fine concentrates are processed in suspension in a gas phase of appropriate chemistry produced by the partial combustion of coal.

Reactors designed to achieve these objectives have many points in common with slagging combustors and slagging combustion technology has been reviewed with respect to its applicability in the taconite plants on the Mesabi Range in Northeastern Minnesota.[4] The motivation for this study was related to the fuel cost savings that would be achieved if either Western coals (low ash fusion point) or high sulfur petroleum coke could be substituted for current fossil fuels. The study therefore sought systems that could achieve both desulfurization and slag rejection. In parallel with this paper study, practical work has been carried out relating to novel methods for suspending particles in a closed fluid dynamic field and a University patent has been filed covering the concept of "dynamic containment"[5] using superposition of two vortex flows.

The University also has a cooperative agreement with the AMAX company relating to the use of iron oxide as a sulfur absorbent in coal combustion as covered by an AMAX patent[6].

Slagging desulfurization using the "dynamic containment" principle and iron oxide as the sulfur absorbent is an advanced concept in coal conversion science and technology that requires extensive research to identify its full potential and underlying principles. Much of this work is expected to be generic with respect to slagging desulfurization.

The objectives of this project were to establish an operating double vortex combustion system capable of carrying out controlled desulfurization testwork and to use the system to compare the sorption characteristics of lime, limestone and iron oxide.

BACKGROUND CONCEPTS

Slagging Combustion

Current developments in high performance coal combustion aim to:

* increase the fuel residence time
* improve the separation of solid particles (slag or ash) from the flame, and
* reduce the production of NO_x and SO_2.

Gupta[7] discussed extensively various types of cyclone burners and their special characteristics. He distinguishes four basic types differing mainly in geometrical aspects of the combustor tube and the air and fuel-air inlets. In principle however all cyclone burners have the following points in common. A strong swirling flow is established through tangential and/or axial injection of air and fuel-air mixtures. In the case of tangential injection the vorticity is determined by inlet velocities and wall curvature. In the case of axial injection, vorticity is developed through vane geometries and flow velocities. Strong centrifugal forces are exerted on fuel and slag or ash particles which tend to be thrown to the combustor wall. Due to high combustion temperatures these walls are often coated with slag in which the particles will be deposited.

The gas velocity distribution of cyclone combustors can vary with the design as well as operating conditions. However in most cases, several distinct annular zones are distinguishable. These adjacent zones exhibit opposite mean flow directions and are interconnected by turbulent zones. Increases in the degree of turbulence, the extent of the recirculation zones and the frequency and amplitudes of any oscillatory motion in the vortex core increase combustion efficiencies, burnout rates and combustion intensities. However these factors can adversely influence separation efficiencies.

Combustor Designs

Some examples of combustors belonging in this class are the B & W cyclone combustor, Figure 1, Alcoa two-stage combustor, Figure 2, ANL two-stage slagging coal combustor, Figure 3, Westinghouse two-stage combustor, Figure 4, Coal Tech cyclone combustor, Figure 5, and the TRW combustor shown in Figure 6. The underlying concept common to all these designs, as outlined above, becomes apparent on examining the particle trajectories in each burner.

It was shown[8] that at increased gas velocities secondary circulation patterns appear which increase mixing and flame stabilization through recirculation of hot combustion products. These secondary circulation patterns however tend to work against the slag/ash removal capabilities of the combustor and therefore its usefulness can be greatly reduced in controlling the fly ash and its potential for reducing the sulfur content in the combustion product. Not much information is available on the relationship between secondary flow patterns and particle emissions in combustors. However since the combustor design is based on the same principles that apply to cyclone separators the information obtained from

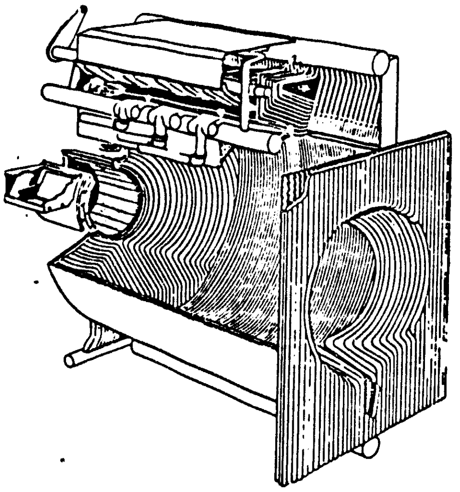


Figure 1.
B & W cyclone combustor

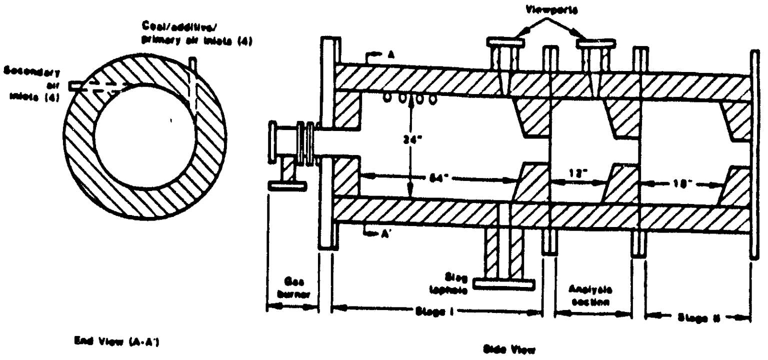


Figure 2.
Alcoa two-stage combustor

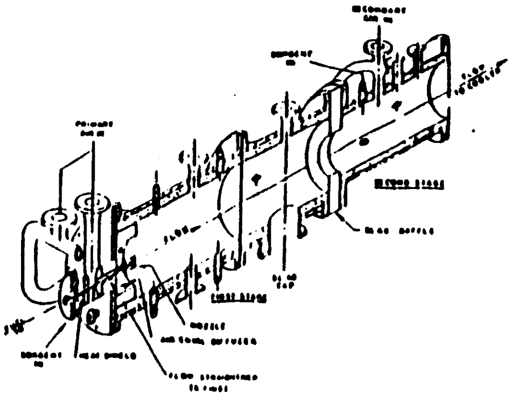


Figure 3.
ANL two-stage slagging coal combustor

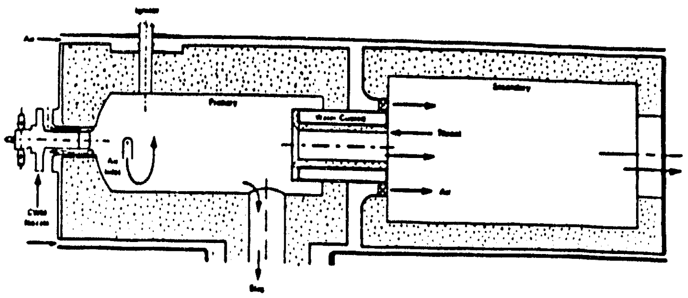


Figure 4.
Westinghouse two-stage combustor

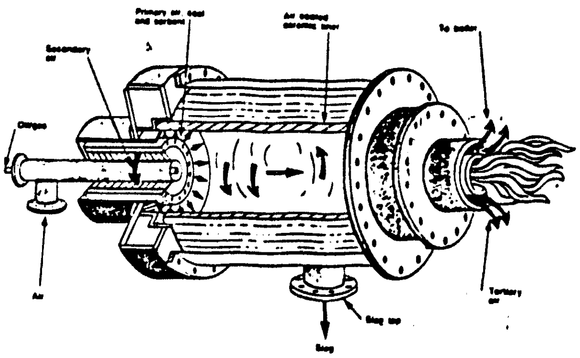


Figure 5.
Coal Tech cyclone combustor

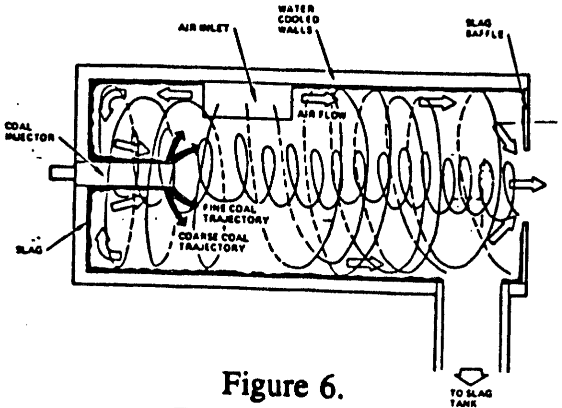


Figure 6.
TRW combustor

cyclones[9,10,11] can be used to gain insight into this phenomenon.

By multi-staging the combustor, which is easily achieved, the combustion process can be divided into two or more stages, a first stage with slightly reducing atmosphere and a second one operating under oxidizing conditions. In this way NO_x and SO_2 production can be greatly reduced. Also, the two-stage systems generally provide better ash/slag removal than a single stage.

The EERC combustor Figure 7 is a deviation from the standard cyclone burner and comprises a cyclonic burner of very large diameter to length ratio attached to a relatively short, conical slag disengagement section similar to a classical cyclone. The advantages of this approach seem to be the absence of secondary recirculation flows and very high swirl numbers. Both contribute to high specific heat release and good slag/ash removal properties. The Avco burner (Figure 8) uses jet interaction as well as wall impingement for its high combustion rate and ash removal properties. Two separate ring vortices are set up through wall interaction which should aid wall scrubbing and recirculation in the first stage of the burner and slag/ash separation in the second stage.

The Solar Turbines combustor (Figure 9) also relies on jet interaction and impact separation. It is different from the Avco burner mainly in chamber geometry and ash removal mechanism.

Although there has been a great deal of research effort and funding invested in the design, development and testing of these slagging combustors there has been little commercial application and it would appear that an optimal solution combining low cost, simplicity and high performance efficiency has not yet been achieved.

It should also be noted that the first stage of a two-stage slagging combustor operated

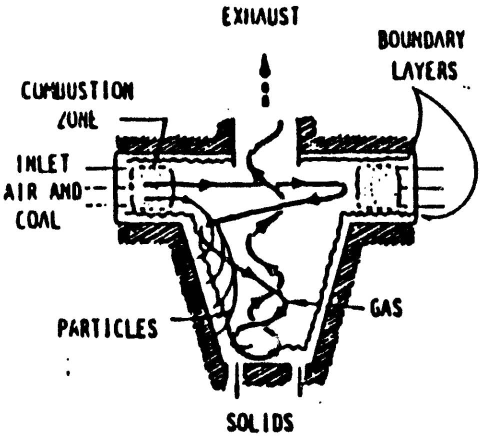


Figure 7.
EERC combustor

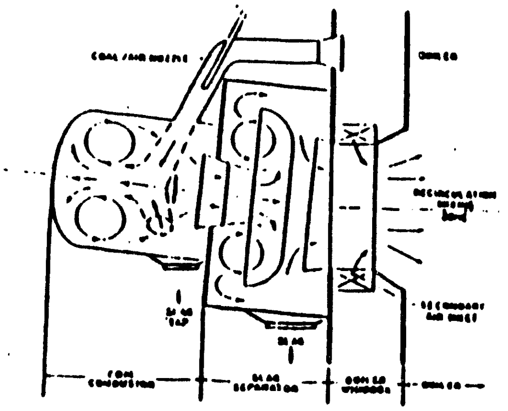


Figure 8.
Avco combustor

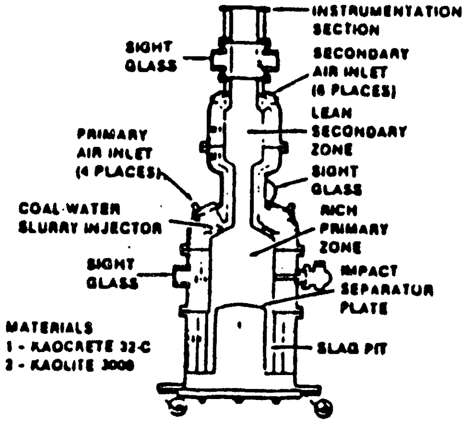


Figure 9.
Solar Turbines combustor

under reducing conditions is operating as a gasifier. The first stage performance can therefore be optimized for either slagging combustion or slagging gasification.

Slag Rejection

Few details have been reported on the removal efficiencies of slag or ash particles from the combustion gas in relation to operating conditions or combustor geometry. However, considering the underlying basic design concepts of different combustors, it can be deduced that the designers intended to improve collection efficiencies with two mechanisms, through increased vorticity or by direct impingement of gases onto combustor walls or special baffles.

Increased vorticity can be achieved through a combination of increased inlet velocities, reduced combustor diameters, restriction in outlet opening and change in outlet geometry. These approaches follow standard particle control measures as they are usually taken in dust control devices, such as cyclone or impingement separators.[12] However, since the main objective in a combustor is to recirculate gases for flame and ignition stability, a compromise has to be reached between collection efficiency and combustion performance.

In practice, the problem becomes quite complex. Most high performance combustors operate at temperatures at which the resulting slag appears in the form of liquid droplets. Under less than ideal conditions these droplets will begin to solidify, attach themselves to the wall and gradually deteriorate the performance of the burner to the point where the burner has to be shut down and the slag physically removed. In addition to this so-called "ringing" problem severe mechanical and chemical erosion of the ceramic combustor lining can be expected[13], especially under high velocity flow conditions. Increase in wall temperatures to keep the slag in liquid form is not always feasible, especially under varying load conditions. The load dependent secondary flow patterns can create temporal and spacial nonuniform temperature distributions that will add to the "ringing" problem.

Dynamic Containment

In general terms the concept of dynamic containment can be considered as a means of retaining material in a given space using velocity dependent forces only.

The dynamic containment concept, first developed in plasma research to contain high temperature gases with magnetic fields, was invented in the USSR in the mid 60's and resulted in the Tokamak reactor.[14] In principle by replacing the magnetic fields of this reactor with fluid dynamic fields, a more generally useful dynamic containment vessel can be obtained. This can be accomplished with the superposition of a ring and a line vortex.

The line vortex is mainly responsible for particle circulation around the main axis of the dynamic containment vessel and the ring vortex component of the flowfield contributes to the end to end circulation. Superimposing these two movements results in a double vortex. In practice this double vortex can be generated by superimposing two concentric flows with opposing mean velocities, the outside one, a potential flow, the inside one a rotating flow.

In order to understand and use the fluid dynamic containment system in practical applications a more detailed look at the various forces that are involved is helpful. An analytical or numerical approach to model the double vortex is extremely difficult and has not yet been attempted. Therefore a rather simplified qualitative approach will be presented here by considering the dynamic containment structure divided into four regions as shown in Figure 10. These are:

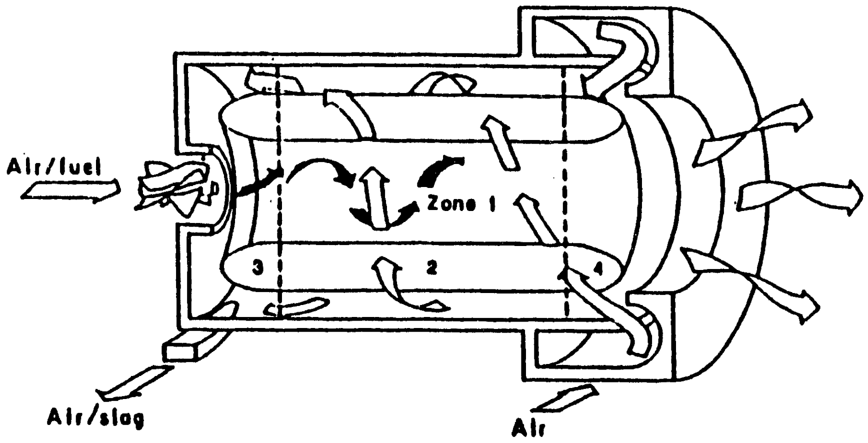


Figure 10
Single-stage Dynamic Containment Combustor
Showing Four Basic Regions.

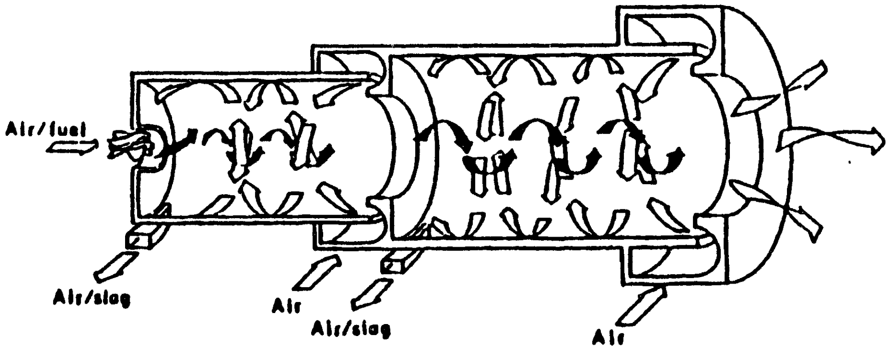


Figure 11.
Two-stage Dynamic Containment Combustor

1. a low pressure core
2. the vortex mixing/containment zone itself
3. the top region defined as the area adjacent to the outer jet.
4. the bottom region, the area surrounding the inner jet.

In each region different forces dominate.

The first region, the vortex core is a low pressure zone. Fluids are transported from this zone into the containment region (zone 2) by the rotating flow. In this process the element of fluid begins to rotate and at that point centrifugal forces aid the entrainment process.

The containment zone is characterized by two forces in balance. One force, generated by the outer flow field, is proportional to $1/(R-r)^2$ and is directed towards the center of the vessel (centripetal force) (R - radius of physical vessel, r - distance from the axis). The second force is produced by the central rotating flow and is proportional to $1/r$ and is directed away from the center of the vessel (centrifugal force). A fluid or solid particle will therefore move on a mean circle with radius Rm which is defined as the locus where centrifugal and centripetal forces are in balance.

In the two end regions adjacent to the outer and inner jets respectively flow patterns are dominated by entrainment forces as defined by Weeks theorem[15]. This entrainment mechanism will reverse the axial velocities of the approaching particles and thus a closed particle trajectory perpendicular to that in zone 2 is established. The superposition of these two trajectories results in a double spiral. As indicated earlier the actual processes are much more complicated and as yet are still incompletely understood especially as to the mechanism of the end zones.

More information about the main containment zone (Zone 2) can be gained by returning briefly to the model of superimposed line and ring vortices. Line vortices show a detailed structure composed of smaller line vortices, rotating about their own axes and simultaneously about the main vortex axis.[16] This complicated structure contributes to high shear and mixing forces within the containment zone. The high stability of ring vortices[17] contributes to the overall stability of the containment region and it is especially important in preventing particle escape from the end zones.

From these descriptions a number of conclusions can be drawn regarding the characteristics of fluid dynamic containment systems:

1. Fluid dynamic containment vessels are in principle independent of physical enclosure and are solely defined by jet interaction. However, it can be expected that suitable enclosures can increase the efficiency with which the dynamic containment region can be generated by the jets. Furthermore, since the influence of enclosure wall on the dynamic containment system is of secondary importance, it can be expected that with decreasing volume to surface ratio of the enclosure vessel the establishment and maintenance of the dynamic containment region will become increasingly unstable. The corollary to this is that the larger the volume to surface ratio becomes, the smaller the influence of disturbances will be on the stability of the dynamic containment zone.
2. Combustion reactions will be mainly confined to the containment zone. Therefore there will be little or no convective heat transfer to the wall. With non luminous flames the enclosure walls will remain relatively cool despite

high combustion rates. The dynamic containment does not influence radiative heat transfer, and with luminous flames the walls will heat up. However, fuel and ash particles spiraling on the outside of the containment region will absorb some of this radiation. In addition, the potential flow will cool the wall somewhat and thereby reduce heat losses and temperature loads. There should be no abrasion due to fast moving slag, ash or fuel particles and the enclosure vessel can be constructed of light sheet metal instead of refractory or heavy castings.

3. The ash generated during burnout of fuel particles should melt in the concentrated flame in the dynamically contained flame zone. These molten slag droplets should agglomerate with other dust or liquid droplets and, as they grow, be dropped out in one of the end zones of the containment region. The end zones can be aerodynamically designed to remove particles predominantly at the front end, that is the end opposite to the potential flow jets. In the return flow the particle will be in the relatively cool potential flow region, solidify and due to its increased weight avoid re-entrainment. The ash/slag can be removed at both ends of the end zone and therefore good particle removal can be obtained.

4. Dynamically contained combustion has certain similarities with large scale forest fires, which can be viewed as heat engines. Therefore it can be expected that this combustor will show similar features, that is convert some of the heat released into mechanical energy, namely vorticity that will stabilize the dynamic containment zone and reduce the jet energy needed to sustain the

system. This mechanism should become more and more prominent with increasing volume to surface ratios of the combustor.

It can be expected that increased vorticity in the containment zone should result in a large central depression, that is increased amounts of air should be entrained from that zone into the containment zone where it will be intimately mixed. In other words the burner will use a portion of its released energy to drive the mixing process. This is an almost ideal condition for the second stage in a multiple burner combustion system.

Previous Work

Prior to the current project, a dynamic containment combustor had been tested with different materials over a period of about two years. Most of the test were performed with a sawdust sand mixture. Due to lack of suitable instrumentation the resulting observations can be considered only as qualitative. However they do corroborate the predicted characteristics of the combustor and can therefore be used as a basis to develop in depth investigations into the physical and chemical processes involved in this combustor. In the initial work a series of combustors was built with varying diameter but fixed diameter to length ratio of 1:3. The combustor concept was tested with a 24", 12" 8" and 6" diameter system. It became evident that it was increasingly difficult to achieve stable operating conditions with reduced diameters. Operating conditions were considered acceptable when; stable burner operation could be achieved, sawdust fuel ignition could be achieved without auxiliary fuels, the off gases were devoid of detectable particle emissions, and the combustor would work unattended over a reasonable period of time.

It was possible to achieve these conditions for each of the given diameters. However in the larger systems the influence and absolute amount of jet energy generating the necessary potential and rotating flow fields could be varied to a large extent, without negatively affecting the overall operation conditions. The 6" model worked stably in a narrow range of adjustment for all parameters (potential and rotating jet energy, potential and rotational flow rates, total fuel input).

Throughout the testwork little wear was observed either on the inside of the combustor walls or at the end plates. By contrast, in one test an elbow in the fuel feed line failed due to abrasion after a couple of months.

All slag/ash removed was in a granular form that indicated previous melting, supporting the arguments developed in the discussion above. The actual formation of slag and its disengagement from the combustion zone remains unknown.

In tests with natural gas the flame remained stable up to 12 MM Btu's, (the limit of the test set up) and the combustor shell and mouth section remained relatively cool at all times.

A 2 stage model, Figure 11, was also tested and an extremely clean flame was obtained even during temporary solid fuel overload conditions.

Inspection of solids collected in the second stage, especially from tests where the first stage operated under reducing conditions, showed similar characteristics to those discharged from the first stage operation.

Desulfurization

The need to reduce sulfur emissions to the atmosphere has been recognized for some time and considerable abatement has been achieved through flue gas scrubber systems and improved coal cleaning.

Coal cleaning reduces the sulfur content of the fuel supply while flue gas scrubbing removes the sulfur from the gaseous products of combustion. There are technical limits to coal cleaning by simple mineral separation processes since this approach does not appreciably remove organic sulfur. For flue gas scrubbing the cost of sulfur removal becomes prohibitively costly as the sulfur content of flue gas increases. As a result of these factors there are many U.S. coals that have moderately high organic sulfur content that cannot achieve environmental compliance economically. One solution to this problem lies in sulfur removal during, or immediately after, the combustion process and considerable attention has been focussed on this technical field in recent years.[19]

Most of this work uses calcium chemistry and a major thrust in sulfur absorption using lime is the Lime Injection Multiple Burner (LIMB) technology. This is of major interest for retrofit applications in Europe[20] and results from a U.S. demonstration project have been recently reported[21]. SO_2 removal in the range 50 to 60% is achievable but Ca/S stoichiometric ratios on the order of 2 are required.

Some of the reactions involved in sulfur transfer to limestone sorbents are as follows:

$$CaCO_3 \text{ --> } CaO + CO_2 \qquad 1$$

$$H_2S + O^{2-} \text{ --> } H_2O + S^{2-} \qquad 2$$

$$CaO + S^{2-} \text{ --> } CaS + O^{2-} \qquad 3$$

$$CaS + 2O_2 \text{ --> } CaSO_4 \qquad 4$$

$$2\,CaS + 3O_2 \text{ --> } 2\,CaO + 2SO_2 \qquad 5$$

Major rate controlling steps are the diffusion of S^{2-} species from the surface to the interior of the solid and the diffusion of O^{2-} species from the interior to the surface.

Reactions 2 and 3 occur in the surface diffusion boundary layer. The influence of chemical and microstructural characteristics of limestone sorbents on desulfurization has been studied in the Netherlands[22] and it was shown that sulfidation conversion was higher than sulfation conversion for all sorbents and that conversions could vary by over a factor of two depending on the particular sorbent used. In a similar U.S. study[23] it was also shown that sulfur capture by limestone sorbents was greatly influenced by the sorbent characteristics and that the Ca/S ratio in sorbent products could vary over a two-fold range.

Reactions 4 and 5 are also important with respect to overall sulfur capture efficiency since under adverse operating conditions the reverse reaction 5 leads to SO_2 losses and inefficient use of the sorbent.

Reaction kinetics and overall absorption efficiency can be improved by using a finer particle size but this has to be balanced against grinding costs and increased dust loading. Significant precipitator fouling has been reported for a full scale LIMB test in Germany[24]. Lime is the currently preferred sorbent since its is a readily available bulk commodity with reasonably low cost. There are, however, hidden costs associated with the large volumes of solid waste generated and associated environmental control and with the additional CO_2 released to the atmosphere from the production of lime from calcium carbonate.

This has led some researchers to seek an alternative absorbent and iron oxide appears to be a candidate with some potential. A cost comparison for several absorbents shown in Table 1, and shows magnetite (Fe_3O_4) to be cost effective relative to the lime based absorbents. This is of particular interest to Minnesota since very large tonnages of fine magnetite concentrate are produced on the Mesabi Iron Range as feedstocks to the taconite pellet induration plants. Due to the decrease in demand for steel in the early 1980's there is considerable excess concentrator capacity and an additional outlet for this product would be welcomed. Sulfur absorption into an iron based absorbent is achieved by the formation of low melting point iron oxysulfides which are stable over a wide temperature range. Also, since molten droplets are formed, mass transfer is expected to be more rapid than in the case of absorption onto a solid as in the lime case.

Preliminary work carried out at the AMAX R & D laboratories[3] to examine the use of iron oxide for desulfurization during coal combustion confirmed the basic concept and a patent[6] was issued in 1986. The work at AMAX was discontinued when the principal investigator left AMAX to take up a faculty position at the University of Minnesota and a cooperative agreement was drawn up between the University and AMAX to permit continuation of the work at the University.

Basic work on the sulfur absorption capacity of iron oxysulfides has been carried out by Turkdogan and Kor[25] and Sherman, et. al.[26]. Figure 12 reported by Hepworth and Wickes[3] shows the sulfur/oxygen chemical potential diagram at 1200°C for the iron-oxygen-sulfur system using the H_2S/H_2 and CO_2/CO partial pressure ratios. The stable iron oxysulfide region is indicated and contains a heavy dashed line representing a fixed iron to sulfur molal ratio of 1.5. This line indicates that the optimal sulfur removal (lowest log pH_2S/pH_2) is achieved at low oxygen potential (i.e., under reducing conditions). A slagging desulfurizing burner using iron based sulfur absorbents would therefore require two stage combustion with the sulfur absorption in the first, reducing stage. A two-stage burner of this type would have the additional benefit of maximizing slag removal in the first stage, and also have the second stage for back up slag removal. Two-stage combustion is also preferred for minimization of NO_x formation and reduction of CO emission due to the improvement in

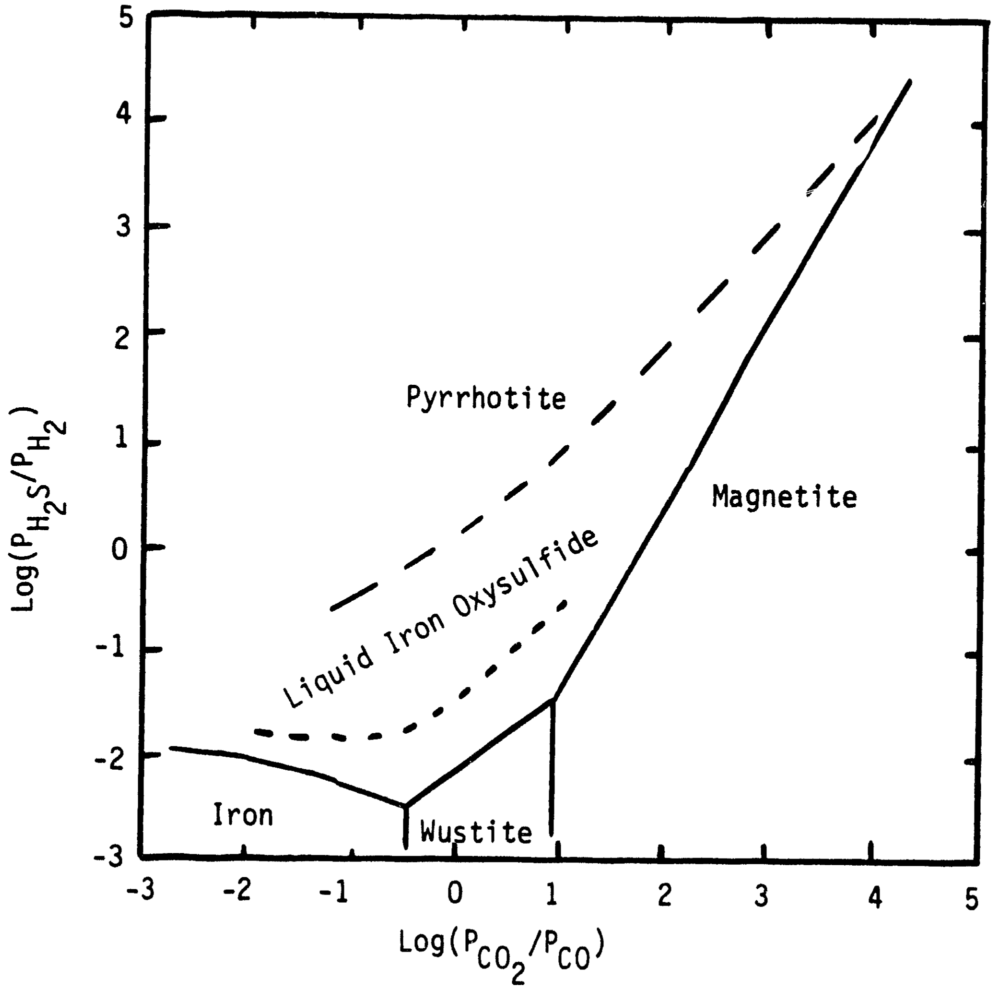


Figure 12.
Phase Equilibria in the Fe-O-S system at 1200°C

overall combustion efficiency.

The basic concept of iron based desulfurization in a two-stage slagging combustor using the double vortex dynamic containment principle is illustrated in Figure 11.

Evaluation of the potential for this novel approach to sulfur removal during coal combustion requires research in several topic areas including details of the fluid dynamic principle and their applicability in coal combustion systems, the behavior of solid and/or liquid particles in double vortex flow fields and the performance of potential sulfur adsorbents under appropriate operating conditions. Considerable progress in understanding the Fe-0-S system has been achieved during the time frame of this project in a parallel DOE project also at the University of Minnesota(27).

APPROACH

This project is related to an overall program aimed at achieving a combustion system with the following characteristics:

- good mixing and burnout rates under varying loads and conditions.
- Superior specific energy release.
- Reduced thermal and mechanical combustor wall loading.
- Good slag rejection characteristics under varying loads.
- Suitability to suppress SO_2 formation through the efficient use of suitable sorbents.

In order to achieve these objectives it was felt that a departure form the current approach of high performance combustors based on the standard cyclone principle was warranted.

The double vortex dynamic containment combustor has provided considerable initial promise towards achieving these objectives. The main different between this approach and existing combustor concepts lies in the fact that in the dynamic containment system all processes and circulations within the combustor are directly produced by powerful fluid jets, and not through jet wall interactions. Therefore all fluid and solid particles are subjected to and can be influenced directly at all times by jets. Any jet wall interactions will be secondary, serving only to improve the jet efficiency.

In conventional high performance burners this is not the case, since most flow patterns are created by the interaction of input flows with combustor walls. Secondary flow patterns are mainly produced by vortex breakdown mechanisms.[18]

Preliminary testwork has indicated low thermal loading and abrasion on the combustor walls, the ability to reject slag in granular form and favorable scale up characteristics. Further development of the dynamic containment combustor for potential slagging desulfurization application requires research in the following three main areas,

- Basic coal combustion characteristics
- Slag rejection performance
- Sulfur sorbent behavior.

Data from these investigations are expected to provide a maximum return on the research effort, provide insight into possible practical solutions to pressing combustion problems and provide important insight into the basic principles of dynamic containment.

Bearing in mind the basic concepts outlined above, the purpose of the current project was to design install and commission a double vortex combustion test rig that could be used for sulfur sorption tests using lime, limestone and iron oxide as potential sorbents.

COMBUSTOR DESIGN AND TEST PROGRAM

Design Consideration

The basic design of a dynamic containment combustor is deceptively simple comprising a front plate with a central exhaust orifice and a peripheral gas inlet system to provide the outer vortex drive, a back plate with a gas inlet to provide the inner vortex drive and a cylindrical body separating the two end plates as illustrated in Figure 10. Fuel can be introduced axially through the back plate (preferable) or peripherally near the back of the cylindrical body.

Unknown factors influencing the performance of the system include:

- length to diameter ratio
- outer vortex drive design
- inner vortex drive design
- drive flow angle (tangential/axial flow)
- drive velocities (inner and outer)
- drive volumetric flows
- exhaust diameter to end plate diameter ratio

The project was not funded for a detailed systematic study of those factors and an empirical approach was adopted based on experience gained in earlier work. The main objective of this approach was to simply establish an operating system in which some preliminary combustion and desulfurization tests could be performed. Optimization of design and operating variables would have to wait for more detailed fundamental studies in the future.

It has been shown that dynamic containment can be achieved by controlling the leakage flow that normally occurs in the end-wall boundary layers and is mainly responsible for any particle escape from a confined vortex.[28] The two end-walls usually found in a combustor (the front wall, incorporating the burner mouth and the back wall) assume different fluid dynamic functions in the dynamic containment scheme and therefore are controlled differently. As described by Leaner et al.[28], any confined vortex creates, through centrifugal forces, a pressure maximum along the periphery of the confinement vessel. The resulting forces are balanced throughout the vessel by centrifugal forces, except in the end-wall boundary layers. Here, by definition, the tangential velocity vanishes and therefore the peripheral pressure can accelerate the fluids radially inward.

This leakage flow, under certain, conditions can be substantial[29] and is the primary cause for the escape of matter from confined vortices. The radial acceleration in the front end-wall can be reversed in its direction by applying internal suction along the end-wall periphery. This can be accomplished (based on ejector technology) through a ring-jet entering the combustor along the periphery of the front wall, with an axial momentum component directed towards the opposite end. This jet, by entraining gases from the immediate surrounding, will generate a secondary flow at its base with a flow direction 90° to that of the jet. In other words, the entrained flow will come predominantly from the boundary-layer region. This effect is desirable in that it reverses the normally occurring flow from radially-inwards to radially-outward. It has been observed that this suction can be strong enough to entrain air along the entire front wall through the burner mouth.

This effect also has the additional benefit of cooling the burner mouth and alleviating the necessity of refractory materials in that area. As in conventional ejector technology, it is also important in dynamic containment technology to match the fluid dynamic conditions of the combined flow (primary and secondary flow) to those prevalent in the surrounding bulk fluid. In the dynamic containment combustor this is achieved in two ways:

- By impressing on the primary jet a rotational velocity higher than that of the surrounding gas. (This will tend to keep the primary jet from dissipating its momentum too rapidly into the surrounding gas column.)

- By designing the burner side-walls in a conical form, with the apex of the truncated cone at the front end of the combustor. (It was shown by Volchkov et al.[30], that the ideal contour of the side walls does not take on the form of a straight cone, but follows a hyperbolic function. To date , because of their simplicity, only straight cones have been tested. This geometry appears to increase the suction pressure close to the burner mouth, reduce the overall effect of the front end wall and improve the "coupling" of the "front ejector" flow to the bulk flow within the combustor.)

As the flow from the burner front reaches the back wall, it will be decelerated by friction and spiral towards the center. Simultaneously during this process, the predominantly potential-flow will be converted into a rotating flow for which, by definition, the vorticity is non zero throughout the fluid.

This conversion process establishes the vortex core, whose diameter appears to depend to an equal degree on the burner mouth opening. Control over the fluid dynamic conditions within the core and by extension, over the flow within the back wall boundary layer, can be gained by injecting vorticity into the core. Through a rotating axial jet, fluid is entrained from the surrounding boundary layer and accelerated towards the front end of the combustor. Also the geometry and momenta of this primary jet are chosen such that the resulting mixed-flow will couple easily with the bulk of the gases in the burner with a minimum of losses.

This description of a dynamic containment flow-field can be summarized as superposition of three distinct circulation patterns:

- the confined vortex flow,
- the front-to-back recirculation along the burner wall
- and the back-to-front recirculation, increasing the vortex core diameter and simultaneously re-dispersing the matter flowing through the rear wall boundary layer (In other words, two perpendicularly rotating recirculation patterns.)

As a result of research completed to date the existence and control of the so-called dynamic-containment flow-regime have been experimentally and practically proven. The actual processes appear complicated, and in order to describe the behavior of the system as a combustor, a number of different models have been invoked to highlight specific aspects of the system. These models have been formulated based on well-established information gathered from various branches of fluid dynamic and combustion research. Although some of the observed burner characteristics can, in principle, be described with reference to these models, it is necessary to investigate these phenomena in detail in order to fully develop the dynamic containment combustor to its perceived practical potential.

Conceptual Models

Some of the highlights of the dynamic containment combustor and the respective, possible processes involved, can be described with the following three models:

1) **Uniform Internal Mixing through Micro Vortices and Acoustic Resonance.**

A good analog to the two rotating fluid columns generated by the front jet on the outside and the core, largely driven by the rotating center jet, can be represented by two concentric rotating cylinders. The flow pattern generated under various operating conditions between these cylinders have been studied extensively[34,32], and are known as Taylor vortices or Cuvette flow, depending on the respective dynamic conditions. In essence, Taylor vortices can be described as double vortex cells stacked one on top of the other along the entire length of the cylinders. At sufficiently high rotational velocities of the cylinders, these cells begin to show different structures, described in the literature as standing or traveling waves[32]. Similar patterns have been observed in a dynamic containment combustor operating with propane as fuel. These observations were accompanied by strong acoustic emissions. Largely due to the strength of these emissions and the apparent correlation with the flame structure, it is postulated that these vibrations appear to be in resonance with the flame itself. The benefits accruing to the combustion process from these phenomena can be deducted from experiences gained with pulse combustors[33]. The high specific energy release, as observed in the dynamic containment combustor, can also be related to the above-mentioned flow patterns. In the dynamic containment burner, the size of the flame, external to the burner, can be influenced to the point that it can be totally withdrawn into the combustor. This requires the capability of intense and rapid internal mixing, which again can be explained by the formation of Taylor vortices and their various structures. At least, in the case of gaseous fuels, the burner, under these operating circumstances, appears to perform similar to, what is normally described as a premix burner.

2) Gas Acceleration by Direct Conversion of Thermal Energy Released in the Flame into Kinetic Energy.

Measurements taken on the dynamic containment combustor with and without flame indicated that the core depression did not change significantly between the two conditions. Assuming, conservatively, a gas expansion of at least 3 to 4 times its original volume, the combustion gases must be accelerated substantially in order maintain the core pressure constant. The associated increase in kinetic energy appears to be derived from the thermal energy released by the flame. The velocity increase is also easily discernable through an observed accompanying rise in sound frequency and level. The occurrence of gas accelerations, due to direct heat release within the gas, have been predicted and verified in a number of reports[34-37]. Two conclusions can be made:

- A substantial portion of the mixing process is directly driven by the flame itself, without additional power input; and
- the containment of matter in general, but especially the retention of particles, is increased after ignition.

The first point again indicates that the burner operates in a similar fashion as a premix burner, with the mixing occurring within the flame itself. This eliminates the addition of secondary or tertiary air and the associated mixing problems and should prove beneficial in dual fuel operations. The second point has been observed during the initial dynamic containment combustor development, which showed that especially fine particles, that tended to escape from the combustor under a particular set of dynamic conditions, appeared to be completely retained after the flame had been established.

3) Integral Ejector Drive of the Dynamic Containment Combustor with High Pressure Steam or Hot Water.

High pressure steam, and to a lesser degree, high-pressure hot water, are frequently used to provide reliable, maintenance-free suction or compressor services, if, of course, low cost steam is available[38,39,40]. It has been shown that the dynamic containment burner can be driven successfully with high-pressure, high-temperature saturated or unsaturated steam. This made it possible to achieve very high dynamic containment velocities without the necessity of expensive and maintenance intensive compressor equipment.

Using well-designed ejectors properly matched to and integrated with the fluid dynamics of the rest of the dynamic containment system, a rough calculation indicates that the energy consumption can be expected to be favorable, compared with that needed when mechanical equipment is used. The steam, after spending its free energy accelerating the combustion air, is reheated in the combustor to flame temperatures that are substantially higher than the original steam temperature. It enters the heat exchange portion of the burner with the rest of the combustion gases where it emits most of its heat and finally is discharged at the stack temperature with very little remaining enthalpy.

It is reasonable to compare this process with an "integrated top cycle". In order to reduce operating costs even further, the steam can be used to heat water, as it is usually available in cooling towers, under sufficiently high pressure, which in turn will flash into steam in the ejector nozzle. This concept was successfully employed in France to drive very economically high velocity wind tunnels. The water that did not flash into steam, or recondensed prior to entering the combustor proper, can of course, be recirculated. If wet scrubbing of the exhaust gases is employed, no additional net water consumption is required, since the combustion gases ultimately are released to the atmosphere under saturated conditions.

Besides expected reduced initial and operating costs this approach promises additional benefits. It can easily be seen that the fluid dynamic effects, discussed earlier, can be substantially increased, without the penalty of substantial equipment and operating costs. Therefore more power can be made available within the combustor itself for pollution control purposes. It was also shown in the literature that injection of steam into combustors can reduce the production of NO_x and CO simultaneously. This is not entirely attributable to a lowering of the flame temperature but seems to be connected with the oxidizing properties of water at high temperature.

The dynamic containment combustor, due to its dynamic and related properties, some of which have been pointed out above, appears to be well suited for a broad range of industrial and commercial applications. Since it is expected that a great deal of pollution can be eliminated within this burner itself, it seems to be well suited for dual-fuel or multi-fuel applications.

Glass Model Tests

Figure 10, depicts the cross-section of a single-stage cylindrical of Dynamic Containment Burner. In this Figure the burner is shown in a horizontal position, but it was actually operated in a vertical configuration with the flame emitted from the top. Air and fuel is injected along the center-line of the burner at the left (bottom of the burner) with a swirling action. The fuel was either propane or propane plus acetylene (C_2H_2). Acetylene was employed for two reasons:

- to simulate the hydrogen-to-carbon molal ratio in coal;
- since acetylene has a higher enthalpy of combustion than propane, the

additional enthalpy enables steady-state operation at temperatures approaching 1400°C even under the highly sub-stoichiometric conditions required for desulfurization.

Although coal should be the fuel which is to be utilized by this burner, the tests which were planned for this work were for a gaseous fuel rather than a solid one in order to avoid the additional problems of combustion of coal. This additional complication should be included in further studies and is not part of this project.

The diagram shows an "air/slag" exit port designed to permit discharge of quenched (iron-oxysulfide) products from the feeding of iron oxide to the acetylene/air flame. If and when coal is fed as a fuel in later studies, the oxysulfide will be combined with the ash constituents of the coal.

The fuel/primary air mixture follows the swirling trajectory shown by the black arrows in the center of the burner in Zone 1 where it is met toward the end of the path by the primary air stream added tangentially by a header piece with tangentially-bored holes for ingress air. The motion of the air is shown by the open arrows. The motion of the combustion products is shown schematically in Figure 13.

Preliminary tests were carried out in a cylindrical glass test model and demonstrated the basic stability of the dynamic containment combustion system. Figures 14 and 15 show examples of the flame geometry obtained in the cylindrical glass unit.

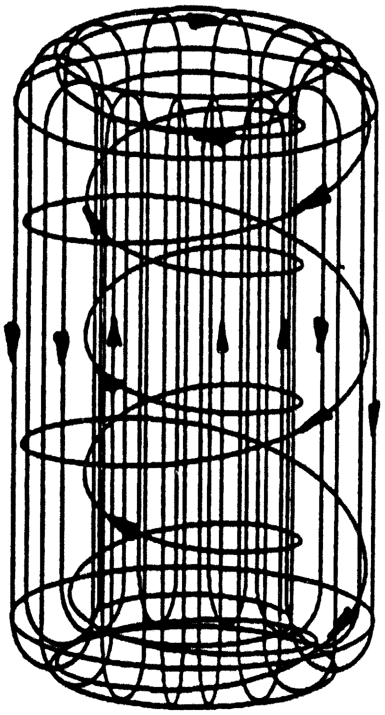
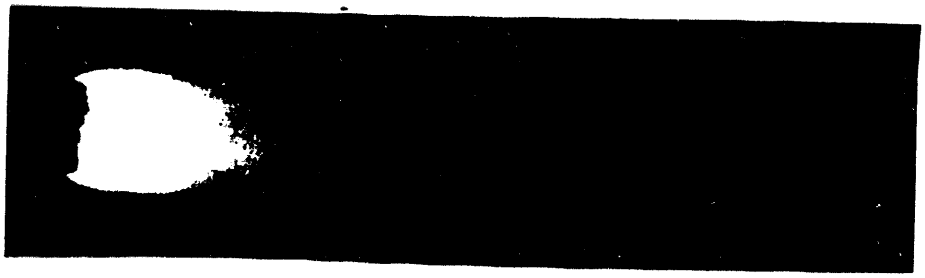
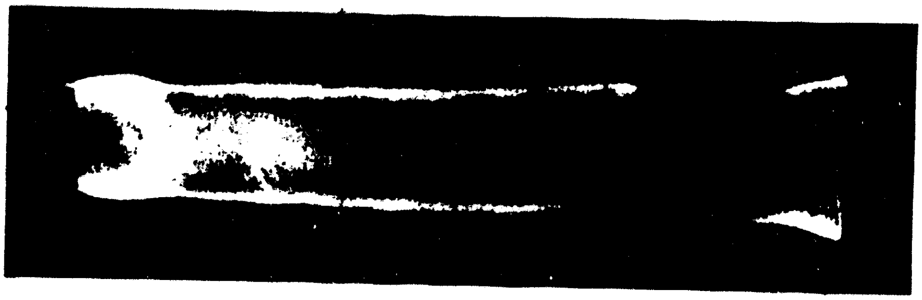


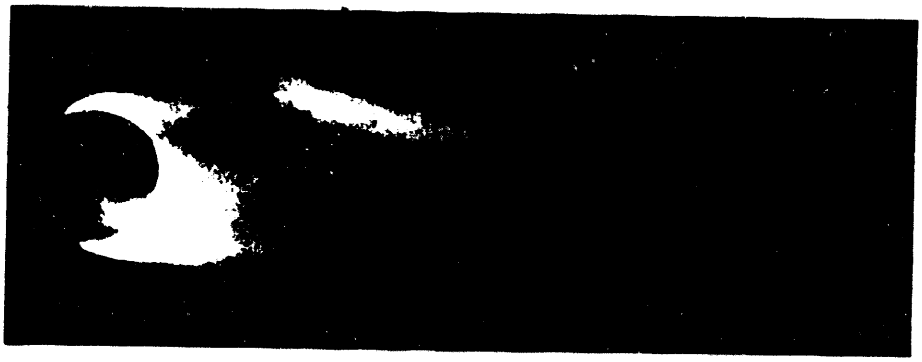
Figure 13 Flow Patterns in the Dynamic Containment Burner



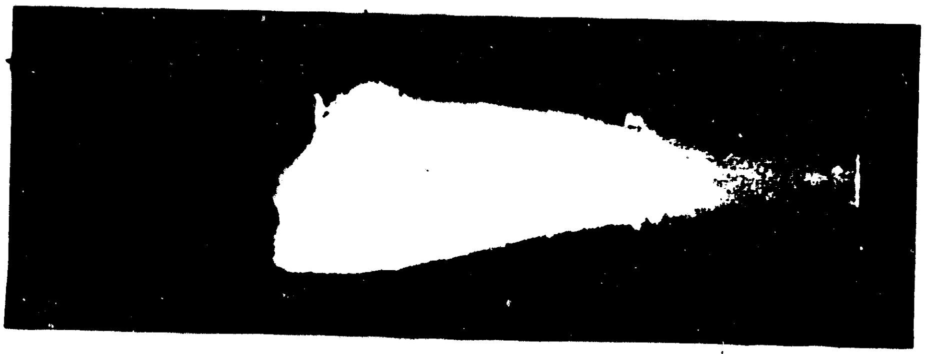
A) High Rotating Flow



B) Stable Balanced Operation

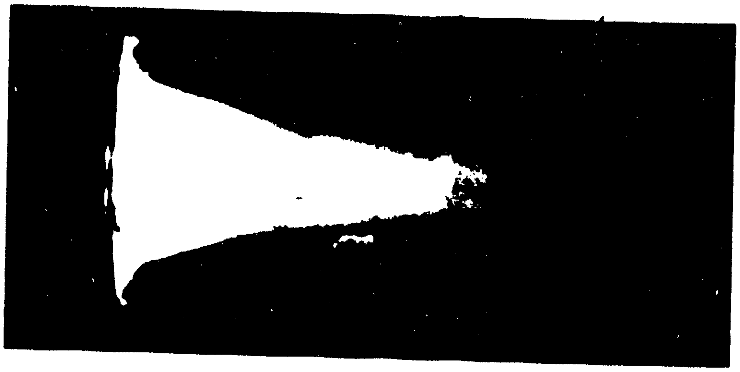


C) Expanding Core



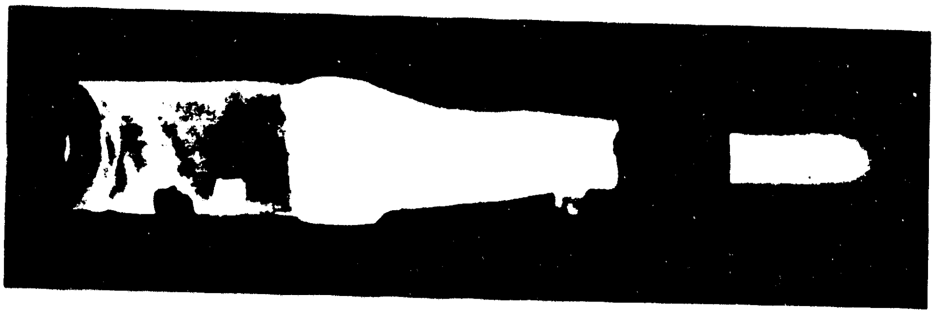
D) Overdrive Flow

Figure 14. Flow Characteristics for Type I Flame

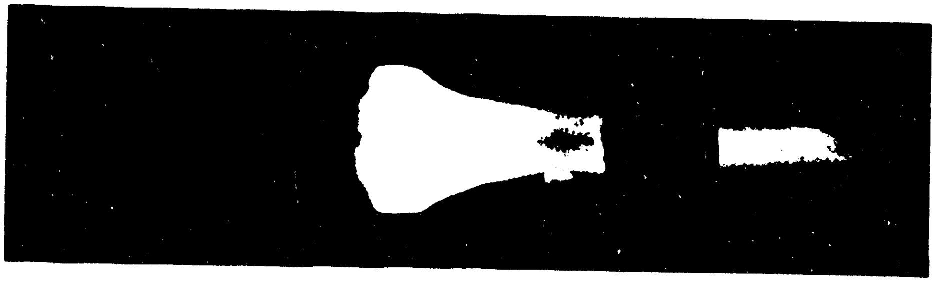


A) High Rotating Flow.

B) Stable Balanced Operation.



C) Start of Overdrive.



D) Overdrive Operation.

Figure 15. Flow Characteristics for Type II Flame

Subsequent tests demonstrated that a conical configuration was more stable and hence a glass version was constructed to view the flow patterns. The dimensions of this glass version were:

Top I.D.	4.5 inches
Bottom I. D.	9.0 inches
Cone length	18.0 inches
Cone angle	≈ 30°

The outer-drive nozzle assembly has:

Tangential velocity control: scroll type diffuser with adjustable nozzle ring;

Axial velocity control: adjustable gap between inlet section and cone.

The inner-drive nozzle assembly has:

One and a half inch Whirljet spray nozzle from Spraying Systems, Inc;

Several different jet geometries (axial versus rotational flow) which can be obtained with different nozzle geometries.

At this stage of the development of a practical combustor unit for high temperature sulfur removal, the details given above represent the best combination of design parameters obtained to date and were used in the stainless steel prototype burner used in subsequent testwork.

Glass Model Results

Cold testing using magnetite particles was conducted in the glass model. Figure 16 is a photograph of the assembly. Figure 17 is a photograph of cold testing with sawdust showing the swirling action produced. Figure 18 is a test at temperature (flame temperature approximately 1500°C) in which the pyrex glass walls remained relatively cool.

The experience and information obtained from the glass model work can be summarized as follows:

1) Establishment of Dynamic Containment Zone, Particle Retention, Wall Abrasion, Convective Heat Transfer:

In prior tests using sand-contaminated sawdust as fuel, the inside of the burner walls appeared to be covered with a thin carbon deposit (black sheen) with no scouring marks observable. From this observation, one can deduce that the fuel as well as the ash/slag particles did not touch the wall but were, however, suspended within the so-called Dynamic Containment Zone. There is also the possible inference that convective heat transfer does not occur between the flame zone and burner side-walls. Although the operating time with solids was very low in the current project these observations were not contradicted in any of the testwork.

2) Visual Observations on the Dynamic Containment Zone and Convective Heat Transfer.

A 4-inch diameter, 12-inch long combustor, using compressed air and propane was

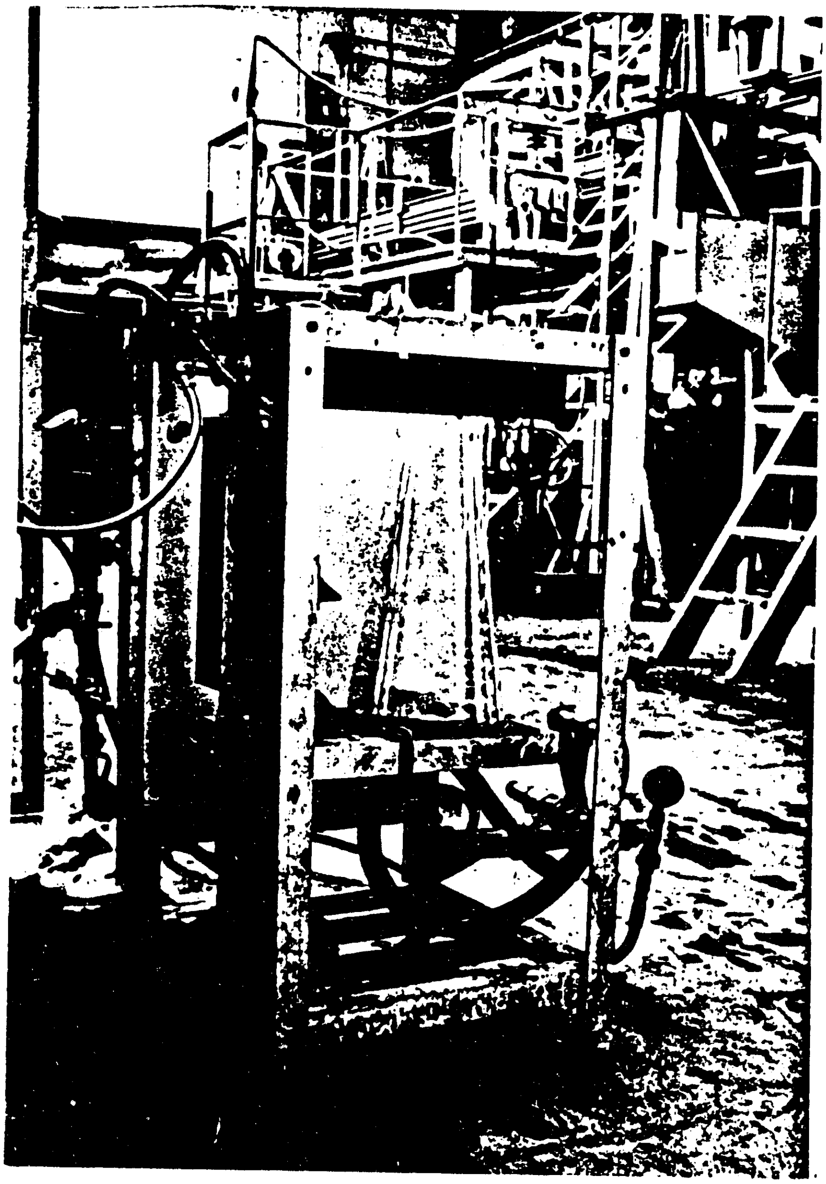


Figure 16. Glass Model of Burner System

Figure 17. Photograph of Flow Patterns in Glass Model using Sawdust as Media

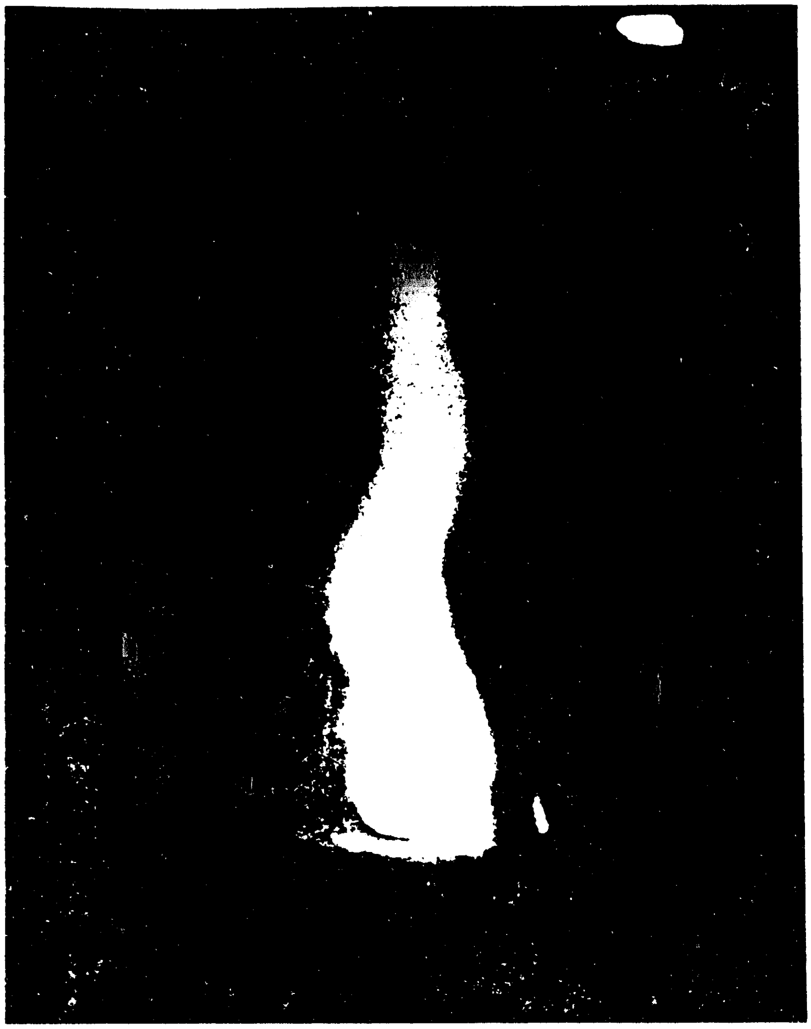


Figure 18. Photograph of Flame in Glass Model

operated at an output of about 1 million Btu. After an operating time of about 0.5 hours, the outside wall of the combustor still showed no sign of heat-up but remained cool to the touch. Immediately after shut-down, condensed water from the compressed air line collected at the burner mouth in the form of droplets without any visible sign of boiling or rapid evaporation. The visual observations of the flame zone indicated a well-defined containment zone. It was also noted that the front jets not only expanded the flame diameter in the vicinity of the burner mouth, but also entrained outside air through the burner exit opening along its wall in a flow counter-current to the exiting gases. Again this observation explains the lack of heat build-up on the combustor wall and corroborated the above-mentioned observations and deductions.

3) Direct Conversion of Heat into Kinetic Energy

Pressure measurements taken before an after ignition from a location on the rear section of the core region showed no appreciable change. The measurements were taken outside the immediate influence of the rear nozzle assembly. Assuming a conservative expansion of the combustion gases due to the flame temperature rise (about three times their original volume before ignition), a core pressure rise should be expected; however, this pressure rise was not observed. It was also noted that the inlet pressures remained constant before and after ignition; therefore, the gas/air flow rates through the nozzle assemblies remained constant. One conclusion that can be drawn from this observation is that the rotating velocity of the burned gases increased in such manner so as to counterbalance any volumetric increase resulting from the temperature rise. The energy to accomplish this can only come from the thermal energy released in the combustion process.

4) Fuel Residence Time and Total Fuel Loading

In the model described above, the combustor was loaded with about one pound of sawdust and operated for about one hour without flame (See Figure 4.) During this operating time, no significant loss of solids was detected. The amount of solids suspended at any time was clearly dependent upon the gas/air velocities at the end-wall (situated opposite to the burner exit). and therefore was dependent upon the outer jet velocities. The distribution of the suspended particles through the Dynamic Containment zone is also a function of the dynamic conditions.

5) Alternative Nozzle Drive

An alternative to compressed air jet drives for both nozzles is high pressure steam. Properly designed steam ejectors can supply the required air for combustion purposes and deliver this air with the necessary momentum to both nozzle assemblies. By carefully designing the ejector as well as the interconnecting ducts and the nozzles themselves, the efficiency of such a system can be maximized. Such an approach has several advantages, some of which are:

- Reduced overall combustor complexity and service requirements.
- Reduced NO_x production during combustion.
- Excellent particulate control and corresponding fly ash reduction due to potentially very high jet momenta.

A 4-inch diameter combustor with a cylindrical 12-inch long burner tube was used in the proof of this principle. Although the 180 psi steam which was use was saturated and no provisions were available to remove any condensate prior to entry of the steam into the ejector,a stable operation of the burner was achieved with propane as a fuel. As expected, all moisture was fully evaporated in the flame.

This approach would not be appropriate for use in systems in which iron oxide in the sorbent due to the adverse effect of high hydrogen levels on the equilibrium between sulfur and hydrogen sulfide in the gas atmosphere and subsequent depression of the sorption potential.

Stainless Steel Combustor Tests.

Following the closure of the Mineral Resources Research Center the stainless steel conical burner test rig was moved to the High Bridge power plant of the Northern States Power Company for further testwork.

The system consisted of a vertical conical burner having the dimensions described previously. Fuel and air in various combinations could be added both to the bottom and the top of the burner. Off-gas analyses were performed using infra-red spectrometry with a mobile probe. The probe positions with respect to exit location enabled gas assays to be taken with the results being mapped as shown in Figures 19-26.

Stainless Steel Combustor Results

.The results of these burner tests are presented in Tables 3-14, while Table 2 outlines burner conditions and the related figures.

Table 2. Burner Conditions and Related Figures

Table #	Fuel	Rate SCFM	Addition Point	Air Rate SCFM Top/Bottom	Figure #
3	Propane Acetylene	2.4 3.6	Bottom	Variable	-
4	Propane	Variable	Top	50/50	-
5	Propane	Variable	Top	60/60	-
6	Propane	Variable	Top	80/80	-
7	Propane	6	Bottom	Variable	19
8	Propane	7	Bottom	Variable	20
9	Propane	8	Bottom	Variable	21
10	Propane	9	Bottom	Variable	22
11	Propane	6	Top	Variable	23
12	Propane	7	Top	Variable	24
13	Propane	8	Top	Variable	25
14	Propane	9	Top	Variable	26

Figures 19-26 contain a matrix of black square markers which represent actual data points. The curves through the data are locii of equi-volume ratios of CO/CO_2 and therefore represent regions of constant oxygen potential. These plots permit operation of the burner at the oxygen potentials required to maintain the pre-calculated operating conditions for the formation of an iron oxysulfide phase and optimal pickup and retention of sulfur by liquid iron oxysulfide droplets.

Table 3

Burner Conditions: Effect of Variation of Air
Fuel Added with Bottom Air

Fuel: Propane plus Acetylene; Flows Maintained Constant
Propane: 2.4SCFM + Acetylene: 3.6SCFM
Stoichiometric Air Requirements:

Propane:	2.4SCFM	Acetylene:	3.57SCFM
Air:	57.1SCFM	Air:	42.5SCFM

SCFM Air		Assay Vol %		Ratio
Bottom	Top	CO	CO2	CO/CO2
50	70	0.01	4.77	0.00
40	70	0.01	5.31	0.00
30	70	0.01	5.13	0.00
50	60	0.01	5.86	0.00
40	60	0.01	6.23	0.00
30	60	0.01	5.86	0.00
40	50	0.09	6.80	0.01
30	50	0.33	6.42	0.05
30	40	1.80	5.49	0.33
30	30	3.01	4.77	0.63

Combustion Constant Data:

	Density lb/ft3	Enthalpy Btu/ft3
Propane	0.120	2590
Acetylene	0.070	1499

Table 4

Burner Conditions: Effect of Variation of Fuel
Fuel Added with Top Air

Fuel: Propane
Bottom Air: 50SCFM + Top Air: 50SCFM
Air Flows Maintained Constant

SCFM	Assay Vol%		Ratio
Fuel	CO	CO2	CO/CO2
8.7	13.28	6.42	2.07
8	11.01	5.86	1.88
7	8.91	6.99	1.27
6.6	5.25	8.36	0.63
6	3.35	10.21	0.33
5	0.09	10.84	0.01
4	0.01	7.97	0.00
3	0.01	5.67	0.00

Table 5

Burner Conditions: Effect of Variation of Fuel
Fuel Added with Top Air

Fuel: Propane
Bottom Air: 60SCFM + Top Air: 60SCFM
Air Flows Maintained Constant

SCFM	Assay Vol%		Ratio
Fuel	CO	CO2	CO/CO2
8.5	8.42	6.61	1.27
8	7.45	7.19	1.04
7	2.08	10.21	0.20
6.6	0.85	11.70	0.07
6	0.05	11.27	0.00
5	0.02	8.67	0.00
4	0.01	6.42	0.00

Table 6

Burner Conditions: Effect of Variation of Fuel
Fuel Added with Top Air

Fuel: Propane
Bottom Air: 80SCFM + Top Air: 80SCFM
Air Flows Maintained Constant

SCFM	Assay Vol%		Ratio
Fuel	CO	CO2	CO/CO2
8.8	1.80	11.05	0.16
8	0.49	11.92	0.04
7	0.09	11.05	0.01
6	0.01	6.80	0.00

Table 7

Burner Conditions: Effect of Variation of Air
Fuel Added with Bottom Air

Fuel: Propane; Flows Maintained Constant
Propane: 6SCFM

SCFM Air		Assay Vol%		Ratio
Bottom	Top	CO	CO2	CO/CO2
80	80	0.01	7.28	0.00
80	70	0.01	6.90	0.00
70	80	0.01	7.48	.0.00
60	80	0.01	8.27	0.00
50	80	0.01	8.77	0.00
40	80	0.89	12.47	0.07
30	80	7.22	8.67	0.83
70	70	0.01	7.87	0.00
60	70	0.01	8.67	0.00
50	70	0.01	9.89	0.00
40	70	0.01	11.05	0.00
30	70	0.01	10.52	0.00
60	60	0.01	8.77	0.00
50	60	0.01	10.73	0.00
40	60	0.01	12.35	0.00
30	60	0.01	13.02	0.00
50	50	0.01	11.06	0.00
40	50	0.57	12.69	0.04
30	50	1.93	11.59	0.17
40	40	2.22	10.42	0.21
30	40	8.17	7.38	1.11
30	30	11.01	5.86	1.88

Figure 19

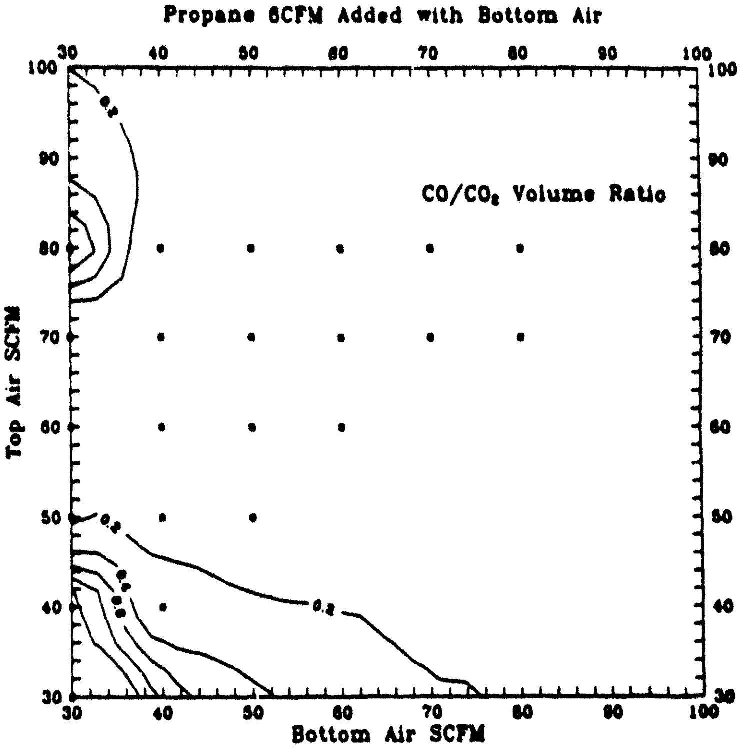


Table 8

Burner Conditions: Effect of Variation of Air
Fuel Added with Bottom Air

Fuel: Propane; Flows Maintained Constant
Propane: 7SCFM

SCFM Air		Assay Vol%		Ratio
Bottom	Top	CO	CO2	CO/CO2
90	100	0.01	8.46	0.00
80	100	0.01	8.87	0.00
70	100	0.01	9.17	0.00
60	100	0.01	11.70	0.00
50	100	0.49	12.24	0.04
40	100	5.66	8.57	0.66
90	90	0.01	8.87	0.00
80	90	0.01	9.79	0.00
70	90	0.01	9.79	0.00
60	90	0.01	10.52	0.00
50	90	0.01	12.03	0.00
40	90	3.70	9.58	0.39
80	80	0.01	9.07	0.00
70	80	0.01	9.17	0.00
60	80	0.01	10.00	0.00
50	80	0.01	10.42	0.00
40	80	1.66	11.05	0.15
30	80	6.76	8.07	0.84
70	70	0.01	10.21	0.00
60	70	0.01	11.16	0.00
50	70	0.01	11.92	0.00
40	70	0.27	12.14	0.02
30	70	2.52	10.52	0.24
60	60	0.15	12.91	0.01
50	60	0.66	12.58	0.05
40	60	4.45	10.00	0.44
30	60	7.69	8.36	0.92
50	50	5.45	9.17	0.59
40	50	8.03	7.77	1.03
30	50	9.68	7.09	1.37
40	40	10.47	6.52	1.61
30	40	11.84	5.90	2.01

Figure 20

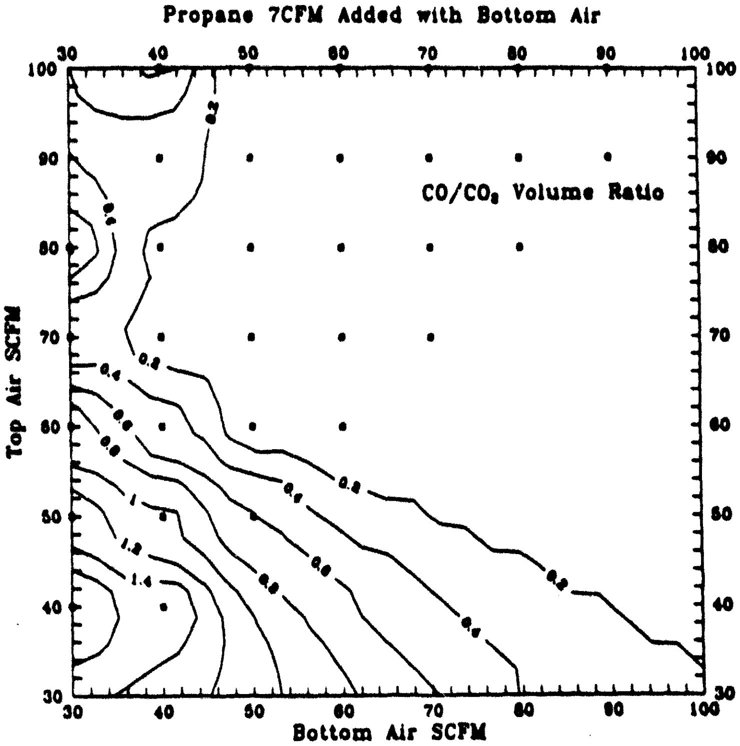


Table 9

Burner Conditions: Effect of Variation of Air Fuel Added with Bottom Air

Fuel: Propane; Flows Maintained Constant
Propane: 8SCFM

SCFM Air		Assay Vol%		Ratio
Bottom	Top	CO	CO2	CO/CO2
90	90	0.01	12.80	0.00
80	90	0.09	12.69	0.01
70	90	0.49	12.47	0.04
60	90	5.25	9.38	0.56
50	90	8.42	7.57	1.11
40	90	11.01	6.14	1.79
90	80	0.02	12.24	0.00
80	80	0.33	12.69	0.03
70	80	2.08	11.59	0.18
60	80	4.07	10.00	0.41
50	80	6.09	8.77	0.70
40	80	9.94	6.80	1.46
30	80	12.13	5.31	2.28
80	70	0.02	11.92	0.00
70	70	0.20	12.69	0.02
60	70	2.08	12.35	0.17
50	70	5.25	11.37	0.46
40	70	9.94	6.42	1.55
30	70	10.21	6.33	1.61
60	60	9.42	6.42	1.47
50	60	10.74	6.14	1.75
40	60	11.01	5.86	1.88
30	60	11.01	5.86	1.88
50	50	11.01	5.86	1.88
40	50	11.56	5.49	2.11
30	50	11.56	5.31	2.18
40	40	12.13	5.13	2.37

Figure 21

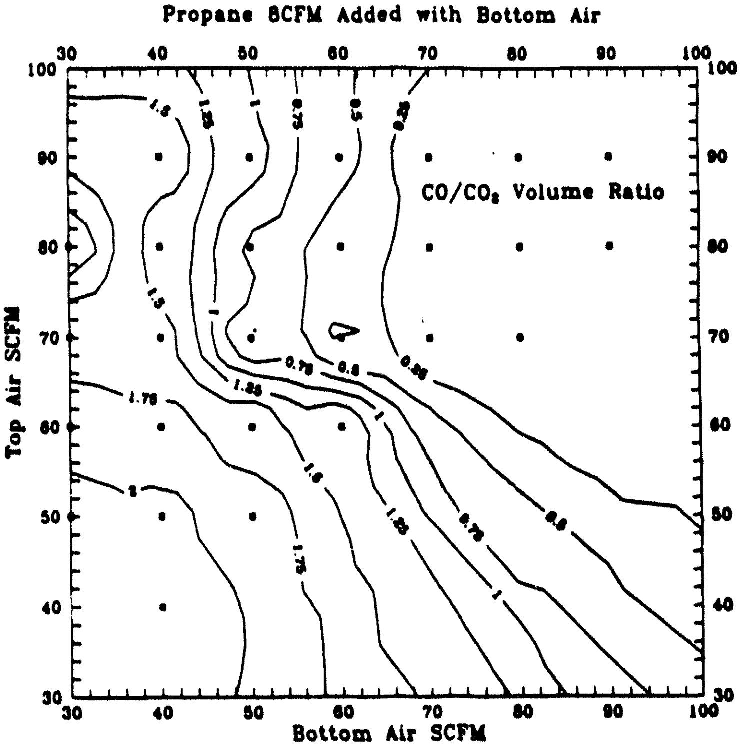


Table 10

Burner Conditions: Effect of Variation of Air
Fuel Added with Bottom Air

Fuel: Propane; Flows Maintained Constant
Propane: 9SCFM

SCFM Air		Assay Vol%		Ratio
Bottom	Top	CO	CO2	CO/CO2
100	100	0.01	12.69	0.00
90	100	0.15	12.91	0.01
80	100	0.57	12.35	0.05
70	100	2.08	10.73	0.19
60	100	3.88	10.31	0.38
50	100	9.17	7.28	1.26
90	90	1.06	12.03	0.09
80	90	2.08	11.16	0.19
70	90	4.64	9.27	0.50
60	90	7.69	7.87	0.98
50	90	10.21	6.80	1.50
40	90	11.29	5.95	1.90
80	80	2.84	10.52	0.27
70	80	5.25	8.97	0.59
60	80	9.68	6.99	1.38
50	80	9.84	6.80	1.45
40	80	10.74	6.33	1.70
30	80	10.74	6.33	1.70
70	70	9.68	6.90	1.40
60	70	11.29	5.86	1.93
50	70	12.41	5.58	2.22
40	70	12.70	5.77	2.20
30	70	12.41	5.86	2.12
60	60	11.84	5.77	2.05
50	60	12.41	5.40	2.30
40	60	12.99	5.22	2.49
30	60	12.99	5.04	2.58
50	50	12.70	5.04	2.52
40	50	14.18	4.68	3.03
30	50	14.18	4.68	3.03
40	40	14.80	4.14	3.57

Figure 22

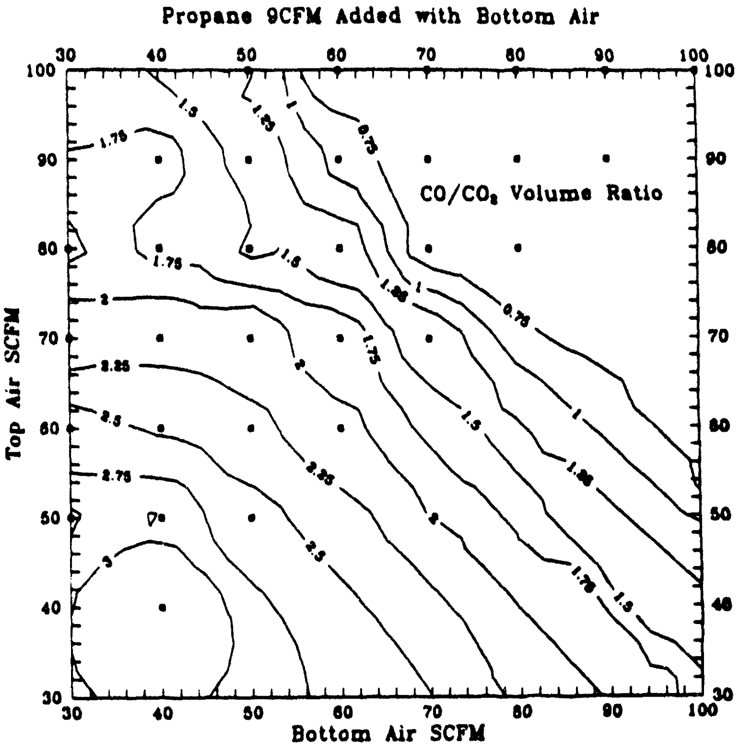


Table 11

Burner Conditions: Effect of Variation of Air
Fuel Added with Top Air

Fuel: Propane; Flows Maintained Constant
Propane: 6SCFM

SCFM Air		Assay Vol%		Ratio
Bottom	Top	CO	CO2	CO/CO2
80	80	0.01	7.38	0.00
80	70	0.01	8.57	0.00
80	60	0.01	9.38	0.00
80	50	0.01	9.89	0.00
80	40	0.01	10.10	0.00
70	80	0.01	8.07	0.00
60	80	0.01	7.97	0.00
50	80	0.01	9.17	0.00
40	80	0.01	10.25	0.00
70	70	0.01	8.97	0.00
60	70	0.01	9.07	0.00
50	70	0.01	10.16	0.00
40	70	0.01	11.70	0.00
70	60	0.01	9.58	0.00
70	50	0.01	10.31	0.00
70	40	0.41	11.48	0.04
60	60	0.01	10.31	0.00
50	60	0.01	11.48	0.00
40	60	0.09	12.47	0.01
30	60	3.35	10.00	0.33
60	50	0.09	11.27	0.01
60	40	0.09	9.79	0.01
50	50	0.33	12.47	0.03
40	50	3.01	10.52	0.29
30	50	7.45	7.97	0.94
50	40	1.80	11.16	0.16

Figure 23

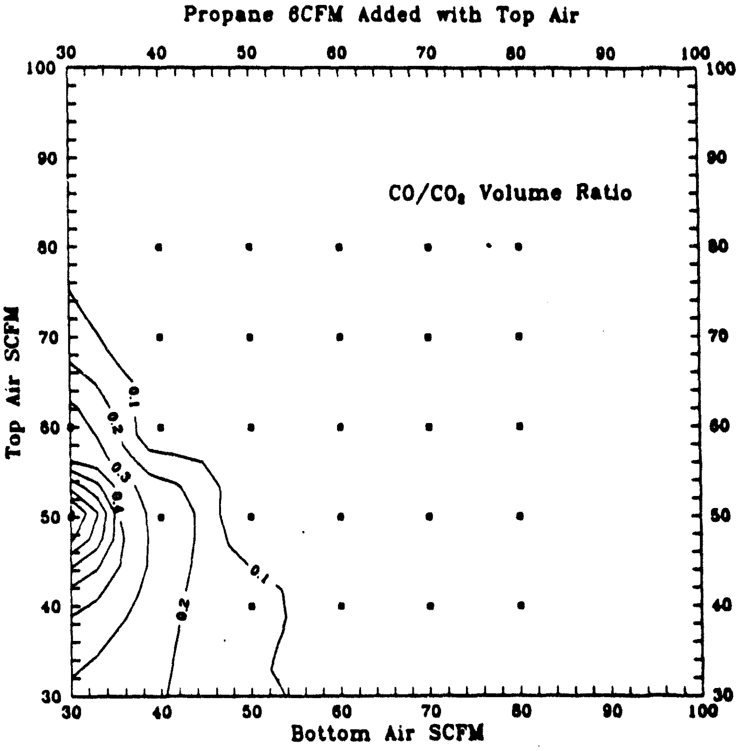


Table 12

Burner Conditions: Effect of Variation of Air
Fuel Added with Top Air

Fuel: Propane; Flows Maintained Constant
Propane: 7SCFM

SCFM Air		Assay Vol%		Ratio
Bottom	Top	CO	CO2	CO/CO2
90	90	0.05	10.63	0.00
90	80	0.02	11.27	0.00
90	70	0.18	11.81	0.02
90	60	0.31	11.70	0.03
80	90	0.02	10.59	0.00
70	90	0.02	11.31	0.00
60	90	0.02	11.70	0.00
80	80	0.09	11.05	0.01
80	70	0.07	11.66	0.01
80	60	0.33	11.59	0.03
80	50	0.49	11.48	0.04
70	80	0.01	9.58	0.00
60	80	0.01	10.52	0.00
50	80	0.01	11.92	0.00
70	60	0.41	12.14	0.03
70	50	5.04	9.27	0.54
70	40	8.66	6.80	1.27
60	70	0.15	12.58	0.01
50	70	0.95	11.81	0.08
40	70	3.01	10.52	0.29
60	60	2.08	10.21	0.20
60	50	6.09	8.46	0.72
60	40	9.68	6.71	1.44
60	30	10.74	5.58	1.92
50	60	3.88	9.96	0.39
40	60	6.99	7.57	0.92
50	50	8.91	6.99	1.27
50	40	12.41	5.53	2.25
50	30	12.82	4.91	2.61
40	40	12.41	5.49	2.26

Figure 24

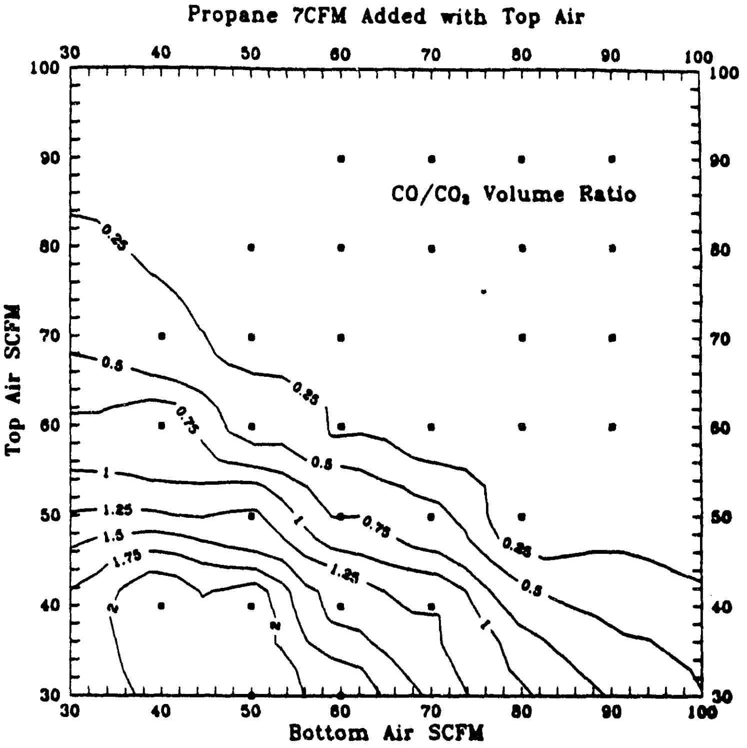


Table 13

Burner Conditions: Effect of Variation of Air
Fuel Added with Top Air

Fuel: Propane; Flows Maintained Constant
Propane: 8SCFM

SCFM Air		Assay Vol%		Ratio
Bottom	Top	CO	CO2	CO/CO2
90	90	0.01	7.48	0.00
80	90	0.01	8.36	0.00
70	90	0.01	10.00	0.00
60	90	0.01	10.95	0.00
50	90	0.03	12.91	0.00
40	90	2.37	9.58	0.25
30	90	4.84	8.97	0.54
90	80	0.01	8.77	0.00
80	80	0.01	10.31	0.00
70	80	0.01	11.37	0.00
60	80	0.01	12.91	0.00
50	80	1.29	12.35	0.10
40	80	4.45	10.21	0.44
30	80	7.45	8.27	0.90
80	70	0.01	11.27	0.00
70	70	0.05	12.58	0.00
60	70	0.66	12.80	0.05
50	70	3.70	10.63	0.35
40	70	6.54	8.97	0.73
30	70	10.47	6.80	1.54
70	60	0.33	12.58	0.03
60	60	1.29	2.53	0.51
50	60	5.88	9.27	0.63
40	60	8.66	7.57	1.14
30	60	12.13	4.59	2.64
60	50	4.84	9.58	0.51
50	50	9.94	6.80	1.46
40	50	11.01	6.23	1.77
30	50	12.70	5.31	2.39
50	40	12.13	5.49	2.21
40	40	10.47	6.52	1.61
30	40	13.28	4.95	2.69

Figure 25

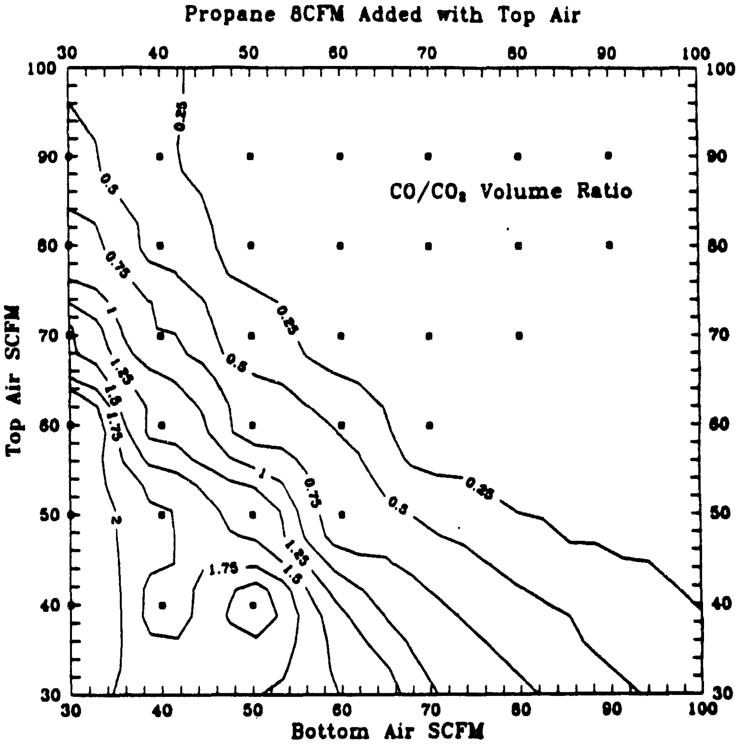


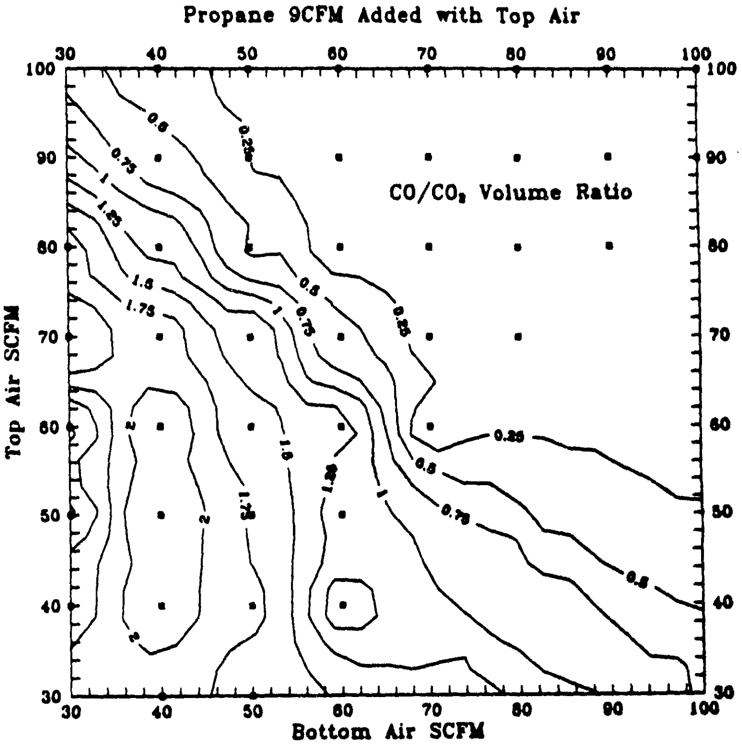
Table 14

Burner Conditions: Effect of Variation of Air
Fuel Added with Top Air

Fuel: Propane; Flows Maintained Constant
Propane: 9SCFM

SCFM Air		Assay Vol%		Ratio
Bottom	Top	CO	CO2	CO/CO2
100	100	0.01	6.61	0.00
90	100	0.01	6.99	0.00
80	100	0.01	7.77	0.00
70	100	0.01	9.48	0.00
60	100	0.05	10.95	0.00
50	100	1.17	11.70	0.10
40	100	3.88	10.10	0.38
100	90	0.01	9.58	0.00
90	90	0.01	10.52	0.00
80	90	0.01	10.95	0.00
70	90	0.01	11.81	0.00
60	90	0.20	12.80	0.02
50	90	2.52	11.16	0.23
40	90	5.25	9.38	0.56
90	80	0.01	10.84	0.00
80	80	0.01	11.48	0.00
70	80	0.02	12.80	0.00
60	80	1.06	12.03	0.09
50	80	4.45	9.89	0.45
40	80	8.66	7.28	1.19
30	80	11.01	5.95	1.85
80	70	0.02	11.16	0.00
70	70	1.80	11.48	0.16
60	70	4.84	9.48	0.51
50	70	9.68	6.61	1.46
40	70	11.01	5.77	1.91
30	70	12.70	5.04	2.52
70	60	0.66	11.92	0.06
60	60	9.42	6.80	1.39
50	60	10.21	6.42	1.59
40	60	11.84	5.13	2.31
30	60	2.08	1.80	1.16
60	50	8.42	7.38	1.14
60	40	5.25	6.61	0.79
50	50	10.47	6.05	1.73
40	50	11.84	4.77	2.49
30	50	4.84	4.06	1.19
50	40	10.21	5.58	1.83
50	30	8.42	5.40	1.56
40	40	11.56	4.95	2.34
30	40	7.93	4.86	1.63
40	30	9.58	4.95	1.94

Figure 26



Magnetite Tests

Due to the extended time required for the design and construction of an operating burner system it was not possible to carry out the high temperature sorption tests with the injection of solids as originally planned.

However, in order to obtain an initial indication of system performance with the injection of magnetite powder several exploratory tests were done in the glass models to observe the retention characteristics of fine dense powders. This work provided guidance in selecting flow balance parameters to minimize powder rejection with the exit gas and maximize the retention of the solids in the dynamic containment vessel.

At the end of the project period one very crude test was carried out with the injection of a small quantity of taconite concentrate (95% magnetite) into a flame containing injected H_2S gas. The solids were essentially retained within the burner and showed evidence of the formation of a molten phase at the corners of the fine particles. In a later test at the NSP installation the exit gas sulfur content was decreased by approximately 50% after the introduction of taconite concentrate into the burner.

Apart from these two encouraging indications no further sorption tests were performed.

CONCLUSIONS

This research project has lead to the following conclusions:

1. Stable Combustion in the dynamic containment combustor can be achieved under a range of operating conditions. These include
    - a) complete combustion within the burner
    - b) partial combustion within the burner and completion of combustion in a flame ejecting from the burner.
    - c) substoichiometric combustion in the burner to maintain a reducing atmosphere.
2. Flame stability is more easily achieved in larger burners with high energy levels than in small burners.
3. Specific energy levels in the order of 3-4 million BTU per cubic ft. of burner volume have been achieved in the present study with relatively small burners.
4. For the smaller systems used in this study improved performance was achieved with a small angle conical combustion chamber relative to a cylindrical combustion chamber. This advantage may not be significant for larger combustors (5 MMBTU or greater).
5. The basic fluid dynamic characteristics of the dynamic containment burner are such that flame contact with the burner walls is prevented and low wall temperatures are achieved.
6. Pressure measurements support the conclusion that the rotational velocity in the flame increases to counterbalance the volumetric increase of the gases due to combustion.

7. The dynamic containment system is effective in retaining solids within the dynamic containment vessel and has been proven with solids with specific gravities ranging from 0.8 to 4.5.

8. Steam is a practical alternative to compressed air as a fluid for the dynamic containment jet drives.

9. Preliminary tests have indicated that taconite concentrate containing over 90% of the iron oxide magnetite (Fe_30_4) is capable of absorbing sulfur from sulfur bearing flames operated under reducing conditions to form an iron oxysulfide compound.

10. Although comprehensive data on the sorption characteristics of solids injected into a dynamic containment combustor were not achieved in this project the basic principles of sorbent retention and sulfur removal have been demonstrated.

RECOMMENDATIONS

This project was the most complex of a multilevel approach to exploring the potential of the principles of dynamic containment and of iron oxide sulfur sorption for high temperature sulfur removal.

Due to the complexities of establishing a small scale dynamic containment burner the final objective of the original proposal — to compare the sorption behavior of lime and iron oxide — was not accomplished.

In a parallel project focused narrowly on the kinetics and thermodynamics of the iron-oxygen-sulfur system considerable progress was made and a clear delineation of the operating conditions required for effective sorption of sulfur from coal flames into an iron oxide sorbent has been obtained.

In order to complete the original objective of exploring the applicability of dynamic containment principles for higher temperature sulfur removal a considerable amount of work is required to establish a more detailed understanding of dynamic containment fundamentals while at the same time establishing a pilot scale test facility.

Recommendations for further work are as follows:

1. Basic fluid dynamic studies of the dynamic containment systems for
   - a) gas phase only — no combustion
   - b) gas phase only — with combustion
   - c) gas phase with solids injection - no combustion
   - d) gas phase with solids injection - with combustion

2. Fundamental studies on the influence of design variables on the fluid dynamics of dynamic containment vessels.
3. Fundamental and experimental studies of acoustic resonance in dynamic containment combustors.
4. Detailed practical studies of solid injection, retention, and removal from dynamic containment vessels.
5. Experimental studies on the combustion characteristics and performance of coal burning in a dynamic containment combustor.
6. Detailed theoretical and experimental studies of the practical operating regimes for steam driven dynamic containment.
7. Establishment of a pilot scale test rig for one stage and two stage dynamic containment combustion test work.
8. Extensive practical testwork using a range of possible sorbents in the pilot scale equipment.

ACKNOWLEDGEMENTS

The Regents of the University of Minnesota owns the basic patent for the dynamic containment technology (U.S. Pat# 5,11,757), and exclusive rights to the technology have been assigned to Dynamic Containment Inc.

The support and technical contributions made to this project by Dynamic Containment Inc., are gratefully acknowledged.

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