THE UNIVERSITY OF CALGARY

PERFORMANCE OF THE EYEHILL IN SITU COMBUSTION PILOT

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled,

"PERFORMANCE OF THE EYEHILL IN SITU COMBUSTION PILOT"

submitted by Richard William Thornton

in partial fulfillment of the requirements for the degree of Master of Engineering.

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Abstract

A burn tube study of core and fluids from the Eyehill Cummings Pool was done in 1984 under the auspices of a joint project sponsored by Energy, Mines, and Resources and The University of Calgary. This thesis presents a summary of a detailed analysis of field production data from the Eyehill Cummings Pool In Situ Combustion Pilot and a comparison to the data generated in this burn tube study. An attempt is made to determine the degree of correlation between the laboratory burn tube test results and the field results, and to use the burn tube test results to evaluate the field performance. The two main areas of investigation are the determination of the burn mode and the nearness of the fire front to the production wells.

The pilot project is operated by Murphy Oil Company Ltd., and joint venture partners in the project are Texaco Canada Resources and Canadian Occidental Petroleum Ltd.. Permission to use the confidential data from this field pilot was obtained from the joint venture partners on the condition that the thesis would only present this data in normalized form.

The field data was collected and consolidated into a form which would allow analysis of each sector of each pattern of the field project as an equivalent "combustion tube". Data was reduced to monthly totals or averages as appropriate and summarized into databases for the period June, 1980 through December, 1987. Plots of various appropriate ratios and indicators were then prepared for each sector and for each injection pattern (an average of the associated sectors) in a format to allow direct comparison to the combustion tube results.

Although the project is still very immature with the average burn volume less than 10% of the sector volume, the results indicate that when applied to a sector based analysis of the field data, the combustion tube results can be of benefit in analyzing the burn mode and the nearness of the combustion front to the production wells. The degree of correlation between the test and field results, and the validity of the evaluation of the field results using the test results should improve as the project matures.

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1. Introduction

Combustion tube tests have historically been used to determine fuel loadings and air requirements for use by the Reservoir Engineer in the design of in situ combustion pilots or for the calibration of numerical simulators. Although these tests are not scaled, they do have value in analyzing and predicting performance in field pilots.

Two questions of prime interest to the engineer are:

(1) Is the in situ process operating in the desired combustion mode?

(2) When will the fire front arrive at the production wells?

The data from properly designed combustion tube tests can be used as a guideline when interpreting the field data to answer these questions.

The Eyehill Thermal Project has been operational since June, 1980 and the data from start-up to December 31, 1987 has been used in conjunction with combustion tube data for the same reservoir to analyze the effectiveness of the in situ combustion process and the nearness of the fire front to the production wells.

Computer aided data storage and manipulation have enabled the comparison of the combustion tube test data to a statistically significant number of field elements which most closely correlate in structure to the combustion tube. Each injector-producer pair (sector) of the 9 pattern pilot (45 sectors in total) has been analyzed as an effective combustion tube. Documentation on the computer based databases and programs are held by Murphy Oil Company Ltd.

Past applications of combustion tube results to field data done on a pattern or project basis have established some validity for the use of combustion tube data in the interpretation of field data and analysis of field performance. This application of the data on a sector basis has resulted in a better understanding of the variability of the combustion process in a field pilot.

The combustion parameters and field data have varying degrees of usefulness in predicting the nearness of the fire front to the production wells when analyzed on a producer-injector pair (sector) basis. They indicate that the in situ combustion process has a wide range of performance across the pilot but when analyzed on a pattern basis these variations are masked by the averaging process. Based on the analysis of combustion parameters by pattern, (particularly the atomic Hydrogen to Carbon ratio and the Oxygen to Fuel ratio), the Eyehill In Situ Combustion Pilot appears to be operating in a good high temperature combustion mode and the fire front is not about to intersect any of the producers. On a sector basis analysis however, some problems are indicated with the combustion mode and the front is indicated to be in proximity to some of the producers.

These observations are supported by the project and combustion tube gas analyses. Based on the stabilized concentration of carbon-dioxide measured in the produced gas, the project appears to be operating in a mode similar to the wet normal air combustion tube test. Using the sector data, however, again demonstrates a wide variation in the combustion performance between sectors.

2. Field Project

2.1 Location

The Eyehill Cummings Pool is located approximately 60 miles south of Lloydminster, Alberta on the Alberta-Saskatchewan border. The pool location is shown in Figure 1. The In Situ Pilot was constructed during 1979 and ignition of the first of the nine patterns started in June, 1980. Ignition was completed in March, 1982 and the project has been under continuous operation since that time. Details of the Pilot operations are presented by Farquharson (1985).

The Pilot originally consisted of nine inverted twenty acre five spot patterns arranged to form a totally enclosed central pattern. Subsequent to start-up, wells 3C12-15, 3B13-15, and 3D09-16-40-28 W3M were directionally drilled in the northernmost pattern (Pattern A) and an existing well drilled for primary production (16-16-40-28 W3M) was placed on production to create an inverted nine spot pattern. This resulted in modification of the flow patterns in Patterns B and C. Patterns B, D, E, G, H, and I were modified by placing on production off-pattern wells as shown in Figure 2 (05-15, 01-16, 07-16 and 09-16-40-28 W3M). The combination of injector-producer pairs results in 48 field pattern sectors for comparison to the two laboratory tests. Due to the field configuration, some of the data has been combined to result in 45 effective sectors for analysis.

The data associated with the project is voluminous and is summarized in the Pilot annual reports (Thornton 1983, Thornton 1984, Thornton 1985, Kiprenko 1986, Harms 1987 and Harms 1988). The data for the 45 sectors and nine associated patterns was used to generate 648 plots as well as associated tables of the combustion data and parameters. Copies of these reports presenting selected results are held by the operator of the project (Murphy Oil Company Ltd.) and the data is considered to be confidential. A summary of the normalized data and parameters and selected results are included in this thesis.

2.2 Geology

The Eyehill Cummings member is a basal sand of the lower Cretaceous Manville group located at a depth of 2500 feet. The deposition is considered to be related to a river channel that was, in part, controlled by the underlying Devonian topography. The reservoir is considered to be a sequence of point bars made up of medium to fine grained unconsolidated sub-rounded quartz fragments. The channel configuration is truncated on the updip flank unconformably with Devonian topography and on the downdip side by bottom water.

The thickness of the pool varies across the pilot with the average net oil pay being 14 meters. To the north the net pay becomes thinner and interbedded with shales, and to the south-west the pilot is underlain by 15 meters of bottom water. Figure 3 shows the total thickness of the pay zone which contains the oil and water. Figure 4 shows the total thickness of the oil bearing zone with the difference in thickness being bottom water. Figure 5 shows the contour of the top of the pay zone. Where the top of the pay zone is situated below -310 feet sub-sea, the entire zone is saturated with water as shown by the O/W line on this figure. The datum line used in the structural cross-section in Figure 6 roughly corresponds to the oil/water contact and any zone below the contact is saturated with water.

Table 1 presents a comparison of the general reservoir data for the Pilot to the initial sand pack properties of the combustion tube test with the main difference being porosity. Although this comparison is favorable, the combustion tube tests could not model the bottom water situation found in the field. The existence of the bottom water zone is anticipated to prejudice the field results to more closely match the wet combustion tests, even though the field pilot is conducted as a dry combustion project.

2.3 Air Injection

Air injection into the injection wells started at low rates to allow the establishment of the burning front, and was slowly increased over time to 35490 m^3 per day per well. The start-up of the injection wells was staggered over almost a two year period due to problems with the ignition procedure. These problems have shown no correlation with project performance. The injection rates over this period were inconsistent and sometimes intermittent.

Subsequent to the ignition of the last well, other operational problems contributed to continued unstable injection rates. One of the injection wells (A12-15) was redrilled in close proximity to the original well as a result of collapsed casing in the original well. Core analysis indicated that this well intercepted the burn front from the original well and thus reignition was not required.

Air injection volumes are distributed through a manifold and the air flow to each injection well is measured continuously using an orifice meter. These meters are calibrated regularly to ensure the accuracy of measurement of the injected volumes.

2.4 Production

All of the production wells were placed on production at the start of the project, although some were shut in after only one or two months of production until the adjacent injector was ignited. Due to the ignition problems, and subsequent production related servicing or workover problems, the wells were cycled on and off at irregular intervals and were produced at irregular rates for the life of the project.

In the early stages of the project, fluid withdrawal rates from the production wells were restricted in an effort to avoid the severe water coning problems noted during the production of offsetting primary wells. This has no doubt resulted in lower rates of oil recovery than would be predicted by the combustion tube tests.

Gas production was not restricted in the early stages of the pilot. Depending on the production characteristics and the calculated air distribution in the patterns, some attempts were made later in the project to control gas production rates through the use of wellhead chokes or shutting-in of production.

At a later stage in the pilot two of the off-pattern primary wells were placed on production (01-16 and 07-16-40-28 W3M). This has added a degree of complexity to the analysis of the results. The assumption of radial burn front propagation early in the life of the pilot has been used to distribute a proportionate share of production from offsetting pilot wells to these locations to allow for the calculation of the burn front location in these sectors.

These off-pattern wells are more or less aligned with two of the pilot wells, but are located outside of the pattern. The fluid and gas production from these wells has been assigned to the pilot wells. These data manipulations have resulted in 45 injector-producer pairs for analysis. Each pair is referred to as a sector, and is treated as an equivalent "combustion tube" for analysis and comparison to the laboratory combustion tube tests.

The fluid production rates from each of the original 16 pilot production wells is measured continuously by means of patented mass flow measuring devices. These devices are calibrated on a regular basis to ensure the accuracy of the fluid production measurements. The water cut of the produced fluid is determined daily by sampling from the mass flow device and centrifuging the sample. This data is used to determine the oil and water production volumes. All produced water is disposed through a meter to a disposal well and the meter reading is used to prorate the water production volumes. Similarly, all produced oil is metered at the point of sale and this information is used to prorate the oil production volumes.

The mass flow devices also separate the produced gas from the liquids, and this gas passes through orifice meters for measurement on a continuous basis. These devices are also calibrated regularly. All produced gas is incinerated on site.

2.5 Oil and Water Analysis

Oil and water analyses were not performed on a regular basis during the early stages of the pilot. Most of the analyses during this period were done by commercial laboratories or treating and corrosion inhibition chemical sales companies. As the pilot matured, more regular analyses were done on site resulting in more consistent results. All on-site analyses are carried out according to ASTM standards.

The major characteristics of the oil which are regularly analyzed are the density and the viscosity. This data is presented as measured, at a consistent temperature, but has not been corrected to standard conditions. The produced water is analyzed for various cations and anions as well as for hardness, turbidity, pH, and density. The primary water characteristics of interest are pH and sulfate ion concentration.

2.6 Gas Analysis

The produced gas from each production well is sampled twice a month and analyzed using standard gas chromatographic techniques for mole per cent nitrogen, oxygen, carbon dioxide, carbon monoxide, methane, ethane, propane, and butane. The chromatograph is calibrated to a standard gas sample prior to each set of analyses, and the columns are conditioned as required. The gas is sampled in stainless steel containers and analyzed on site to minimize the potential for compositional changes.

The organization of the data in the databases and the one to one relationships required to create the combined database necessitated that only month end gas analyses were used in the preparation of this thesis. The data was perused, and no unusual analyses or sudden changes were noted which would indicate that this methodology would introduce any significant error.

2.7 Temperature Observation

The central pattern of the pilot project was equipped with three dry temperature observation wells at the start of the project. These wells were each equipped with a set of twenty fixed location Type K thermocouples with downhole temperature reference for stability.

Two of these wells are located approximately 20 m from the central injector (A09-16-40-28 W3M), on line that would pass between the original pattern producers at 90° to each other. The third well is located on a line between the injector and a producer, about 20 m from the producer.

Data was collected daily from the two central observation wells until they failed in service and is still being collected daily from the third observation well. The wells which failed suffered burn out of the nickel-alloy steel casing. Maximum measured temperatures prior to burn out were in excess of 400° C.

3. Combustion Tube Testing

The laboratory testing was carried out in a joint project between Mr. M. Raicar of Energy, Mines and Resources and Drs. Bennion and Moore of the University of Calgary. The core material, oil, and water were supplied by Murphy Oil Company Ltd. from the Eyehill Cummings Pool Pilot area. A detailed description of the apparatus and procedures is included in the final report by Bennion (1985).

Four combustion tube tests were run, one of which corresponds to the designed field operating conditions (Bennion 1984). The dry normal air (Test EMR/Murphy 1) and wet normal air (Test EMR/Murphy 4) data is compared to the field data in the discussion of results section of this thesis.

Based on the above tests, the magnitude of the stabilized gas phase combustion tube parameters are presented in Table 1.

4. Combustion Parameters

The combustion parameters have been calculated in a manner consistent with that used in the combustion tube analysis and as presented by White (1983), Farouq Ali (1979), and Butler (1986). A summary of the calculations is included in Appendix A. The field data has been reduced to monthly averages or sums as appropriate, and then prorated to the field sectors according to geometry and pattern recovery factors.

Since the solution of the volume of air stored behind the front would be an iterative process, and the volume would be relatively insignificant in comparison to the volume which has passed through the front, the burn volume is calculated assuming that all injected air has passed through the front. Inherent in this analysis is the assumption that all unrecovered gas is distributed in the same proportion as the recovered gas and that this unrecovered gas has the same composition as the recovered gas. These assumptions are consistent with best engineering judgement and are anticipated not to prejudice the analysis. Also inherent in the analysis is the assumption of early radial flow based on a homogeneous reservoir and a lack of directional permeability trends. Horizontal and vertical sweep efficiencies are assumed to be 100 per cent since this does not affect any of the comparisons to the combustion tube results. The burn radius calculated with these assumptions is the minimum radius of the front for each sector for a given fuel loading and air requirement. Volumetric conformance can be assumed in order to calculate other radii based on best engineering judgement.

5. Normalization of Field Data

To protect the confidentiality of the pilot field data, the data is presented in normalized form. The pattern data as presented in Tables 2 through 8 and the sector data presented in Tables 9 through 15 has been normalized such that the average pattern or sector is 100 and all others are a ratio thereof. Table 3 includes reference gas analyses for the project average (start-up to 1987), stabilized project (1985 to 1987), the normal dry combustion test (Test EMR/Murphy 1) and the normal wet combustion test (Test EMR/Murphy 4). All plots with volume burned on the abscissa present normalized volume burned such that the volume burned to the end of the reference period is 100. Since the project is very immature these plots represent in the order of one-tenth of the expected time for the firefront to reach the production wells.

Tables 2 through 6 show the normalized average data by pattern. Tables 7 and 8 show the normalized cumulative data by pattern. Tables 9 through 13 show the normalized average data by sector, and Tables 14 and 15 show the normalized cumulative data by sector. In general, these tables are organized with the raw data in the earlier tables and the more manipulated data in the later tables within each group. The order of the figures has been maintained from the combustion tube test reports resulting in a non-sequential reference in the discussion of results.

6. Selection of Field Data For Presentation

Since the volume of plots and printouts from the analysis of the field data is so large, only that portion which is most beneficial in the presentation of results is included in this thesis. Twelve plots were originally generated for each of the 45 sectors and 9 patterns for a total of 648 plots. The associated data has not all been printed, but that portion which has fills 87 pages. All of this information is held by the project operator (Murphy Oil Company Ltd.)

The normalization of the data has simplified to a certain extent the comparison of the data and has allowed the presentation of some data for all patterns and sectors. Plots for the dry combustion tube test, Pattern A, and Sectors 1 and 5 are presented in this thesis. Pattern A has been selected because it is the most mature pattern with the highest recovery factor. Sectors 1 and 5 are the north and south sectors in Pattern A and have been chosen because they demonstrate the wide range of performance within this pattern and are oriented such that directional permeability should not affect the results. Many of the results and conclusions presented based on these sectors and this pattern can be demonstrated with other sectors and patterns.

7. Results

7.1 Initial Properties

The combustion tube test sand packs were made of reservoir sand selected from Eyehill Cummings Pool cores. Since this sand is relatively homogeneous, the core material selected should be representative of the reservoir material. A comparison of combustion tube sand pack and reservoir data is presented in Table 1. Clays and fines tend to accumulate at each interface between the sequential pack stages in the preparation of the combustion tube and this results in a reduced permeability (2.1 μm^2 vs. 6.0 μm^2). The unconsolidated sand has a higher porosity after packing than in the reservoir (40.6% vs. 34%).

The fluid saturations of the sand pack are comparable to the field data. The factor which could have the largest influence in terms of saturations on the combustion tube results is the gas saturation which is unfortunately not known for the original field reservoir conditions.

The major variance between the field and combustion tube data are in the areas of oxygen flux and bottom water effects. The field oxygen flux is approximately 1/3 of the combustion tube flux near the start of the project decreasing to 1/20 by the end of the time frame in consideration. The bottom water effects have not been tested in the combustion tube and would be extremely difficult to test due to the lack of scaling in the test design.

7.2 Production

Production profiles are shown in Figures 14 and 15. Oil and water production rates and cumulative production volumes vary significantly between patterns as shown in Tables 2 and 7. This variation is even more significant between sectors as shown in Tables 9 and 14.

These wide variations are mainly due to the presence of a bottom water zone which varies in thickness across the pilot area. This active aquifer has caused the operator to control withdrawal rates in areas of the pilot and has still resulted in the production of large volumes of water from some wells. This bottom water zone is expected to distort the field results (particularly production and air requirements) to more closely resemble the wet combustion tube test results. Pattern A has the least bottom water with Sector 1 being essentially bottom water free and Sector 5 having an average amount of bottom water.

Pattern A has recovered about 2.5 times the project average oil recovery. Sector 1 has recovered the highest amount of oil per sector and Sector 5 has recovered less than an average amount of oil. Pattern A has produced an average amount of water even with the thinner bottom water zone. Sectors 1 and 5 have both produced relatively the same amount of water which is slightly less than the average amount per sector. Gas production for Pattern A and for Sectors 1 and 5 is slightly above average.

Within each pattern, large variations of oil, water and gas recovery are seen. The oil and water recovery appear to be independent of the gas recovery which is unexpected since the gas recovery is thought to be indicative of the movement of the burn front and the displacement of oil and the cumulative air recovery ratio from the project is over 0.9. Little attempt has been made during the project life to control gas production rates at the producing wells.

7.3 Air Injection

Average air injection rates and cumulative air injected by pattern show little variation as shown in Tables 2 and 7. This same small variation in rates and cumulatives is demonstrated for the sectors in Tables 9 and 14.

The method used to distribute gas production based on air injection volumes into influencing injectors has resulted in a recovery factor greater than unity in some sectors. A means of redistributing this overproduction has not been identified or implemented. Air injection and recovery profiles are presented in Figure 7.

The small variation in average air injection rates and volumes should result in very consistent combustion results in all patterns and sectors. As will be discussed later, this is not the case and the wide variations must find their explanation in the reservoir heterogeneities as gas analyses indicated success in the ignition operation in all injection wells.

7.4 Produced Oil Analysis

The averaged data for the patterns shows little variation in API gravity and viscosity as shown in Table 4. The API gravity also shows little variation between sectors, but the viscosity shows a very wide variation as shown in Table 11. Many of the sectors produced very tight emulsions and due to the difficulty in cleaning these emulsions, the viscosity measurements reflect the emulsion viscosity. Plots of API gravity and viscosity trends are presented in Figure 17. Some oxygen has been produced which may have resulted in low temperature oxidation near the producer, where the oxygen flux increases, causing the tight emulsions.

The API gravity is expected to rise and the viscosity to drop as the fire front approaches the production well. It is too early in the life of the project to see these effects in the field data, although some short term fluctuations have occurred and some unexplained differences between sectors remain.

7.5 Produced Water Analysis

Based on the available literature, the sulfate ion concentration and pH of the produced water have been identified as the prime indicators to monitor the approach of the fire front. To date the field pilot data does not permit definitive conclusions on the usefulness of these indicators.

There is little range in the averaged pH values for the patterns, but there is a significant range in the sulfate ion concentration as shown in Table 4. The variations between sectors is similar as shown in Table 11. Historical sulfate ion concentration and pH trends are presented in Figure 18. Zero values indicate data is not available. The water analysis has not been consistently performed resulting in a limited number of measurements. The high sulfate concentrations have been noted to correspond with the tight emulsions and in some cases with small temperature increases at the production wells further supporting the theory of low temperature oxidation in the vicinity of the production well. It is expected that variations in these indicators will be masked because of the presence of bottom water and the large volumes of water production which results in a dilution of the water of combustion.

7.6 Produced Gas Analysis

The produced gas analysis only shows large variation in the concentration of carbon monoxide both on a pattern and sector comparison as shown in Tables 3 and 10, although significant variations in the concentrations of carbon dioxide and oxygen also are seen in the sector comparison. Table 3 includes reference gas analyses which will allow direct comparison of the field project gas analyses with the combustion tube gas analyses. Without a superwet combustion tube test for comparison, a conclusion cannot be drawn with respect to the average gas analysis, but the stabilized gas analysis indicates a wet combustion mode in the field project.

The gas analysis early in the project life was incomplete in that the concentration of carbon monoxide was not being accurately measured due to the incorrect configuration of the on-site gas chromatograph. Carbon dioxide arrived at the production wells soon after ignition and the concentration rapidly rose to stabilized levels in the order of 14%. The delayed arrival of carbon monoxide at the production wells is thought to have resulted from some reaction of the carbon monoxide in the reservoir. This is somewhat substantiated by the large variations in the ratio of carbon oxides as compared to the relatively stable atomic hydrogen to carbon ratio as shown in Figure 13. The concentration of the carbon monoxide is expected to increase as the fire front approaches the production wells as noted in the combustion tube tests.

7.7 Temperature Response

The temperature response data from the field observation wells is not presented in this thesis, but it was felt necessary to address this point briefly. The field data for the area covered by the observation wells indicates good areal sweep, good vertical conformance, and a high temperature combustion mode in the inner 20 meter radius of the central pattern (Pattern E) with maximum temperatures in excess of 400° C measured at the observation wells.

7.8 Combustion Parameters

The combustion parameters evaluated are presented for the patterns in Table 5 and for the sectors in Table 12. There is a significant variation in the atomic hydrogen to carbon ratio, the ratio of carbon dioxide to carbon monoxide, and the ratio of total carbon oxides to carbon monoxide for the patterns. The variations between patterns in the other parameters are not large, however they may be significant in that relatively small variations in the ratio of carbon oxides to nitrogen are seen between the wet and dry combustion tests.

The largest variation between sector combustion parameters is seen in the atomic hydrogen to carbon ratio with smaller variations in the carbon oxide ratios. The trends in these parameters are presented in Figures 8 through 13.

The atomic hydrogen to carbon ratio is a representation of the apparent fuel composition which is an indicator of the burn mode. High values of this ratio are indicative of a low temperature oxidation mode. High values are expected very early in the pilot life because of the solubility of carbon oxides in the reservoir fluids. When the high values persist, concern over the burn mode is due. On the average, this ratio is in line with the laboratory results although somewhat higher. This may indicate the presence of low temperature oxidation reactions in the field.

The ratios of carbon dioxide to carbon monoxide and the total carbon oxides to carbon monoxide are very subject to the previously noted apparent reaction of the carbon monoxide in the reservoir fluids and also to the errors in accurately measuring the composition of the gas which contains only a fraction of a per cent of this component. These ratios are expected to decrease as the front approaches and the true values of this ratio are finally apparent. Field data does not yet allow for definitive conclusions regarding these trends. The ratios from the field data are noted to be much higher than the laboratory based ratios.

The ratio of carbon oxides to nitrogen is closely related to the Oxygen to Fuel ratio and is an indicator of the combustion performance. The values for this parameter fall in a narrow range for all sectors and patterns and would indicate good high temperature combustion in all sectors. This conclusion is weak in that a superwet combustion tube test was not run and therefore combustion tube data on low temperature combustion in this reservoir are not available. This parameter is not expected to provide any indication of the approach of the combustion front.

The oxygen utilization efficiency is calculated from the composition of the produced gas and the ratio of oxygen to nitrogen in the injected air. This indicates the amount of oxygen consumed in all reactions in the reservoir. The fraction of air consumed in the high temperature burn zone is calculated based on the ratio of carbon oxides in the produced gas, the atomic hydrogen to carbon ratio derived from the produced gas analysis and the theoretical hydrogen to carbon ratio derived from the combustion tube experiment. The burn efficiencies are the product of the oxygen utilization efficiency and the fraction of air consumed in the high temperature zone. These burn efficiencies indicate good high temperature combustion in all sectors and all patterns. The atomic hydrogen to carbon ratio is an indicator of the apparent fuel composition. High values indicate low temperature oxidation is occuring in some sectors, but this is not apparent from the pattern based analysis.

7.9 Combustion Performance

The volume of gas produced from each sector is used to calculate the amount of air which was injected based on the ratio of the nitrogen concentration in the produced gas to the concentration in the injected air. Depending on the geometry of the particular sector this air may have originated from more than one injector. The amount of this air which originated with a particular injector is determined by the ratio of the air injected into the injector being considered to the sum of the air injected into all injectors which influence the sector. This is referred to as the equivalent air produced.

The ratio of the sum of all equivalent air produced for a pattern to the air injected into the pattern is the air recovery ratio for the pattern. This ratio is used to determine the equivalent air burned in the sector by dividing the equivalent air produced by the air recovery ratio. This incorporates the assumption that all air injected passes through the burn zone. The equivalent air burned is used to calculate the burn volume based on the combustion tube test derived air to fuel ratio and fuel loading. This volume is converted into an equivalent burn radius based on simple geometry and the assumption of full vertical conformance and radial flow.

Combustion performance is summarized for the patterns in Tables 6 and 8. These tables show surprisingly little variation in the combustion performance indicators between patterns. Tables 13 and 15 demonstrate the variation in combustion performance indicators between sectors which is much more significant than the variations between patterns. There is a fifteen-fold variation in burn volume and a five-fold variation in burn radius.

Oxygen to oil ratios are perhaps the best indicator of the project economics due to the high capital and operating costs associated with air injection. This parameter shows significantly different historical trends as shown on Figure 16. Pattern A and Sector 1 both show a similar profile to the combustion tube results with the ratio dropping rapidly to a stabilized low level and remaining there, but Sector 5 shows an increasing trend in this ratio to a peak value followed by a slow decrease, with a much higher stabilized value.

Although the pattern based analysis shows good results in all patterns, and some correlation to the combustion tube results, there is less consistency in the sector based analysis and poorer correlation to the combustion tube results indicating a greater variability in the combustion performance exists than is apparent from the pattern based analysis.

8. CONCLUSIONS

1) All field data from the Eyehill In Situ Combustion Pilot was collected for the period 01 June 1980 through 31 December 1987. Personal computer based databases were created for a monthly summary of all of the data. The data was assigned to sectors (injector-producer pairs) and analyzed both on a sector and a pattern basis where the pattern is the sum or average of the sectors.

2) The field project is immature and thus definitive conclusions are hard to draw with respect to the analysis of the approach of the burn front.

3) The early lack of analysis and the reaction of the carbon monoxide with the reservoir fluids significantly impacts the analysis of the combustion parameters which are used to analyze the burn mode.

4) The presence of bottom water in the field impacts the analysis of the combustion performance by its effect on water recovery, oil recovery, and the dilution effect on the produced water.

5) Analysis of a complex field project on a pattern basis will result in the masking of important variations in combustion performance indicators and parameters which will show up on a sector based analysis.

6) The reservoir is sufficiently heterogeneous that even though the air injection by pattern shows little variation, the gas distribution varies significantly, and thus the combustion performance varies significantly between sectors.

7) Rigorous application of the distribution of gas production based on air injection into influencing injectors does not result in a correct distribution as witnessed by some recovery factors greater than unity. Solution gas volumes are comparatively insignificant and have been ignored in this analysis.

8) Combustion performance parameters do not agree in all cases in their indication of the combustion mode. The averaging effect when these parameters are analyzed on a pattern basis tends to hide the poor performance of related sectors.

9) The carbon oxides ratios and the atomic hydrogen to carbon ratio display the widest ranges in values. The atomic hydrogen to carbon ratio is the most useful parameter when comparing the in situ combustion mode of the field sectors.

10) The stabilized gas analysis indicates a wet combustion mode in the field project based on carbon-dioxide concentration, but large variations are seen between field patterns and sectors.

11) The oxygen to oil ratio shows significantly different trends between sectors and is useful in comparing the combustion performance of the field sectors.

12) The project is too young for definitive conclusions to be drawn regarding the usefulness of the oil and water analysis in projecting the approach of the fire front to the production wells.

13) Taking into consideration the presence of bottom water and the reservoir heterogeneities, the combustion tube data is useful in providing a reference for the analysis of the combustion mode and the approach of the fire front to the production wells in the field project. Significant variations in the gas analyses from the combustion tube data correlate with poorer field performance on a sector basis.

9. RECOMMENDATIONS

1) This analysis should be updated when the project is more mature.

2) The operator should closely monitor those sectors showing significant departure from the combustion tube predicted parameters for further signs of low temperature oxidation, or should attempt to make operational changes in the field to affect the performance and monitor the results.

3) The operator should attempt to make changes to the field operations to try to affect the oxygen to oil ratios in sectors such as Sector 5 which is demonstrating an uneconomic level of oxygen to oil ratio.

4) When a better understanding of the reaction kinetics of in situ combustion has been developed and implemented, numerical simulation of the field results should be carried out to better understand the variations in the sector performance and to assist the operator in making adjustments to the field operations to improve the effectiveness of the pilot.

5) As the pilot matures, the data should be monitored to watch for trends in the oil and water analysis data and in the carbon monoxide and hydrogen sulfide concentrations to predict the approach of the fire front to the production wells.

6) Further analysis could be carried out by the operator on the non-normalized data to better compare the oil recoveries and economics of the patterns and sectors with the goal of improving the project economics and predicting oil recoveries.

7) Further work could be done to make best engineering judgements on the volumetric conformance of the in situ process and predict the location of the fire front, the size of the burning area, the oxygen flux, the extinction radius, etc. for the various patterns and sectors.

8) A superwet combustion tube experiment should be run to provide a reference for low temperature combustion which might allow more definitive conclusions to be drawn based on the field data analysis.

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Table 1

Comparison of Reservoir and Sand Pack Data

Parameter	Field	Combustion Mode Normal Dry	Combustion Mode Normal Wet
Porosity (%)	34	40.6	40.8
Oil Saturation (%)	86	82.5	82.6
Water Saturation (%)	14	17.5	11.1
Gas Saturation (%)	UNKNOWN	0	6.3
Permeability (μm^2)	6.0	2.1	10.4
Pressure (kPa)	5000	6200	6200
Oxygen Flux (m^3(ST)/m^2h)	VARIABLE[1]	6.31	6.02
Oxygen Concentration (mole %)	20.99	20.99	20.07
Water/Oxygen Ratio (kg/m^3(ST))	0	0	10.86
Oxygen/Fuel Ratio (m^3(ST)/kg)	2.37	2.35	2.24
Atomic Hydrogen/Carbon Ratio	2.85	1.64	1.22
$(CO_2+CO)/N_2$ [2]	.156	.197	.200

[1] The Field Oxygen Flux at a burn radius of 1 m is 1.76 (m^3(ST)/m^2h) and at a burn radius of 50 m is 0.035 (m^3(ST)/m^2h).

[2] The stabilized field $(CO_2+CO)/N_2$ ratio is 0.180 .

Table 2

Summary of Normalized Average Fluid Rates by Pattern

PATTERN	AIR INJECTED	GAS PRODUCED	OIL PRODUCED	WATER PRODUCED
A	92	115	232	88
B	107	100	72	83
C	91	80	97	72
D	101	87	89	148
E	100	93	56	57
F	100	111	135	109
G	107	102	61	91
H	104	91	72	99
I	98	121	86	154

Table 3

Summary of Normalized Average Gas Analysis by Pattern With Reference Analysis[1]

PATTERN	O_2	CO_2	CO	N_2
A	115	97	184	96
B	106	105	78	100
C	112	92	111	99
D	87	104	77	100
E	104	100	88	101
F	90	95	64	100
G	91	107	84	101
H	99	96	88	101
I	96	104	126	101
PROJECT AVERAGE	.22	12.48	.17	80.93
PROJECT STABILIZED	.21	14.05	.19	79.21
BURN TUBE DRY	.36	13.65	2.69	83.00
BURN TUBE WET	.14	14.62	1.95	82.70

[1] PROJECT AVERAGE is the basis for normalization

PROJECT STABILIZED is the average for the period 1985 - 1987

BURN TUBE DRY is Test EMR/Murphy 1

BURN TUBE WET is Test EMR/Murphy 4

Table 4

Summary of Normalized Average Fluid Analysis by Pattern

PATTERN	SO_4	pH	°API	VISCOSITY
A	119	100	101	84
B	159	100	99	99
C	125	100	103	103
D	157	100	98	108
E	120	100	100	89
F	58	100	104	118
G	80	100	98	92
H	44	99	100	108
I	37	100	99	100

Table 5

Summary of Normalized Average Combustion Parameters by Pattern

PATTERN	ATOMIC H:C RATIO	CO2 / CO	O2 / FUEL	CO2+CO / CO	CO2+CO / N2	EO_2	FB
A	101	41	102	42	99	100	101
B	77	125	97	125	106	100	103
C	122	66	107	66	91	100	94
D	75	213	97	212	105	100	103
E	81	88	99	88	100	100	98
F	151	126	105	126	94	100	99
G	65	96	94	96	107	100	105
H	157	82	103	82	95	100	95
I	72	62	96	62	103	100	102

Table 6

Summary of Normalized Average Combustion Volumes by Pattern

PATTERN	EQUIVALENT AIR PRODUCED	EQUIVALENT AIR BURNED	BURN EFFICIENCY	BURN VOLUME
A	118	95	101	88
B	97	104	103	114
C	78	86	94	84
D	89	104	103	106
E	92	96	98	102
F	102	91	99	97
G	114	132	105	107
H	91	99	95	100
I	118	94	102	103

Table 7

Summary of Normalized Cumulative Fluid Volumes by Pattern

PATTERN	AIR INJECTED	GAS PRODUCED	OIL PRODUCED	WATER PRODUCED
A	95	119	225	85
B	104	98	77	86
C	86	77	93	68
D	104	90	94	153
E	96	91	60	60
F	91	101	118	92
G	132	117	64	94
H	99	89	76	101
I	94	118	93	161

Table 8

Summary of Normalized Cumulative Combustion Volumes by Pattern

PATTERN	EQUIVALENT AIR PRODUCED	EQUIVALENT AIR BURNED	BURN VOLUME	BURN RADIUS	OIL[1] RECOVERY
A	118	95	90	102	259
B	97	104	111	98	67
C	78	86	79	102	124
D	89	104	108	95	79
E	92	96	98	94	54
F	102	91	88	111	166
G	114	132	132	106	56
H	91	99	96	99	78
I	118	94	98	94	84

[1] Oil recovery is expressed as a percentage of oil-in-place by pattern normalized against project oil recovery expressed as a percentage of oil-in-place for the project. The average of the pattern recoveries is therefore different than the project average recovery since the oil-in-place differs by pattern.

Table 9

Summary of Normalized Average Fluid Rates by Sector

SECTOR	PATTERN	AIR INJECTED	GAS PRODUCED	OIL PRODUCED	WATER PRODUCED
1	A	92	99	349	45
2	A	92	158	257	87
3	A	92	98	180	104
4	A	92	29	47	31
5	A	92	84	56	60
6	A	92	37	59	126
7	A	92	17	62	91
8	A	92	203	293	43
9	B	107	19	62	91
10	B	107	40	59	126
11	B	107	94	56	60
12	B	107	147	134	53
13	B	107	101	44	62
14	B	107	130	94	129
15	C	91	108	180	104
16	C	91	132	110	88
17	C	91	29	41	49
18	C	91	83	56	60
19	C	91	28	47	31
20	D	101	122	94	129
21	D	101	93	44	62
22	D	101	82	85	122
23	D	101	109	191	354
24	E	100	92	56	60
25	E	100	34	41	49
26	E	100	112	31	59
27	E	100	98	44	62
28	E	100	134	134	53
29	F	100	167	110	88
30	F	100	240	323	174
31	F	100	52	70	139
32	F	100	37	41	49
33	G	107	102	44	62
34	G	107	107	31	59
35	G	107	174	92	145
36	G	107	86	85	122
37	H	104	36	41	49
38	H	104	49	70	139
39	H	104	95	95	31
40	H	104	142	133	211
41	H	104	114	31	59
42	I	98	106	31	59
43	I	98	126	133	211
44	I	98	191	174	371
45	I	98	168	92	145

Table 10

Summary of Normalized Average Gas Analysis by Sector

SECTOR	PATTERN	O_2	CO_2	CO	N_2
1	A	91	84	199	91
2	A	136	115	207	99
3	A	88	90	131	94
4	A	157	102	128	102
5	A	132	102	111	101
6	A	88	102	96	101
7	A	99	91	102	97
8	A	120	118	222	100
9	B	99	91	102	97
10	B	88	102	96	101
11	B	132	102	111	101
12	B	80	118	69	97
13	B	95	108	90	100
14	B	97	107	104	99
15	C	88	90	131	94
16	C	90	93	81	101
17	C	89	81	67	104
18	C	132	102	111	101
19	C	157	102	128	102
20	D	97	107	104	99
21	D	95	108	90	100
22	D	92	99	62	101
23	D	79	99	74	98
24	E	132	102	111	101
25	E	89	81	67	104
26	E	94	101	91	102
27	E	95	108	90	100
28	E	80	118	69	97
29	F	90	93	81	101
30	F	95	103	84	98
31	F	75	92	58	100
32	F	89	81	67	104
33	G	95	108	90	100
34	G	94	101	91	102
35	G	82	107	103	101
36	G	92	99	62	101
37	H	89	81	67	104
38	H	75	92	58	100
39	H	90	111	63	101
40	H	137	103	126	100
41	H	94	101	91	102
42	I	94	101	91	102
43	I	137	92	126	100
44	I	80	107	96	101
45	I	82	91	103	101

Table 11

Summary of Normalized Average Fluid Analysis by Sector

SECTOR	PATTERN	SO_4	pH	°API	VISCOSITY
1	A	86	107	100	60
2	A	148	94	101	62
3	A	29	98	101	77
4	A	116	92	102	59
5	A	158	99	99	112
6	A	153	101	105	61
7	A	128	104	100	87
8	A	101	65	98	61
9	B	128	104	100	87
10	B	153	101	105	61
11	B	158	99	99	112
12	B	113	103	100	93
13	B	154	99	97	75
14	B	158	100	97	83
15	C	29	98	101	77
16	C	146	101	104	130
17	C	88	111	106	70
18	C	158	99	99	112
19	C	116	92	102	59
20	D	158	100	97	83
21	D	154	99	97	75
22	D	57	99	98	120
23	D	182	101	98	117
24	E	158	99	99	112
25	E	88	111	106	70
26	E	54	100	97	57
27	E	154	99	97	75
28	E	113	103	100	93
29	F	146	101	104	130
30	F	134	100	103	86
31	F	28	99	99	134
32	F	88	111	106	70
33	G	154	99	97	75
34	G	54	100	97	57
35	G	18	100	98	83
36	G	57	99	98	120
37	H	88	111	106	70
38	H	28	99	99	134
39	H	46	104	98	102
40	H	34	98	99	122
41	H	54	100	97	57
42	I	54	100	97	57
43	I	34	98	99	122
44	I	29	100	100	659
45	I	18	100	98	83

Table 12

Summary of Normalized Average Combustion Parameters by Sector

SECTOR	PATTERN	ATOMIC H:C RATIO	$\frac{CO2}{CO}$	$\frac{O2}{FUEL}$	$\frac{CO2+CO}{CO}$	$\frac{CO2+CO}{N2}$	EO_2	FB
1	A	116	42	106	42	99	100	91
2	A	34	48	86	48	117	100	114
3	A	174	62	102	63	114	100	95
4	A	41	73	96	73	100	100	110
5	A	80	91	100	91	101	100	99
6	A	46	117	101	117	101	100	111
7	A	77	97	106	97	92	100	101
8	A	33	39	86	39	118	100	114
9	B	77	97	106	97	92	100	101
10	B	46	117	101	117	101	100	111
11	B	80	91	100	91	101	100	99
12	B	32	138	85	137	120	100	115
13	B	47	104	93	104	107	100	102
14	B	77	94	95	94	107	100	103
15	C	174	62	102	63	114	100	95
16	C	156	100	107	100	91	100	93
17	C	179	119	119	119	77	100	84
18	C	80	91	100	91	101	100	99
19	C	41	73	96	73	100	100	110
20	D	77	94	95	94	107	100	103
21	D	47	104	93	104	107	100	102
22	D	78	154	101	154	97	100	95
23	D	95	126	102	126	98	100	98
24	E	80	91	100	91	101	100	99
25	E	179	119	119	119	77	100	84
26	E	116	93	100	93	98	100	96
27	E	47	104	93	104	107	100	102
28	E	32	138	85	137	120	100	115
29	F	156	100	107	100	91	100	93
30	F	76	140	97	140	102	100	102
31	F	92	152	107	151	90	100	96
32	F	179	119	119	119	77	100	84
33	G	47	104	93	104	107	100	102
34	G	116	93	100	93	98	100	96
35	G	48	81	93	82	105	100	102
36	G	78	154	101	154	97	100	95
37	H	179	119	119	119	77	100	84
38	H	92	152	107	151	90	100	96
39	H	41	132	91	132	109	100	110
40	H	347	65	98	65	101	100	102
41	H	116	93	100	93	98	100	96
42	I	116	93	100	93	98	100	96
43	I	347	65	98	65	101	100	102
44	I	84	80	105	80	90	100	97
45	I	48	81	93	82	105	100	102

Table 13

Summary of Normalized Average Combustion Volumes by Sector

SECTOR	PATTERN	EQUIVALENT AIR PRODUCED	EQUIVALENT AIR BURNED	BURN EFFICIENCY	BURN VOLUME
1	A	94	89	91	73
2	A	149	97	114	91
3	A	96	76	95	78
4	A	34	19	110	52
5	A	87	126	99	105
6	A	32	16	112	16
7	A	18	22	101	17
8	A	217	115	114	114
9	B	20	26	101	24
10	B	35	30	112	30
11	B	97	110	99	106
12	B	144	142	115	165
13	B	100	125	102	128
14	B	127	134	103	146
15	C	105	108	95	110
16	C	131	138	93	139
17	C	30	30	84	27
18	C	86	139	99	118
19	C	34	31	110	30
20	D	120	138	103	150
21	D	93	135	102	137
22	D	85	102	95	98
23	D	112	102	98	106
24	E	95	117	99	112
25	E	35	45	84	40
26	E	109	114	96	122
27	E	98	116	102	124
28	E	131	131	115	115
29	F	165	144	93	145
30	F	230	212	102	223
31	F	58	48	96	44
32	F	38	38	84	28
33	G	98	107	120	107
34	G	107	112	96	110
35	G	176	178	102	174
36	G	88	103	95	99
37	H	37	44	84	34
38	H	53	52	96	51
39	H	95	96	110	99
40	H	141	185	102	180
41	H	112	132	96	138
42	I	104	84	96	90
43	I	125	108	102	115
44	I	189	138	97	132
45	I	170	147	102	156

Table 14

Summary of Normalized Cumulative Fluid Volumes by Sector

SECTOR	PATTERN	AIR INJECTED	GAS PRODUCED	OIL PRODUCED	WATER PRODUCED
1	A	95	117	422	51
2	A	95	102	164	52
3	A	95	111	209	114
4	A	95	16	23	15
5	A	95	93	66	66
6	A	95	12	15	39
7	A	95	9	39	64
8	A	95	133	187	26
9	B	104	10	39	64
10	B	104	13	15	39
11	B	104	103	66	66
12	B	104	108	95	35
13	B	104	108	57	76
14	B	104	149	112	149
15	C	86	114	209	114
16	C	86	138	126	96
17	C	86	29	40	47
18	C	86	88	66	66
19	C	86	15	23	15
20	D	104	139	112	149
21	D	104	106	57	76
22	D	104	95	113	155
23	D	104	110	190	383
24	E	96	99	66	66
25	E	96	35	40	47
26	E	96	120	41	75
27	E	96	104	57	76
28	E	96	99	95	35
29	F	91	166	126	96
30	F	91	254	346	177
31	F	91	49	77	142
32	F	91	35	40	47
33	G	132	127	57	76
34	G	132	137	41	75
35	G	132	212	111	167
36	G	132	107	113	155
37	H	99	37	40	47
38	H	99	50	77	142
39	H	99	78	75	23
40	H	99	159	147	218
41	H	99	123	41	75
42	I	94	114	41	75
43	I	94	142	147	218
44	I	94	165	165	346
45	I	94	170	111	167

Table 15

Summary of Normalized Cumulative Combustion Volumes by Sector

SECTOR	PATTERN	EQUIVALENT AIR PRODUCED	EQUIVALENT AIR BURNED	BURN VOLUME	BURN RADIUS	OIL RECOVERY
1	A	116	104	84	124	383
2	A	95	60	70	120	416
3	A	112	84	85	143	281
4	A	16	9	32	78	50
5	A	96	131	107	129	62
6	A	9	4	6	33	39
7	A	9	11	9	47	59
8	A	134	69	90	128	347
9	B	11	14	13	36	31
10	B	10	9	9	38	26
11	B	105	115	108	121	52
12	B	106	104	118	127	203
13	B	105	126	128	108	34
14	B	149	150	160	120	39
15	C	116	111	111	158	229
16	C	144	142	141	123	82
17	C	31	29	25	50	23
18	C	90	136	114	120	48
19	C	15	13	13	56	71
20	D	140	158	168	109	41
21	D	102	146	144	102	24
22	D	98	115	108	89	48
23	D	112	100	102	84	91
24	E	102	117	109	105	40
25	E	37	44	38	53	18
26	E	118	115	121	99	23
27	E	101	112	118	110	34
28	E	97	92	121	136	138
29	F	173	151	149	130	92
30	F	257	225	232	184	193
31	F	49	41	37	66	42
32	F	38	37	27	53	29
33	G	117	139	135	99	24
34	G	132	151	145	104	19
35	G	209	231	222	126	48
36	G	108	138	129	98	49
37	H	39	43	33	52	13
38	H	49	45	43	71	54
39	H	78	75	97	135	133
40	H	162	200	190	151	107
41	H	121	134	137	107	20
42	I	113	88	92	84	16
43	I	144	120	123	100	73
44	I	166	118	111	92	80
45	I	169	142	148	104	46

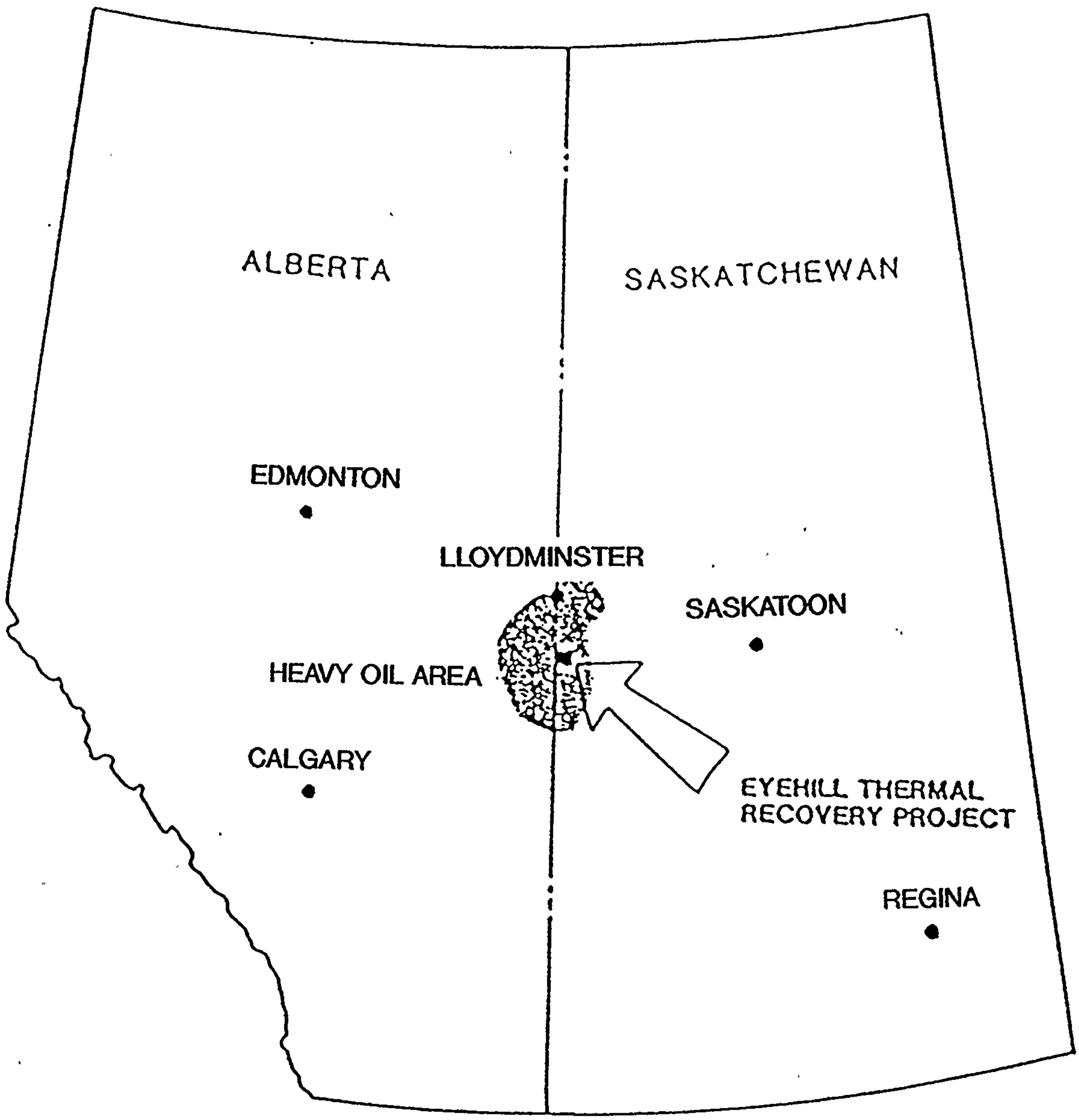


Figure 1

Eyehill Cummings Pool Location Map

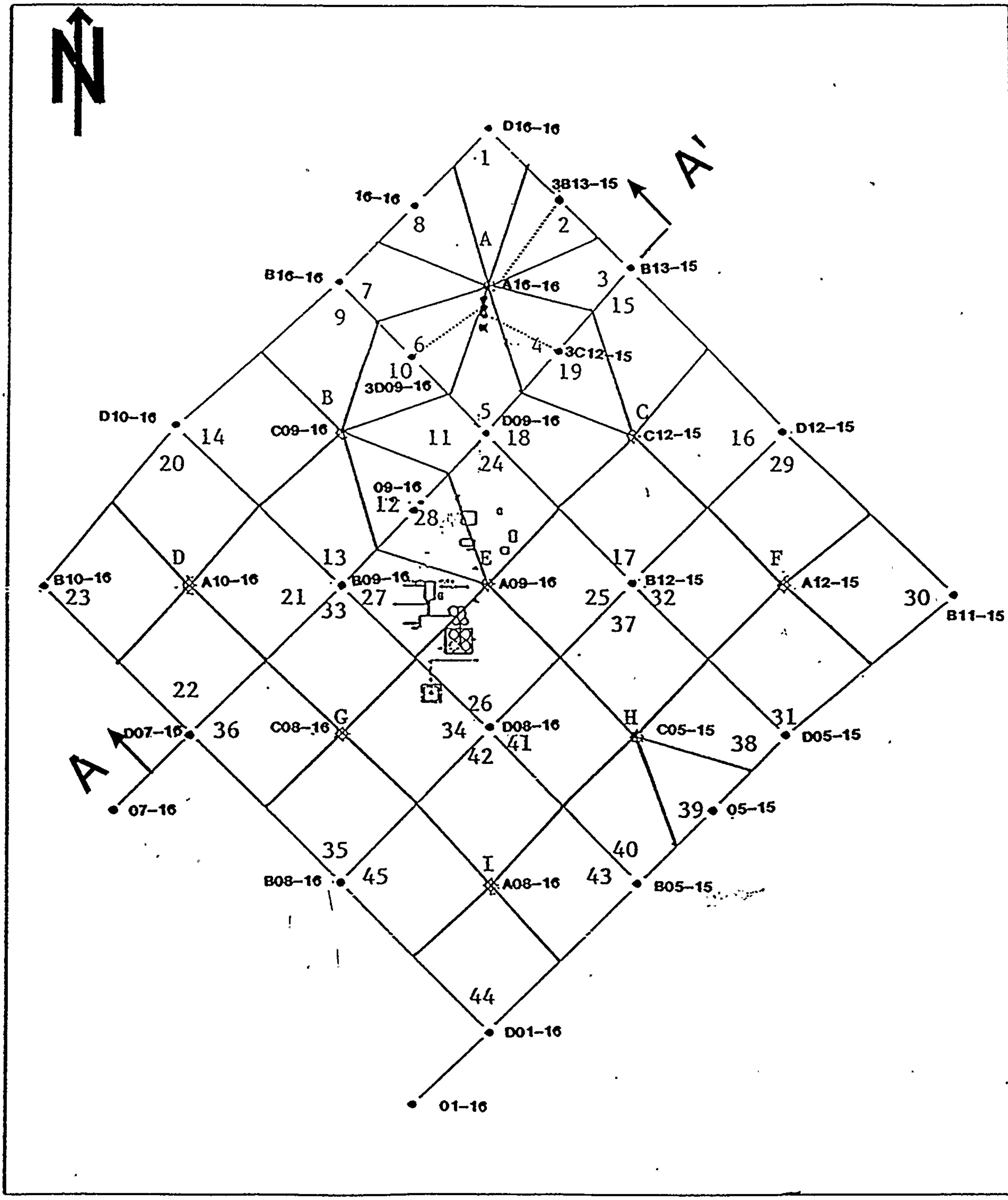
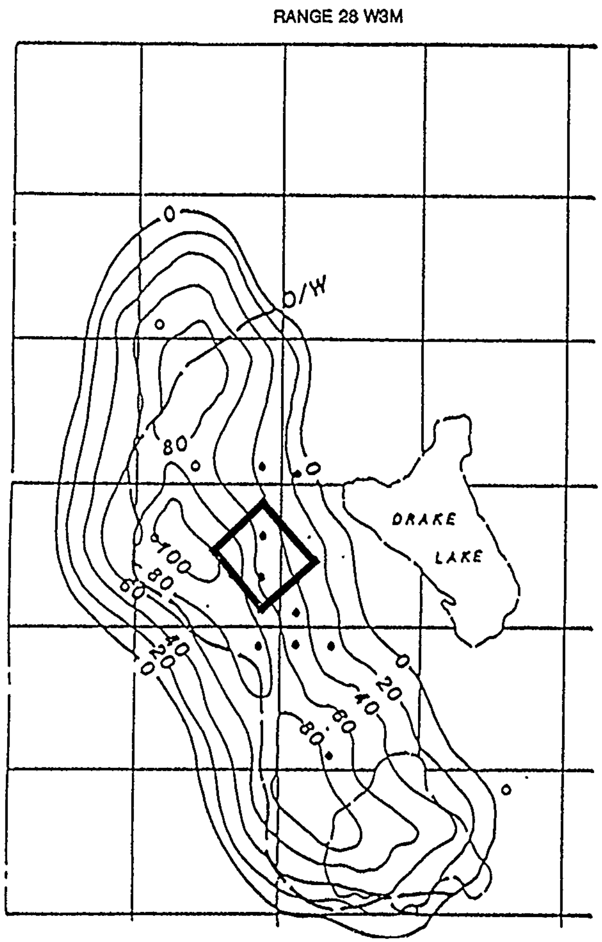


Figure 2

Eyehill Thermal Project Pattern and Sector Numbering

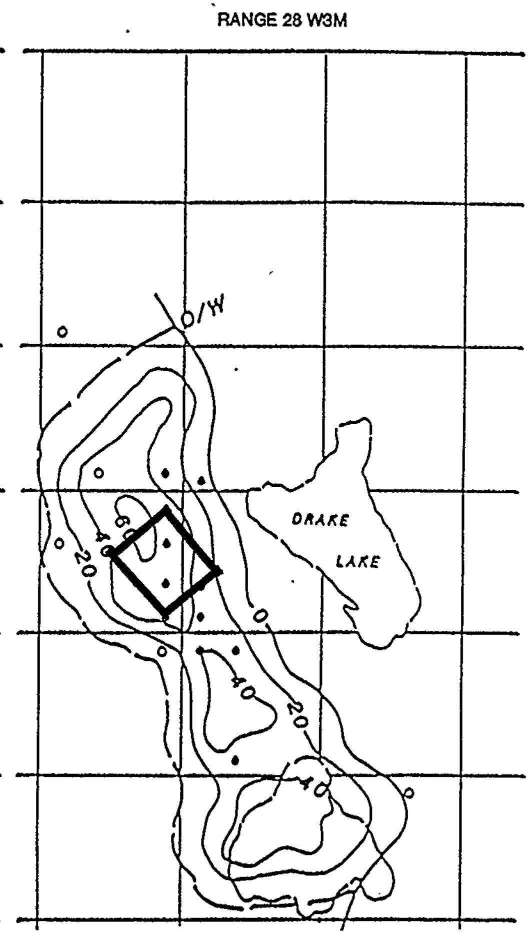
(ORIGINAL MODIFIED BY AUTHOR)



EYEHILL CUMMINGS
POROUS SAND

CONTOUR INTERVAL 20 FT

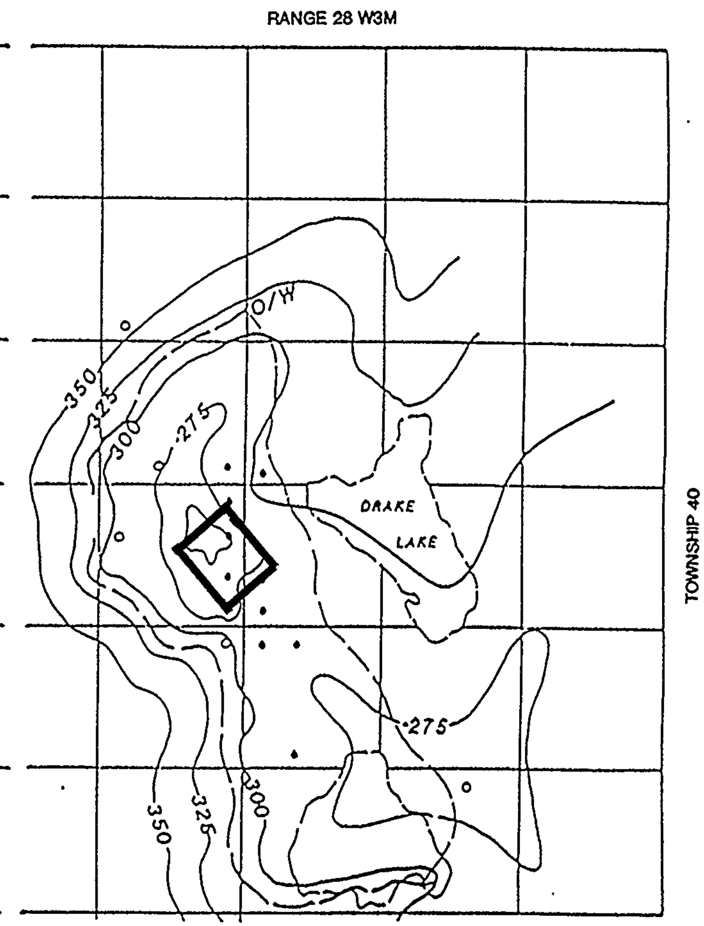
FIGURE 3



EYEHILL CUMMINGS
NET PAY

CONTOUR INTERVAL 20 FT

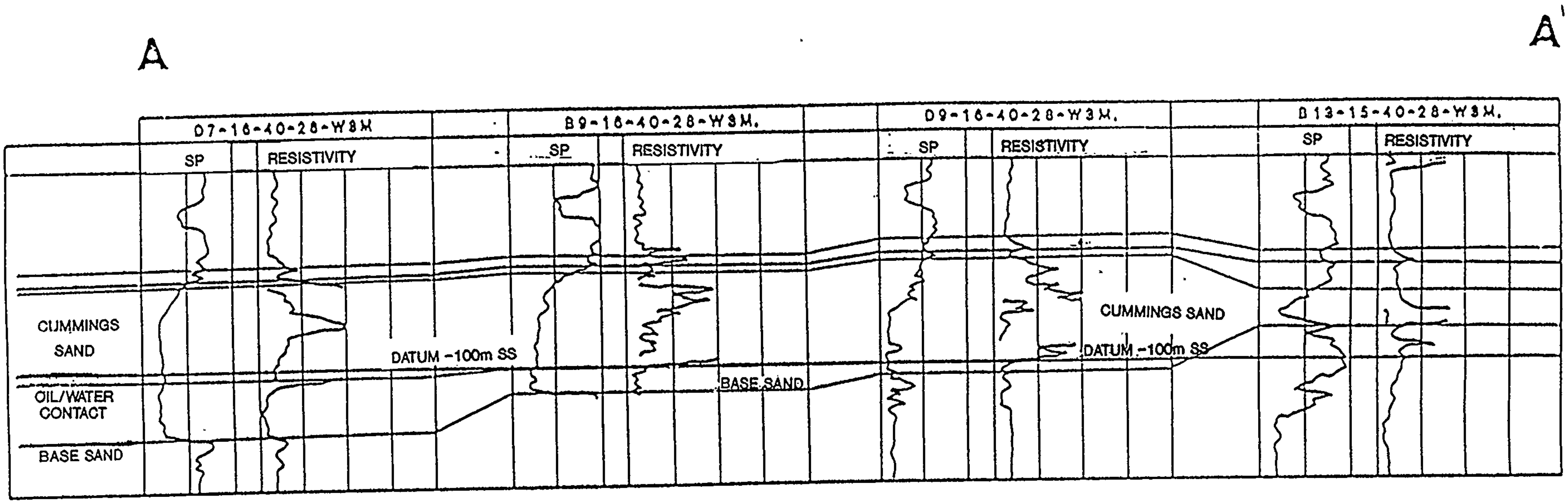
FIGURE 4



EYEHILL CUMMINGS
STRUCTURE

CONTOUR INTERVAL 25 FT

FIGURE 5



EYEHILL CUMMINGS STRUCTURAL CROSS SECTION A-A'

FIGURE 6

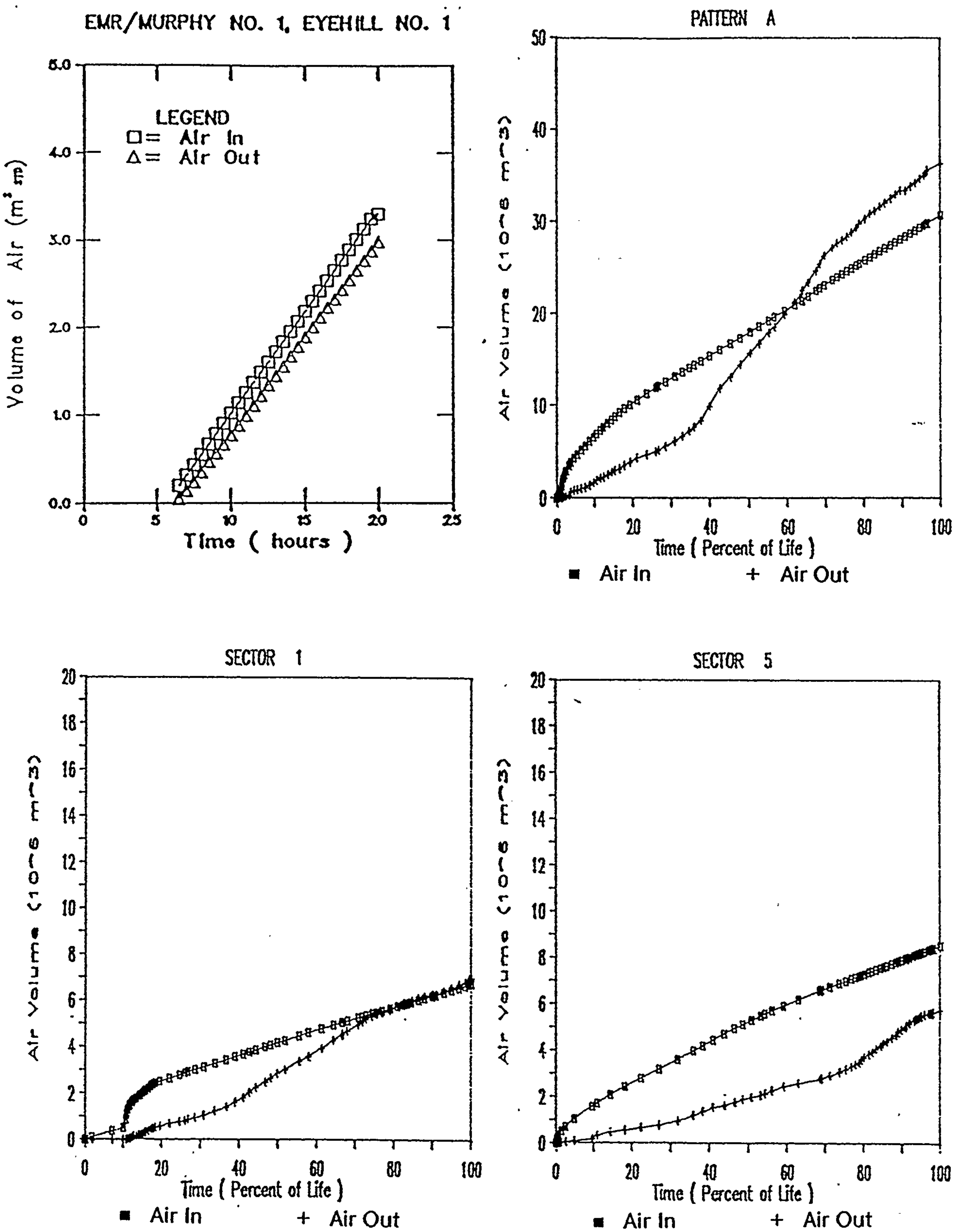


Figure 7

Air Storage Volume vs. Time

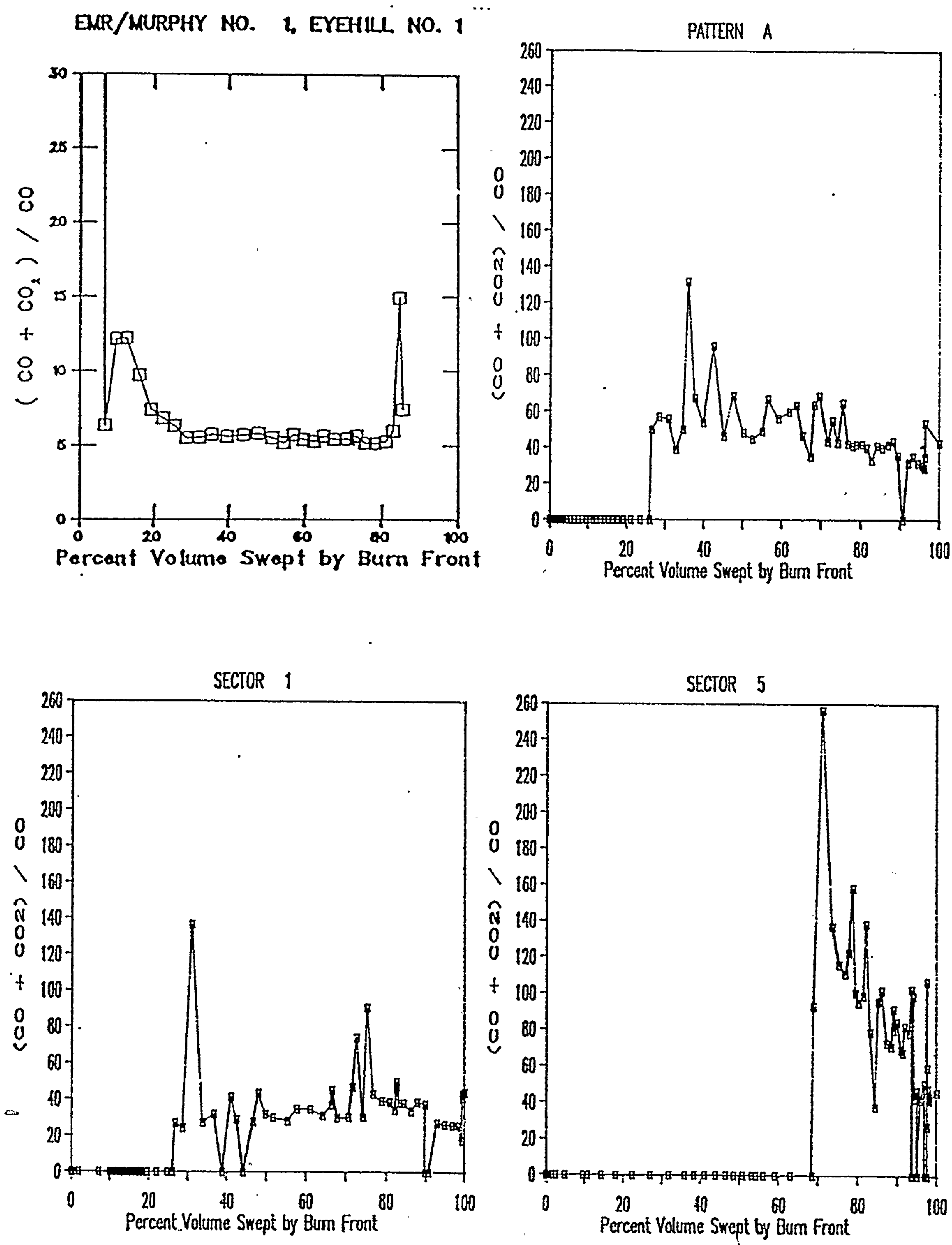


Figure 8

$(CO_2+CO)/CO$ vs. Volume Burned

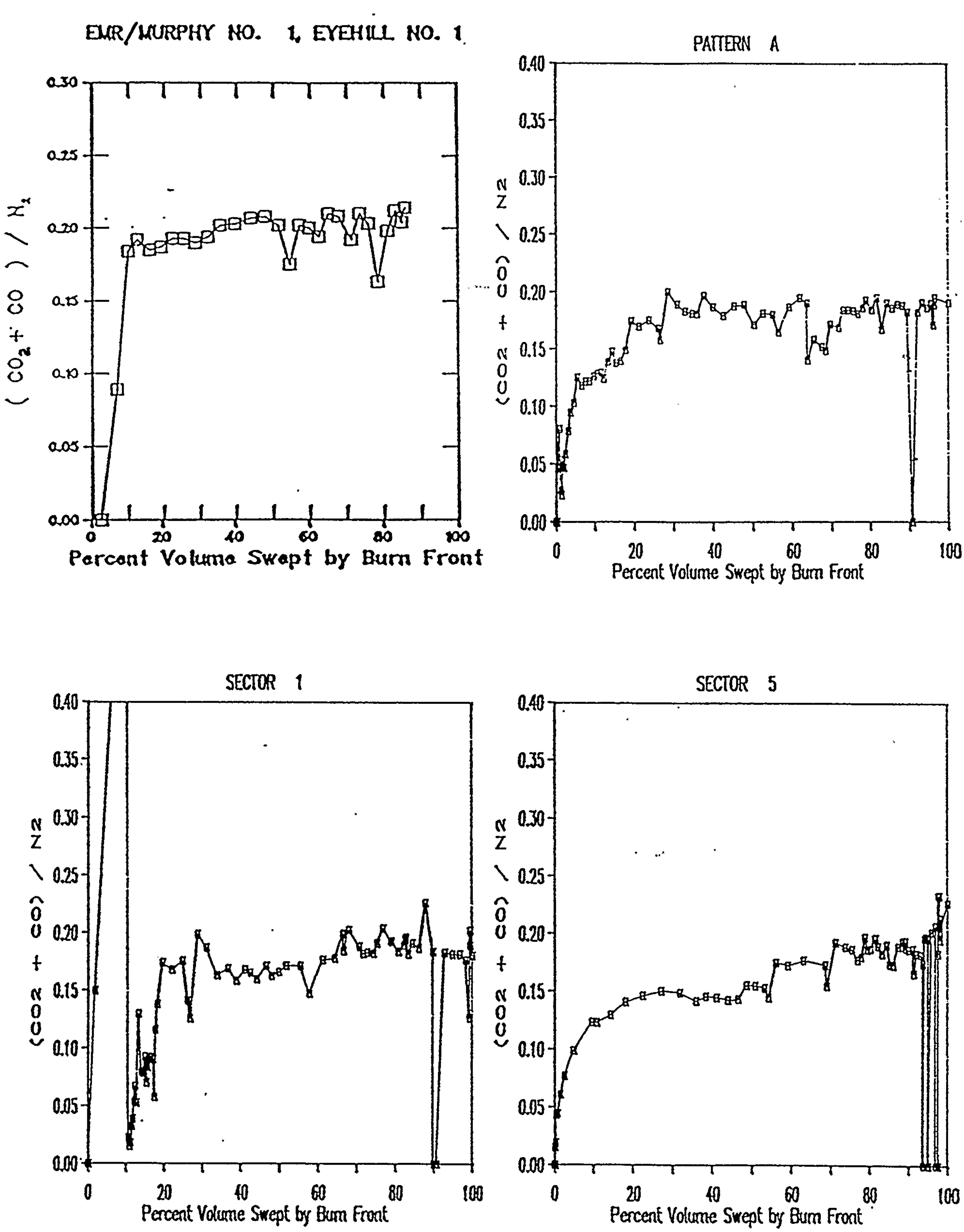


Figure 9

$(CO_2+CO)/N_2$ vs. Volume Burned

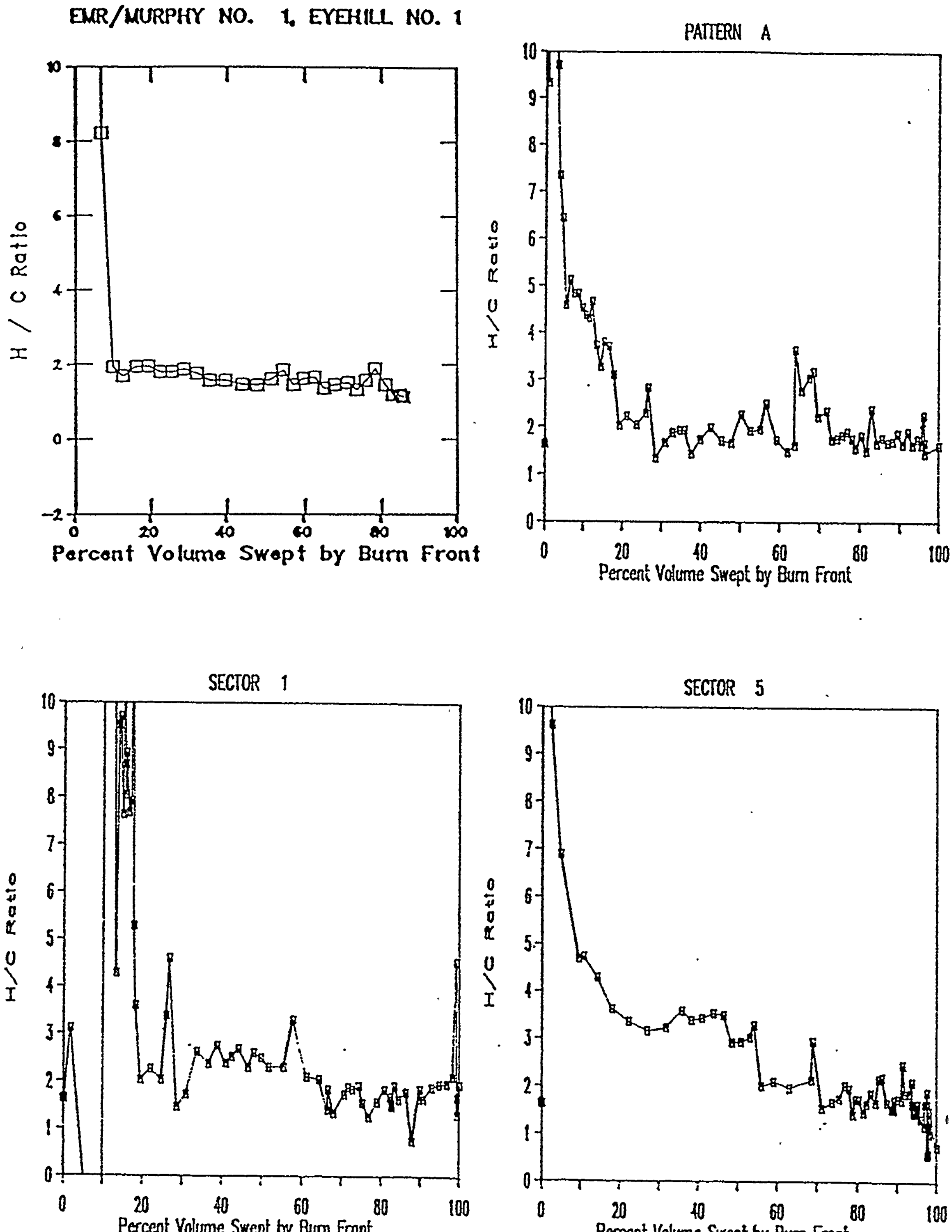


Figure 10 .

Hydrogen/Carbon Atomic Ratio vs. Volume Burned

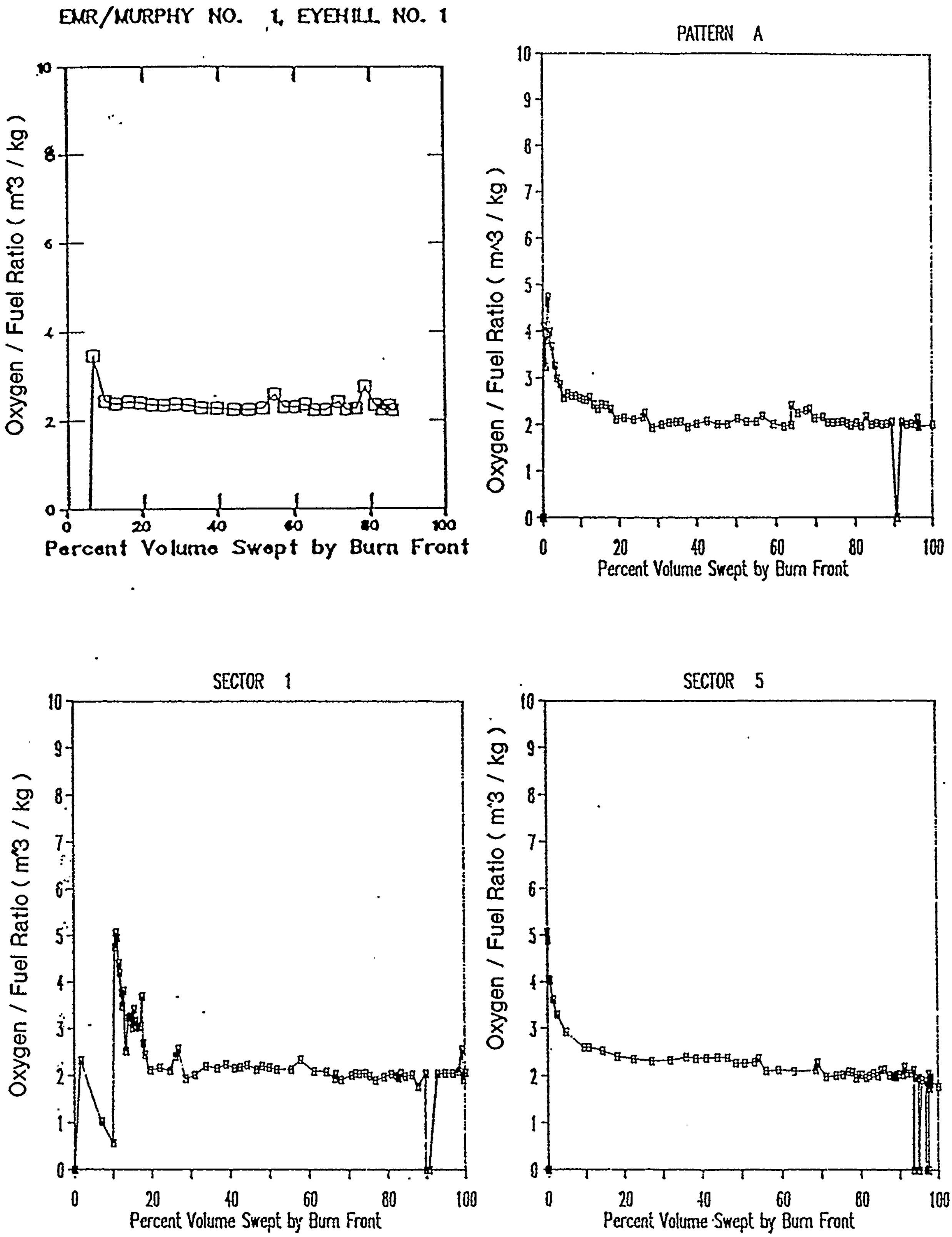


Figure 11

Oxygen/Fuel Ratio vs. Volume Burned

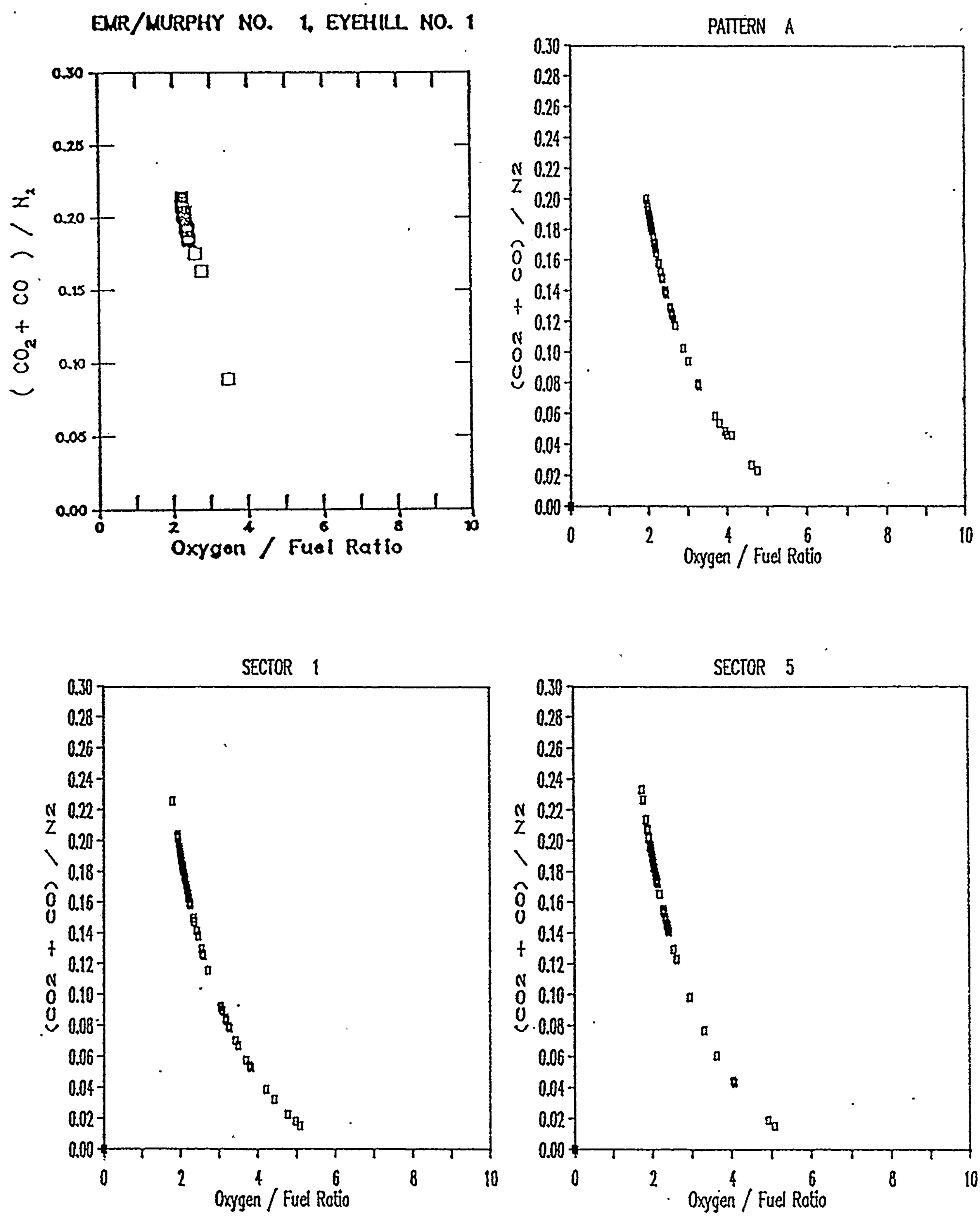


Figure 12

$(CO_2 + CO)/N_2$ vs. Oxygen/Fuel Ratio

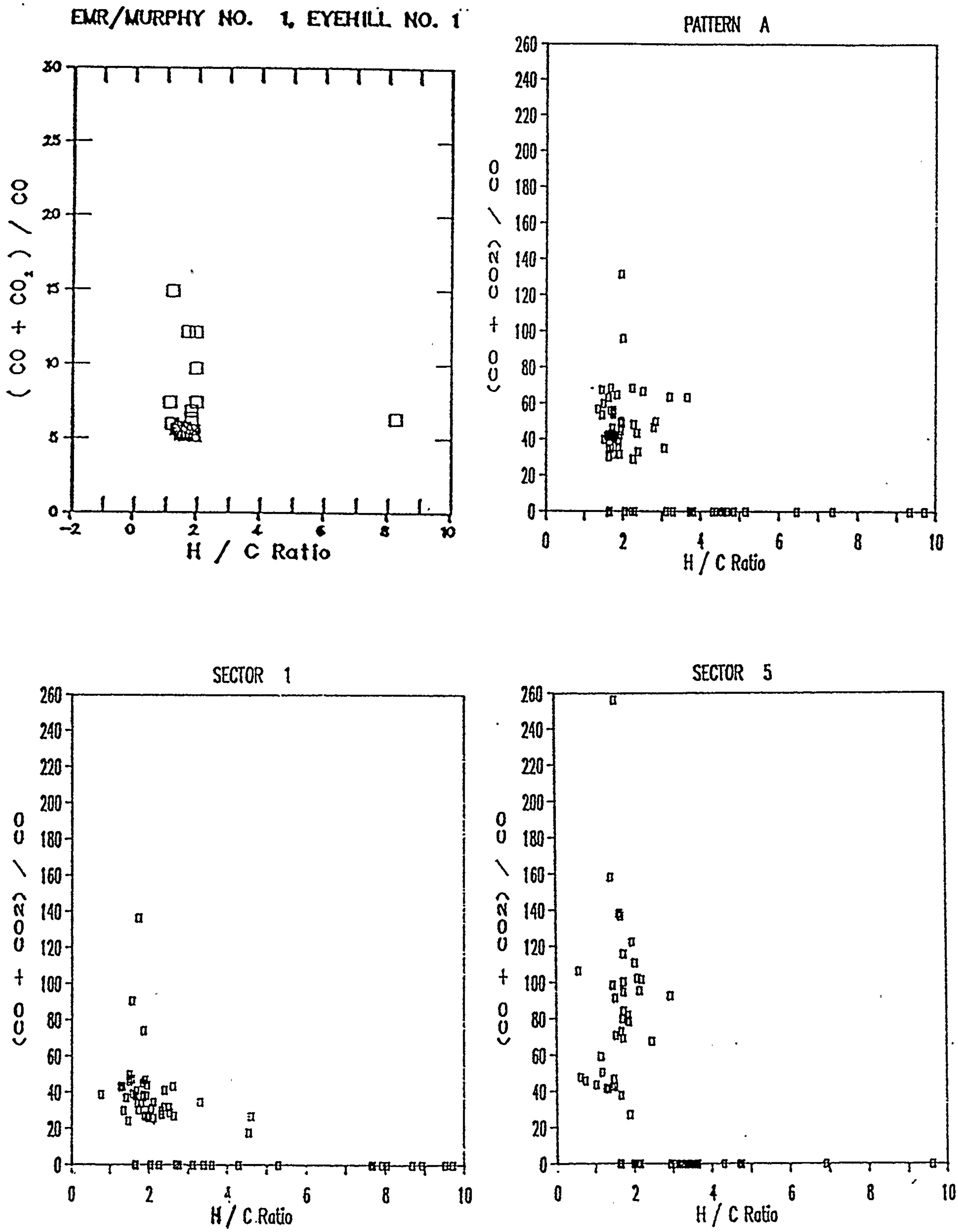


Figure 13

$(CO_2+CO)/CO$ vs. Atomic Hydrogen/Carbon Ratio

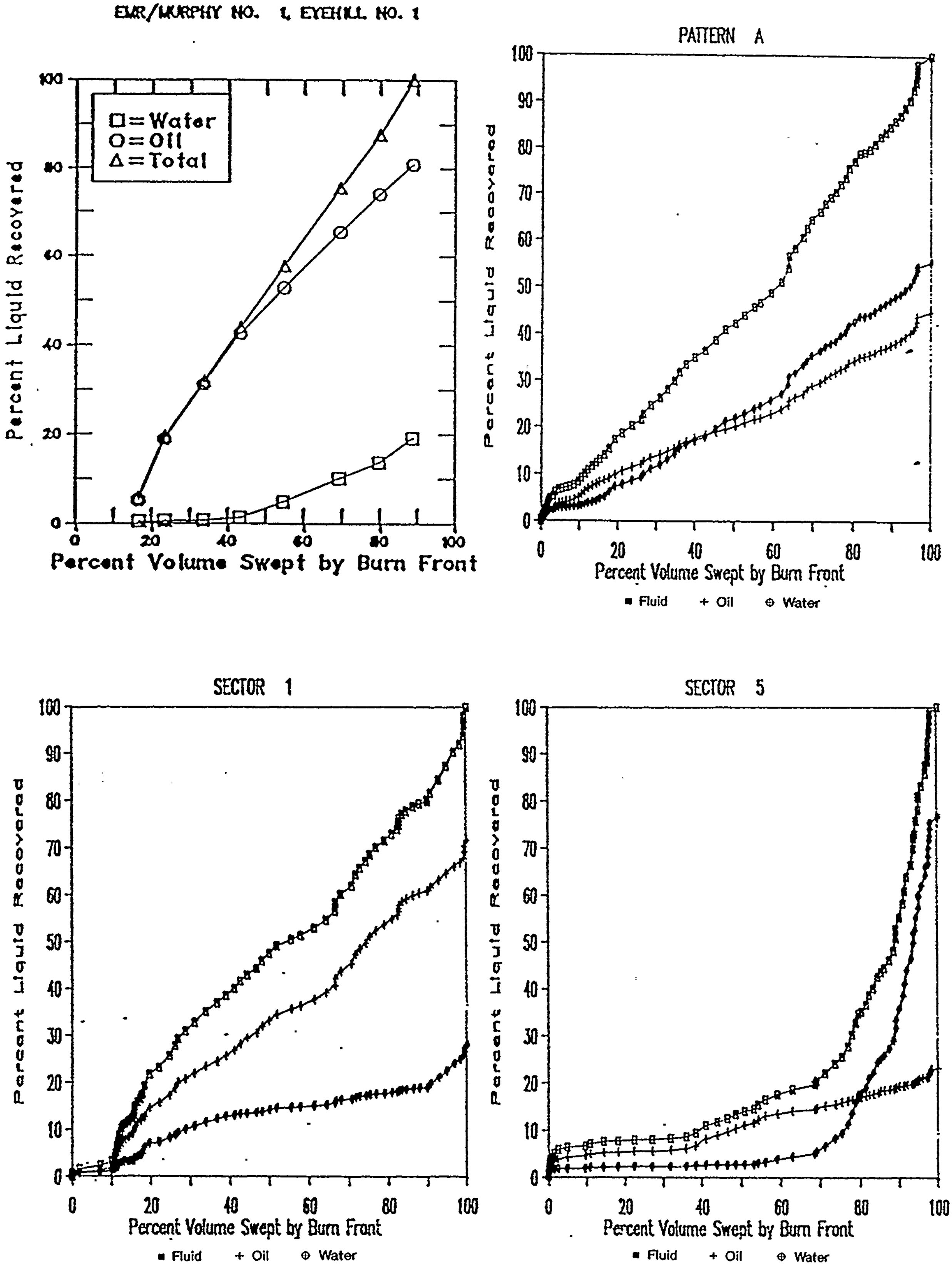


Figure 14

Total Liquid Production vs. Volume Burned

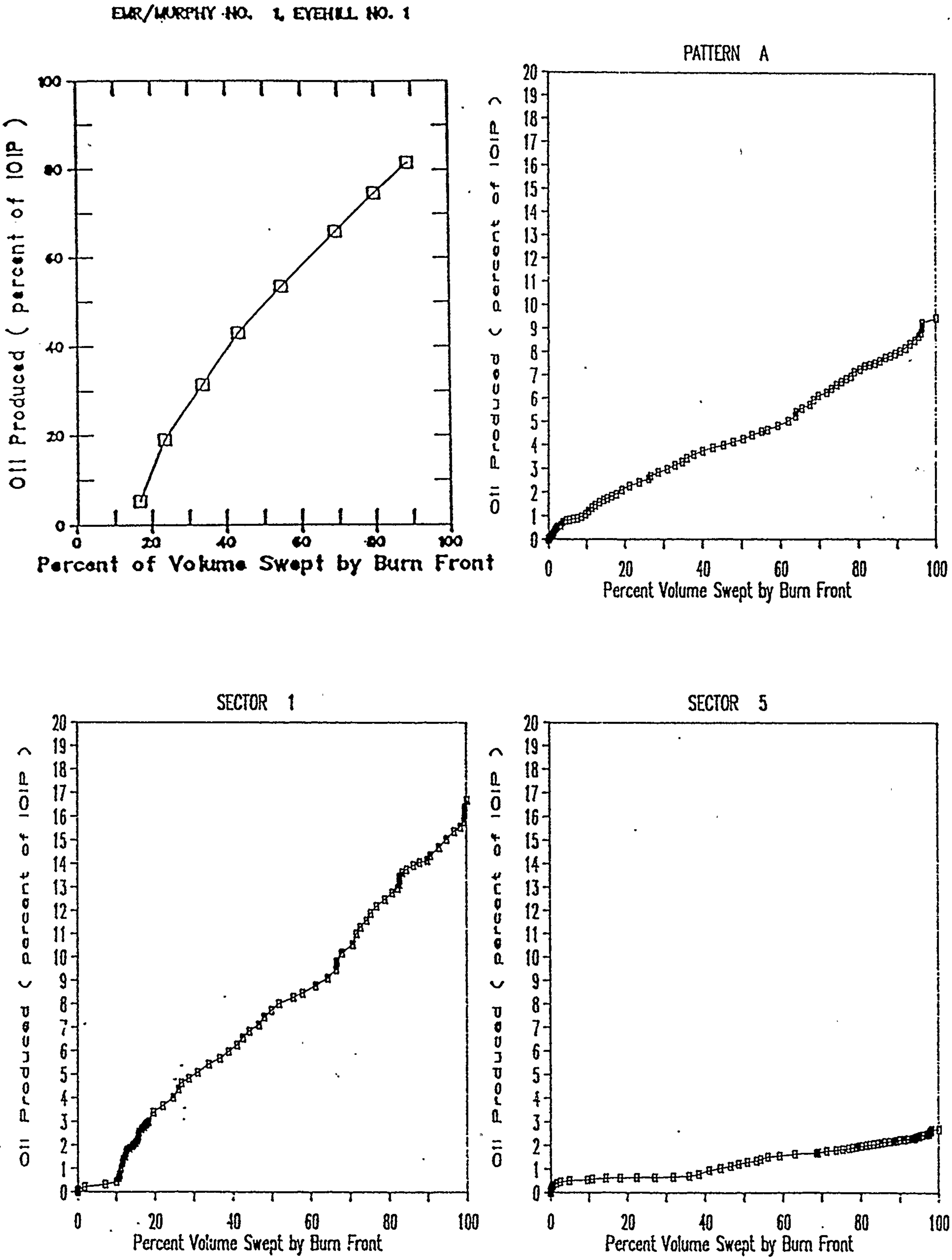


Figure 15

Oil Produced vs. Volume Burned

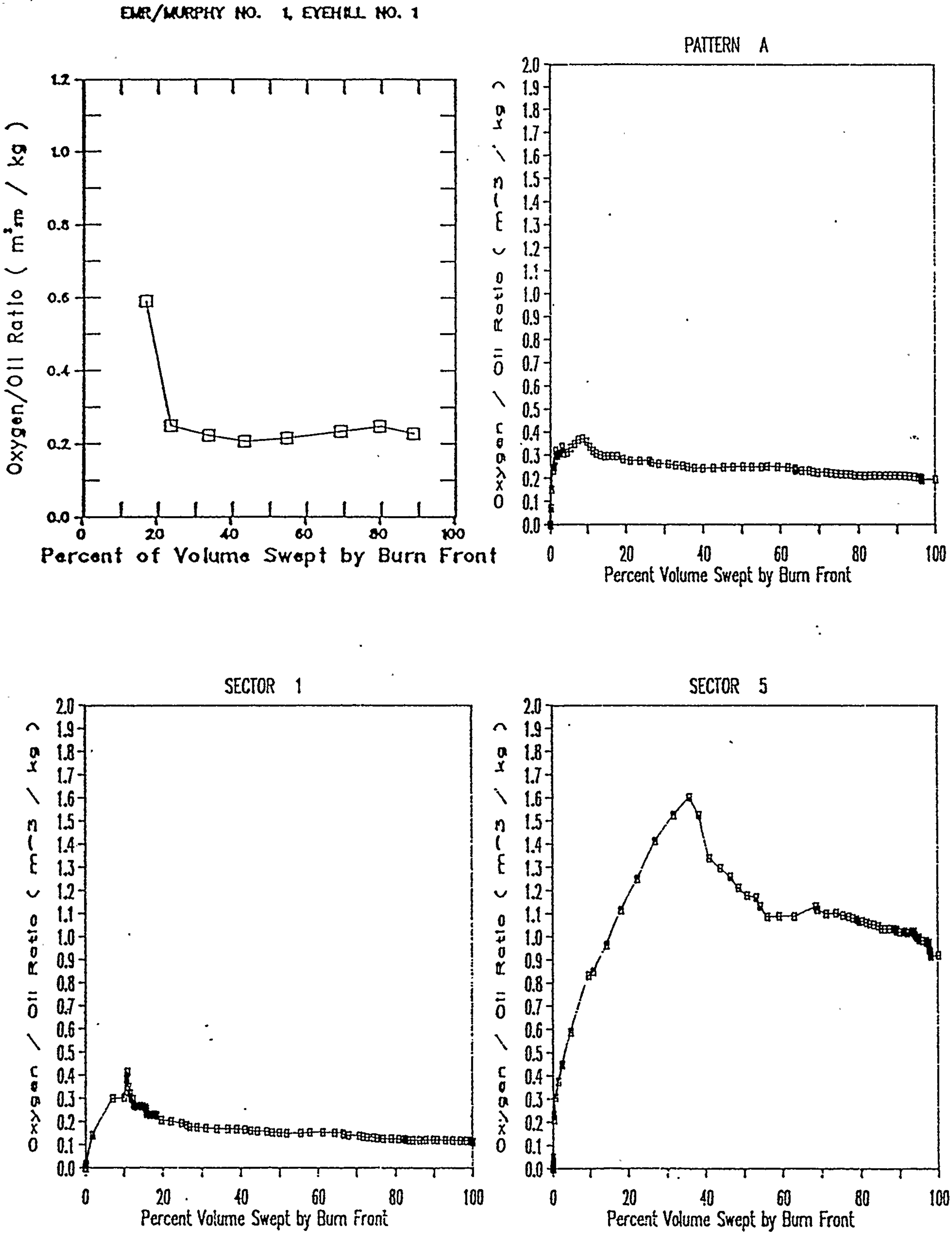


Figure 16

Oxygen/Oil Ratio vs. Volume Burned

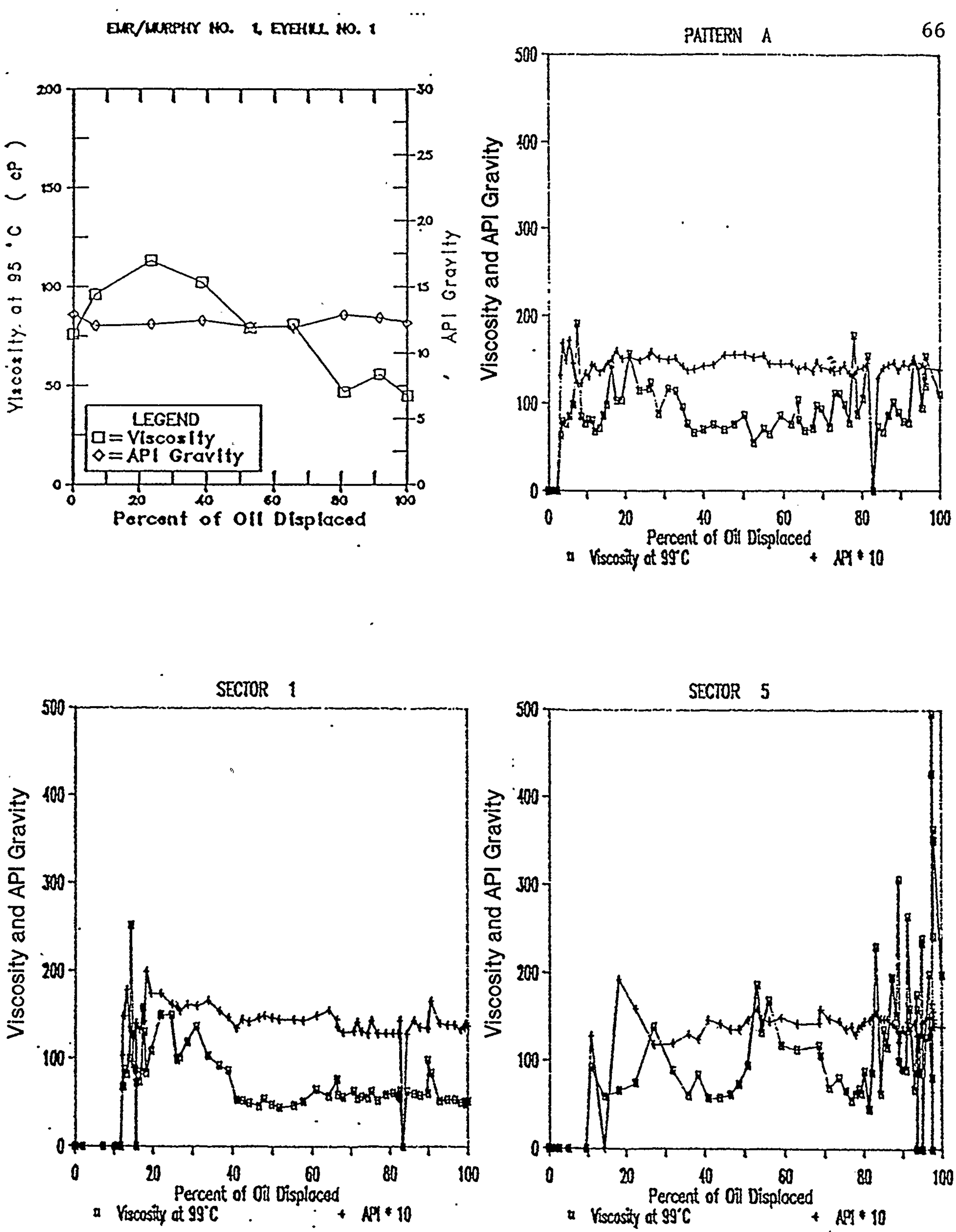


Figure 17

Viscosity and API Gravity of Produced Oil

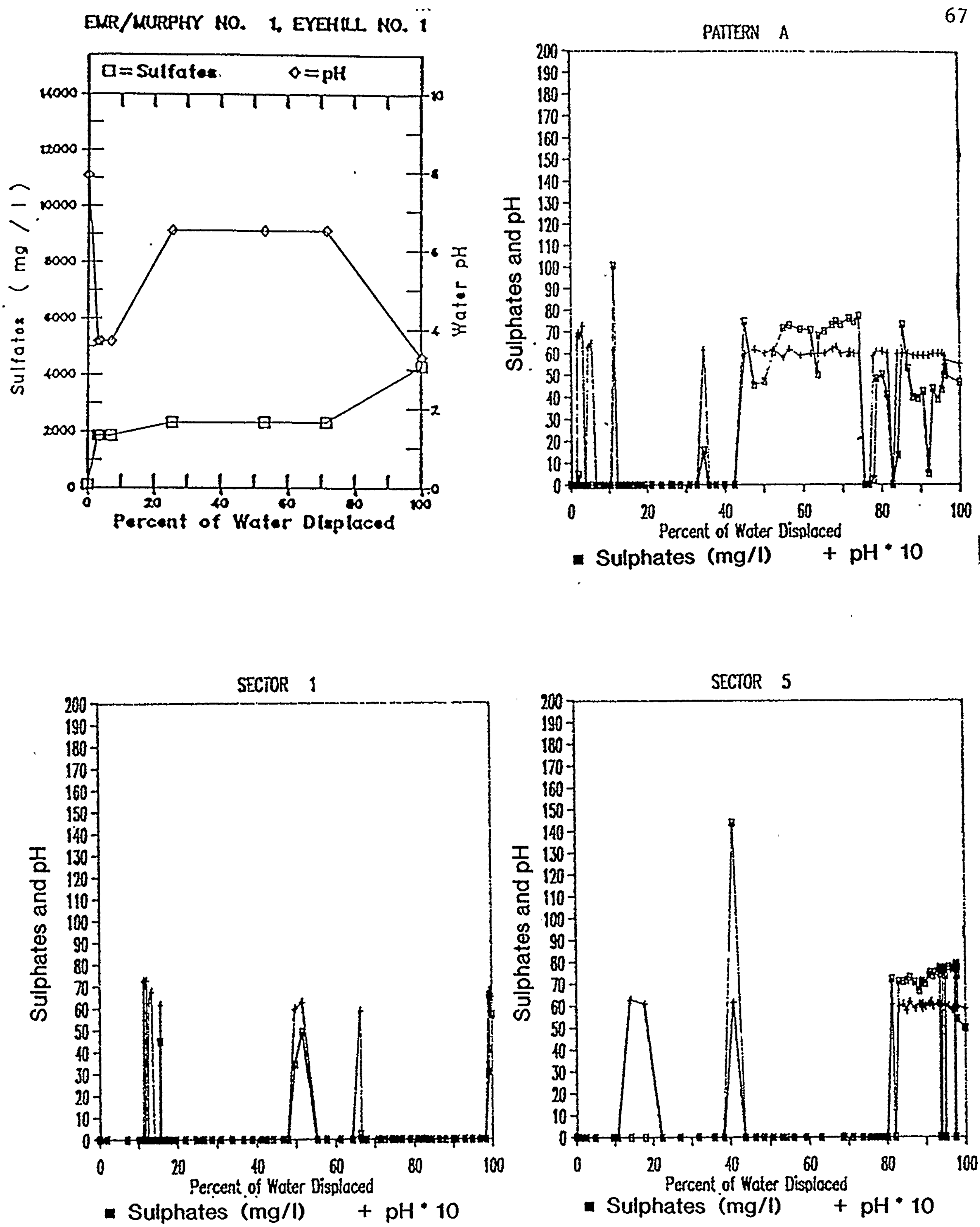


Figure 18

Sulfate Concentration and pH of Produced Water

Appendix A

Description of Combustion Parameter Calculations

Overview

The method of calculating combustion parameters basically follows White (1983), but additional parameters as used by Bennion (1985) have been included to make the comparison to the combustion tube tests more complete.

The analysis of the field data follows the steps outlined below for each time step:

1) Determine the volume of air injected to result in the volume of produced gas measured for each sector of each pattern.

2) Determine the distribution of produced gas to the influencing injectors based on injection volumes for each sector of each pattern (pattern factors).

3) Determine the distribution of injected air to each sector of each pattern based on the produced gas distribution and the calculated air recovery ratio for each pattern.

4) Determine the combustion parameters including burn efficiency from the produced gas analyses for each sector of each pattern.

5) Determine the incremental burn volume for each sector of each pattern.

When all time steps are calculated, the cumulative burn volume is calculated from the incremental burn volumes for each time step, and then the burn radius at each time step is determined from the burn volume and assumptions regarding the areal and vertical sweep efficiencies.

Calculations

The fire front location is determined based on air injection and gas production volumes and compositions. Since nitrogen is not native to the reservoir in significant quantities, it is a reasonable assumption that the amount of air injected to result in a particular volume of gas produced is determined by the air to produced gas ratio (AG) as follows:

$$AG = \%N2 \; / \; 78\% \qquad (1)$$

For an isolated pattern, the calculation of the equivalent air produced (EAP) to result in the production of a volume of gas (GP) is straightforward:

$$EAP = GP * AG \qquad (2)$$

For multiple adjoining patterns, the gas produced from a sector may originate from more than one pattern. The gas produced is assumed to originate in direct proportion to the ratio of the volume of air injected into the pattern (AIP) to the volume of air injected into all of the patterns influencing the sector (AII):

$$PF = AIP / AII \tag{3}$$

This ratio is referred to as the pattern factor (PF) after White (1983). The EAP for a multiple pattern project is therefore:

$$EAP = GP * AG * PF \tag{4}$$

The air recovery ratio for a pattern is determined as the ratio of the sum of the equivalent air produced for all sectors of the pattern to the air injected into the pattern:

$$ARR = \Sigma\ EAP / AIP \tag{5}$$

The equivalent air burned (EAB) for each sector is then determined by the following equation:

$$EAB = EAP / ARR \qquad (6)$$

Early in the project life, prior to the recovery of significant volumes of injected air (ie. ARR = 0), the distribution of the injected air is assumed to be radial and the equivalent air burned is determined by equation 7:

$$EAB = EAP / SF \qquad (7)$$

where SF is the denominator of the fraction of a circle that the production sector represents.

The combustion process can be represented by the following stoichiometric equation:

$$CH_n + \left[\frac{2m+1}{2m+2} + \frac{n}{4}\right] O_2 = \left[\frac{m}{m+1}\right] CO_2 + \left[\frac{1}{m+1}\right] CO + \frac{n}{2} \; H_2O \qquad (8)$$

where n is the atomic hydrogen to carbon ratio of the fuel and m is the ratio of CO_2 to CO in the combustion gas.

The calculation of the burn volume (BV) for each sector is dependent on the oxygen utilization efficiency (EO2), the fraction of air which is consumed in the high temperature burn zone (FB), and the laboratory determined air-fuel requirement (AR).

The oxygen utilization efficiency is calculated based on the analysis of the injected air and the produced gas. When the injected air is normal (not enriched) EO2 is calculated as follows:

$$EO2 = \frac{0.2692 * \%N2 - \%O2}{.2692 * \%N2} * 100 \qquad (9)$$

The fraction of air which is consumed in the high temperature combustion zone (FB) is determined based on the stoichiometry assumed for in situ combustion processes as presented in Equation (8) after Farouq Ali (1979) with parameter calculations following Bennion (1985) and Butler (1986). The following parameters are used in the calculation of FB:

$$R = \frac{\text{mole fraction N2}}{\text{mole fraction O2}} \quad \text{in the feed gas}$$

$$H/C = 4 * \left[\frac{\frac{\%N2}{R} - \%CO2 - \frac{\%CO}{2} - \%O2}{\%CO2 + \%CO} \right] \qquad (10)$$

$$m = \%CO2 \ / \ \%CO \qquad (11)$$

$$FB = \left[1 - \frac{(m + 1) * (H/C - H/CT)}{[2 + 4 * m + H/C * (1 + m)]} \right] \quad (12)$$

where H/CT is the theoretical atomic hydrogen to carbon ratio of the fuel as determined by the combustion tube tests.

The overall burning efficiency (EB) is then determined as follows:

$$EB = EO2 * FB \quad (13)$$

During the early stages of the field project, CO was not measured in the produced gas, and thus the value of m is calculated to be infinite therefore FB is not valid. The oxygen utilization efficiency is used during this period as an indicator of the burn efficiency. Inherent in this is the assumption that all injected air passes through the high temperature zone.

The laboratory determined air requirement (AR) is used to determine the incremental burned volume (IBV) as follows:

$$IBV = EAB * \frac{EB}{AR} \qquad (14)$$

The cumulative burned volume is then determined as the sum of the incremental burned volumes, and the burn radius (BR) is determined as follows:

$$BR = \sqrt{\frac{\Sigma IBV * SF}{(\pi * ANP)}} \qquad (15)$$

where SF has been previously defined, and ANP is the average value of the net pay in the reservoir in the sector. This calculation assumes radial front movement, and 100 % vertical and horizontal sweep efficiencies. These assumptions have been made to simplify the analysis and the comparison to the combustion tube test data.

In addition, the following parameters have been calculated for comparison to the combustion tube test data:

1) (CO_2 + CO) / CO Ratio
2) (CO_2 + CO) / N_2 Ratio
3) Oxygen / Fuel Ratio

The Oxygen / Fuel Ratio (O/F) is defined by the following equation:

$$O/F = \left[\frac{23.6445 * \frac{\%N2}{R}}{12.011*(\%CO2+\%CO)+4.032*\left(\frac{\%N2}{R} - \%CO2 - \frac{\%CO}{2} - \%O2 \right)} \right] \qquad (15)$$