STOICHIOMETRY OF IN-SITU COMBUSTION

by

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ABSTRACT

The high temperature underground in-situ combustion process of oil recovery can be described by a general chemical equation. This equation of the combustion reaction serves as the basis for deriving general reservoir engineering equations of the variables involved in the in-situ combustion process.

The independent variables of these equations are the combustion gas analysis on a water-free basis, injected gas analysis and the fuel content.

The experimentally-sought variables of these equations are the ratio of CO_2 to CO "m", the hydrogen to carbon atomic ratio "F_{HC}", the oxygen utilization efficiency "e_{O2}", the injected gas requirements and the combustion front velocity.

Using reported data from 136 experimental tube runs falling into 10 different data sets, values calculated from these equations are in good agreement with results reported from laboratory tube runs.

These derived stoichiometric equations serve as valuable tools in evaluating in-situ combustion projects.

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INTRODUCTION

In-situ combustion is a thermal recovery process in which heat is generated within the formation by burning part of the crude oil which is used as fuel to sustain combustion and recover the unburned remaining oil. The use of in-situ combustion process for increasing oil recovery from an oil reservoir has been intensively studied and used since the late 1940's and early 1950's.

Design of the in-situ combustion process involves experimental evaluation of the process variables in laboratory experiments. Laboratory experiments and field tests have been widely used to investigate the in-situ combustion process whereby a portion of the crude in the reservoir is burned to generate the necessary heat to increase the mobility of the crude oil by reducing its viscosity. The results of a number of laboratory experiments in which the combustion process was studied in a sand-pack are reported in the literature.

Studies such as these indicate that with the temperatures involved, the oil is partially coked in this process and it is this coke which provides the fuel for combustion. The combustion of this coke can be analyzed by applying simple stoichiometric principles to the combustion process.

It is the ultimate objective of this work to analyze the stoichiometry of the combustion reaction, derive the general stoichiometric equations for any injected gas, apply these equations to in-situ combustion laboratory experiments reported in the literature and compare the results obtained from the stoichiometric equations with those reported from the experiments.

The stoichiometric equations are generally applied to the dry in-situ combustion process. The equations provided for any injected gas with any mole fraction of oxygen in it to be used as input. An attempt was made to apply the equations to wet and quenched combustion tube runs and the results were highly encouraging.

A total of a hundred and thirty six combustion tube runs falling into ten data sets were used to compare the results reported in these experiments with those calculated from the stoichiometric equations.

Variables obtained experimentally from tube runs are usually hydrogen to carbon atomic ratio of the residual fuel, fuel concentration at the burning front, oxygen utilization efficiency, the amount of injected gas required to burn one pound of coke, the amount of injected gas necessary to burn one cubic foot of sand-pack and the combustion front velocity. All these variables come into consideration when the stoichiometry of the combustion process is studied.

The produced gas analysis and other necessary experimental conditions for each set of data appearing in the literature are tabulated in appendix D. For purposes of comparison with calculated results, it was necessary to change some of the units of a number of variables reported in the literature to the appropriate units adopted in this work. The results for each set of data are separately tabulated and graphically presented.

Most of the published experimental tube run data were for air injection. Recently, oxygen-enriched in-situ combustion process has received increased attention in both pilot field testing and laboratory tube runs.[5, 9, 13, 38] Equations derived from stoichiometric considerations were used to evaluate the different process variables for oxygen-enriched in-situ combustion. The results are presented in tables and graphically illustrated.

IN-SITU COMBUSTION

In-situ Combustion Theory

In-situ combustion is a thermal process for recovering crude oil from reservoirs. A schematic diagram of an in-situ combustion process is illustrated in Figure 1. The lower portion of the diagram shows the temperature distribution from the injection well to the production well. The in-situ combustion involves burning part of the crude oil in the reservoir to provide the necessary heat in order to improve the flow of the unburned part.

In an in-situ combustion process, air or more generally an oxygen-containing gas is injected into the reservoir at one or more injection wells, the reservoir temperature near the injection well-bore is raised to a temperature high enough to cause ignition of part of the crude oil in the reservoir. The ignition temperature ranges between 500-600 °F, but not high enough to sustain combustion. The ignition is accomplished by means of an ignition system "ignitor" used in the well-bore.

The heat generated during the combustion is sufficient to raise the temperature high enough to enable the burning front to self-propagate after initial ignition. Since the temperature and heat content of the burned zone are quite large, the combustion zone temperature will be between 600-1200 °F and the oil will be heated to fairly high

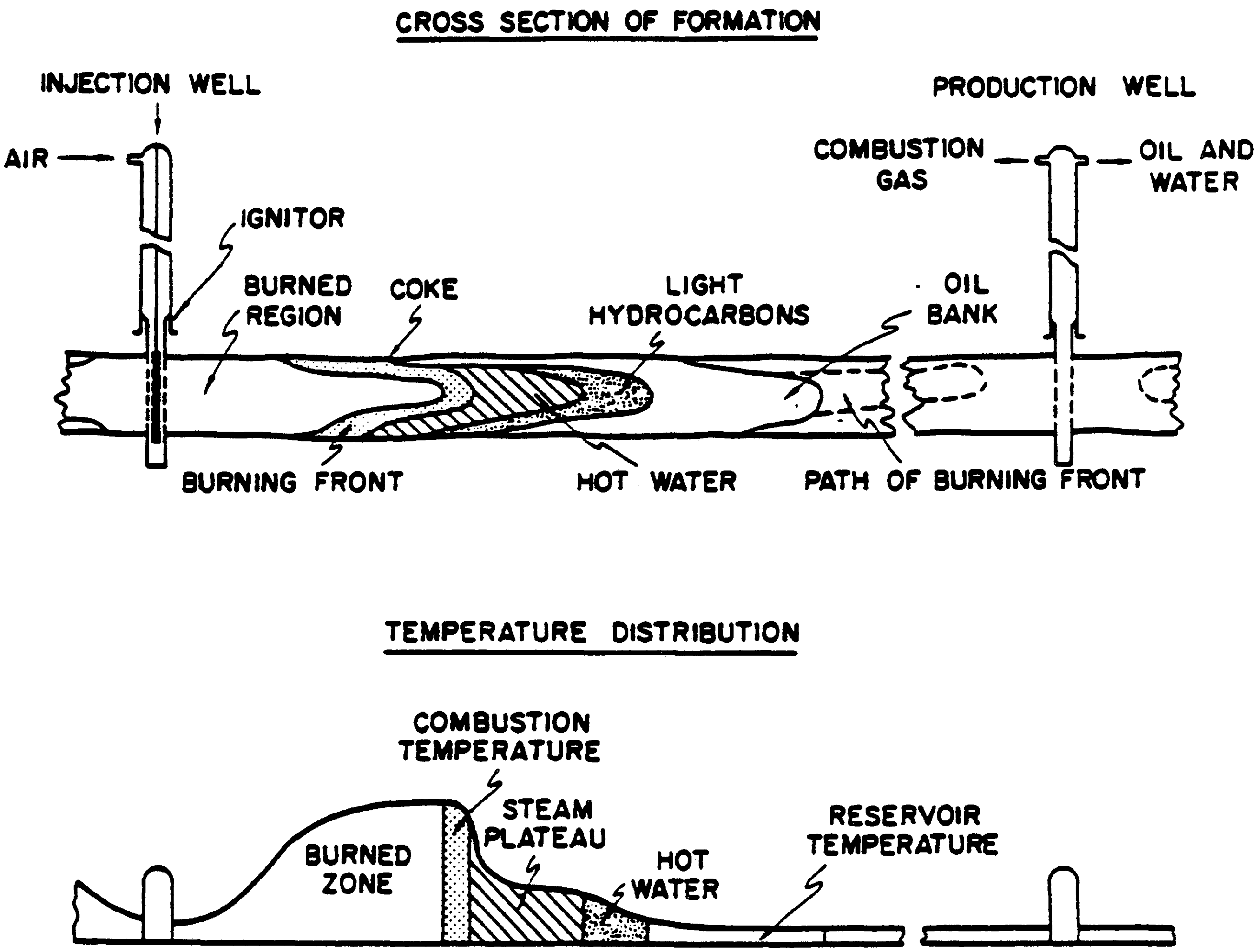

Figure 1. Schematic diagram of in situ combustion process
(Modified from reference no. 22)

temperatures. These high temperatures reduce the viscosity of the oil by several orders of magnitude, thereby allowing high viscosity crude to flow freely towards the producing well.

Laboratory experiments show that most of the in-place oil is banked ahead of the combustion front, with no oil left after a high-temperature burn. In field tests, however, the burn can be limited to a smaller portion of the reservoir because of the sweep efficiency.[1]

Figure 1. depicts the locations of the various zones in an in-situ combustion process. Six regions are recognized in this figure. These regions, which move in the direction of the injected-gas flow, are:

1. Burned Region: Is the region that has been subjected to the highest temperatures for the longest period. It is filled with injected gas and may contain as much as 2% of the unburned solid fuel residue which decreases as the combustion temperature increases. Due to heat losses to the adjacent formations and the influx of a relatively cold injected gas through the injection well into the reservoir, the temperature downstream of the region is higher than the upstream temperature.

2. Burning Front: It is visualized that a burning front moves through the sand, much in the way that the burning front moves through a cigarette. This narrow region moves to its fuel supply leaving behind the fuel-depleted sand. It is the highest temperature zone where rapid and exothermic reactions occur. Combustion gases (carbon oxides) are considered to be generated within this zone. The burning front can not advance if the injected gas flux passing through the front is too low because frontal temperatures will drop below the minimum level at which combustion can occur.[21]

Water generated by the combustion is present as super-heated steam and flows along with other vapors into and through the evaporation zone of the steam plateau region.[27]

3. Steam Plateau: Heat generated at the burning front, where temperatures may range from 600 °F to 1200 °F, will vaporize formation water to create a steam zone.[32] Two zones are distinguished in the steam plateau region:

(a) Evaporation Zone: Although temperatures in this zone are lower than those in the burning front, they are high enough to keep water in the state of super-heated steam. The heavy ends of the crude in this zone are thermally cracked, distilled by the gas stream, and decarboxylated (-CO groups break off on mild heating, giving off CO_2). Hydrocarbon gases are given off in this zone.

(b) Condensation Zone: In this zone the temperature is fairly uniform and the hydrocarbon vapors condense and dissolve in the crude, thus reducing its viscosity. Steam also condenses. Crude oil is displaced by the advancing steam zone, so that the evaporation zone only sees the oil remaining in the steam zone.

4. Hot Water Bank: This region is characterized by water saturations somewhat higher than those in the oil bank. The temperature in this zone is intermediate between those of the initial reservoir and the steam plateau region.

5. Oil Bank: Most of the mobile oil ahead of the burning front is displaced by the steam plateau. The oil left behind, which is often the heavy hydrocarbons of the crude, is used as the fuel to sustain the combustion.[33] Oil displaced from the upstream zones accumulates in this zone where the temperature is lowest.

6. Virgin Region: This is the portion of the reservoir that has not been affected except by the flow of combustion gases. It should be noted that there are transition strips between each two adjacent zones, in which the mechanism of the previous zone grades to the next one.

Methods of in-situ combustion

There are fundamentally two different methods of in-situ combustion. One method is that in which the zone surrounding the injection well-bore is brought to a sufficiently high temperature, ignition takes place in the vicinity and the burning front travels in the direction of the production well, i.e. the combustion front advances in the same direction as the injected gas flow. This is known as the forward or conventional combustion. Continued air or gas injection maintains the combustion and drives the combustion front through the reservoir in the general direction of the injected gas flow. The second method is called the reverse or countercurrent combustion, in which the zone surrounding the production well is heated, ignition takes place near this well and the combustion front travels towards the injection well, i.e. the combustion front advances in the opposite direction to the injected gas flow.

Forward Combustion Process

The forward combustion process consists of initiating combustion in the formation surrounding an injection well and driving the combustion front through the formation towards the production well by means of a continuous injection of oxygen-containing gas.

Burger and Sahuquet[35] stated that since the coke combustion follows the coke formation, then the velocity of a forward combustion front is related to the fuel content available for combustion.

There are many variations of the forward in-situ combustion process, dry, wet, quenched and partially quenched combustion are amongst these variations.[22]

A. Dry Forward Combustion

In a dry forward combustion, the combustion front moves out from the injection well to the production well as air or oxygen-enriched injected gas is continued, i.e. in the same direction as the injected gas flow. In this process, the combustion front acts as a piston which pushes ahead of it the unburnt crude from the swept zones.[24]

Figure 2. shows a schematic diagram of a dry forward combustion. Under steady-state conditions, the reservoir can be divided into four principal zones:

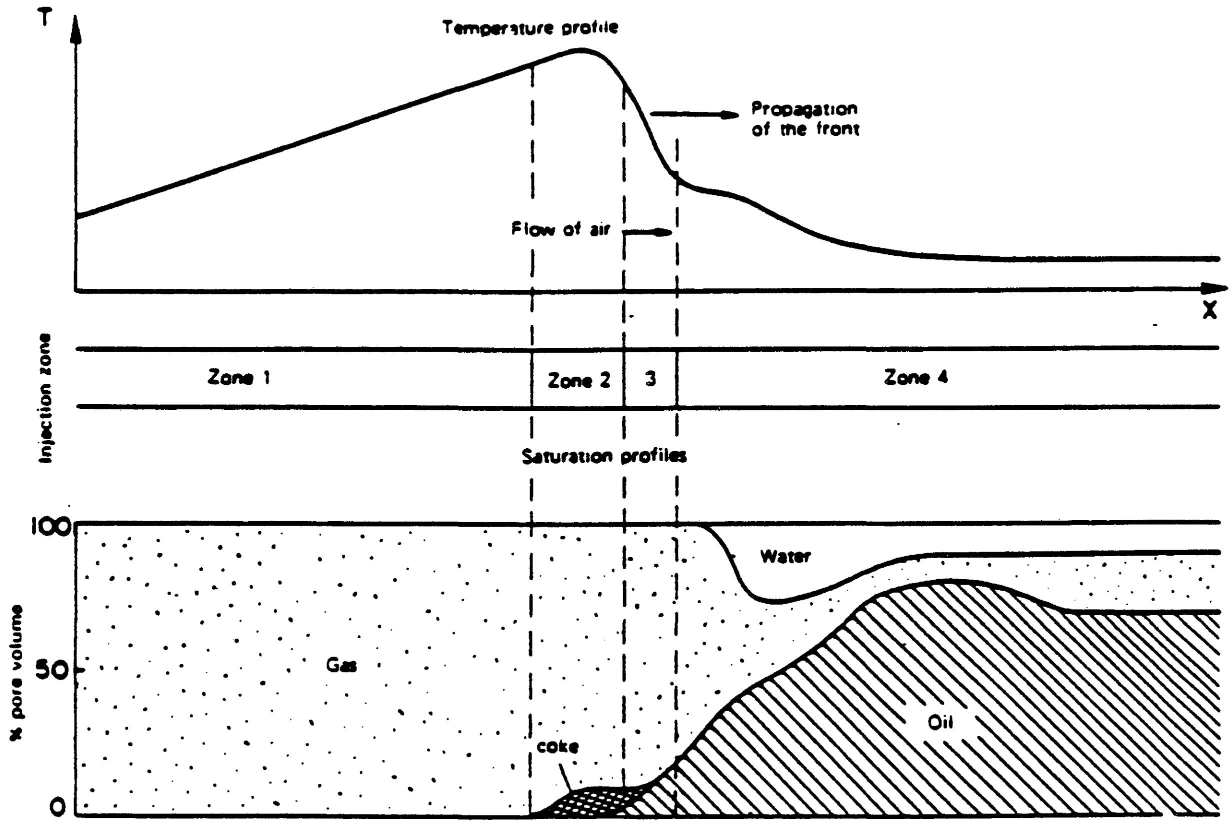

Figure 2. Schematic diagram of dry forward combustion (Modified from reference no. 24)

Zone 1: Combustion has already taken place and the formation in this zone is completely clean. The injected gas or air is heated by the hot matrix and part of the combustion energy is recovered in this way; temperature decreases upstream.

Zone 2: The combustion zone. Oxygen is consumed by combustion reactions involving the hydrocarbons and the coke remaining on the rock surface. The temperature reached in this zone depends essentially on the nature of the solids, liquids and gases present per unit formation volume.

Zone 3: The coke formation zone. The heavy oil fractions which have been neither displaced nor vaporized undergo pyrolysis. These cracking reactions may occur in the presence of oxygen, if the latter has not been completely consumed in the combustion zone.

Zone 4: Where the temperature has fallen sufficiently, there are no further significant chemical changes. This zone is swept by the combustion gases and displaced fluids, and the following phenomena takes place:

(a) In the downstream region nearest the reaction zone, successive vaporization and condensation of the light oil fractions and the interstitial water take place, as does condensation of the water of combustion. This tends to accelerate the downstream heat transfer.

(b) In the region where the temperature is lower than that of water condensation, a zone with a water saturation higher than the initial water saturation exists (water bank) which pushes a zone with an oil saturation higher than original (oil bank). If the oil is highly viscous this may result in plugging of the formation. In every case, these two banks are a zone of high pressure loss. Beyond the oil bank the formation progressively approaches its original conditions.[24]

> A characteristic of the dry forward combustion process is that the temperature of the burned zone remains quite high because the heat capacity of the air injected is too low to transfer a significant amount of heat. For this reason, water sometimes is used during or after the combustion process to help transfer the heat from the burned zone and to use it efficiently downstream, where the oil is.[27]

In recent years oxygen-enriched in-situ combustion has received increased attention in both field and laboratory combustion tube tests. Enriched air injection has high potential for recovering heavy and medium oils. Among the many advantages is a higher concentration of CO_2 in the flue gas resulting from the absence of nitrogen. This allows more CO_2 dissolution in the oil that helps swell the oil and reduce its viscosity, thus enhancing oil recovery.

Hansel et. al[38] reported that the overall characteristics of the combustion with oxygen appear to be superior to the characteristics with air. They mentioned that oxygen in-situ combustion offers several advantages over similar combustion with air. These advantages may include faster oil production, reduced compression costs, ability to sustain combustion under reservoir conditions adverse for combustion with air, increased CO_2 content for decreased oil viscosity, and increased CO_2 concentration in the produced gas for reinjection into the same or another reservoir.

Garon et. al[42] concluded that oxygen offers many process and operational advantages over normal air in-situ combustion.

Fairfield and White[43] concluded that injecting oxygen rather than air would reduce the sanding and gas locking problems and accelerate the recovery schedules.

Shahani and Hansel[44] reported that oxygen enrichment was found to have a very pronounced effect on the combustion process as evidenced by a substantially higher burn front velocity.

B. Wet Forward Combustion

In-situ combustion for the case of injecting water in moderate amounts along with air is called wet forward combustion. In this case, water flashes into super-heated steam a short distance from the injection well; the evaporation front then moves away from the injection well. As the super-heated steam mixed with air reaches the combustion front, only the oxygen is utilized in the burning process. Upon crossing the combustion front, the super-heated steam mixes with nitrogen from the air and flue gas consisting mainly of CO and CO_2. This mixture of gases displaces the oil in front of the combustion zone and condenses as soon as its temperature drops to about 400 °F.[22]

The purpose of injection water along with air is to take advantage of the residual heat left in the burned region. The addition of water during the combustion process offers three advantages over conventional dry in-situ combustion:[36]

I. It helps to efficiently use the heat from the burned region. In this way the high thermal capacity of water may be used to recover the amount of heat remaining behind the burning front and transport it downstream. Indeed, the addition of water during forward in-situ combustion significantly increases the amount of heat transported by water from the burned region to the region downstream from the combustion front[25,26].

Burger and Sahuquet[29] experimentally found that in-situ combustion with water injection led to more efficient heat utilization. If a little water is injected along with air, part of the burned region has been cooled and some of the injected water establishes a water saturation in this region. The remainder of the water is vaporized at a high temperature zone behind the combustion front. This steam passes through the combustion zone carrying heat to the oil ahead. If more water is injected, more cooling occurs and the evaporation front moves closer to the burning front, more heat is transported downstream, and the steam zone expands. If air-water ratio is reduced further below 3000 scf/bbl, the trailing edge of the combustion front is cooled so that some unburned fuel is left behind, with the evaporation front catching up with the combustion front. Finally if more water is injected, it is possible to cause the high temperature region to vanish. In general, there is a lower limit to the air-water ratio that would not put the fire out and still operate efficiently.

The temperature throughout the heated region would be at the boiling point of water at the reservoir pressure. In this case, more coke would be left behind.

II. It reduces the fuel requirements. In other words, wet combustion is an improvement of dry combustion which offers a better sweep efficiency and lower air and fuel requirements.[3] Burger and Sahuquet[29] emphasized that when water was injected along with air, the fuel content decreased as a result of a more efficient sweep in the steam plateau.

III. It causes faster movement of the combustion front through the reservoir. Burger and Sahuquet[29] emphasized that water injection was efficient even at a water/air ratio of 0.001 cu m/s cu m. and the condensation front had a notably higher velocity than the combustion front. Thus combustion front velocity and oil recovery increased.

Figure 3. presents a schematic diagram of a wet forward combustion process in which it can be conveniently divided into five zones:

Zone 1: This zone has already been swept by the combustion front and contains little or no

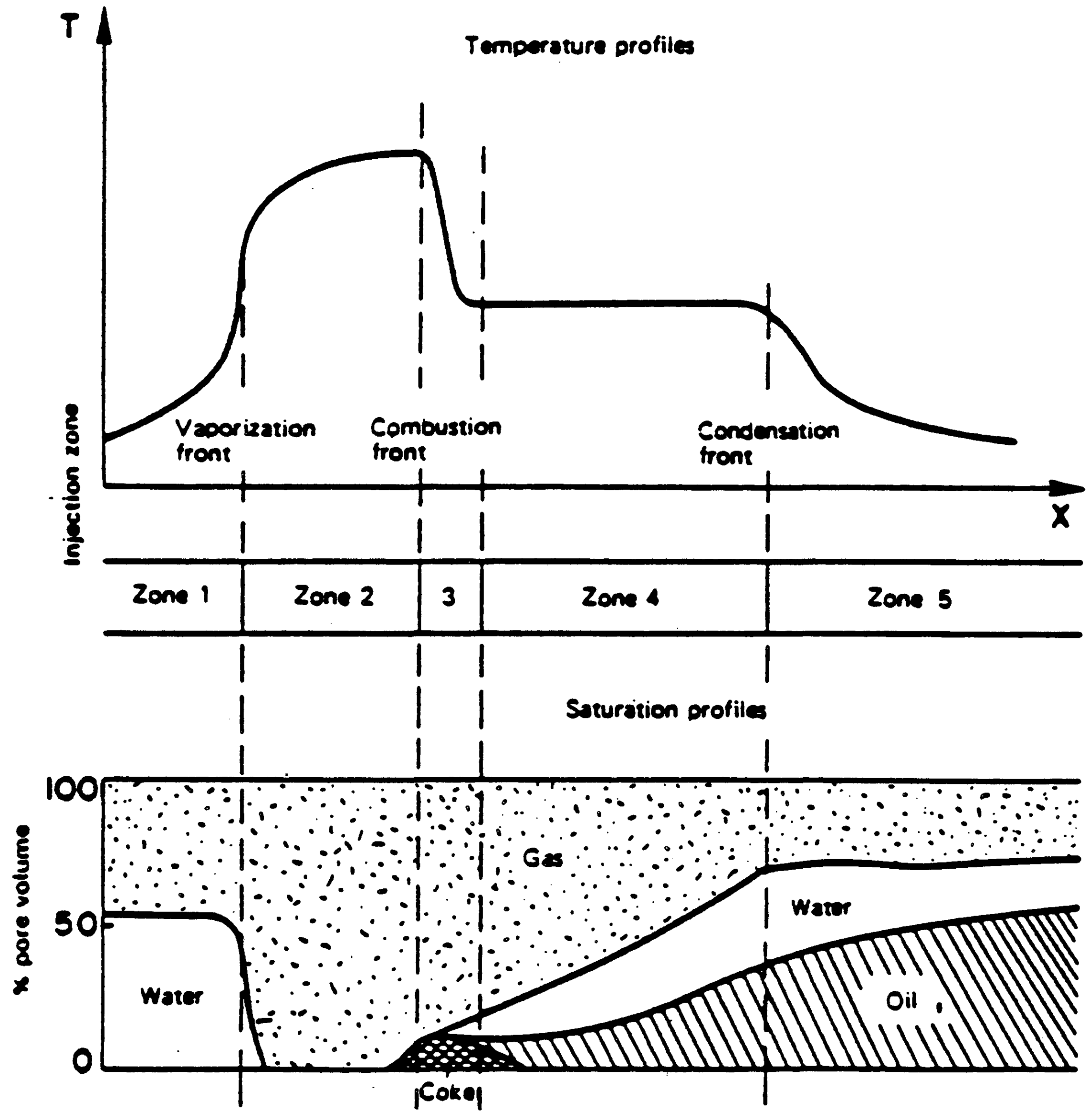

Figure 3. Schematic diagram of wet forward combustion process (Modified from reference no. 24)

hydrocarbon. However, since the temperature is lower than the boiling point of water, the pores contain a liquid water saturation, the remainder of the space being occupied by the injected gas.

__Zone 2:__ Water is in the vapor phase in this zone, and the pores are saturated with a mixture of injected gas and steam. The injected water vaporization front is at the boundary between zones 1 and 2.

__Zone 3:__ The combustion zone. Oxygen is consumed in the combustion of the deposited coke formed in the downstream part of the zone.

__Zone 4:__ The vaporization-condensation zone. The temperature in this zone is close to that of the vaporization of water. Progressive condensation of steam takes place in this zone. In addition, some light and intermediate oil fractions are vaporized and carried downstream. If the temperature is high enough certain chemical reactions may occur in this zone.

__Zone 5:__ Just downstream of the vaporization-condensation zone is a zone of high back-pressure, due to the formation of a water bank preceded by an oil bank. Further downstream the formation gradually approaches its initial conditions.[24]

C. Quenched Forward Combustion

Quenched forward combustion occurs when water is injected in sufficient amounts in order to bring the evaporation front as close as possible to the combustion front. This would result in transporting nearly all the excess heat of the burned zone to the steam zone. Thus, the steam zone would increase in size, and for a given well spacing the combustion front would travel a much shorter distance than in the case of dry combustion in order to effectively sweep the oil towards the production wells. This is due to the lower fuel content.

Laboratory results showed that quenched combustion requires only about one-third as much air as that needed for dry combustion.

D. Partially Quenched Combustion

Partially quenched combustion occurs when water is introduced in sufficient amounts into the combustion zone. At the upstream side, the cooling by water prevents the complete consumption of the fuel, and for this reason it is called "partially quenched" combustion.

Laboratory experiments showed that the introduction of water in the combustion zone would partially quench the combustion, and thus the oxygen must travel until it comes in contact with oil. In this way, the combustion zone moves at the speed of the cooling water and all the processes (heating and partial evaporation of water, heat recovery from the formation and heat generation by combustion) occur in one fast-traveling front.

For partially quenched combustion the oxidation rate and the combustion-zone velocity no longer depend on the coke formation.[35]

Dietz and Weijdema[26] concluded that quenched combustion was a feasible recovery process; the air requirement was much less than for dry or normal wet combustion.

Reverse Combustion Process

The reverse combustion process is first started as a forward combustion, after burning out a short distance from the ignited well, gas injection is switched to adjacent wells.[22] Gas is continuously injected into the adjacent wells hence driving the oil towards the previously ignited wells while the combustion front moves against the injected gas flow towards the adjacent wells as illustrated in Figure 4a.

> Picture yourself smoking a cigarette in the conventional manner. The flame front and the products of combustion both travel toward your mouth (forward combustion). If you blow into the cigarette, however, the products of combustion travel outward while the flame front still moves toward your mouth (reverse combustion). Thus, in forward combustion both oil and the heated zone are moving toward the producing well and away from the injection well, while in reverse combustion the flame front moves away from the producing well.[28]

Figure 4b. presents a schematic diagram of the reverse combustion process. Four Zones can be defined starting from the injection well, as shown in Figure 4b.:

Zone 1: The formation is at original conditions. However, it is being swept by injected gas, and if the formation temperature and oxidability of the oil are high, certain oxidation reactions may occur.

Zone 2: The temperature increases by conduction from the hot zone downstream. The start of oxidation also contributes to the temperature increase. The following phenomena occur: vaporization of the formation water, distillation of the light fractions of the oil and cracking of

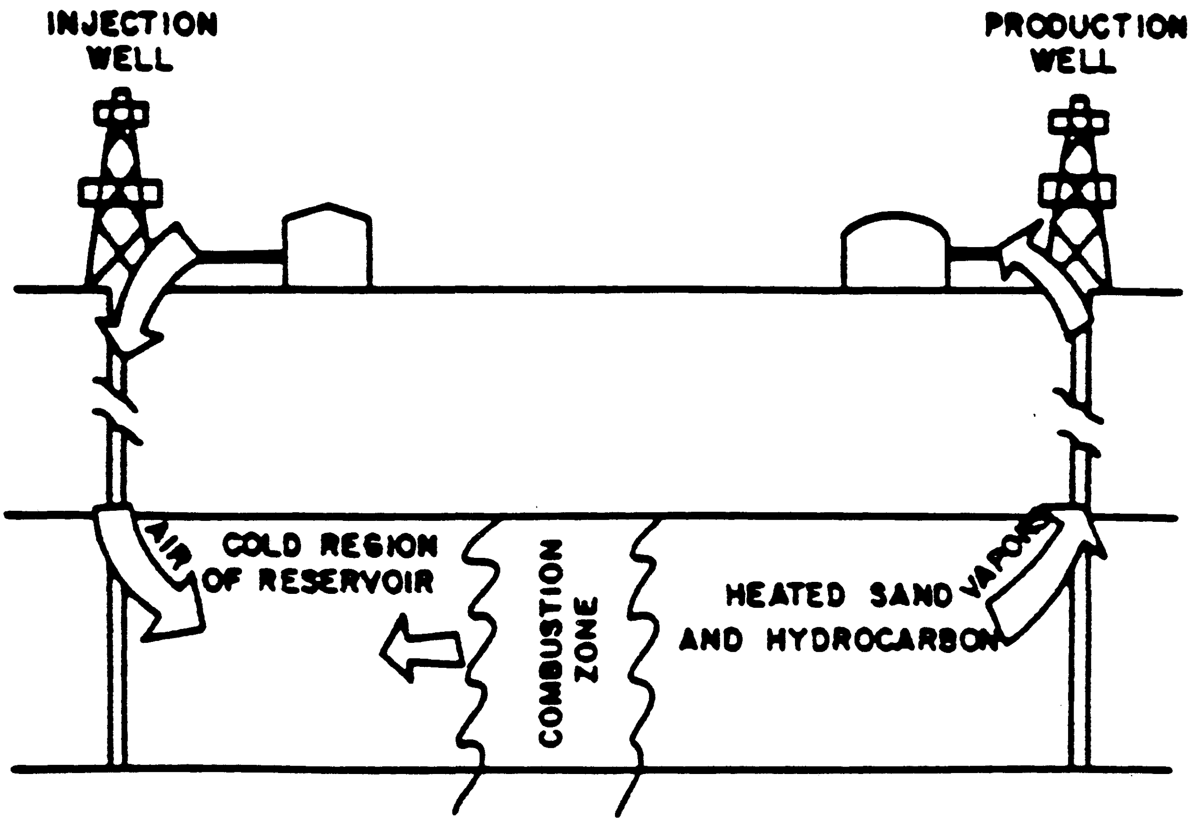

Figure 4a. Illustration of reverse combustion process (Modified from reference no. 22)

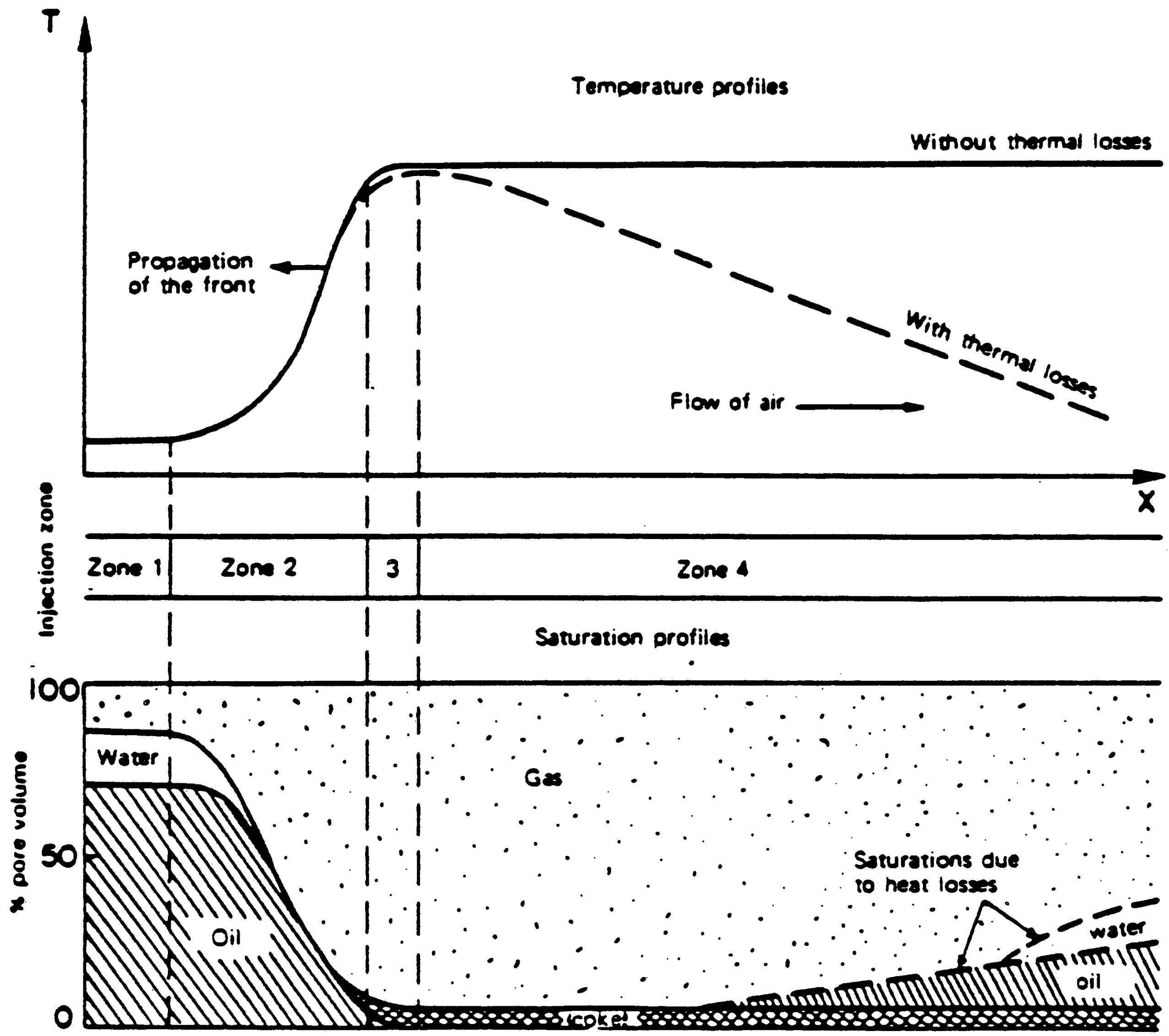

Figure 4b. Schematic diagram of reverse combustion process (Modified from reference no. 24)

certain hydrocarbons in the presence of oxygen. The liquid and vapor fractions are displaced downstream, while certain components from the carbon deposit or "coke".

Zone 3: The combustion zone. The temperature reaches its maximum value. The oxidation and combustion reactions involving the most reactive hydrocarbon molecules consume all the oxygen not used by the reactions in the preceding zones.

Zone 4: The unburnt coke remains deposited on the matrix while the vapor and liquid phases flow downstream. If there were no heat losses, the downstream temperature would remain equal to that of the combustion front. In reality, the temperature decreases with distance from the combustion zone. Thus condensation of the distilled oil fractions occur, and possibly of the steam.[24]

During the reverse combustion process, the reaction generally takes place with a large excess of fuel, and it may be assumed that fuel content is constant throughout the reaction zone.[35]

All the above mentioned combustion processes are examined in laboratory experiments for evaluation and comparison purposes. However, in field applications, only the following processes were used:

1) Dry forward in-situ combustion which is the dominant,

2) Combination of Forward Combustion and Water-flooding which is known as COFCAW, and

3) Use of oxygen enriched injection.

Quality of Combustion

The oxidation reactions of the hydrocarbons were accurately described by laboratory studies. Urban and Udell[34] classified the reactions that may take place during an in-situ combustion process into three general classes: pyrolysis, low-temperature oxidation, and char or high-temperature oxidation. They defined the pyrolysis reaction as the one which is responsible for the deposition of residual carbonaceous material. They also mentioned that the low-temperature oxidation is the reaction that occurs near 570 °F or lower and which is very important because it has been shown to increase the oil viscosity, and is exothermic. They also emphasized that the high-temperature oxidation is the reaction which is responsible for oxidizing the residual carbonaceous material that has been produced by the pyrolysis reactions. They also mentioned that this reaction is believed to provide the major fraction of the thermal energy released during in-situ combustion and consume the oxygen necessary for the burning front propagation. This is the reaction in which the combustion temperatures are from 600-1200 °F at the combustion front.

Low-Temperature Oxidation (LTO)

Low-temperature oxidation takes place upon air injection either before or after ignition, if oxygen is available downstream from the combustion front.[30]

Alexander, et al.[23] illustrated the effect of the combustion temperature on the fuel availability. They stated that the fuel content increases linearly from zero near 300°F to a maximum of 1.75 weight per cent carbon at 650°F, and then it decreases again to about 1.15 weight per cent carbon at 1,000°F. They also mentioned that at combustion temperatures below 650°F, residual hydrocarbons are observed on the "combusted" oil sand. Furthermore, decreased levels of carbon oxides are found in the produced gases, and more oxygen has reacted than can be accounted for in the produced fluids. Most of this oxygen is chemically combined with, or absorbed by, the residual hydrocarbons on the sand grains. They also emphasized that LTO increases the viscosity and alters the distillation characteristics of the crude oil.

In other words, it can be said that low-temperature oxidation is characterized by low levels of carbon oxides in the produced gases, and more oxygen reacts with the hydrocarbons than can be found in the produced gases. Thus, LTO significantly influences the amount of fuel available for combustion. At very high combustion temperatures, very little LTO may take place if oxygen enrichment is high.

High-Temperature Oxidation (HTO)

Combustion in the temperature range of 650°F to 1200°F can be termed high-temperature oxidation reaction HTO. Alexander, et al.[23] experimentally found that there are less residual hydrocarbons deposited on the sand grains as temperatures increase toward 650°F, and the principal reaction products are carbon oxides and water. They also mentioned that the displacement efficiency increases with temperature and, as a result, decreased amounts of oil-like materials are left in the pore spaces to be oxidized. Burger and Sahuquet[29] concluded from their experiments on wet-combustion tests that no residual fuel deposition was recorded as long as the high-temperature zone existed. Urban and Udell[34] stated that the HTO is the reaction which is believed to provide the major fraction of thermal energy released during in-situ combustion and consume the oxygen necessary for front propagation. The HTO reaction is described by the following stoichiometric equation:

$$CH_{F_{HC}} + \left(\frac{1+2m}{2+2m}+\frac{F_{HC}}{4}\right) O_2 \xrightarrow{600-1200°F} \left(\frac{m}{1+m}\right) CO_2 + \left(\frac{1}{1+m)}\right) CO + \left(\frac{F_{HC}}{2}\right) H_2O$$

LITERATURE REVIEW

Laboratory experiments, mathematical models, and field tests have been widely used to investigate the in-situ combustion process. A number of studies have been made using material balance and mathematical models for both forward, dry and wet, and reverse combustion processes.

Nelson and McNeil[14] presented a paper regarding the engineering of an in-situ combustion project applying material balance calculations on experimental combustion tube data.

Numerical models for simulating wet or dry combustion processes were reported in the literature. Coats[40] presented a paper that describes a model for simulating wet or dry, forward or reverse combustion in one, two, or three dimensions. The paper includes comparisons of the model results with reported laboratory tube test results.

Very little has been written on the stoichiometry of the in-situ combustion process. For example, Poettmann[15, 18] derived the equations of the underground stoichiometric reaction and applied them to data from Martin et al.[6]

Youngren[41] presented a paper that describes a numerical model that uses the stoichiometric reaction to describe the combustion process taking place.

EXPERIMENT

Experimental Apparatus

Combustion tube tests are useful in determining the amount of fuel deposition and injected gas requirement. A Schematic diagram of a combustion tube apparatus is illustrated in Figure 5. Combustion tubes used in laboratory experiments vary in size, length, and mode of operation.[19] In general, the main part of a combustion tube apparatus usually consists of a combustion tube, sand pack, thermocouples, heating elements and necessary insulation.

The combustion tube is a thin-walled stainless steel tube which is 3 to 10 feet long, 2 to 10 inches diameter and 0.040-0.065 inch wall thickness. The tube is packed with sand saturated with oil and water and then suspended horizontally in an insulated pressure shell. The combustion-tube and pressure-shell package is then mounted on a rotation assembly to allow simulation of dipping reservoirs. The annulus between the two tubes is filled with nitrogen gas supplied from a nitrogen cylinder at a pressure approximately equal to the injection pressure.

The combustion tube is surrounded with electrical resistance heating elements which are used to maintain the adjacent sections of the wall of the pipe at temperatures equal to the temperatures of the contained sand. The heating

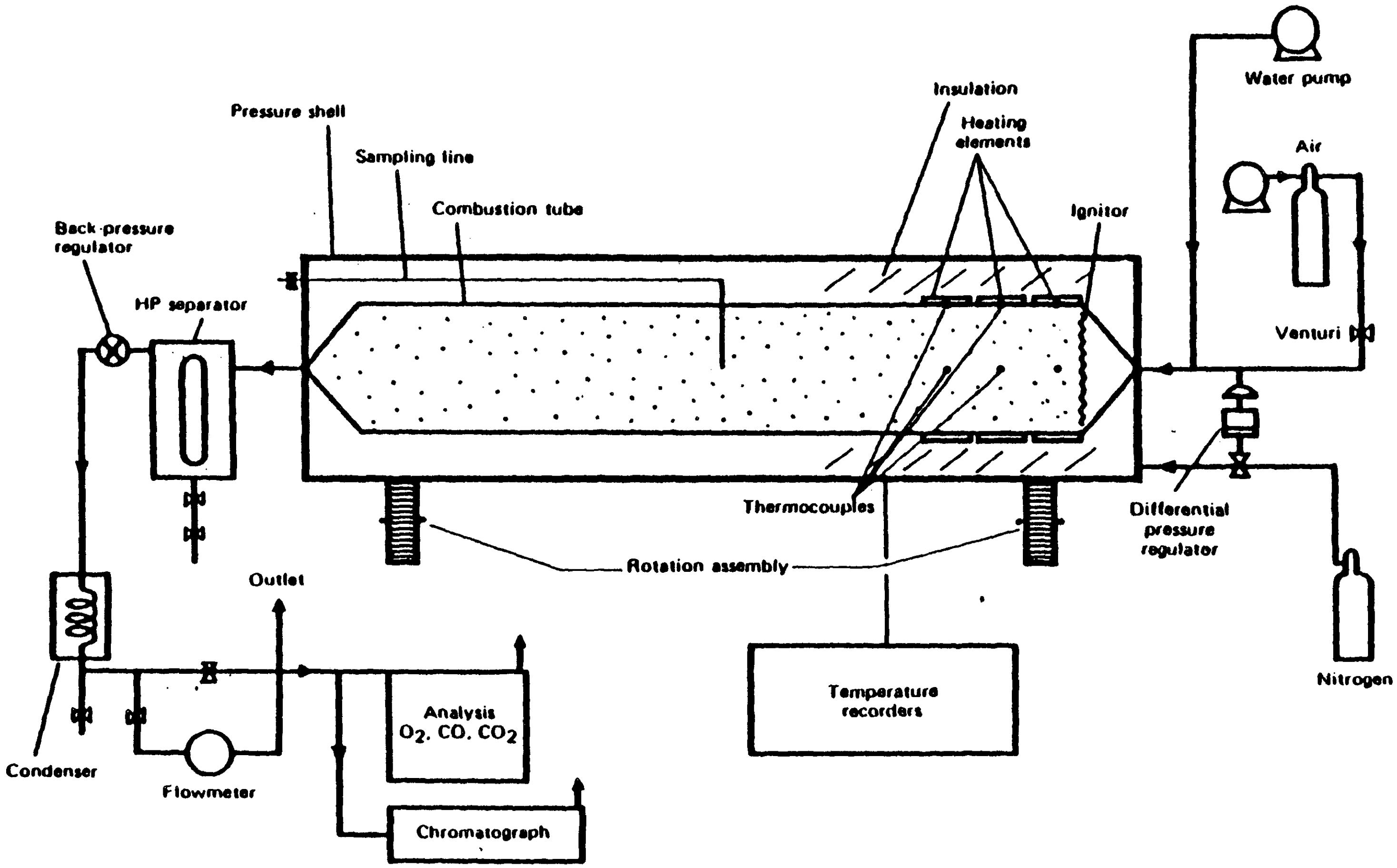

Figure 5. Schematic diagram of a combustion tube apparatus (Modified from reference no. 24)

elements also compensate for heat losses from the sand section, thereby causing the sand section to simulate more closely a horizontal increment of a combustion-drive reservoir.

Thermocouples placed along the axis and at the wall of the combustion tube allow the propagation of the combustion front to be monitored. Temperatures along the combustion tube centerline are continuously recorded with temperature recorders. Ignition takes place by way of a resistance element "ignitor" covering one end of the combustion tube.

Air or oxygen is supplied from gas cylinders and the injected gas flow rate is metered by a venturi meter. The injection gas flows into the combustion tube where combustion takes place. The differential pressure regulator controls the inlet gas pressure. In a wet combustion test, water is injected through a water pump. Produced gases leave the end of the tube and flow through the high-pressure and low-pressure separators where free liquid is collected. The back-pressure regulator controls the outlet pressure. It is periodically reset during a combustion tube run to maintain a constant injection pressure.[9] The produced gases are continuously analyzed and the production gas volume is metered by a wet test meter before venting to the atmosphere.

A gas chromatograph is used for analyzing nitrogen, hydrocarbons, and sulfur compounds. Continuous analyzers measure the percentage of the CO_2, CO and O_2 in the produced gases. The volumes of oil and water produced are measured and their properties are determined.[24]

Experimental Procedure

The combustion tube is packed with a mixture of dry sand, oil and water to yield the desired fluid saturation distributions. The mixture is tamped down with a special tool to obtain a uniform porosity.[1] Porosity, permeability and oil saturation of the sand pack are then determined.

Raw linseed oil which yields a fast and uniform ignition may be placed on the sand face before placing the flange and ignitor assembly.[19] The combustion tube is then secured in the insulated pressure shell. Inlet gas connections, separators, traps and temperature recorders are connected into the system.

The combustion tube is pressured with nitrogen to test for gas leaks and establish a stable flow rate. The ignitor, the inlet gas and temperature recorders are then turned on, initiating the beginning of the run. The ignitor gradually heats the inlet of the sand pack to the ignition temperature at the desired injection pressure. When the combustion front is established, the injected gas flux is fixed.[1]

Produced fluids are collected in weighing jars which are frequently removed for liquid analysis. Dry gases are tested with the chromatograph to detect CO_2, CO, O_2, N_2 and hydrocarbon gases. Produced gas volumes are determined with the wet test meter.

Traversing thermocouples are used to accurately determine the combustion front position and temperature distribution. Temperature distribution along the combustion tube centerline is continuously recorded with the temperature recorders. Inlet and outlet pressures are recorded periodically. All of the data-taking operations are performed throughout the run until the burning front reaches the bottom flange of the combustion tube, the run is then terminated.[19]

Steady-state Combustion Characteristics

Combustion parameters are evaluated at steady-state burning conditions. It is difficult if not impossible to evaluate the different combustion parameters if the steady-state conditions are not reached. This is due to the difficulty of averaging the values of the produced gas analysis.

Shu and Lu[9] experimentally found that the steady-state burning period was achieved during a time period of two to seven hours after ignition at a maximum combustion temperature of 900°F. They also evaluated the combustion parameters based on the average produced gas analysis over this stabilized period.

Showalter[4] stated that the quantity of fuel consumption was calculated only for a portion of the sand section in which burning had been as uniform as possible. Values for the amount of fuel consumption were calculated excluding the nonequilibrium burning portion.

Most of the workers on combustion tubes select the steady-state burning portion of the run for the produced gas analysis and the calculation of the combustion parameters.[1,2,7,8,9,11,12,13,14,16,19]

Experimental Measurements-High-Temperature Oxidation

As mentioned earlier, the combustion parameters are evaluated at the stabilized burning conditions. This is due to the ease of analyzing the produced gas over this period.

Since combustion tube runs are conducted at high temperatures, the high temperature reaction predominates. The reported results from the tube runs and the results calculated from the stoichiometric equations are compared.

The comparison between reported experimental data and the calculated data are based on the high temperature oxidation reactions to get a better interpretation and comparison.

Hydrogen to Carbon Atomic Ratio

From a material balance, the hydrogen to carbon atomic ratio of the fuel can be calculated by assuming that the unaccounted O_2 has been consumed in the formation of water. This may not be true if some oxygen is consumed in low temperature oxidation (LTO) reactions. For this reason the H/C ratio is considered to be an apparent value rather than the true ratio in LTO reactions.

Alexander et al.[23] experimentally showed that the apparent H/C ratio decreases as the combustion temperature increases.

In the temperature range of the high combustion reactions (650 °F to 1200 °F), the H/C ratio is representative of the fuel combusted. It is to be noted that at combustion temperatures in excess of 650 °F, the H/C ratio of the fuel was lower than that the H/C ratio of the original crude. They also showed that there is a general decrease in fuel availability as the atomic H/C ratio of the crude oil increases. Thus, emphasis should be brought again that the produced gas analysis must be at a constant-temperature high oxidation reaction for better comparison agreement between the reported and the calculated parameters.

LTO takes place below the ignition temperature of the fuel. It is difficult to see how LTO takes place in a combustion tube at high temperature if the oxygen utilization efficiency is high.

FUEL CONTENT

The primary fuel to sustain combustion is derived from distillation and thermal cracking of the heavy ends of the crude oil molecules with gas being injected into the reservoir to sustain combustion.[18]

It is generally accepted that the chemical processes involve: (1) coke formation from the heavy ends of the crude, and (2) coke combustion. These reactions occur at temperatures higher than about 600 °F on the interface area of the fuel beads (solid particles or liquid droplets).[35] Alexander et al.[23] found that original and residual oil saturation, API gravity, viscosity, H/C ratio and Conradson carbon residue are the most important factors affecting fuel availability.

Showalter[4] experimentally found that there is approximately a linear relationship for oil gravities between 40 °API and 17 °API and the fuel content where the fuel content decreases as the API increases. He also found that below 17 °API, the fuel content increases very rapidly as oil gravity decreases.

The fuel content, which is controlled by rock properties, oil characteristics, temperature and pressure, is a measure of the amount of oil or coke consumed by oxidation. Combustion tube tests are useful in determining this variable which is very important in evaluating an in-situ combustion project.

It is most important, however, that such tests be conducted with oil and rock samples from the reservoir in question if the best analysis is to be made.[18]

Experimentally the fuel content is calculated as follows:[37]

At a given increment of time, the volume of gas injected, the composition of the produced combustion gases and the length of the burned region (how far the combustion front has moved) are known. Based on the nitrogen balance, the volume of the produced gases is calculated on a dry basis based on the known volume of gas injected. The amount of carbon that has been burned to CO_2 and CO is calculated. By material balance on the oxygen injected compared to the measured oxygen out as O_2, CO and CO_2, the difference is assumed to have formed water. The amount of hydrogen atoms burned is then calculated from which the total mass of fuel is calculated. During this time span the volume burned is known and the fuel content is simply the ratio of the total mass of fuel burned to the volume burned.

Oxygen Utilization Efficiency

Oxygen consumption is a measure of the efficiency of the combustion process. Experimentally, it is calculated based on a material balance from the total injected and produced oxygen during the stabilized portion of the combustion run:

$$\text{oxygen utilization efficiency} = \frac{O_{2\ inlet} - O_{2\ outlet}}{O_{2\ inlet}}$$

It is to be noted that in the above equation, the inlet and outlet oxygen is the total amount or volume, not composition or concentration, i.e.:

$$e_{O_2} = \frac{\text{total oxygen injected} - \text{total oxygen produced}}{\text{total oxygen injected}}$$

Combustion Front Velocity

Combustion front velocity can be experimentally measured from temperature profiles, the distance between adjacent thermocouples, and the time the peak temperature takes to move from one thermocouple to the other.[31]

Showalter[4] stated that the combustion front moves to its fuel supply only as fast as it depletes its fuel supply.

Hansel et al.[38] experimentally found that the combustion front velocity increases with percentage oxygen in the injected gas. They also found that the velocity increases with the injected gas flux.

Rates of advance of the combustion front are determined experimentally from slopes of plots similar to Figure 6.

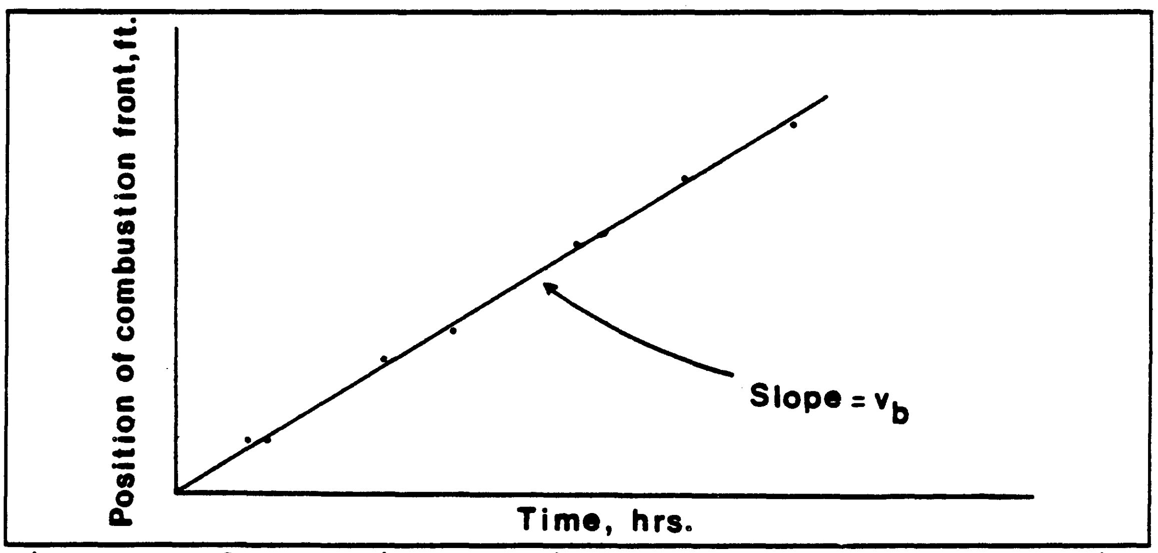

Figure 6. Plot of time vs. distance travelled by combustion front from top of sand-pack

Injected Gas Requirement

The volume of injected gas required to burn one cubic foot of sand-pack is experimentally measured based on the injected gas flux and the velocity of the combustion front as follows:

$$\text{gas requirement} = \frac{\text{gas flux}}{\text{combustion front velocity}} \ \text{scf/cu.ft.}$$

The gas requirement can also be experimentally measured by dividing the total gas injected over a steady-state time period by the volume of sand-pack burned during that same time period.

Showalter[4] found that the air required to drive the burning front through oil sand depends primarily on the quantity of fuel for combustion which in turn can be predicted from the API gravity of the in-situ oil. He also listed three other factors which affect the air requirement; first, the H/C atomic ratio, second, the relative amount of carbon which is incompletely oxidized and appears in the exhaust gas as CO, and third, the air requirement as affected by the oxygen utilization efficiency.

Alexander et al.[23] showed that, regardless of the crude oil or porous medium used, the total amount of injected gas required to burn one pound of fuel is approximately the same at temperatures in excess of 650 °F, that is HTO. At temperatures below 650 °F, partial oxidation reactions increase the apparent H/C ratio and cause the gas requirement to exceed the average value. They also found that there is a general trend of increasing gas requirement as fuel content increases. They concluded that for best results, the fuel availability and gas requirements for specified field applications should be determined using actual reservoir crude and core material and process conditions approximating those expected during in-situ combustion in the reservoir.

STOICHIOMETRY OF DRY IN-SITU COMBUSTION

The stoichiometry of the combustion reaction process is represented by the following general stoichiometric equation:[1]

$$CH_{F_{HC}}+\left(\frac{1}{(y_{io_2})\,.\,(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)G_i \longrightarrow \left(\frac{m}{m+1}\right)CO_2+\left(\frac{1}{m+1}\right)CO$$
$$+\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{e_{O_2}}-1\right)O_2+\left(\frac{y_{i_{N_2}}}{y_{io_2}\,.\,e_{O_2}}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)N_2+\left(\frac{F_{HC}}{2}\right)H_2O \tag{5.1}$$

where:

+ F_{HC} is the hydrogen to carbon atomic ratio of fuel
+ m is the ratio of moles of carbon dioxide to carbon monoxide
+ y_{iO2} is the mole fraction of oxygen in the injected gas
+ e_{O2} is the oxygen utilization efficiency
+ G_i denotes any oxygen-containing injected gas

This equation indicates that the fuel is a hydrocarbon material that has a hydrogen to carbon atomic ratio of F_{HC}. When the fuel is oxidized it generates CO_2, CO and H_2O as the combustion products. It is assumed that nitrogen is completely inert in the reaction, and that none is accumulated in the sand-pack during the burning run. This means that the amount of nitrogen injected equals the amount produced.

---

[1] Derivation of the stoichiometric equation is in appendix A.

For the general situation where the injected gas consists of any composition of oxygen and nitrogen:

1. $m = \dfrac{y_{pCO_2}}{y_{pCO}}$ (5.2)

2. $F_{HC} = \dfrac{4\cdot\left(\dfrac{y_{iO_2}}{y_{i_{N_2}}}\right)+2\cdot y_{pCO}-\left(4\cdot\dfrac{y_{iO_2}}{y_{i_{N_2}}}+4\right)\left(y_{pO_2}+y_{pCO}+y_{pCO_2}\right)}{y_{pCO_2}+y_{pCO}}$ (5.3)

3. $e_{O_2} = 1-\dfrac{y_{i_{N_2}}}{y_{iO_2}}\cdot\dfrac{y_{pO_2}}{y_{pN_2}}$ (5.4)

For the situation where the injected gas is pure oxygen:

1. $y_{iO_2} = 1.0$ (5.5)

2. $y_{i_{N_2}} = 0.0$ (5.6)

3. $m = \dfrac{y_{pCO_2}}{y_{pCO}}$ (5.7)

$$4.\ F_{HC} = \frac{4\ .\ (1-y_{pO_2}-0.5y_{pCO}-y_{pCO_2})}{y_{pCO_2}+y_{pCO}} \tag{5.8}$$

$$5.\ e_{O_2} = 1-y_{pO_2} \tag{5.9}$$

Assuming that all the fuel laid down in the sand is burned, the ratio of moles of the injected gas required to burn one mole of coke can be written as follows:

$$F_{gF} = \left(\frac{1}{(y_{iO_2})\,(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right) \tag{5.10}$$

In terms of moles of injected gas per pound coke

$$n_{gF} = \left(\frac{1}{(y_{iO_2})\,(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) \tag{5.11}$$

If the injected gas is measured in standard cubic feet at T_{sc} °F and p_{sc} psia, then standard cubic feet of injected gas to burn one pound of coke is calculated from

$$G_F = \left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) \tag{5.12}$$

Knowing the fuel concentration in pounds per cubic foot of sand-pack, m_E, then standard cubic feet of injected gas necessary to burn out one cu. ft. of sand-pack at the combustion front is given by:

$$G_{CF} = \left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E \qquad (5.13)$$

In general, combustion takes place in a relatively narrow zone "the combustion front" which moves in the same direction as the injected gas. If the number of scf of injected gas per cu. ft. of sand-pack was to be evaluated at the inlet of the tube, then the volume of injected gas stored behind the combustion front has to be accounted for by adding that volume to the required volume of injected gas to burn one cu. ft. of sand-pack as follows:

$$G_i = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E\right]+\left[\frac{\phi_E}{B_{gi}}\right] \qquad (5.14)$$

Where:

G_i = Scf of injected gas per cu. ft. of sand-pack at the inlet of the combustion tube

B_{gi} = Formation volume factor of the injected gas

ϕ_E = porosity of sand-pack, fraction

If u_{Ei} is defined as the injection gas flux (scf/ft² hr), then the velocity of a point in the combustion front v_b (ft/hr) can be solved for as follows:

$$v_b = \frac{u_{Ei}}{\left[\left(\frac{(10.732)(T_{sc}+460)}{(y_{iO_2})(e_{O_2})(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right)m_E + \frac{\phi_E}{B_{gi}}\right]} \quad (5.15)$$

Knowing the oil saturation and the equivalent oil saturation burned as fuel, the scf of injected gas per one barrel of oil displaced at the combustion front is calculated by:

$$G_{CFO} = \left(\frac{(10.732)(T_{sc}+460)}{(y_{iO_2})(e_{O_2})(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{5.615}{12+F_{HC}}\right)\left(\frac{m_E}{\phi_E(S_o - S_{FrE})}\right)$$

(5.16)

Where:

$$S_{FrE} = \frac{m_E}{\phi_E\,\rho_o} \quad (5.17)$$

If the volume of injected gas is to be calculated at the injection side of the combustion tube, then the volume of gas stored behind the combustion front should be accounted for by adding this volume to the volume of injected gas required at the front.

Thus Scf of injected gas required to displace one barrel of oil at the inlet is given by the following equation:

$$G_{io} = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E + \frac{\Phi_E}{B_{gi}}\right] \times$$

$$\left[\frac{5.615}{\Phi_E (S_o - S_{FrE})}\right] \qquad (5.18)$$

From the general stoichiometric equation it can be seen that one mole of coke generates $\frac{F_{HC}}{2}$ moles of H_2O, thus

$18.016 \; \frac{F_{HC}}{2} \cdot \frac{1}{350.376}$ bbl of H_2O are generated per one mole of coke burned. Thus barrels of water generated per one cu.ft. of bulk sand-pack volume or reservoir volume burned is:

$$\delta_{wb} = \frac{18.016 \; . \; F_{HC} \; . \; m_E}{(12 + F_{HC})\;(2\times350.376)} = 0.02571 \; \frac{F_{HC} \; . \; m_E}{(12 + F_{HC})} \qquad (5.19)$$

Finally, the volume of gas produced at the combustion front per cu. ft. of the injected gas passing through the front is given by:

$$G_{p_i} = \frac{1 + \left[\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right]\left[\frac{1}{e_{O_2}}\left(1 - e_{O_2} + \frac{y_{i_{N_2}}}{y_{iO_2}}\right)\right]}{\left(\frac{1}{(y_{iO_2})\ (e_{O_2})}\right)\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)} =$$

$$\left[\frac{(y_{iO_2})\ (e_{O_2})}{\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)}\right] + \left[1 - (y_{iO_2})\ (e_{O_2})\right] \tag{5.20}$$

If scf of produced gas at the exit of the combustion tube per cu. ft. of sand-pack burned is to be calculated, then the gas volume occupying the pore spaces downstream of the combustion front should be accounted for and added to that at front as follows:

$$G_{pCF} = \left[G_{CF}\ .\ G_{p_i}\right] + \left[\frac{(\phi_E)\ (1 - S_o)}{B_{gp}}\right]$$

$$G_{pCF} = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E\right] \times$$

$$\left[\left(\frac{(y_{iO_2})\ (e_{O_2})}{\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)}\right)+\left(1-(y_{iO_2})\ (e_{O_2})\right)\right]+\left[\frac{(\phi_E)\ (1-S_o)}{B_{pg}}\right] \qquad (5.21)$$

The above equations are applicable to reservoir conditions after correcting the fuel availability from sand-pack conditions to reservoir conditions on the assumption that all parameters, but porosity, are the same. This correction is achieved as follows:

$$m_R = m_E \cdot \left(\frac{1-\phi_R}{1-\phi_E}\right) \qquad (5.22)$$

COMPARISON WITH REPORTED TUBE RUN RESULTS

An important question one may pose is: how well do the predictions of the theoretical stoichiometric analysis compare with the experimentally reported results.

The general stoichiometric equation and equations for the ratio of carbon dioxide to carbon monoxide "m", the hydrogen to carbon atomic ratio "F_{HC}" and the oxygen utilization efficiency "e_{02}" for any injected gas on a water-free, hydrocarbon-free basis are used to derive the applied stoichiometric equations necessary for evaluating an in-situ combustion project.[2]

The produced gas analysis reported with each tube run on a water-free and hydrocarbon-free basis was used to calculate the different variables derived from the stoichiometric equation.

The agreements between the calculated and the reported values of the variables were good, especially where there were good produced gas analyses. In some of the reported data, where the steady-state burning portion of the run was not reported for the produced gas analysis, the agreement was not good. In one set of data the produced gas analysis contained appreciable hydrocarbon gases despite reported high combustion

[2] See appendix A for the derivation of the stoichiometric equations

temperatures. In analyzing the experimental data of this set, there appear to be inconsistencies in the observed measurements of the produced gas analysis. The author did not report any values for the oxygen concentration in the produced gas analysis yet in some cases he reported values of the oxygen utilization efficiencies less than 100%. Thus there should be some oxygen in the produced gases. For this data set, the agreement was poor.

It is helpful to understand the method of measuring the different combustion parameters by different authors before comparing their results with those predicted by stoichiometry. This discussion was presented in the previous chapters and comments will be presented separately for each set of data.

In some sets of data the authors did not mention how the reported results were obtained, i.e. experimentally measured or theoretically calculated.

In this section, comparison between each set of reported data found in the literature and the calculated data using the stoichiometric equations will be tabulated and graphically illustrated. Notes and comments for each set of data will be discussed.

Statistical analysis will also be presented for data sets that contain more than 10 combustion runs conducted under the same combustion conditions, i.e. dry, wet, 21% or 100% oxygen injection etc. The analysis includes the following statistics:

1) Average Deviation,
2) Absolute Deviation,
3) Standard Deviation, and
4) Analysis of variance (ANOVA) of the reported data sets.

1) Average Deviation:

The average deviation of a data set is calculated as follows:

$$Average\ deviation = \frac{1}{N} \cdot \left[\sum_{i=1}^{N} \left(\frac{x_i - y_i}{x_i}\right)\right]$$

2) Absolute Deviation:

The absolute deviation of a data set is calculated as follows:

$$Absolute\ deviation = \frac{1}{N} \cdot \left[\sum_{i=1}^{N} ABS\left(\frac{x_i - y_i}{x_i}\right)\right]$$

3) Standard Deviation:

The standard deviation, sometimes called the standard error, of a data set is calculated as follows:

$$Standard\ deviation = S_x = \sqrt{S_x^2}$$

Where S_x^2 is the variance which is given by

$$S_x^2 = \left(\frac{1}{N-1}\right)\left[\sum_{i=1}^{N}\left(\frac{x_i - y_i}{x_i}\right)^2 - \frac{1}{N}\left(\sum_{i=1}^{N}\left(\frac{x_i - y_i}{x_i}\right)\right)^2\right]$$

x_i = the calculated value,

y_i = the reported value, and

N = number of runs.

4) Analysis of Variance:

The analysis of variance (ANOVA) is used here to analyze the experimental reported data. This model is a statistical tool for studying the relation and testing the quality of two or more experimental data sets. This statistical tool was applied to all data sets having three or more data points.

The analysis of variance (ANOVA) summary table is usually written as follows:

Source	df	S.S.	M.S.	F-ratio
Factor	k - 1	SST	MST	MST/MSE
Error	n - k	SSE	MSE	
Total	n - 1	TSS		

Analysis of Variance of F_{HC} Reported Values:

ANALYSIS OF VARIANCE

Source	df	S.S.	M.S.	F-ratio
Factor	7	17.44	2.49	1.13
Error	105	231.88	2.21	
Total	112	249.32		

CONFIDENCE INTERVALS

```
                               INDIVIDUAL 95 PCT CI'S FOR MEAN
                               BASED ON POOLED STDEV
LEVEL   N   MEAN   STDEV  -----+---------+---------+---------+-
BOUS    14 1.923   0.674              (----*----)
SHOW     8 1.202   0.404       (------*------)
CADY     6 2.842   1.210                 (-------*-------)
PUSCH   20 1.246   0.498          (---*----)
FASSI   14 1.387   1.061          (----*----)
PETIT   44 1.834   2.146               (--*--)
BURGER   5 2.010   0.201           (--------*--------)
                          -----+---------+---------+---------+-
POOLED STDEV =   1.486        0.0       1.5       3.0       4.5
```

Analysis of Variance of e_{O2} Reported Values:

ANALYSIS OF VARIANCE

Source	df	S.S.	M.S.	F-ratio
Factor	5	3806.0	761.2	10.71
Error	85	6043.6	71.1	
Total	90	9849.6		

CONFIDENCE INTERVALS

```
                               INDIVIDUAL 95 PCT CI'S FOR MEAN
                               BASED ON POOLED STDEV
LEVEL    N   MEAN    STDEV ---+---------+---------+---------+---
BOUS    14  91.71    5.96            (----*---)
MARTIN   6  84.10   12.58 (------*------)
PUSCH   20  81.90   12.96  (---*---)
PETIT   44  97.53    5.55                    (--*-)
BURGER   5  90.60    8.11        (-------*------)
                           ---+---------+---------+---------+---
POOLED STDEV =   8.43      80        90        100       110
```

Analysis of Variance of G_{CF} Reported Values:

ANALYSIS OF VARIANCE

Source	df	S.S.	M.S.	F-ratio
Factor	8	644952	80619	9.42
Error	118	1010094	8560	
Total	126	1655045		

CONFIDENCE INTERVALS

```
                                INDIVIDUAL 95 PCT CI'S FOR MEAN
                                BASED ON POOLED STDEV
LEVEL   N   MEAN   STDEV  ------+---------+---------+---------+
BOUS    14 241.29   83.30         (-----*-----)
SHOW    16 261.25   85.18            (-----*----)
CADY     6 314.50  137.51               (---------*---------)
MARTIN   6 278.17   50.03          (---------*--------)
PUSCH   20 300.62   73.29                 (-----*----)
FASSI   14 341.61   95.19                      (-----*-----)
PETIT   44 147.58  105.97 (--*---)
BURGER   5 214.20   17.47   (---------*---------)
                          ------+---------+---------+---------+
POOLED STDEV =      92.52     160       240       320       400
```

Analysis of Variance of v_b Reported Values:

ANALYSIS OF VARIANCE

Source	df	S.S.	M.S.	F-ratio
Factor	6	1.1717	0.1953	12.57
Error	84	1.3045	0.0155	
Total	90	2.4762		

CONFIDENCE INTERVALS

```
                              INDIVIDUAL 95 PCT CI'S FOR MEAN
                              BASED ON POOLED STDEV
LEVEL    N   MEAN   STDEV  ------+---------+---------+---------
BOUS    14  0.49   0.1714                          (----*---)
CADY     6  0.49   0.3046                        (------*-----)
MARTIN   6  0.16   0.1073   (------*------)
FASSI   14  0.33   0.0917                (---*----)
PETIT   44  0.23   0.0808           (-*--)
BURGER   5  0.16   0.0515   (------*------)
                           -------+---------+---------+---------
POOLED STDEV =     0.1246        0.15      0.30      0.45
```

Data from Bousaid (1,2)

Summary:

A study of dry, wet, and quenched combustion allowed the analysis of the mechanisms of quenching and reignition of oil in sand-packs. Laboratory results indicated that the cycle of quenching and reignition can be repeated to yield a fast moving front with an increase in oil rates.

The initial objective of this study was to extend the limits of wet combustion by replacing cold-water injection with hot-water or steam injection. The paper presents laboratory results that support a combustion process where reignition after quenching the burning front is a feasible recovery method. Dry, wet, and quenched combustion tube runs are presented in this paper.

The produced gas analyses for different runs were not included in this paper, but they, along with other data, were obtained directly from the author.[2]

Experimental Procedure:

1. On the production end of the combustion tube are two liquid/vapor separators. The first allows oil and water to be produced into the fraction collector and the second is cooled in an ice bath to condense entrained vapors in the produced gas. A small volume is sampled for gas chromatograph (GC) analysis for the main ingredients, including CO_2, CO and O_2,

before the gas volume is measured through a wet-test meter and then vented. The procedure is essentially the same for all combustion tube runs. The study involved dry, wet, and quenched combustion-tube results on two crude oils.

2. The fuel consumption was lower in clean sand, resulting in a lower air requirement. A minimum fuel value of about 0.80 lbm/ft^3 was considered adequate for efficient combustion in the cell at temperatures above 600 °F.

3. The author did not report any information about calculating the fuel content for each tube run.

4. The steady-state combustion interval of each test was used to evaluate the different combustion parameters.

5. Temperature measurements were used to monitor the frontal advance of the burn. The front's position was obtained as a function of time by tracking the progress of the peak temperature along the sand-pack.

6. The author did not give any description of how he obtained the H/C atomic ratio.

Discussion:

In this set of data, the study involved dry, wet and quenched combustion tube runs. The combustion temperature ranges for the dry runs were between 689-905 °F, for the wet runs were between 769-910 °F and for the quenched runs were between 551-815 °F.

The reported experimental variables from the tube runs were calculated using the derived stoichiometric equations and then were compared to the experimental results. The comparisons are tabulated and also graphically presented.

The agreement between the experimental and the calculated data, in general, is good except for the H/C atomic ratio for the wet and quenched combustion tube runs. The author did not explain how the values of the H/C ratio were obtained.

Generally, the poor agreement of H/C ratio for the wet and quenched combustion tests may be explained by the discussion mentioned before that the apparent H/C atomic ratio is affected by the lower combustion temperature and other factors affecting wet and quenched combustion over the dry combustion process.

Experimental dry combustion results were in an excellent agreement with calculated values.

Table 1. Comparison of calculated vs. reported data Bousaid (1, 2[3])

Run[4] #	F_{HC} calc.	F_{HC} rep.	e_{O2} % calc.	e_{O2} % rep.	G_{CF} scf/cu ft calc.	G_{CF} scf/cu ft rep.	v_b ft/hr calc.	v_b ft/hr rep.
8306	3.11	3.09	77.89	77.90	212.4	213.0	0.507	0.505
8301	1.18	1.19	90.56	90.60	423.4	427.0	0.261	0.259
8603	1.34	1.39	95.50	95.50	299.0	298.0	0.348	0.350
8305	1.70	2.00	89.44	89.40	182.9	179.0	0.590	0.604
8303	1.46	1.36	91.76	91.70	336.3	339.0	0.317	0.315
8604	2.18	1.88	94.72	94.70	274.2	279.0	0.369	0.363
8606	1.05	1.11	99.49	99.50	217.8	215.0	0.472	0.478
8607a	2.15	2.42	99.55	99.60	224.9	219.0	0.472	0.486
8607b	1.99	2.42	99.55	99.60	186.6	179.0	0.558	0.583
8401	1.99	2.48	89.53	89.50	157.1	151.0	0.681	0.709
8402	2.41	3.07	90.26	90.30	131.9	124.0	0.818	0.870
8404	3.42	1.75	91.39	91.40	265.5	295.0	0.414	0.370
8403a	1.39	1.38	85.29	85.20	288.4	288.0	0.362	0.360
8403b	2.05	1.38	89.04	89.10	167.7	172.0	0.633	0.619

[3] See appendix D for full set of data

[4] Runs 8306, 8301 and 8603 are dry combustion runs
Runs 8305, 8303, 8604, 8606, 8607a and 8607b are wet combustion runs
Run 8401 is a wet/semi-quenched combustion run
Run 8402 is a wet/quenched combustion run
Run 8404 is a quenching test run
Run 8403a is a pre-quenched test
Run 8403b is a quenched test

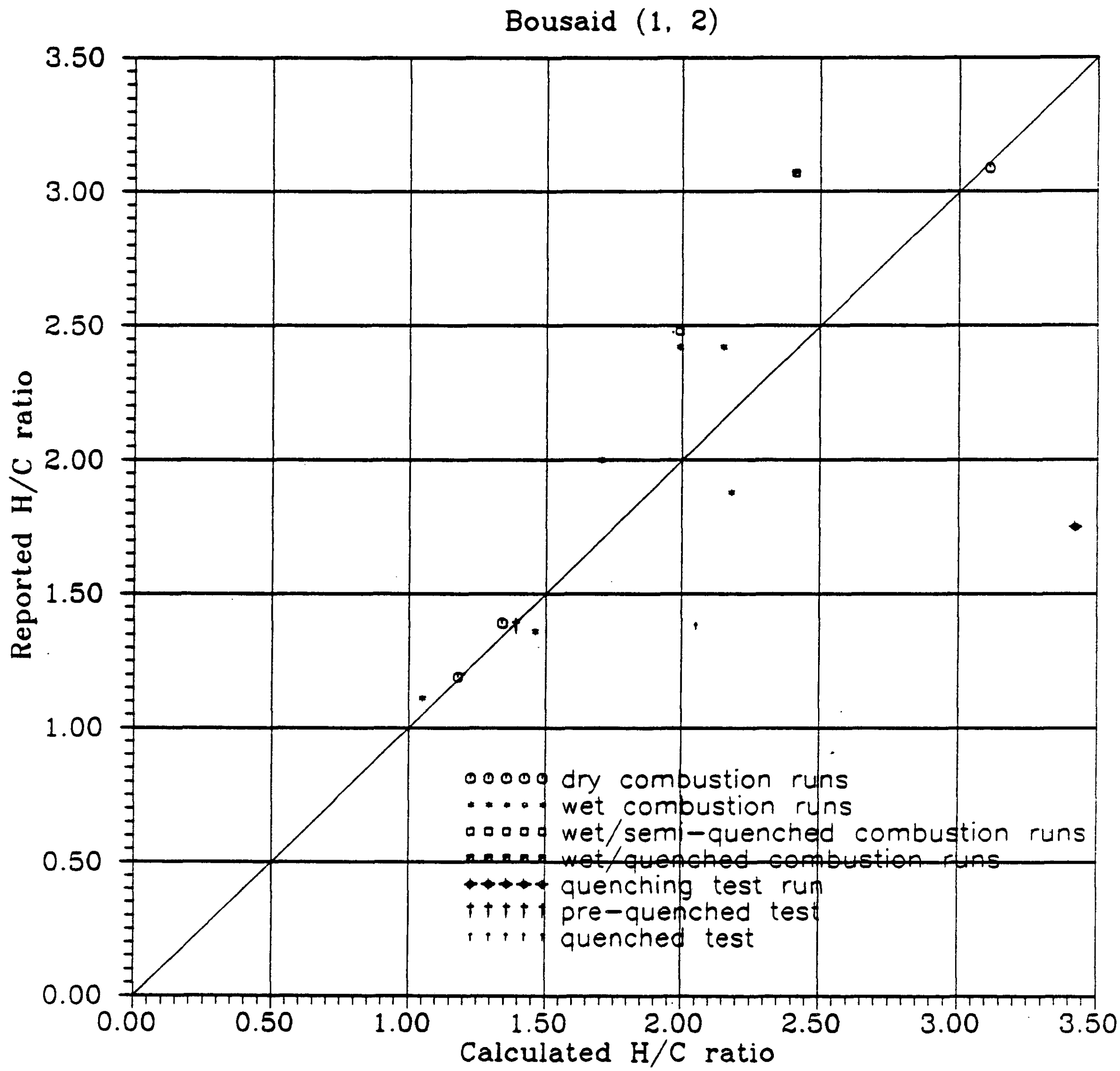

Figure 7. Comparison of calculated vs. reported H/C ratio

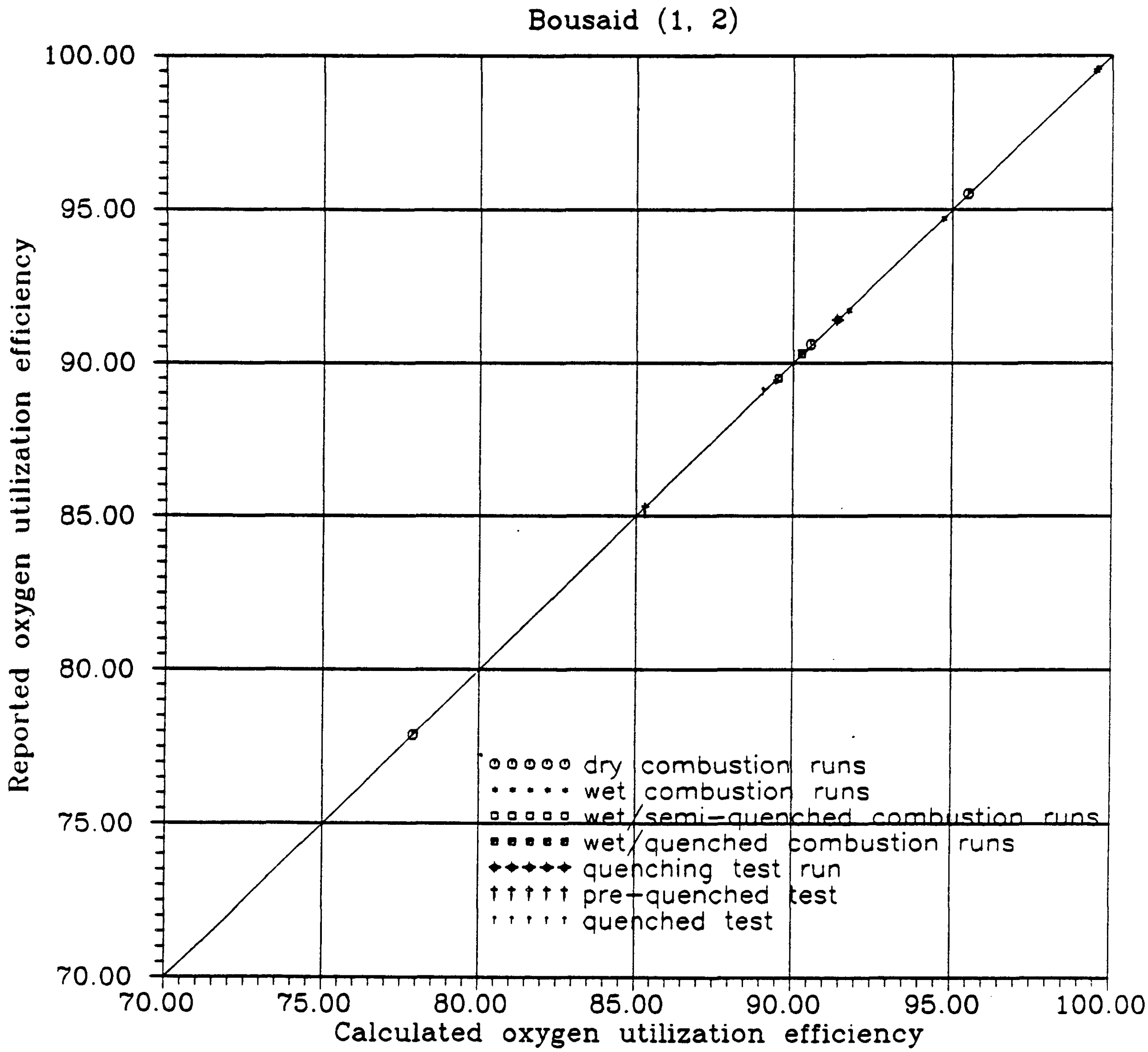

Figure 8. Comparison of calculated vs. reported oxygen utilization efficiency

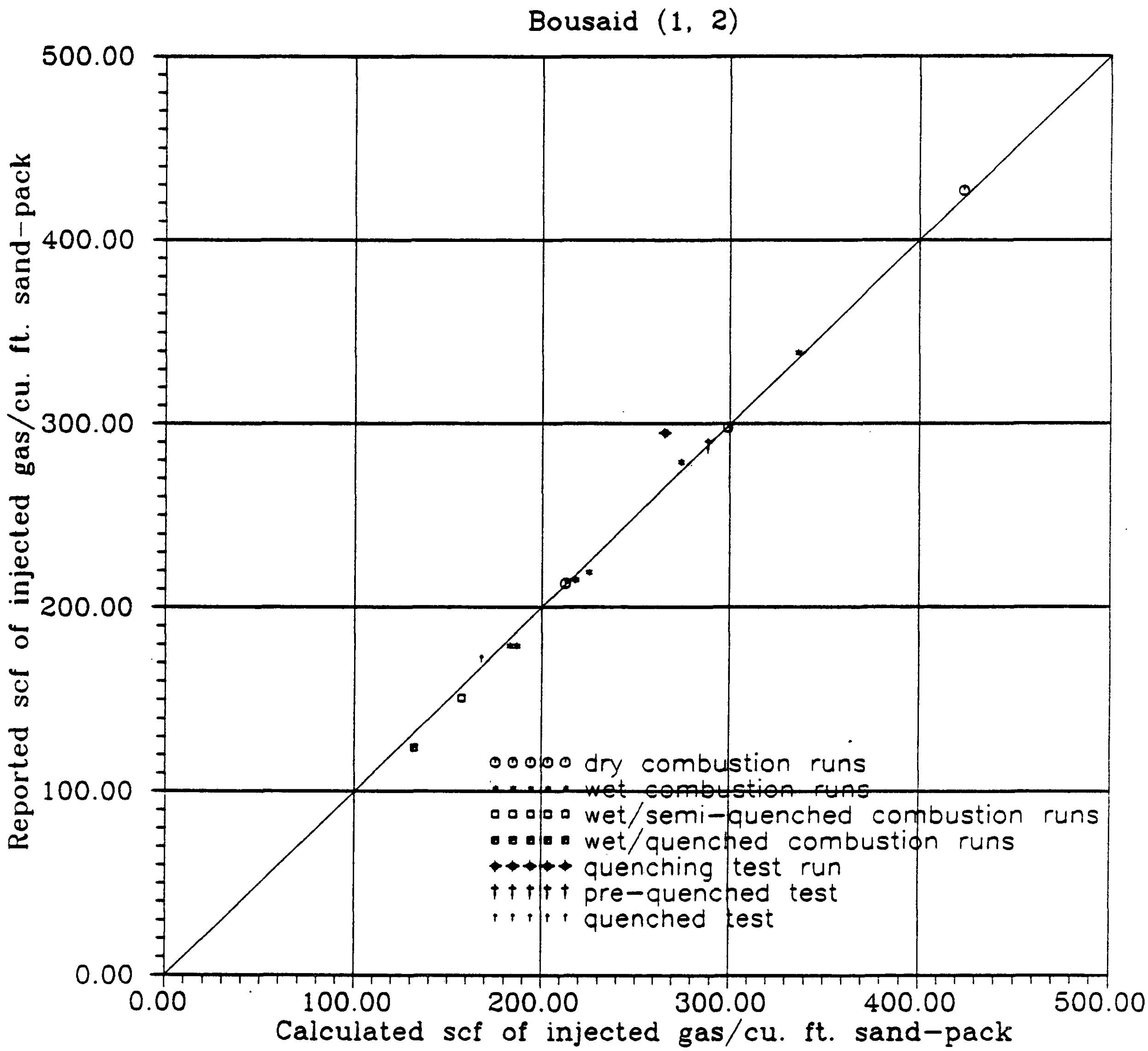

Figure 9. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

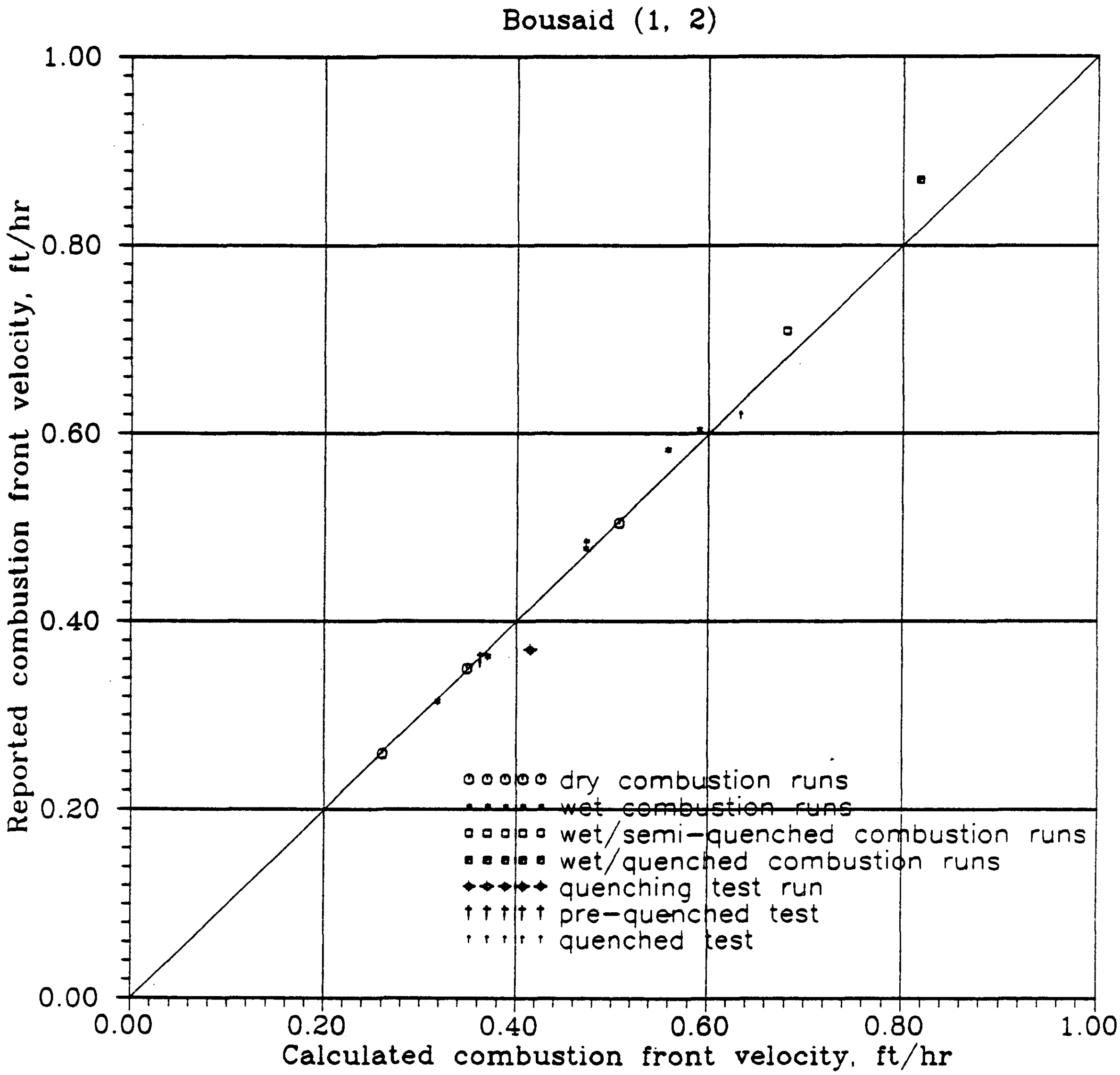

Figure 10. Comparison of calculated vs. reported combustion front velocity, ft/hr

Data from Showalter (4)

Summary:

The paper showed some of the results of tests which were made in a test cell for the purpose of studying the nature of the combustion-drive process. The paper presented combustion tube data which indicate that the API gravity of the in-situ oil is a significant indicator of the amount of air required to drive a burning front through oil sand. It was shown that air requirement varies inversely as the API gravity of the in-situ oil.

Data from an actual combustion-drive producing well of South Belridge thermal recovery experiment also was presented. The exhaust gas analyses from this well were corrected to a methane-free basis and averaged month by month. For each month the $CO + CO_2$, the CO/CO_2 and the O_2/CO_2 were calculated. The C/H weight ratio of the fuel and the volume of air required to burn a pound of fuel were determined for each month from stoichiometric equations.

Experimental Procedure:

1. Exhaust gas from the cell was sampled periodically and tested for the principal ingredients, including CO_2, CO and O_2.

2. The fuel content was calculated only for a portion of the sand section in which burning had been as uniform as

possible. This section was 4 feet from the upstream sand face and 2 feet from the downstream sand face.

3. Material balance calculations were used to calculate the fuel content.

4. The nonequilibrium burning portion of each run was excluded.

5. H/C weight ratio and air required to burn 1 lb of fuel were calculated from stoichiometric considerations at 32 °F and 14.7 psia.

Discussion:

This discussion is concerned principally with the comparison between the reported and the calculated data. The author used the following equation to calculate the reported C/H weight ratio:

$$R=\frac{(A+B)}{\frac{21-(A+B+C)}{2.37}+\frac{B}{6}}$$

Where:

R = C/H weight ratio,

A = per cent CO_2 in the exhaust gas,

B = per cent CO in the exhaust gas, and

C = per cent O_2 in the exhaust gas.

He also used the following equation for calculating the air required to burn 1 lb of fuel:

$$V=\frac{\left(\frac{R}{R+1}\right)\times\left[\frac{(2.667\,(A+0.5B+C)}{(A+B)}\right]+\left(\frac{8}{R+1}\right)}{0.01873}$$

Where:

V = volume of air required (at 32 °F and 14.7 psia) to burn 1 lb of fuel at the combustion front, scf and

R = C/H weight ratio

The combustion temperatures reported in this data set ranged from 650 °F to 1000 °F which indicates that high-temperature oxidation reactions were taking place.

The air required to burn out one cubic foot of sand-pack at the combustion front calculated from the stoichiometric relationships compared very well with the reported data as it should since the reported data was apparently also calculated from a stoichiometrically derived equation and not experimentally measured. The very slight discrepancies between the calculated and the reported data may be due to the approximation or rounding off error since using the same stoichiometric equations.

In this data set, the author did not include the volume of air stored behind the combustion front and he only calculated the amount of air required to burn out one cubic foot of sand-pack at the front which is less than the actual amount needed at the inlet of the combustion tube.

Table 2. Comparison of calculated vs. reported data Showalter (4[5])

Run #	G_{CF} scf / cu ft calc.	rep.
1	513.47	510.00
2	351.77	350.00
3	284.15	285.00
3A	249.74	250.00
4	239.89	240.00
5	197.64	195.00
6	169.41	170.00
7	141.85	140.00
8	247.09	255.00
9	228.16	225.00
10	182.12	180.00
11	289.64	290.00
12	262.91	255.00
13	261.33	260.00
14	301.25	300.00
15	281.86	275.00

[5] See appendix D for full set of data

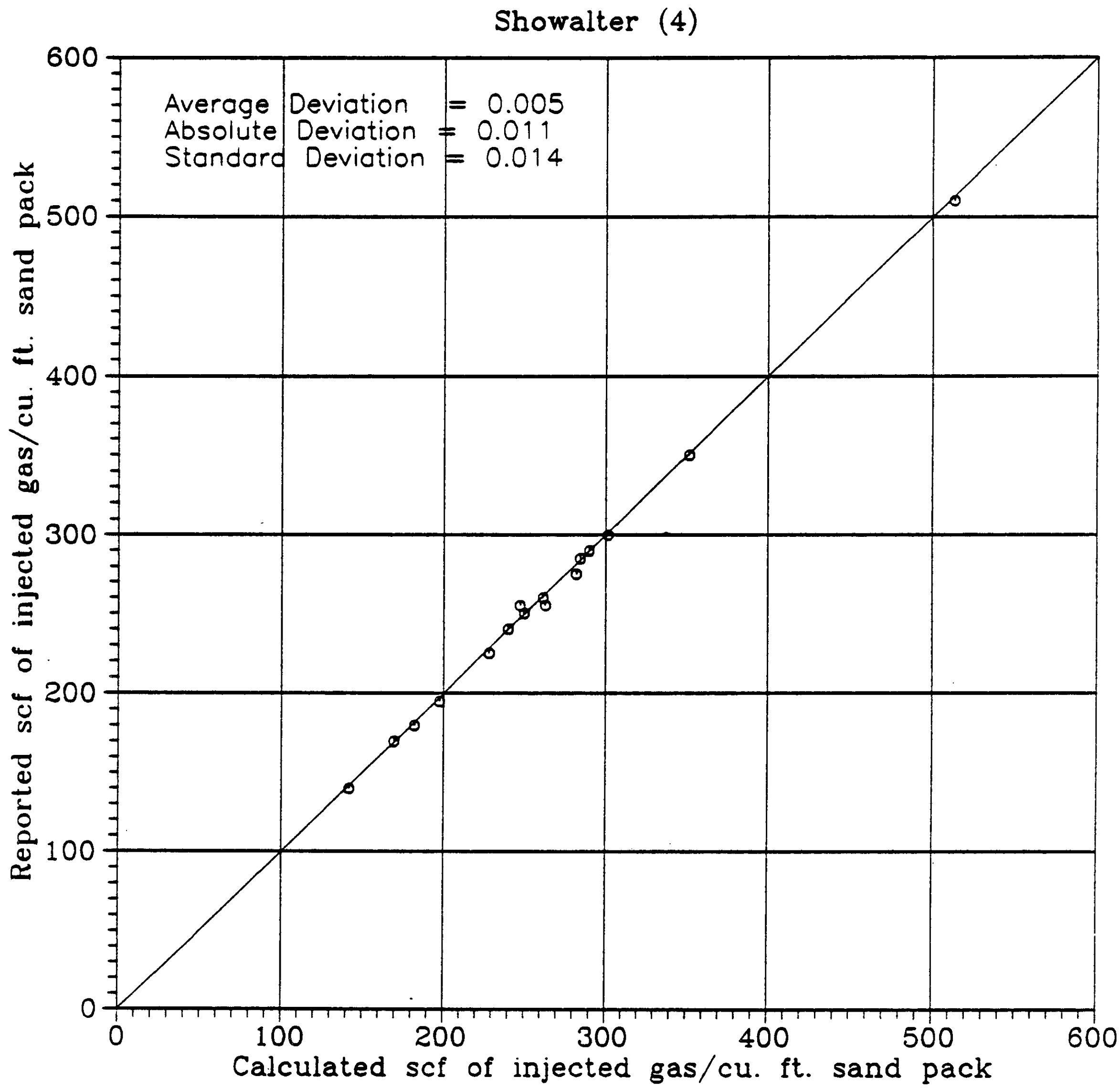

Figure 11. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

Table 3. Comparison of calculated vs. reported data
Showalter (4[6])
Production Well Data
South Belridge Thermal Recovery Experiment

Month	F_{HC}		G_F scf / lb	
	calc.	rep.	calc.	rep.
A	0.85	0.857	157.71	157
B	0.81	0.800	154.51	153
C	1.07	1.000	155.48	154
D	0.93	0.923	163.62	162
E	1.36	1.333	174.37	172
F	1.65	1.500	189.11	173
G	1.96	2.000	384.68	378
H	0.83	1.200	369.39	358

[6] See appendix D for full set of data

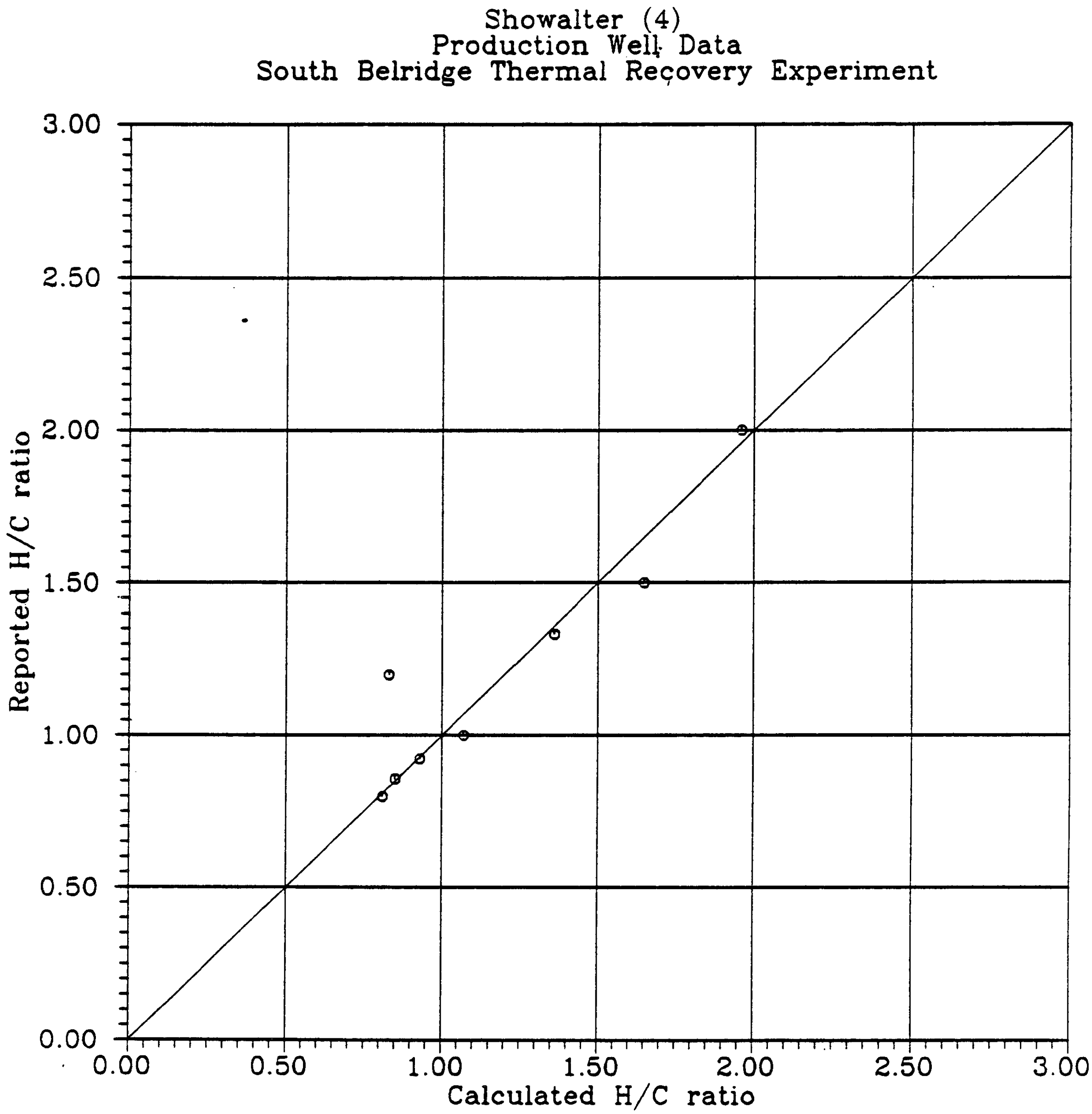

Figure 12. Comparison of calculated vs. reported H/C ratio

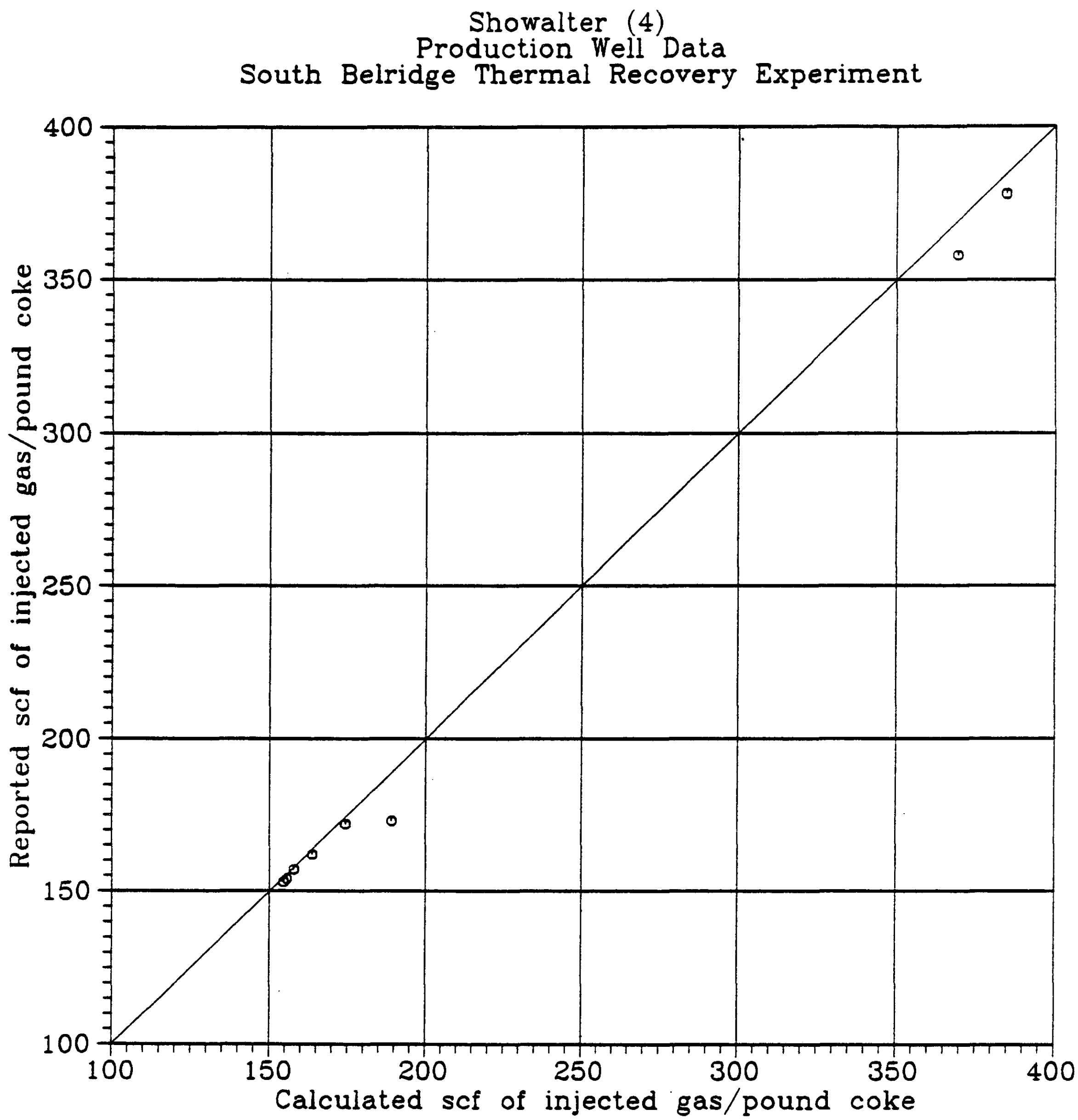

Figure 13. Comparison of calculated vs. reported scf of injected gas / pound coke

Data from Cady and Satchwell (5)

Summary:

Combustion studies for heavy crude oils were made with nitrogen gas containing oxygen concentrations from 20.7 to 40.0 mole percent.

The main purpose of this study is to obtain data from combustion tube tests that would allow defining process variables for in-situ combustion using oxygen enriched gas.

Experimental Procedure:

1. Produced dry gases were tested with a chromatograph to detect CO_2, CO, O_2, N_2 and hydrocarbon gases. Produced gas volumes were determined with a wet test meter which was read every hour.

2. The fuel content was studied using SEM micrographs. These studies indicated that the fuel's association with clay materials present in the sand-pack.

3. Fuel content, hydrogen to carbon atomic ratio, and gas requirements to burn one cubic foot of oil-saturated sand were described by the Arrhenius equation.

4. The steady-state burning portion of each run was used to evaluate the different combustion parameters.

5. Temperatures along the combustion tube centerline were recorded with thermocouples. These measurements were used to monitor the rate of the burning front advance.

Discussion:

The combustion results reported in this paper were described by the Arrhenius equation which can be written as:

$$\acute{R} = (f_a \cdot Y_{m+1} \cdot Pl) \cdot \phi \cdot S_o \cdot \rho_o \cdot A \cdot \exp\left(-\frac{B}{T_n + 460}\right)$$

Where:

R' = reaction rate for oxygen,

f_a = gas saturation,

m = reaction order,

Pl = Plank's constant,

ρ_o = oil density,

B = Arrhenius constant,

T = reaction temperature, and

A = Arrhenius frequency factor

The reported combustion temperatures in this data set ranged from 910 °F to 1050 °F which means that high temperature- oxidation reactions were dominant.

The comparison between the experimental reported results and the calculated values is tabulated and graphically presented.

In general, the agreement is good. The experimental reported results of gas required to burn one pound of coke correlate well with the calculated values with some discrepancies about the 45° line.

In the case of the H/C atomic ratio, the gas required to burn one cubic foot of sand-pack and the velocity of the combustion front, the reported results correlate very well with the calculated values without any discrepancies as shown in the following figures.

Table 4. Comparison of calculated vs. reported data Cady and Satchwell (5[7])

Run #	F_{HC} calc.	F_{HC} rep.	G_F scf/lb calc.	G_F scf/lb rep.	G_{CF} scf/cu ft calc.	G_{CF} scf/cu ft rep.	v_b ft/hr calc.	v_b ft/hr rep.
1	1.07	1.08	166.3	166.7	353.7	354.0	0.246	0.246
2	2.34	2.54	155.3	157.0	316.3	322.0	0.416	0.410
3	2.30	2.28	152.7	158.5	311.3	322.0	0.423	0.410
4	3.47	3.44	146.9	152.7	223.1	230.0	0.592	0.574
5	3.02	3.02	129.3	129.1	537.6	536.0	0.246	0.246
6	4.72	4.69	121.6	122.0	122.7	123.0	1.059	1.060

7 See appendix D for full set of data

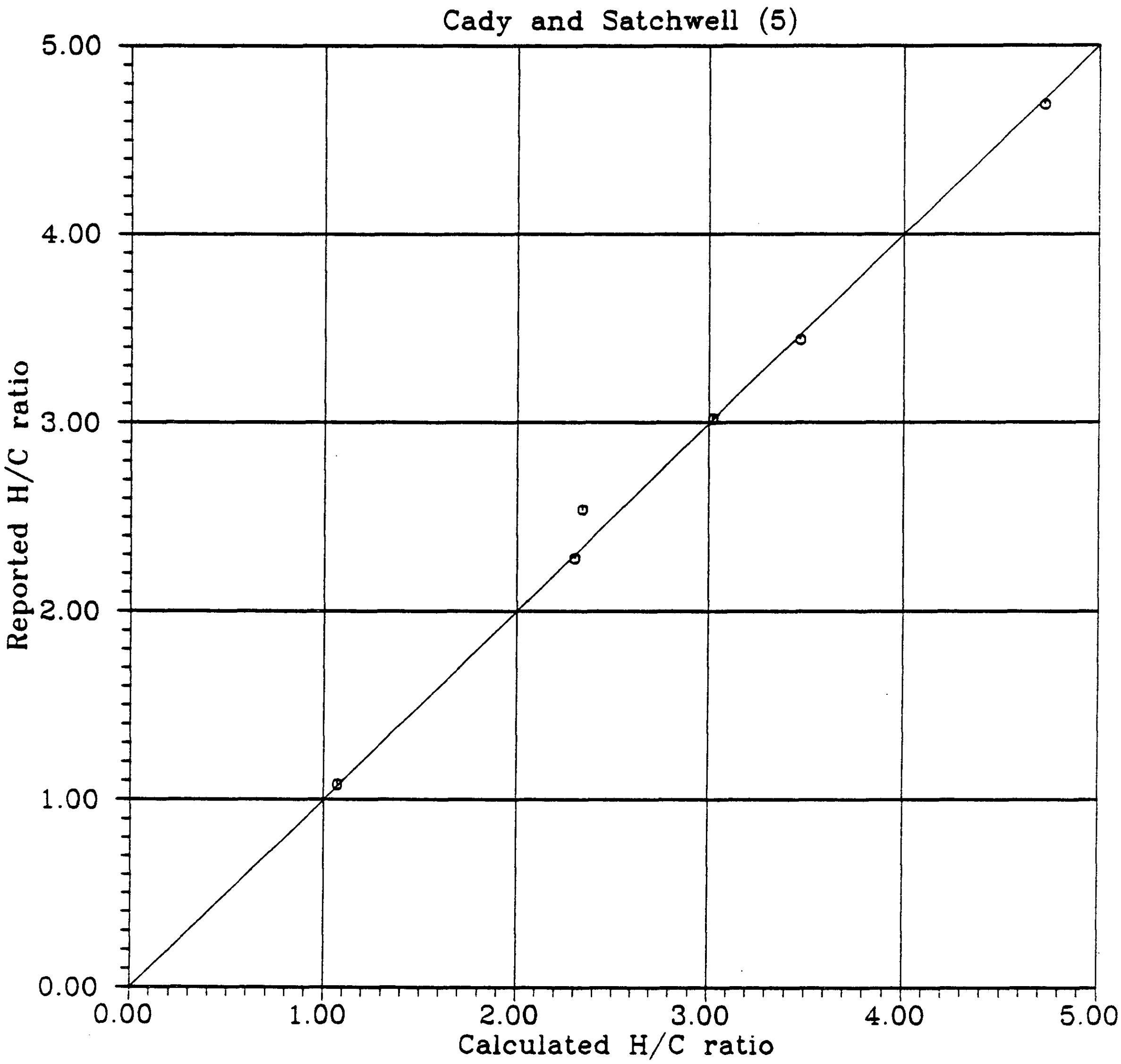

Figure 14. Comparison of calculated vs. reported H/C ratio

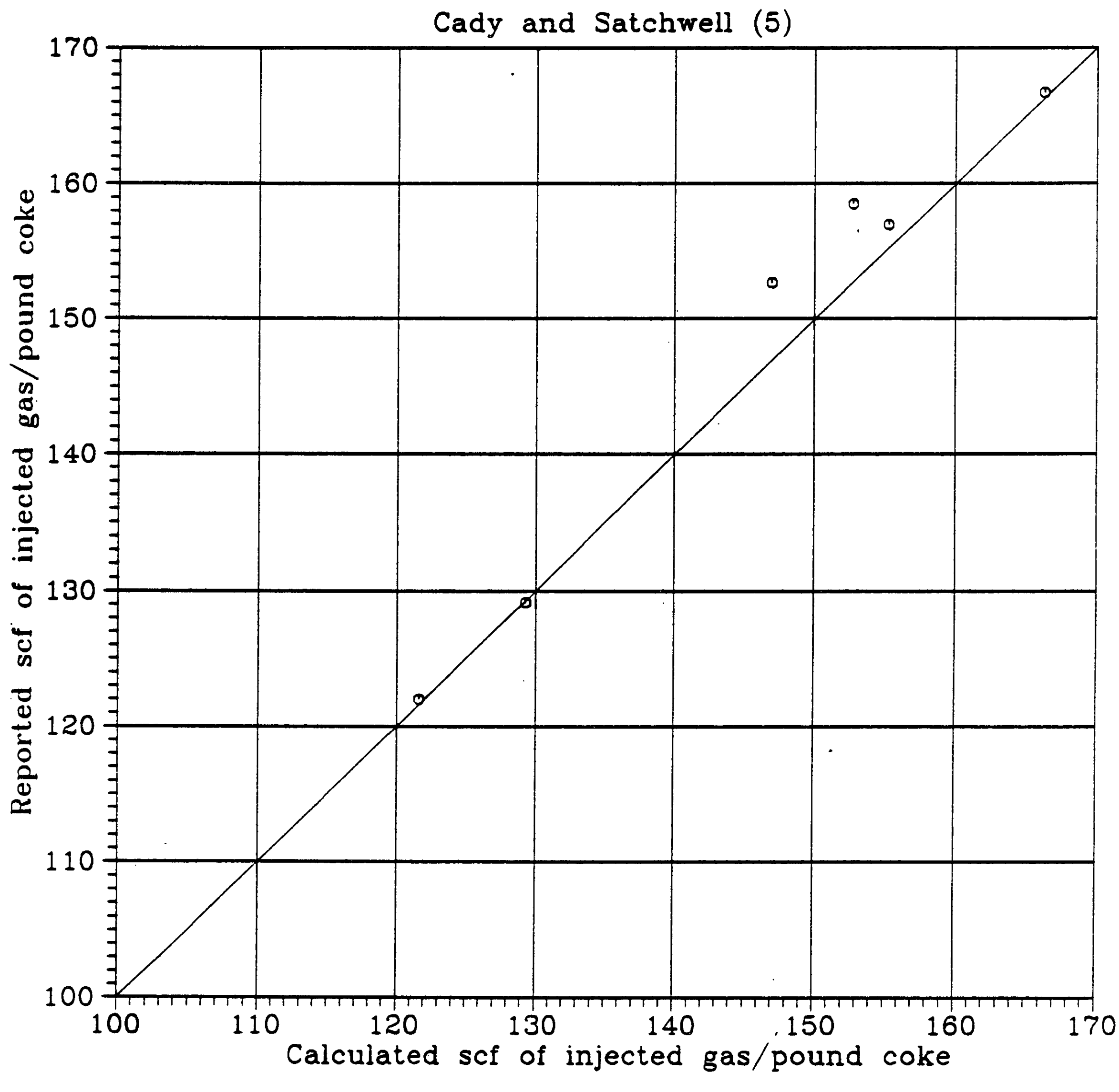

Figure 15. Comparison of calculated vs. reported scf of injected gas/pound coke

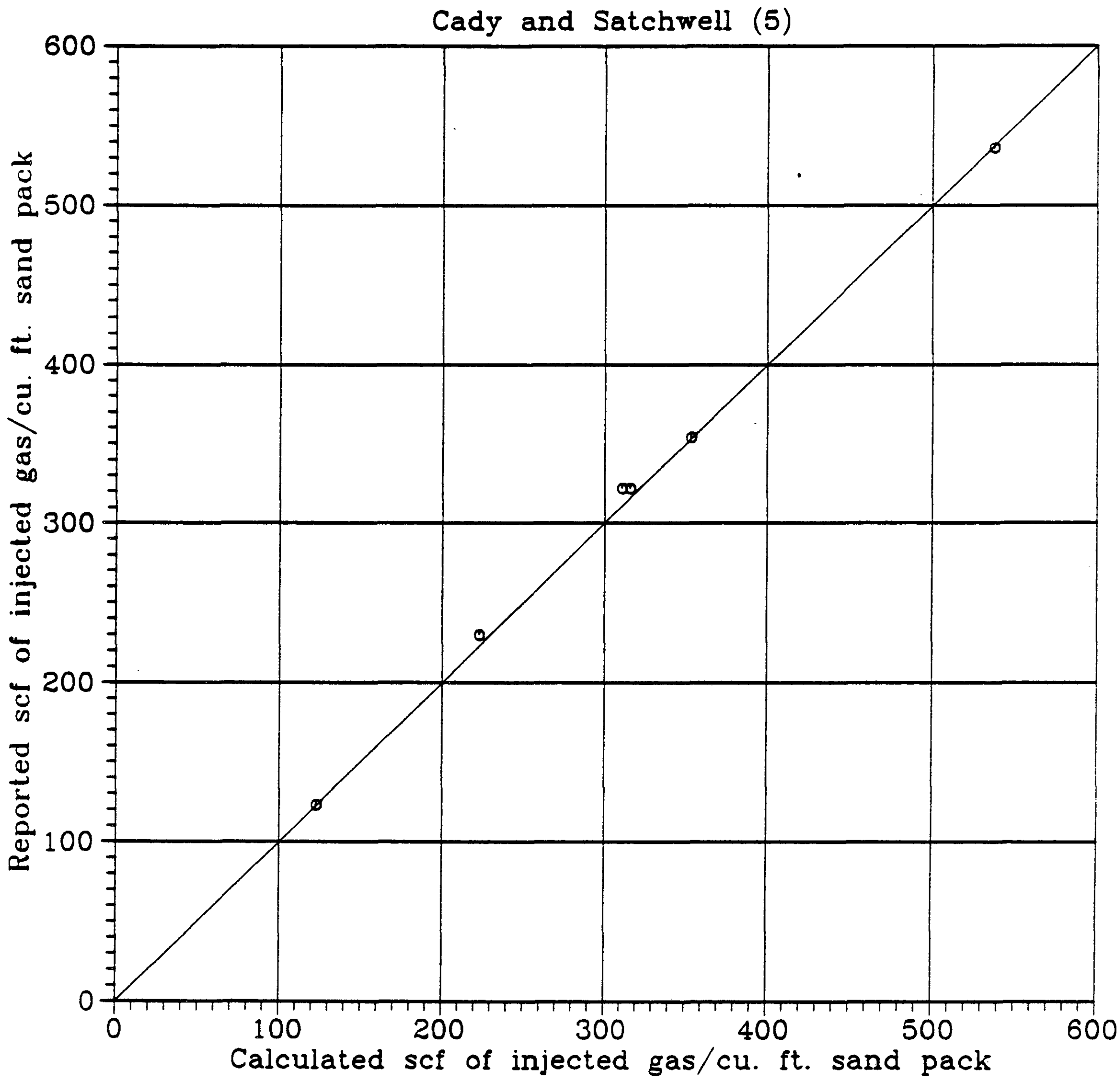

Figure 16. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

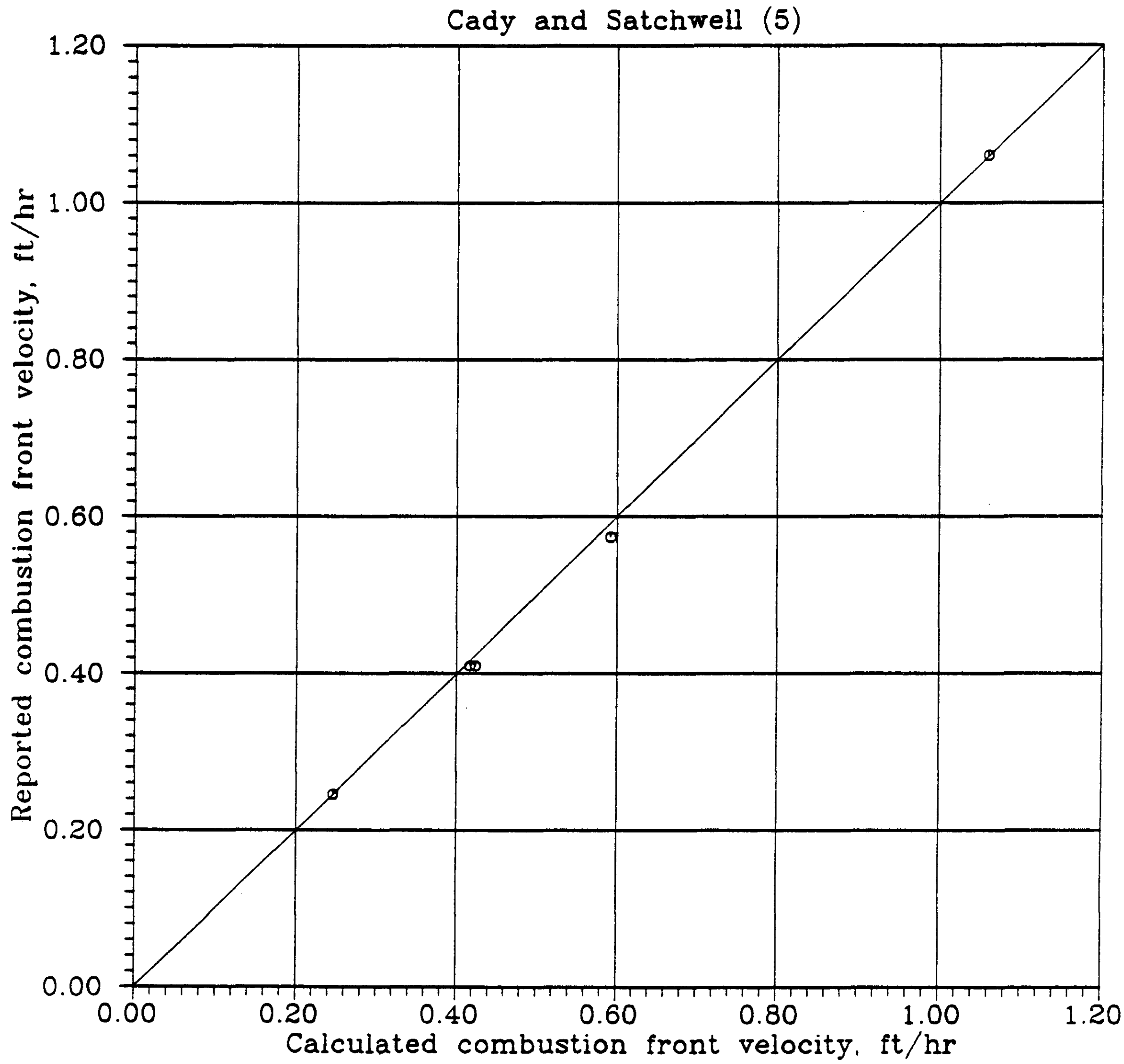

Figure 17. Comparison of calculated vs. reported frontal velocity, ft/hr

Data from Martin et al. (6)

Summary:

The purpose of this work was to obtain laboratory data for an evaluation of the in-situ combustion process. The first phase of this investigation was exploratory in nature and was conducted at injection pressures less than 100 psig. Data were obtained over a wide range of experimental conditions in an effort to observe, qualitatively, the effect of some of the many variables that affect the in-situ combustion process. At times several air flow rates were studied during a single experiment. During the second phase of the work, the effects of pressure and injected air flux were studied by means of long-term, stabilized experiments conducted at constant inlet pressure and exit gas flow rate.

Experimental Procedure:

1. Pack temperatures were recorded continuously on a multipoint recorder. The outside temperatures at all levels were maintained slightly less than the corresponding inside temperatures by manually adjusting the tube wall heater.

2. During the experiments, cumulative oil and water production, pressure drop across the pack, pressure at pack inlet, and the location of the combustion front were all measured as a function of cumulative run time.

3. Rates of advance of the combustion front were experimentally obtained from slopes of plots of time against distance from top of the sand-pack travelled by the combustion front.

4. The oxygen utilization efficiency was experimentally calculated by dividing the rate at which oxygen was consumed by the rate of oxygen injection.

5. The amount of air required to burn out one cubic foot of sand-pack was calculated experimentally from the rate of advance of the combustion front and the gas flux.

Discussion:

The combustion parameters reported in this paper were experimentally measured as stated before. The average combustion temperatures are indicative of a high temperature-oxidation, ranging from 650 °F to 850 °F.

The experimental reported values were plotted against the calculated values from stoichiometric equations. The agreement is excellent.

Table 5. Comparison of calculated vs. reported data Martin et al. (6[8])

Run #	e_{O2} %		G_{CF} scf/cu ft		v_b ft/hr	
	calc.	rep.	calc.	rep.	calc.	rep.
13	84.99	84.90	245.2	245.0	0.120	0.121
14	90.03	90.10	218.9	219.0	0.136	0.136
15	91.47	91.40	250.7	251.0	0.127	0.127
16	82.30	82.30	294.8	295.0	0.215	0.215
17	60.40	60.30	357.9	358.0	0.349	0.350
18	95.55	95.60	300.1	301.0	0.036	0.036

[8] See appendix D for full set of data

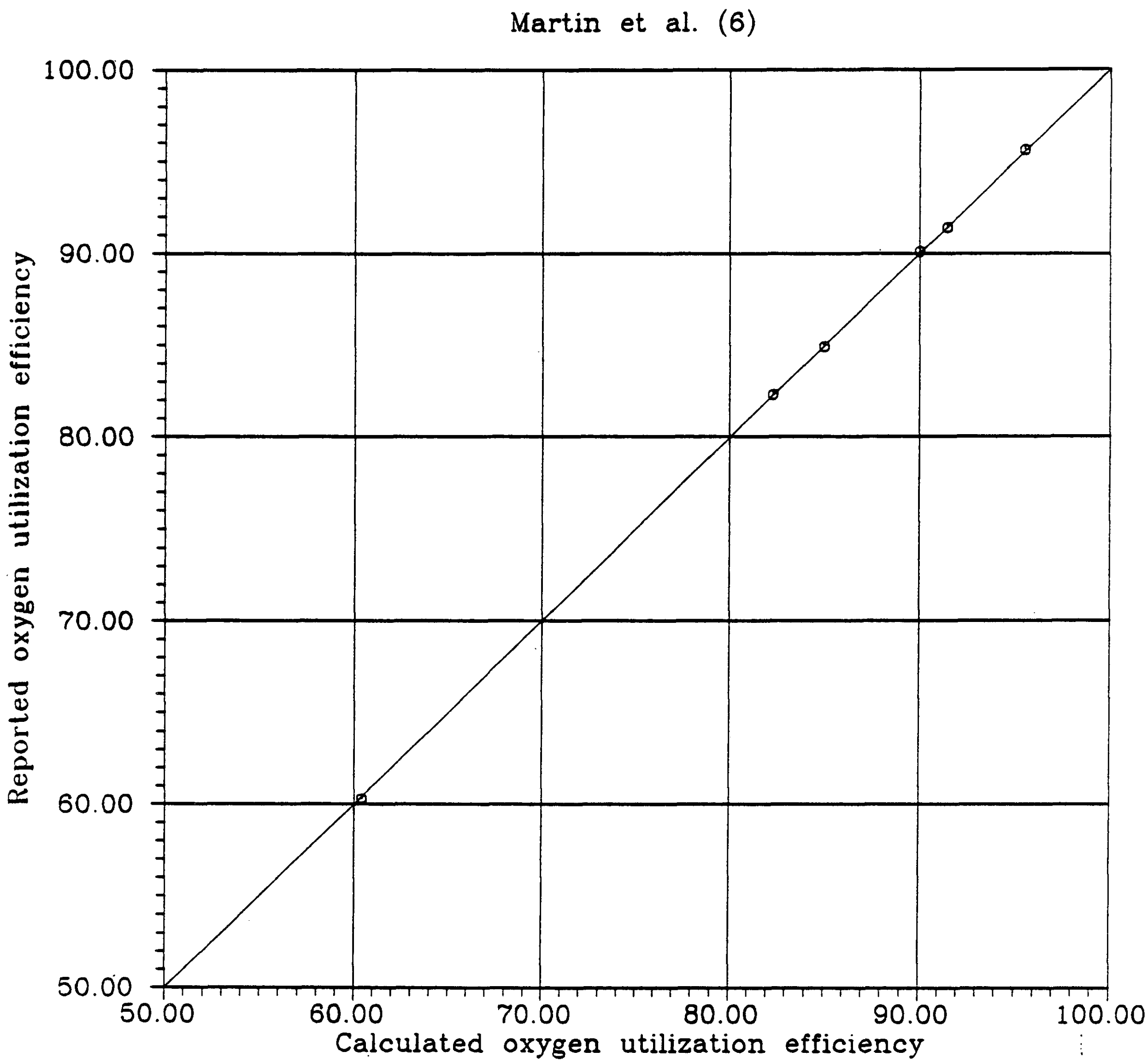

Figure 18. Comparison of calculated vs. reported oxygen utilization efficiency

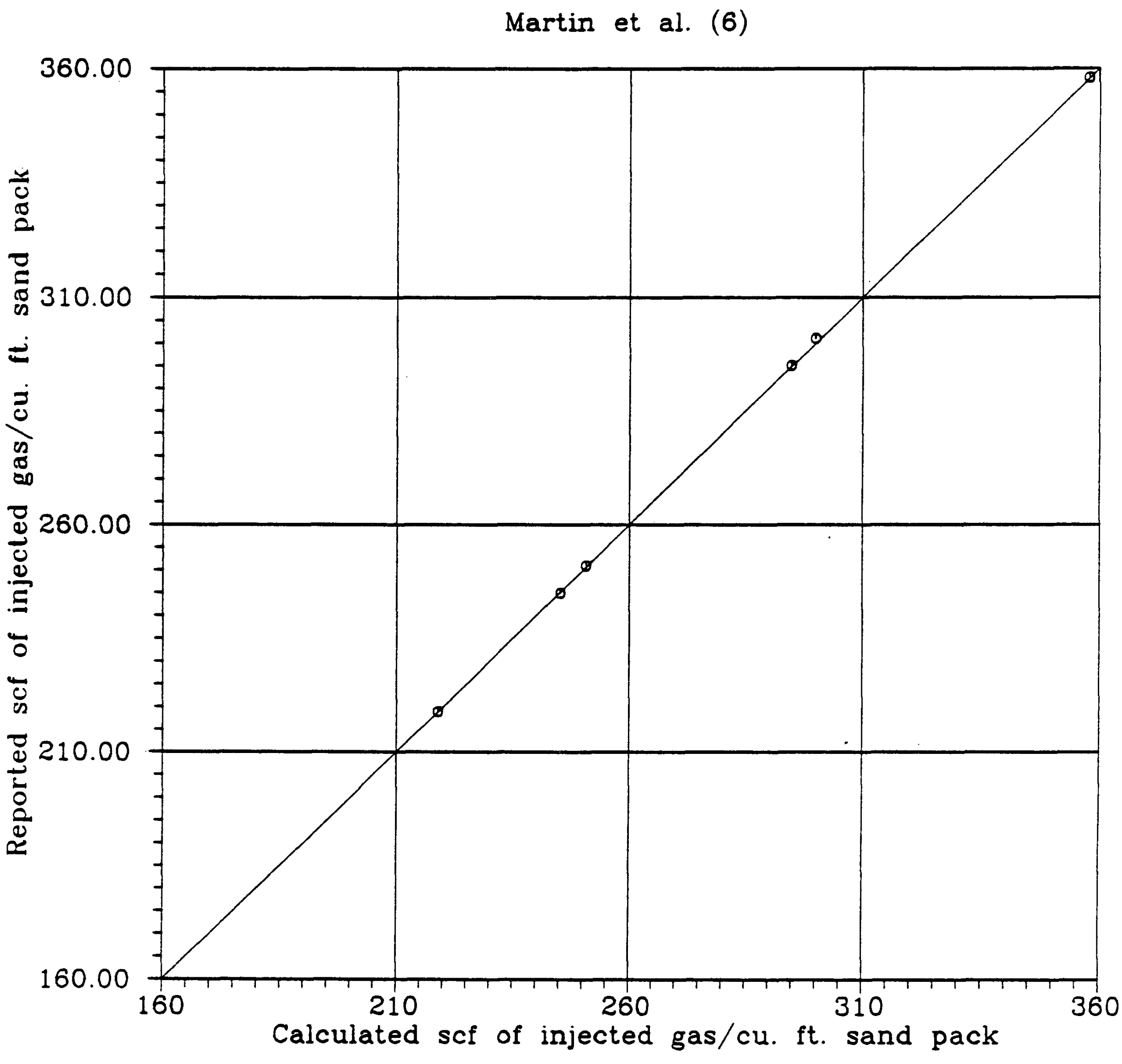

Figure 19. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

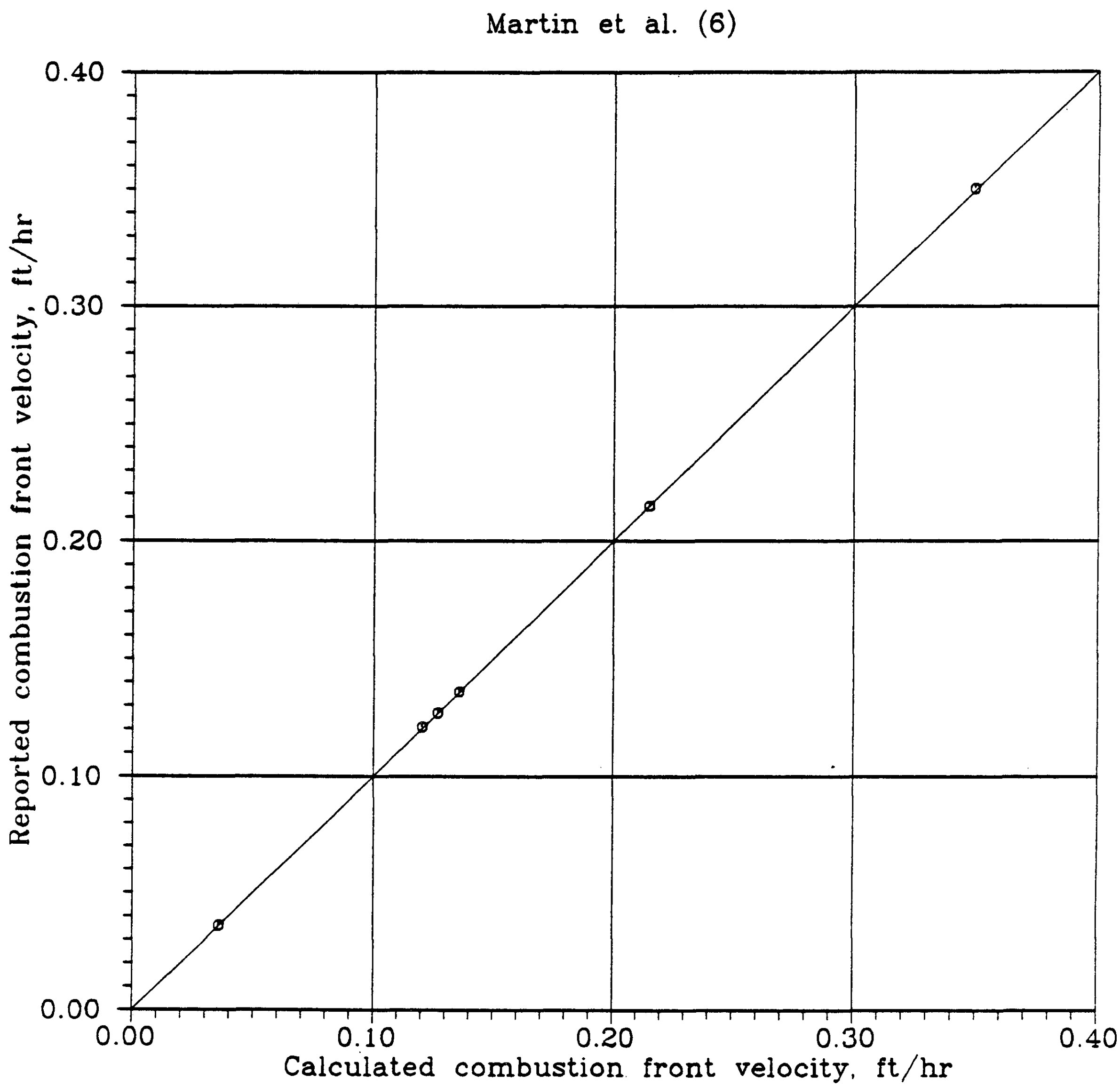

Figure 20. Comparison of calculated vs. reported frontal velocity, ft/hr

Data from Luengo-C and Sanyal (7)

Summary:

A single forward combustion tube run was conducted by Luengo-C utilizing core material from one of the heavy oil reservoirs in Venezuela. The purpose of the project was to obtain some important laboratory data to evaluate the applicability of the in-situ combustion process in the Jobo Field, located in Eastern Venezuela.

Experimental Procedure:

1. The following measurements were recorded every 20 minutes throughout the run: liquid production, gas composition, inlet and outlet pressures and volume of gas metered out of the system.

2. The fuel content was calculated using the following equation:

$$C_F = (scf/hr) \cdot \left(\frac{\frac{\%CO_2 + \%CO}{100\%} \times \frac{12 + n}{379}}{\frac{V}{12} \cdot \left(r_{tb}^2 - 2r_{th}^2\right)} \right) \qquad (lb/ft^3)$$

Where:

v = burning front velocity, in/hr, and

r = radius, ft

However, the above equation is questionable. The author did not indicate how he arrived at that equation.

3. Stoichiometric equations were used to calculate the reported combustion parameters.

4. The steady-state burning portion of the run was selected for the produced gas analysis and hence for calculating the different combustion parameters.

Discussion:

The author calculated his results using stoichiometric equations, however he did not correct for the amount of air stored in the burned out sand-pack behind the combustion front.

The combustion temperature for this run was 1100 °F. As would be expected, the agreement is almost exact. The difference of 0.5 scf/cu. ft. of sand-pack burned represents the air stored behind the combustion front.

Data from Shu and Lu (8,9)

Summary:

In-situ combustion with oxygen instead of air has high potential for recovering heavy and medium oils. Among the many advantages is a higher concentration of CO_2 in the flue gas resulting from the absence of nitrogen.

In an attempt to simulate the nitrogen-free environment of oxygen combustion and to study the CO_2 effect, Shu and Lu conducted a combustion tube run in which a CO_2/O_2 gas mixture was used in place of air. For comparison purposes a parallel test was performed that involved use of air at the same operating conditions.

Experimental Procedure:

1. Both runs were made in the dry combustion mode with 21% oxygen in the injected gas.

2. Operations of both tests were smooth and ignition with the CO_2/O_2 mixture was successful.

3. Stabilized combustion was achieved between 2 and 7 hours after ignition for both runs and the burning characteristics averaged over this time period.

4. The reaction temperature, the combustion front velocity, and the produced gas composition for both tests were similar, except that the air test had a lower oxygen utilization.

5. The oxygen/fuel ratios were the same, indicating that the elemental compositions of the fuel were identical. It therefore appeared that substituting N_2 in air with CO_2 did not change the combustion characteristics for this oil.

6. The air test had a higher pressure drop that was associated with a bank of oil at the original viscosity. The oil bank in the CO_2/O_2 run, on the other hand, contained oil at a lower viscosity because of CO_2 dissolution. As a result, less pressure drop was required to displace the oil at the same rate.

Discussion:

Both runs were performed at a maximum combustion temperature of 900 °F which indicates that a high temperature-oxidation reaction was dominant.

The authors did not discuss the evaluation of the combustion parameters. In general, the agreement between the reported and the stoichiometrically calculated values is excellent except for the amount of injected gas required to burn one cubic foot of bulk reservoir volume. The theoretical calculations are higher than the reported values. This may lead to the conclusion that the reported values are calculated from material balance considerations at the combustion front neglecting the pore volume behind the front. Thus the values are less than those obtained from stoichiometric considerations.

Table 6. Comparison of calculated vs. reported data Luengo-C and Sanyal (7[9])

Run #	F_{HC}		G_F scf/lb		G_{CF} scf/cu ft		v_b ft/hr	
	calc.	rep.	calc.	rep.	calc.	rep.	calc.	rep.
1	1.27	1.27	177.8	178.0	355.6	355.1	0.252	0.278

Table 7. Comparison of calculated vs. reported data Shu and Lu (8, 9[10])

Run #	F_{HC}		e_{02} %		G_{CF} scf/cu ft		v_b ft/hr	
	calc.	rep.	calc.	rep.	calc.	rep.	calc.	rep.
1	1.49	1.49	98.82	98.80	265.2	258.6	0.339	0.344
2	1.31	1.31	94.04	93.80	268.8	250.0	0.335	0.325

[9] See appendix D for full set of data

[10] See appendix D for full set of data

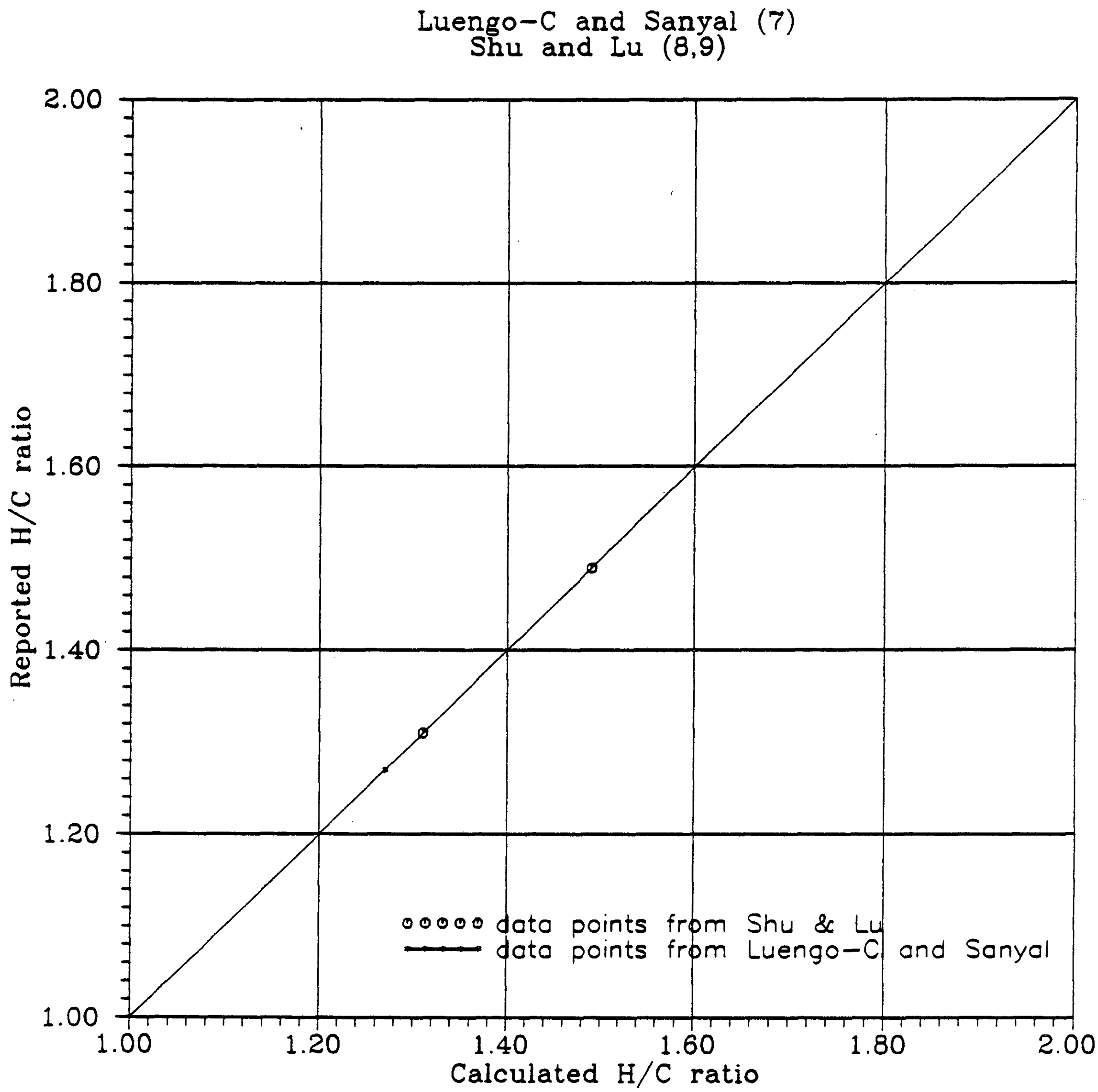

Figure 21. Comparison of calculated vs. reported H/C ratio

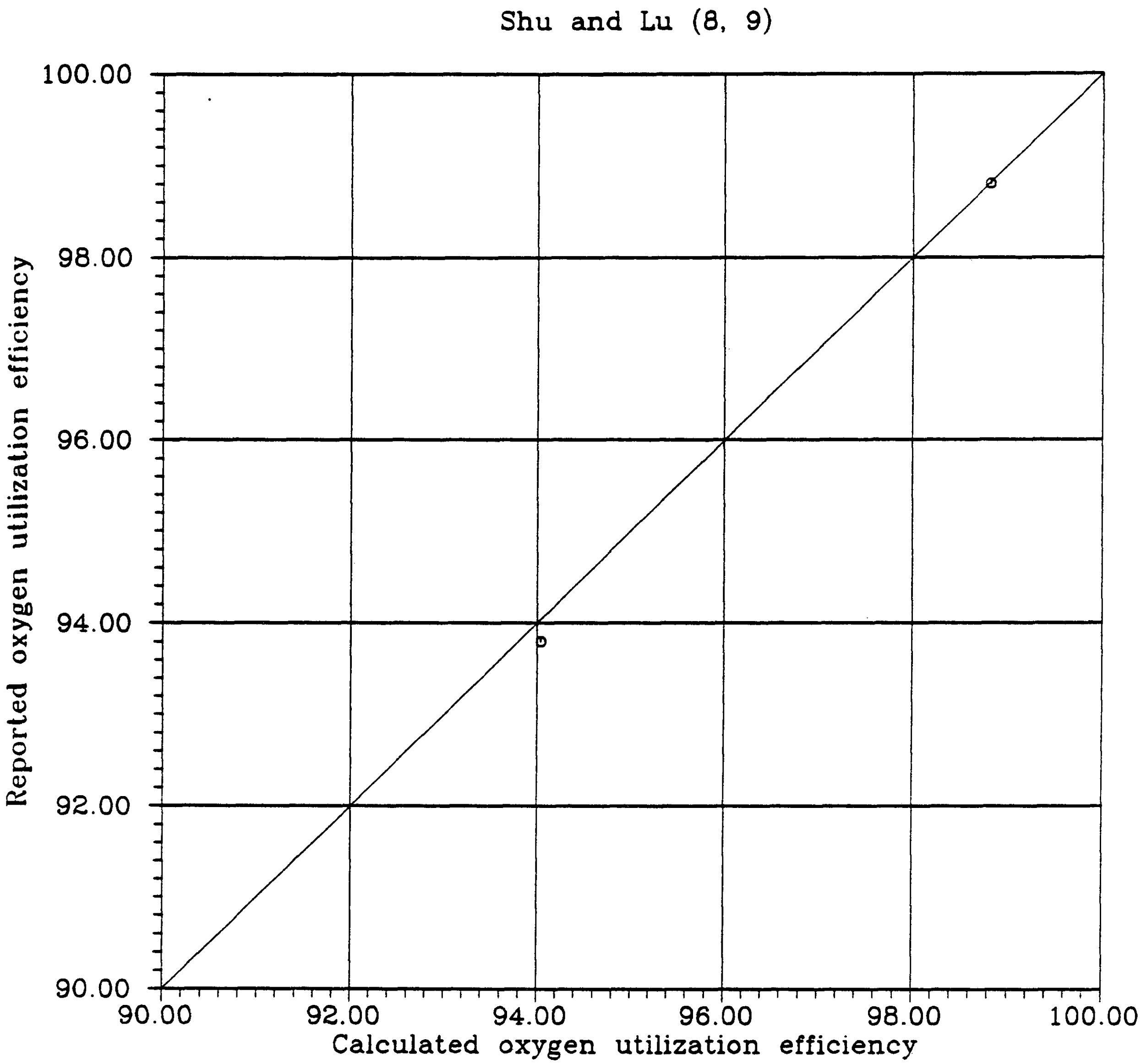

Figure 22. Comparison of calculated vs. reported oxygen utilization efficiency

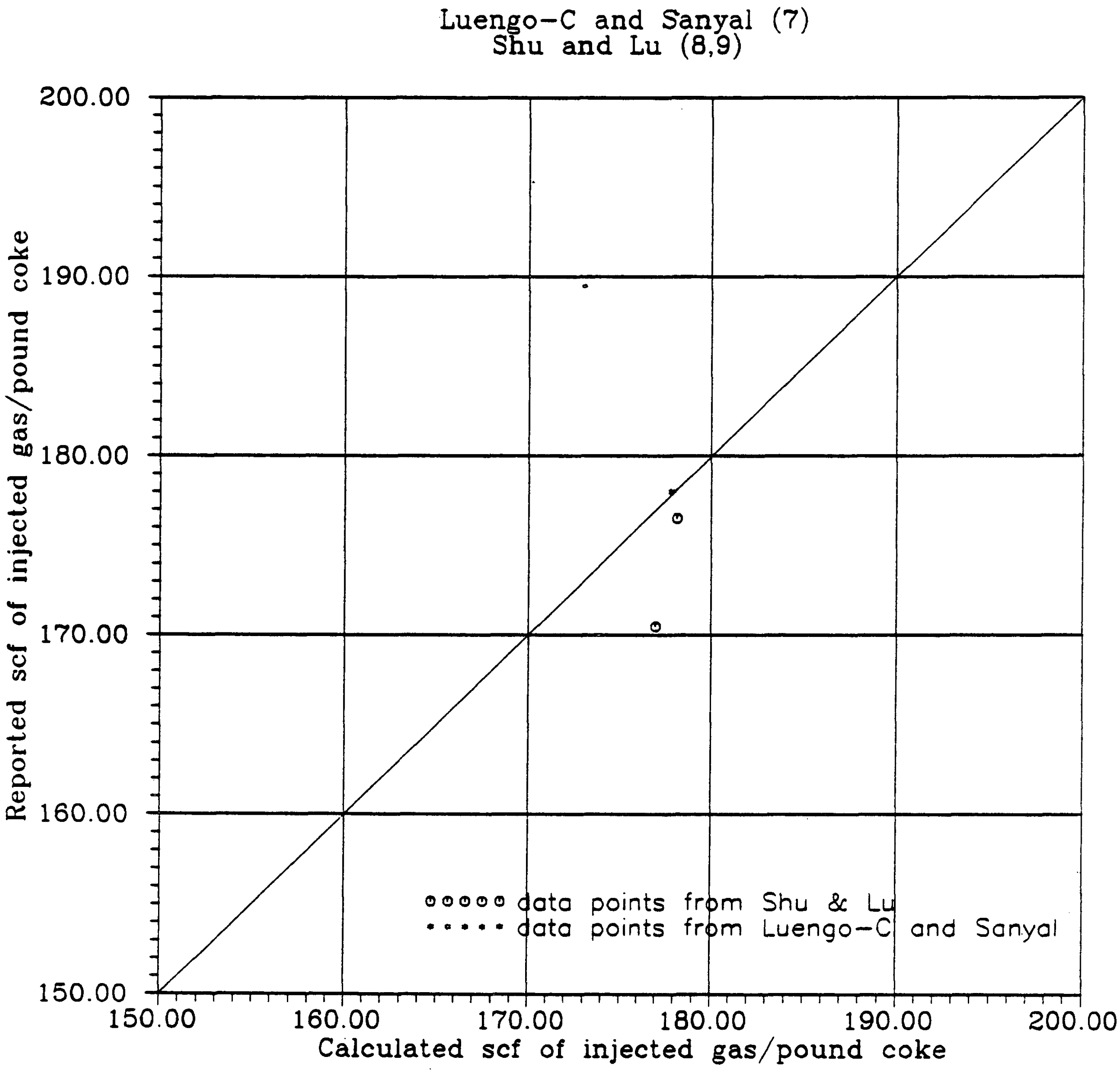

Figure 23. Comparison of calculated vs. reported scf of injected gas/pound coke

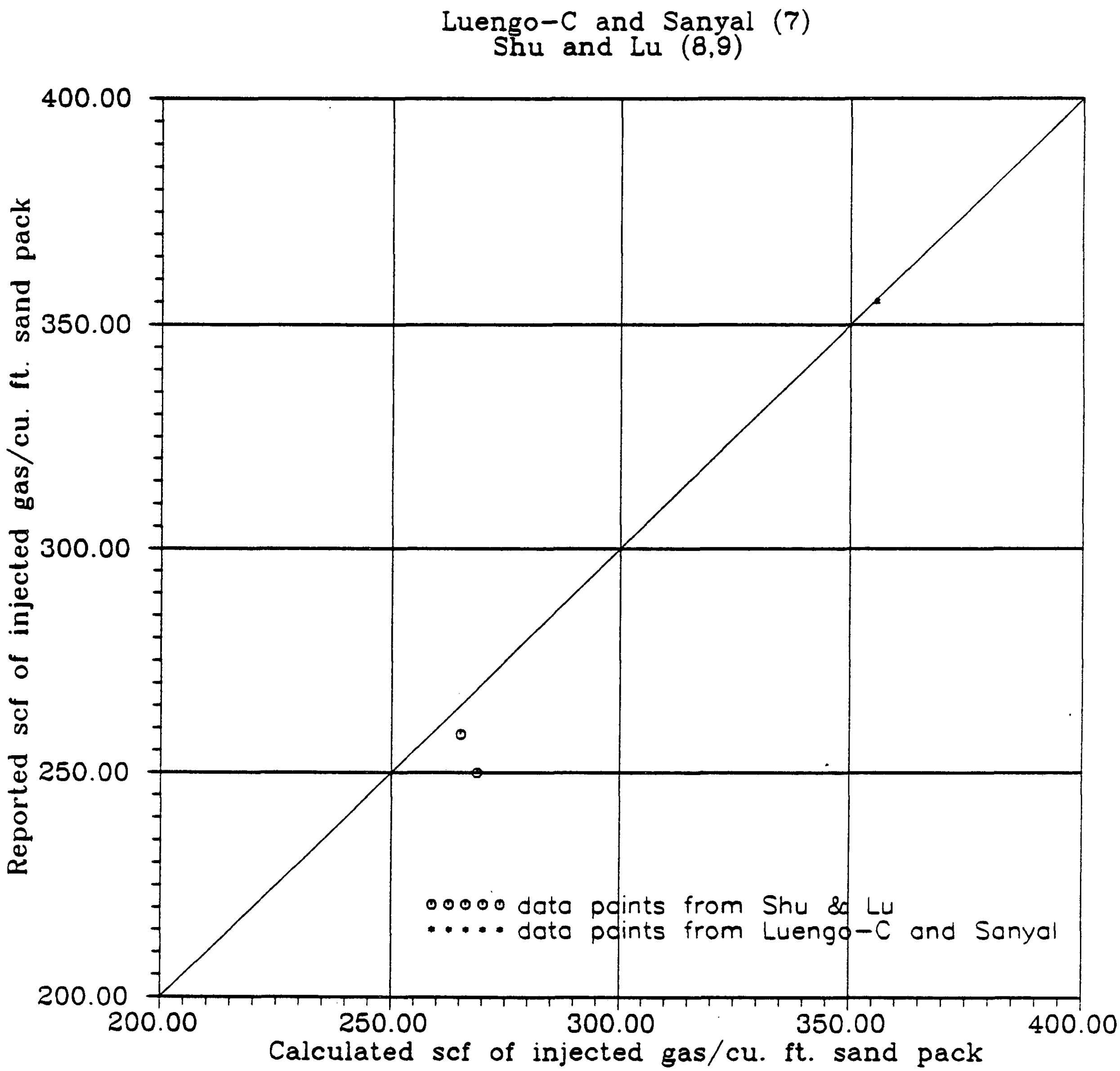

Figure 24. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

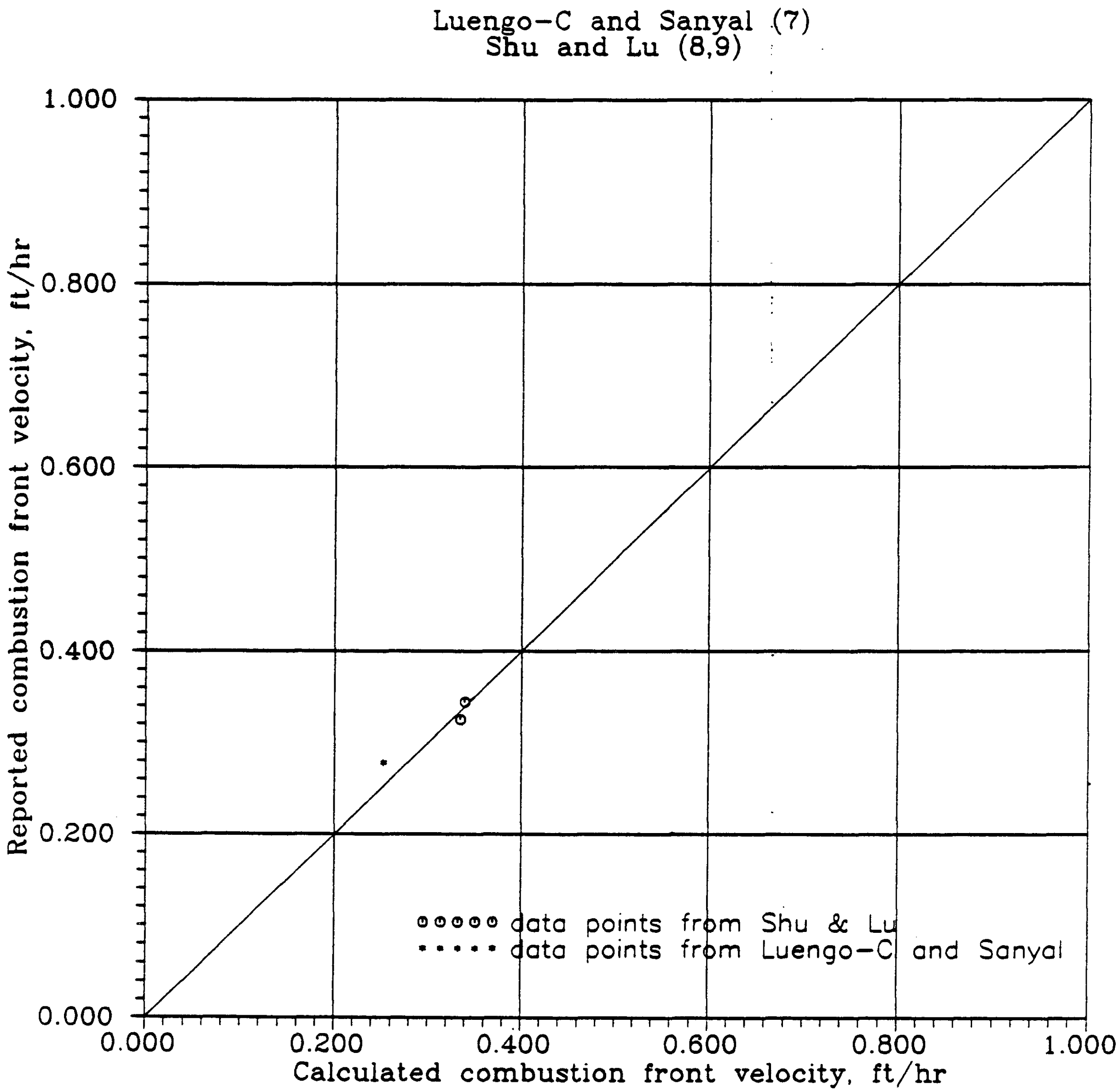

Figure 25. Comparison of calculated vs. reported frontal velocity, ft/hr

Data from Pusch (10)

Summary:

A series of combustion tube tests were performed at the Cities Service Research Laboratory using Bellevue reservoir core samples and produced oil. The objectives of the study were to obtain information concerning the basic in-situ combustion that would aid in understanding the performance of the Bellevue in-situ combustion project. Also investigated was the effect of injecting water along with air.

Experimental Procedure:

1. Data recorded during each run included air and water injection rates, injection pressure, produced oil, produced water, combustion gas volume and combustion front movement.

2. The gases produced were sampled and analyzed for oxygen, carbon dioxide and carbon monoxide using both an Orsat apparatus and a gas chromatograph. Oxygen was monitored continuously with an oxygen analyzer.

3. Thermocouples were used to monitor the combustion front movement. The location of the combustion front was recorded as a function of time.

4. Air flow rate was controlled using a rotameter and exit gases were monitored with a wet test meter.

Discussion:

The reported data included the H/C atomic ratio, oxygen utilization efficiency, the amount of air necessary to burn one cubic foot of reservoir and the combustion front velocity.

It was not directly indicated how these data were measured or calculated. However, from the result of the comparisons and input data plots, it could be inferred that the reported results were experimentally measured and not calculated. The produced gas analysis was given as a function of time i.e. it was not averaged over the steady-state burning period. Most of the plots associated in this project indicate that the steady-state combustion characteristics were not reached. An effort was made to average the gas analysis over the middle portion of the burning period. The general comparison for both dry and wet combustion runs is not good as illustrated in the figures. There is a general trend between the calculated and the reported H/C ratio and the oxygen utilization efficiency where the points are scattered about the 45° line, whereas the calculated amount of air required to burn one cubic foot of sand-pack was higher, thus the points are shifted to the right of the plot.

The combustion temperatures reported in this data set are indicative of a high temperature-oxidation reaction. They ranged from 823 °F to a high of 1531 °F with half of the combustion temperatures being well over 1000 °F.

Table 8. Comparison of calculated vs. reported data
Pusch (10)

Run #	F_{HC} calc.	F_{HC} rep.	e_{O2} % calc.	e_{O2} % rep.	G_F scf/lb calc.	G_F scf/lb rep.	G_{CF} scf/cu ft calc.	G_{CF} scf/cu ft rep.
1*	1.58	1.37	70.90	74.00	235.4	164.0	659.2	458.1
2*	0.77	0.77	84.67	80.00	179.6	151.0	350.7	293.6
3*	1.41	1.59	95.73	83.00	171.5	167.0	227.0	219.0
4	1.70	1.67	93.63	90.00	182.5	170.0	276.1	254.8
7	1.48	1.70	90.55	76.00	188.8	175.0	334.2	307.6
8	1.60	1.64	86.64	89.00	204.9	178.0	319.9	276.3
9	1.81	1.90	99.46	99.00	186.8	187.8	357.6	355.3
10	1.45	1.58	84.26	87.00	201.1	171.0	358.7	303.0
11	1.03	1.17	93.56	92.00	171.6	163.0	304.5	287.2
12	1.79	1.80	88.44	86.00	199.3	175.0	291.8	253.9
13	1.34	1.65	88.85	84.00	184.2	171.0	277.2	253.7
14	1.69	1.52	79.27	82.00	217.3	169.0	489.6	377.5
15*	1.66	1.54	98.23	99.00	177.3	172.0	332.1	319.3
17*	0.96	1.11	100.0	98.00	157.2	159.0	403.0	405.6
18*	1.08	1.18	98.43	98.00	162.9	161.0	455.3	446.0

Table 8. (continued)[11]

Run #	F_{HC} calc.	F_{HC} rep.	e_{02} % calc.	e_{02} % rep.	G_F scf/lb calc.	G_F scf/lb rep.	G_{CF} scf/cu ft calc.	G_{CF} scf/cu ft rep.
19*	0.51	0.55	60.65	62.00	244.3	149.0	386.0	234.8
20	0.63	0.71	80.97	74.00	180.5	148.0	300.6	244.2
23	0.59	0.60	61.27	61.00	245.2	150.0	328.5	199.9
24	0.68	0.66	51.61	58.00	297.3	151.0	468.9	238.1
25	0.53	0.21	67.81	66.00	217.4	140.0	445.5	284.5

* indicates the dry runs, others are wet combustion runs.

[11] See appendix D for full set of data

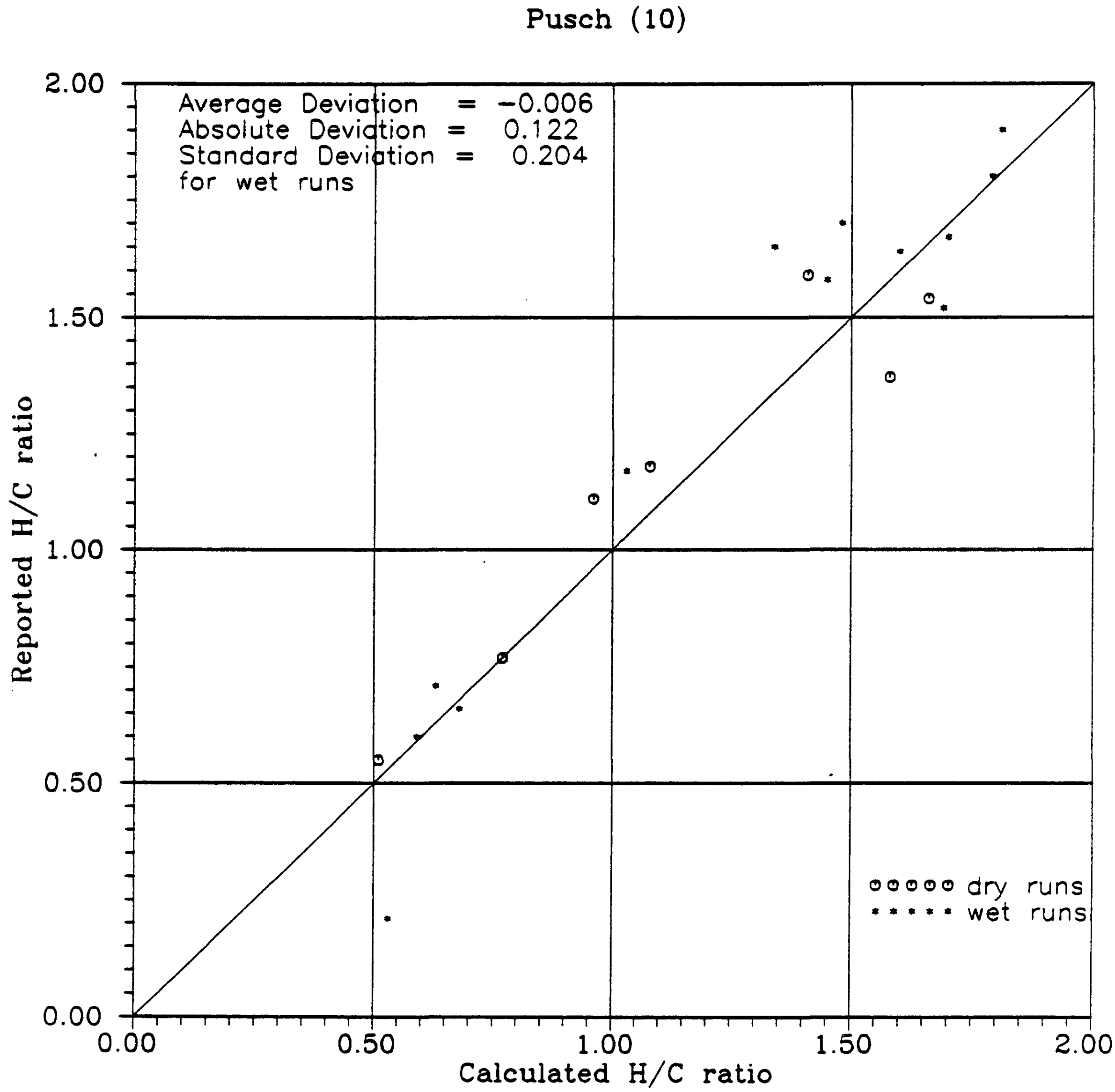

Figure 26. Comparison of calculated vs. reported H/C ratio

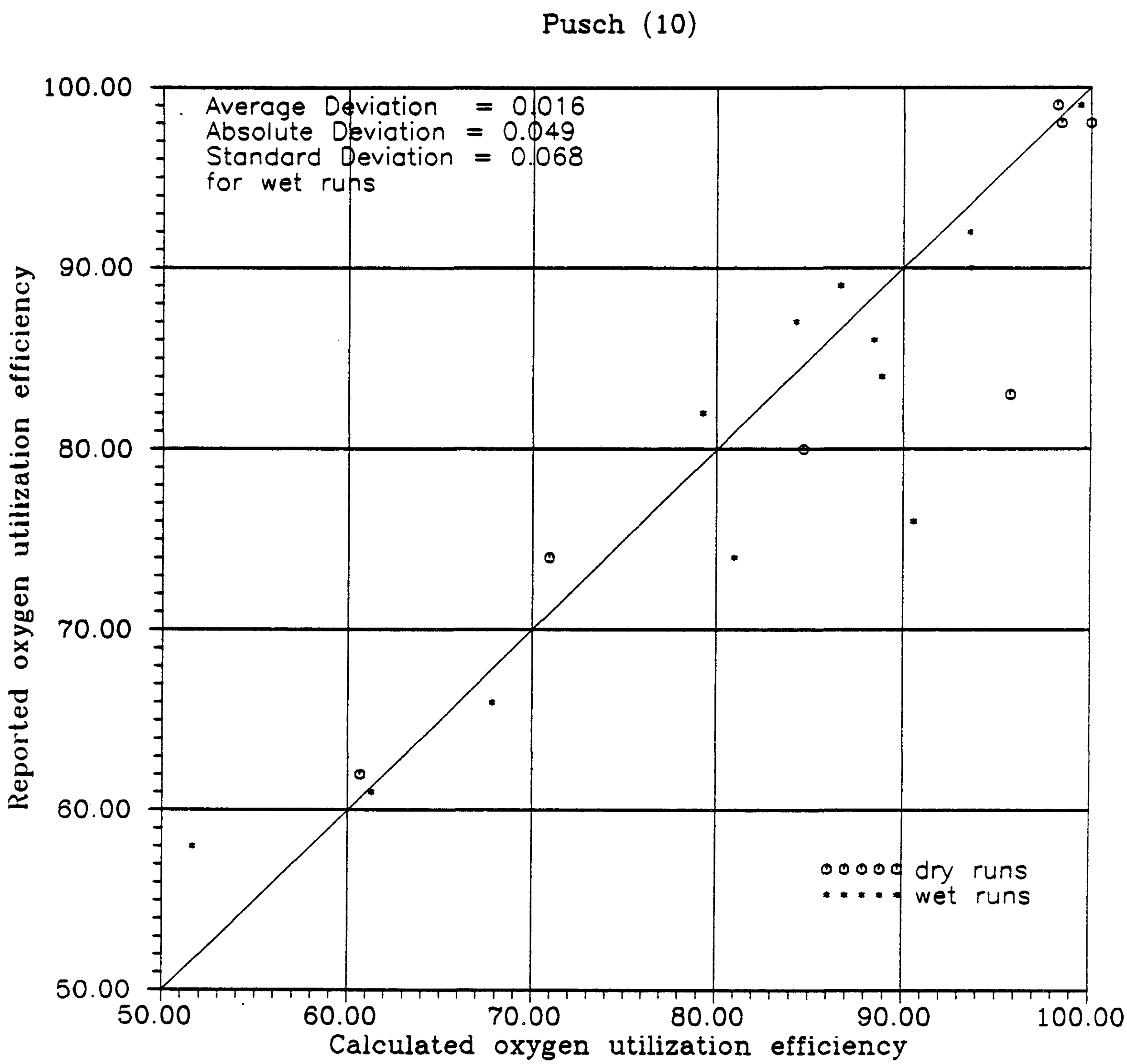

Figure 27. Comparison of calculated vs. reported oxygen utilization efficiency

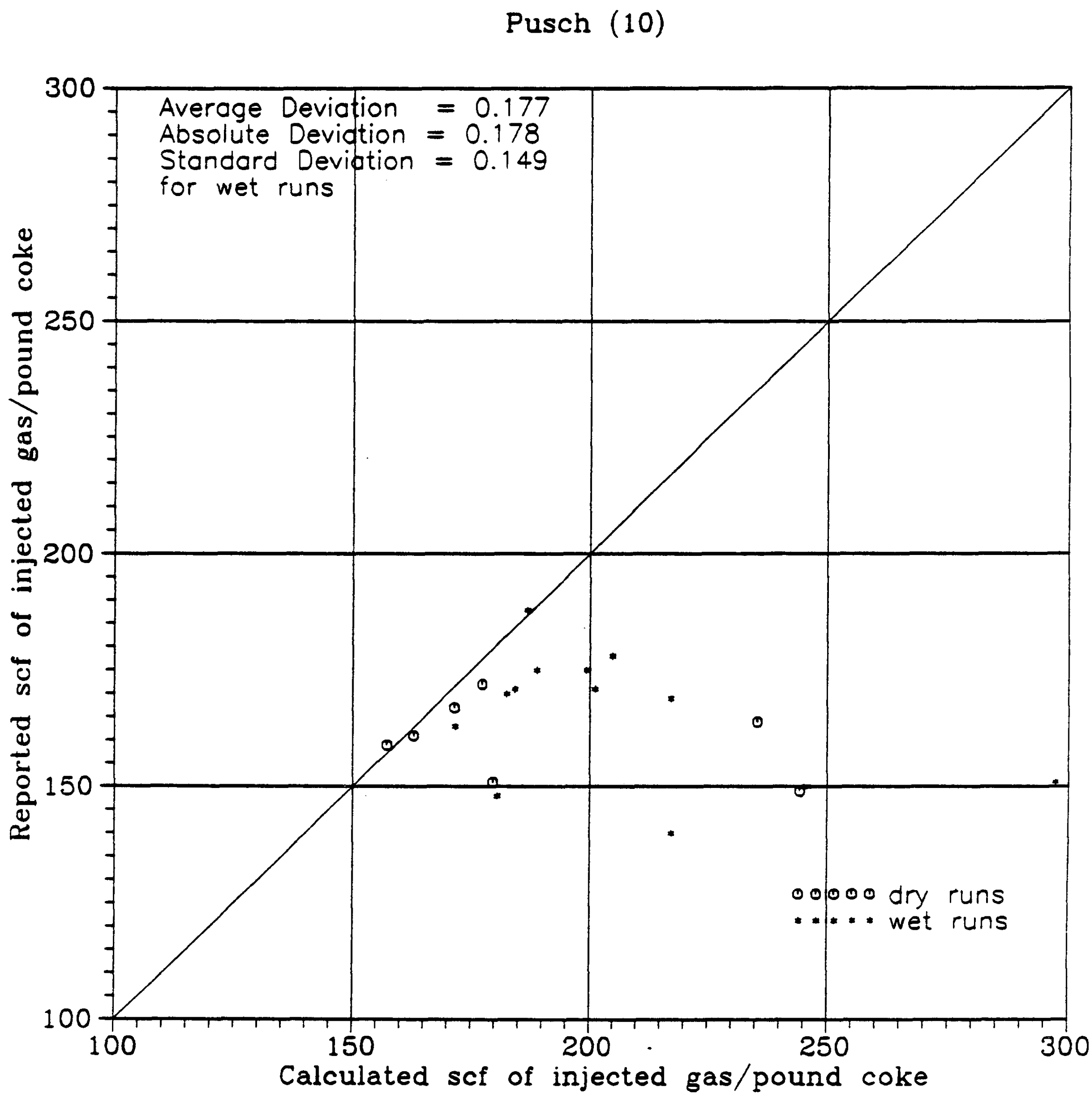

Figure 28. Comparison of calculated vs. reported scf of injected gas/pound coke

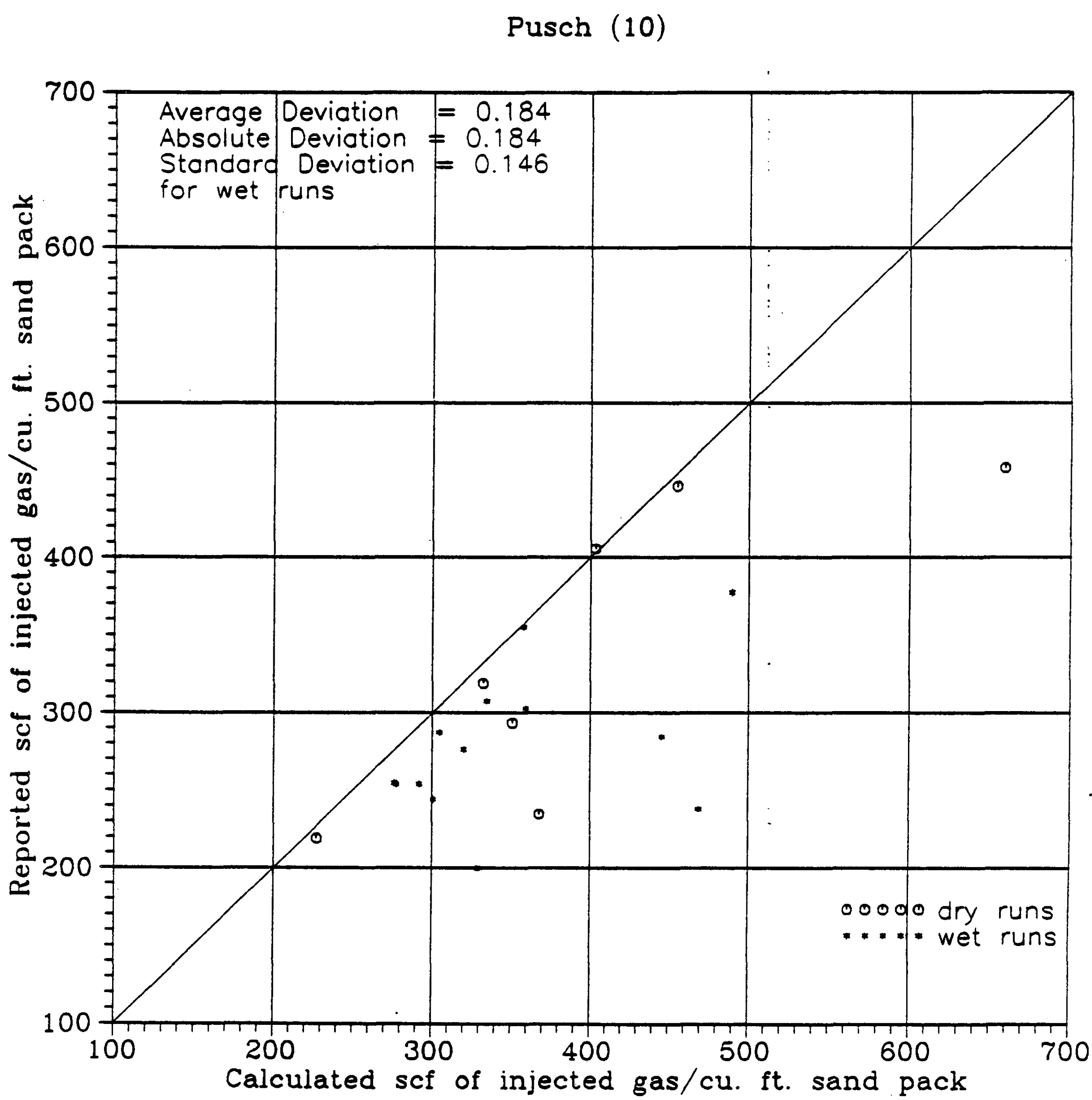

Figure 29. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

Data from Fassihi et al. (11)

Summary:

The work on in-situ combustion oil recovery adopted here is aimed at understanding the overall mechanism of this process and the effects of different process variables on it. This reference presented the complete laboratory results which were submitted to the Department of Energy (DOE).

Experimental Procedure:

1. Produced gas rate, inlet and outlet pressures, and produced gas composition (all as a function of time) and temperature (as a function of distance from the top of the pack) were measured periodically.

2. Several heterogeneous packs were prepared to determine the residual oil saturation at the steam plateau, and to monitor the fuel availability and the effect upon it of temperature and pressure. One section was oil sand, while the neighboring sections had no oil. Hence the displaced oil could move into that portion of the tube that was originally dry. As a result, it was possible to see the behavior of the front in these sections.

3. The major problem encountered in combustion runs was blocking, either in the main tube or in the gas sampling lines. As the front moves, an oil bank grows ahead of the steam plateau. The growth of this zone can be observed through the large pressure drop caused in the tube.

4. Following each run, the burned volume was weighed and produced liquids were analyzed for oil, water, and sediments. Thus material balance calculations were used to evaluate the different combustion parameters.

5. Steady-state burning portion of each run was used to evaluate the different combustion parameters.

Discussion:

Material balance equations were used here to evaluate the combustion parameters. The agreement between the calculated and the reported values is good with some fluctuations about the 45° line.

One of the combustion parameters evaluated using stoichiometry is the combustion front velocity. The authors used the following equation:

$$V_f = \left(\frac{U}{C_f \cdot AFR}\right)$$

Where:

V_f = combustion front velocity, ft/hr,

U = air flux, scf/sqft-hr,

C_f = fuel consumption, lb of fuel/cu.ft. of sand-pack, and

AFR = air-fuel ratio, scf/lb

This equation is identical to the stoichiometric derived equation used in this study. However, the authors did not include the correction of the pore space volume stored behind the combustion front. This may explain some of the fluctuation of the points about the 45° line, taking into account that the operating pressure ranged from 100 psig to 197 psig while, on the other hand, the combustion temperatures ranged from 649 °F to 1112 °F with only one run at 649 °F and all other runs were above 880 °F indicating high temperature operation. In addition, experimental errors in measuring the air-fuel ratio may account for some of the scatter.

Table 9. Comparison of calculated vs. reported data Fassihi et al. (11[12])

Run[13] #	F_{HC} calc.	F_{HC} rep.	G_F scf/lb calc.	G_F scf/lb rep.	G_{CF} scf/cu ft calc.	G_{CF} scf/cu ft rep.	v_b ft/hr calc.	v_b ft/hr rep.
78-1	1.93	1.93	230.5	232.0	247.9	246.3	0.335	0.387
78-2	0.86	0.86	175.9	177.0	270.3	270.0	0.338	0.335
78-3	1.28	1.29	169.5	169.3	245.4	244.5	0.374	0.374
78-4	0.56	0.66	165.0	168.5	367.5	374.0	0.240	0.237
78-5	0.50	0.67	153.9	162.5	278.4	293.8	0.441	0.425
78-6	0.69	0.68	163.7	164.0	227.9	227.3	0.502	0.505
78-7	0.92	0.45	171.5	155.0	336.6	296.1	0.383	0.420
79-1	0.52	0.52	167.7	168.0	347.0	346.6	0.348	0.354
79-2	0.87	0.74	177.6	172.0	381.1	369.6	0.300	0.310
79-4	1.45	1.55	175.9	175.0	323.0	326.0	0.354	0.361
79-5	1.28	1.27	178.5	178.0	356.4	355.8	0.252	0.278
79-6	2.27	2.30	201.5	203.0	359.8	381.1	0.306	0.321
79-7	2.20	2.10	203.0	210.0	488.0	475.2	0.179	0.164
80-1	4.61	4.40	314.0	316.0	582.4	576.2	0.189	0.205

[12] See appendix D for full set of data

[13] Runs 79-1, 79-2, 79-3, 79-4, and 79-6 are heterogeneous runs

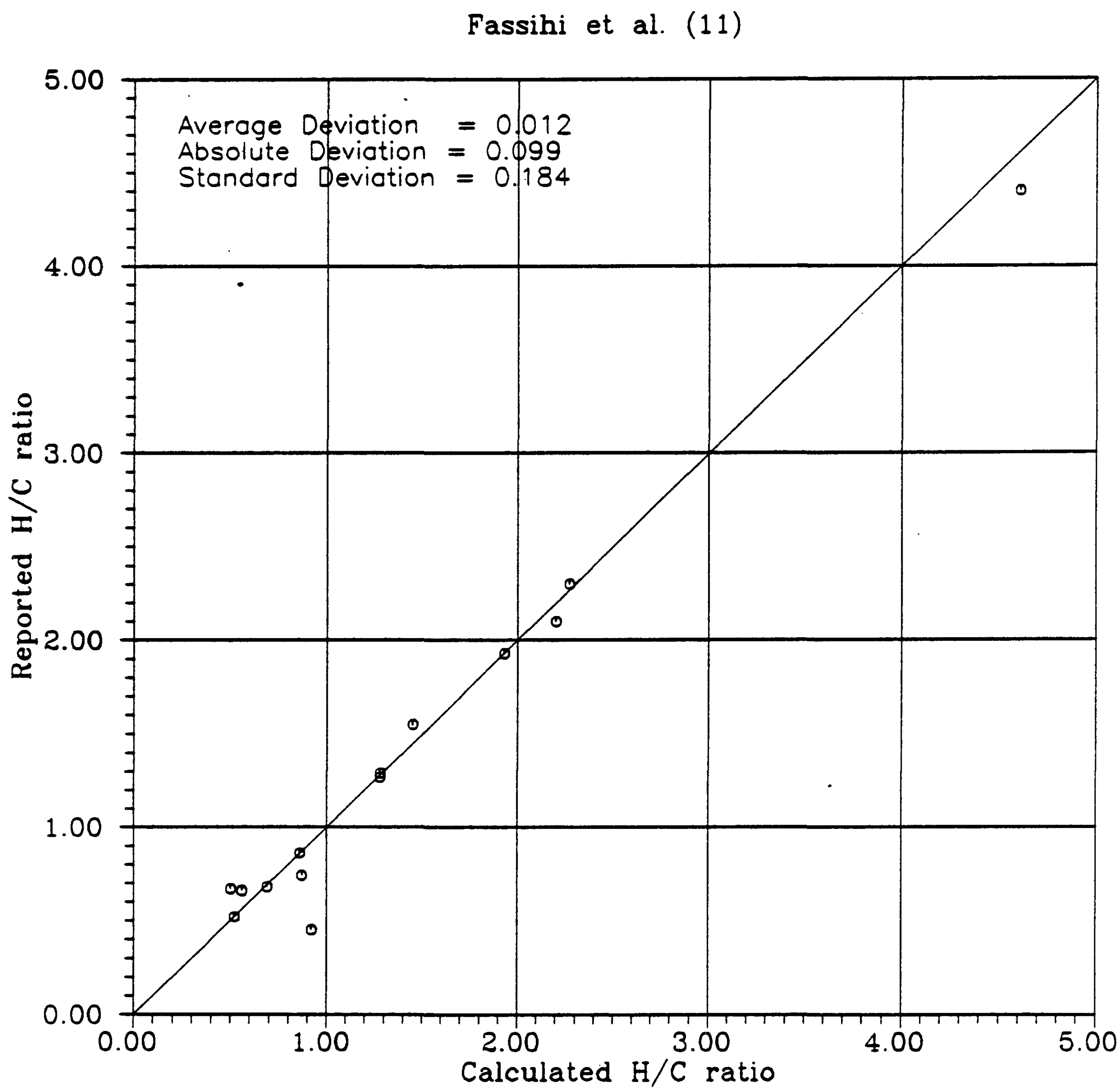

Figure 30. Comparison of calculated vs. reported H/C ratio

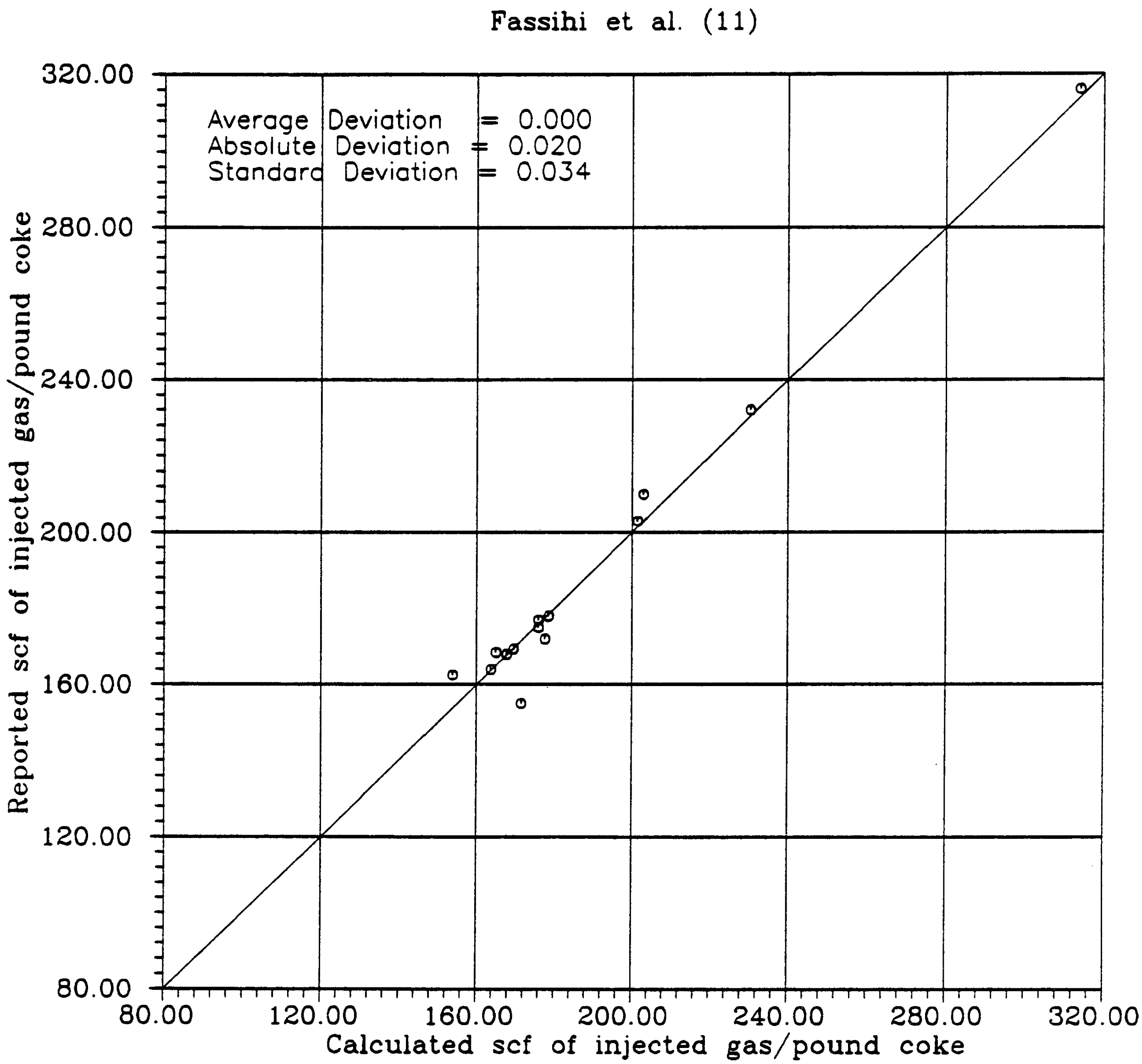

Figure 31. Comparison of calculated vs. reported scf of injected gas/pound coke

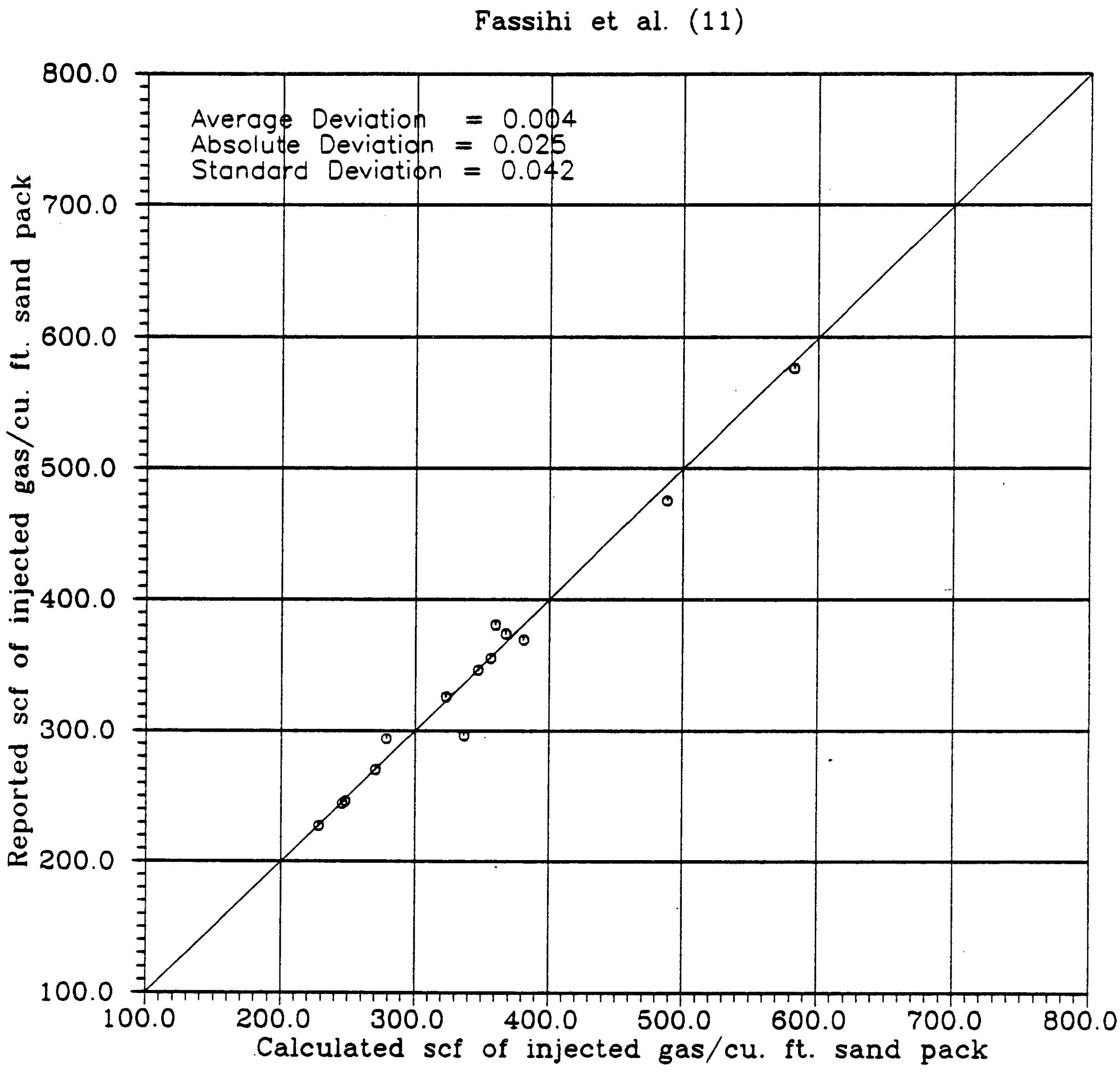

Figure 32. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

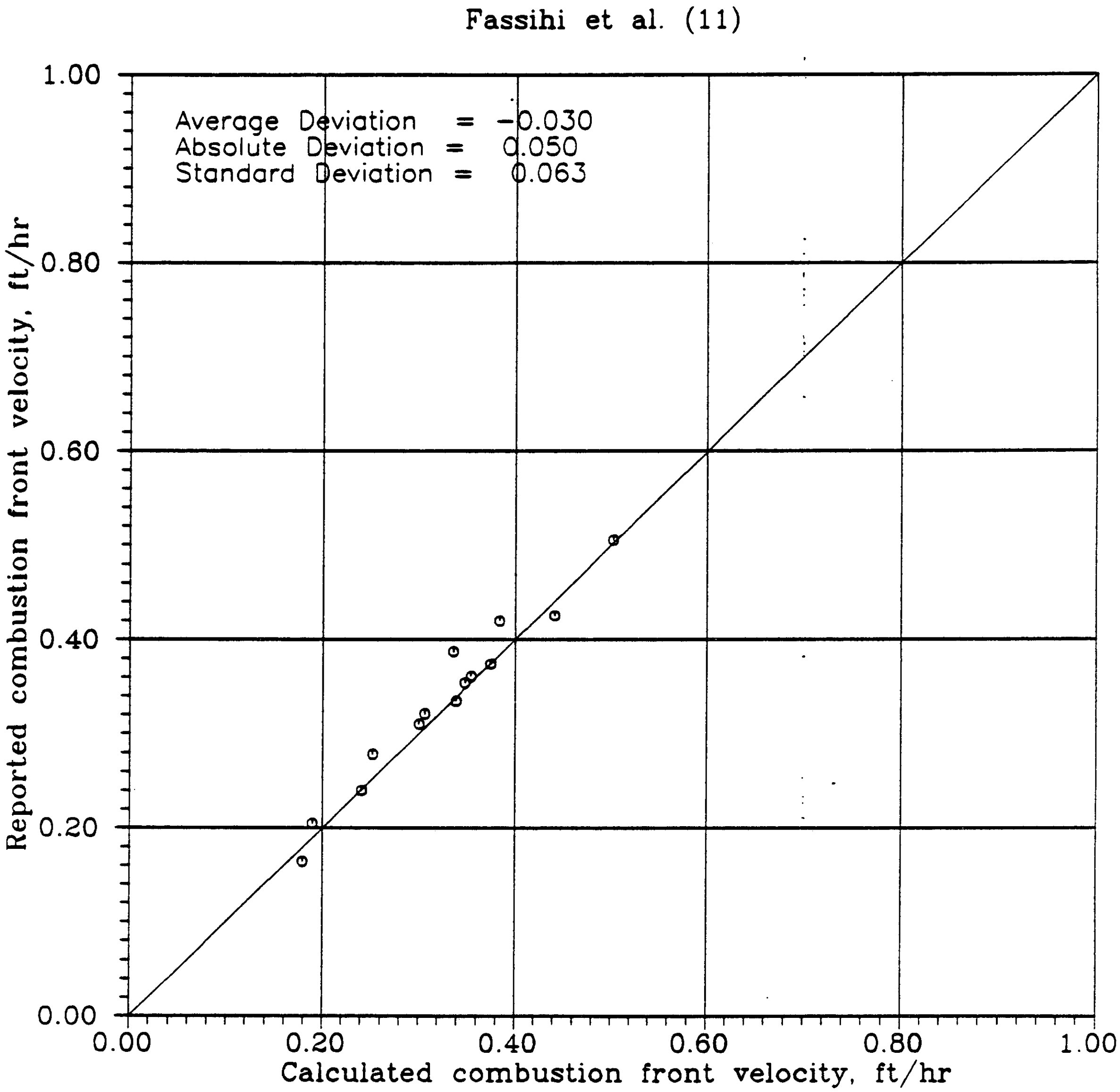

Figure 33. Comparison of calculated vs. reported frontal velocity, ft/hr

Data from Petit (13)

Summary:

This research was performed to evaluate the application of in-situ combustion with oxygen-enriched air as compared to conventional combustion with air.

Experimental Procedure:

1. The combustion tube apparatus was combined with a computerized control system (flow-rates, pressures, heat losses control) as well as data acquisition and processing of the experimental results.

2. Computer software were used for quick interpretation of the experimental results during or at the end of the experiment.

3. The author did not indicate the procedure of measuring the different combustion characteristics and whether it is experimentally measured or theoretically calculated.

4. Several series of in-situ combustion experiments with air or enriched air were performed.

Discussion:

The produced gas analysis presented in this paper was not satisfactory at all for our research purposes due to the following reasons:

1. The produced gas analysis does not contain any oxygen concentration although some reported efficiencies were not 100% i.e. there must be some produced oxygen in the flue gas.

2. High percentages of hydrocarbon gases were reported in the produced gas analysis which are believed not to be high-temperature combustion products yet the maximum combustion temperatures reported ranged from 850 °F to 1382 °F.

Figure 34. is a plot of the calculated vs. the reported H/C values for all different oxygen percents. It is apparent that the calculated H/C ratio for the 100% oxygen injection is always much less than the reported values, whereas in case of air and other oxygen concentrations the points are scattered about the 45° line. The situation becomes much better in the comparison of the amount of injected gas required to burn one cubic foot of sand-pack and the frontal velocity as shown in Figures 35 and 36.

Generally, the bad agreement between the calculated and the reported values is principally due to the poor reported produced gas analysis.

Because of the scatter, the reported values were probably experimentally measured, particularly since the worst agreement is with the H/C atomic ratio when compared to the injected gas requirement and combustion front velocity.

Table 10. Comparison of calculated vs. reported data Petit (13)

Run #	F_{HC} calc.	F_{HC} rep.	e_{02} % calc.	e_{02} % rep.	G_{CF} scf/cu ft calc.	G_{CF} scf/cu ft rep.	v_b ft/hr calc.	v_b ft/hr rep.
1	1.72	1.20	100.0	95.00	295.6	286.0	0.212	0.219
2	0.64	1.02	100.0	98.00	126.0	133.6	0.209	0.197
3	1.68	1.42	100.0	100.0	96.5	92.1	0.170	0.178
4	1.80	1.66	100.0	100.0	269.4	261.0	0.242	0.250
5	1.80	1.05	100.0	98.50	298.7	271.9	0.235	0.258
6	1.77	1.77	100.0	100.0	108.1	107.1	0.243	0.246
7	0.44	2.01	100.0	100.0	50.2	60.6	0.262	0.217
8	0.39	1.21	100.0	100.0	53.2	60.1	0.247	0.217
9	0.45	2.70	100.0	100.0	209.2	270.0	0.299	0.233
10	1.67	1.60	100.0	100.0	126.6	131.0	0.208	0.201
11	1.41	1.01	100.0	100.0	128.8	127.2	0.204	0.208
12	0.11	0.67	100.0	100.0	67.2	67.8	0.196	0.193
13	0.10	1.95	100.0	100.0	51.7	67.4	0.254	0.195
14	1.72	2.20	100.0	100.0	117.6	240.9	0.226	0.109
15	0.44	2.07	100.0	100.0	49.3	61.7	0.534	0.426
16	2.82	1.06	100.0	100.0	316.3	271.0	0.084	0.097
17	0.09	0.42	100.0	100.0	71.3	81.1	0.369	0.324

Table 10. (continued)

Run #	F_{HC} calc.	F_{HC} rep.	e_{02} % calc.	e_{02} % rep.	G_{CF} scf/cu ft calc.	G_{CF} scf/cu ft rep.	v_b ft/hr calc.	v_b ft/hr rep.
18	0.09	0.43	100.0	100.0	83.5	88.8	0.315	0.296
19	1.99	2.60	100.0	78.00	208.4	251.4	0.300	0.249
20	1.32	1.80	100.0	93.60	96.1	100.0	0.273	0.263
21	0.39	1.08	100.0	98.50	42.2	53.3	0.311	0.262
22A	6.29	4.41	100.0	79.00	438.3	489.0	0.180	0.161
22B	2.96	1.94	100.0	81.70	359.0	390.0	0.183	0.169
23	4.83	1.92	100.0	97.60	265.3	216.2	0.142	0.173
24	2.10	1.46	100.0	99.00	94.0	89.0	0.168	0.177
25	0.41	1.35	100.0	100.0	33.2	38.5	0.238	0.205
26	2.89	2.30	100.0	100.0	196.1	190.9	0.192	0.197
27	2.02	2.10	100.0	100.0	228.8	218.6	0.164	0.172
28	4.57	1.50	100.0	100.0	74.1	66.0	0.213	0.262
29	0.19	14.7	100.0	100.0	26.3	40.7	0.300	0.193
30	0.08	3.60	100.0	100.0	28.5	33.2	0.277	0.238
31	2.21	1.55	100.0	91.0	201.1	203.3	0.132	0.129
32	0.48	2.18	100.0	88.50	42.5	57.8	0.618	0.455
33	4.84	1.66	100.0	100.0	96.9	80.2	0.271	0.328

Table 10. (continued)[14]

Run[15] #	F_{HC} calc.	F_{HC} rep.	e_{O2} % calc.	e_{O2} % rep.	G_{CF} scf/cu ft calc.	G_{CF} scf/cu ft rep.	v_b ft/hr calc.	v_b ft/hr rep.
34	0.15	0.59	100.0	100.0	60.1	64.1	0.437	0.410
35	0.12	1.18	100.0	100.0	54.5	62.4	0.482	0.422
36	1.05	0.97	100.0	99.50	242.5	240.9	0.258	0.260
37	0.38	0.87	100.0	100.0	58.3	63.2	0.211	0.195
38	0.31	1.00	100.0	100.0	245.3	270.9	0.255	0.232
39	0.10	0.40	100.0	100.0	72.2	78.1	0.182	0.168
40	2.06	1.69	100.0	93.80	233.6	237.1	0.253	0.248
41	0.39	0.10	100.0	99.50	44.4	41.0	0.113	0.122
42	0.86	0.80	100.0	100.0	149.6	166.5	0.251	0.226
43	0.07	1.5	100.0	100.0	36.5	41.8	0.216	0.189

[14] See appendix D for full set of data

[15] Run 22A is a 10% oxygen injection run
Run 22B is a 12% oxygen injection run
Runs 1, 4, 5, 9, 14, 16, 19, 23, 26, 27, 31, 36, 38, and 40 are 21% oxygen injection runs
Run 42 is a 23% oxygen injection run
Runs 2, 6, 10, 11, 20, 24, 28, and 33 are 50% oxygen injection runs
Run 3 is an 80% oxygen injection run
Runs 7, 8, 12, 13, 15, 17, 18, 21, 25, 29, 30, 32, 34, 35, 37, 39, 41, and 43 are 100% oxygen injection runs

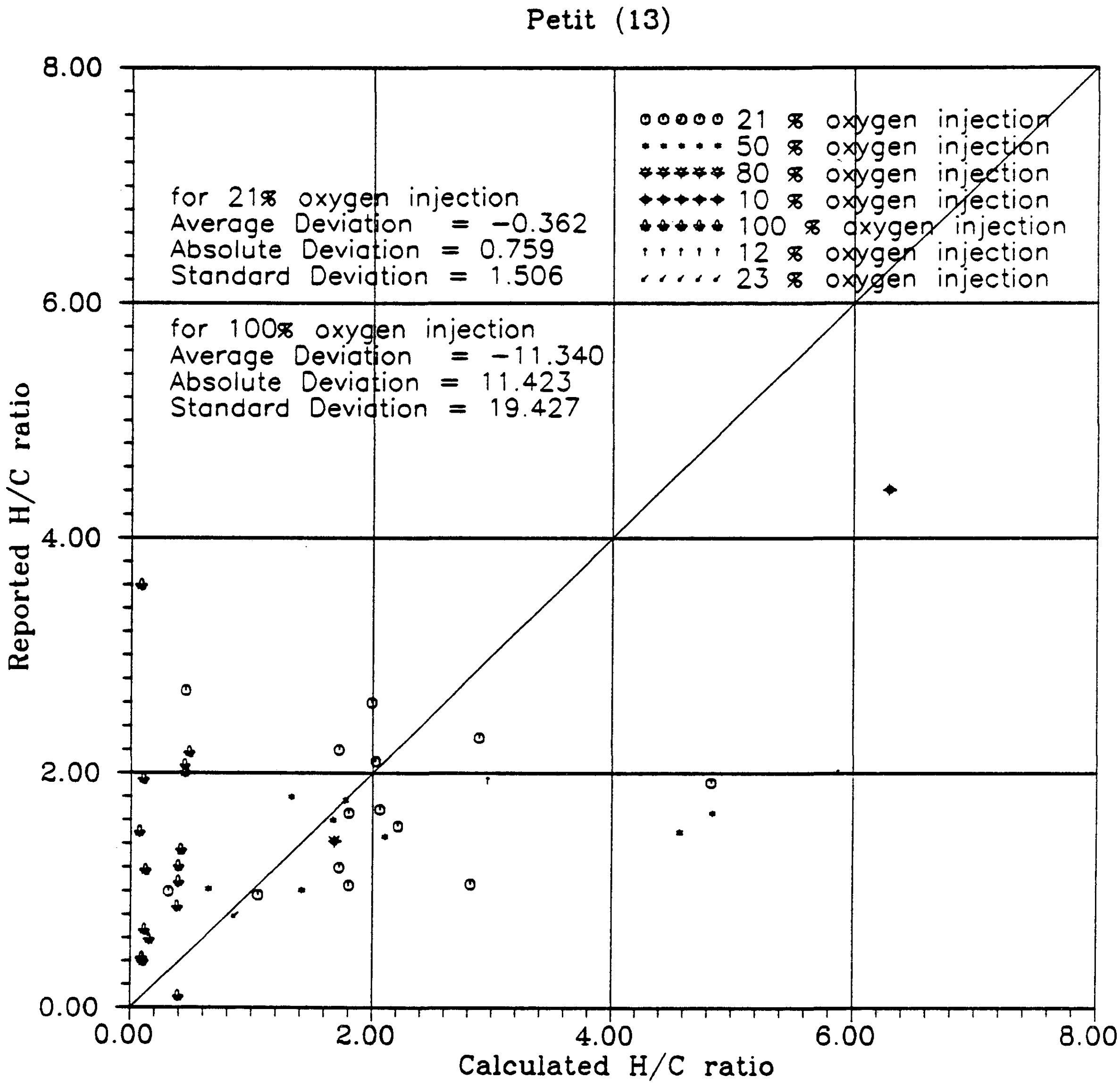

Figure 34. Comparison of calculated vs. reported H/C ratio

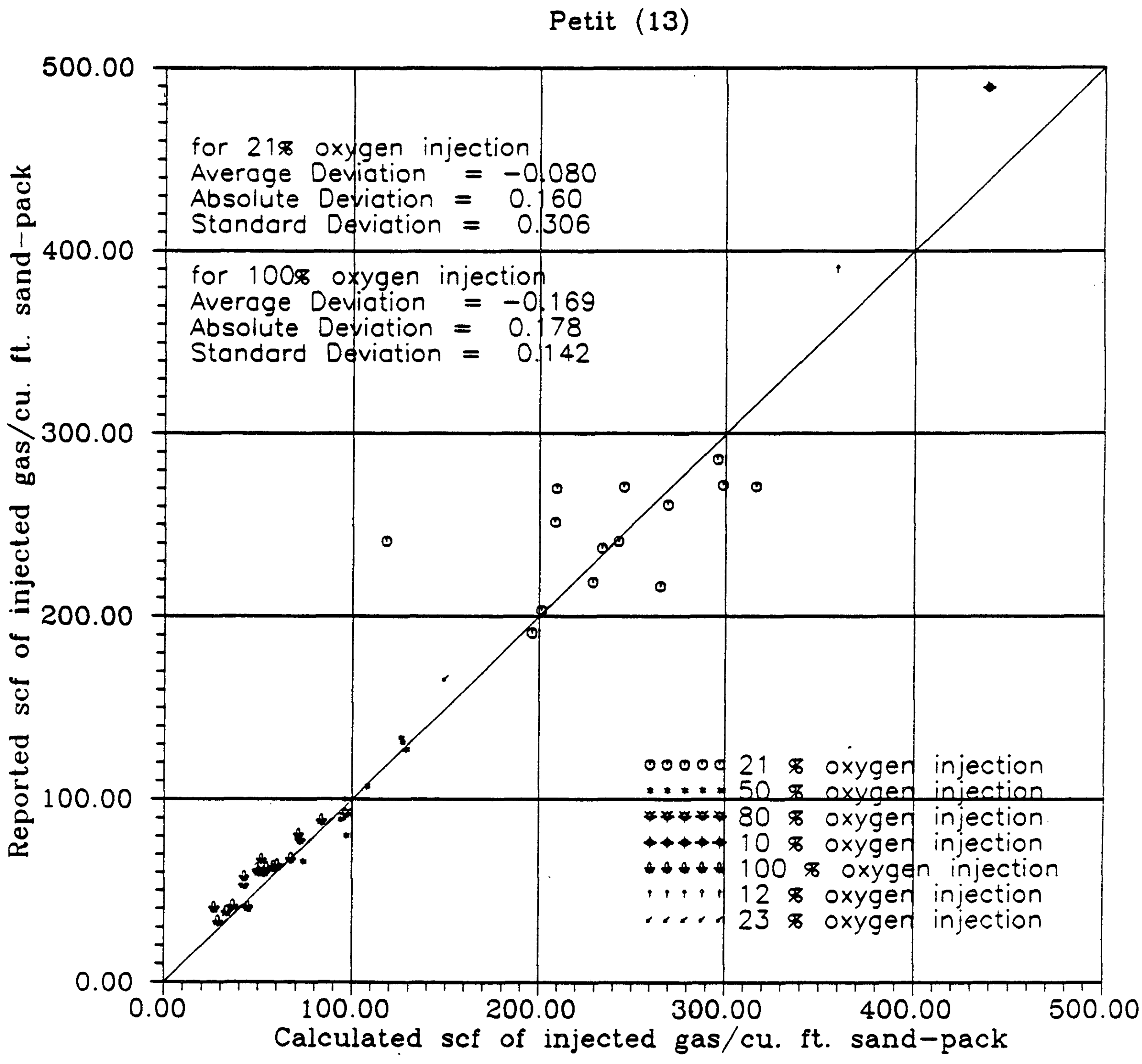

Figure 35. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

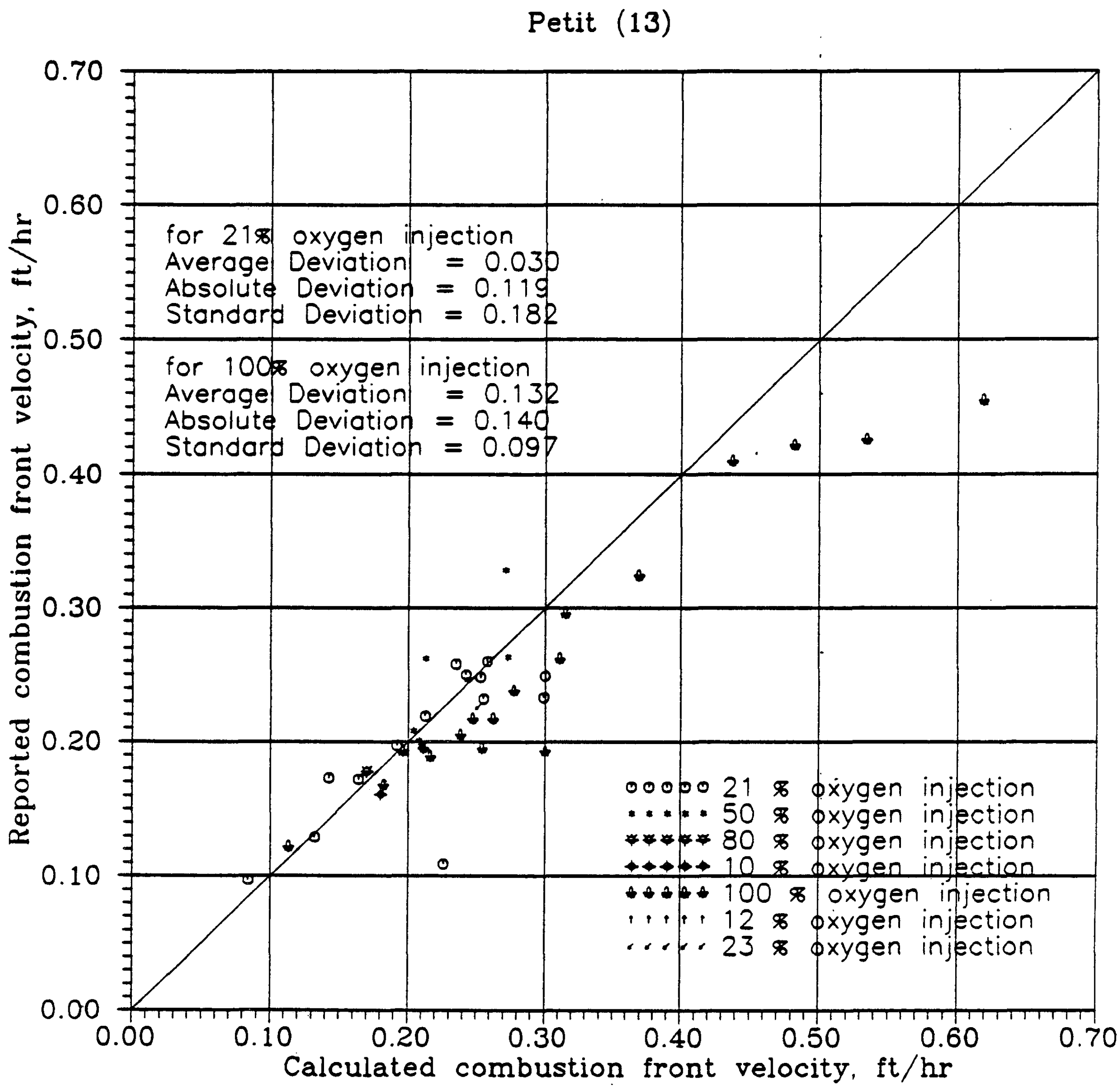

Figure 36. Comparison of calculated vs. reported frontal velocity, ft/hr

Data from Burger and Sahuquet (29)

Summary:

The research discussed here focused on the effect of water/air ratio on the amount of air required for the combustion front to sweep a defined volume of the porous medium. It also studied the influence of water injection on the condensation front velocity downward from the combustion front. A number of dry and wet combustion tests were performed. No attempt was made to use the wet combustion tube runs due to the lack of the produced gas analysis for these runs.

Experimental Procedure:

1. The first set of combustion runs was carried out, without water injection, with clean unconsolidated sands. These runs were used in our study.

2. Combustion parameters evaluated included the H/C atomic ratio, the oxygen utilization efficiency, the amount of air necessary to burn one cubic foot of sand-pack and the combustion front velocity.

3. The combustion front velocity was experimentally determined from the slope of a plot of the front position against the time.

4. The author did not explain how he measured the other combustion parameters.

Discussion:

The variation in the agreements between the reported and the calculated values indicate that the parameters were experimentally measured.

The reported combustion temperatures ranged from 761 °F to 824 °F which are indicative of high temperature-oxidation reactions.

A plot of the calculated and reported H/C ratio indicates that the calculated are higher than the reported values. This discrepancy may be explained by the fact that this measured ratio is only for the apparent H/C ratio of the fuel since it is affected by the operating combustion parameters.

The calculated oxygen utilization efficiency and combustion front velocity correlate well with the reported results.

In the case of the amount of air required to burn one cubic foot of sand-pack, the calculated values are higher than the reported values for runs A1, A5 and A9 which indicates experimental inconsistencies in the measurements.

Table 11. Comparison of calculated vs. reported data Burger and Sahuquet (29[16])

Run #	F_{HC}		e_{O2} %		G_{CF} scf/cu ft		v_b ft/hr	
	calc.	rep.	calc.	rep.	calc.	rep.	calc.	rep.
A1	2.05	1.90	97.75	98.00	199.4	193.0	0.148	0.153
A5	2.02	1.96	86.40	86.00	233.7	230.0	0.126	0.129
A6	2.35	2.22	88.77	88.00	216.5	216.0	0.136	0.137
A8	2.26	2.21	81.91	81.00	232.1	232.0	0.254	0.255
A9	1.84	1.76	100.0	100.0	204.9	200.0	0.144	0.148

16 See appendix D for full set of data

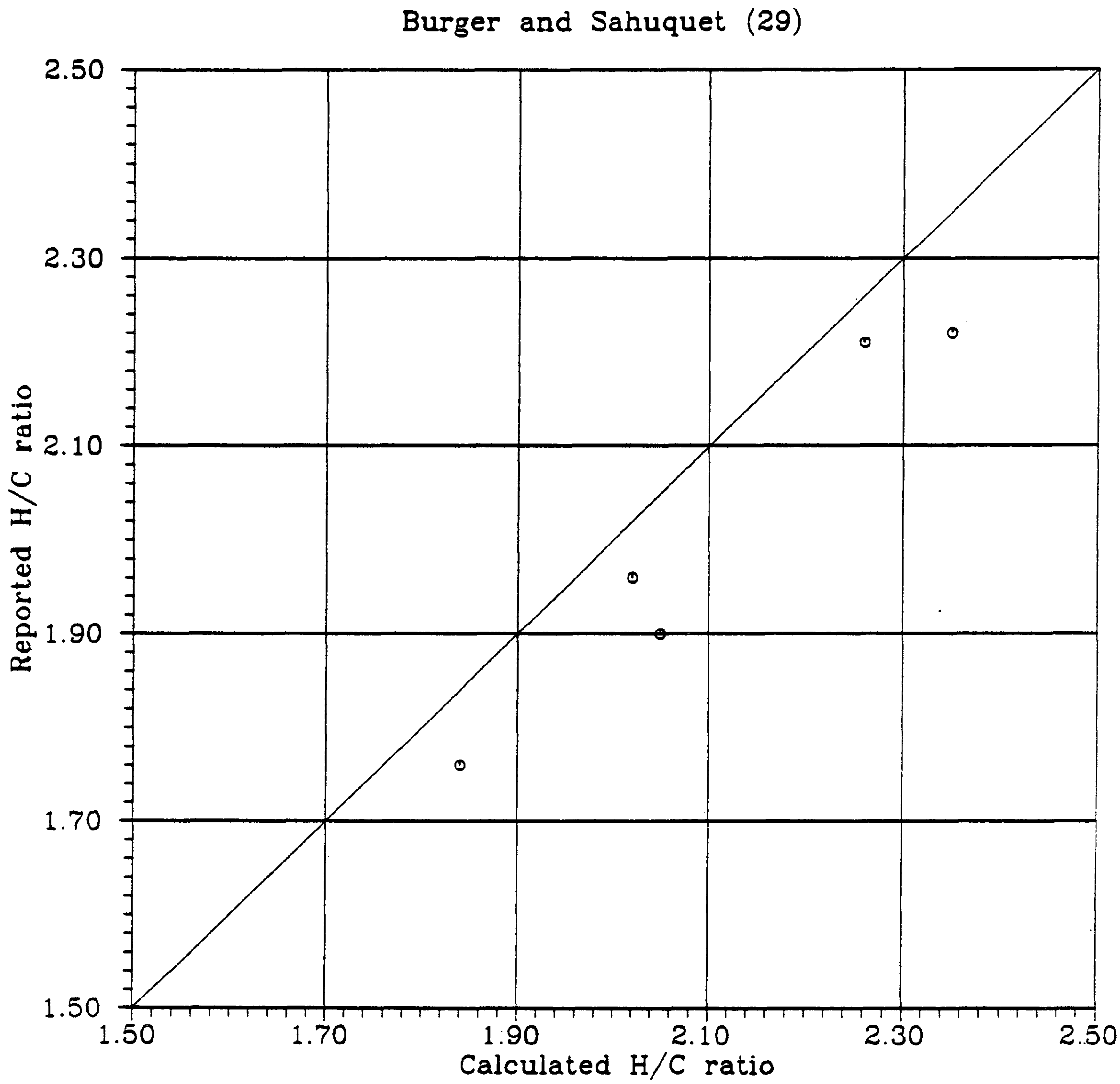

Figure 37. Comparison of calculated vs. reported H/C ratio

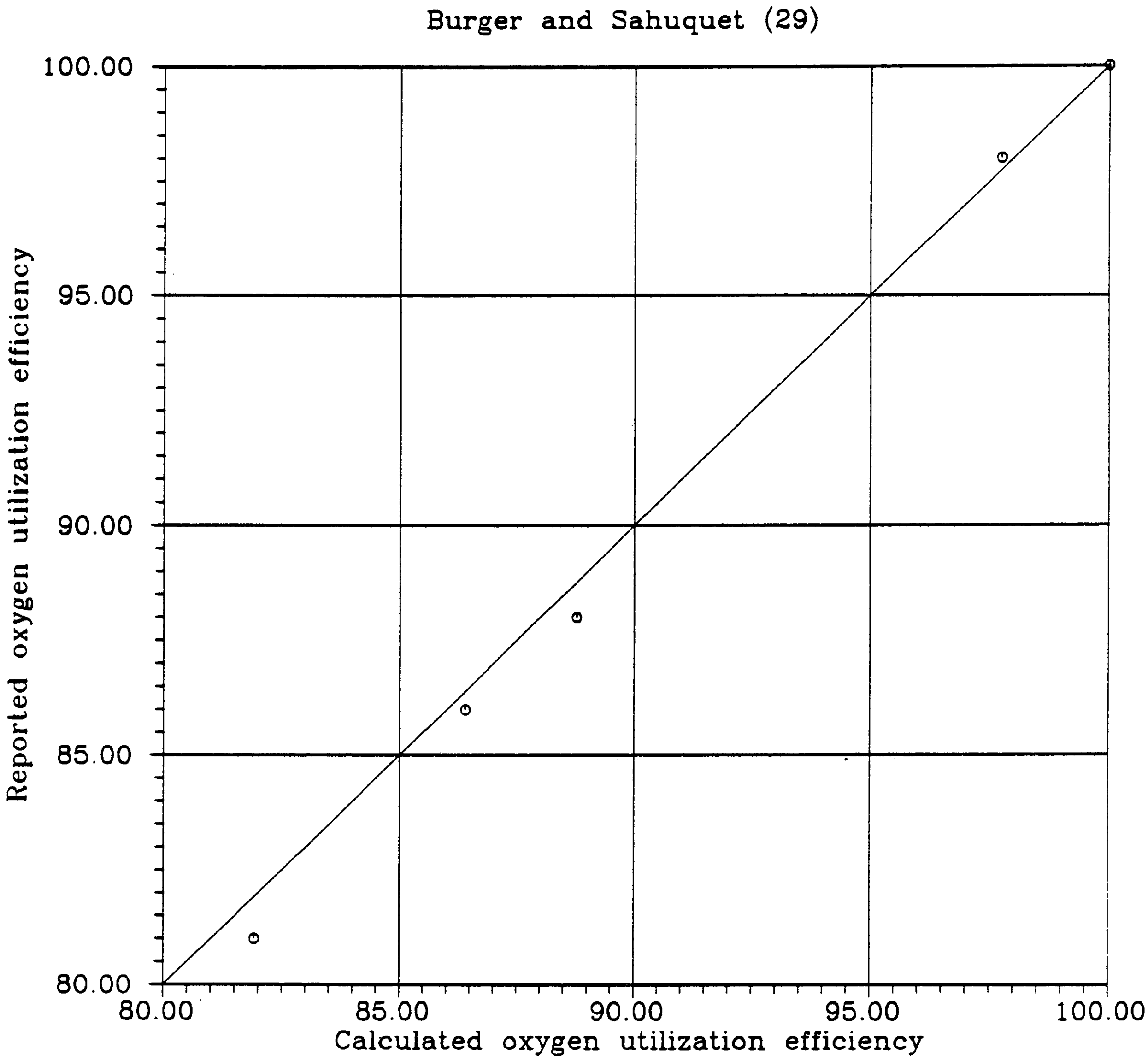

Figure 38. Comparison of calculated vs. reported oxygen utilization efficiency

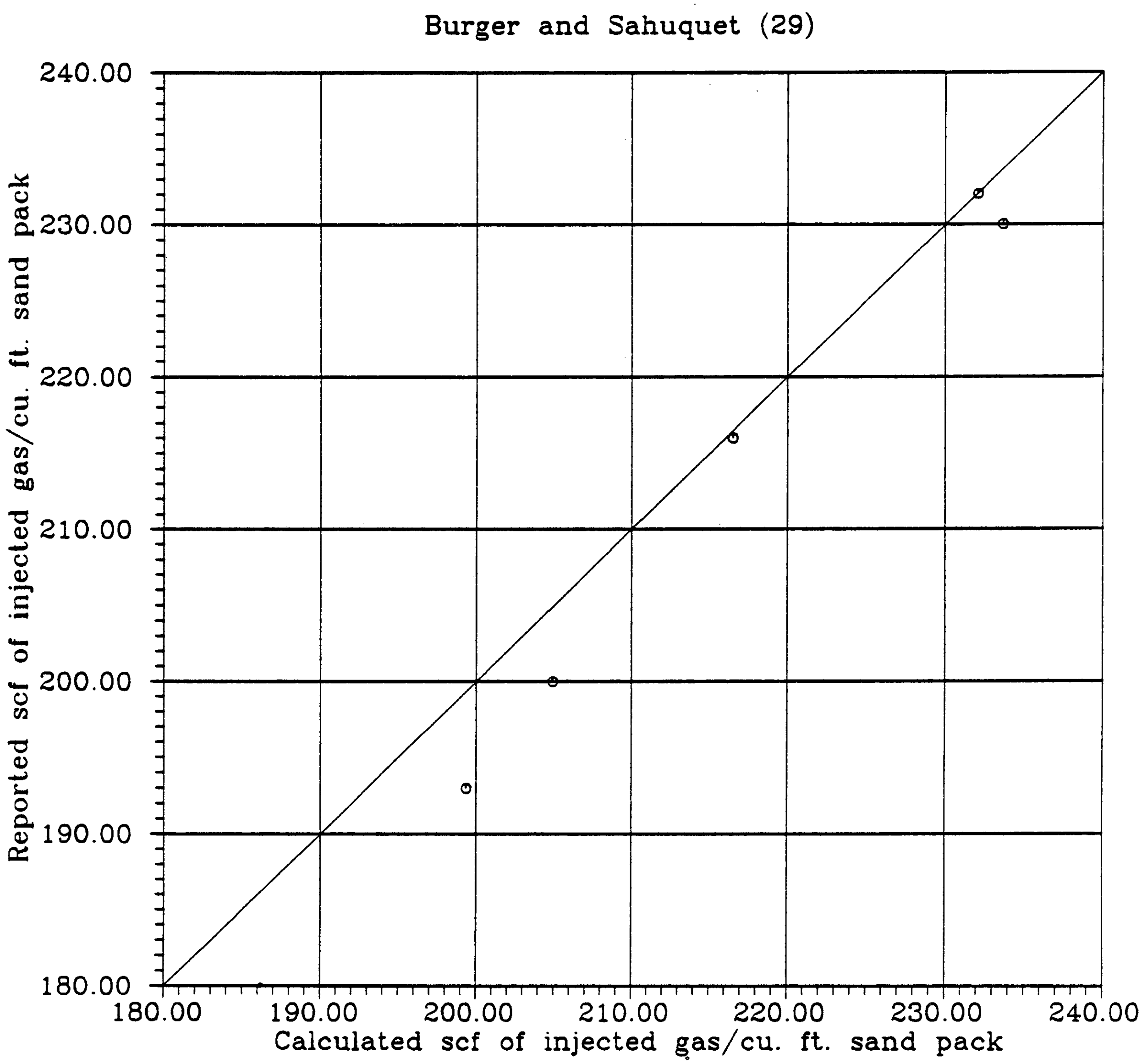

Figure 39. Comparison of calculated vs. reported scf of injected gas/cu. ft. sand-pack

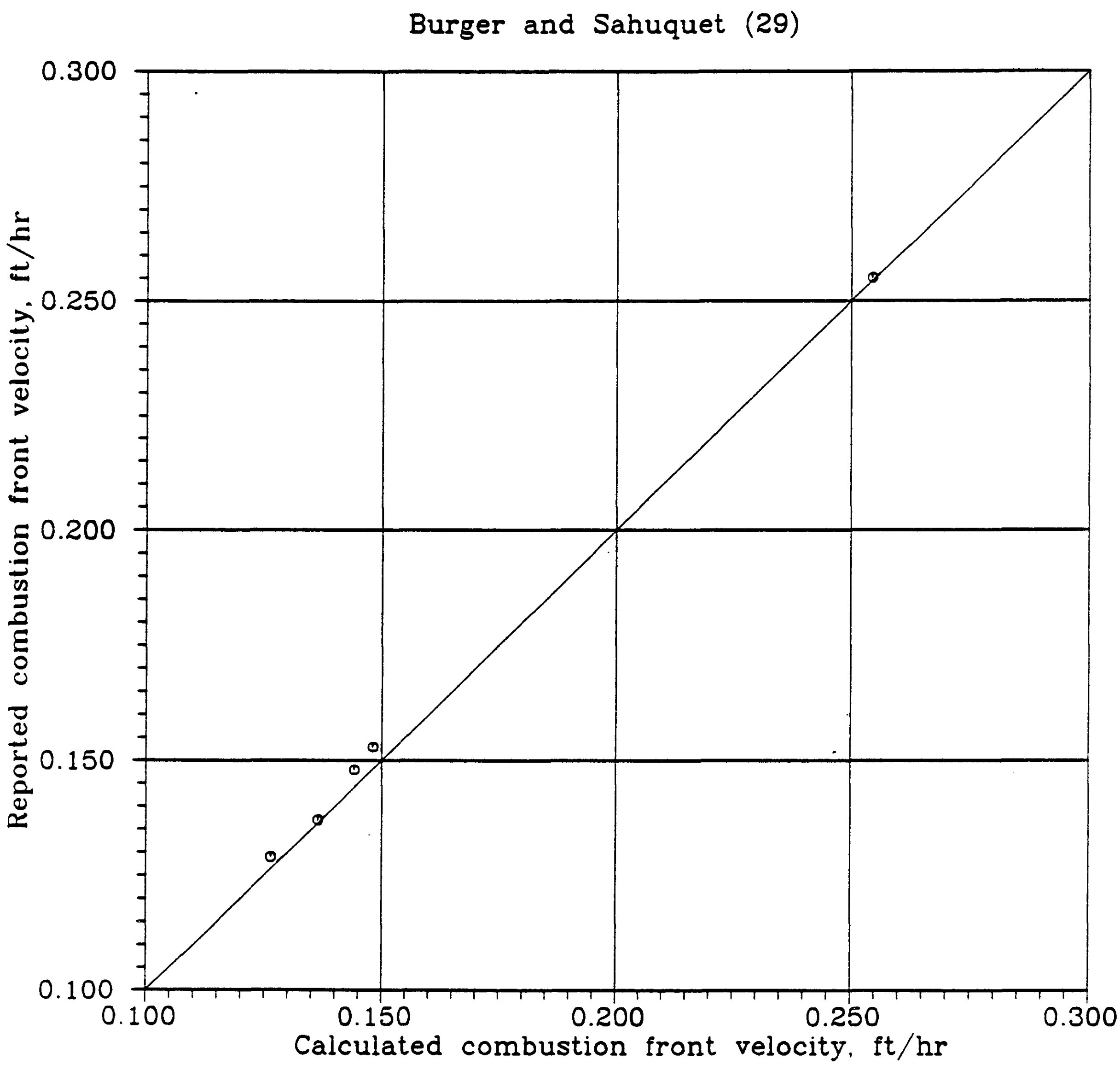

Figure 40. Comparison of calculated vs. reported frontal velocity, ft/hr

EVALUATING AN IN-SITU COMBUSTION PROJECT USING STOICHIOMETRIC CONSIDERATIONS

Engineering calculations for an in-situ combustion project often are made with the assumption that oil is recovered only by frontal displacement from the volume burned.[27] This method assumes constant air/oil ratios throughout the reservoir.

Evaluation of an in-situ combustion recovery process can't begin unless the following things are known:[14,18]

I. The amount of fuel consumed per unit of reservoir volume swept by the combustion zone,

II. Total Injected Gas Requirement,

III. Total Oil Production,

IV. Total Water Production, and

V. Total Gas Production.

It is the objective of this chapter to describe a procedure which utilizes laboratory combustion tube data and stoichiometric equations as a basis for evaluating an in-situ combustion project.

Example calculations of a field case history are presented in appendix C.

The experimental data needed from the laboratory tube runs are:

1. **Composition of Injected Gas:**

   Mole fraction of oxygen, y_{iO2} and

   Mole fraction of nitrogen, y_{iN2}

2. **Stabilized Effluent Gas Compositions:**

   Mole fraction of carbon dioxide, y_{pCO2}

   Mole fraction of carbon monoxide, y_{PCO}

   Mole fraction of unreacted oxygen, y_{pO2} and

   Mole fraction of nitrogen, y_{pN2}

   Fuel Consumption, m_E, lbs of coke/cu. ft. sand-pack burned

3. **Standard Conditions:**

   Ambient temperature, T_{sc}, °F and

   Atmospheric pressure, p_{sc}, psia

4. **Reservoir and production data needed for evaluating an in-situ combustion project:**

   Reservoir porosity,

   Reservoir pressure,

   Reservoir temperature,

   Reservoir thickness,

   Reservoir characteristics such as permeability, layering

   Oil saturation, and oil gravity.

Volume of produced gases from individual wells as well as a stabilized produced gas composition,

Oil produced from individual wells, and

Water produced from individual wells,

In other words, the project should be carefully monitored and pertinent data taken.

The general stoichiometric equation involved in this process is:

$$CH_{F_{HC}}+\left(\frac{1}{(y_{iO_2})\cdot(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)G_i \longrightarrow \left(\frac{m}{m+1}\right)CO_2+\left(\frac{1}{m+1}\right)CO$$

$$+\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{e_{O_2}}-1\right)O_2+\left(\frac{y_{i_{N_2}}}{y_{iO_2}\cdot e_{O_2}}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)N_2+\left(\frac{F_{HC}}{2}\right)H_2O \qquad (5.1)$$

The first problem is to calculate the quantities involved in the above equation. This is done as follows:

__1.__ Normalize the produced gas composition from the reservoir on a water-free and hydrocarbon-free basis as follows:

$$A.\ XSUM = (y_{pCO_2} + y_{pCO} + y_{pO_2} + y_{pN_2}) \qquad (7.1)$$

$$B.\ \tilde{y}_{pCO_2} = \frac{y_{pCO_2}}{XSUM} \tag{7.2}$$

$$C.\ \tilde{y}_{pCO} = \frac{y_{pCO}}{XSUM} \tag{7.3}$$

$$D.\ \tilde{y}_{pO_2} = \frac{y_{pO_2}}{XSUM} \tag{7.4}$$

$$E.\ \tilde{y}_{pN_2} = \frac{y_{pN_2}}{XSUM} \tag{7.5}$$

2. Calculate m, F_{HC}, and e_{O2}, where:

$$m = \frac{\tilde{y}_{pCO_2}}{\tilde{y}_{pCO}}$$

$$F_{HC} = \frac{H}{C} \quad \textit{atomic ratio}$$

$$e_{O_2} = \textit{oxygen utilization efficiency}$$

The produced gas analysis is always on a water-free basis.

For the general situation where the injected gas consists of any composition of oxygen and nitrogen:

1. $$m = \frac{\tilde{y}_{pCO_2}}{\tilde{y}_{pCO}} \tag{7.6}$$

2. $$F_{HC} = \frac{4\cdot\left(\dfrac{y_{iO_2}}{y_{i_{N_2}}}\right)+2\cdot\tilde{y}_{pCO}-\left(4\cdot\dfrac{y_{iO_2}}{y_{i_{N_2}}}+4\right)(\tilde{y}_{pO_2}+\tilde{y}_{pCO}+\tilde{y}_{pCO_2})}{\tilde{y}_{pCO_2}+\tilde{y}_{pCO}} \tag{7.7}$$

3. $$e_{O_2} = 1-\frac{y_{i_{N_2}}}{y_{iO_2}}\cdot\frac{\tilde{y}_{pO_2}}{\tilde{y}_{pN_2}} \tag{7.8}$$

For the situation where the injected gas is pure oxygen:

1. $$y_{iO_2} = 1.0 \tag{7.9}$$

2. $$y_{i_{N_2}} = 0.0 \tag{7.10}$$

3. $$m = \frac{\tilde{y}_{pCO_2}}{\tilde{y}_{pCO}} \tag{7.11}$$

$$4.\ F_{HC} = \frac{4\ .\ (1-\tilde{y}_{pO_2}-0.5\tilde{y}_{pCO}-\tilde{y}_{pCO_2})}{\tilde{y}_{pCO_2}+\tilde{y}_{pCO}} \qquad (7.12)$$

$$5.\ e_{O_2} = 1-\tilde{y}_{pO_2} \qquad (7.13)$$

Next step is to correct the laboratory determined fuel content for any difference in the porosity of the laboratory sand-pack and that of the reservoir by:

$$m_R = m_E\ .\ \left(\frac{1-\phi_R}{1-\phi_E}\right) \qquad (5.22)$$

where:

ϕ_R = reservoir porosity

ϕ_E = sand-pack porosity

m_E = sand-pack fuel content

m_R = fuel content corrected to reservoir porosity

I. Therefore, the amount of fuel consumed per unit of reservoir volume swept by the combustion zone is evaluated using equation (5.22).

II. Total standard cubic feet of injected gas required to burn one cubic foot of bulk volume of reservoir is given by:

$$G_i = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{io_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right)\, m_R\right]+\left[\frac{\phi_R}{B_{gi}}\right] \quad (5.14)$$

Where:

B_{gi} = Formation volume factor of the injected gas[17]

III. With the above calculated stoichiometric constants, the amount of injected gas required to displace one barrel of oil is evaluated as follows:

$$G_{io} = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{io_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right)\, m_R + \frac{\phi_R}{B_{gi}}\right] \times$$

$$\left[\frac{5.615}{\phi_R(S_o - S_{FrR})}\right] \quad (5.18)$$

Where:

$$S_{FrR} = \frac{m_R}{\phi_R\, \rho_o}$$

[17] See appendix A for the calculation of B_{gi}

IV. The volume of gas produced per one cubic foot of bulk reservoir volume burned is calculated by:

$$G_{pCF} = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{io_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right)\,m_R\right] \times$$

$$\left[\left(\frac{(y_{io_2})\;\;(e_{O_2})}{\left(\dfrac{2m+1}{2m+2}\;+\;\dfrac{F_{HC}}{4}\right)}\right) + \left(1\;-\;(y_{io_2})\;\;(e_{O_2})\right)\right] + \left[\frac{(\phi_R)\;\;(1\;-\;S_o)}{B_{pg}}\right] \qquad (5.21)$$

The amount of oil displaced from a zone surrounding a well can be calculated from the cumulative gas produced at the well, the oil saturation, the fuel saturation, and the volume of gas produced per one cubic foot of bulk reservoir burned. Thus the cumulative oil displaced from the swept out area can be calculated.

Knowing the volume of gas necessary to displace one barrel of oil and the total amount of oil displaced enables us to calculate the volume of injected gas consumed in each zone. Also, the gas consumed can be calculated from the produced gas to injected gas ratio and the cumulative gas produced. Therefore, the cumulative gas consumed can be calculated.

V. The position of the combustion front can be calculated from the total gas consumed and from the amount of air required to burn one cubic foot of bulk reservoir volume. The area of the burned out region and the areal sweep efficiency then can be estimated.

<u>**VI.**</u> The amount of water <u>generated</u> per one cu. ft. of bulk reservoir volume is estimated by this equation:

$$\delta_{wb} = \frac{18.016 \cdot F_{HC} \cdot m_R}{(12 + F_{HC})\ (2 \times 350.376)} = 0.02571\ \frac{F_{HC} \cdot m_R}{(12 + F_{HC})} \qquad (5.19)$$

Using the cumulative water produced, which is a combination of water displaced from the burned out volume and the water generated from the combustion process, a check of the oil balance can be performed.

The terms in these equations are defined completely in the Table of Nomenclature.

In the above equations, the following need emphasizing:

(1) The fuel content, m_R, is derived from the oil only.

(2) The calculated injected gas requirement does not take into account factors affecting the gas demand such as immobile carbonaceous materials in the reservoir and oxidizing minerals such as iron pyrite.

(3) The water generated by the combustion process must be added to the water displaced from the formation.

(4) Gases generated by other influencing factors such as thermal decomposition of minerals are not accounted for in equation (5.21).

CONCLUSIONS

1) Design of the in-situ combustion process involves experimental evaluation of the process variables in laboratory combustion tubes.

2) The underground combustion reaction of an in-situ combustion process can be described by a general stoichiometric equation.

3) From a consideration of the stoichiometry of the combustion reaction of the underground combustion process, equations can be derived relating carbon dioxide to carbon monoxide ratio, hydrogen to carbon atomic ratio, and oxygen utilization efficiency from the produced gas analysis on a water-free and hydrocarbon-free basis.

4) Applied stoichiometric equations for reservoir calculations are derived from the general stoichiometric equation and the equations mentioned in conclusion # 3. However, the independent variables are the combustion gas analysis and the fuel content.

5) The agreement between the calculated values from stoichiometric equations and the reported values from combustion tube runs differs from one parameter to another in a given data set. However, the stoichiometric equations compare very well where there is a good experimental produced gas analysis.

6) The stoichiometric equations gave excellent agreement in <u>all</u> parameters in 72 of the combustion tube runs, which is 53.0 % of the total combustion tube runs used in this study. In the remaining 47.0 % of the tube runs, the agreement varied depending on the parameter. The most inconsistent variable in the 47.0 % of the data was the F_{HC} varying from very poor to excellent.

7) The stoichiometric equations are also useful in analyzing experimental data for apparent inconsistencies.

8) The stoichiometric analysis is very useful in evaluating in-situ combustion field projects. It indicated that 2740.57 STBO were displaced directly by the combustion process from the Lower Hospah formation of the South Hospah field, McKinley County, NM. The actual production was 2692.00 STBO.

9) Areal sweep efficiency, sweep pattern and other useful information on the mechanics of the combustion project can be calculated.

10) The oil and fuel saturations are critical parameters in evaluating the amount of injected gas required to displace one barrel of oil.

11) The reservoir geology, geometry, layering, permeability variations etc.; all are important factors necessary to successfully evaluate an in-situ combustion project.

RECOMMENDATIONS

The following recommendations were derived from this study and are applicable to future in-situ combustion researches.

1) Reservoir lithology should be accurately described for any carbonaceous material that may affect the produced gas analysis.

2) The experimental evaluation of the produced gas analysis must be for the steady-state burning portion of the combustion tube run for the best evaluation.

3) An accurate reservoir description including geology, geometry, layering, and permeability variations is important in evaluating in-situ combustion projects. All available core and log data should be thoroughly evaluated.

4) Effects of mineralogy changes and clay content should also be studied.

5) In-situ combustion tube tests for carbonate reservoirs should extensively be studied.

6) Studying the in-situ combustion process for well stimulation is highly recommended for future projects.

7) In conducting an in-situ combustion project, the following variables should be carefully monitored:

- The volume of the produced gases (on an individual well basis) from the time of ignition to the end of the combustion project.
- Monitor the produced gas analysis. This information is used to evaluate the steady-state burning conditions.
- The volume of the injected gas and its analysis should also be carefully monitored.

<u>- Laboratory Measurement:</u>

Laboratory measured fuel content corrected to reservoir porosity should be available.

NOMENCLATURE

B_{gi} = formation volume factor of the injected gas at injection pressure and average combustion temperature, cu ft/scf

B_{gp} = formation volume factor of the produced gas at injection pressure and average combustion temperature, cu ft/scf

e_{O2} = oxygen utilization efficiency, fraction

F_{gF} = moles of injected gas per one mole of coke

F_{HC} = atomic hydrogen-to-carbon ratio of fuel

G_b = standard cubic feet of injected gas per one barrel of sand-pack passing through the combustion front

g_{bi} = standard cubic feet of injected gas per one barrel of sand-pack at the injection side

G_{CF} = standard cubic feet of injected gas per cubic foot of sand-pack at the combustion front

G_{CFi} = standard cubic feet of injected gas per cubic foot of sand-pack at the injection side

G_{CFO} = standard cubic feet of injected gas per one barrel of oil displaced at the combustion front

G_F = standard cubic feet of injected gas per one pound of coke

G_i = injected gas

G_{iO} = standard cubic feet of injected gas per one barrel of oil displaced at the injection side

G_{NCF} = standard cubic feet of N_2 injected per cubic foot of sand-pack at the combustion front

G_{NCFO} = standard cubic feet of N_2 injected per one barrel of oil displaced at the combustion front

G_{Ni} = standard cubic feet of N_2 injected per cubic foot of sand-pack at the injection side

G_{NiO} = standard cubic feet of N_2 injected per cubic foot of oil displaced at the injection side

G_{pCF} = standard cubic feet of gas produced at the outlet side of the combustion tube per cubic foot of bulk sand-pack volume burned.

G_{pi} = standard cubic feet of gas produced at the combustion front per cubic foot of injected gas at the front

L = length of sand-pack burned, ft

m = molar ratio of CO_2 to CO in produced gas

m_E = fuel content, lbm coke/ft^3 sand-pack

m_R = fuel content corrected to reservoir porosity, lbm coke/ft^3 reservoir

n_{gF} = moles of injected gas per one pound of coke

p_c = critical pressure, psia

p_E = sand-pack gas injection pressure, psia

p_r = reduced pressure

p_R = reservoir pressure, psia

p_{sc} = atmospheric pressure, psia

S_{FrE} = sand-pack equivalent saturation of fuel, fraction

S_{FrR} = reservoir equivalent saturation of fuel, fraction

S_o = oil saturation, fraction

T_c = critical temperature, °F

T_E = sand-pack average combustion temperature, °F

T_r = reduced temperature

T_R = reservoir temperature, °F

T_{sc} = temperature at standard conditions, °F

u_{Ef} = sand-pack injected gas flux at the combustion front, $scf/hr\text{-}ft^2$

u_{Ei} = sand-pack injected gas flux at the injection side, $scf/hr\text{-}ft^2$

u_{Rf} = reservoir injection gas flux at the combustion front, $scf/hr\text{-}ft^2$

u_{Ri} = reservoir injection gas flux at the injection well, $scf/hr\text{-}ft^2$

v_b = velocity of the combustion front, ft/hr

V_E = volume of injected gas at sand-pack operating conditions, ft^3

V_R = volume of injected gas at reservoir operating conditions, ft^3

V_{sc} = volume of injected at standard conditions, scf

y_{iN2} = mole fraction of nitrogen in the injected gas

y_{iO2} = mole fraction of oxygen in the injected gas

y_{pCO} = mole fraction of CO in the produced gas

y_{pCO2} = mole fraction of CO_2 in the produced gas

y_{pN2} = mole fraction of N_2 in the produced gas

y_{pO2} = mole fraction of O_2 in the produced gas

Z = gas compressibility factor

δ_{wb} = barrels of water generated per one cubic foot of sand-pack burned

ρ_o = density of oil, lbm/ft^3

ϕ_E = sand-pack porosity, fraction

ϕ_R = reservoir porosity, fraction

$\tilde{}$ = refers to the normalized value

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APPENDIX A

DERIVATION OF THE STOICHIOMETRIC EQUATIONS

The Stoichiometry of the Combustion Reaction

The coke or fuel laid down on the sand grains can be represented as $(CH_{F_{HC}})_x$. By considering only one unit of coke, i.e. $CH_{F_{HC}}$, where:

F_{HC} = hydrogen to carbon atomic ratio

the stoichiometric reaction is represented by:

$$CH_{F_{HC}} + O_2 \longrightarrow CO_2 + CO + H_2O$$

This equation needs to be balanced:

1. Consider only one unit of coke, i.e. $CH_{F_{HC}}$

2. Since hydrogen appears only once on either sides of the equation, then balance it first. Thus, number of moles of water will be $\frac{F_{HC}}{2} H_2O$

3. The steps for balancing oxygen are as follows:

a. Let m = ratio of moles of CO_2 to CO produced, i.e. $m = \frac{CO_2}{CO}$. For dry combustion, all the coke laid down is burned, so if there is one mole of CO, then there should be m moles of CO_2, i.e. total moles of CO and CO_2 is (1 + m) moles. Thus,

- $moles\ of\ CO = \frac{1}{1+m}$

- $moles\ of\ CO_2 = \frac{m}{1+m}$

b. If there is $\frac{1}{1+m}$ moles of CO, then there should be $\frac{1}{1+m}$ oxygen atoms in it.

c. If there is $\frac{m}{1+m}$ moles of CO_2, then there should be $\frac{2m}{1+m}$ oxygen atoms in it.

d. If there is $\frac{F_{HC}}{2}$ moles of H_2O, then there should be $\frac{F_{HC}}{2}$ oxygen atoms in it.

e. Thus, the total oxygen atoms = $\left(\frac{1}{1+m}+\frac{2m}{1+m}+\frac{F_{HC}}{2}\right)$

f. To make one molecule of oxygen, divide the whole term by two, i.e. $\left(\frac{1}{2+2m}+\frac{2m}{2+2m}+\frac{F_{HC}}{4}\right)$. Thus, the oxygen molecules per one unit of coke = $\left(\frac{1+2m}{2+2m}+\frac{F_{HC}}{4}\right)$

Thus, the combustion reaction is represented by

$$CH_{F_{HC}} + \left(\frac{1+2m}{2+2m}+\frac{F_{HC}}{4}\right) O_2 \longrightarrow \left(\frac{m}{1+m}\right) CO_2 + \left(\frac{1}{1+m}\right) CO + \left(\frac{F_{HC}}{2}\right) H_2O$$

4. If air is used instead of pure oxygen, then the number of moles of air for every mole of coke burned should be equal to:

$$\left(\frac{1}{(0.21).(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)$$

Where:

0.21 is the mole fraction of oxygen in the air

e_{O_2} is oxygen utilization efficiency

5. If any injected gas is used instead of air, and the mole fraction of oxygen is y_{iO2}, then the number of moles of injected gas for every mole of coke burned is

$$\left(\frac{1}{(y_{iO_2}).(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right) G_i$$

G_i denotes any injected gas

6. If the mole fraction of nitrogen in the injected gas is y_{iN2}, then the number of moles of nitrogen that passes through the combustion zone is

$$\left(\frac{y_{i_{N_2}}}{(y_{iO_2}).(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)$$

7. It is assumed that nitrogen is completely inert in the reaction and that none is accumulated in the sand-pack during the burning run. This means that the amount of nitrogen injected equals to the amount produced. Thus the number of moles of nitrogen produced is

$$\left(\frac{y_{i_{N_2}}}{(y_{iO_2}).(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)$$

8. If the combustion reaction is not complete, then there should be some oxygen produced which is equal to the total number of moles of oxygen minus the number of moles consumed.

Total number of moles of oxygen = $\left(\frac{1}{e_{O_2}}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)$, Moles of oxygen consumed = $\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)$, thus the number of

moles of produced oxygen is

$$\left(\frac{1}{e_{O_2}}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right) - \left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right) = \left(\frac{1}{e_{O_2}}-1\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)$$

Thus the general stoichiometric equation can be written as follows:

$$CH_{F_{HC}}+\left(\frac{1}{(y_{io_2})\cdot(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)G_i \longrightarrow \left(\frac{m}{m+1}\right)CO_2+\left(\frac{1}{m+1}\right)CO$$

$$+\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{e_{O_2}}-1\right)O_2+\left(\frac{y_{i_{N_2}}}{y_{io_2}\cdot e_{O_2}}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)N_2+\left(\frac{F_{HC}}{2}\right)H_2O$$

Where:

CHF_{HC} = Unit molecular weight of fuel

y_{iO2} = mole fraction of oxygen in the injected gas

y_{iN2} = mole fraction of nitrogen in the injected gas

y_{pO2} = mole fraction of oxygen in the produced gas

y_{pN2} = mole fraction of nitrogen in the produced gas

y_{pCO_2} = mole fraction of carbon dioxide in the produced gas

y_{pCO} = mole fraction of carbon monoxide in the produced gas

$$m = \frac{y_{pco_2}}{y_{pco}}$$

$$F_{HC} = \frac{H}{C} \quad \textit{atomic ratio}$$

e_{O_2} = *oxygen utilization efficiency*

The produced gas analysis is always on a water-free basis.

For the general situation where the injected gas consists of any composition of oxygen and nitrogen:

$$1.\ m = \frac{y_{pco_2}}{y_{pco}}$$

2. $$F_{HC} = \frac{4\cdot\left(\dfrac{y_{iO_2}}{y_{i_{N_2}}}\right)+2\cdot y_{pCO}-\left(4\cdot\dfrac{y_{iO_2}}{y_{i_{N_2}}}+4\right)\left(y_{pO_2}+y_{pCO}+y_{pCO_2}\right)}{y_{pCO_2}+y_{pCO}}$$

3. $$e_{O_2} = 1-\frac{y_{i_{N_2}}}{y_{iO_2}}\cdot\frac{y_{pO_2}}{y_{pN_2}}$$

For the situation where the injected gas is pure oxygen:

1. $y_{iO_2} = 1.0$

2. $y_{i_{N_2}} = 0.0$

3. $$m = \frac{y_{pCO_2}}{y_{pCO}}$$

4. $$F_{HC} = \frac{4\ \cdot\ (1-y_{pO_2}-0.5y_{pCO}-y_{pCO_2})}{y_{pCO_2}+y_{pCO}}$$

5. $e_{O_2} = 1-y_{pO_2}$

Derivation of H/C atomic ratio

Since $F_{HC} = \frac{H}{C}$, therefore:

1. atoms of carbon = $y_{pCO_2} + y_{pCO}$

2. atoms of hydrogen can be found as follows:

a. moles of oxygen used in combustion = oxygen injected - oxygen produced

oxygen injected = $y_{iO_2} \cdot \frac{y_{pN_2}}{y_{i_{N_2}}}$

oxygen produced = y_{pO_2} thus,

moles of oxygen used in combustion = $\left(y_{iO_2} \cdot \frac{y_{pN_2}}{y_{i_{N_2}}} - y_{pO_2}\right)$

b. moles of oxygen in the produced water =

$$\left(\frac{y_{iO_2}}{y_{i_{N_2}}} \cdot y_{pN_2} - y_{pO_2} - 0.5y_{pCO} - y_{pCO_2}\right)$$

c. for every mole of oxygen, there are two moles of water, thus the number of moles of water =

$$2 \times \left(\frac{y_{iO_2}}{y_{i_{N_2}}} \cdot y_{pN_2} - y_{pO_2} - 0.5 y_{pCO} - y_{pCO_2} \right)$$

d. for every mole of water, there are two atoms of hydrogen, thus the number of atoms of hydrogen =

$$4 \times \left(\frac{y_{iO_2}}{y_{i_{N_2}}} \cdot y_{pN_2} - y_{pO_2} - 0.5 y_{pCO} - y_{pCO_2} \right)$$

Realizing that $y_{p_{N_2}} = \left[1 - \left(y_{pO_2} + y_{pCO} + y_{pCO_2}\right)\right]$

the general equation of F_{HC} can be written as:

$$F_{HC} = \frac{4 \cdot \left(\frac{y_{iO_2}}{y_{i_{N_2}}} \right) + 2 \cdot y_{pCO} - \left(4 \cdot \frac{y_{iO_2}}{y_{i_{N_2}}} + 4 \right) \left(y_{pO_2} + y_{pCO} + y_{pCO_2} \right)}{y_{pCO_2} + y_{pCO}}$$

For air, substitute $y_{iO2} = 0.21$ and $y_{iN2} = 0.79$

For pure oxygen injection, i.e. $y_{iO2} = 1.0$, the above equation blows up.

Derivation of H/C ratio for pure oxygen injection

$$\because\ F_{HC} = \frac{4\left(\dfrac{y_{iO_2}}{y_{i_{N_2}}} y_{pN_2}\right) - 4y_{pO_2} - 2y_{pCO} - 4y_{pCO_2} - 2y_{pCO} + 2y_{pCO}}{y_{pCO_2} + y_{pCO}}$$

therefore, taking the limit of F_{HC} as $y_{iN2} \longrightarrow 0.0$, yields

$$\lim_{y_{i_{N_2}} \to 0} F_{HC} = \lim_{y_{i_{N_2}} \to 0} \frac{4\left(\dfrac{y_{iO_2}}{y_{i_{N_2}}} y_{pN_2}\right) - 4y_{pO_2} - 2y_{pCO} - 4y_{pCO_2} - 2y_{pCO} + 2y_{pCO}}{y_{pCO_2} + y_{pCO}}$$

$$= \frac{4y_{iO_2} - 4y_{pO_2} - 2\,y_{pCO} - 4y_{pCO_2} - 2y_{pCO} + 2y_{pCO}}{y_{pCO_2} + y_{pCO}}$$

$$= \frac{4\left(y_{iO_2} - y_{pO_2} - 0.5\,y_{pCO} - y_{pCO_2}\right)}{y_{pCO_2} + y_{pCO}}$$

$$= \frac{4\left(1 - y_{pO_2} - 0.5\,y_{pCO} - y_{pCO_2}\right)}{y_{pCO_2} + y_{pCO}}$$

Derivation of oxygen utilization efficiency

Assuming one mole of dry combustion gas, i.e.:

$$y_{pN_2} + y_{pCO} + y_{pCO_2} + y_{pO_2} = 1.0$$

1. total moles of oxygen in the injected gas = $\dfrac{y_{iO_2}}{y_{i_{N_2}}} y_{pN_2}$

2. moles of nitrogen associated with oxygen used in combustion

$$= \left(y_{pN_2} - \frac{y_{i_{N_2}}}{y_{iO_2}} y_{pO_2} \right)$$

3. moles of oxygen used in combustion = $\dfrac{y_{iO_2}}{y_{i_{N_2}}} \left(y_{pN_2} - \dfrac{y_{i_{N_2}}}{y_{iO_2}} y_{pO_2} \right)$

$$= \frac{y_{iO_2}}{y_{i_{N_2}}} y_{pN_2} - y_{pO_2}$$

4. $\because e_{O_2} = \dfrac{\textit{moles of consumed oxygen}}{\textit{total moles of oxygen}}$

$$\therefore\ e_{O_2} = \frac{\dfrac{y_{iO_2}}{y_{i_{N_2}}} y_{pN_2} - y_{pO_2}}{\dfrac{y_{iO_2}}{y_{i_{N_2}}} y_{pN_2}}$$

Thus, the oxygen utilization efficiency can be written as follows:

$$e_{O_2} = 1 - \frac{y_{i_{N_2}}}{y_{iO_2}} \cdot \frac{y_{pO_2}}{y_{pN_2}}$$

Derivation of oxygen utilization efficiency for pure oxygen injection

$$\because e_{O_2} = 1 - \frac{y_{i_{N_2}}}{y_{iO_2}} \cdot \frac{y_{pO_2}}{y_{pN_2}}$$

This equation blows up for pure oxygen injection, i.e. when $y_{iO2} = 1.0$. By taking the limit of e_{O2} as $y_{iN2} \longrightarrow 0.0$, the equation becomes:

$$\lim_{y_{i_{N_2}} \to 0} e_{O_2} = \lim_{y_{i_{N_2}} \to 0} \left[1 - \frac{y_{i_{N_2}}}{y_{iO_2}} \cdot \frac{y_{pO_2}}{y_{pN_2}} \right] = 1 - y_{pO_2}$$

STOICHIOMETRIC EQUATIONS

Stoichiometric Equations For Experimental Tubes

By considering the general stoichiometric equation, the applied equations are derived fairly easy:

1. Moles of injected gas per one mole of coke burned is

$$F_{gF} = \left(\frac{1}{(y_{iO_2})\,(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)$$

2. Moles of injected gas per one pound of coke burned is

$$n_{gF} = \left(\frac{1}{(y_{iO_2})\,(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right)$$

3. Scf of injected gas per one pound of coke burned equals

$$G_F = \left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right)$$

4. Scf of injected gas per cu.ft. of sand-pack at the combustion front can be found as follows

$$G_{CF} = \left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E$$

5. To convert to standard cubic feet of injected gas per cu.ft. of sand-pack at the injection side of the tube, one must add $\frac{\Phi_E}{B_{gi}}$ to G_{CF} to take care of the injected gas stored in the burned out area.

Where:

ϕ_E = porosity of sand-pack,

B_{gi} = formation volume factor of the injected gas which can be calculated as follows:

$$B_{gi} = \frac{V_E}{V_{sc}} = \frac{T_E \times Z}{T_{sc}} \times \frac{p_{sc}}{p_E}$$

Z may be calculated as follows:

a. Gases in the zone are oxygen and nitrogen

b. Calculate T_c and p_c:

Comp.	y_i	T_c	p_c	y_iT_c	y_ip_c
O_2	y_{iO2}	278.8	736.9	$(278.8)(y_{iO2})$	$(736.9)(y_{iO2})$
N_2	y_{iN2}	227.3	493.0	$(227.3)(y_{iN2})$	$(493.0)(y_{iN2})$
				Σ T_c	p_c

c. Calculate T_r and p_r

$$T_r = \frac{(T_E+460)}{T_c} \qquad p_r = \frac{p_E}{p_c}$$

d. Knowing T_r, and p_r determine Z

6. Knowing the desired velocity of the combustion front, v_b, the gas flux at a point in the combustion front is

$$u_{Ef} = \left(\frac{(10.732)(T_{sc}+460)}{(y_{iO_2})(e_{O_2})(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E \cdot v_b$$

7. Gas flux at the injection side = u_{Ei}

$$u_{Ei} = \left[\left(\frac{(10.732)(T_{sc}+460)}{(y_{iO_2})(e_{O_2})(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E + \frac{\phi_E}{B_{gi}}\right] \cdot v_b$$

or if the injection gas flux is known, u_{Ei}, then solve for v_b

$$v_b = \frac{u_{Ei}}{\left[\left(\frac{(10.732)(T_{sc}+460)}{(y_{iO_2})(e_{O_2})(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E + \frac{\phi_E}{B_{gi}}\right]}$$

8. Scf of injected gas per one barrel of oil displaced at the combustion front is calculated from

$$G_{CFO} = \left(\frac{(10.732)(T_{sc}+460)}{(y_{iO_2})(e_{O_2})(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{5.615}{12+F_{HC}}\right)\left(\frac{m_E}{\phi_E(S_o - S_{FrE})}\right)$$

Where $S_{FrE} = \dfrac{m_E}{\phi_E \rho_o}$

9. The standard cubic feet of injected gas per one barrel of oil displaced at the injection side equals

$$G_{io} = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E + \frac{\Phi_E}{B_{gi}}\right] \times$$

$$\left[\frac{5.615}{\Phi_E(S_o - S_{FrE})}\right]$$

10. Since one mole of coke generates $\frac{F_{HC}}{2}$ moles of H_2O, thus

$18.016\ \frac{F_{HC}}{2} \cdot \frac{1}{350.376}$ bbl of H_2O are generated per one mole

of coke burned. Thus barrels of water generated per one cu.ft. of bulk sand-pack volume burned is

$$\delta_{wb} = \frac{18.016\ .\ F_{HC}\ .\ m_E}{(12 + F_{HC})\ (2\times 350.376)} = 0.02571\ \frac{F_{HC}\ .\ m_E}{(12 + F_{HC})}$$

11. Standard cubic feet of gas produced at the combustion front per standard cubic foot of gas injected at the combustion front can be calculated as follows:

a. since number of moles of injected gas passing through the combustion front is $\left(\frac{1}{(y_{iO_2}).(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)$, and

b. number of moles of produced gas passing through the combustion front equals:

$$\left(\frac{m}{m+1}\right)+\left(\frac{1}{m+1}\right)+\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{e_{O_2}}-1\right)+\left(\frac{y_{i_{N_2}}}{(y_{iO_2})\ (e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right) =$$

$$1+\left[\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right]\left[\left(\frac{1}{e_{O_2}}-1\right)+\left(\frac{y_{i_{N_2}}}{(y_{iO_2})\ (e_{O_2})}\right)\right] =$$

$$1+\left[\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right]\left[\frac{1}{e_{O_2}}\left(1-e_{O_2}+\frac{y_{i_{N_2}}}{y_{iO_2}}\right)\right]$$

Thus, the standard cubic feet of gas produced at the combustion front per standard cubic foot of gas injected at the front is given by:

$$G_{p_i} = \frac{1 + \left[\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right]\left[\frac{1}{e_{O_2}}\left(1 - e_{O_2} + \frac{y_{i_{N_2}}}{y_{iO_2}}\right)\right]}{\left(\frac{1}{(y_{iO_2})\ (e_{O_2})}\right)\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)} =$$

$$\left[\frac{(y_{iO_2})\ (e_{O_2})}{\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)}\right] + \left[1 - (y_{iO_2})\ (e_{O_2})\right]$$

12. standard cubic feet of produced gas at the outlet side of the combustion tube per cu. ft. of bulk sand-pack volume burned is calculated as follows:

$$\because\ G_{pCF} = \left[G_{CF}\ .\ G_{p_i}\right] + \left[\frac{(\phi_E)\ (1 - S_o)}{B_{gp}}\right]$$

$$\therefore\ G_{pCF} = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_E\right] \times$$

$$\left[\left(\frac{(y_{iO_2})\ (e_{O_2})}{\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)}\right) + \left(1 - (y_{iO_2})\ (e_{O_2})\right)\right] + \left[\frac{(\phi_E)\ (1 - S_o)}{B_{pg}}\right]$$

Where:

B_{gp} = formation volume factor of produced gas which can be calculated as follows:

$$B_{gp} = \frac{V_E}{V_{sc}} = \frac{T_E \times Z}{T_{sc}} \times \frac{p_{sc}}{p_E}$$

Z may be calculated as follows:

a. Gases in the zone are O_2, N_2, CO_2, CO

b. Calculate T_c and p_c:

Comp.	y_p	T_c	p_c	$y_i T_c$	$y_i p_c$
O_2	y_{pO2}	278.8	736.9	$(278.8)(y_{pO2})$	$(736.9)(y_{pO2})$
N_2	y_{pN2}	227.3	493.0	$(227.3)(y_{pN2})$	$(493.0)(y_{pN2})$
CO_2	y_{pCO2}	547.87	1071	$(547.87)(y_{pCO2})$	$(1071)(y_{pCO2})$
CO	y_{pCO}	239.59	507.5	$(239.59)(y_{pCO})$	$(507.5)(y_{pCO})$
				Σ T_c	p_c

c. Calculate T_r and p_r:

$$T_r = \frac{(T_E+460)}{T_c} \qquad p_r = \frac{p_E}{p_c}$$

d. Knowing T_r, and p_r determine Z

Stoichiometric Equations For Reservoir Calculations

The previous stoichiometric equations for experimental tubes are general equations and can be applied to reservoir calculations after correcting the laboratory determined fuel content to reservoir porosity (assuming all other controlling factors such as lithology and shaliness are the same) by:

$$m_R = m_E \cdot \left(\frac{1-\phi_R}{1-\phi_E}\right)$$

where:

ϕ_R = reservoir porosity

ϕ_E = sand-pack porosity

m_E = sand-pack fuel content

m_R = fuel content corrected to reservoir porosity

After making this correction, all experimental stoichiometric equations are applied to reservoir calculations exactly the same way by replacing the sand-pack parameters by reservoir parameters.

APPENDIX B

LIST OF THE DRY IN-SITU COMBUSTION PROGRAM

```
START:
REM ********************* Introduction *********************
CLS : CLEAR , , 2000
LOCATE 10, 16
PRINT "Dry In-Situ Combustion Reservoir Simulator, 1989"
LOCATE 11, 16: PRINT "--------------------------------------"
LOCATE 14, 39: PRINT "By"
LOCATE 16, 31: PRINT "Fred H. Poettmann"
LOCATE 18, 38: PRINT "And"
LOCATE 20, 31: PRINT "Hassan S. A. Naji"
LOCATE 23, 26: PRINT "Press any key to continue..."
DO
LOOP WHILE INKEY$ = ""
REM ******************  End Introduction  ******************
REM
REM ********************* Nomenclature *********************
REM
REM BGi         Injected gas formation volume factor
REM BGp         Produced gas formation volume factor
REM CHFHC       Unit molecular weight of coke (fuel).
REM
REM                                          yiN2   ypO2
REM eO2 Oxygen utilization efficiency = 1 - ---- * ----
REM                                          yiO2   ypN2
REM
REM eO2 Oxygen utilization efficiency= 1 - ypO2  for 100 % O2
REM
REM                    yiO2          yiO2
REM                  4(----)+ypCO-(4(----)+4)(ypO2+ypCO+ypCO2)
REM                    yiN2          yiN2
REM FHC H/C ratio = ---------------------------------------
REM                               (ypCO+ypCO2)
REM
REM                    4(yiO2-ypO2-0.5(ypCO)-ypCO2)
REM FHC H/C ratio= ----------------------------  for 100 % O2
REM                          (ypCO + ypCO2)
REM
REM ID          Inside diameter of combustion tube, ft
REM L           Length of combustion tube, ft
REM             ypCO2
REM m           -----
REM             ypCO
REM ME          Fuel consumption, lbs/cu ft of sand pack.
REM MR          Fuel consumption, lbs/cu ft of reservoir.
REM PHIE        Porosity of sand pack
REM PHIR        Reservoir porosity
REM Pr          Reduced temperature, °F
REM PRES        Reservoir pressure, psia
```

```
REM Psc         Pressure at standard conditions, psia
REM SFrE       Oil saturation consumed as fuel in sand pack
REM SFrR       Oil saturation consumed as fuel in reservoir
REM So         Oil saturation
REM TE        Average combustion temperature of sand pack, °F
REM Tr         Reduced temperature, °F
REM TRES      Average combustion temperature of reservoir, °F
REM Tsc        Temperature at standard conditions, °F
REM UE Gas flux at a point in the combustion front, Scf/hr/ft²
REM UiE          Injection gas flux, scf/hr/ft²
REM Vb The point velocity of the combustion front, ft/hr.
REM yiN2         Mole fraction of N2 in the injected gas.
REM yiO2         Mole fraction of O2 in the injected gas.
REM ypCO         Mole fraction of CO in the produced gas.
REM ypCO2        Mole fraction of CO2 in the produced gas.
REM ypN2         Mole fraction of N2 in the produced gas.
REM ypO2         Mole fraction of O2 in the produced gas.
REM Z            Gas compressibility factor
REM
REM *****************  End Nomenclature  *******************
REM
REM ***********************  Input data *********************
REM
700
CLS : CLEAR , , 2000
PRINT "Keyboard or Disk data input (K,D) : "
AGAIN1:
A$ = INKEY$
IF A$ = "K" OR A$ = "k" THEN GOTO KEYBOARD
IF A$ = "D" OR A$ = "d" THEN GOTO DISK ELSE GOTO AGAIN1
KEYBOARD:
REM ***************** REFERENCE DATA ************************
REM
CLS
PRINT "Please input the following data for reference : "
LOCATE 5, 1: PRINT "Reference title  : "
LOCATE 10, 1: PRINT "Reference number : "
LOCATE 15, 1: PRINT "Author(s)        : "
        LOCATE 20, 1: PRINT "Publisher        : "
        LOCATE 5, 20: LINE INPUT RT$
        LOCATE 10, 20: LINE INPUT RN$
        LOCATE 15, 20: LINE INPUT AUS$
        LOCATE 20, 20: LINE INPUT PUB$
REM ************************* END *************************
REM
REM ****************** COMBUSTION TUBE DATA ****************
REM
        CLS
```

```
PRINT "Input the following data for the combustion tube : "
        LOCATE 5, 1: PRINT "Inside diameter, in. : "
        LOCATE 10, 1: PRINT "Length of sand pack, in. : "
        LOCATE 5, 24: INPUT ID: ID = ID / 12
        LOCATE 10, 28: INPUT L: L = L / 12
BEGIN:
        GOSUB INITIALIZE
        CLS
        INPUT "Run no. : ", RUN$
REM ************************* END ***************************
REM
        CLS
        PRINT "Composition of the injected gas : "
        LOCATE 2, 1: PRINT "--------------------------------"
LOCATE 5, 1: INPUT "Mole % of O2 in the injected gas : ", yiO2
        yiO2 = yiO2 / 100: yiN2 = 1 - yiO2
        CLS
        PRINT "Composition of produced gas :"
        LOCATE 2, 1: PRINT "-----------------------------"
        LOCATE 5, 1: PRINT "Mole % of CO2 : "
        LOCATE 10, 1: PRINT "Mole % of CO : "
        LOCATE 15, 1: PRINT "Mole % of O2 : "
LOCATE 20, 1: PRINT "Mole % of N2 (ENTER if none) : "
        LOCATE 5, 17: INPUT ypCO2: ypCO2 = ypCO2 / 100
        LOCATE 10, 16: INPUT ypCO: ypCO = ypCO / 100
        LOCATE 15, 16: INPUT ypO2: ypO2 = ypO2 / 100
        LOCATE 20, 32: INPUT ypN2: ypN2 = ypN2 / 100
        IF ypN2 = 0 THEN GOTO CHECK1 ELSE GOTO NORMALIZE
CHECK1:
        IF yiN2 = 0 THEN GOTO CHECK2 ELSE GOTO CHECK3
CHECK2:
        ypN2 = 0
        GOTO NORMALIZE
CHECK3:
        ypN2 = 1 - (ypCO2 + ypCO + ypO2)
NORMALIZE:
        SUM = (ypCO2 + ypCO + ypO2 + ypN2)
ypCO2 = ypCO2 / SUM: ypCO = ypCO / SUM: ypO2 = ypO2 / SUM:
ypN2 = ypN2 / SUM
        CLS
        PRINT "Surface temperature, °F (default 60 °F) : "
LOCATE 3, 1: PRINT "Atmospheric pressure, psia (default 14.7
psia) : "
        LOCATE 5, 1: PRINT "Sand pack average burning
temperature, °F : "
        LOCATE 7, 1: PRINT "Injection pressure, psig : "
        LOCATE 9, 1: PRINT "Fuel consumed per cu. ft. of sand
pack burned, lb./cuft : "
```

```
        LOCATE 11, 1: PRINT "Injection gas flux, scf/hr-sqft
(Enter if none) : "
        LOCATE 15, 1: PRINT "Sand pack porosity % : "
        LOCATE 17, 1: PRINT "Oil saturation % : "
LOCATE 19, 1: PRINT "Oil density, lbs/cu ft (Enter if none) :
"
        LOCATE 1, 43: INPUT Tsc: IF Tsc = 0 THEN Tsc = 520
ELSE Tsc = Tsc + 460
        LOCATE 3, 50: INPUT Psc: IF Psc = 0 THEN Psc = 14.7
        LOCATE 5, 45: INPUT TE: TE = TE + 460
        LOCATE 7, 28: INPUT PE: PE = PE + Psc
        LOCATE 9, 59: INPUT ME
        LOCATE 11, 51: INPUT UiE
        IF UiE = 0 THEN 710 ELSE 810
710       LOCATE 11, 1: PRINT "Input the desired rate of
combustion front advance (ft/hr) : "
        LOCATE 11, 62: INPUT Vb
        IF Vb = 0 THEN 720 ELSE 810
720     LOCATE 13, 15: PRINT "Please specify either flux or
desired velocity ..!"
        LOCATE 11, 1: PRINT "Injection gas flux, scf/hr-sqft
(Enter if none) :             "
        LOCATE 11, 51: INPUT UiE
        IF UiE = 0 THEN 710
810
        LOCATE 13, 15: PRINT "
                    "
        LOCATE 15, 24: INPUT PHIE: PHIE = PHIE / 100
        LOCATE 17, 20: INPUT So: So = So / 100
130     LOCATE 19, 42: INPUT RHOO
        IF RHOO = 0 THEN 70
        SG = RHOO / 62.4: API = (141.5 / SG) - 131.5: GOTO
CALCULATIONS
70
        LOCATE 19, 1: INPUT "Oil Specific Gravity (water = 1)
(Enter in none) : ", SG
        IF SG = 0 THEN 90
        RHOO = 62.4 * SG: API = (141.5 / SG) - 131.5: GOTO
CALCULATIONS
90
        LOCATE 19, 1: PRINT "Oil °API :
                   "
        LOCATE 19, 12: INPUT API
        IF API = 0 THEN 110
        SG = 141.5 / (131.5 + API): RHOO = 62.4 * SG: GOTO
CALCULATIONS
110
        LOCATE 21, 8
```

```
        PRINT "Please, you must input either density, specific
gravity, or °API"
        LOCATE 19, 1: PRINT "Oil density, lbs/cu ft (Enter if
none) : "
        GOTO 130
CALCULATIONS:
REM ************ Applied Stoichiometric Equations ***********
        REM
        CLS
        LOCATE 5, 1
        PRINT "To have the applied stoichiometric equations
calculated for you, you": PRINT
        PRINT "must input the following reservoir properties:
"
        LOCATE 10, 15: PRINT "1. Reservoir Porosity"
        LOCATE 12, 15: PRINT "2. Reservoir Pressure"
        LOCATE 14, 15: PRINT "3. Reservoir Average Combustion
Temperature"
        LOCATE 17, 1
        PRINT "Would you like to have them calculated (Y/N) :"
AGAIN20:
        A20$ = INKEY$
        IF A20$ = "Y" OR A20$ = "y" THEN 920 ELSE GOTO 910
910     IF A20$ = "N" OR A20$ = "n" THEN GOTO EXPER ELSE GOTO
AGAIN20
920     CLS
        FLAG$ = "Y"
        LOCATE 5, 1: PRINT "Reservoir Porosity (%) : "
        LOCATE 10, 1: PRINT "Reservoir Pressure (psia) : "
        LOCATE 15, 1: PRINT "Reservoir Average Combustion
Temperature (°F) : "
        LOCATE 5, 26: INPUT PHIR: PHIR = PHIR / 100
        LOCATE 10, 29: INPUT PRES
        LOCATE 15, 49: INPUT TRES: TRES = TRES + 460
EXPER:
REM ****************** Experimental Data ******************
        CLS
        PRINT "Experimental data input for comparison
purposes. Hit ENTER if not available.."
P               R               I               N               T
"-------------------------------------------------------------
------------------": PRINT : PRINT
        INPUT "H/C ratio 'FHC' : ", EFHC$: PRINT
        IF VAL(EFHC$) = 0 THEN EFHC$ = "not available"
        INPUT "Oxygen utilization Efficiency 'eO2' : ", EeO2$:
PRINT
        IF VAL(EeO2$) = 0 THEN EeO2$ = "not available"
```

```
        INPUT "SCF of injected gas / pound coke : ",
ESCFIGPPC$: PRINT
        IF VAL(ESCFIGPPC$) = 0 THEN ESCFIGPPC$ = "not
available"
        INPUT "SCF of injected gas / CF sand pack : ",
ESCFIGPCFSP$: PRINT
        IF VAL(ESCFIGPCFSP$) = 0 THEN ESCFIGPCFSP$ = "not
available"
        INPUT "Velocity of the combustion front : ", EVb$:
PRINT
        IF VAL(EVb$) = 0 THEN EVb$ = "not available"
        INPUT "Bbl of water / CF sand pack burned : ",
EBWPCFSPB$: PRINT
        IF VAL(EBWPCFSPB$) = 0 THEN EBWPCFSPB$ = "not
available"
        INPUT "SCF of effluent gas / CF injected gas : ",
ESCFEGPCFIG$: PRINT
        IF VAL(ESCFEGPCFIG$) = 0 THEN ESCFEGPCFIG$ = "not
available"
        CLS
        FILES "THESIS.*"
        LOCATE 23, 1
        INPUT "Output file name : THESIS.", FILEN$
        OPEN "THESIS." + FILEN$ FOR OUTPUT AS #1
        PRINT #1, EFHC$
        PRINT #1, EeO2$
        PRINT #1, ESCFIGPPC$
        PRINT #1, ESCFIGPCFSP$
        PRINT #1, EVb$
        PRINT #1, EBWPCFSPB$
        PRINT #1, ESCFEGPCFIG$
        PRINT #1, RT$
        PRINT #1, RN$
        PRINT #1, AUS$
        PRINT #1, PUB$
        PRINT #1, ID
        PRINT #1, L
        PRINT #1, RUN$
        PRINT #1, yiO2
        PRINT #1, yiN2
        PRINT #1, ypCO2
        PRINT #1, ypCO
        PRINT #1, ypO2
        PRINT #1, ypN2
        PRINT #1, Tsc
        PRINT #1, Psc
        PRINT #1, TE
        PRINT #1, PE
```

```
        PRINT #1, ME
        PRINT #1, UiE
        PRINT #1, Vb
        PRINT #1, PHIE
        PRINT #1, So
        PRINT #1, RHOO
        PRINT #1, API
        PRINT #1, SG
        PRINT #1, FLAG$
        PRINT #1, PHIR
        PRINT #1, PRES
        PRINT #1, TRES
        CLOSE #1
        GOTO 900
DISK:
        GOSUB INITIALIZE
        CLS
        FILES "THESIS.*"
        LOCATE 23, 1
        INPUT "Input file name THESIS.", FILEN$
        OPEN "THESIS." + FILEN$ FOR INPUT AS #1
        IF EOF(1) THEN GOTO 900
        LINE INPUT #1, EFHC$
        LINE INPUT #1, EeO2$
        LINE INPUT #1, ESCFIGPPC$
        LINE INPUT #1, ESCFIGPCFSP$
        LINE INPUT #1, EVb$
        LINE INPUT #1, EBWPCFSPB$
        LINE INPUT #1, ESCFEGPCFIG$
        LINE INPUT #1, RT$
        LINE INPUT #1, RN$
        LINE INPUT #1, AUS$
        LINE INPUT #1, PUB$
        INPUT #1, ID
        INPUT #1, L
        LINE INPUT #1, RUN$
        INPUT #1, yiO2
        INPUT #1, yiN2
        INPUT #1, ypCO2
        INPUT #1, ypCO
        INPUT #1, ypO2
        INPUT #1, ypN2
        INPUT #1, Tsc
        INPUT #1, Psc
        INPUT #1, TE
        INPUT #1, PE
        INPUT #1, ME
        INPUT #1, UiE
```

```
        INPUT #1, Vb
        INPUT #1, PHIE
        INPUT #1, So
        INPUT #1, RHOO
        INPUT #1, API
        INPUT #1, SG
        INPUT #1, FLAG$
        INPUT #1, PHIR
        INPUT #1, PRES
        INPUT #1, TRES
        CLOSE #1
        REM
900
REM ******************* Calculations ***********************
        REM
        M = ypCO2 / ypCO
        IF yiO2 = 1 THEN
        FHC = (4 * (yiO2 - ypO2 - (.5 * ypCO) - ypCO2)) /
(ypCO + ypCO2): eO2 = 1 - ypO2: GOTO 40
        ELSE
        FHC = ((4 * (yiO2 / yiN2)) + (2 * ypCO) - (((4 * (yiO2
/ yiN2)) + 4) * (ypO2 + ypCO + ypCO2))) / (ypCO + ypCO2)
        eO2 = 1 - ((yiN2 / yiO2) * (ypO2 / ypN2))
        END IF
40
        REM                             2 m + 1    FHC
        REM Moles of oxygen = MO2 = ------- + ----
        REM                             2 m + 2     4
        MO2 = (((2 * M) + 1) / ((2 * M) + 2)) + (FHC / 4)
        REM
        REM Weight of coke = WOC = 12 + FHC
        REM
        WOC = 12 + FHC
        REM Moles of injected gas per one mole of coke =
MIGPMC
        MIGPMC = (1 / (yiO2 * eO2)) * MO2
        REM Moles of injected gas per one pound coke =
MIGPPC
        MIGPPC = MIGPMC / WOC
        REM SCF of injected gas per one pound coke = SCFIGPPC
        SCFIGPPC = ((10.732 * Tsc) / Psc) * MIGPPC
        REM SCF of injected gas per one cu ft sand pack at the
front = SCFIGPCFSPAF
        SCFIGPCFSPAF = SCFIGPPC * ME
        REM SCF of injected gas per one cu ft sand pack at the
injection side = SCFIGPCFSPAI
        Tci = (278.8 * yiO2) + (227.3 * yiN2)
        Pci = (736.9 * yiO2) + (493! * yiN2)
```

```
        Tc = Tci: Pc = Pci
        Tr = TE / Tc: Pr = PE / Pc
        GOSUB ZFACTOR
        BGi = (Tsc / (TE * Z)) * (PE / Psc)
        SCFIGPCFSPAI = SCFIGPCFSPAF + (PHIE * BGi)
        REM Velocity of the combustion front = Vb , ft / hr.
        IF UiE = 0 THEN UE = Vb * SCFIGPCFSPAF: UiE = Vb *
SCFIGPCFSPAI
        IF Vb = 0 THEN Vb = UiE / SCFIGPCFSPAI: UE = Vb *
SCFIGPCFSPAF
        REM SCF of injected gas per one barrel sand pack
passing through front = SCFIGPBSPAF
        SCFIGPBSPAF = 5.615 * SCFIGPCFSPAF

        REM SCF of injected gas per one barrel sand pack at
the injection side = SCFIGPBSPAI
        SCFIGPBSPAI = 5.615 * SCFIGPCFSPAI
        SFrE = (ME / (PHIE * RHOO))
        REM SCF of injected gas per one barrel of oil
displaced at the combustion front = SCFIGPBODAF
        SCFIGPBODAF = SCFIGPBSPAF / (PHIE * (So - SFrE))
        REM SCF of injected gas per one barrel of oil
displaced at the injection side = SCFIGPBODAI
        SCFIGPBODAI = SCFIGPBSPAI / (PHIE * (So - SFrE))
        REM SCF of N2 per one CF of sand pack at the
combustion front = SCFN2PCFSPAF
        SCFN2PCFSPAF = yiN2 * SCFIGPCFSPAF
        REM SCF of N2 per one CF of sand pack at the injection
side = SCFN2PCFSPAI
        SCFN2PCFSPAI = yiN2 * SCFIGPCFSPAI
        REM SCF of N2 per one barrel oil displaced at front =
SCFN2PBODAF
        SCFN2PBODAF = yiN2 * SCFIGPBODAF
        REM SCF of N2 per one barrel oil displaced at
injection side = SCFN2PBODAI
        SCFN2PBODAI = yiN2 * SCFIGPBODAI
        REM Barrels of water per one cu.ft. sand pack burned
= BWPCFSPB
        BWPCFSPB = .02571 * ((FHC * ME) / WOC)
        REM SCF of gas produced at the combustion front per
scf of injected gas = SCFPGPCFIGAF
        SCFPGPCFIGAF = ((yiO2 * eO2) / MO2) + (yiO2 - (yiO2 *
eO2) + yiN2)
        REM SCF of gas produced at front per cu.ft. sand pack
= SCFPGPCFSPAF
        SCFPGPCFSPAF = (SCFIGPCFSPAF * SCFPGPCFIGAF)
        REM SCF of gas produced at the outlet side per cu.ft.
sand pack = SCFPGPCFSPAP
```

```
        Tcp = (278.8 * ypO2) + (227.3 * ypN2) + (547.87 *
ypCO2) + (239.59 * ypCO)
        Pcp = (736.9 * ypO2) + (493! * ypN2) + (1071! * ypCO2)
+ (507.5 * ypCO)
        Tc = Tcp: Pc = Pcp
        Tr = TE / Tc: Pr = PE / Pc
        GOSUB ZFACTOR
        BGp = (Tsc / (TE * Z)) * (PE / Psc)
        SCFPGPCFSPAP = SCFPGPCFSPAF + (PHIE * (1 - SFrE) *
BGp)
REM ********* Applied Stoichiometric Calculations **********
        REM
        IF FLAG$ = "Y" THEN GOTO 234 ELSE GOTO PRINTING
234     MR = ME * ((1 - PHIR) / (1 - PHIE))
        SCFIGPCFRAF = SCFIGPPC * MR
        Tc = Tci: Pc = Pci
        Tr = TRES / Tc: Pr = PRES / Pc
        GOSUB ZFACTOR
        BGi = (Tsc / (TRES * Z)) * (PRES / Psc)
        SCFIGPCFRAI = SCFIGPCFRAF + (PHIR * BGi)
        IF UiE = 0 THEN UR = Vb * SCFIGPCFRAF: UiR = Vb *
SCFIGPCFRAI
        IF Vb = 0 THEN Vb = UiE / SCFIGPCFRAI: UR = Vb *
SCFIGPCFRAF
        SCFIGPBRAF = SCFIGPCFRAF * 5.615
        SCFIGPBRAI = SCFIGPCFRAI * 5.615
        SFrR = (MR / (PHIR * RHOO))
        SCFIGPBODRAF = SCFIGPBRAF / (PHIR * (So - SFrR))
        SCFIGPBODRAI = SCFIGPBRAI / (PHIR * (So - SFrR))
        SCFN2PCFRAF = SCFIGPCFRAF * yiN2
        SCFN2PCFRAI = SCFIGPCFRAI * yiN2
        SCFN2PBODRAF = SCFIGPBODRAF * yiN2
        SCFN2PBODRAI = SCFIGPBODRAI * yiN2
        BWPCFRB = .02571 * ((FHC * MR) / (12 + FHC))
        Tc = Tcp: Pc = Pcp
        Tr = TRES / Tc: Pr = PRES / Pc
        GOSUB ZFACTOR
        BGp = (Tsc / (TRES * Z)) * (PRES / Psc)
        SCFPGPCFRAF = (SCFIGPCFRAF * SCFPGPCFIGAF)
        SCFPGPCFRAP = SCFPGPCFRAF + (PHIR * (1 - SFrR) * BGp)
        PFCPAFRB = 43560 * MR
        MMSCFIGPAFRAF = SCFIGPCFRAF * 43560 / 1000000
        MMSCFIGPAFRAI = SCFIGPCFRAI * 43560 / 1000000
REM *************** End of calculations *****************
        REM
PRINTING:
        CLS
        LOCATE 12, 23
```

```
        PRINT "Send to Printer or Monitor (P/M) :"
AGAIN3:
        A2$ = INKEY$
        IF A2$ = "M" OR A2$ = "m" THEN 300
        IF A2$ = "P" OR A2$ = "p" THEN 500 ELSE GOTO AGAIN3
500
        OPEN "LPT1:" FOR OUTPUT AS #1
        CLS
        LOCATE 10, 15
        PRINT "Switch on the printer and hit any key when
ready ..."
        DO
        LOOP WHILE INKEY$ = ""
        REM LPRINT CHR$(27); CHR$(54);
        REM LPRINT CHR$(27); CHR$(69);
        REM LPRINT CHR$(27); CHR$(78); CHR$(5);
        GOSUB 400
        PRINT #1, "         "
        PRINT #1, "         ": PRINT #1, "              ": PRINT
#1, "         "
        PRINT #1, "File name is THESIS."; FILEN$
        PRINT #1, CHR$(12)
        GOSUB 7000
        GOTO 2000
300
        CLOSE #1
        OPEN "SCRN:" FOR OUTPUT AS #1
        GOSUB 400
        LOCATE 24, 16
        PRINT "Hit any key for applied stoichiometric
equations"
        DO
        LOOP WHILE INKEY$ = ""
        CLS
        GOSUB 7000
        GOTO 2000
400
        PRINT #1, "Dry in-situ combustion simulator :"
        PRINT #1, "----------------------------------": PRINT
#1, "   ": PRINT #1, "    "
        PRINT #1, UCASE$(RT$): PRINT #1, "         "
        PRINT #1, UCASE$(AUS$): PRINT #1, "         "
        PRINT #1, UCASE$(PUB$); "              "
        PRINT #1, UCASE$(RN$)
        PRINT #1, "              "
        PRINT #1, "Input Data :"
        PRINT #1, "------------"
        PRINT #1, "              "
```

```
        PRINT #1, "Inside diameter of combustion tube=   "; ID
* 12; " inches"
        PRINT #1, "Length of sand pack                 =   "; L;
" feet"
        PRINT #1, "Run #                                =    ";
RUN$
        PRINT #1, "yiO2                                 =    ";
yiO2 * 100; " %"
        PRINT #1, "yiN2                                 =    ";
yiN2 * 100; " %"
        PRINT #1, "ypCO2                                =    ";
ypCO2 * 100; " %"
        PRINT #1, "ypCO                                 =    ";
ypCO * 100; " %"
        PRINT #1, "ypO2                                 =    ";
ypO2 * 100; " %"
        PRINT #1, "ypN2                                 =    ";
ypN2 * 100; " %"
        PRINT #1, "Tsc                                  =    ";
Tsc - 460; " °F"
        PRINT #1, "Psc                                  =    ";
Psc; " psia"
        PRINT #1, "Sand pack average burning temp.   =   "; TE
- 460; " °F"
        PRINT #1, "Injection pressure                 =   "; PE
- Psc; " Psig"
        PRINT #1, "Sand pack fuel consumption          =    ";
ME; " lb./cu.ft."
        PRINT #1, "Injection gas flux                  =    ";
UiE; " scf/hr-ft²"
        PRINT #1, "Sand pack porosity                  =    ";
PHIE * 100; " %"
        PRINT #1, "Oil saturation                     =   "; So
* 100; " %"
        PRINT #1, "Oil °API gravity                    =    ";
API
        PRINT #1, "
calc.                  exp."
        PRINT #1, "
-----                  ----": PRINT #1, "          "
        PRINT #1, "m                                   =   ";
        PRINT #1, USING "#####.##"; M
        PRINT #1, "FHC                                 =   ";
        PRINT #1, USING "#####.##"; FHC;
        PRINT #1, "                 "; EFHC$
        PRINT #1, "eO2                                 =   ";
        PRINT #1, USING "#####.##"; eO2 * 100; : PRINT #1, "
 %";
```

```
        PRINT #1, "                      "; EeO2$
        PRINT #1, "Moles injected gas / mole of coke =   ";
        PRINT #1, USING "#####.##"; MIGPMC
        PRINT #1, "Moles injected gas / pound coke   =   ";
        PRINT #1, USING "#####.##"; SCFIGPPC
        PRINT #1, "SCF   injected gas / pound coke   =   ";
        PRINT #1, USING "#####.##"; SCFIGPPC;
        PRINT #1, "                      "; ESCFIGPPC$
        PRINT #1, "SCF   injected gas / CF sand pack =   ";
        PRINT #1, USING "#####.##"; SCFIGPCFSPAI;
        PRINT #1, "                      "; ESCFIGPCFSP$
        PRINT #1, "Velocity of the combustion front  =   ";
        PRINT #1, USING "#####.#######"; Vb; : PRINT #1, "
ft/hr";
        PRINT #1, "      "; EVb$
        PRINT #1, "SCF   injected gas /bbl sand pack =   ";
        PRINT #1, USING "#####.##"; SCFIGPBSPAI
        PRINT #1, "SCF   injected gas /bbl oil disp. =   ";
        PRINT #1, USING "#####.##"; SCFIGPBODAI
        PRINT #1, "SCF   N2 / CF sand pack           =   ";
        PRINT #1, USING "#####.##"; SCFN2PCFSPAI
        PRINT #1, "SCF   N2 / bbl oil displaced      =   ";
        PRINT #1, USING "#####.##"; SCFN2PBODAI
        PRINT #1, "Bbl   water / CF sand pack burned =   ";
        PRINT #1, USING "#####.####"; BWPCFSPB;
        PRINT #1, "                    "; EBWPCFSPB$
        PRINT #1, "SCF produced gas /CF injected gas =   ";
        PRINT #1, USING "#####.##"; SCFPGPCFIGAF;
        PRINT #1, "                      "; ESCFEGPCFIG$
        PRINT #1, "SCF produced gas /CF sand pack    =   ";
        PRINT #1, USING "#####.##"; SCFPGPCFSPAP
        RETURN
7000
        IF FLAG$ = "Y" THEN 8000 ELSE 9000
8000
        PRINT #1, "The Applied Stoichiometric Equations :":
PRINT #1, "    ": PRINT #1, "    "
        PRINT #1, "        ": PRINT #1, "            "
        PRINT #1, "Fuel consumed per cu.ft. of reservoir
burned = "; MR; " lb./cu.ft.": PRINT #1, "          "
        PRINT #1, "Fuel consumed per acre-ft of reservoir
burned = "; PFCPAFRB; " lb./acre-ft"
        PRINT #1, "        "
        PRINT #1, "SCF of injected gas per cu.ft. of reservoir
= "; SCFIGPCFRAI; " scf/cu.ft.": PRINT #1, "          "
        PRINT #1, "SCF of injected gas per barrel of reservoir
= "; SCFIGPBRAI; " scf/bbl": PRINT #1, "          "
        PRINT #1, "SCF of injected gas per acre-ft reservoir
```

```
= "; MMSCFIGPAFRAI; " MMscf/acre-ft"
        PRINT #1, "           "
        PRINT #1, "SCF of injected gas per barrel of oil
displaced = "; SCFIGPBODRAI; " scf/bbl": PRINT #1, "
"
        PRINT #1, "Velocity of the combustion front = "; Vb;
" ft/hr": PRINT #1, "           "
        PRINT #1, "SCF N2 per cu.ft. of reservoir = ";
SCFN2PCFRAI; " scf/cu.ft.": PRINT #1, "           "
        PRINT #1, "SCF N2 per barrel of oil displaced = ";
SCFN2PBODRAI; " scf/bbl": PRINT #1, "           "
        PRINT #1, "Barrels of water / cu.ft. of reservoir
burned = "; BWPCFRB; " bbl/cu.ft.": PRINT #1, "           "
        PRINT #1, "Barrels of water / acre-ft of reservoir
burned = "; BWPCFRB * 43560; " bbl/acre-ft": PRINT #1, "
 "
        PRINT #1, "SCF of produced gas / cu.ft. reservoir = ";
SCFPGPCFRAP; " scf/cu.ft.": PRINT #1, "           "
        PRINT #1, "SCF of produced gas / acre-ft reservoir =
"; SCFPGPCFRAP * 43560 / 1000000; " MMscf/acre-ft": PRINT #1,
"         "
        RETURN
9000
        LOCATE 12, 23
        PRINT "No applied data were specified ..!"
        RETURN
2000
        CLOSE #1
        LOCATE 24, 21
        IF A$ = "K" OR A$ = "k" THEN GOTO SAMERUN ELSE GOTO
800
SAMERUN:
        PRINT "Another run for this reference (Y/N) :"
AGAIN4:
        AB$ = INKEY$
        IF AB$ = "Y" OR AB$ = "y" THEN GOTO BEGIN
        IF AB$ = "N" OR AB$ = "n" THEN GOTO 800 ELSE GOTO
AGAIN4
800
        LOCATE 24, 21
        PRINT "               Again (Y/N) :            "
AGAIN5:
        AC$ = INKEY$
        IF AC$ = "Y" OR AC$ = "y" THEN GOTO 700
        IF AC$ = "N" OR AC$ = "n" THEN END ELSE GOTO AGAIN5
ZFACTOR:
        RHO = .27 * Pr / Tr
        A = .06423
```

```
        B = .5353 * Tr - .6123
        C = .3151 * Tr - 1.0467 - (.5783 / Tr ^ 2)
        D = Tr
        E = .6816 / Tr ^ 2
        F = .6845
        G = .27 * Pr
        H = 2.718281828#
2200    FRHO = A * RHO ^ 6 + B * RHO ^ 3 + C * RHO ^ 2 + D *
RHO + E * RHO ^ 3 * (1 + F * RHO ^ 2) * H ^ (-F * RHO ^ 2) -
G
        FPRHO = 6 * A * RHO ^ 5 + 3 * B * RHO ^ 2 + 2 * C *
RHO + D + E * RHO ^ 2 * (3 + F * RHO ^ 2 * (3 - 2 * F * RHO ^
2)) * H ^ (-F * RHO ^ 2)
        ORHO = RHO
        RHO = RHO - (FRHO / FPRHO)
        IF ABS(RHO - ORHO) < .000001 THEN 2300 ELSE 2200
2300    Z = (.27 * Pr) / (RHO * Tr)
        RETURN
INITIALIZE:
        REM INITIALIZING ALL VARIABLES
        RUN$ = "": yiO2 = 0: yiN2 = 0: ypCO2 = 0: ypCO = 0:
ypO2 = 0: ypN2 = 0: Tsc = 0: Psc = 0
        TE = 0: PE = 0: ME = 0: UiE = 0: Vb = 0: PHIE = 0: So
= 0: RHOO = 0: SG = 0: API = 0: PHIR = 0: PRES = 0
        TRES = 0: EFHC$ = "": EeO2$ = "": ESCFIGPPC$ = "":
ESCFIGPCFSP$ = "": EVb$ = ""
        EBWPCFSPB$ = "": ESCFEGPCFIG$ = ""
        RETURN
```

APPENDIX C

EXAMPLE CALCULATIONS

IN-SITU COMBUSTION PROJECT--FIELD CASE

Introduction

A field combustion pilot on the Lower Hospah formation of the South Hospah field, McKinley County, NM,[45] began in Aug. 1980. The pilot pattern was a small inverted five-spot. It was designed to include two existing well-bores (Wells 48 and 18) and required the drilling of three new wells (Wells 65, 66 and 67), as shown in Figure C1. Well 67 was drilled in the center of the pilot and used for air injection. The total pattern area was 0.592 acres.

The Lower Hospah postcombustion reservoir model consists of three zones as was depicted from two core holes drilled in the pattern area to determine the vertical sweep efficiency of the combustion front. These zones are:

1) The upper zone which appeared to be altered by the combustion process, because the heat of combustion drained some oil from this zone; i.e., thermal displacement (but not combustion).

2) The cleanly burned zone which was completely burned.

3) The lower partially burned zone which was partially burned (evidenced by alternating streaks of clean rock and coke).

This model would accurately describe the pilot reservoir characteristics in the quadrants around Wells 65, 66, and 18. However, it is probably not a good description of the Lower Hospah interval in the vicinity of Well 48. Well 48 had been

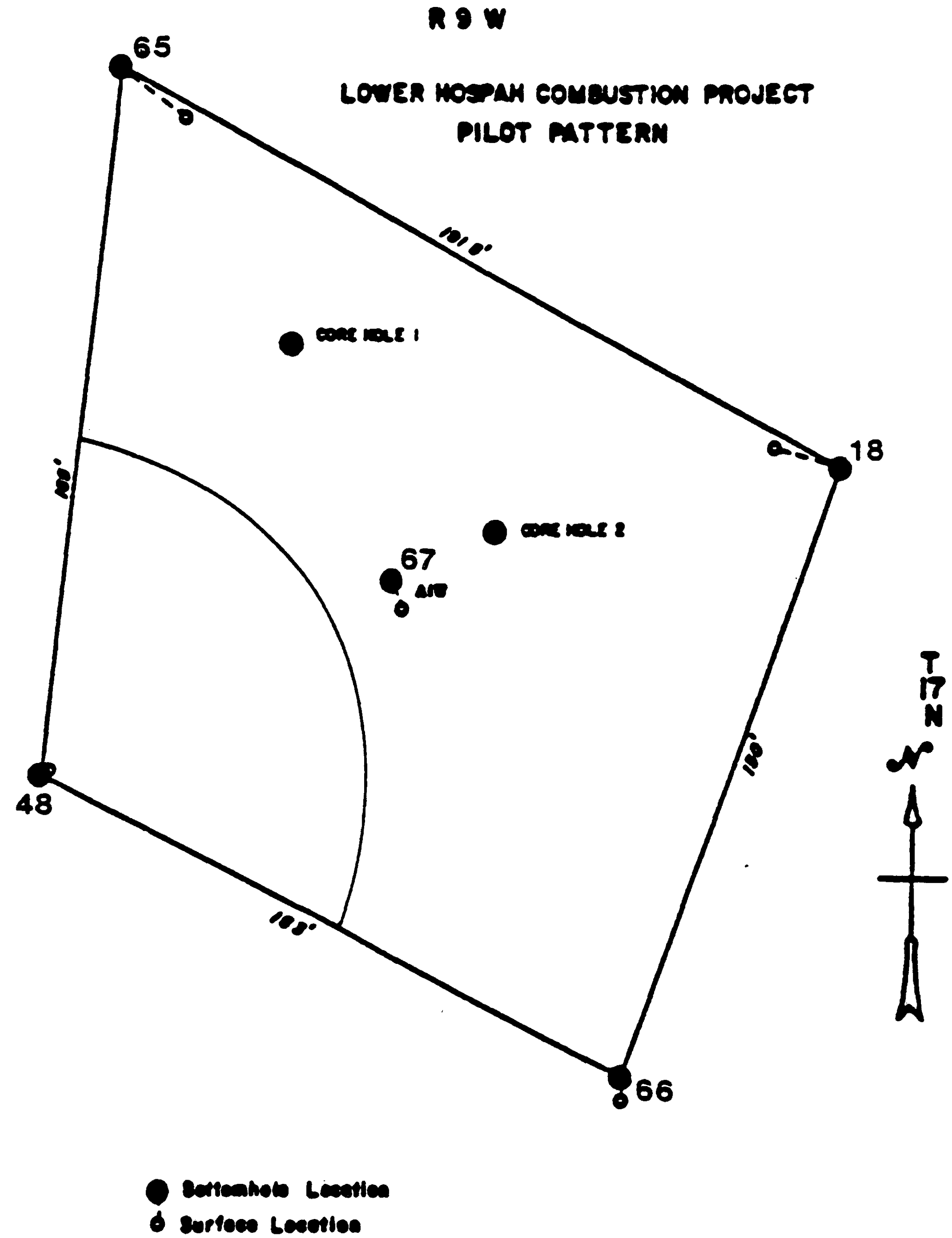

Figure C1. Pilot pattern well location (From reference no. 45) producing from the Lower Hospah since 1971, whereas none of the other pilot wells were Lower Hospah producers before project startup.

Stoichiometric Calculations

Stoichiometric relationships are used to evaluate the performance of the in-situ combustion pilot test on the Lower Hospah formation. The theoretical Lower Hospah oil displacement can be calculated from these relationships, the amount of air injected, the fuel content, and the reservoir model. If theoretical oil displacement, as predicted by stoichiometry, is similar to actual recovery near the end of the project life, the model can be said to be realistic.

Produced gas analysis was measured during the combustion pilot with portable ORSAT equipment; numerous samples were sent also to the laboratory for chromatographic analysis.

Two sets of average pilot compositions were measured. Pilot Average 1 is the arithmetic average of the compositions from both the ORSAT and laboratory-derived analyses. Pilot Average 2 is the arithmetic average of only the laboratory-measured values.

It is reasonable to assume that the laboratory-derived compositions would be more accurate than those done with portable field equipment. Thus, the values obtained from Pilot Average 2 will be used in these calculations. There are two primary reasons for this choice. First, this average represents compositions measured chromatographically in a laboratory, which should yield more accurate analyses. Second, this average yielded a value of F_{HC} which is < 2 whereas Pilot Average 1 yielded F_{HC} = 2.660, which is high for a combustion project even when possible gas-analysis error is considered. Thus the data applied to this project are as follows:

1. **Composition of Injected Gas:**

Mole fraction of oxygen, y_{iO2}	21 %
Mole fraction of nitrogen, y_{iN2}	79 %

2. **Stabilized Effluent Gas Compositions:**

Mole fraction of carbon dioxide, y_{pCO2}	11.95 %
Mole fraction of carbon monoxide, y_{pCO}	1.45 %
Mole fraction of oxygen, y_{pO2}	3.20 %
Mole fraction of nitrogen, y_{pN2}	83.40 %

3. **Standard Conditions:**

Ambient temperature, T_{sc}	60 °F
Atmospheric pressure, p_{sc}	14.7 psia

4. **Reservoir and Fluid Properties:**

Reservoir porosity, ϕ_R	27.0 %
Reservoir pressure[18], p_R	350 psi
Reservoir temperature[19], T_R	340 °F
Oil gravity	25.8 °API
Fuel content corrected to reservoir porosity	1.69 lb/ft^3

---

[18] average in burned out volume

[19] average in the burned out volume

Thickness and initial oil saturation of the burned zones:

Zone	h, ft.	S_o, Well 48	S_o, Wells 66, 65, 18
Upper zone	8	0.313	0.474
Cleanly burned	18	0.183	0.286
Lower partially burned	14	0.157	0.157

Lower Hospah Combustion Pilot Production Summary

Cumulative oil produced, STB	2692.000
Cumulative air injected, MMcf	174.870
Cumulative effluent gas produced, MMcf	168.844

Individual Well Oil and Gas Production Statistics

Well	Cumulative Oil (STB)	Cumulative Gas (MMcf)
18	714.130	20.641
48	154.493	23.555
65	1158.239	81.551
66	665.138	43.097
Total	2692.000	168.844

Transmissibility of the burned zones:

Zone	h, ft.	K_{abs}, md.	K_H, md-ft	Transm., %
Upper zone	8	596	4,768	10.35
Cleanly burned	18	1,471	26,478	57.45
Lower partially burned	14	1,060	14,840	32.20
			46,086	

The general stoichiometric equation involved in this process is:

$$CH_{F_{HC}}+\left(\frac{1}{(y_{iO_2})\cdot(e_{O_2})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)G_i \longrightarrow \left(\frac{m}{m+1}\right)CO_2+\left(\frac{1}{m+1}\right)CO$$

$$+\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{e_{O_2}}-1\right)O_2+\left(\frac{y_{i_{N_2}}}{y_{iO_2}\cdot e_{O_2}}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)N_2+\left(\frac{F_{HC}}{2}\right)H_2O \qquad (5.1)$$

The first problem is to calculate the quantities involved in the above equation. This is done as follows:

1. Normalize the produced gases on a water-free and hydrocarbon-free basis:

$$\because XSUM = (y_{pCO_2} + y_{pCO} + y_{pO_2} + y_{pN_2}) \qquad (7.1)$$

$$\therefore XSUM = (11.95 + 1.45 + 3.20 + 83.40) = 100.0$$

$$\because \tilde{y}_{pCO_2} = \frac{y_{pCO_2}}{XSUM} \qquad (7.2)$$

$$\therefore \tilde{y}_{pCO_2} = \frac{11.95}{1.00} = 11.95\%$$

$$\because\ \tilde{y}_{pCO} = \frac{y_{pCO}}{XSUM} \tag{7.3}$$

$$\therefore\ \tilde{y}_{pCO} = \frac{1.45}{1.00} = 1.45\%$$

$$\because\ \tilde{y}_{pO_2} = \frac{y_{pO_2}}{XSUM} \tag{7.4}$$

$$\therefore\ \tilde{y}_{pO_2} = \frac{3.20}{1.00} = 3.20\%$$

$$\because\ \tilde{y}_{pN_2} = \frac{y_{pN_2}}{XSUM} \tag{7.5}$$

$$\therefore\ \tilde{y}_{pN_2} = \frac{83.40}{1.00} = 83.40\%$$

2. Calculate m, F_{HC}, and e_{O2} as follows:

For the general situation where the injected gas consists of any composition of oxygen and nitrogen:

$$\because\ m = \frac{\tilde{y}_{pCO_2}}{\tilde{y}_{pCO}} \tag{7.6}$$

$$\therefore\ m = \frac{11.95}{1.45} = 8.2414$$

$$\because\ F_{HC} = \frac{4\cdot\left(\frac{y_{iO_2}}{y_{i_{N_2}}}\right)+2\cdot\tilde{y}_{pCO}-\left(4\cdot\frac{y_{iO_2}}{y_{i_{N_2}}}+4\right)\left(\tilde{y}_{pO_2}+\tilde{y}_{pCO}+\tilde{y}_{pCO_2}\right)}{\tilde{y}_{pCO_2}+\tilde{y}_{pCO}} \tag{7.7}$$

$$\therefore\ F_{HC} = \frac{4\cdot\left(\frac{0.21}{0.79}\right)+2\times0.0145-\left(4\cdot\frac{0.21}{0.79}+4\right)(0.0320+0.0145+0.1195)}{0.1195+0.0145}$$

$$= 1.8790$$

$$\because\ e_{O_2} = 1-\frac{y_{i_{N_2}}}{y_{iO_2}}\cdot\frac{\tilde{y}_{pO_2}}{\tilde{y}_{pN_2}}$$

$$\therefore\ e_{O_2} = 1-\frac{0.79}{0.21}\cdot\frac{.032}{.834} \tag{7.8}$$

$$= 85.57\%$$

__I.__ Since the fuel content is corrected to reservoir porosity, therefore the amount of fuel consumed per unit of reservoir volume swept by the combustion zone is __1.690__ lbs/ft^3

__II.__ Total standard cubic feet of air required to burn one cubic foot of bulk volume of reservoir is given by:

$$G_i = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right)m_R\right]+\left[\frac{\Phi_R}{B_{gi}}\right] \quad (5.14)$$

Where:

B_{gi} = Formation volume factor of the injected gas which can be calculated as follows:

$$B_{gi} = \frac{V_R}{V_{sc}} = \frac{T_R \times Z}{T_{sc}} \times \frac{p_{sc}}{p_R}$$

Z may be calculated as follows:

a. Gases in the zone are oxygen and nitrogen

b. Calculate T_c and p_c:

Comp.	y_i	T_c	p_c	y_iT_c	y_ip_c
O_2	0.21	278.8	736.9	(278.8)(0.21)	(736.9)(0.21)
N_2	0.79	227.3	493.0	(227.3)(0.79)	(493.0)(0.79)
			Σ	T_c = 238.115	p_c = 544.219

c. Calculate T_r and p_r as follows:

$$T_r = \frac{(T_R+460)}{T_c} = 3.360 \qquad p_r = \frac{p_R}{p_c} = 0.643$$

d. Knowing T_r, and p_r determine Z = <u>1.000387</u>

therefore, the Z value at this pressure and temperature can be approximated to 1.

$$\therefore B_{gi} = \frac{340\times1.0}{520} \times \frac{14.7}{350} = 0.0275$$

$$\therefore G_i = \left[\left(\frac{(10.732)(60+460)}{(.21)(.8557)(14.7)}\right)\left(\frac{2\times8.24+1}{2\times8.24+2} + \frac{1.879}{4}\right)\left(\frac{1}{12+1.879}\right)\times1.69\right]$$

$$+ \left[\frac{0.2700}{0.0275}\right] = 364.4084 + 9.8182 = 374.2266\ scf/cu.ft.$$

<u>**III.**</u> With the above stoichiometric constants describing the Lower Hospah combustion process, the volume of air necessary to displace one barrel of oil can be calculated using the following equation:

$$G_{io} = \left[\left(\frac{(10.732)(T_{sc}+460)}{(y_{iO_2})(e_{O_2})(p_{sc})}\right)\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right) m_R + \frac{\Phi_R}{B_{gi}}\right] \times$$

$$\left[\frac{5.615}{\Phi_R(S_o - S_{FrR})}\right] \quad scf/bbl \qquad (5.18)$$

Where:

$$S_{FIR} = \frac{m_R}{\phi_R \, \rho_o} = \frac{1.69}{(0.270)\ .\ (56.1322)} = 0.1115$$

Because this calculation is dependent on the initial oil saturation, it was performed for each air-swept layer in the post-combustion reservoir model. The calculation was performed twice (because it is assumed that only the lower two zones in the post-combustion model were subjected to air flux) for the quadrant surrounding Well 48 and twice for the remainder of the pilot.

1) In the vicinity of Well 48, the cleanly burned zone had an initial oil saturation of 0.183. The calculated air required to displace 1 bbl of oil is <u>108,847</u> scf/bbl.

2) For the lower partially burned zone around Well 48, the initial oil saturation is 0.157. Here, the air required to displace 1 bbl of oil is <u>171,045</u> scf/bbl.

3) In the remainder of the reservoir, the initial oil saturation in the cleanly burned zone was 0.286; here the air/oil displacement ratio is <u>44,599</u> scf/bbl.

4) For the lower partially burned zone in the remainder of the reservoir, the initial oil saturation was the same initial saturation (0.157) over the entire pilot area, so here, the air required to displace 1 bbl of oil is <u>171,045</u> scf/bbl.

IV. The volume of gas produced per one cubic foot of bulk reservoir volume burned is calculated as follows:

$$G_{pCF} = \left[\left(\frac{(10.732)\,(T_{sc}+460)}{(y_{iO_2})\,(e_{O_2})\,(p_{sc})}\right)\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)\left(\frac{1}{12+F_{HC}}\right)\,m_R\right] \times$$

$$\left[\left(\frac{(y_{iO_2})\;(e_{O_2})}{\left(\frac{2m+1}{2m+2}+\frac{F_{HC}}{4}\right)}\right) + \left(1 - (y_{iO_2})\;(e_{O_2})\right)\right] + \left[\frac{(\phi_R)\;(1 - S_o)}{B_{pg}}\right]$$

Because this calculation also depends on the initial oil saturation, it was performed for each air-swept layer in the post-combustion reservoir model.

1) In the vicinity of Well 48, the cleanly burned zone had an initial oil saturation of 0.183. The calculated volume of gas produced per one cubic foot of bulk reservoir volume burned is <u>353.1891</u> scf/cu. ft.

2) For the lower partially burned zone around Well 48, the initial oil saturation is 0.157. Here, the volume of gas produced per one cubic foot of bulk reservoir volume burned is <u>353.4443</u> scf/cu. ft.

3) In the remainder of the reservoir, the initial oil saturation in the cleanly burned zone was 0.286; here the

volume of gas produced per one cubic foot of bulk reservoir volume burned is 352.1778 scf/cu. ft.

4) For the lower partially burned zone in the remainder of the reservoir, the initial oil saturation was the same initial saturation (0.157) over the entire pilot area, so here, the volume of gas produced per one cubic foot of bulk reservoir volume burned is 353.4443 scf/cu. ft.

It is also necessary to determine the contribution of each layer in the postcombustion model. It is assumed that only the cleanly burned and the lower partially burned zones contributed in the combustion process. Thus, normalizing the transmissibility contained in these two layers indicates that the cleanly burned zone contributed 64.08% of the total transmissibility, and the lower partially burned zone contributed to 35.92% of the total transmissibility.

V. At this point, it is obvious that the stoichiometrically derived oil displacement for each layer can be calculated as follows:

$$\frac{Cum.\ G_{pCF} \times \%\ Trans. \times \phi_R \times (S_o - S_{FrR})}{G_{pCF} \times 5.615}$$

Where:

Cum. G_{pCF} = the cumulative gas produced,

% Trans. = the transmissibility,

G_{pCF} = the volume of produced gas per one cubic foot of bulk reservoir volume burned. Thus,

1) In Well 48's quadrant, the amount of oil displaced from the cleanly burned zone is 146.9327 STB

2) In Well 48's quadrant, the amount of oil displaced from the lower partially burned zone is 52.3750 STB

3) In the remainder of the reservoir, the amount of oil displaced from the cleanly burned zone is 2218.2102 STB

4) In the remainder of the reservoir, the amount of oil displaced from the partially burned zone is 323.0528 STB

Thus, the total displaced oil as calculated from stoichiometry is 2740.5707 STB. This number is fairly close to the 2692 STB of the actual production.

VI. From the above analysis, it is possible to calculate the amount of air consumed in each zone.

1) In Well 48's quadrant, the amount of air consumed in the cleanly burned zone is 15.9932 MMscf.

2) In Well 48's quadrant, the amount of air consumed in the partially burned zone is 8.9585 MMscf.

3) In the remainder of the reservoir, the amount of air consumed in the cleanly burned zone is 98.9300 MMscf.

4) In the remainder of the reservoir, the amount of air consumed in the partially burned zone is 55.2566 MMscf.

Thus, the cumulative air consumed in the pilot as calculated from stoichiometry is 179.1383 MMscf. This number also compares well with the actual cumulative air consumed of 174.870 MMscf.

The model presented here yielded very good agreement between stoichiometrically calculated displacement and actual production as summarized below.

STOICHIOMETRICALLY DERIVED DISPLACEMENT

Area	Layer	Air Consumed (MMscf)	Air/Oil Displacement Ratio (scf/bbl)	Oil Displaced (bbl)
Quad. 48	Cleanly burned	15.9932	108,847	146.9327
	Lower partially burned	8.9585	171,045	52.3750
Quad. 18, 65 and 66	Cleanly burned	98.9300	44,599	2218.2102
	Lower partially burned	55.2566	171,045	323.0528
Totals		179.1383		2740.5707

COMPARISON BETWEEN THE ACTUAL AND THE STOICHIOMETRICALLY DERIVED DISPLACEMENT

	Actual	Derived
Cumulative air injected, MMscf	174.870	179.1383
Actual recovery, STB	2692.000	2740.5707

VII. The position of the combustion front can be estimated from the air consumed in each quadrant's cleanly burned zone and from the amount of air required to burn one cubic foot of bulk reservoir volume as follows:

$$r = \sqrt{\frac{Cum.G_i \times 4}{G_i \times h \times \pi}}$$

Where:

r = the radius of the burned out area

Cum. G_i = the cumulative air consumed in each zone

G_i = the amount of air required to burn one cubic foot of reservoir

h = thickness of that zone of interest. Thus,

1) In quadrant 18, it is obvious that the contribution of this quadrant is 7.83% of the total air consumed. Therefore, the radius of the burned out area is 51.49 ft. and the area is 0.0478 acres.

2) Quadrant 48 has an 8.93% contribution of the total air consumed. Therefore, the radius of the burned out area is 54.98 ft. and the area is 0.0545 acres.

3) Since quadrant 65 has a 30.95% contribution of the total air consumed. Thus, the radius of the burned out area is 102.37 ft. and the area is 0.1890 acres.

4) In quadrant 66, the contribution is 16.35% of the total air consumed. Therefore, the radius of the burned out area is 74.41 ft. and the area is 0.100 acres.

From the above analysis, the areal sweep efficiency can be calculated by dividing the total area swept (0.3913) by the total pilot area (0.592). Therefore, the areal sweep efficiency is 66.10%.

Difficulties in estimating the water volumes produced from the surrounding waterflood, combined with the fact that pressure and temperature data (necessary to estimate the water content in the produced gas phase) were unavailable, made reliable water-balance calculations impossible.

The stoichiometric equations provided a reliable means to compare the pilot reservoir model quantitatively to actual combustion performance and to identify the reasons for the pilot's lack of recovery.

The high air injection costs compounded economic failure. The high air/oil ratio resulted from low oil saturation in the burned regions and relatively high fuel saturations.

APPENDIX D

REPORTED DATA OBSERVED DURING STABLE PORTION OF RUNS

TABLE D1.1

REPORTED DATA FROM BOUSAID (1, 2)

FOR ALL TUBE RUNS

Inside diameter of combustion tube = 2.916 inch

Standard Conditions:

Surface temperature = 60 °F

Atmospheric pressure = 14.7 psia

Oil Density = 18.0 °API for runs 8603, 8604, 8606, 8607a and 8607b

Oil Density = 21.0 °API for other runs

TABLE D1.2
REPORTED DATA FROM BOUSAID (1, 2)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	L	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	ft	°F	psig	lb/cf	scf/hr-ft²	%	%
8306	21	7.22	3.60	4.95	84.23	2.28	689	300	0.843	107.7	38.9	39.7
8305	21	11.43	3.62	2.32	82.63	2.61	815	300	0.932	108.0	39.8	41.1
8401	21	10.96	3.41	2.32	83.32	0.53	798	300	0.771	107.0	40.4	42.8
8402	21	10.43	3.16	2.18	84.23	0.87	551	300	0.617	107.9	40.1	38.2
8301	21	13.56	2.62	2.05	81.68	4.01	839	300	2.283	110.4	38.9	39.7
8303	21	13.46	2.06	1.81	82.61	2.05	843	500	1.740	106.8	40.3	42.0
8404	21	9.73	2.11	1.97	86.10	0.46	603	500	1.141	109.9	41.0	47.9
8403a	21	12.44	2.20	3.21	82.11	0.72	815	500	1.404	104.3	40.5	48.6
8403b	21	11.68	2.14	2.44	83.74	0.57	581	500	0.775	106.2	40.5	48.6
8603	21	13.06	3.98	0.98	81.84	0.52	905	500	1.697	104.1	41.7	40.6
8604	21	11.56	3.18	1.18	84.08	1.09	769	500	1.388	101.3	39.7	41.1
8606	21	14.78	3.66	0.11	81.11	2.74	910	500	1.311	102.7	41.0	46.1
8607a	21	11.93	3.76	0.10	84.01	1.32	833	500	1.205	106.2	41.0	41.0
8607b	21	12.36	3.66	0.10	83.80	0.52	792	500	1.006	104.1	41.0	41.0

TABLE D2.1

REPORTED DATA FROM SHOWALTER (4)

FOR ALL TUBE RUNS

Length of sand-pack burned = 10.0 feet

Inside diameter of combustion tube = 10.0 inch

Standard Conditions:

Surface temperature = 32 °F

Atmospheric pressure = 14.7 psia

TABLE D2.2
REPORTED DATA FROM SHOWALTER (4)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	ρ_o	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	°API	°F	psig	lb/cf	scf/hr-ft²	%	%
1	21	15.00	1.60	1.30	82.10	11.0	780	350	3.000	19.42	45.0	60.0
2	21	12.20	2.30	4.60	80.90	12.5	840	300	1.800	20.73	45.0	50.0
3	21	11.80	1.70	3.40	83.10	17.0	940	200	1.400	62.07	45.0	60.0
3A	21	14.00	1.70	1.50	82.80	17.0	730	200	1.400	8.33	45.0	60.0
4	21	10.80	2.80	3.50	82.90	25.0	780	450	1.200	68.50	45.0	60.0
5	21	11.40	2.50	3.50	82.60	30.0	830	450	1.000	55.02	45.0	60.0
6	21	13.80	1.50	0.70	84.00	35.0	670	200	0.940	7.18	45.0	60.0
7	21	13.40	1.70	1.90	83.00	40.0	650	200	0.770	5.43	45.0	60.0
8	21	15.10	3.30	0.15	81.45	17.0	1000	470	1.600	54.70	45.0	60.0
9	21	15.20	3.50	0.01	81.29	17.0	835	470	1.500	18.51	45.0	60.0
10	21	15.30	3.50	0.23	80.97	17.0	830	45	1.200	18.28	45.0	60.0
11	21	10.00	3.40	5.50	81.10	17.0	826	450	1.400	59.01	45.0	60.0

TABLE D2.2 (continued)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	ρ_o	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	°API	°F	psig	lb/cf	scf/hr-ft²	%	%
12	21	11.40	3.40	3.60	81.60	17.0	830	300	1.400	58.91	45.0	60.0
13	21	10.20	3.60	5.10	81.10	17.0	815	200	1.300	57.18	45.0	60.0
14	21	11.60	2.70	1.50	84.20	17.0	907	500	1.600	69.05	45.0	60.0
15	21	10.90	2.80	4.30	82.00	17.0	883	330	1.400	71.43	45.0	60.0

TABLE D3.1
REPORTED DATA FROM SHOWALTER (4)
PRODUCTION WELL DATA
SOUTH BELRIDGE THERMAL RECOVERY EXPERIMENT

Month	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	ρ_o	T_R	p_R	m_R	v_b	ϕ_R	S_o
	%	%	%	%	%	°API	°F	psig	lb/cf	ft / hr	%	%
A	21	17.28	1.04	0.00	81.68	12.5	700	350	1.900	0.037	45.0	60.0
B	21	16.98	1.70	0.00	81.32	12.5	700	350	1.900	0.037	45.0	60.0
C	21	15.36	2.92	0.00	81.72	12.5	700	350	1.900	0.037	45.0	60.0
D	21	14.65	2.78	1.46	81.11	12.5	700	350	1.900	0.037	45.0	60.0
E	21	14.00	2.10	1.40	82.50	12.5	700	350	1.900	0.037	45.0	60.0
F	21	12.26	2.33	2.57	82.84	12.5	700	350	1.900	0.037	45.0	60.0
G	21	6.45	0.45	11.6	81.49	12.5	700	350	1.900	0.037	45.0	60.0
H	21	6.06	1.58	12.7	79.63	12.5	700	350	1.900	0.037	45.0	60.0

TABLE D4.1

REPORTED DATA FROM CADY & SATCHWELL (5)

FOR ALL TUBE RUNS

Inside diameter of combustion tube = 2.87 inch

Standard Conditions:

Surface temperature = 60 °F

Atmospheric pressure = 14.7 psia

Oil Density = 14.2 °API

TABLE D4.2

REPORTED DATA FROM CADY & SATCHWELL (5)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	L	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	ft	°F	psig	lb/cf	scf/hr-ft²	%	%
1	20.7	14.80	3.20	0.15	81.85	3.25	910	100	2.120	86.96	40.7	52.1
2	25.8	15.40	3.20	0.30	81.10	3.25	960	100	2.030	131.78	40.7	52.1
3	25.8	15.00	3.90	0.30	80.80	3.25	910	100	2.030	131.78	40.7	52.1
4	30.0	15.10	4.00	0.70	80.20	3.25	965	100	1.510	132.00	40.7	52.1
5	34.3	18.10	4.30	2.20	75.40	3.25	1050	100	4.150	132.07	40.7	52.1
6	40.0	18.30	5.00	1.70	75.00	3.25	1050	100	1.000	130.00	40.7	52.1

TABLE D5.1

REPORTED DATA FROM MARTIN et al. (6)

FOR ALL TUBE RUNS

Inside diameter of combustion tube = 5.68 inch

Standard Conditions:

Surface temperature = 60 °F

Atmospheric pressure = 14.7 psia

Oil Density = 21.2 °API

TABLE D5.2

REPORTED DATA FROM MARTIN et al. (6)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	L	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	ft	°F	psig	lb/cf	scf/hr-ft²	%	%
13	21.0	10.80	3.20	3.30	82.70	6.00	825	80	1.189	29.50	36.0	52.3
14	21.0	10.70	4.10	2.20	83.00	6.00	800	80	1.128	29.70	36.0	56.6
15	21.0	10.90	3.40	1.90	83.80	6.00	775	600	1.232	31.80	36.0	76.2
16	21.0	9.90	3.30	3.90	82.90	6.00	800	600	1.341	63.50	36.0	61.0
17	21.0	7.70	2.00	8.60	81.70	6.00	850	600	1.204	125.0	36.0	69.6
18	21.0	11.4	3.10	1.00	84.50	6.00	650	600	1.504	10.70	36.0	67.7

TABLE D6.1

REPORTED DATA FROM LUENGO-C & SANYAL (7)

Inside diameter of combustion tube = 2.97 inch

Standard Conditions:

Surface temperature = 60 °F

Atmospheric pressure = 14.7 psia

Oil Density = 9.5 °API

TABLE D7.1

REPORTED DATA FROM SHU & LU (8, 9)

FOR ALL TUBE RUNS

Inside diameter of combustion tube = 1.96 inch

Standard Conditions:

Surface temperature = 60 °F

Atmospheric pressure = 14.7 psia

Oil Density = 13.4 °API

TABLE D6.2
REPORTED DATA FROM LUENGO-C & SANYAL (7)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	L	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	ft	°F	psig	lb/cf	scf/hr-ft²	%	%
1	21	13.83	2.63	1.16	80.94	2.54	1110	100	1.993	89.71	47.5	36.6

TABLE D7.2
REPORTED DATA FROM SHU & LU (8, 9)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	L	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	ft	°F	psig	lb/cf	scf/hr-ft²	%	%
1	20.34	13.23	3.25	0.25	0.0[20]	2.67	900	250	1.470	90.00	40.8	55.7
2	21.00	13.37	3.33	1.30	82.00	2.67	900	250	1.500	90.00	40.8	58.0

[20] N_2 has been substituted with CO_2 in the injected gas which did not change the combustion characteristics for this oil

TABLE D8.1

REPORTED DATA FROM PUSCH (10)

FOR ALL TUBE RUNS

Inside diameter of combustion tube = 2.5 inch

Standard Conditions:

Surface temperature = 60 °F

Atmospheric pressure = 14.7 psia

Oil Density = 19.1 °API

TABLE D8.2
REPORTED DATA FROM PUSCH (10)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	L	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	ft	°F	psig	lb/cf	scf/hr-ft²	%	%
1	21	8.80	3.45	6.30	81.45	6.08	1053	200	2.790	435.0	51.0	31.0
2	21	12.80	3.96	3.26	79.98	6.08	1116	200	1.940	435.0	48.0	36.0
3	21	12.52	4.60	0.93	81.95	6.08	980	200	1.310	435.0	44.0	19.0
4	21	11.78	4.12	1.40	82.70	6.08	936	200	1.500	435.0	43.0	21.0
7	21	12.58	2.97	2.07	82.38	6.08	1531	200	1.760	435.0	49.0	30.0
8	21	12.44	1.84	2.94	82.78	6.08	1022	200	1.550	435.0	47.0	25.0
9	21	14.62	1.06	0.12	84.20	6.08	965	200	1.900	435.0	51.0	22.0
10	21	11.62	2.95	3.43	82.00	6.08	908	200	1.770	435.0	50.0	23.0
11	21	13.96	3.49	1.39	81.16	6.08	1023	200	1.760	435.0	50.0	28.0
12	21	11.50	3.00	2.55	82.95	6.08	919	200	1.450	435.0	52.0	25.0
13	21	11.88	4.08	2.42	81.62	6.08	931	200	1.490	435.0	51.0	18.0
14	21	10.15	3.13	4.53	82.19	6.08	823	200	2.240	435.0	49.0	33.0

TABLE D8.2 (continued)

RUN #	y_{iO2} %	y_{pCO2} %	y_{pCO} %	y_{pO2} %	y_{pN2} %	L ft	T_E °F	p_E psig	m_E lb/cf	u_{Ei} scf/hr-ft²	ϕ_E %	S_o %
15	21	13.23	3.26	0.39	83.12	6.08	1031	200	1.860	435.0	45.0	25.0
17	21	14.78	4.30	0.00	80.92	6.08	1094	200	2.550	435.0	41.0	57.0
18	21	14.28	4.06	0.34	81.32	6.08	941	200	2.780	435.0	47.0	34.0
19	21	9.92	2.54	8.29	79.25	6.08	967	200	1.570	435.0	46.0	23.0
20	21	12.17	4.54	4.01	79.28	6.08	976	200	1.650	435.0	52.0	21.0
23	21	9.87	2.50	8.18	79.45	6.08	1048	200	1.330	435.0	47.0	19.0
24	21	8.25	1.90	10.24	79.61	6.08	1199	200	1.570	435.0	48.0	18.0
25	21	10.9	3.08	6.78	79.24	6.08	1361	200	2.040	435.0	46.0	25.0

TABLE D9.1

REPORTED DATA FROM FASSIHI et al. (11)

FOR ALL TUBE RUNS

Length of sand-pack burned = 2.59 feet

Inside diameter of combustion tube = 2.97 inch

Standard Conditions:

Surface temperature = 60 °F

Atmospheric pressure = 14.7 psia

TABLE D9.2
REPORTED DATA FROM FASSIHI et al. (11)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	ρ_o	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	°API	°F	psig	lb/cf	scf/hr-ft²	%	%
78-1	21	10.8	1.50	4.40	82.30	11.2	910	110	1.070	83.20	40.5	30.1
78-2	21	10.6	6.10	3.70	78.70	11.2	900	100	1.530	91.50	40.0	43.7
78-3	21	12.5	4.70	1.10	80.70	11.2	1000	100	1.440	91.78	47.8	24.1
78-4	21	14.7	3.54	1.91	78.84	11.2	1000	100	2.220	88.33	46.4	39.2
78-5	21	14.5	5.16	1.42	78.85	11.2	1000	100	1.800	122.7	51.5	29.0
78-6	21	12.9	5.20	2.20	78.40	11.2	964	197	1.380	114.4	39.0	48.0
78-7	21	14.4	2.90	1.40	79.90	11.2	880	197	1.950	129.0	39.7	37.8
79-1	21	14.2	3.80	2.50	78.80	11.2	934	128	2.060	120.7	41.6	33.9
79-2	21	13.2	3.40	2.50	79.10	13.5	950	100	2.140	114.4	36.9	18.9
79-4	21	11.5	4.90	1.60	80.90	14.0	934	100	1.830	114.4	36.9	18.7
79-5	21	13.8	2.60	1.20	81.00	10.1	1112	100	1.990	89.80	47.5	36.6
79-6	21	10.1	3.70	2.20	82.70	12.2	950	124	1.780	110.2	34.7	28.7
79-7	21	11.5	2.30	1.80	82.90	10.4	1099	123	2.400	87.40	27.4	31.3
80-1	21	6.30	1.50	6.50	84.80	11.2	649	100	1.850	110.3	41.0	31.0

TABLE D10.1

REPORTED DATA FROM PETIT (13)

FOR ALL TUBE RUNS

Length of sand-pack burned = 3.12 feet

Inside diameter of combustion tube = 3.94 inch

Standard Conditions:

Surface temperature = 59 °F

Atmospheric pressure = 14.5 psia

TABLE D10.2
REPORTED DATA FROM PETIT (13)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	ρ_o	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	°API	°F	psig	lb/cf	scf/hr-ft²	%	%
1	21	13.0	3.80	1.05	82.15	15.9	887	145	1.676	62.62	34.0	67.3
2	50	38.0	10.8	1.00	50.20	15.9	864	145	1.952	26.30	35.0	65.7
3	80	57.0	18.5	0.00	24.50	15.9	905	145	2.085	16.44	36.0	64.0
4	21	12.8	3.8	0.00	83.40	15.9	932	145	1.514	65.28	34.0	48.0
5	21	12.8	3.8	0.31	83.08	15.9	923	145	1.679	70.29	35.0	50.0
6	50	33.0	10.0	0.00	57.00	15.9	959	145	1.442	26.30	36.0	52.0
7	100	77.78	22.2	0.0	0.0	15.9	1283	145	1.586	13.15	37.0	54.0
8	100	80.75	19.2	0.0	0.0	15.9	986	145	1.666	13.15	38.0	56.0
9	21	18.0	2.0	0.0	80.0	15.9	1094	1025	1.288	62.62	34.0	48.0
10	50	39.0	3.0	0.0	58.0	15.9	1112	1025	1.526	26.30	35.0	50.0
11	50	40.0	3.2	0.0	56.8	15.9	1166	1025	1.601	26.30	36.0	52.0
12	100	94.74	5.3	0.0	0.0	15.9	1292	1025	1.873	13.15	37.0	54.0

TABLE D10.2 (continued)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	ρ_o	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	°API	°F	psig	lb/cf	scf/hr-ft²	%	%
13	100	95.05	4.9	0.0	0.0	15.9	1193	1025	1.363	13.15	38.0	56.0
14	21	13.0	3.8	0.0	83.2	15.9	968	145	0.662	26.61	34.0	67.3
15	100	77.78	22.2	0.0	0.0	15.9	1382	145	1.561	26.30	35.0	65.7
16	21	12.0	2.0	0.0	86.0	15.9	1130	1025	1.528	26.61	36.0	64.0
17	100	95.74	4.2	0.0	0.0	15.9	1310	1025	2.001	26.30	37.0	54.0
18	100	95.74	4.2	0.0	0.0	15.9	1292	1025	2.377	26.3	38.0	56.0
19	21	12.5	3.6	4.6	79.28	25.7	887	145	1.142	62.62	36.0	48.7
20	50	35.3	9.7	3.2	51.8	25.7	941	145	1.342	26.3	38.0	52.3
21	100	79.2	19.2	1.6	0.0	25.7	968	145	1.311	13.15	40.0	56.0
22A	10	3.0	1.4	2.1	93.5	25.7	635	145	0.861	78.90	35.2	47.2
22B	12	5.8	2.0	2.2	90.0	25.7	797	145	1.036	65.75	36.4	49.4
23	21	8.2	3.2	0.5	88.1	25.7	905	145	1.174	37.57	37.6	51.6

TABLE D10.2 (continued)

RUN #	Y_{iO2} %	Y_{pCO2} %	Y_{pCO} %	Y_{pO2} %	Y_{pN2} %	ρ_o °API	T_E °F	P_E psig	m_E lb/cf	u_{Ei} scf/hr-ft²	ϕ_E %	S_o %
24	50	32.15	9.3	0.5	58.05	25.7	851	145	1.199	15.78	38.8	53.8
25	100	79.53	20.5	0.0	0.0	25.7	896	145	1.018	7.89	40.0	56.0
26	21	12.4	1.3	0.0	86.3	25.7	1004	1450	.893	37.57	35.2	47.2
27	21	14.0	1.4	0.0	84.6	25.7	1040	1450	1.136	37.57	36.4	49.4
28	50	30.3	1.8	0.0	67.9	25.7	1040	1450	.624	15.78	37.6	51.6
29	100	90.6	9.4	0.0	0.0	25.7	1004	1450	.400	7.89	38.8	53.8
30	100	96.2	3.8	0.0	0.0	25.7	992	1450	.449	7.89	40.0	56.0
31	21	11.8	3.9	1.9	82.41	25.7	887	145	1.086	26.61	36.0	48.7
32	100	66.9	21.0	12.0	0.0	25.7	977	145	1.330	26.30	40.0	56.0
33	50	28.7	2.9	0.0	68.4	25.7	1121	1450	.858	26.30	37.6	51.6
34	100	92.6	7.4	0.0	0.0	25.7	1121	1450	1.501	26.30	38.8	53.8
35	100	94.2	5.8	0.0	0.0	25.7	1211	1450	1.330	26.30	40.0	56.0

TABLE D10.2 (continued)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	ρ_o	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	°API	°F	psig	lb/cf	scf/hr-ft²	%	%
36	21	14.8	4.4	0.1	80.7	15.9	932	145	1.498	62.62	35.0	66.0
37	100	81.0	19.0	0.0	0.0	15.9	995	145	1.835	12.36	36.0	69.0
38	21	19.3	2.0	0.0	78.67	15.9	1112	1025	1.548	62.62	35.0	66.0
39	100	95.1	4.8	0.0	0.0	15.9	1292	1025	2.035	13.15	36.0	69.0
40	21	11.8	4.5	1.3	82.4	25.7	950	145	1.298	59.02	34.0	45.0
41	100	80.1	19.4	0.5	0.0	25.7	914	145	1.380	5.03	40.0	56.0
42	23.6	21.5	1.1	0.0	77.4	25.7	1094	1450	.918	37.61	34.0	45.0
43	100	96.7	3.3	0.0	0.0	25.7	1052	1450	.718	7.89	40.0	56.0

TABLE D11.1

REPORTED DATA FROM BURGER & SAHUQUET (29)

FOR ALL TUBE RUNS

Inside diameter of combustion tube = 7.72 inch

Standard Conditions:

Surface temperature = 68 °F

Atmospheric pressure = 14.7 psia

Oil Density = 27.0 °API

TABLE D11.2
REPORTED DATA FROM BURGER & SAHUQUET (29)

RUN #	y_{iO2}	y_{pCO2}	y_{pCO}	y_{pO2}	y_{pN2}	L	T_E	p_E	m_E	u_{Ei}	ϕ_E	S_o
	%	%	%	%	%	ft	°F	psig	lb/cf	scf/hr-ft²	%	%
A1	21	11.5	4.30	0.50	83.70	6.89	761	147	1.074	29.53	37.4	47.5
A5	21	10.0	4.00	3.00	83.00	6.89	770	147	1.124	29.53	37.0	49.0
A6	21	9.6	4.15	2.50	83.75	6.89	770	44	1.043	29.53	32.8	58.8
A8	21	9.0	3.80	4.00	83.20	6.89	824	147	1.036	59.06	35.5	51.6
A9	21	12.2	4.50	0.00	83.30	6.89	770	514	1.136	29.53	33.8	55.5