Chapter 16 (Reservoir Engineering Section)

Insitu Combustion

William E. Brigham and Louis Castanier

1. INTRODUCTION

Insitu Combustion (ISC) is the oldest thermal recovery technique. It has been used for over nine decades with many economically successful projects. Nevertheless, it is regarded as a high-risk process by many, primarily because of many failures of early field tests. Most of those failures came from application of a good process (ISC) to the wrong reservoirs or to the poorest prospects. An objective of this chapter is to clarify the potential of ISC as an economically viable oil recovery technique for a variety of reservoirs. This chapter is a summary containing a description of ISC, a discussion of laboratory screening techniques, an illustration of how to apply laboratory results to field design, a review of performance prediction methods, a discussion of operational practices and problems, and an analysis of field results. For a more complete review, the work of Sarathi[1], Prats[2] and Burger *et al.*[3] should be consulted.

2. PROCESS DESCRIPTION

In situ combustion is basically injection of an oxidizing gas (air or oxygen-enriched air) to generate heat by burning a portion of the resident oil. Most of the oil is driven toward the producers by a combination of gas drive (from the combustion gases), steam and water drive. This process is also called fire flooding to describe the movement of a burning front inside the reservoir. Based on the respective directions of front propagation and air flow, the process can be forward, when the combustion front advances in the same direction as the air flow, or reverse, when the front moves against the air flow.

2.1. Reverse Combustion

This process has been studied extensively in laboratories and has been field tested. The idea is that it could be a useful way to produce very heavy oils with high viscosity. In brief, it has not been successful economically for two major reasons.

First, combustion started at the producer results in hot produced fluids that often contain unreacted oxygen. These conditions require special, high-cost tubulars to protect against high temperatures and corrosion. More oxygen is required to propagate the front compared to forward combustion, thus increasing the major cost of operating an insitu combustion project.

Second, unreacted, coke-like heavy ends will remain in the burned portion of the reservoir. At some time in the process the coke will start to burn and the process will revert to forward combustion with considerable heat generation but little oil production. This has occurred even in carefully controlled laboratory experiments.

In summary reverse combustion has been found difficult to apply and economically unattractive.

2.2. Forward Combustion

As only forward combustion is practiced in the field we will only consider this case. Forward combustion can be further characterized as “dry” when only air or enriched air are injected or “wet” when air and water are co-injected.

2.2.1. Dry Combustion

The first step in dry forward insitu combustion is to ignite the oil. In some cases auto-ignition occurs when air injection begins if the reservoir temperature is fairly high and the oil reasonably reactive. This often occurs in California reservoirs. Ignition has been induced using down hole gas burners, electrical heaters, and/or injection of pyrophoric agents or steam injection. Ignition will be discussed in more detail later.

After ignition the combustion front is propagated by a continuous flow of air. Rather than an underground fire, the front is propagated as a glow similar to the hot zone of a burning cigarette, or to hot coals in a barbecue. As the front progresses into the reservoir, several zones exist between injector and producer as a result of heat and mass transport and the chemical reactions. Figure 17.1[4] is an idealized representation of the various zones and the resulting temperature and fluid saturation distributions. In the field there are transitions between zones, however the concepts illustrated provide insight on the combustion process.

2.2.2. Zone Definitions

Starting from the injector, seven zones have been defined:

A. The burned zone is the volume already burned. This zone is filled with air and may contain small amounts of residual unburned organic solids. As it has been subjected to high temperatures, mineral alterations are possible. Because of the continuous airflow from the injector, the burned zone temperature increases from injected air temperature at the injector to combustion front temperature at the combustion front.

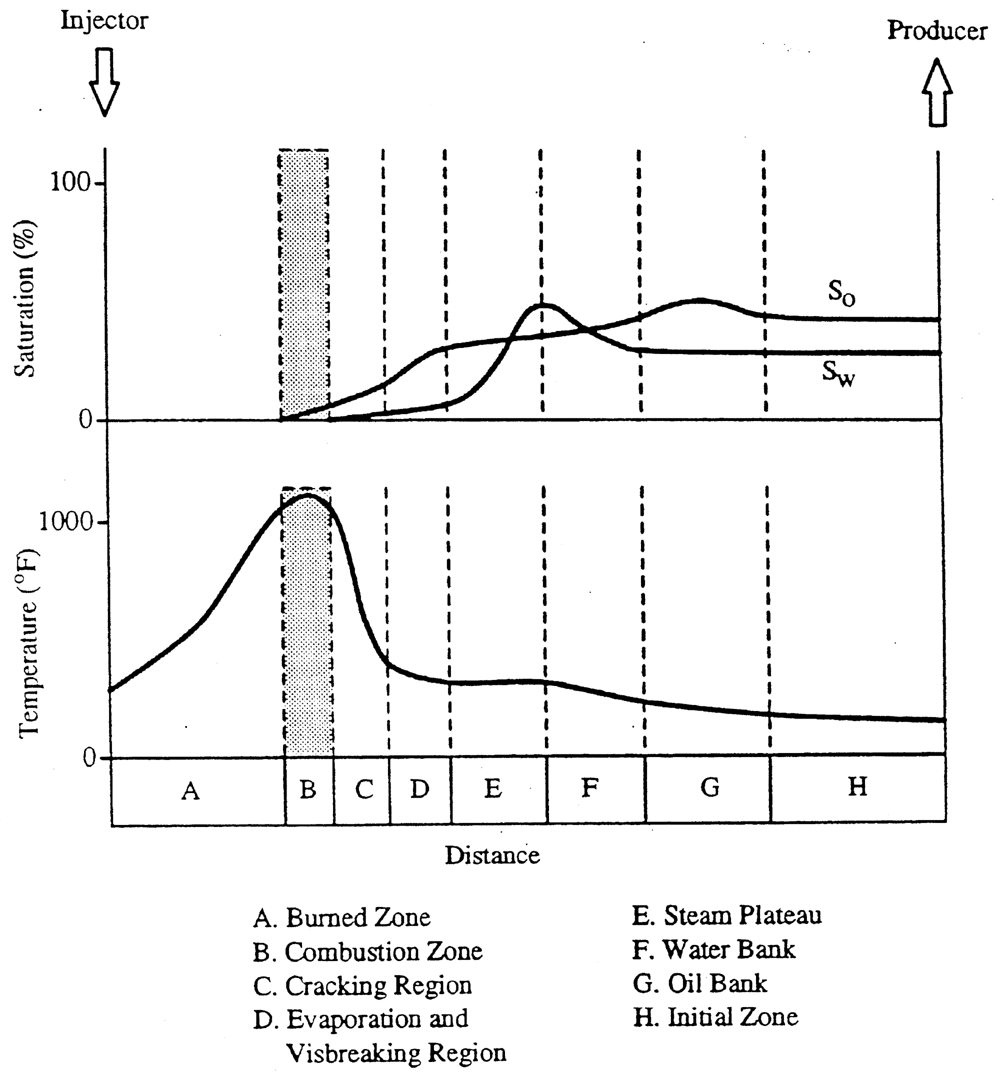


Figure 17.1 Schematic Diagram Of Temperature And Saturation Profiles And Zones In Insitu Combustion[4]

B. The combustion front is the highest temperature zone. It is very thin, often no more than several inches thick. It is in this region that oxygen combines with the fuel and high temperature oxidation occurs. The products of the burning reactions are water and carbon oxides. The fuel is often misnamed coke. In fact it is not pure carbon but a hydrocarbon with H/C atomic ratios ranging from about 0.6 to 2.0. This fuel is formed in the thermal cracking zone just ahead of the front and is the product of cracking and pyrolisis which is deposited on the rock matrix. The amount of fuel burned is an important parameter because it determines how much air must be injected to burn a certain volume of reservoir.

C/D. The cracking/vaporization zone is downstream of the front. The crude is modified in this zone by the high temperature of the combustion process. The light ends vaporize and are transported downstream where they condense and mix with the original crude. The heavy ends pyrolize, resulting in CO_2, CO, hydrocarbon gases and solid organic fuel deposited on the rock.

E. The steam plateau. This is the zone where some of the hydrocarbon vapors condense. Most of those condense further downstream as the steam condenses. The steam plateau temperature depends on the partial pressure of the water in the gas phase. Depending on the temperature the original oil may undergo a mild thermal cracking, often named visbreaking that usually reduces oil viscosity.

F. A water bank exists at the leading edge of the steam plateau where the temperature is less than steam saturation temperature. This water bank decreases in temperature and saturation downstream, with a resulting increase in oil saturation.

G. The oil bank. This zone contains most of the displaced oil including most of the light ends that result from thermal cracking.

H. Beyond these affected areas is the undisturbed original reservoir. Gas saturation will increase only slightly in this area because of the high mobility of combustion gases.

2.2.3. Wet Combustion

A large amount of heat is stored in the burned zone during dry forward insitu combustion (Fig. 17.1), because the low heat capacity of air cannot transfer that heat efficiently. Water injected with the air can capture and advance more heat stored in the burned zone.

During wet combustion injected water absorbs the heat from the burned zone, vaporizes, moves through the burning front and condenses, expanding the steam plateau. This results in faster heat movement and oil displacement.

Depending on the water/air ratio, wet combustion is classified as: (1) incomplete when the water is converted into superheated steam and recovers only part of the heat from the burned zone, (2) normal when all the heat from the burned zone is recovered, and (3) quenched or super wet when the front temperature declines as a result of the injected water.

When operated properly, water assisted combustion reduces the amount of fuel needed, resulting in increased oil recovery and decreased air requirements to heat a given volume of reservoir. Up to a 25% improvement in process efficiency can be achieved[5]. Determination of the optimum water/air ratio is difficult because of reservoir heterogeneities and gravity override that can affect fluid movement and saturation distributions. Injecting too much water can result in an inefficient fire front, thus losing the benefits of the process.

Some authors recommend, as a best practice, injecting water at high rates to achieve "partially quenched combustion". This method has limited application. A high temperature burn is preferred but is difficult to achieve with oils that are not highly reactive. Injecting large amounts of water can lower combustion temperatures resulting in a greater fraction of oil burned and higher costs for oxygen. At the same time these types of burns only partially oxidize the oil. This partial oxidation results in a much more viscous liquid, which in turn lowers the flow rate. So, in brief, if water injection is used, great care should be taken to assure that liquid water never reaches the high temperature combustion front. A discussion of heat and material balance calculations that include chemical reactions and the effect of injected air and water, is presented later in some detail.

3. LABORATORY STUDIES

In situ combustion mechanisms are largely a function of oil composition and rock mineralogy. The extent and nature of the chemical reactions between crude oil and injected air, as well as the heat generated, depend on the oil-matrix system. Laboratory studies, using crude and matrix from a prospective ISC project, should be performed prior to the design of any field operation.

3.1. The Reactions

The chemical reactions associated with ISC are complex and numerous. They occur over a broad temperature range. Most researchers group them into three classes in ascending temperature ranges:

- Low temperature oxidation (LTO) - heterogeneous gas/liquid reactions producing partially oxygenated compounds and few carbon oxides.
- Medium temperature reactions - cracking and pyrolisis of hydrocarbons to form fuel.
- High temperature oxidation (HTO) - heterogeneous *H/C* bond breaking reactions in which the fuel reacts with oxygen to form water and carbon oxides.

A more recent and more accurate kinetics model has been developed[6]. Only two reactions are used, but in addition the geometry of the reacting residual fuel in the pore spaces is taken into account as indicated in Figure 17.2. This figure represents the fuel remaining on two sand grains at different times in the combustion process, as discussed by Mamora *et al.*[6] The crude oil oxidation consists of two stages, low temperature oxidation forming an oxygenated hydrocarbon fuel, and high temperature combustion of this fuel. A detailed description of the different reaction regimes is outside the scope of this handbook; some practical comments on the role of LTO, however, are appropriate at this stage.

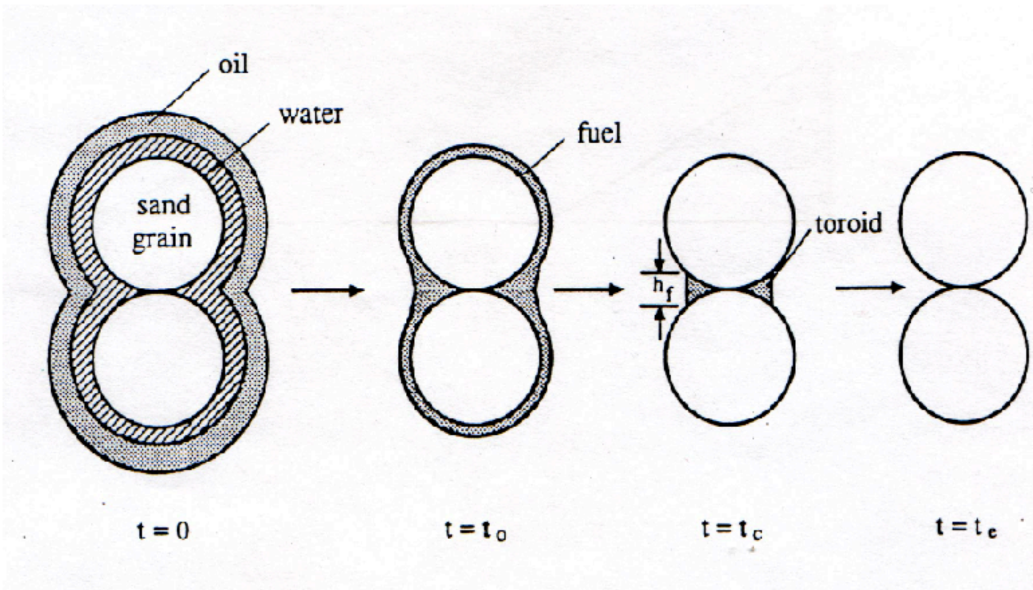


Figure 17.2. Schematic Diagram Of Varying-Fuel-Geometry[6].

Low temperature oxidation (LTO) can be described as oxygen addition to the crude oil. LTO yields water and oxygenated hydrocarbons such as ketones, alcohols, and peroxides. A good description of LTO can be found in Burger and Sahuquet.[7] LTO generally increases original oil viscosity, boiling range and density. LTO increases the amount of fuel. LTO is promoted by low air flux in the oxidation zone. Poor crude oxidation characteristics can also play a role. In heavy oil reservoirs (API gravity $< 20^o$), LTO tends to be more pronounced when oxygen rather than air is injected in the reservoir[8].

Research has shown that, for heavy oils, LTO reactions must be minimized. Figure 17.3 shows the oxygen uptake as the temperature of a typical heavy oil is raised linearly with time. Notice the negative temperature gradient region where oxygen rate uptake decreases with temperature increase. If the temperature of the ISC process stays at or below the negative temperature gradient region, the oil displacement efficiency will be very low. This is because LTO increases the oil viscosity and fuel content.

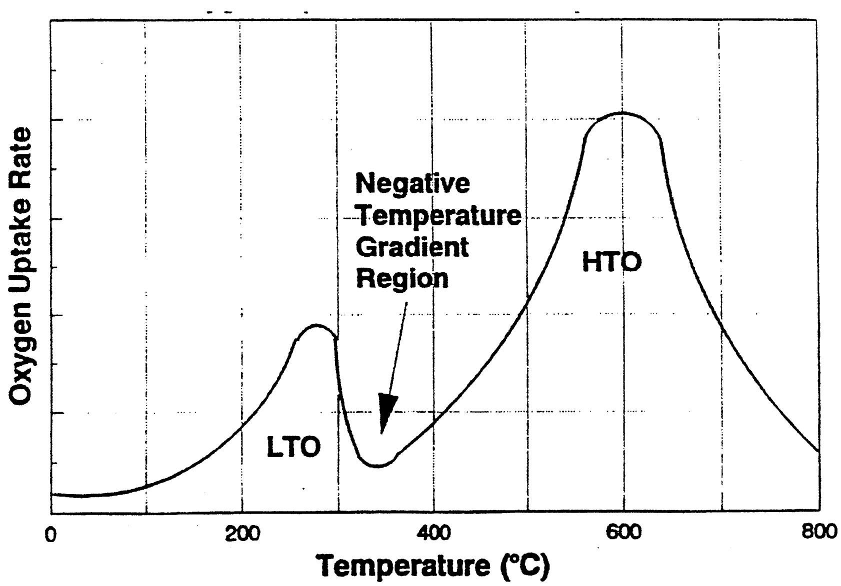


Figure 17.3. Schematic of dry combustion temperature profile showing the general effect of temperature on oxygen uptake rate for heavy oils and the negative temperature gradient region[8].

The injected air flux in a heavy oil project should be maintained at a value well above the value needed to maintain the reactions in the high temperature oxidation regime. LTO generally has almost no effect on light oils in terms of mobility or recovery despite the fact that light oils are more susceptible to LTO than heavy oils.

Fuel deposition determines the feasibility and economic success of a combustion project. It occurs at intermediate temperatures after the LTO reactions. Numerous studies have been conducted aimed at understanding fuel formation and deposition at intermediate temperatures. The oil type and chemical structure determine the rate and extent of the different reactions. Catalytic effects from the matrix and/or injected solutions of metals may affect the type and amount of fuel formed. Again all laboratory experiments must include not only the crude to be tested but also representative core material from the reservoir of interest.

3.2. Kinetics

Kinetics of combustion reactions can be defined by how fast the chemical reactions occur and how much of the oil is affected. It is important to study kinetics for several reasons:

- Characterization of oil reactivity
- Determination of ignition conditions
- Insight on the nature of the fuel and its combustion characteristics

- Use of kinetic parameters as input for possible numerical simulation of the process.

As crude oils contain hundreds of different compounds, it is impossible to accurately represent all the reactions occurring during ISC. Even if it were possible to detail all the reactions, the use of such information in numerical models would be impossible because of cost and computer limitations. Consequently we will concentrate on useful simple models describing ISC reaction kinetics that have been published in the literature. Most studies use the Arrhenius reaction expressions defined as follows. The model assumes a functional dependency on fuel concentration and oxygen partial pressure. It is given by,

$$R_c = \frac{dC_f}{dt} = K\, p_{O_2}^{a}\ C_f^{b} \qquad (17.1)$$

where

R_c = reaction rate of the crude, $kg/m^3\text{sec}$

C_f = the concentration of fuel, kg/m^3

p_{O_2} = oxygen partial pressure, Pa

K = reaction rate constant, $(kg/m^3)^{1-b}/(Pa)^a\,\text{sec}$

The exponent constants, a and b, are the orders of the reactions with respect to oxygen partial pressure (a), and fuel concentration (b). Data shows that "a" ranges between 0.5 and 1.0, while "b" is close to 1.0. The reaction rate constant, K, is based on the Arrhenius constant, expressed as a function of temperature, as follows,

$$K = A\exp(-E/RT) \qquad (17.2)$$

where

A = Arrhenius constant $(kg/m^3)^{1-b}/(Pa)^a\,\text{sec}$
E = activation energy, kJ/mole
T = absolute temperature, ºK
R = universal gas constant, kJ/mole ºK

When using literature values one has to be careful because the parameters in Eqs. 17.1 and 17.2 vary depending on the system of units used.

A variety of experimental techniques can be used to determine the kinetics of ISC reactions. Among those are differential thermal analysis, thermogravimetric analysis, accelerating rate calorimetry and effluent analysis. The additional references contain several descriptions of various methods and results.

The effluent analysis method, also called the ramped temperature method is quantitative and consists in heating a sample of oil and rock while flowing oxygen (for oxidation) or nitrogen (for pyrolisis) through the sample. The kinetic parameters can be calculated from effluent gas evolution with temperature, and chemical analysis of post test cores. Details of the analysis techniques can be found in the references.[3,6,9]

3.3. Combustion Tube Studies

Although the kinetic studies can provide useful insight on ISC reactions, combustion tube experiments are mandatory to determine the parameters needed to design and implement field projects. These data are used to make predictions of field test performance. As Sarathi[1] points out, "Combustion tube studies are the necessary first step in the design of an ISC project."

Combustion tubes aim at representing a small volume of the reservoir. They are usually packed with native reservoir cores or representative samples of matrix material and oil, placed in vertical position to minimize gravity effects and heated to reservoir temperature. Ignition is usually started at the top by electrical heaters and the combustion front is propagated downward. This allows propagation of a combustion front and the associated chemical reactions at conditions close to those in a reservoir.

Temperature profiles, pressures, gas and liquids injection and production rates, and composition histories at the inlet and outlet are recorded. ISC tube runs are unscaled and direct correlation of combustion tube results to the field is not possible. However, as long as the runs are performed with reservoir rock and fluids at reservoir conditions, the reactions of fuel deposition and combustion will be similar in both tube and reservoir. Tube runs will not provide information on ISC sweep efficiency. They adequately model the chemistry of the process but not the flow behavior in the reservoir, and only partially model the heat transfer processes. Flow behavior in the reservoir is affected by gravity override, well spacing and geometry and reservoir heterogeneities, and tube runs cannot reproduce these phenomena. Heat transfer from the tube to the surroundings can be much higher than reservoir heat losses.

Two different schools of thinking exist on this heat transfer problem. Many experimenters use strip heaters around the tube to lower the temperature gradient between the tube and the surroundings. This reduces heat losses and allows front propagation at fluxes similar to those in the field. It can, however, lead to overestimation of water/oil ratios in wet combustion if the strip heaters provide too much energy to the system, as they often do. Information on front cooling by injected water may also be masked by the heaters. As a result, the extent of the steam plateau may not be correct. Most of these types of experiments are bulky and time consuming and require extensive instrumentation.

The other solution is to increase the air flux and minimize heat losses by insulation alone. This may slightly overestimate air requirements and fuel content but is much simpler and easier to operate. As a result, it is widely used. Description of various setups for combustion tube studies have been provided.[5,6,10,11,12]

The information that can be acquired from tube runs includes:

- Fuel burned
- Air required to burn a unit volume of reservoir
- Atomic H/C ratio of burned fuel
- Excess air and oxygen utilization
- Air/Fuel ratio
- Oil recovery from the swept zone
- Optimization of water/air ratio in wet combustion
- Composition of produced fluids
- Front temperature and stability

This last information is quite important in heavy oils to determine if the process is operating properly in the desired high temperature regime. If high temperature cannot be achieved in ideal laboratory conditions it is likely that field results would be worse.

3.3.1. Data Analysis

The following is a simple analysis of data from tube runs. It assumes that the combustion occurs at high temperature where the fuel exclusively combines with oxygen to produce water and carbon oxides. The stoichiometric equation[13] is then:

$$CH_n + \left[\left(\frac{2m+1}{2m+2}\right) + \frac{n}{4}\right] O_2 = \left(\frac{m}{m+1}\right) CO_2 + \left(\frac{1}{m+1}\right) CO + \left(\frac{n}{2}\right) H_2O \qquad (17.3)$$

where n = hydrogen/carbon atomic ratio of fuel

m = CO_2/CO concentration ratio produced

The other symbols indicate the various components in the chemical balance equation.

This equation is only an approximation of the process. It neglects LTO reactions, oxygen /minerals reactions and water/organic fuel reactions. Alternate analysis when some of these reactions are important are detailed in Sarathi[1] based on information provided by Moore and Mehta of the University of Calgary. Assuming Eq. 17.3 to be valid the apparent H/C ration, n, can be estimated from the concentration of exhaust gases and the injected oxygen concentration[13].

$$n = \frac{4[O_2 - CO_2 - CO/2 - (O_2)_{\text{prod}}]}{CO_2 + CO} \qquad (17.4)$$

where $(O_2)_{\text{prod}}$ = Oxygen concentration produced

It is prudent to normalize the concentrations by making a balance on the nitrogen, which in these conditions can be considered inert. The basic chemical equation is then:

$$CH_n + aO_2 + RaN_2 = bCO_2 + dCO + fO_2 + RaN_2 \qquad (17.5)$$

where R is the molar ratio of nitrogen to oxygen in the feed gas and $a, b, d,$ and f are stochiometric coefficients similar to those in Eq. 17.3.

The range of the ratio, n, for high temperature reactions should be from 0.5 to 2. Calculation of an unusually high value of n indicates that low temperature oxidation is important. In the very early stages of field projects high "n" values are often observed because of the solubility of the combustion gases, particularly CO_2, in the oil.

Once n and m are known, the amount of air required to burn one unit weight of fuel is found from Eq. 17.3. The heat generated by burning a unit weight of fuel can be calculated by simple addition of the heat generated by each reaction as described in the stoichometric equation (Eq. 17.3). The calculation of heat produced must take into account the production of carbon monoxide. The following formula[13] can be used to estimate heating values of fuels as a function of n and m.

$$H_c = \frac{m(174{,}000)}{(m+1)(n+12)} + \frac{52{,}500}{(m+1)(n+12)} + n\frac{61{,}500}{(n+12)} \qquad (17.6)$$

where

H_c = heating value, Btu/lb fuel

To convert to Joules/kg multiply by 2,326.

The air required to burn a given volume of reservoir is of course a very important design parameter and one of the keys to the economics of the combustion process. This is directly calculated from the experimental data by dividing the amount of oxygen consumed by the volume swept during the tube run. The mass of fuel burned in a unit volume of reservoir can be calculated from the oxygen consumed by a unit volume and applying Eq. 17.3. All the other relevant parameters can be estimated[13,14]. It is prudent to perform multiple laboratory tube runs prior to field implementation.

4. COMBINING MATERIAL AND HEAT BALANCE CALCULATIONS

Many useful and reasonably accurate calculations can be made on ISC to predict the behavior of a proposed project. These ideas will be explained in the following diagrams and example calculations. They start with a very simple heat balance, and are then extended to more closely represent what happens in the laboratory and reservoir.

4.1. First Assumptions

Start by assuming no combustion data is available to get an initial idea of the feasibility of a project. This preliminary work gives the engineer a sound basis to decide whether further work has economic promise. Assume a sandstone formation with a porosity of 22%, a temperature of 100°F, a 24° API oil at a saturation of 65%, and an injection pressure of 300 psia. Also assume the CO_2/CO atomic ratio, m, will be,

$$m = \frac{CO_2}{CO} = 20 \tag{17.7}$$

This is a reasonable ratio to assume, based on both laboratory and field experience. Since there is no tube run data, generalized correlation curves[13], Figs. 17.4 and 17.5, will be used to calculate expected results. From Fig. 17.4, the fuel availability, W, for 24°API crude is,

$$W = 0.95\, lb\, C / 100\, lb \text{ Rock} \tag{17.8}$$

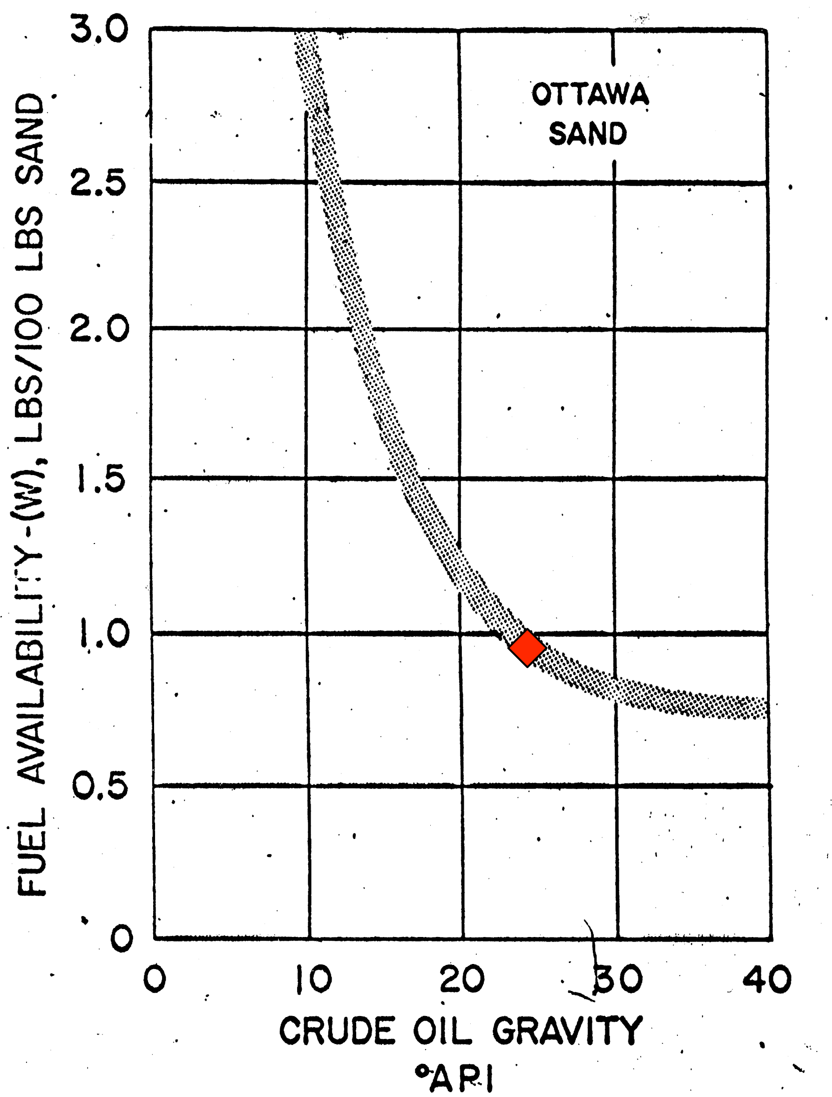


Figure 17.4. Fuel Availability vs Oil/Gravity[13]

The apparent *H/C* atomic ratio (*n*) of the fuel is also needed. This is a function of the combustion front temperature[13] as shown on Fig. 17.5. Selected data from the graph are listed in Table 17.1.

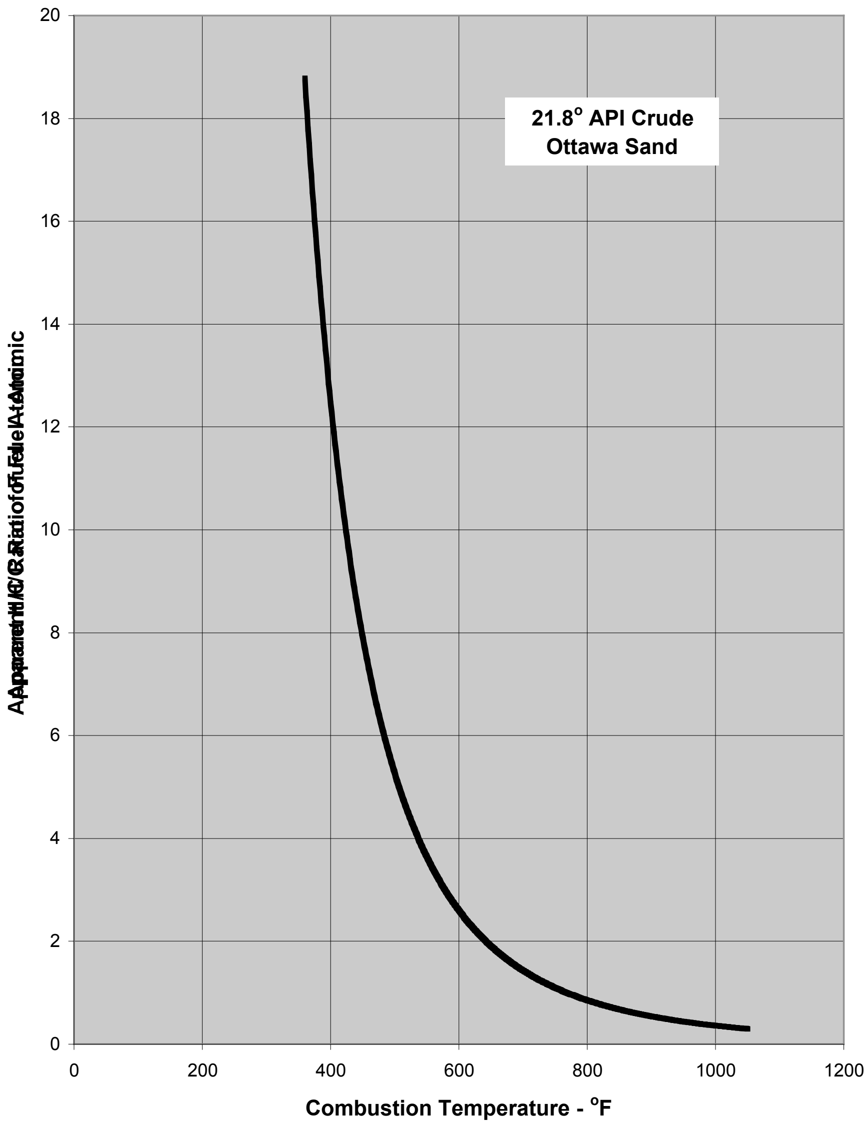


Figure 17.5. H/C ratio vs. combustion temperature[13].

Table 17.1 Effect of Temperature on H/C Ratio, 21.8° API Crude

H/C Ratio, n	Comb. Temp (°F)
0.40	1,000
0.80	800
1.40	700
2.40	600

These data for 21.8° API crude are close enough to 24°API crude for initial estimates.

4.2. Calculate Initial Heat Balances and Temperatures

Start by assuming all heat generated is used to heat the rock formation through which the combustion front has moved. This assumption is incorrect, but simplifies understanding of the mathematics and concepts involved in heat balance calculations. A sketch of the temperature profile generated is shown in Fig. 17.6. Corrections to this heat balance calculation will be discussed later.

Assuming 1.0 ft^3 of rock formation burned and the front temperature is 1000°F, from Eq. 17.8, and Table 17.1, we get,

$$\frac{\text{lb Fuel}}{100\,\text{lb Rock}} = \frac{\text{lb Carbon}}{100\,\text{lb Rock}} + \frac{\text{lb Hydrogen}}{100\,\text{lb Rock}} = 0.95 + \frac{0.95(0.40)}{12} = 0.9817 \qquad (17.9)$$

Quartz weighs about 164 lb/ft^3. The amount of fuel for a cubic foot of formation equals

$$\frac{(0.9817)(164)(1-0.22)}{100} = 1.256\,\text{lb Fuel/ft}^3\,\text{Rock} \qquad (17.10)$$

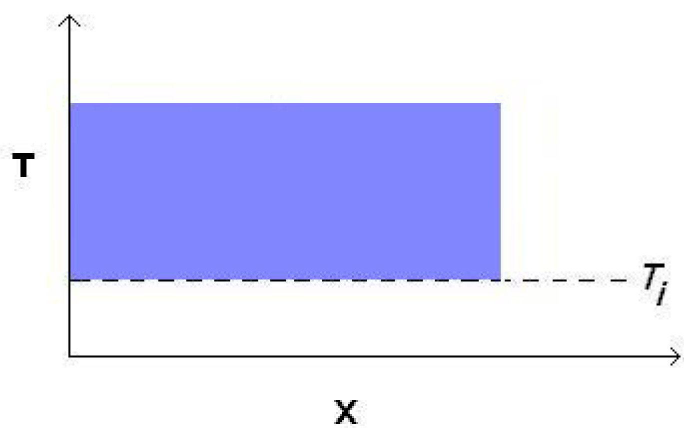


Figure 17.6 Idealized Temperature Profile Assuming All
Heat Stays In The Burned Zone.

Using the heat of combustion, Eq. 17.6, with the appropriate parameters, it becomes,

$$H_c = \frac{(20)(174{,}000)}{(21)(12.4)} + \frac{52{,}500}{(21)(12.4)} + \frac{(0.4)(61{,}500)}{12.4} = 15{,}550\,\text{BTU/lb Fuel} \qquad (17.11)$$

Thus the total heat generated is,

$$\frac{\text{Heat generated}}{\text{ft}^3\ \text{Rock}} = (15{,}550)(1.256) = 19{,}530 \frac{\text{BTU}}{\text{ft}^3\ \text{Rock}} \tag{17.12}$$

Next, calculate the temperature rise of the formation behind the front by performing a heat balance to see if it matches the temperature assumed. Since, for practical purposes, the only fluid in the formation behind the front is air, which has a very small volumetric heat capacity, we only need to calculate a heat balance on the sandstone itself. A good equation for average sandstone heat capacity is[13],

$$c_s = \frac{T_1 + 2000}{10{,}000} + \frac{T_2 - T_1}{20{,}000} \tag{17.13a}$$

$$= 0.21 + \frac{1000 - 100}{20{,}000} = 0.255\ \text{BTU/lb}-{}^{\circ}F \tag{17.13b}$$

where T_1 = Initial reservoir temperature, ºF,
T_2 = Final reservoir temperature, ºF

From a heat balance calculation, the reservoir sand temperature is as follows,

$$T_2 - 100 = \frac{19{,}530}{(0.255)(164)(1-0.22)} = 598.7$$

or $$T_2 = 699^{\circ}F \tag{17.14}$$

The result from Eq. 17.14 does not agree with the assumed temperature of 1000ºF. Calculations using other assumed temperatures result in calculated temperature values shown in Table 17.2.

Table 17.2 Assumed and Calculated Temperatures as a Function of H/C Ratios

Assumed Temperatures (°F)	H/C Ratio	Calculated Temperature (°F)
1000	0.40	699
800	0.80	802
700	1.40	939

The tabular data is graphed as circles in Figure 17.7. The two temperatures match at 801°F. This is the calculated combustion front temperature if all the heat generated is used to heat the formation behind (upstream of) the combustion front.

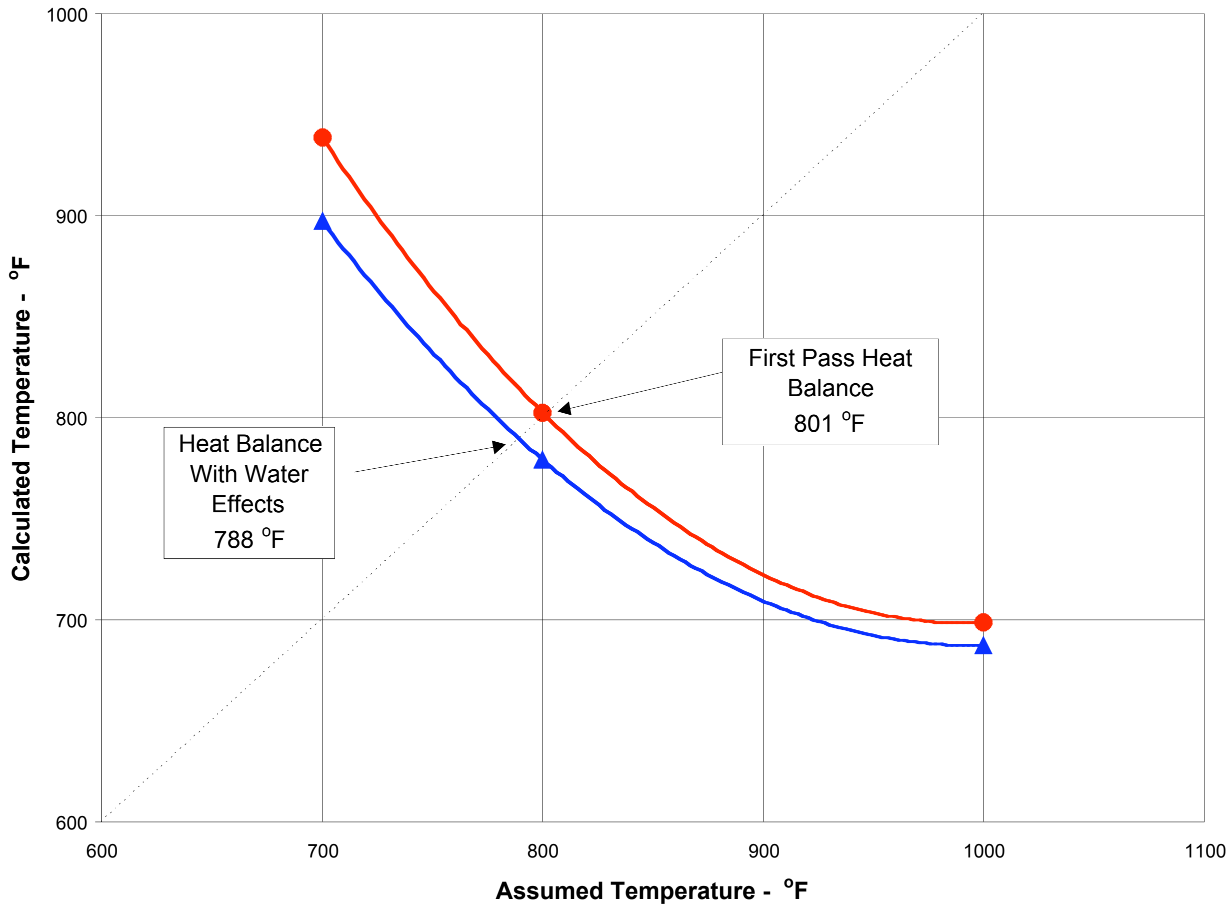


Figure 17.7. Assumed and calculated combustion zone temperatures.

4.3. Correction for Water of Combustion

These results don't include all the processes occurring in the reservoir. First, the water formed by combustion will condense beyond the combustion front, absorb some heat of combustion and reduce the heat of the formation behind the combustion front. This effect can be calculated as follows.

From Eq. 17.9, 0.0317 lb of H_2 are formed per 100 lb of rock at 1000° F. Assuming that a pound of steam will release 1,000 BTU when cooling from combustion temperature and condensing (This number is not exactly correct, but is adequate for estimation purposes.) the amount of heat carried forward by the steam is calculated using concepts similar to Eqs. 17.10 and 17.12,

$$\text{Heat carried ahead by steam} = 0.0317\left(\frac{18}{2}\right)\frac{(1000)(164)(1-0.22)}{100} = 365\,BTU/\text{ft}^3 \text{ Rock burned} \qquad (17.15)$$

In this equation, 18/2 is the ratio of molecular weight of water and hydrogen. The heat given up by the steam is 1000 BTU/lb, and the other numbers are similar to those in Eq. 17.10. Thus, the calculated temperature is lower than it was in Eq. 17.14 as shown below,

$$T_2 - 100 = \frac{19{,}530 - 365}{(0.255)(164)(1-0.22)} = 587.5$$

or,

$$T_2 = 688^{\circ}F \qquad (17.16)$$

Other temperatures were calculated similarly and the results, graphed as triangles in Figure 17.7, show a corrected combustion temperature of 788ºF. At this temperature the *H/C* ratio is 0.85 as indicated in Figure 17.8 below.

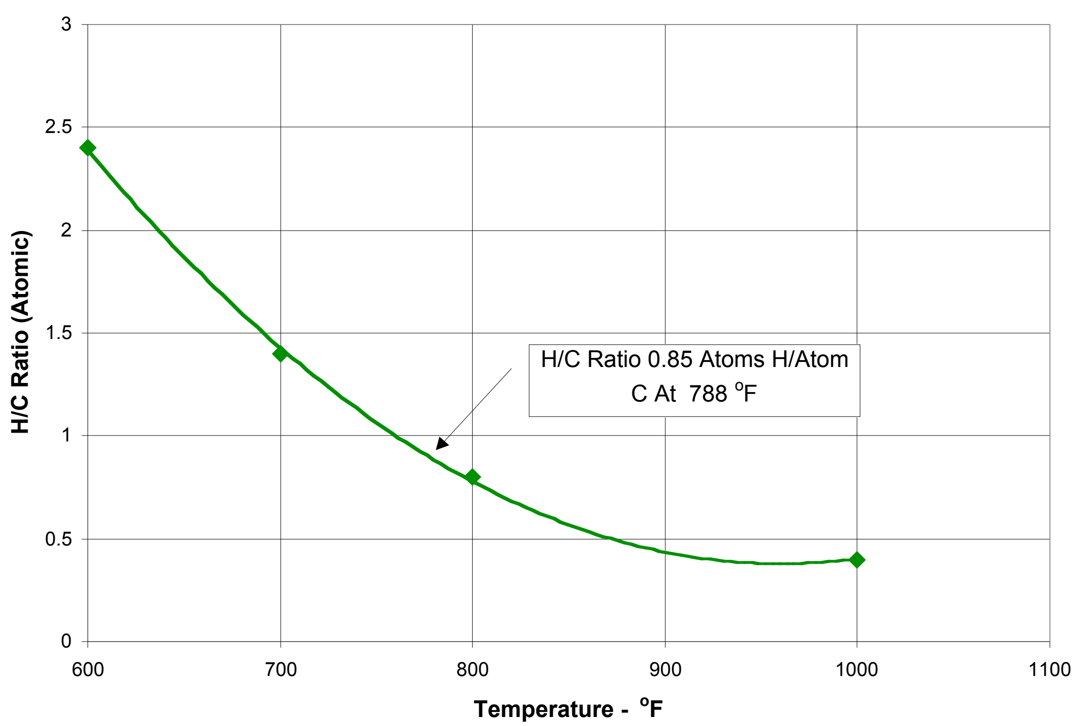


Figure 17.8. H/C atomic ratio versus combustion temperature[13]

4.4. Calculating the Volume and Temperature of the Steam Plateau

No calculations on the steam plateau were necessary in the above calculations. The steam plateau temperature and volume directly affect the volume of oil moved as a result of the combustion process. To calculate these terms, use the *H/C* ratio of 0.85 and calculate the partial pressure of the water as follows.

The fuel composition is $CH_{0.85}$. From Eq. 17.3 the moles of oxygen used per mole of fuel are,

$$O_2 = \frac{2m+1}{2m+2} + \frac{n}{4} = \frac{2(20)+1}{2(20)+2} + \frac{0.85}{4} \tag{17.17}$$
$$= 1.189 \quad \text{moles} \quad \text{O}_2$$

Combustion products are calculated in a similar way,

$$CO_2 = \frac{m}{m+1} = \frac{20}{21} = 0.952 \qquad \text{Moles } CO_2 \tag{17.18}$$

$$CO = \frac{1}{m+1} = \frac{1}{21} = 0.048 \qquad \text{Moles } C\text{O} \tag{17.19}$$

$$H_2O = \frac{n}{2} = \frac{0.85}{2} = 0.425 \qquad \text{Moles } H_2O \tag{17.20}$$

$$N_2 = \left(\frac{79}{21}\right)(O_2) = \frac{79}{21}(1.189) = 4.473 \qquad \text{Moles } N_2 \tag{17.21}$$

The operating pressure is 300 psia. The partial pressure of H_2O in the combustion gas is,

$$p_{\text{water}} = \frac{0.425(300)}{0.952 + 0.048 + 0.425 + 4.473}$$
$$= 21.6 \text{ psia}$$

From steam tables, the saturation temperature for 21.6 psia is 232ºF. This is the temperature of the steam plateau.

The volume of the steam plateau is a function of the amount of H_2O formed. Knowing that there are 0.95 lb C/100 lb rock burned, and knowing from Figure 17.8, that the H/C ratio is 0.85, an equation similar to Eq. 17.10 yields the amount of water formed per cubic foot of rock burned.

$$\text{Water formed} = 0.95\left(\frac{0.85}{12}\right)\left(\frac{18}{2}\right)\frac{(164)(1-0.22)}{100}$$
$$= 0.775 \frac{lb\,H_2O \text{ Formed}}{\text{ft}^3 \text{Rock burned}} \tag{17.22}$$

Thus the total heat carried forward by the water formed, is,

$$\text{Heat carried by steam} = 0.775\,(1{,}000) \\ = 775 \text{ BTU/ft}^3 \text{ rock burned} \tag{17.23}$$

Using Eq. 17.13a, the heat capacity of the formation is,

$$c_s = 0.21 + \frac{232 - 100}{20{,}000} = 0.2166\ BTU/lb-{}^oF \tag{17.13c}$$

The amount of heat needed to raise a cubic foot of sand from 100ºF to 232ºF, from a heat balance, is,

$$\Delta H = \frac{0.2166\,\text{BTU}}{\text{lb-}^oF}\left[\frac{164\,(1 - 0.22)\,lb}{\text{ft}^3}\right](232 - 100)^o F \\ = 3{,}701 \text{ BTU/ft}^3 \tag{17.24}$$

Thus the volume of rock heated by condensing steam is Eq. 17.23 divided by Eq. 17.24,

$$\text{Volume of steam heated rock} = \frac{775}{3{,}701} = \frac{0.209\ \text{ft}^3\ \text{Steam zone}}{\text{ft}^3\ \text{Rock burned}} \tag{17.25}$$

A sketch of the resulting temperature profile is shown in Figure 17.9.

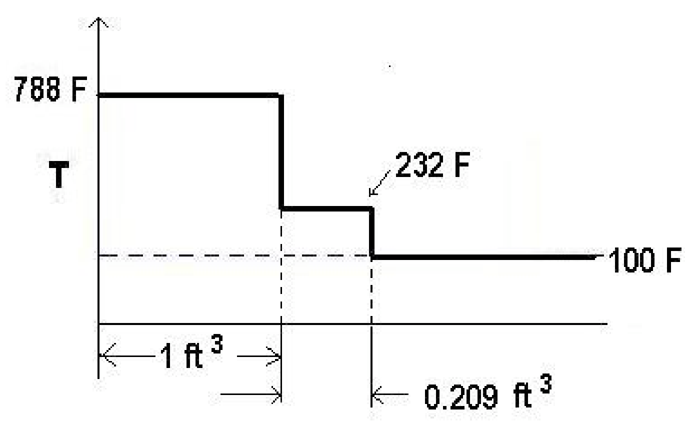


Figure 17.9. Idealized Temperature Profile With Steam Plateau Ahead of Combustion Front.

4.5. Calculating Effects of Injected Air and Water

Further corrections are needed to the temperature profile in Figure 17.9. Injected air will partially cool the burned zone, rise in temperature as it approaches the combustion front, and carry heat forward. This will have little effect on the combustion kinetics or the amount of heat generated by combustion; so, in essence, this amount of energy is merely carried forward to extend the size of the steam plateau.

A sketch of this idea is shown in Figure 17.10 below. In this sketch, the area marked 1 is the temperature profile behind the burning front; Area 2 is the steam plateau, which is now larger than calculated before because of the heat carried forward by the combustion gases.

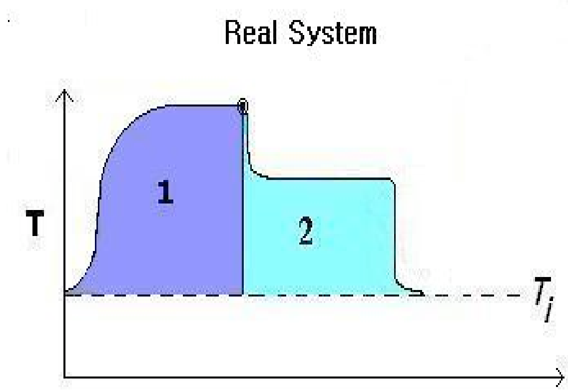


Figure 17.10. Schematic of Combustion Temperature Profile Including Cooling by Injected Air.

This temperature profile can be approximated as indicated in Figure 17.11 where the profiles of the burned zone and steam plateau are treated as square waves that have been adjusted so that the total heat in Areas 1 and 2 are the same as in Figure 17.10.

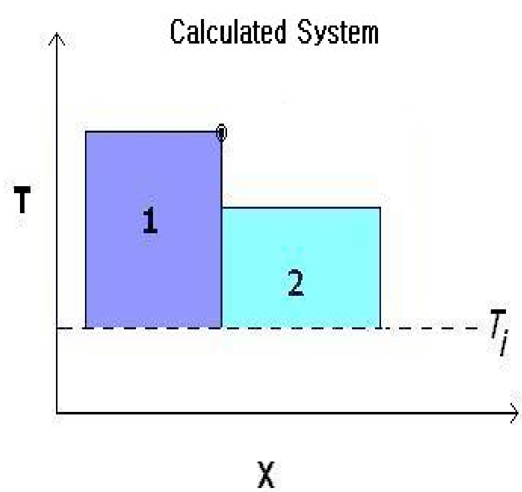


Figure 17.11. Idealized Temperature Profile Including Injected Air Cooling.

There are several reasons for using this square wave concept. One is that it makes it easier to calculate heat losses to be expected from either a laboratory or field combustion operation using superposition calculations similar to those discussed by Ramey[15] as seen in Prats' Thermal Recovery Monograph[2]. These references also indicate that the heat losses calculated using Figure 17.11 are quite adequate.

When wet combustion is used, the temperature behind the front tends to be a sharp front, as shown in Figure 17.11. As a result, heat and material balances of the sort discussed next, can be used to calculate the movement of the resulting cooling front, burn front, and steam plateau.

The amount of air injected per cubic foot of rock burned and the heat capacity of air are needed to calculate this heat transfer process for dry combustion. The volume of combustion gas should also theoretically be calculated, but normally this isn't necessary, for its volume is nearly identical to the air volume. Further its heat capacity is nearly the same – remember that most of the combustion gas is nitrogen.

The moles of air injected are calculated by adding the O_2 from Eq. 17.17 to N_2 from Eq. 17.21,

$$\text{Air injected} = 1.189 + 4.473 = \frac{5.662\ \text{Mole air}}{\text{Mole fuel}} \qquad (17.26)$$

Combining a heat capacity for air of 7.00 BTU/lb Mole - ºF with previously determined factors of 0.95 lb of carbon burned for 100 lb rock, 164(1 - 0.22) pounds of rock per cubic foot of rock, 12 lb of carbon per mole, a combustion zone temperature of 788ºF (Figure 17.7), and the results of Eq. 17.26 yields the amount of heat carried forward by the injected air as follows.

$$\frac{\text{Heat carried by air}}{\text{Cubic ft rock burned}} = \left(\frac{0.95}{100}\right)\left[\frac{(164)(1-0.22)}{12}\right](5.662)(7.00)(788-100) = \frac{2761\ \text{BTU}}{\text{ft}^3\ \text{Rock burned}} \qquad (17.27)$$

This heat extracted behind the burned zone is deposited into the steam plateau. The resulting size of the steam plateau can be calculated in a way similar to Eq. 17.25 by adding the heat carried by the combustion gas to that by the water, as follows,

$$\text{Vol of steam heated rock} = \frac{775 + 2761}{3701} = 0.901\ \text{ft}^3 \qquad (17.28)$$

This calculation shows the condensing steam front is far enough ahead of the combustion front to displace oil efficiently and it is unnecessary to have the combustion front cover the entire reservoir to get good recovery. Recovery can be estimated by knowing the amount of fuel burned, by estimating the residual oil saturation in the steam plateau, and by estimating the sweep efficiency of the process.

4.6. Heat Losses

An estimate of heat losses using the superposition concepts seen in Prats' Thermal Recovery Monograph[2] based on Ramey's[15] work, will make the calculations just presented more accurate. These estimates are particularly important if a laboratory heat balance indicates significant heat losses. The temperature profiles just calculated assuming no heat losses can be used to make a first estimate of heat losses and a recalculated steam plateau size. This is a reasonable way to handle the heat balance. Since all heat transferred was assumed to be in the steam plateau, any reduction in that transferred heat because of losses will reduce the amount of heat in the plateau.

As the size of the steam zone and the size of the calculated heat losses are interdependent, iterative calculations are necessary until the assumed and calculated heat balances match. This will usually require only two to three interations.

Data used in the previous calculations were based on generalized predictions of combustion behavior, i.e., the amount of fuel per cubic feet of formation, and the *H/C* ratio of the fuel. If combustion tube runs are made in the laboratory, those parameters are known and can be used in the calculations. In addition, accurate temperature and saturation profiles versus time will allow reasonably accurate heat balance calculations to determine the heat losses from the experiment. As an alternative, reasonable assumptions about the heat losses can be used to check the heat balance calculations and indicate if there is significant experimental error.

Computer assisted tomography, CAT, scanner measurements produce the most accurate saturation histories. Alternatively, accurate measurements of temperature profiles and accurate oil, water and gas production data also make it possible to estimate reasonable saturation histories. These are the major sources of error in the overall heat balance calculations, but are fairly small compared to the amount of heat stored in the hot matrix.

5. DESIGN CONSIDERATIONS

Conditions favoring the use of ISC rather than steam include the following: 1) high reservoir pressure where steam is not efficient, 2) potential for severe well bore heat losses (i.e., depth, offshore, permafrost), 3) reservoir clay swelling in contact with fresh water, 4) limited water supply and 5) environmental regulations prohibiting steam generation.

Like any other injection process, the design of ISC projects must consider injection pressure limitations and reservoir flow resistance. These are especially important in heavy oil reservoirs where combustion must occur in the high temperature regime to be successful. The minimum air flux needed to maintain high temperatures at the front is estimated to be 0.125 ft/day (0.04 m/day).[14] As the burn zone growth is directly proportional to the injected air, the maximum air injection rate determines the minimum lifetime of the project. Ways to increase the air injection rate are often needed, especially in heavy oil reservoirs. They may include reduced well spacing, cyclic steaming of injectors and producers and an increase in injection pressure. These factors will determine the compressor pressure and volume output.

There has often been some controversy over whether ISC projects should be developed using patterns or line drives. Many early projects were started as pilots with a single injector. Usually this resulted in an inverted five-spot pattern. These pilots behaved contrary to plan with the combustion front moving in only one direction because of permeability variations, gravity effects, well spacing differences or a combination of these factors.

Attempts to correct the unbalanced flow included stimulating unresponsive wells and limiting withdrawal rates of wells that produced excessive volumes of combustion gas. Generally these efforts did not have the desired effect.

In retrospect, this reservoir behavior makes sense. Once a combustion front is even slightly asymmetric, the higher temperature and thus higher mobility will cause greater flow in that direction. Thus the flow will become more asymmetric, finally resulting in flow principally in only one direction.

Since it is often difficult to decide, a priori, which direction the major flow will take, operating plans should remain flexible until field performance indicates what injection scheme best utilizes the flow directions.

For the above reasons many of the more successful ISC projects have been line drive operations that start near the top of the reservoir and move downdip. In such an operation, the direction of the fire front is known. The operating engineers can then plan their completion and operating history in a rational way that will mirror the front movement and breakthrough history. This operating practice can be seen in most of the successful ISC field projects that will be discussed later.

6. PERFORMANCE PREDICTION

Predicting the production response to ISC has been the topic of various studies. Complete numerical simulation of ISC is difficult because of the complex reactions and the thin burning front that requires small grid blocks for representation. Simulators range from tank models to complex three-dimensional simulators. In addition to simulation, empirical models, hybrid models and correlation methods have been developed. A discussion of some of these methods follows.

The easiest method is essentially a tank balance[14] adapted by Prats[2]. The oil and water produced are given by,

$$N_p = \phi V_b (S_{oi} - S_f) + 0.4 S_{oi}(V_p - V_b) \tag{17.29}$$

and

$$W_p = V_b \phi (S_{wi} + S_{wf}) \tag{17.30}$$

where
S_{oi} = initial oil saturation, fraction
S_f = oil saturation burned, fraction
V_b = volume burned, m^3
N_p = oil produced, m^3
W_p = water produced, m^3
ϕ = porosity, fraction
V_p = volume of the pattern, m^3
S_{wf} = water saturation resulting from the combustion process, fraction
S_{wi} = initial water saturation, fraction

If the volumes are in acre-feet and the production terms are in barrels, a multiplication factor of 7,758 must be used. The estimate of 40 percent of the oil in place produced from outside the burned volume is an empirical value based on experience. This is the 0.4 term in Eq. 17.29.

Figure 17.12, presented by Gates and Ramey[16], combines laboratory results and field observations from the Belridge ISC projects. It shows the effect of initial gas saturation on the oil recovery history. Oil production rates and instantaneous air/oil ratios can be estimated from the slopes of the curves. At late times the above two techniques give similar results.

Brigham *et al.*[17] used data from dry combustion field tests to obtain two empirical correlations. Those are presented in Figs. 17.13 and 17.14. The terms in the ordinates are: ΔN_p, cumulative incremental oil produced; N_i, original oil in place; ΔN_b, fuel burned; and N, oil in place at the start of the project.

In addition to original oil saturation, S_o, thickness, h, oil viscosity, μ_o, and porosity ϕ; the abscissas include, a_i, cumulative air injected, N, oil in place at the start of the project, and e_{o_2}, fraction oxygen utilization. The second correlation, Figure 17.14, is the most accurate except for oils of less than 10 cp viscosity where the first correlation should be used. These correlations were generated from small scale floods, thus they would not be expected to be accurate for large scale pattern flooding. However, the narrative in the previous section points out that pattern flooding is generally not the best way to operate an ISC project, and these correlations are expected to be reasonably accurate for line drive projects.

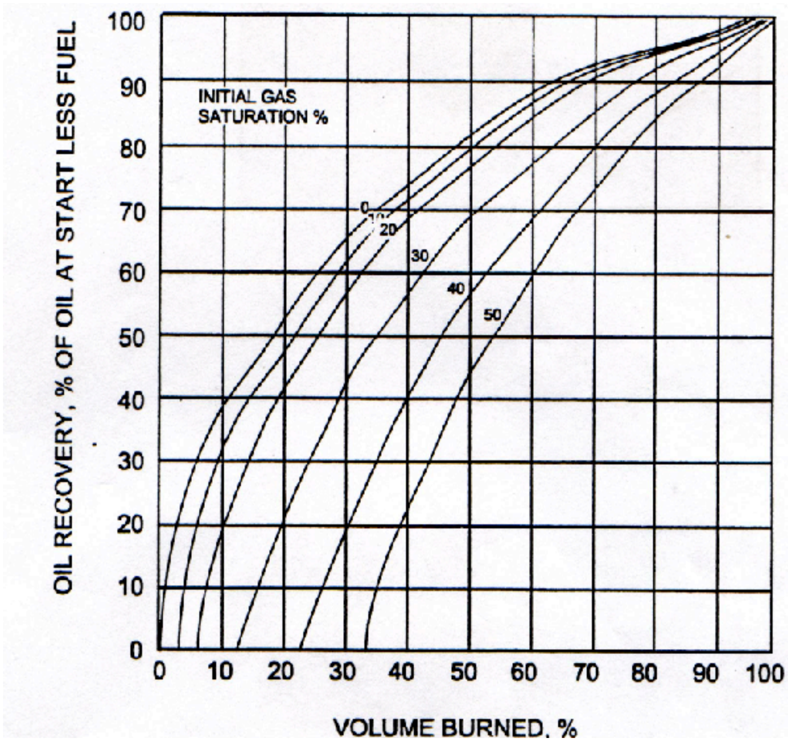


Figure 17.12. Gates and Ramey Method[16]

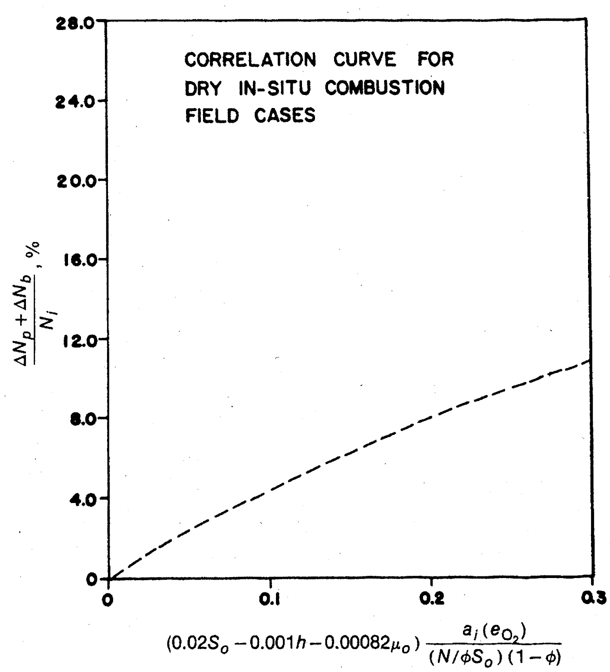
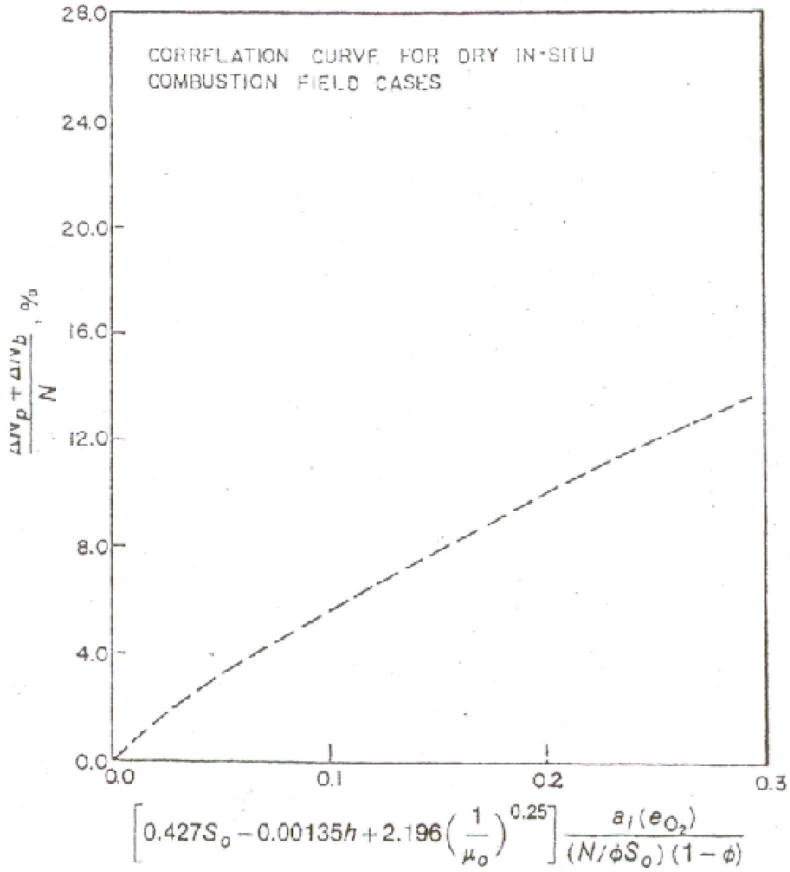


Figure 17.13. First Satman correlation[17]



17.14. Second Satman correlation[17]

7. OPERATING PRACTICES

In addition to the standard field equipment for oil production, ISC requires particular attention to air compression, ignition, well design, completion, and production practices.

7.1. Compressors

Air compression systems are critical to the success of any ISC field project. Failures of the past can often be traced to poor compressor design, faulty maintenance or operating mistakes. A detailed discussion of compressors and sizing considerations appears in Chapter 7 of the Facilities Section of this handbook. Other discussions are available in Sarathi[1].

The factors to be considered when selecting compressors include peak air requirements, injection pressure, capital cost, power requirements, operation and maintenance costs and other relevant technical and economic parameters specific to the field considered. Compressor terminology varies among manufacturers. It is best to obtain a complete description including compressor, driver, interstage cooling system, and all ancillary equipment including control and safety systems from each vendor being consulted.

Air compression causes high temperatures because of the high c_p / c_v ratio of air. Compressor design must consider these high temperatures to ensure continuous, sustained operations free from the corrosive effects of air and the explosion hazards of some lubricating fluids. Mineral oils are not recommended. Synthetic lubricants withstand the higher temperatures and offer lower volatility and flammability than conventional lubricants.

7.2. Ignition

Ignition and maintenance of high combustion temperatures, especially in heavy oil projects, are the most critical factors of an ISC project. Shallcross[18] presented a complete review of ignition methods. The following is a summary of this study.

Ignition can occur spontaneously if the oil is reactive, the reservoir temperature high enough, and the reservoir is reasonably thick. Various models have been proposed to determine the time for spontaneous ignition[19,20].

When spontaneous ignition does not occur or is not desired (i.e., in heavy oil reservoirs where it is important to maintain high combustion temperatures), the most appropriate ignition method to use depends on the reservoir and the equipment available on site.

Down hole gas-fired burners allow good control of the temperature of injected gases and may be operated at a greater depth than other methods. The disadvantages include the need to run multiple tubing strings in the injection wells. Some particulates, such as soot, may be carried into the formation if the gas does not burn cleanly.

Catalytic heaters run at lower temperatures but are sometimes prohibitively expensive. Electrical heaters can be lowered with a single cable, and can provide excellent temperature control. They can be reused repeatedly. There is, however, a depth limitation because of electrical power losses in the cable.

Chemically enhanced ignition does not have a depth limitation but may require handling and storage of dangerous materials. Fuel packs are not recommended because of poor temperature control and nonuniform ignition across the entire reservoir thickness. Well damage from elevated temperatures and plugging by particulate matter may occur.

Steam may be used to locally increase reservoir temperature and facilitate auto ignition. It suffers from depth limitation because of wellbore heat losses, but when the conditions are right it can be a very simple and effective method for ignition.

The additional references include details of design and implementation of the above methods.

7.3. **Well Design and Completions**

ISC wells must be designed to account for several factors amplified by the combustion process, namely high temperature, corrosive environment and sand and clay control. Safe operations should be the primary concern.

Typical well designs for injection and production are shown in Figs. 17.15 and 17.16[1]. Completion type and design depends on the reservoir being considered. Laboratory testing for sand control and completions can help to determine the best completion technique for a given field. Care has to be taken to properly cement the wells. There are cement formulations that are stable at high temperatures[21]. Open hole completions may be used in conjunction with slotted liners, screens, gravel packs or various other sand and clay control methods. To maximize productivity, producing wells should be completed toward the bottom of the zone of interest to take advantage of gravity drainage and avoid hot gases as long as possible. Rat holes have been used successfully in certain heavy oil combustion projects to increase the effect of gravity drainage[22].

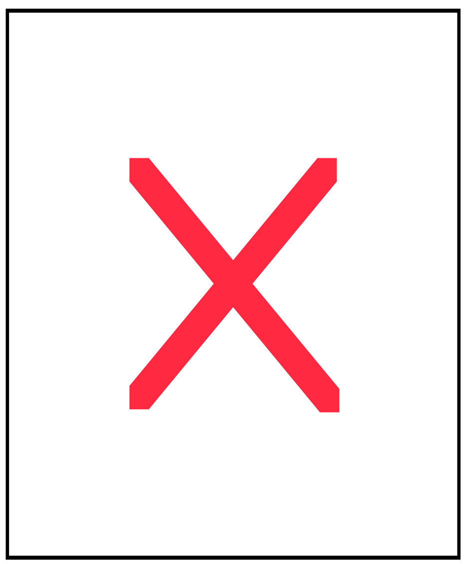


Figure 17.15. Typical injection well design[1]

7.4. **Injection and Production Practices**

Safe air injection requires that the surface injection equipment and the injection well are free of hydrocarbons. All lubricants used in compression and down hole operations should be synthetic or non hydrocarbon types. All equipment, tools, lines, tubing, work strings and injection strings must be clean and hydrocarbon free. Personnel at all levels should be aware of the importance of preventing hydrocarbons in the injection wells. As a safety measure to protect injection wells if the compressor is shut down, a system to prevent backflow of oil from the formation must be present at every injection well.

Downhole temperatures in producing wells increase as displaced oil, hot water and steam fronts reach the well. Producers are preserved by downhole cooling and proper material selection. Figure 17.17 provides an estimate of the water requirements to maintain bottom hole temperature no higher than 250ºF as a function of oil and water production rate and formation flowing temperature. Significant additional oil recovery can be obtained from hot wells with downhole cooling, especially if the well is completed in the lower section of the producing zone to maximize gravity segregation in the reservoir. In many cases, after the combustion front has moved through the well it is possible to convert the former producer to a new air injector, thus realizing significant cost reductions over the life of the project.

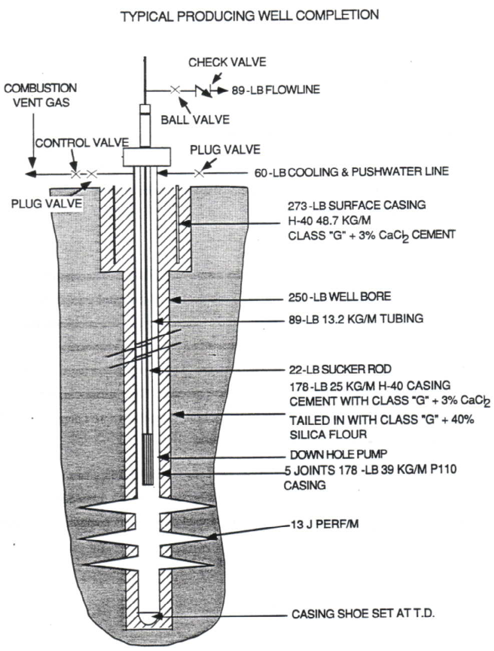


Figure 17.16. Typical production well design[1]

Monitoring is crucial for proper combustion operations. In addition to testing individual producers for oil and water rates, injected fluids must be measured. Also, produced gases must be measured and analyzed to determine the efficiency of the combustion operation. Down hole temperature measurements are essential to calculate the size and location of the burned zone. Flow line temperatures can indicate thermal stimulation or down hole problems.

Combustion projects generate waste water, flue gases and pollutants from compression and oil handling equipment. Local pollution disposal regulations must be consulted prior to the design of any insitu combustion operation.

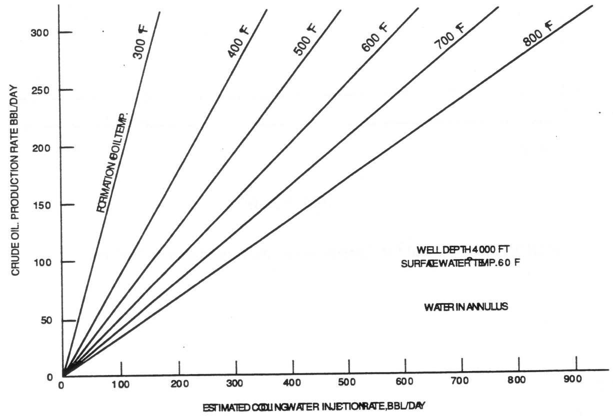


Figure 17.17 Water needed to cool hot wells[1]

Table 17.3. Application of Pollution Control Systems to a Fireflood Project[1]

Equipment	**Gas Treated**	**Pollutant Removed**	**Method**	**Suggested Application**
Flare stack	Flue gas	None	Vent to atmosphere	Flue gas meets air quality regulations
Flare stack with flame burner	Flue gas	H/C (1) ,CO (1) , S-gases (1,2)	Burn	Flue gas with enough H/C to support combustion (>200Btu/Scf)
Thermal incinerator	Flue gas	H/C, CO, S-gases (1,2)	Burn	Flue gas not suitable for a flare with burner or a catalytic incinerator (heat value > 85 Btu/Scf but < 200 Btu/Scf)
Catalytic incinerator (excess air)	Flue gas	H/C, Co, S-gases (2)	Burn	Flue gas with heat value < 85 Btu/Scf
H_2S scrubber	Flue gas	H_2S (4)	Chemical reaction	Flue gas containing H_2S but acceptable amounts of other S gases
SO_2 scrubber	Incinerator exhaust	SO_2 (4)	Chemical reaction	When H_2S removed from flue gas is inadequate or impractical

1. Removal efficiency may be poor
2. S-gases are converted to SO_2
3. May increase amount of CO
   For flue gas with heat values > Btu/Scf
4. Typical removal efficiency is 90-95%.

In general, environmental problems are similar to those posed by steam injection. The produced water may contain H_2S and/or CO_2 which may require special handling and anti-corrosion equipment. Flue gases may contain hydrocarbons, H_2S, CO_2, CO and other trace amounts of sulfur gases. Table 17.3[1] summarizes the various pollution control systems suitable for combustion projects and their recommended applications. Sarathi[1] also provides detailed descriptions of the various types of systems and their uses. Some other problems that can be encountered are sand production, corrosion, emulsions, well failures or compressor failures.

8. FIELD EXPERIENCE

Insitu combustion has been used in the field since 1920. In the U.S. over 230 projects have been implemented. Many of those were technically and economically successful. Unfavorable reservoir and fluid characteristics, poor design and engineering or operational problems caused failures. Most of the failed projects were small pilot projects implemented in unfavorable reservoirs. Worldwide, combustion accounts for about 10% of the oil produced by thermal methods. Steam injection accounts for the rest and is discussed in Chapter 16. Twenty nine projects were active as of 1998[1]. Most of the projects outside of the U.S. are large heavy oil projects while the current trend in the U.S. is to use ISC in deep, lighter oil reservoirs where water flooding or steam flooding are not effective. Brief comments on these projects follow.

8.1. Heavy Oils

For oil with 20º API gravity or less, 19 projects using ISC were active in 1998. Some general comments apply:

- Most of these projects last a long time; projects initiated in the 1960's are still active. Economics of successful projects are favorable even as compared to steam and water flooding[23].
- All of the successful projects operate in the high temperature mode.
- Gravity override and channeling do occur. Gravity drainage of the hot oil is an important mechanism and should be maximized. Frequently, improved production of oil continues after the air injection has been terminated.
- Line drive projects, starting at the top of the reservoir and moving downward, exhibit superior performance compared to repeated pattern projects.
- Most of the projects failed when air injection was attempted in different layers of the reservoir at the same time. Air injectivity is a critical parameter and injectivity contrasts between layers is usually too difficult to overcome.

As a detailed description of all or even a few of the projects is outside the scope of this narrative, the reader can find additional information on several current projects in the following references:

- Projects in Romania: Supplacu de Barcau is the world's largest combustion project. It started in 1964 and is operated in a line drive mode from the top downward. Videle and Balaria are other ISC projects.[24,25]

- In India, Balol, started as a pilot in 1990, was expanded to the whole field. Designed as a wet combustion project, the water injection rate had to be cut in half because of too much cooling. This project was also changed from patterns to updip line drive because of premature breakthrough in the producers.[26,27]
- Projects in Russia, Kasakhstan, and Azerbaijan, are not very well described in western literature.[28]
- The Albanian project of Kasnice is described in Marko.[29]
- Batrum in Canada is a successful Mobil project using horizontal wells as producers. Eyehill field is another Mobil project with horizontal wells.[27,30] Wabaska also uses the same concept of horizontal wells as producers.[31] This technology has been used in Canada since 1993.

Cyclic applications such as pressure up and blow down, have been described[31,32]. This operational technique allows production from very low mobility oil fields or tar sands where fracturing or cyclic steaming are needed prior to air injection. The Wabaska project is a cyclical combustion project with horizontal wells. This type of pressure up, blow down, technique has also been successfully implemented at Wolf Lake[32]. Air was injected until the front arrived at the producers. When the front reached a given producer, this well was shut down and cooling water circulated. When all the producers were shut down, injection was stopped and the producers reopened to blow down the reservoir. This process was repeated for several cycles. Operating combustion in this fashion allows production from fields where injectivity is low because of a high crude viscosity at reservoir conditions.

U.S. projects at Bellevue and Midway-Sunset have been described.[27] More details on the Midway-Sunset project can be found in Hoffmann.[33] Ramey, *et al.*[22] describe the Belridge project as an economic success.

Insitu combustion in heavy oil reservoirs has been successful in both the dry and wet mode. Dry combustion early in the life of the project is the preferred method to form the desired high temperature regime. When the process is well established, moderate amounts of water can be added to improve efficiency. Quenched or super wet combustion seems to have limited success except when used at the end of a field operation to scavenge the heat remaining in the rock.

Another operating variation includes the use of enriched air or pure oxygen. Oxygen enriched combustion presents technical and economic advantages for reservoirs with high pressure or very low injectivity. It has been successfully demonstrated in the field.[34,35] More detailed literature covering the special handling methods and additional precautions needed for enriched air injection is listed in the additional references. Commercial application of the oxygen technology has been limited because of oil price variations.

8.2 Light Oils

In situ combustion is used in light oil reservoirs for a variety of processes:

- To reduce the viscosity of unconventional light oils such as Demjen in Hungary[36]or Niemangu in China[1]. In these cases, thermal effects are important. In the case of Demjen, a catalyst had to be injected to promote combustion. Iron was used to increase the amount of fuel burned because the light oil by itself was not depositing enough fuel to sustain combustion. The oil is parafinic and almost solid at reservoir temperature despite an API gravity of 32º.
- To produce from light oil reservoirs where water flooding or other enhanced oil recovery methods are not attractive. Combustion is used to generate flue gases for reservoir pressure maintenance and production by gravity drainage. Thermal effects are only minor for this process. An interesting case is the West Hackberry double displacement process[37] in which the gas cap is expanded for gravity drainage to recover residual oil after waterflood.
- To burn thin, light oil reservoirs. Combustion is successful in tight carbonate reservoirs, located in the Dakotas, such as Medicine Pole Hill, Buffalo, West and South Buffalo[38] and Horse Creek.[39] In those cases, combustion allows exploitation of thin reservoirs with large well spacing.

8.3. Screening Guidelines

Insitu combustion is a complex process. It combines effects of steam drive, hydrocarbon miscible and immiscible flood, immiscible gas drive and hot and cold water flood. Because of its complexity there is a misconception that combustion has a low probability of success. The truth is that combustion is an economically attractive, proven recovery process, capable of economically recovering a large fraction of the oil in place.

Insitu combustion can be applied to many different reservoirs. Some suggested screening guidelines are:

- Nature of the Formation : The rock type is not important provided that the matrix/oil system is reactive enough to sustain combustion. As in any drive process, high permeability streaks are detrimental. Swelling clays may be a problem in the steam plateau area.
- Depth: Depth should be large enough to ensure containment of the injected air in the reservoir. There is no depth limit, except that this may affect the injection pressure.
- Pressure: Pressure will affect the economics of the process, but does not affect the technical aspects of combustion.
- Temperature: Temperature will affect auto ignition but is otherwise not critical.
- Reservoir Thickness: Thickness should be greater than about 4m (15 ft)[2,3] to avoid excessive heat losses to surrounding formations. Very thick formations may present sweep efficiency problems because of gravity override.

- Permeability: This has to be sufficient to allow injection of air at the designed air flux. The air injectivity is especially important for heavy oil reservoirs. Conditions are favorable when kh / μ is greater than about 5md m/cp.[3]
- Porosity and Oil Saturation: These have to be large enough to allow economic oil recovery. The product, ϕS_o, needs to be greater than 0.08 for combustion to be economically successful.
- Oil Gravity: This parameter is not critical. Insitu viscosity has to be low enough to allow air injection and resulting oil production at the design rate.
- Oil Nature: In heavy oil projects the oil should be readily oxidizable at reservoir and rock matrix conditions. This relationship must be determined by laboratory experiments. The same laboratory experiments can also determine the amount of air needed to burn a given reservoir volume. This is key to the profitability of the process.

9. CONCLUSIONS

In situ combustion can be applied to a wide array of reservoirs. In fact it is the only thermal method that can presently be applied to deep reservoirs, though deep downhole steam generation is being tested. It can be used at any stage of reservoir depletion. It can be used in special situations such as offshore or in arctic regions. Because of the lack of heat losses at the surface and in the injection wells, it is the most thermally efficient thermal recovery method. The injectant (air) is readily available. Combustion allows wider well spacing than steam. Economic results are comparable to those of steam injection.

Several aspects of operating ISC projects are important. First is the large compression ratios and associated costs required to inject air into the formation. Second is planning and design requirements for a combustion project that are more difficult than steam. Third is extensive laboratory work to assess fuel availability, air requirements and burning characteristics of the crude that are required before designing insitu combustion projects. Fourth is the high degree of technical sophistication, and careful monitoring needed to ensure proper operation of a project. Fifth is the limitation of numerical simulation and other techniques that make predictions of recovery more difficult than most other enhanced oil recovery methods.

Considerable improvements in the application of insitu combustion have been made since the early projects. New developments, such as application to light oil reservoirs, injection of gases at high oxygen concentrations, and the use of horizontal wells are reviving interest in ISC. This process deserves consideration for many reservoirs including those in hostile environments or not amenable to other recovery methods.

10. NOMENCLATURE

A	Arrhenius constant, $(kg/m^3)^{1-b} / (Pa)^a$ sec
a	Order of reaction with respect to oxygen, dimensionless
a_i	Cumulative air injected, scf
b	Order of reaction with respect to fuel concentration, dimensionless
C_f	Fuel concentration, kg/m^3
c_p	Heat capacity at constant pressure, BTU/lb $^\circ F$
c_s	Heat capacity of sandstone, BTU/lb$^\circ F$
c_v	Heat capacity at constant volume, BTU/lb $^\circ F$
E	Activation energy, kJ / mole
e_{o2}	Oxygen utilization efficiency, fraction
H_c	Heating value of fuel, BTU/lb
h	Vertical thickness of reservoir, ft
K	Reaction rate constant, $(kg/m^3)^{1-b} / (Pa)^a$ sec
m	CO_2 / CO concentration ratio produced, dimensionless
N	Oil in place at the start of the project, bbl
ΔN_b	Fuel burned, bbl
N_i	Initial oil in place, bbl
N_p	Oil produced, m^3
ΔN_p	Cumulative incremental oil produced, bbl
n	Hydrogen/carbon atomic ratio of fuel, dimensionless
O_2	Oxygen concentration, injected
$(O_2)_{\text{prod}}$	Oxygen concentration produced,
p_{O_2}	Oxygen partial pressure, Pa
R	Universal gas constant, kJ/mole $^\circ K$
R_c	Reaction rate of the crude, kg/m^3 sec
S_f	Oil saturation burned, fraction
S_o	Oil saturation, fraction
S_{oi}	Initial oil saturation, fraction
S_{wf}	Water saturation resulting from the combustion process, fraction
S_{wi}	Initial water saturation, fraction
T	Absolute temperature, $^\circ K$
T_1	Initial temperature, $^\circ F$
T_2	Final temperature, $^\circ F$

V_b Volume of reservoir burned, m^3

V_p Volume of the pattern, m^3

W Fuel availability, lb /100 lb rock

W_p Water produced, m^3

Greek Letters

ϕ Porosity, fraction

μ_o Oil viscosity, cp

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