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ENERGY FROM TRUE IN-SITU PROCESSING OF ANTRIM
SHALE—METHANE BURNER IGNITION SYSTEM

Topical Report

By
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August 1980
Date Published

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The Dow Chemical Company
Process Development Department
Midland, Michigan

U. S. DEPARTMENT OF ENERGY

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ABSTRACT

A rugged yet simple burner that can be easily ignited and reignited is a necessity if in situ thermal methods of energy extraction are to be feasible.

During extraction trials at the Dow Chemical Company's oil shale site at Peck, Michigan such a burner was utilized. The performance of the TOR Development burner and ignitor system proved to be reliable and practical under field conditions. However, some recently discovered measures are crucial in protecting the burner and associated downhole hardware. With such precautions burner life was extended by a factor of 15. In the first trial burner life was two days and in the second trial the burner remained intact at least thirty days.

Also described is a system which monitored burner performance by continuously analyzing burner exhaust gases. A slip stream sampling technique utilized the high well pressure to transport, at nearly Mach 1, a sample of burner exhaust gas to the analytical trailer. There the sample was analyzed for CO, CO₂, unburned hydrocarbons, and O₂ by a bank of high speed process gas analyzers. Burner flameouts could be detected in less than 2 minutes. Also the system allowed burner (air/fuel) ratios to be determined on a real time basis. These ratios were used for (1) setting the proper air-fuel mixtures for ignition and steady state operation, (2) leak detection, (3) estimation of burner deterioration after extended use, and (4) study of the burner's steady state and transient response characteristics.

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INTRODUCTION

In late 1976, The Dow Chemical Company entered into a four-year contract with the Department of Energy to investigate the feasibility of recovering energy from Michigan's Antrim shale by an in situ process. This process requires that combustion be initiated in situ to consume part of the organic content of the shale to produce heat. The heat from the combustion process serves to retort the kerogen, thereby driving off a portion of it as a combustible gas or oil. The contract required that an in situ extraction trial be made using an existing site in which Dow had previously drilled several wells. This work has been reported (Reference 1). The contract also required that three techniques be tried and evaluated for in situ fracturing and that the site which appeared to be most promising be used in a second in situ extraction trial. This second set of extraction trials (results reported in Reference 2) utilized a burner and ignition system provided by TOR Developments, Inc. of Dallas, Texas.

During the first of these trials, F80-1, the burner and associated downhole equipment were installed unprotected in the well cavity. This hardware was destroyed in less than two days by the severe environment generated there. During the second trial, F80-2, the burner and ancillary equipment were protected as described in detail in this report. All evidence indicates that the burner was still intact after 30 days. The third trial was of 17 days duration and there was no evidence of burner deterioration during that time. Ignition and reignitions proved not to be difficult. The burner was operated over a wide range of pressure, from 400 psi to nearly 1300 psi.

Burner operation was greatly aided by the use of the burner exhaust gas sampling and analytical system. This system capably reported the performance of the burner. Any flameout was verified within two minutes. Also as a result of the analytical system the ignition stage is now more completely understood. Operating procedures during light-off can be more closely tailored to the system variables, e.g. burner size, fuel rate, and depth of burner. In addition, the fast response of the system gave early warning signals of incipient flameout.

Previous Burner Experience

Prior to the DOE contract, several unsuccessful attempts to ignite the shale were attempted at the Peck site. Always a major shortcoming was the lack of a reliable ignition system. Successful shale ignitions were achieved in 1977 and 1978, but as reported in Reference 1, the burners and ignition systems were far from satisfactory. In the spring of 1979 the TOR system was given a field test at the site. This test gave encouraging results as reported in Reference 3. Table 1 summarizes the Dow experience with the TOR Developments, Inc. ignition system.

TABLE 1

SUMMARY OF TOR IGNITION EXPERIENCE

Event	Date	Operating Duration	Apparent Condition of Burner
Field Test	March, 1978	82 hours	Good
Extraction Trial 1 (F80-1)	October, 1979	30 hours	Destroyed
Extraction Trial 2 (F80-2)	November, 1979	30 days	Functional
Extraction Trial 3 (F80-3)	March, 1980	12 days	Functional

Dow's experience with downhole burners before utilizing the TOR system is summarized in Table 2.

TABLE 2

DOW BURNER EXPERIENCE
(prior 1979)

Type	Results	Main Failing	Other Problems
Propane w/spark ignition	Fair	Reignition	Plugging from propane cracking
Propane w/methane pilot & spark ignition	Fair	Reignition	flame indication
Electric	Poor	Limited life (hrs) of materials of construction	-

It was very clear after the unsuccessful approaches listed in Table 2 that a downhole burner must have the following characteristics:

1. Rugged construction - must withstand handling prior to and during insertion.
2. Simple design - there is no opportunity for adjusting or fine tuning a complicated device after the burner is in place.
3. Reignition capabilities - one shot burners no matter how good in other aspects are of no value for deep underground in situ experiments.

This report documents that the TOR system fulfills the above criteria providing the precautions contained herein are fully observed.

PART I THE SYSTEM

The burner design and the ignitor system including the method of introducing the hypergolic material triethyl borane (TEB) is covered by a patent to Amoco. A license to practice the teachings of this patent is held by TOR Developments, Inc..

TOR offers, as they have for nearly twenty years, a complete ignition service. Included are the following:

1. Burner - several designs and sizes.
2. Equipment for running the TEB cup downhole. (Gin pole and wire line).
3. Technical manpower for actual ignition.
4. Manpower for monitoring fuel flow.
5. Fuel compressor.
6. Instruments and controls for fuel rate control.
7. A supply of TEB.

Burner Description

The burner is shown schematically in Figure 1. It consists of two simple parts, a barrel and a foot piece. The barrel is a length of pipe (3-6 inches O.D.) which is necked down to match the air piping string. The large diameter section is lined with ceramic, 1/2 inch to one inch thick. The foot piece is a one inch diameter piece of pipe with a machined collar. This collar seats on three radial studs in the barrel wall and thus provides the correct relationship between barrel and foot piece. This is a positive way to achieve the correct position. Such a system is needed since each piece was inserted separately in the well.

The barrel was inserted downhole on the end of the 1200 foot air supply string. The foot piece, on the end of the methane supply string, was positioned after the barrel was in place. For the first trial, both parts were of 304 SS construction. For the second and third trials, the foot piece material was Hastelloy C276, which eliminated corrosion-erosion damage experienced during the first trial.

Figure 2 shows schematically the complete burner installation. Note that above the wellhead was an air-lock device (Slick Line Oil Saver) which allows loading the TEB into the ignitor cup and reinserting the cup downhole with the well under pressure. Figure 3 shows this device in detail.

TOR DEVELOPMENTS, INC BURNER

FIGURE 1

SCHEMATIC OF BURNER INSTALLATION
IN THE IGNITION WELL

Figure 2

TOR TRIETHYLBORANE LOADER ASSEMBLY

FIGURE 3

PART II MONITORING BURNER OPERATION

Methods

Four methods were used to determine whether or not there was combustion at the burner. The primary system was a high volume burner exhaust sampling system coupled with a fast response analytical system. This system and its varied capabilities are the subjects of the next section of this report. During F80-3, at least two methods were available at all times. As reported in Reference 3 downhole burner status had been heretofore very difficult to determine. The other three methods utilized were:

1. Type K thermocouples (4) attached to the burner tailpipe or anchored in the burner collar. These were 1/4" and 1/8" diameter thermocouples with an Inconel 600 sheath.
2. Rhythmic (2-3 sec periods) fluctuations in methane pressure (+ 10PSI) as read on the TOR guage near the methane skid, were present when combustion was occurring at the burner.
3. Fluctuations in the output of a pressure transducer were displayed in the control room on a Fluke digital voltmeter. This system was reliable and sensitive to changes in combustion intensity. In most cases small fluctuations indicating a weak reaction preceded loss of burner flame. Large fluctuations indicated a vigorous fire. These interpretations are based on thermocouple readings and on burner exhaust analysis. This system is described in Reference 4.

Burner Exhaust Gas Sampling And Analytical System

Description

Figure 4 shows a new technique for monitoring downhole burner performance. A sample of exhaust gas was taken from the burner tailpipe. This exhaust gas sample was transmitted 1200 feet up the injection well and 1000 feet overland to the analytical trailer through 1/4" alloy tubing. In the analytical trailer, the exhaust gas sample flowed into the outer chamber of a Balston type 36/12 coalescing filter. Most of the sample flowed out the drain of the filter to vent. The pressure in the outer filter chamber was maintained at ~35 psig by the Taylor pressure indicating controller (PIC) and a Worchester ball control valve. The pressure at the burner, in the bottom of the injection well, was 700-1200 psig. The large pressure differential across the sample line caused the exhaust gas sample to flow at nearly Mach 1. Actual gas velocities of 906 ft/sec were measured at the analytical trailer. This high velocity reduced sample transport to less than 3 seconds. The 35 psig in the filter chamber was sufficient to force a 3.5 l/minute of sample gas through the filter element to a Permapure Type PD750-24-S semipermeable membrane drier, followed by a final dessicant drier.

The clean dried sample was metered to the Beckman Multi Instrument System (BMIS) for analysis and then vented. The BMIS determined carbon monoxide (CO), carbon dioxide (CO₂), and total hydrocarbons as methane equivalent (THC) with Beckman model 864 nondispersive infrared absorbance analyzers. A Beckman model 755 paramagnetic resonance analyzer was used to measure oxygen (O₂). These four analyzers continuously analyzed the sample gas and provided both a meter readout and 0-1 VOLT DC concentration signal. The BMIS signals were multiplexed into a single minicomputer I/O port for processing. The minicomputer was a fully expanded Perkin Elmer Sigma-10 located in the analytical trailer near the BMIS. Current values of CO, CO₂, THC, and O₂ were compared against flameout alarm set points. An alarm in the control

room was triggered if a burner flameout was detected. Current reports of burner exhaust gas composition were periodically printed on the control room's TI-733 teleprinter. The entire system was able to respond to a burner flameout in less than two minutes. In addition, the system allowed the burner dynamic response to be studied. The Balston filter, Taylor PIC, Worchester ball control valve, associated regulators, manual valves, driers, rotameters, etc. were all mounted on one board in the analytical trailer and designated as the hi volume sampler.

In addition, the burner exhaust sample was periodically analyzed on a Carle III-H gas chromatograph (GC) with application 155, refinery gas analysis. This GC was set up to determine H_2 , CO, CO_2 , O_2 + Argon, N_2 , H_2S , SO_2 , itemized C_1 - C_5 hydrocarbon species, and lumped C_6 + hydrocarbon species. This analysis required an hour to complete and the data were collected and processed by the Sigma-10 minicomputer. The BMIS and GC analyses of the burner exhaust samples were in excellent agreement.

Salient Considerations In The Design And Maintenance Of Transport System

The most serious burner flameout monitor problem was downhole clogging of the sample inlet port and/or sample line. Figures 5 and 6 illustrate the sample port design which proved successful. The two figures show the collar which was attached to the burner in the F80-2 extraction trial. This collar had eight cooling fins and eight thermocouple wells machined into it as well as the sample inlet ports. The ID of the sample line was 0.19". Burner exhaust sample was able to flow in through any of four 0.5" diameter ports. Together, the area available for flow in the four ports reduced the sample gas inlet velocity by a factor of at least 27. This reduced velocity plus the 45° downward angle of the ports greatly reduced the chances of entraining particulate matter in the burner exhaust gas sample.

An air-methane mixture would be expected to burn cleanly. Downhole exhaust gas sampling experience did not bear this out. Temperatures over 1200°C will cause methane to thermally crack to form elemental carbon or coke. The naturally occurring brine and high temperature can cause severe stress corrosion cracking, with the corrosion products flaking off as both flecks of metal and as chloride salts of the metals. Simple sustained high temperature will eventually cause oxidation-corrosion products to peel off the burner and associated piping. Thermal and mechanical shock can cause the burner's ceramic liner to break into fine pieces. Misuse of pipe dope when installing the burner can also contribute to a clogged sample line. A piece of metal or ceramic liner blocking the sample inlet port can be blown away by backflowing the sample line using a high pressure gas cylinder on the surface. In the F80-1 extraction trial, a more serious type of blockage occurred. During a temperature runaway, a slug of molten metal and chloride salts was sucked into the sample inlet port. Moving at Mach 1, this molten slug traveled 90 feet up the sample line before encountering a small burr in one of the socket weld unions used

FIGURE 4

BURNER FLAMEOUT MONITOR

"A" - Slip fit with Burner Outlet (Both Ends)
 "B" - Match ID of Burner Outlet

BURNER COLLAR F80-2

FIGURE 5

BURNER COLLAR - SECTION THRU SAMPLE PORTS

FIGURE 6

to assemble the tubing sections. Here it solidified and turned into a six inch long solid crystal of metal and chloride salts, completely blocking flow thru the exhaust gas sample line. It is beyond present technology to sample or operate a burner under conditions which developed during F80-1. Fortunately, the measures taken to cool and protect the burner in the F80-2 extraction trial were effective. The downhole sample line functioned over 90 percent of the time. A temperature excursion in the F80-3 extraction trial caused loss of two thermocouples and also caused sample line clogging. This thermal runaway welded the burner tail pipe to the casing so that recovery was impossible. The exact nature of the F80-3 sample line clog is unknown, but 5000 psig of hydraulic pressure was unable to dislodge the obstruction. These trials taught that it would have been helpful to have a solenoid 3-way valve installed on the sample line near the well head as in Figure 7.

SCHEMATIC - SAMPLE LINE BACKFLUSHING

FIGURE 7

The high pressure N₂ cylinder could be kept in place and ready for immediate backflushing. The solenoid valve could be triggered in a number of ways:

1. Manually from the control room
2. Periodically by a small drum and cam timer
3. Automatically by a low burner sample flow alarm

Assuming proper sample inlet port design, a sample line backflush system, and careful burner operation, the downhole exhaust gas sampling technique can be made to function reliably. The rewards for this effort are significant, as the burner exhaust gas analyses provided the most complete information on burner performance.

Determination of Burner (air/fuel) Ratios From Burner Exhaust Composition

The burner temperature was controllable by regulating the relative amounts of air and methane fed to the burner. This control parameter was usually expressed as the air-to-fuel ratio (air/fuel). This ratio was routinely computed from surface flow rate measurements. It can be shown, from first principles, that the (air/fuel) ratio can also be determined from the burner exhaust gas composition. The BMIS instruments furnished enough data to calculate the ratio in two different ways. For a partially burned exhaust gas sample:

$$[\text{air/fuel}]_{\text{CO}_2} = \frac{100}{\left[\% \text{CO}_2 + \% \text{CH}_4 + \% \text{CO} \right]} + 1 \quad (1)$$

$$[\text{air/fuel}]_{\text{O}_2} = \frac{209.6}{20.96 - \left[\% \text{O}_2 - 2\% \text{CH}_4 - \frac{\% \text{CO}}{2} \right]} \quad (2)$$

The denominator of equation (1) is the equivalent % by volume of carbon dioxide which would have formed if combustion had been complete. Similarly, the denominator of equation (2) is the equivalent % by volume of oxygen which would have been consumed if combustion had been complete. Both equations assume the analytical data are on a dry basis.

When the BMIS was properly calibrated, $(\text{air/fuel})_{\text{CO}_2}$ and $(\text{air/fuel})_{\text{O}_2}$ agreed to within $\pm 7\%$ relative. Usually the arithmetic mean of the $(\text{air/fuel})_{\text{CO}_2}$ and $(\text{air/fuel})_{\text{O}_2}$ was reported. This average was referred to as $(\text{air/fuel})_{\text{BMIS}}$. The (air/fuel) ratio computed from surface flow rate measurements was known as $(\text{air/fuel})_{\text{TOR}}$. $[\text{air/fuel}]_{\text{BMIS}}$ and $[\text{air/fuel}]_{\text{TOR}}$ usually agreed with $\pm 5\%$ relative. On several occasions, a greater disagreement than $\pm 5\%$ led to the discovery of a methane or air leak in the surface equipment. This technique was proven to be a very powerful and reliable method of leak detection. Discrepancies which were not resolvable by BMIS calibration or fixing leaks were noted later in the extraction trials. Deterioration of the downhole injection well casing and burner were believed to be responsible. This deterioration allowed casing gases to contaminate the burner exhaust gas sample.

Once there was confidence in the system, it was routinely used to verify methane arrival at the burner and to set proper (air/fuel) ratios for burner ignition.

Use of Analytical Exhaust Gas Analysis to Determine Transient Responses of TOR Burner

On November 26, 1979 at about 1715 the TOR burner was ignited. This ignition was immediately confirmed by burner temperature and exhaust gas composition measurements. The burner operated well for about 17 minutes. TOR operators do not leave their ignitor tool in the burner seat longer than a few minutes. As the burner warms up it can cause the tool to become coked and/or warped. Either of these can cause the tool to become jammed. In this case, when TOR lifted their ignitor tool, the burner had a flameout. This was confirmed by both burner temperature and exhaust gas composition.

In Figure 8 the burner temperature is plotted vs time. The points at which the ignitor tool first reached the burner and at which the ignitor tool was lifted are noted. Burner ignition is indicated by increasing temperature after the ignitor tool reached the burner. Burner flameout is indicated by decreasing temperature after the ignitor tool was lifted.

FIGURE 8

This temperature was measured by a thermocouple imbedded inside of a collar welded around the outside of the burner. This collar weighed about 250 lbs and had integral longitudinal slots for cooling the burner. (see Figure 5 and 6). The collar also contained the exhaust gas sampling ports. Heat from the burner had to conduct approximately two inches through the steel alloy collar to reach the thermocouple. In addition, gas flowing past the slots continuously carried heat away. For these reasons the thermocouple was not expected to read the actual burner exhaust temperature. In addition, the thermocouple response was expected to be slow because of the long heat transfer path and large thermal inertia of the collar. These disadvantages were accepted to make the thermocouple rugged enough to survive well insertion and provide the longest possible service life. Figure 8 shows the thermocouple gave a reasonably fast response time. The temperatures give good clues to the downhole conditions.

In Figure 9 the same burner temperature plus the % by volume of oxygen, unburned hydrocarbons, carbon dioxide, and carbon monoxide in the burner exhaust are plotted vs time. When the burner ignited, the oxygen and methane concentrations decreased as the carbon dioxide and carbon monoxide concentrations increased. As the burner warmed up, it began to operate more efficiently as evidenced by a gradual decrease in carbon monoxide and a corresponding increase in carbon dioxide. Data from other burner ignitions indicated that combustion efficiency reached essentially 100% after one hour of warm up.

Also in Figure 9, note the small fluctuations in the concentrations of the various components, especially carbon dioxide. This oscillation was typical of the TOR burner. There could be several causes:

1. The burner was not a well mixed system. The fluctuations could have been caused by small pockets of gas with a higher or lower (air/fuel) ratio than the bulk average in the gas. (eg. - a diffusion flame as opposed to a homogeneous flame)
2. The fluctuations could have been caused by small changes in the air and/or methane flow rates to the burner.
3. The inherent noise levels in the BMIS instruments.

Since all four components seem to cycle together with the proper phase shift (eg - CO₂ goes up as O₂ goes down), items 1 and 2 were probably the two biggest contributors to the fluctuations. This small instability was always present, even after several days of operation. On some occasions, an impending flameout showed up as a growing instability in the concentrations of the various exhaust gas components. Evidently, the burner often "flickered" several times before going out.

In any case, burner ignition and flameout were reliably detected by the exhaust gas analysis. The burner flameout monitor was responding to changes in burner status only seconds behind the burner thermocouple.

The thermocouple, despite all that was done to protect it, failed in seven days. The burner sample line operated for the entire F80-2 extraction trial.

FIGURE 9

BURNER EXHAUST GAS PROPERTIES DURING
IGNITION AND FLAMEOUT

Why did the burner flameout? In Figure 10 the instantaneous (air/fuel)_{BMIS} and temperature are plotted vs time. There are three interesting features to this plot:

1. For ~5 minutes before the TOR ignitor tool reached the burner, note there was an enriching of the (air/fuel) ratio (lower (air/fuel) is a "richer" mixture) (stoichiometric is 10:1).
2. At the moment the ignitor tool reached the burner, note the brief "lean" spike.
3. At the moment the ignitor tool was lifted, again note the brief "lean" spike.

The ignitor tool ran up and down in the one inch methane supply line to the burner. It was a close fit, so there was an appreciable pressure drop across the tool. As the ignitor tool was lowered like a piston from the surface, it forced methane to flow faster below it. This increased methane flow caused the (air/fuel) ratio to decrease. When the ignitor tool reached the burner, there was a partial vacuum behind it. Methane flow almost stopped and the (air/fuel) ratio became very lean until additional methane could flow into the void. The fact that there was burner light-off despite the "lean" spike possibly indicated that the rich mixture from a few minutes earlier was still in the vicinity. This richer mixture may have sustained the burner until additional methane arrived. In addition, the TEB in the ignitor tool was probably still burning. As the ignitor tool was lifted, again the methane flow was nearly stopped by the pressure drop across the moving tool. The (air/fuel) ratio became too lean and a flameout occurred. By the time any additional methane reached the burner, the inside of the burner had cooled below the auto ignition temperature and the flameout became permanent.

One TOR procedure, which was learned from long experience, is to lower the ignitor tool within 100' of the burner and then wait several minutes. Then the ignitor tool is lowered the rest of the way to the burner. This procedure was not tried on the ignition attempt described in this report. But, the data suggest why the procedure is beneficial. Waiting 100 ft. above the burner allows the vacuum behind the ignitor tool to fill in. There will still be a lean spike when the ignitor tool reaches the burner. However, it would not last as long. The Triethyl Borane in the ignitor cup would not be used up and there is an improved probability for sustained ignition.

This insight suggests some improvements:

1. Redesign the ignitor tool for reduced pressure drop.
2. Move the ignitor tool slowly, especially near the burner.
3. Increase the methane flow rate just before lifting the ignitor tool off the burner. This will enrich the (air/fuel) ratio. The lean spike will still occur, but the (air/fuel) ratio will not become too lean to burn. The burner can withstand the increased heat from the richer (air/fuel) ratio for a short duration.

When using several instruments to study transient phenomena, it is important that all the instruments have nearly identical frequency response. This matched frequency response must also be much greater than the highest frequency of the incoming data to avoid distortion.

FIGURE 10

TEMPERATURE AND AIR/FUEL RATIO AT THE BURNER
DURING IGNITION AND FLAMEOUT

The frequency responses of the BMIS instruments were all electronically adjusted to 90% response to a step change in 5 seconds. This frequency response was fine tuned by adjusting the sample flow rate to each instrument. The matching was routinely checked by plotting the response to zero and span gases. As can be seen from Figures 9 and 10, the burner exhaust composition data and (air/fuel)^{BMIS} ratios require about 20 seconds minimum to complete a step change. Thus, the BMIS was able to faithfully describe the burner's transient response. Reference 5 discusses the BMIS hardware and data processing in more detail.

PART III METHANE SUPPLY SYSTEM

Commercial grade methane, minimum purity 93%, was supplied in tube trailers from Linde Division, Union Carbide Corporation. Each tube trailer contained over 100 M scf of methane gas at 2000 psig as delivered. When pressure in the supply trailer was above well pressure the methane was metered to the burner as shown in Figure 11. The instruments and controls were skid-mounted in close proximity to the tube trailers. Tube trailers and methane control skid were located over 1000 feet from the experimental wells for increased safety. To prevent hydrate forming conditions in the system, all instruments, controls and skid piping were heat traced with 1/4" tubing containing 80°C glycol. When pressure in the trailer tubes fell below well pressure, the methane was supplied to the burner as shown in Figure 12. The TOR compressor was powered with a gas engine using either propane or methane as fuel.

PART IV BURNER PERFORMANCE DURING THREE EXTRACTION TRIALS

First Trial (F80-1) Burner Performance

The position of the burner with respect to the casing and cavity is shown in Figure 13. The position was determined by the location of the primary fractures leading to the production wells. By having the burner close to the fracture opening, the exhaust gases would enter the fracture at the maximum gas temperature. Note that the burner is 91 feet into the cavity. As described fully in Reference (2) an intense fire in the cavity destroyed the equipment located within it. Figure 14 shows the time temperature history within the cavity to the time of thermocouple failure.

It is postulated that there was a "sweating out" of combustible vapors from the shale during the initial 30 hours of cavity heating. These vapors and other well gases were exposed to the oxygen rich atmosphere in the cavity where the high rugosity of the wells presented a large area of hot surface and at the proper moment these produced a veritable fire storm in the cavity. The extreme heat in well #301 that occurred after the shale ignited caused the 2-inch air line to break off approximately 30 ft above the bottom of the burner. The body of the burner then dropped to the bottom of the well and was not retrieved. The thermocouples and 40 ft of sample line were also lost. The entire 1-inch methane injection line was removed intact. The footpiece was filled with carbon, presumably caused by thermal cracking of methane, but tests showed that it could still pass 10 scfm of air with only a moderate pressure drop (~50 psig). This char and loss of the burner indicate temperatures in excess of 2000°F existed in the wellbore around the burner.

Figure 11
 METHANE SUPPLY SYSTEM
 (Tube Pressure Above Well Pressure)

Figure 12
METHANE SUPPLY SYSTEM
 (Tube Pressure Below Well Pressure)

POSITION OF EQUIPMENT DURING
OCTOBER 1979 BURN

FIGURE 13

FIGURE 14

Data obtained from the burner auxiliaries that were retrieved, i.e., part of the exhaust gas sampling tube and parts of the thermocouples, indicated that conditions in the borehole were more severe than anticipated. Stress corrosion cracking of type 316 stainless steel and high temperature oxidation of Inconel* 600 and carbon steel were found. Even Hastelloy** C-276 did not endure, and this had been considered the alloy best suited for downhole conditions. Figure 15 is a summation of the fate of the downhole hardware.

Conclusions From First Trial (F80-1)

1. The burner and ancillary equipment must be protected from the cavity fire.
2. Air cooling is effective as evidenced by the recovery of an intact methane line.
3. Based on the condition of the Hastelloy 276 retrieved, there is no practical way to solve the corrosion problem by choice of materials alone.

Second Extraction Trial (F80-2)

Preparation

Figure 16 shows the burner installation for the second trial. The following are the primary changes which were incorporated to protect the downhole equipment:

1. The burner was mounted in the casing. Only two feet of the four foot long tailpipe extended into the cavity.
2. A collar was placed between the burner and tail pipe. Details are shown in Figures 5 and 6. The collar with the integral extended surface for enhanced heat transfer shielded the sample line, thermocouples and the heater itself from the conditions which developed in the cavity. Also, whenever casing air was momentarily lost, the collar prevented any appreciable backflow of the hot cavity gases.
3. Two thermocouples were located 10 feet above burner to detect any temperature rise in the casing.
4. A water injection system was installed in the event the temperature of the casing could not be controlled by air alone.

Effects of Coolant Addition Thru Casing

In the case of a runaway combustion which threatened to damage the downhole equipment, the capability of cooling through the casing was improved. With water injection and the additional casing thermocouples, the probability of a repeat of the first trial was minimized. Figure 17 shows two cases how the formation temperature theoretically responds to 1) water injection and 2) nitrogen purging.

BURNER FAILURE DESCRIPTION

FIGURE 15

FIGURE 16

MAXIMUM FORMATION TEMPERATURE AS A
FUNCTION OF OXYGEN AT THE PRODUCTION
WELL AND SHOWING THE EFFECT OF
ADDING COOLANT THROUGH THE CASING

FIGURE 17

It shows that formation temperature during ignition phase can readily be depressed about 1000°F.

As was shown in Table 1, the burner was operational 30 days from the first ignition. (Actual on-time was 24 days during that 30 day period.) There was no reason to believe that the burner was not functional after 30 days. At that time the combustion moved into the formation and no reignition was attempted. Both water injection and nitrogen were used for short intervals during the first few days to cool off the burner environment. The effect was plainly evident in the thermocouple readouts.

Third Extraction Trial (F80-3)

Plans for the downhole equipment for the third trial originally included all the features that performed successfully in F80-2. However, an obstruction at the 500 ft. level prevented the installation of the collar. In a large bore hole as used in the second trial (9 inch I.D.) with a 4 inch diameter burner, the collar was believed to be essential. In the case of F80-3, with a smaller bore hole (5 inch I.D.) with a 3 inch diameter burner, the lack of a collar was not believed to be critical and such proved to be the case. The burner performed well during the trial with no indications of burner deterioration. The equipment location in the well is shown in Figure 18.

PART V CONCLUSION

After the burner performance of the second and third trials, burner ignition, maintenance and monitoring are no longer problem areas. If the systems, procedures and precautions described in this report are duplicated, reliable and predictable burner operation is assured.

**MODIFIED BURNER AND DOWNHOLE HARDWARE LOCATIONS
IN INJECTION WELL #305, F80-3**

FIGURE 18

REFERENCES

1. McNamara, Patrick H., "Energy From True In Situ Processing of Antrim Oil Shale - Initial In Situ Extraction Trials" Topical Report FE-2346-42.
2. VanDerPloeg, M. L., et al, "Energy From True In Situ Processing of Antrim Shale - Extraction Trials In An Explosively Fractured Site" Topical Report FE-2346-73.
3. Cole, J. L., Pihlaja, R. K., "In Situ Combustion of Antrim Oil Shale - Field Test of Tejas Petroleum Engineers Burner" Topical Report FE-2346-48.
4. Frost, J. R., Pihlaja, R. K., "Energy From True In Situ Processing of Antrim Shale - Process Control and Data Collection" Topical Report FE-2346-70.
5. Pihlaja, R. K., "Energy From True In Situ Processing of Antrim Shale - Sampling and Analytical Systems" Topical Report FE-2346-75.