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FIELD TEST OF TWO HIGH-PRESSURE DIRECT-CONTACT
DOWNHOLE STEAM GENERATORS, VOLUME II: OXYGEN/DIESEL SYSTEM

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ABSTRACT

A field test of an oxygen/diesel fuel, direct contact steam generator has been completed. The field test, which was a part of Project DEEP STEAM and was sponsored by the U. S. Department of Energy, involved the thermal stimulation of a well pattern in the Tar Zone of the Wilmington Oil Field. The activity was carried out in cooperation with the City of Long Beach and the Long Beach Oil Development Company. The steam generator was operated at ground level, with the steam and combustion products delivered to the reservoir through 2022 feet of calcium-silicate insulated tubing. The objectives of the test included demonstrations of safety, operational ease, reliability and lifetime; investigations of reservoir response, environmental impact, and economics; and comparison of those points with a second generator that used air rather than oxygen. The test was extensively instrumented to provide the required data. Approximately 114 tons of fuel, 371 tons of oxygen, and 2388 tons of coolant water were consumed over a four month period; this resulted in the injection of 4115 MMBtu of thermal energy, 15130 cold-water-equivalent bbls of steam, and 5.9 MMscf of carbon dioxide. Typically, the combustion efficiency was 95% and the steam quality was 50%. Thermal efficiency of the insulated tubing delivery system was estimated to be 73% early in the steam injection program and 62%

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after two months of intermittent use. Excluding interruptions not attributable to the oxygen/diesel system, steam was injected 78% of the time. System lifetime was limited by the combustor, which required some parts replacement every 2-3 weeks. For the conditions of this particular test, the use of trucked-in LOX resulted in less expense than did the production of the equivalent amount of high pressure air using on site compressors. No statistically significant production change in the eight-acre oxygen system well pattern occurred during the test, nor were any adverse effects on the reservoir character detected. Gas analyses during the field test showed very low levels of SOX (≤ 1 ppm) in the generator gaseous effluent. The SOX and NOX data did not permit any conclusion to be drawn regarding reservoir scrubbing. Appreciable levels of CO ($\leq 5\%$) were measured at the generator, and in this case produced-gas analyses showed evidence of significant gas scrubbing. During the test, on-site briefings were provided to approximately 250 individuals, representing 60 private concerns, universities, or government agencies (from the United States and 5 other countries).

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I. INTRODUCTION

Sandia National Laboratories has been the technical manager of the United States Department of Energy's Project DEEP STEAM since 1978. The objective of this project has been to develop the technology required to economically produce heavy oil from reservoirs greater than 2500 feet in depth using steam injection. This effort has had three main thrusts:

1. The evaluation of insulated tubing performance.
2. The development and testing of thermal packers.
3. The development and testing of downhole steam generators (DHSG's).

An Advisory Panel of government, industry and university representatives was formed and has convened periodically to review Project progress and to make recommendations on the future course of the Project.⁽¹⁻⁵⁾ Results from Project DEEP STEAM have frequently been reported over the past five years.⁽¹⁻²⁷⁾ The present report is one of several final reports on item 3, the DHSG program under Project DEEP STEAM.^(28,29) Initially, a number of approaches to downhole steam generation were identified; this included electric heating, hydrogen/oxygen combustion, and combustion of gaseous and liquid hydrocarbon fuels. The last approach was assessed to be the most promising.⁽⁶⁾ Two DHSG concepts utilizing hydrocarbon combustion have been pursued:

1. Direct-contact generation--water is flashed to steam by injection into hot high-pressure combustion products, and the resulting mixture is injected into the oil reservoir.
2. Indirect-contact generation--heat is transferred from low-pressure combustion products to water via a heat exchanger to form high-pressure steam for injection into the reservoir. Combustion products are piped to the surface for exhaust into the atmosphere.

A comparative analysis of steam delivery costs for surface and DHSG technologies was carried out^(25a,b) for the following systems:

1. Surface steam generation with insulated tubing delivery,

2. Direct-contact downhole steam generation using air as the oxidizer,
3. Direct-contact downhole steam generation substituting pure oxygen for air,
4. Indirect-contact downhole steam generation using air.

The major conclusions were:

1. The dominant cost factor for all systems is fuel.
2. The steam delivery cost for a surface system with uninsulated tubing increases rapidly between 1000 and 3000 feet depth.
3. Surface and downhole technologies costs are not readily distinguishable with low injection rates.
4. High injection rates result in slightly higher costs for the direct-contact technologies relative to the other; however, the ability of the combustion gases to mobilize oil could offset or even dominate these higher costs.
5. The use of oxygen rather than air in direct-contact systems helps decrease cost (for high injection rates) by lowering the compression requirements.

Consistent with these conclusions, development of DHSG technology has proceeded through both contract and in-house programs. A conceptual, feasibility, and design study of an indirect-contact DHSG by The Rocketdyne Division of Rockwell International has culminated in several reports.⁽²⁶⁻²⁷⁾ The development of a refractory-lined (hot wall) direct-contact DHSG by Foster-Miller Associates has reached the field-testing stage. An equivalent 5-day test of the Foster-Miller design in a simulated downhole environment was recently completed.⁽²¹⁾ At Sandia National Laboratories, a metal-walled direct-contact DHSG design has evolved from a steam generator originally burning propane in air. Current designs burn No. 2 diesel fuel in air and in pure oxygen, and the ultimate goal in this evolution is to burn lease-produced crude oil. Supporting studies of combustion physics and materials problems have been previously reported.⁽¹⁻¹⁹⁾

The initial Sandia air/propane design was successfully field-tested at ground level, injecting into a well in the Kern River Field, Bakersfield, California, in early 1980.⁽²³⁾ This test demonstrated the feasibility of long-term operation in the oil field environment and showed substantial environmental improvements over indirect-contact surface generation of steam. During the test, approximately 275 on-site briefings were provided to individuals representing 67 government agencies, universities, or private concerns, from the United States and 6 other countries.

Based on the successful completion of the Bakersfield field test in May of 1980, plans were finalized to extend the direct-contact generator design to burn No. 2 diesel fuel and to extend the test effort to an actual downhole environment. In addition, a parallel program was initiated to develop a second direct-contact steam generator and support system that would use pure oxygen instead of air. This second generator was designed to be tested at ground level with steam and combustion products delivered to the reservoir through insulated tubing. Operation at ground level was specified for this generator because of its less-developed state. Plans were made to field test both the air/diesel and oxygen/diesel direct-contact steam generators beginning in the first quarter of 1981. The objectives of the test included demonstrations of safety, operational ease, reliability and lifetime; investigations of reservoir response, economics, and environmental impact; and comparison on each of these points between the air/diesel and oxygen/diesel units.

Prospective oil-field operators were solicited for partnership in a cooperative field-test program in mid-1980. A joint DOE/Sandia committee ranked the candidate sites; this resulted in the selection, in October of 1980, of a site operated by the Long Beach Oil Development Company for the City of Long Beach, California. A formal agreement between Sandia National Laboratories and the City of Long Beach was completed in February of 1981. Two injection wells, in adjacent patterns in the Tar Zone of the Wilmington Oil Field, were re-drilled and completed for steam injection by Long Beach Oil Development

Company. Development of the air/diesel system was completed and its components were shipped to Long Beach in March, 1981. Development of the oxygen/diesel system continued at Sandia through June 1981 and the components were shipped in early July.

Further details of the air/diesel system field test can be found in a separate report.⁽²⁸⁾ A report on the metallurgical results from the entire field test is in preparation.⁽²⁹⁾ The present report will continue with Section II, which is an overview of the oxygen/diesel system field test at Long Beach. The test site is described in Section III; the description includes the reservoir characteristics, well patterns, and the injection well completion. In Section IV the oxygen/diesel steam generator is described along with the design considerations, configurations tested, materials, combustion characteristics, and appropriate steam quality relationships. The overall system layout and its parts are discussed in Section V. Included are the fluid-handling equipment, flow-rate controls, instrumentation, computerized data-acquisition system, and safety provisions. Operational considerations are discussed in Section VI. A narrative of the field-test experience, elaborating on Section II, is presented in Section VII. The resultant data on consumption rates, injection rates, temperatures, pressures, steam qualities, and the computed delivery-system efficiency are presented in Section VIII. Hardware performance, combustor development, and economics are discussed. Reservoir response and environmental impact are also addressed. Finally, a summary and conclusions are presented in Section IX.

II. FIELD TEST OVERVIEW

Most of the people at or under contract to Sandia, who contributed directly to the development and field-testing of the oxygen/diesel-oil steam generator system, are listed in Table 1. Inevitably, omissions occur in such lists, and therefore, apologies are offered to anyone overlooked.

Figure 1 illustrates a brief history of the oxygen/diesel steam generator development. The steam generator and its support system both were developed by making appropriate modifications to the air/diesel system design. Thus, the two systems had many similarities. The oxygen-system instrumentation, computer software, pumps, controls, and plumbing, as well as the generator itself, were nearly identical to their air system counterparts. The most important differences were in the combustion head, in the safety provisions connected with the use of oxygen, in the liquid and gaseous-oxygen storage and pumping that replaced the air system compressors, and in the use of a diesel/water emulsion to moderate flame temperature. The oxygen/diesel steam generator was in an earlier stage of development than the air system, and was therefore configured as a surface rather than downhole unit with a flanged bolt-on combustor head. As shown in Figure 1, the system development at Sandia's Albuquerque test site was sufficiently advanced by July of 1981 to permit shipping to the Long Beach test site.

At Long Beach an injector well in an inverted five-spot pattern, situated in the Tar Zone at a depth of approximately 2200 feet, had been made available by Long Beach Oil Development Company. By the end of July the well was completed, including installation of a Baker thermal packer, 2022 feet of Conoco-design calcium-silicate-insulated steam delivery tubing, and a Baker expansion joint. Daily quantitative analysis of the produced gas from the surrounding wells in the pattern was already underway as part of the environmental and reservoir-response studies. The methodology used has been described in Reference 28. Trial runs of the assembled steam generator system began in August.

Before steam injection could begin, two key development program elements had to be completed:

1. Establishment of a stable manual or computer-operated control system for fuel, emulsion water, oxygen, and coolant water.
2. Demonstration of an acceptable combustor head lifetime.

Early in October the first of these program elements was successfully completed and a manually-operated system was established. The most important part of this system was a variable-venturi oxygen-flow control. With this device sonic isolation of the flow rate from the combustor pressure was achieved with minimal pressure loss. Given a stable oxygen flow rate, a manual-control system became feasible. The other (constant) flow rates were then simply determined by the settings on their respective pump-motor speed controllers. Operating parameters were manually set at startup, and deviations were corrected typically once a day. A table-top Hewlett Packard (HP) computer was used for data logging and to activate warnings and emergency shutoff valves under prescribed conditions. Personnel were present 24 hours a day, but only to monitor the system for equipment malfunctions and for supplementary data logging. Through early December 1981 a Mod-Comp Computer based data acquisition system was also used as backup to the HP system.

The second program element, demonstration of a reasonable combustor head lifetime, was achieved in early November 1981. The original head design was limited in lifetime to 50-80 hours by the development of cracks believed to be stress-corrosion related. Two different design modifications were shown to extend head life by up to a factor of 10. These are described later in this report. Combustor head failures were reduced to an acceptable rate of once every 2-3 weeks.

Steam injection into the test pattern began on November 9, 1981. A program to further improve combustor head lifetime proceeded in tandem with the steam injection effort for the next five months. Excluding interruptions not attributable to the oxygen/diesel system, steam was injected 78% of the time.

Typical operating parameters were: 3.45 lb/min of diesel fuel, 4.08 lb/min of emulsion water, 11.4 lb/min of oxygen, 68.0 lb/min of coolant water, and 1200 psi combustion pressure. This produced a nominal firing rate of 4.1 MMBtu/hrs and a steam quality of 50% at 550°F. A total of 114 tons of fuel, 371 tons of oxygen, and 2388 tons of coolant water were consumed. This resulted in the injection of 15130 bbl cold-water equivalent of steam, 4115 MMBtu, and 5.9 MMscf of carbon dioxide. Thermal efficiency of the insulated delivery system was estimated to be 73% early in the program, and 62% after two months of intermittent use. Throughout the test period, the injected gases as well as the produced gases were periodically sampled and analyzed by a contract employee at the site. During the test, on-site briefings were provided to approximately 250 individuals, representing 60 private concerns, universities, or government agencies (from the United States and 5 other countries).

At the end of March 1982 the decision was made, in cooperation with the City of Long Beach and the Long Beach Oil Development Company, to end the injection program and clear the site. This decision was made in conjunction with a similar decision regarding the air/diesel system. This concluded the field test of both Sandia-design steam generators at Long Beach.

III. TEST SITE DESCRIPTION

In mid-1980 prospective oil-field operators were solicited for partnership with Sandia National Laboratories in a cooperative field test of Sandia's oxygen/diesel and air/diesel direct-contact steam generators. The desired well, well-site, and field circumstances as listed in the solicitation were:

1. 2000-3000 ft. depth.
2. 1000-1500 psi steam injection pressure.
3. 7 to 7 5/8" casing.
4. Thermal-operations compatible.
5. 2 to 5 acre patterns.
6. Adequate room at site for air compressors, control skids containing fuel and water pumps, necessary tankage, and office trailers.
7. Access to softened water (comparable to that normally supplied to conventional steam generators).
8. Access to fuel and to electric power.
9. Active thermal recovery operations, preferably steam drive, in adjacent patterns.
10. Response wells equipped with vapor recovery systems.

A joint DOE/Sandia committee ranked the candidate sites; this resulted in the selection in October 1980 of a site operated by the Long Beach Oil Development Company (LBOD) for the City of Long Beach, California. The major deficiencies of this site were noted to be its larger-than-desired pattern sizes and the absence of steam flood operations. Other candidate sites were judged to have more serious deficiencies--such as well patterns that spanned fault blocks or wells that were unsuitable in casing size and pressure for the DEEP STEAM test. A formal agreement between the City of Long Beach and Sandia National Laboratories was completed in February 1981.

Figure 2 illustrates the LBOD test-site locations in the highly-urbanized industrial-shipping complex of the Wilmington Oil Field at Long Beach. The

City of Long Beach Wilmington oil properties have been under development since 1939. Water injection began in 1953, primarily in response to local subsidence. Reinjection of produced water is currently fieldwide to provide both the stabilization of elevations and increased oil recovery. The subsidence area is divided into six fault blocks and seven layers of oil-bearing sand or zones. The test site made available by the City of Long Beach consisted of two adjacent inverted five-spot patterns in the Tar Zone of Fault Block V. The Tar Zone is the shallowest reservoir in the Wilmington Field, with depths from 2000 to 2500 feet. It has both the lowest temperature and the lowest gravity oil in the field, and consequently, the lowest oil recovery by water-flood and the highest residual oil saturation. Table 2 summarizes the reservoir characteristics of the Wilmington Field Tar Zone in the area in which the City of Long Beach has an interest. Figure 3 shows the arrangement of the two inverted-five-spot test patterns at depth. All of the wells in these patterns were directionally drilled and most were on the order of thirty years old at the time of the DEEP STEAM test. The two injection wells were redrilled and completed in 1981 specifically for the test. Figure 4 illustrates the completion of the injection well FSJ-113, used in the test of the oxygen/diesel steam generator. Not shown in this illustration is the Baker expansion joint with approximately 10 feet of available stroke located just below the tubinghead. Details on the downhole equipment can be found in Section V.

IV. OXYGEN/DIESEL-FUEL STEAM GENERATOR

An overall view of the oxygen/diesel-fuel steam generator that was field-tested at Long Beach is presented in Figure 5. This is a water-jacketed design that was evolved from the air/diesel downhole steam generator at Sandia National Laboratories. A flanged, bolt-on combustor head was used to facilitate the combustor development work which proceeded during the field test period. Figures 6 and 7 provide, respectively, cross-sectional schematics of the generator less the combustor head and of the combustor head itself. As the figures show, coolant water circulated through passages in the combustor head and was then routed via external tubing to the bottom of the steam generator. The water then flowed between the body and middle sleeve to the combustor head, reversed direction, and finally flowed between the inner and middle sleeves into the combustion gases. Fuel flowed into an annular plenum in the combustor head and was ducted via four drilled passages to near the back wall of the combustion chamber. A 0.024-inch orifice introduced each fuel stream into the axial oxygen stream.

A number of details have been omitted for clarity of presentation in Figure 7. Not shown for example, are the two glowplugs that were in the original design. The glowplugs screwed into the combustor head in the plane that is both normal to Figure 7 and passes through the centerline of the figure. Figure 5 shows the location of one of the glowplug ports. Other features not shown in Figure 7 are the longitudinal cooling passages, the flow restricting ring, and a helical flow swirler, all on the inner sleeve. Figure 8 is a view of an actual combustor head illustrating these features.

The design outlined in the preceding paragraphs and in Figures 5-8 is the result of an evolution that involved both trial and error and analysis. Major design considerations recognized during the evolution were:

1. Corrosion resistance.
2. Sizing and strength.

3. Heat transfer and thermal expansion.
4. Oxygen/fuel and flue gas/water mixing.
5. Flame quenching and stability.
6. Ignition.
7. Combustion characteristics and steam quality relationships.

Each of these considerations is next discussed in sequence.

Corrosion resistance: The choice of types 304 and 310 stainless steel used throughout the Sandia-design oxygen/diesel steam generator was based on extensive pretesting for corrosion resistance in a mixed steam and combustion-gas environment. Experience during the field test has shown that these materials suffer greatest damage in the regions of highest temperature; namely, on the surfaces of the insert and inner sleeve that form the combustion-chamber walls. Alternative materials including Inconel 625, and Hastelloy-X with a Cobalt-Chromium-Aluminum-Yttrium plasma-spray coating have been tried. Additionally, stress-relief slits were incorporated into some designs to try to reduce stress-corrosion cracking at critical points. Some designs provided for increased coolant flow velocities to reduce wall temperatures. The results of these various attempts to increase combustor lifetimes are discussed in Section VIII.

Downstream of the generator mild-steel components were used exclusively. These components included the well-head valve, the expansion joint, the insulated tubing, the packer, the slotted liner, and the well casing. To protect these parts from catastrophic attack by hot, acidic steam, a 50% by weight solution of sodium hydroxide in water was continuously injected downstream of the generator to obtain a pH near 7. The results and problems associated with this technique are also discussed in Section VIII.

Sizing and strength: The overall dimensions of the oxygen/diesel steam generator are close to those of the air/diesel DHSG. This is primarily because the oxygen unit had been sized to fire at the same rate and pressure and produce the same quality steam as the air unit. The main differences are in the

inner sleeve length and in the sizing and placement of the oxygen and fuel orifices. These differences are traceable directly to the effect on the gas velocities of substituting oxygen for air. The relevant sizing considerations have been discussed in Reference 30.

The most important strength consideration is, of course, the maximum allowable working pressure (MAWP). The pressure bearing structure is the cylindrical body and flathead assembly, and secondarily, the outlet pipe outside of the bottom head. The various material thicknesses were chosen in accordance with Section I of the ASME boiler code⁽³¹⁾ consistent with a MAWP of 2000 psi as outlined in Reference 30.

Heat Transfer and Thermal Expansion: The heat-transfer rates in the generator determine both the wall temperatures and the thermally-induced stresses in the walls. Each of these effects in turn influences the rate of progression of wall-material damage and loss. Cooling of the steam generator walls is accomplished using water that is subsequently injected into the combustion products and flashed to steam. Heat transfer from the combustion products to the walls proceeds both by radiation and turbulent convection. Radiation is important because of the presence of water vapor and carbon dioxide, both of which are strong radiators in the infrared, at typical hydrocarbon flame temperatures.⁽³²⁾ Turbulent convection is important because of the velocities and high gas temperatures attained in the combustor. Heat transfer from the combustor walls to the cooling water proceeds mainly by turbulent convection. This occurs in the top head, behind the inner sleeve, and behind the middle sleeve. At the inner surface of the middle sleeve, where it faces the combustion gases, the coolant water additionally blocks heat transfer to the sleeve and ultimately cools the gases.

While an assessment of orders of magnitudes and trends can be obtained with an approximate heat-transfer analysis,⁽³⁰⁾ a complete treatment does not appear to be practical. The arrangement of coolant passages in the present design is a result of a trial and error procedure. Beyond the initial design

several steps were taken to further reduce wall temperatures and to deal with the effects of nonuniform wall temperature. These were:

1. Use of a water/fuel emulsion to moderate flame temperature.
2. Placement of stress-relief slits to reduce thermally-induced stress and associated stress corrosion in critical areas of the combustor head insert.
3. Redesign of the inner sleeve to reduce thermally-induced stress and to provide higher coolant flow velocities.
4. Redesign of the combustor-head insert to provide higher coolant-flow velocities.

In the initial design of the combustor-head insert, thermally-induced stress concentrations were identified as causing radial stress-corrosion cracks which intersected each fuel-injection orifice. Photographs of the actual damage are presented in Figures 9a and b. Figure 9a shows a square piece cut out of the insert which encompasses the oxygen port and the surrounding four fuel orifices. The piece has been sawed into quarters leaving one orifice per quarter. Figure 9b is a scanning electron photomicrograph showing greater detail. The crack is seen to extend both radially outward along the insert face and downward along the oxygen-port wall. Such cracks in this critical area prevented proper fuel atomization and thus caused the production of soot. Figure 9c illustrates the origin of the thermal stress. Because of the large flux of cool oxygen and fuel near the axis of the insert, this region is relatively cool. Away from the axis the temperature is higher; this gives rise to differential thermal expansion and a hoop-stress distribution that increases as it approaches the injection orifices. The presence of the fuel-injection orifices further concentrates the stress along radial lines intersecting the orifices. Figure 9c also shows the placement of stress-relief slits which cured this problem. Repairs to the first few combustor heads used in Long Beach involved rebuilding the fuel-injection area of the inserts. This was accomplished by milling out the damaged area to a depth of about 0.1 inch,

weld-filling the area, machining the surface flat, and re-drilling all affected holes. The result is referred to in this report as a weld-filled insert.

Figure 10a illustrates another insert design that also permitted stress relief. As shown, the initial insert design was bored out to a larger diameter along its axis to accept a removable concentric-tube oxygen and fuel injector. The concentric tubes were weld-joined, chamfered and drilled at the combustor end to produce an injector configuration equivalent to the initial design. An unused injector is pictured in Figure 10b. The break between the injector and the hotter surrounding region accomplished the same objective as the stress-relief slits in the first design. Figure 10a also indicates that the inner sleeve was re-designed; this resulted in a so-called "thin" sleeve. The longitudinal channels on the outer surface were eliminated to reduce differential thermal expansion. The inner and outer radii were both increased which resulted in a thinner wall and higher coolant velocity in the annulus between the middle and inner sleeves.

Figure 11 illustrates the third and final combustor head design. This head incorporated the removable injector and the thin sleeve into a new insert design. In this design the glow plugs were omitted. Ignition was accomplished by injection of a slug of pyrophoric chemical into the fuel supply line. With the exception of the four fuel-injection ports, this head design was completely cylindrically symmetric. The coolant water passages in the insert provided for higher flow velocities and more uniform distribution of heat flux than in the first two designs.

Two other thermal expansion considerations should be mentioned. Referring to Figure 6, it can be seen that longitudinal differential thermal expansion of the middle sleeve relative to the generator body may close off the coolant flow path between the middle sleeve and the combustor head. Similarly, radial differential thermal expansion of the inner sleeve relative to the middle sleeve can close the gap between the flow restrictor ring on the inner sleeve and the inner surface of the middle sleeve. The location and size of the slots

cut in the flow restrictor ring were chosen to preclude these possibilities and have been validated by actual operation.

Oxygen/Fuel and Flue Gas/Water Mixing: Mixing processes are important with respect to both combustion and cooling. The dimensions and arrangement of oxygen and fuel orifices in the present design were arrived at by trial and error to obtain clean, high-pressure burning of No. 2 diesel fuel in oxygen. The dimensions roughly preserve the fuel and oxidizer velocities used in the air/diesel unit. Downstream of the combustion zone the coolant water is introduced into the combustion gases. Entrainment of both vapor and liquid-phase water occurs. At some point further downstream, an equilibrium temperature can be assigned to the resulting mixture. Upstream of this point, it is advisable that the outlet pipe be water jacketed. This necessary axial extent of water jacketing was also determined by trial and error.

Flame Quenching and Stability: Figure 12 illustrates the primary flow processes and the flame-front structure in the Sandia-designed direct-contact steam generator.

The inner sleeve in the downhole generator serves to segregate the cooling water from the reaction zone of the flame. The flame front is nearly aligned with most stream lines because of the large difference in flow and flame speeds.⁽³⁰⁾ The reaction zone extends only a short distance downstream of the flame front. The fact that the flame is turbulent is not shown. Water entering the combustion chamber from behind the inner sleeve is entrained into the gas flow. Mixing caused by turbulence as well as by droplet explosions occurs. If the inner sleeve is long enough, this mixing will be confined to the post combustion zone and a clean burn will occur. For diesel-fuel/water emulsion-droplets dispersed in oxygen, the axial extent of the flame front is not easily estimated, and the sleeve length that will assure a clean burn must be determined by trial and error.

Referring again to Figure 12, one can see illustrated the recirculation region which stabilizes the flame by constantly providing hot combustion gases

as a source of ignition. The success of this stabilization method depends on turbulent exchange between the free and recirculating streams as well as on heat exchange between the recirculating gases and the walls. Whether or not the method will work for given flow parameters and burner dimensions is not presently calculable.

The stability referred to thus far bears on the question of whether or not the flame will perpetuate itself. A second stability concern has to do with the occurrence of unsteady, periodic combustion waves. Examples are screaming and chugging instabilities which have plagued many rocket-engine development programs. In the present program, screaming instability is believed to have been observed under some circumstances. Moreover, strategies to suppress this instability have been successfully employed. In most cases the instability was detected as an intensely audible, high-pitched "chirp." This chirping became more frequent when a combustor head with undersize fuel-injection orifices was used. It never occurred when the firing rate was below some threshold near the design maximum. The threshold could be raised by decreasing the ratio of emulsion water to diesel oil. When the glow plugs were eliminated in the third design, the combustion chamber was rendered more nearly cylindrically symmetric. Instead of a chirp, a steady high-pitched squealing was observed. This suggests that the glow plug recesses had served to break up an azimuthally-propagating combustion instability. The same strategies that were employed to control chirping were successfully used to suppress squealing.

Ignition: Two methods of ignition have been used in the present program-- glow plugs and the pyrophoric chemical triethyl-borane (TEB).

The glow plugs used were Champion's Model AG42 modified by Champion to have an Inconel 601 rather than Haynes 25 alloy sheath. The AG42 required 5 amperes (24 volts) for nominal operation. Voltage was only applied for a few minutes per startup and not at all once ignition was achieved. The primary and backup glowplugs were situated in recesses in the combustor-head insert in the recirculation zone. Despite the sheath material change and the sheltered

location, glow plug lifetime was generally on the order of one day. Figure 13 shows the appearance of a new glow plug, and one which was not functional after a single 17-hour run. Photomicrographs of the sheath material provided by Champion are also presented in Figure 13. Champion concluded that the sheath material had suffered "severe overheating and oxidation" as evidenced by the dendrite structure in the photomicrographs and by physical examination.⁽³³⁾ During the field test, one glow plug was plasma-spray coated with the same Co-Cr-Al-Y powder used on the Hastelloy-X combustor head. The observed lifetime was at least three days in that particular case.

Pyrophoric-assisted ignition was the only method used in the third combustor design which had no glow plugs. The pyrophoric triethyl-borane was used; this chemical is marketed by Callery Chemical Company, Callery, Pennsylvania. The operational methods used for both glow plug and TEB starts will be discussed in Section V.

Combustion Characteristics and Steam Quality Relationships: Table 3 indicates typical operating conditions for the oxygen/diesel steam generator during the field test at Long Beach. The temperature and steam quality refer to conditions downstream from the generator where the temperatures of combustion gases and injected coolant water have equilibrated.

An analysis⁽³⁴⁾ of the diesel fuel used in the Long Beach field test revealed a hydrogen to carbon molar ratio of 1.76. The major impurity was sulfur at 0.14% molar. Gas chromatographic analysis of the combustion products from the oxygen/diesel stream generator showed CO₂, CO, H₂ and O₂, and trace amounts of H₂S. Most of the fuel-borne sulfur was oxidized and became sulfuric acid in solution in the liquid phase of the exhaust steam.

Based on the above facts, an estimation of combustion efficiency can be made. The small effect of sulfur is neglected. The chemical reactions that apply are:

The latter two reactions are used to account for the loss of heat release represented by the presence of CO and H₂:

$$\text{Combustion efficiency} = \frac{19840 - H_{\text{loss}}}{19840} \text{ and}$$

$$H_{\text{loss}} = \frac{1}{x + 1} (8850 + \frac{x}{y} 8900) \quad .$$

Here x is the ratio of CO₂ to CO concentrations and y is the ratio of CO₂ to H₂ concentrations. In Figure 14, the measured variation of exhaust-gas composition, and the computed variation of combustion efficiency, with changing oxygen/fuel mass ratio, is presented. Because the oxygen/fuel ratio was not consistently recorded at the time that exhaust-gas samples were taken, this parameter has been calculated using atom conservation and the exhaust-gas composition. The relationship is:

Oxygen/fuel mass ratio =

$$1.16 (1.88 X_{\text{CO}} + 2.88 X_{\text{CO}_2} + 2X_{\text{O}_2} - X_{\text{H}_2}) / (X_{\text{CO}} + X_{\text{CO}_2})$$

Here, X_i represents the concentration of species i. The results in Figure 14 show a combustion efficiency of 96% at the stoichiometric oxygen/fuel ratio of 3.33.

Energy-Balance Quality: Measurements downstream of the steam generator also enabled inferences of the steam quality. The relevant ideas have been presented in Reference 35. In that reference, two methods of steam-quality determination were considered: one, the so-called "energy-balance" method, and a second which shall be called the "state" method. In the energy-balance method, the enthalpy of combustion is equated to the enthalpy of the generator effluent referenced to the entering streams of fuel, oxidizer, and water. Each quantity is determined per pound of fuel injected. Given the fuel composition, the injection and effluent temperatures, and the injection rates, the only unknown in the equation is the steam quality. Denoting the quality arrived at

by this energy balance as Q_E ,

$$Q_E \approx [(19840 \eta_c - 0.787 (T-77))/(1.154 + Z) - 1.027 (T-77)] \\ / [1333 - 1.47 (T-77)]$$

Here T is the effluent temperature ($^{\circ}\text{F}$) and Z is the mass ratio of injected water (including emulsion water) to fuel. The inlet streams have been assumed to be at 77°F . The combustion efficiency is represented by η_c . The slight effect of variation of exhaust composition with oxygen/fuel ratio has been neglected. Approximate analytical expressions have been used for the latent heat of vaporization of water and for the specific heats at constant pressure of the liquid-phase water and of the noncondensable gases. The energy-balance determination of quality is applicable immediately downstream of the generator, but only insofar as energy losses from the effluent to the surroundings are negligible.

State-Determined Quality: Reference 35 also presented a relationship between the effluent total pressure, the steam saturation pressure at the effluent temperature, the water to fuel mass ratio, and the steam quality. Depending on which quantity is unknown, this relationship can be regarded as a determination of either total pressure or steam quality. The latter case constitutes the "state" method. In any event the relationship presented in Reference 35 is in error in that the ideal-gas equation of state was used for water vapor. Denoting the corrected state-method quality by Q_s ,

$$Q_s \approx 1.308 f (1 + 0.00035 P_v) / [(1.154 + Z)(P_{\text{TOTAL}}/P_v - 1)]$$

Here P_v is the water-vapor pressure in psi, P_{TOTAL} is the effluent total pressure, and Z is the total water-to-fuel mass ratio. The oxidizer is assumed to be pure oxygen. The factor f is the ratio of noncondensable-gas moles per pound of fuel at stoichiometric conditions to total moles per pound. This is

a correction for both off-stoichiometric operation and for loss of gas to solution in the liquid water present. The term $(1 + 0.00035 P_v)$ is an approximation to the inverse of the compressibility factor for water vapor. It is the correction to Reference 35 made necessary because of the non-ideal behavior of water vapor.

The effect of dissolved solids and gases on the water vapor pressure P_v at a given T must be taken into account. The dominant solid dissolved in the generator effluent was Na_2SO_4 ; it is produced by the neutralization reaction between the effluent and the injected caustic solution. For dilute solutions of NaCl in water from 212 to 572°F, the percentage vapor-pressure depression is approximately independent of temperature and is proportional to the salt concentration as represented by Raoult's law.⁽³⁶⁾ The percentage depression is about the same for Na_2SO_4 in water.⁽³⁷⁾ The Na_2SO_4 concentration is easily determined for the injection rates and the steam quality. This dependence makes the expression for Q_s nonlinear in Q_s so that an iterative solution is necessary. The effect of CO_2 going into aqueous solution is to similarly depress the water vapor pressure. The Henry's law constant describing the solubility of CO_2 in water ranges from about 5000 atmospheres at 500°F to 4200 atmospheres at 550°F.⁽³⁸⁾ Again, a Raoult's law approximation can be employed to calculate the water-vapor pressure lowering caused by dissolved CO_2 . Results for Q_E and Q_s are presented in Section VIII.

Injection-String Thermal Efficiency: The energy-balance method can also be re-interpreted as a way to calculate the energy losses between the steam generator and any downstream point. If the steam quality is known at such a point, say from the state method, then the enthalpy of combustion in the balance can be regarded as the true enthalpy of combustion reduced by losses to the delivery-system surroundings. In particular, the energy method can be used to estimate the thermal efficiency η_T of the insulated tubing:

$$\eta_T \approx \{0.787(T_{DH} - 77) + (1.154 + Z) [1.027 (T_{DH} - 77) + Q_{DH} (1333 - 1.47 (T_{DH} - 77))]\} / (19840 \eta_c)$$

Here T_{DH} is the downhole effluent temperature ($^{\circ}F$) and Q_{DH} is the state-determined downhole quality. All other conditions and assumptions are the same as in the discussion of Q_E .

A sensitivity analysis has been performed for the energy and state-determined surface steam quality, the state-determined downhole quality, and the insulated-string thermal efficiency. Taking as representative conditions

$$\begin{aligned} Z &= 20.89, \\ T &= 550^{\circ}F, \\ T_{DH} &= 520^{\circ}F, \\ P &= 1200 \text{ psi}, \\ P_{DH} &= 1240 \text{ psi, and} \\ \text{Oxygen/Fuel} &= 3.30, \end{aligned}$$

the results shown in Table 4 were obtained. These results demonstrate that 1% errors in the measurement of Z , T , etc., result in less than 4% error in Q_E and η_T . However, the downhole quality is seen to change 15% in response to a 1% error in downhole temperature, and the surface state-determined quality changes 26% in response to a 1% error in surface steam temperature.

As a result of this analysis, the energy-balance method will be regarded as the primary determination of surface steam quality.

V. OXYGEN/DIESEL-FUEL SYSTEM DESCRIPTION

Figure 15 illustrates the overall layout of system components at the Long Beach field test site. The five fluid-supply streams are shown along with all of the major system components. All of the components and supply lines are shown approximately where they were actually located and roughly to scale. Not shown are the electric power lines and the data and command control lines. Also not shown is the mobile van used for NOX and SOX measurements at the generators and wells and the gas chromatographics lab used for analyzing grab samples from either source. The gas analysis equipment has been described in Reference 28.

Altogether the trailers, skids, and other equipment occupied about 4000 square feet of ground space spread out over an area of about 0.6 acres. The test location was on landfill in the Long Beach Harbor District just east of Pier A in the midst of many existing oil wells. The entire area was dependent on a sump pump for drainage and was subject to flooding during heavy rains or pump outages.

Fluid Storage, Pumping, and Flow Measurement: Referring to Figure 15, pre-softened coolant water was supplied and stored, as shown, by Long Beach Oil Development Company (LBOD). This water was subsequently "polished" to less than 4 ppm CaCO_3 using leased softeners. Unsoftened city water for fuel/water emulsification was also made available by LBOD. Diesel fuel was purchased locally, jointly with LBOD, and stored in the indicated tankage. Liquid oxygen (LOX) was also purchased locally and stored in the LOX tanker which was a 4000-gallon insulated tank-truck trailer. Gaseous oxygen was produced as required by high-pressure pumping the LOX through a forced-convection air-to-LOX heat exchanger (vaporizer). High-pressure oxygen was stored in two 39000 scf tube trailers rated at 2500 psi. Lastly, 50% sodium hydroxide (by weight) in water was purchased and stored on site.

A more detailed schematic of the five fluid-supply streams is presented in Figure 16a. All of the high-pressure pumps used were packed-plunger or piston types driven by AC electric motors. For the coolant water, emulsion water and diesel fuel, these pumps were triplex models with appropriate accumulators. The coolant-water pump speed was controlled by an eddy-current clutch. For the emulsion water and diesel fuel, pump speeds were controlled by AC frequency adjustment. The liquid oxygen and caustic pumps were each single-cylinder types. The caustic flow rate was controlled by adjusting the pump-plunger stroke. The liquid oxygen was pumped at a constant rate as required to maintain a stored-gas pressure between approximately 2100 and 2400 psi. The LOX pump was cycled on and off by pressure-sensing switches. Because the liquid oxygen served as the lubricant in the LOX pump, vapor lock was of special concern. When the pump was on, the rate of pressure increase in the tube trailers was monitored by the HP data-aquisition computer. The computer was programmed to use this information to diagnose vapor locking and to sound an alarm if necessary. Downstream of the gaseous oxygen tube trailers, the oxygen pressure was regulated down to about 2000 psi by a dome-loaded regulator. The regulator-dome volume was greatly enlarged by connection to an insulated standard high-pressure gas bottle. This measure was necessary to reduce the effect of the oxygen-stream temperature variation on the regulated pressure. Control of the gaseous oxygen flow rate was accomplished downstream of the regulator by a variable venturi with a manually-set pintel.

Besides flow-rate control, each fluid-supply stream had some provision for flow-rate monitoring. For the caustic, periodic checking of steam-generator effluent pH accomplished this purpose. For the other streams, commercially-available flow-rate meters were used. In the diesel-fuel line, a positive-displacement four-piston meter was employed. It was desired to use a similar piston-type meter in the emulsion-water line, but the meter bearings were not compatible with water service. Thus, first the fuel and emulsion-water streams were brought together at the homogenizer which consisted of a multi-element

inline mixer followed by a homogenizer valve. Both of these devices are commercially available. Downstream of the homogenizer it was possible to use the second four-piston flow meter without causing bearing damage. The difference in measured volumetric flow rates between the two meters was computed as the emulsion water rate. The coolant-water flow rate was determined using an axial-turbine type flow meter and finally, the oxygen flow rate was computed from temperature, absolute pressure, and differential pressure, measured at a fixed venturi. A thermocouple and capacitive-type pressure transducers were used for these measurements.

Downhole Instrumentation: Additional instrumentation was provided to measure a variety of pressures and temperatures. The essentials of the data and control system are outlined in Figure 16b. Shown are the flow-rate meters and controls already discussed. In addition Figure 16b shows temperature and pressure transducer locations just downstream of the steam generator, on the insulated string, and attached to measurement chambers just above the packer. The downhole instrumentation is shown schematically in Figure 4. Another illustration is provided in Figure 17 which shows the arrangement and dimensions of the downhole equipment. Six downhole measurements were made. At the bottom of the first insulated joint below the wellhead, three 1/16-inch type-K sheathed thermocouples were banded to the insulated string, on and 30 inches above and below the collar. The thermocouple sheath material was 316 stainless steel. Just below the bottom-most insulated joint an annular chamber was provided for downhole steam-temperature measurement. The chamber was formed of an inner cylinder through which the steam passed and an outer cylinder to isolate the thermocouples from the surrounding well fluids. Two 1/8-inch sheathed thermocouples (similar to the 1/16-inch models) entered this chamber through swage-type feedthroughs and were fitted into 1/8-inch holes drilled into fins welded to the inner cylinder. As shown in Figure 17, a commercially-available plenum chamber was situated below the temperature chamber. This enabled measurement of the downhole steam pressure. A 0.094" 316-SS capillary tube

allowed this pressure to be communicated to a strain-gauge type transducer located at the surface. The tube was periodically purged with helium from the surface; and the true pressure was computed based on the indicated pressure, the known properties of helium, the average string temperature, and the depth. The capillary tube and the five thermocouples were secured to the insulated string at each collar by a tubing protector banded to each joint (Figure 17). At the wellhead each line was fed through its own 1/4-inch hole and packed off using a compression-type fitting with an elastomeric sealing element.

Computer Functions: The principal data lines to the computer are shown in Figure 16b. The computer was used to reduce, display, and record data; to monitor system operation; to sound appropriate alarms; and to activate emergency shutoff valves as required. These functions were performed by a computing system built around a Hewlett-Packard (HP) desktop calculator which is illustrated in Figure 18. The calculator commanded a scanner to access the various data channels. The channel voltages or resistances were automatically read using a digital multimeter. Activation of alarms and emergency shutoff valves was accomplished by the multiprogrammer responding to commands from the calculator through the multiprogrammer interface. During the first part of the field test, until about mid-December 1981, a second data acquisition system was also used. This system, built around a Mod Comp II minicomputer, has been described in detail elsewhere.⁽²³⁾ Upon withdrawal of the Mod Comp system, all of the data channels it had accessed were connected to the HP system. A complete set of measurements made and calculations performed by the HP system is listed in Table 5. Based on these results, the HP computer activated the alarms and shutoff valves listed in Table 6.

Safety: In addition to the safety provisions outlined in Table 6, there was a thermocouple/relay high-temperature shutdown system and a burn-wire and burn-tube oxygen-fire shutdown system. The burn wire was a low-voltage insulated conductor. The burn tube was a 1/4-inch plastic compressed-air line. Both the wire and tube were routed along and tied to the high-pressure gaseous-

oxygen supply line. Air-operated valves in the oxygen and fuel lines were held in the open position by compressed air supplied through the burn tube. Electrically-operated solenoid valves maintained control air pressure. The solenoids were supplied with current through the burn wire. Thus, a fire which interrupted either the burn tube or the burn wire would cause a shutdown of both the oxygen and fuel flows.

A number of passive safety provisions were also employed. For example, a Monel porous-plug filter was installed between the oxygen-control skid and the generator as a fire break. In-line check valves were used in each fluid stream and relief valves were placed at appropriate points. Of course, stringent cleaning of all oxygen-service components was required, and oxygen compatibility of all materials was observed.

VI. OPERATIONAL CONSIDERATIONS

At the Long Beach field test site, personnel were present 24 hours a day. During normal working hours, at least one Sandia National Laboratories engineering staff assistant and one person without technical training were always present. A contract employee was usually also present to perform gas and liquid sample collections and associated chemical analyses as required. At all other times, two non-technical contract personnel were present to monitor the air/diesel and oxygen/diesel systems for equipment malfunctions, and to perform supplementary data logging. These were people who had been oriented and minimally trained at the test site. The routine onsite tasks performed in connection with the oxygen/diesel steam generator operation are summarized in Table 7.

Hourly System Checks and Data Logging: Initially the hourly system checks and data logging were deemed necessary because of early experience with LOX-pump vapor lock, caustic-pump failure, and the development of steam leaks. A re-design of the LOX tanker-to-pump piping and insulation greatly reduced the incidence of vapor locking. The caustic-pump failures and the incidence of steam leaks can be blamed on less than optimal matching of equipment to the job. This can be corrected.

The hourly data logging also enabled system trends to be assessed--for example, when filters would need replacement, when pump packing would need adjustment, and so on. System trends are now well enough understood that scheduled preventative maintenance should suffice. The manually-collected data involved instrumentation which was partially to fully independent of the automatic acquisition system, thereby serving as a backup; the field test experience has demonstrated a level of instrumentation reliability that makes this backup unnecessary.

One unsolved problem remains: computer "hangup." Throughout the field test period, both the air/diesel and oxygen/diesel computer systems

experienced apparently spontaneous "hangups" in which program execution simply stopped at seemingly random times and program steps. In one 30-day period, 20 such incidents were recorded. Careful logging of all status indicators and consultations with the equipment service representative did not lead to a cause or solution. Other computer/control design concepts will not necessarily exhibit this behavior. The only remedy that was available at the time was to reload the data logging and control program and re-initiate execution. To alert the on site personnel of each "hangup," a "snooze alarm" was devised. This alarm consisted of a solid-state timer which, if allowed to run down, would cause an audible tone to be sounded. The timer was periodically reset by the computer in order to prevent rundown except in the event of a "hangup."

As with the preventative maintenance already mentioned, the daily to weekly tasks listed in Table 7 could also be scheduled to eliminate the need for constant attendance at the site. Alarm signals could be transmitted to a central site. A daily visit for maintenance and visual checking would then suffice.

System Startup: The last set of tasks in Table 7 includes system startup. Since three different successful startup modes were tried a description of startup is in order along with the discussion of personnel required. Initially, startup was accomplished using glow plugs and compressed air with the steam generator discharging to the atmosphere. The technique that evolved was the result of trial and error:

1. A few lbs/min of air was supplied to the O_2 feed line just upstream of the generator by a small diesel-engine powered compressor. The air flow was regulated by a sonic orifice.
2. With approximately 70 lbs/min of coolant water flowing, a valve in the generator exhaust line was adjusted to arrive at a combustor pressure of about 300 psi.
3. Fuel and emulsion water were pumped at their starting values of 1.7 and 1.9 lbs/min respectively. Then the homogenizer valve was opened to obtain minimum upstream pressure and closed to obtain a 50 to 100

psi increase. The fuel and emulsion flows were returned to zero after noting the pump-controller set points.

4. Oxygen flow was initiated by opening a remotely operated blocking valve. The variable venturi was adjusted to yield about 5 lbs/min O_2 . The oxygen blocking valve was then reclosed.
5. The glow plug was turned on and warmed up for one minute.
6. A remotely operated blocking valve in the air line was closed. The fuel and emulsion-water pump controllers were set at their previously determined values.
7. As soon as a positive exhaust-temperature excursion was noted, the oxygen blocking valve was opened and the glow plug was turned off.

Following this procedure, operation usually stabilized at about 1000 psi and one-half the full firing rate. Occasionally indications of detonation occurred during the starting transient. Detonation nearly always produced one or more plugged fuel orifices; this resulted in a high fuel-feed pressure and a dirty burn. The usual fix involved disconnecting the fuel feed line and backflushing with air. Once the generator operation was stabilized, transfer of steam to the well could be carried out. This transfer required careful simultaneous closing of the exhaust-to-atmosphere valve and opening of the valve leading to the wellhead. If the wellhead pressure was very much less than the combustor pressure, throttling would have to be used until the pressures nearly equilibrated. Finally, the generator firing rate could be increased by small incremental increases in the fuel, emulsion water and oxygen flow rates. Throughout the starting procedure, a prudent course was to always station one person at the pump and remote-action-valve controls and have a second person perform the manual valve manipulations. During the development phase of the program preceding well steaming, the generator was always exhausted to atmosphere and throttling was always necessary. The throttle valve required readjustment as the firing rate was increased and periodically thereafter as wear and plugging effects alternated.

The second starting mode used glow plugs also, but involved starting directly into the well without the use of compressed air. This procedure was motivated by the failure of the diesel-powered air compressor. The method required that the well be already pressurized from previous operations. The starting sequence was begun with the generator off and vented to atmosphere, and with the valve leading to the wellhead closed:

1. Coolant water flow was established at about 70 lbs/min.
2. Oxygen flow was initiated by opening a remotely operated blocking valve. The variable venturi was adjusted to yield about 5 lb/min O_2 . The oxygen blocking valve was then reclosed.
3. The exhaust-to-atmosphere valve was slowly closed and the valve to the wellhead slowly opened until transfer of the coolant water flow to the well was complete.
4. Fuel and emulsion water were pumped at their starting values of 1.7 and 1.9 lbs/min respectively. Then the homogenizer valve was opened to obtain minimum pressure upstream and closed to obtain a 50 to 100 psi increase. The fuel and emulsion flows were returned to zero after noting the pump controller set points.
5. The glow plug was turned on and warmed up for one minute.
6. The fuel and emulsion water pump controllers were set at their previously determined values.
7. As soon as the flows stabilized, the oxygen blocking valve was opened and the glow plug was turned off.

This procedure produced reliable starting with negligible pressure excursions. The firing rate could immediately be stepped up as in the first procedure. No throttling was necessary, therefore steam valve wear and pressure fluctuations were minimal throughout the start. Starting directly into the well still required two people on hand as a prudent course.

The third starting mode used the pyrophoric triethyl-borane (TEB) rather than glow plugs. Because of the limited lifetime of glowplugs, this mode would

be attractive for downhole operation of a generator. This third mode also involved starting directly into the well, rather than initially exhausting to the atmosphere. The sequence on steps was identical to the second method up to step 5 which was omitted. Step 7 was modified as follows. The TEB was transferred from an on-site storage bottle by very carefully following the manufacturer's recommendations. Before beginning the starting sequence, the 100-cc bottle was connected into a line parallel to the fuel-emulsion delivery line just upstream of the steam generator. Valving was arranged so that the fuel emulsion flow could be diverted into the parallel line, through the bottle, and back into the delivery line. In this way, the TEB slug could be inserted into the fuel emulsion flow and delivered to the combustor. Step 7 of the second starting mode was modified to read:

7'. As soon as the flows stabilized, the oxygen blocking valve was opened; this was immediately followed by switching the TEB slug into the fuel emulsion flow.

This method also worked reliably although a "ping" always was heard after TEB flow started. As with the first two methods, two people were always used throughout the sequence of steps.

VII. FIELD-TEST EXPERIENCE

An overview of the oxygen/diesel-fuel steam generator field test at Long Beach has been presented in Section II. The field test chronology diagrammed in Figure 1 shows the oxygen/diesel activity at Long Beach beginning in July 1981. Prior to that time, preliminaries were under way at several locations. As described in Section III, site selection was completed in late 1980 and a formal agreement with the City of Long Beach was signed in February 1981. During 1980 and up to June 1981 system design, fabrication, and development proceeded at Sandia National Laboratories in Albuquerque, NM. In early 1981 site preparation was begun. This included redrilling and completion of the wells for steam injection and delivery to the site of the office trailers, gas analysis equipment, and data acquisition systems. Production well baseline gas analysis was underway by March. By the end of June the air/diesel downhole system was in operation.

Figure 1 shows that the oxygen/diesel system field test can be divided into two periods: the pre-injection period spanning July through October 1981 and the injection period from November 1981 through March 1982. The highlights of the pre-injection and injection periods are shown in greater detail in Figures 19 and 20, respectively.

Well Completion and Running-In: Based on injectivity tests made in April with the air unit injection well, both injection wells were recompleted with additional perforations, prepacking of the perforations, and an inside casing gravel pack and liner. A Baker Model DA-T Thermal Perm packer was set at 2077 feet measured depth. The details of this work which was completed in early July are displayed in Figure 4. During July the oxygen system components arrived at the test site and were assembled. Plumbing and electrical supply lines were run and data lines to the HP and Mod Comp Systems were installed. In the last week of July, the insulated string was run into the injection well. A Baker Model NT-22 seal assembly was followed by a Sperry-Sun pressure cham-

ber, a Sandia-designed temperature chamber, and 52 joints of insulated tubing as shown in Figure 4. Thermocouples and a pressure-transmission capillary tube were banded to the insulated string as it was run in. Carbon steel bands and tubing protectors were used as described in Section V. Just below the wellhead a Baker Model TC Thermoseal expansion joint was installed with 7 of its 10-foot stroke extended. Both the casing (during cementing) and the insulated tubing (during manufacture) were pre-stressed to minimize thermal expansion. To avoid overstressing the insulated tubing the inner tubing of the top 15 joints was only prestressed to 15000 lbs tension as opposed to 19000 lbs for the lower 37. The entire running-in required approximately four shifts. Progress was slowed by the discovery of defective welds, by the banding operations, and by the required feeding of instrumentation leads through the blow-out preventer and well head.

Pre-Steamng System Development: By the end of July, the injection well was ready for steaming with all downhole instrumentation connected to the data acquisition systems. The oxygen-system components were completely assembled and trial runs were underway. At this point, two key development program elements remained to be completed before steam injection could begin:

1. Establishment of a stable manual or computer-operated flow control system for fuel, emulsion water, oxygen, and coolant water.
2. Demonstration of an acceptable combustor head lifetime.

The equipment on hand included all the necessary elements for a computer-operated system, however, the software development was incomplete. The trial runs that were underway used manual control, but flow stability was a problem. It was elected to continue development of the manual control option as the quickest route to beginning well steaming. During August and most of September this work was completed. The following steps were taken:

1. The fuel and emulsion water pump systems were reconfigured to greatly reduce unsteadiness.
2. An emulsion premixer was added to improve the emulsion temporal stability.

3. A positive displacement flow meter was installed downstream of the homogenizer valve, replacing a much less reliable meter in the emulsion water line.
4. Accumulator pressures and check/relief-valve settings were optimized.
5. Cryopump operation was automated.
6. Oxygen pressure regulation was improved.
7. Errors in the oxygen metering software were corrected.
8. An existing inline variable venturi was pressed into service as an oxygen flow regulator.

This last step proved crucial in that it enabled sonic isolation of the oxygen flow rate from the combustor pressure.

One problem which was not pursued because of lack of time during the test was the periodic failure of the caustic pump check valve seals. It has since been realized that these seals were made of Buna-N rubber, unsuitable for service in sodium hydroxide. By late September the first 12-hour run at Long Beach was completed with the steam exhausting to atmosphere. The run was terminated five minutes early by blowout of one of the steam-generator glow plugs. Throughout the run, a small steam leak at the glow plug seat had been tolerated. This led to erosion of some of the glow plug threads and failure of the rest. The automatic shutdown system worked as intended and no one was hurt. The glow plug was ejected upward at about 14 degrees from vertical and was not recovered. This was the sole serious incident in the entire field test. Elimination of a copper gasket and careful attention to the preparation and maintenance of the tapered seats greatly reduced the incidence of leakage at glow plugs. Steam leaks of this sort were no longer tolerated. The 12-hour test established that severe material loss was occurring on the walls of the combustor facing the flame, but that longer runs would be needed to establish lifetimes. Consultations with several metallurgists were begun. The hourly, daily, and weekly routines for continuous operation were finalized and swing and graveyard shift personnel were trained.

Early in October the first lifetime results were obtained. The limiting factor was the formation of very small radial-running cracks which intersected each fuel injection orifice. These cracks caused improper fuel atomization and the production of soot. During October the test was repeated as shown in Figure 19 and repeated again with a change of materials. The results were similar. Work was begun on a design modification to circumvent the crack problem. This involved the addition of stress-relief slits as described in Section IV. Also in October the first experience with squealing instability occurred when a combustor head was delivered with inadvertently-undersized fuel orifices. Undersized orifices increased the ratio of fuel-to-oxidizer flow velocities and could be countered by decreasing the emulsion-water flow rate as discussed in Section IV.

Steam-Injection Phase: By the end of the first week in November, convincing evidence was in hand that the stress-relief slit modification had significantly extended head life. The steam-injection phase of the field test (illustrated in Figure 20) was initiated. The annulus between the injection well casing and the insulated tubing was vented to the atmosphere and, during the first day of injection, produced considerable volumes of steam. This could have been attributed to annulus-water boil-off. However, an increasing rate of venting, coupled with a decreasing downhole temperature, suggested that a steam leak had occurred and was enlarging. The decision was made to pull all of the insulated tubing, re-run and hydrotest it. In the process all of the downhole instrumentation wellhead packing assemblies were removed and rebuilt; all of the banding was cut and discarded; the tubing protectors were saved and cleaned for reuse; and the packer seal assembly was re-dressed. Hydrotesting revealed two leaks. One joint had a leak at the weld connecting the inner tubing to the outer tubing. This leak allowed steam to reach the calcium silicate insulation. The second leak was at a collar and allowed steam to escape the delivery string. Threads on one side of the collar and pin were almost completely eroded away. The original expansion joint was replaced

because of pitting discovered on the slick joint. Surface plumbing and electrical connections were re-established and steam injection resumed on November 21, 1981. The entire round trip took 10 shifts.

Steaming continued for the next 2 1/2 weeks with one major and four minor interruptions as shown in Figure 20. During this period, the annulus was open to the atmosphere and no venting of steam was observed. The minor interruptions numbered in Figure 20 are identified as to cause in Table 8. The major interruption in late November was caused by local flooding during rains at the test site. When the water level reached the LOX pump electrical motor, the system was manually shut down. One full day was spent cleaning crude oil deposits off of low-lying equipment and particularly from the LOX transfer area. During the first week in December, steam injection resumed. The steam generator pressure began to increase, gradually at first, and much more rapidly by the end of the week. It was found that the pressure could be decreased by turning off the caustic injection. The downhole pressure did not follow the surface-pressure increases; therefore, it is believed that the problem was caused by wall deposits located in the pipe or valves between the generator and the wellhead. Some evidence of this was found at the end of the test and is presented in the next section. However, a puzzle remains since this phenomenon did not occur again.

By the end of the first week in December, a steam leak had developed at the well head valve bonnet, and by December 9 the decision was made to shut down to repair the valve. To accomplish this, the well had to be "killed." Cold water was pumped into the well for four days followed by injection of a calcium chloride solution. Steaming of the well resumed on December 17 and continued for a little over a week with four minor interruptions. The steam leak at the well-head valve re-occurred, but it was found to be controllable by cooling the valve with a water trickle. On December 18, venting of steam from the injection well annulus resumed for the first time since early November. Because the well had only been steamed for one day since having been killed,

it was concluded that the steam came from another leak rather than boiloff. For the remainder of the field test the annulus was shut in and casing pressure closely followed the steam generator pressure.

As the injection program continued, combustor heads were replaced and rebuilt as necessary. Alternative materials and designs were tried as outlined in Section IV. Late in December this process was disrupted when it was discovered that a replacement combustor head had a fabrication defect. Steam injection was not possible again until January 10. The delay was aggravated by holiday shutdowns of the involved machine shops. From January 10 to February 1, steam injection proceeded with 8 minor interruptions as shown in Figure 20 and Table 8. The most serious of these interruptions was the loss of the downhole temperature signals on January 21. A leak at the capillary-tube wellhead feed-through ten days later led to the discovery that the capillary tube and thermocouples were broken off below their packing. By the end of January, a problem with wellhead vibration led Long Beach Oil Development Company to order a shutdown of the system. During the previous months some thermal "growth" of the 7-inch well casing was noted, evidenced by raising of the casing and welded-on slips out of the well-head bowl. Once this occurred, the casing could move laterally, relative to the wellhead. Lateral vibration became particularly violent in late January, leading to the order to shut down.

Field-Test Termination: During February the field test remained inactive, awaiting a decision from LBOD on the next course of action related to the well-head vibration. In early March, permission was received to resume steam injection, but only so long as wellhead vibration was absent. It was agreed that combustor head development tests would continue with steam exhausting to atmosphere if necessary. Injection continued through March 20 with one major and three minor interruptions. The major interruption was again caused by wellhead vibration. Steam was exhausted to atmosphere during this three-day interruption of injection. In late March, the future plans for the oxygen/diesel system field test were reviewed. Three factors were considered:

1. The continuing difficulty with wellhead vibration.
2. The current 2-3 week combustor lifetime.
3. An in-progress review of the air/diesel field test future.

The decision to terminate further operation of the oxygen/diesel system at Long Beach was made based on the above factors and was consistent with the decision to end the air/diesel test. The decision to end the air/diesel test was based on a change in emphasis in the Department of Energy's enhanced oil recovery program and on the desire of Long Beach Oil Development Company to build upon these tests by placing a commercial DSG into the air unit injection well.

The insulated tubing was removed from the injection well in early May. Leak testing was not performed; however, water and gases were observed squirting out of pinholes in a number of joints. The pinholes in each case occurred where the inner and outer tubing were joined by a weld. The inner and outer surfaces of the insulated tubing appeared to be smooth with no significant loss of material. The packer seal assembly also appeared to be undamaged. All of the downhole equipment was recovered and further description of its condition can be found in the next section. By June of 1982, the site at Long Beach had been vacated and all equipment was returned to Albuquerque.

VIII. RESULTS

A brief history of the oxygen/diesel steam generator field test has already been presented in Figures 1, 19 and 20. The steam injection history shown in Figure 20 is only approximate for schematic purposes. More accurate results for this and all other relevant quantities will now be presented. Flow-rate, pressure, and temperature data were reduced, and along with the time, were recorded on magnetic tape cassettes by the HP 9845 computer system. Additional quantities such as firing rate and steam quality were computed for instantaneous display and were also recorded. Data samples were separated by approximately 30 seconds. Approximately 10 million 6-digit numbers were recorded during the course of the field test. Post-test data processing began with time averaging of the data. For the most part, averaging was performed over 100 data points at a time. Averaging stopped whenever a time discontinuity in the data was encountered. Such times usually corresponded to a period when the generator was shut down. As a result, some averages included less than 100 points. The results from this procedure could be stored on one tape cassette. The data were then plotted using the HP system. The plots are presented in Appendix I.

Flow Rates: Figures I-1 to I-4 show the flow rates of fuel, oxygen, coolant water, and emulsion water during the steam injection period. Initially, the emulsion water flow rate was monitored but not recorded by the HP system. Starting in mid-December, this flow rate was recorded as well as monitored. The greatest unsteadiness is evident in the oxygen flow rate. This reflects the difficulty in controlling oxygen supply pressure and temperature. For the other flows, changes greater than $\pm 1/2\%$ represent operator intervention or startup or shutdown transients. For several days in mid-December, again in January, and for all of March, the firing rate was reduced because of squealing instabilities. The corresponding reduced flow rates for fuel, oxygen and emulsion water are apparent.

Pressures: Figures I-5 to I-10 show the surface and downhole steam pressures, and the fuel, water, oxygen venturi inlet and oxygen storage pressures. Here steam pressure is really the sum of water vapor plus noncondensibles partial pressures. The pressures during shutdown periods were not generally recorded, and therefore, no representations of pressures are shown for such periods. Intermittent operation of the downhole-pressure transducer is evidenced during November and December by the off-scale values. For the first few days of operation in early November, the capillary tube and downhole pressure chamber were not helium-purged to ensure accurate pressure measurement. The downhole pressure transducer was removed from the system on December 20, and a replacement was installed by the time operations resumed in January. On January 31, it was discovered that the capillary tube leading from the transducer to the downhole pressure chamber was broken just below the wellhead. No subsequent downhole pressure data were taken. All of the downhole thermocouple signals were lost on January 21 because, as it was later realized, of breakage just below the wellhead; therefore, downhole-pressure data after January 21 are suspect. The fuel and water pressure in Figures I-7 and I-8 follow the surface-steam pressure, as expected. A few exceptions are noted: a rust-clogged checkvalve in the water line caused abnormally high water pressures early in the program, and several times the homogenizer valve was misadjusted causing a higher than normal fuel pressure. Figure I-9 shows the oxygen venturi inlet pressure, downstream of the dome-loaded regulator. Diurnal fluctuations of $\pm 2\%$ can be seen, associated with the effect of ambient temperature on the regulator. Other variations have to do with long-term temperature changes, drift of the regulator setting, and periodic resetting of the regulator. The stored gaseous oxygen pressure upstream of the regulator is plotted versus time in Figure I-10. Pressure-actuated switches were set to turn the LOX pump on when the pressure fell below 2100 psi and to turn it off when the pressure exceeded 2400 psi. Typically, the pump was on for two hours and then off for two hours. Variability of the pressure switch set points was a signi-

ficant fraction of the 300 psi difference so that widely different pump-cycle times occurred. This was of no consequence to the overall operation.

Temperatures: All of the recorded temperatures are presented in Figures I-11 to I-20. Figure I-11 shows that the generator effluent temperature was nominally $550^{\circ}\text{F} \pm 2\%$. Most of the variations are attributable to the (weak) influence of injection pressure changes and to changes in the generator feed-flow rates. Figures I-12 and I-13 show the behavior of the downhole steam temperature as measured by two independent thermocouples. The second thermocouple, corresponding to Figure I-13, was connected to the HP computer system on December 8 after steam injection was well underway. Throughout the remainder of December, the two thermocouples registered virtually identical temperatures. Upon resumption of operations in January, erratic behavior of the first thermocouple was evident, as seen in Figure I-12. By January 18 both thermocouples were erratic; on January 21 all downhole temperature signals were lost. Figures I-14 to I-16 show additional thermocouple data obtained from the outer diameter of the insulated string on and 30 inches above and below a collar on the bottom of the topmost joint in the well. These thermocouples were connected to the HP system on December 8. Considerably lower temperatures are registered away from the collar, as would be expected. The data for early January show abnormally low temperatures which are suspect and erratic behavior after January 12. As with all the other downhole thermocouples, these signals were lost on January 21. Figure I-17 shows the variation of gaseous-oxygen temperature during the field test. The measurement was made just upstream of the oxygen venturi. This temperature was nearly always below ambient because of the frequent recharging of the tube trailers with freshly evaporated LOX. During January the normally used LOX pump was temporarily out of service because of a failed bearing and was replaced by a faster pump. The evaporator was not able to keep pace with this pump as the temperatures show. Figure I-18 illustrates the results from a thermocouple clamped to the outside diameter of the steam generator body at about the midpoint between the top and bottom

heads. The temperature is seen to range from 130°F to 150°F over the course of the field test. Thermocouples were also clamped to the tubing carrying water into and out of the combustor head. The input temperature, shown in Figure I-19, ranged from 60 to 70°F. The temperature rise, shown in Figure I-20, was typically 4°F with some periods of operation at as low as 2.5°F, and some as high as 7°F. The middle number corresponds to a head cooling rate of about 140,000 Btu/hr.

Computed Results: Figures I-21 to I-24 display some computed results. The firing rate presented in Figure I-21 was computed based on the fuel injection rate, the heat of combustion, and the calculated combustion efficiency. Figure I-22 shows the computed oxygen to fuel mass ratio. The flows were ordinarily adjusted to yield a ratio of 3.25, slightly below stoichiometric, so that with fluctuations the free oxygen in the exhaust would be limited to at most a few percent. The energy balance determination of surface steam quality appears on Figure I-23. This quantity was nominally 50% with major variations traceable to changes in water/fuel ratio. Figure I-24 shows the state determination of surface steam quality. As discussed in Section IV, the state determination is less certain than the energy determination because of a greater sensitivity to measurement errors.

The downhole quality and the insulated tubing thermal efficiency have also been calculated, but only for select periods. These calculations were not possible at all times because of several difficulties. Before November 21, the capillary tube had not been helium purged so that the downhole pressure data are questionable. Both before November 21 and after December 9, steam leaks occurred into the annulus between the insulated tubing and the well casing. After January 18, both downhole thermocouples displayed erratic behavior so that the temperature data are suspect. Of the remaining test time, the longest period of nearly continuous steam injection was December 1-8. The data from those eight days are presented in Figures 21-39.

Data for Select Eight-Day Period: The fuel flow rate shown in Figure 21

indicated two brief shutdowns. The first was caused by a plumber who inadvertently turned off the emulsion water supply; the second was caused by a loose connection at a data cable patch board. Both instances were computer-directed automatic shutdowns. The flow rate shown from Thursday through the following Tuesday demonstrates the very steady control that was possible. The gaseous oxygen flow rate in Figure 22 is noticeably more unsteady than the fuel rate. The unsteadiness amounts to $\pm 2\%$ around the mean. This is directly traceable to the diurnal variation in ambient temperature and its effect on oxygen temperature and pressure regulation (Figures 27 and 33). The water flow rate in Figure 23 indicates only one shutdown. Since automatic shutdowns did not cut off the water injection, this single shutdown is evident only because the on-site operator chose to turn off the water pump. Figure 24 shows the generator effluent ("steam") pressure, which was near reservoir pressure initially, leveled off near 1200 psi after four days, and then suddenly increased to over 1300 psi on the fifth day. The rapid decrease each time caustic injection was stopped is apparent. The downhole pressure illustrated in Figure 25 followed the initial surface pressure behavior but remained leveled-off near 1200 psi for the fourth through eighth days. Deposits found localized in the steam piping between the generator and the wellhead suggest an explanation. The deposits discovered at the end of the field test are pictured in Figure 48. Shown are two end-on views of the open piping--one taken from a distance of a few feet and one close up. During the initial phases of formation, it may be that some scale broke loose and accumulated at a valve. This may have restricted flow and caused the observed high surface pressures. After December 8, this behavior was not seen again. The heavy scaling that is evident was not present in any of the tubing below the wellhead. An analysis of the scale determined that it was mainly calcium carbonate along with much smaller amounts of sodium sulfate and sodium hydroxide. The most likely source of the major constituent is the unsoftened water used for fuel/water emulsification.

Figures 26 and 27 show the gaseous oxygen storage pressure and venturi

inlet pressure, respectively. These figures show that regulation effectively filters out the storage pressure fluctuations; the diurnal effect of the ambient temperature on regulation remains. Figures 28 and 29 show the surface and downhole steam temperatures. The downhole temperature roughly follows the surface temperature variations minus 30°F. The effect of the two brief shutdowns on downhole temperature is, of course, much less than at the surface. The generator temperatures in Figures 30-32 show the diurnal effect of ambient air temperature and the effect of the shutdowns. The temperature rise data for combustor head coolant water are noisy because they represent small differences between the measured thermocouple voltages. The oxygen temperature data in Figure 33 reflect both the diurnal ambient-air variation and the shorter-period LOX-pumping influence. Figure 34 shows the computed firing rate, and Figure 35 illustrates the accuracy with which oxygen-to-fuel ratio was controlled.

The energy and state-determined surface steam qualities are presented in Figures 36 and 37, respectively. The energy-determination is seen to drift down with time in response to the increasing temperature. The state-determination is much noisier and less reliable because of its previously discussed sensitivity to temperature and pressure error. The computed downhole quality is shown in Figure 38. The three "notches" correspond to the three periods of intermittent failure of the downhole-pressure transducer which can be seen in Figure 25. The downhole quality is also state-determined, but for reasons already discussed, is less sensitive to measurement errors than the surface state-quality. The reduction in quality between the surface and downhole locations implies a significant loss of energy along the way. Figure 39 shows the computed thermal efficiency of the insulated delivery system for a period in early December. Again, the notches correspond to intermittent failure of the downhole pressure transducer. The results indicate a quasi-steady efficiency of 73% which implies a heat loss of 597 Btu/ft-hr at the nominal firing rate. The thermal efficiency has also been computed for a later 8-day period

which began on January 10, 1982. By that time a steam leak into the annulus between the casing and string had occurred, the annulus had been shut in, and the annulus pressure had increased to the surface steam pressure. One downhole thermocouple and the downhole pressure capillary tube and transducer still appeared to be working. One interruption in steam injection occurred to permit a change of combustor heads and experimentation on triethyl-borane starting. The results presented in Figure 40 show a quasi-steady thermal efficiency of 62% which implies a heat loss of 856 Btu/ft-hr. Evaluation of thermal efficiency beyond this period was not possible because of loss of reliable downhole signals.

Injection-History Summary: A summary of the injection history for the oxygen/diesel system field test is presented in Figures 41-47. These are plots of flow and firing rates on a per-day basis made by appropriate integration of the data given in Appendix I. Data not initially recorded by the HP system were obtained from the Mod Comp system to complete the set. The steam and CO₂ injection rates were computed based on the known combustion characteristics. The steam injection rate includes the water produced by combustion as well as that emulsified with the fuel and that pumped as coolant. The various rates integrated over the duration of steam injection show that 114 tons of fuel, 371 tons of oxygen, 130 tons of emulsion water, and 2388 tons of coolant water were consumed. This resulted in the injection of 4115 million Btu's, 15130 barrels (cold water equivalent) of steam, and 5.9 million standard cubic feet of carbon dioxide.

Combustor-Head Material Results: The various combustor head designs that were tried in the Long Beach field test have been described in Section IV and Figures 7-11. In Section VII, the initial phase of combustor-head development was described, as outlined in Figure 19. Included were the initial observations of cracks through each fuel orifice in October of 1981 and the demonstration that stress-relief slits cured the problem. The slit modification enabled the steam injection program to begin in early November, but did not

eliminate all concern. Material damage and surface recession on both the inner sleeve and head insert continued and the possibility of eventual failure was evident. Therefore, it was decided to proceed with combustor development in parallel with the steam injection program. Figure 49 chronicles this effort. The slit-modified combustor head did indeed fail after 410 hours of operation in early December. The failure occurred when the receding surface of the head insert intersected a fuel passage resulting in mis-directed fuel and the production of soot. The associated SS-310 inner sleeve was near the end of its life with 58 hours more on it than on the insert. The additional hours were accumulated from prior use of the sleeve on a different head.

During December another head of the same design was tested but using different materials. An SS-304 insert was repaired by applying a weld-fill veneer of Hastelloy-X and remachining. An inner sleeve was fabricated from the same material. The surfaces facing the combustion zone were plasma-spray coated to 0.015-inch thickness using a Co-Cr-Al-Y powder. Because of squealing instabilities, this head was run with nearly equal mass flow rates of fuel and emulsion water. The sleeve perforated after 186 hours and was replaced with an SS-310 sleeve. Figure 50 shows the sectioned HA-X sleeve, and Figures 51-52 show typical damage on some SS-310 sleeves. The asymmetry in the damage is particularly noticeable. The combustor-head insert failed at 293 hours by the same mechanism as its predecessor. In late December an Inconel-625 replacement head was delivered with fabrication errors in the fuel orifice area. This was the first head with the new thin-sleeve design described previously. As a quick fix, the head was bored through and fitted with a removable SS-316 injector as illustrated in Figures 10a and 10b. By late January the thin sleeve was perforated but the injector was still functional at 281 hours. The sleeve is shown in Figure 53 and the injector is shown in Figure 54. The failure of the flow swirler on the sleeve may have contributed to a shortened lifetime.

The last head configuration that was tested was the axially-symmetric design illustrated in Figure 11. The thin sleeve and insert face were In-625

and the injector was SS-316. This head was still functional at 367 hours when the field test was terminated. A reduced firing rate was necessary because of the unusual persistence of squealing instability in this design. The insert is shown partially disassembled after the test in Figure 55. The sleeve and injector are shown in Figures 56 and 57, respectively. Severe corrosion of all parts and cracking of the sleeve are evident. The modification of water passage dimensions to increase the coolant flow velocities seems to have resulted in a reduction in the amount of material lost from the walls. The "orange peel" texture seen in the earlier corrosion is not apparent here. However, the difference in running conditions precludes any definite conclusion. A summary of all the lifetime results for the sleeves is presented in Figure 58 and for all the inserts in Figure 59. Comparable results were achieved with either stress-relief slits or removable injectors. No clear improvement over the original thick-sleeve design can be claimed. Followup metallurgical studies of the various combustor parts which are underway are presented in a separate report. (29)

Hardware-Performance Summary: A recap of the hardware performance discussed up to this point follows:

1. Combustor-head cracking and material loss - discussed in this and other sections.
2. Glow plug lifetime - discussed in Section IV.
3. Insulated tubing leaks and efficiency - discussed in this section and in Section VII.
4. Well head valve leaks - discussed in Section VII.
5. Well head vibration - discussed in Section VII.
6. Expansion joint corrosion - discussed in Section VII and below.
7. Downhole signal loss - discussed in Section VII and below.
8. Caustic pump seal problems - discussed in Section VII.
9. LOX pump bearing failure - mentioned in this section and discussed below.

10. Control air compressor failure - mentioned in Section VII.
11. Downhole pressure transducer failure - mentioned in Section VII.
12. Turbine meter momentary stoppage - mentioned in Section VII.
13. Computer "hangups" - discussed in Section VI.

A few additional details will now be covered to complete the discussion. Two expansion joints were used during the field test: the first was in place for four months, but only experienced a few days of steam injection; the second was in place for about the same time period, but was used for nearly all of the steam injection. Neither expansion joint was salvageable because of pitting corrosion on the plain steel polished surfaces. The LOX-pump bearing failure after only about 33 days of steam injection, or 400 cumulative hours of actual pumping, was premature (item 9 above). An incident earlier in the development program, during which the pump ran vapor locked for over ten minutes, is thought to be the reason for early failure.

At the end of the test, all five sheathed thermocouples in the well plus the capillary tube were found to be in pieces for the first 200 feet below the wellhead. Both the thermocouple sheaths and the capillary tube were made of type 316 stainless steel. Figure 60 illustrates the condition of some of these parts typical of all of them. Follow-up metallurgical studies of these parts were performed and the results are published in a separate report.⁽²⁹⁾

Another unexpected post-test finding was the condition of the 2 3/8-inch tubing between the downhole temperature and pressure chambers (Figure 17). As shown in Figure 61, the tubing had taken on a permanent helical form. An analysis of this buckling phenomena was carried out using a general purpose finite element code.⁽³⁹⁾ The analysis showed that buckling could be expected to occur for a load of 23,360 lbs. This is close to the estimated wet-string weight of 20,771 lbs. The buckling loads predicted by the finite-element analysis tend to be over estimated. The high temperature of the 2 3/8-inch tubing, approximately 500°F, is not high enough to evoke a creep response, but is a significant contributor to buckling through its degrading effects on strength.

Production-Well Response: Figure 62 shows the two well patterns involved in the Long Beach field test along with the starting dates of the major steam injection periods, the dates of gas breakthrough for each well, and representative volume percentages of selected gas species. The appearance of nitrogen is interpreted as breakthrough of gas from the air/diesel downhole steam generator; the appearance of the other combustion gases without the presence of nitrogen is interpreted as breakthrough of gas from the oxygen/diesel unit. The results indicate preferential gas movement in the direction from the air pattern towards the oxygen pattern. Only one well, J-75, on the eastern most corner of the two patterns is seen to be affected by the oxygen system alone, and then only for the period 11/29/81 - 2/20/82. A more detailed presentation of gas analyses for this well and for the oxygen/diesel steam generator appears in Table 9. Gas analyses for NOX and SOX before December 1981 were not obtained because of difficulties with the instrumentation. The NOX data that were obtained were initially believed to be compromised by interferences caused by the presence of high percentages of CO₂ or CH₄. This was alluded to in Reference 28. Subsequent tests have shown this not to be a problem.⁽⁴⁰⁾ However, the scatter in the data illustrated in Table 9 (as well as its paucity) makes it impossible to draw conclusions regarding reservoir scrubbing of NOX. The same is true for SOX, and these conclusions also hold for the air/diesel system.⁽⁴¹⁾

The data for produced gases show no detectable change in CH₄, CO₂, or N₂ volume percentages after operation of the oxygen/diesel steam generator. On the other hand O₂, CO and H₂ percentages are seen to change from below detectability to the order of 1% each. Moreover, the ratios of percentages differ from their values at the generator. This suggests reservoir "scrubbing" of some species. Figure 63 illustrates this point further: the oxygen/diesel-system steam injection rate and the produced-gas volume-percentages of O₂, CO and H₂ are plotted versus time. The volume percentages are seen to correlate roughly with steam injection. The ratios of volume percentages for CO

and H_2 , and for CO and O_2 are noted at selected times. The $CO:H_2$ ratio is typically 0.25, whereas at the generator it is 1.0; this suggests selective scrubbing of CO. The ratio of CO to O_2 is initially on the order of 20 and decays with time to about 0.5. At the generator, this ratio is approximately 3. This suggests a preferential scrubbing of O_2 initially and of CO later.

Figure 64 shows the water-cut data for the eight production wells that surround the two steam generator injection wells. Although a change in production for one of the wells in the air system pattern was noted,⁽²⁸⁾ these and other production data show no statistically significant changes which could be attributed to the test. The relatively low firing rate of the steam generators, the limited test time, and the large size of the test pattern are all factors which are felt to have contributed to this outcome.

Economics: Table 10 summarizes certain capital and operating costs which illustrate some differences between the oxygen/diesel and air/diesel systems tested at Long Beach. There are many pitfalls in any such comparison. For example, no comparison could be complete without reference to incremental production results for each system. This in itself is hazardous because of differences in the production patterns. In the present case the obvious differences are the pattern acreages and their injection histories. Another difficulty in the present case is the apparent migration of gases from the air/diesel system into the oxygen/diesel test pattern. Yet another difficulty is the difference in steam quality at the sandface because of the losses suffered in the oxygen/diesel insulated delivery system. This difference highlights the less developed state of the oxygen/diesel system; with additional work this system might also permit downhole placement of the steam generator. For all of the above reasons, Table 10 is intended to offer a very limited comparison. Only those costs that are necessary to show differences between the two systems are presented. Moreover, differences associated with the downhole equipment are omitted since significant changes in future downhole hardware may be expected. Therefore, Table 10 mainly shows the difference in expense between the

use of trucked-in LOX and the on-site production of the equivalent amount of high pressure air. This comparison is slightly in favor of the former approach. A different conclusion might be reached at another site depending particularly on the local cost of LOX. Hazienda⁽⁴⁰⁾ has shown that on-site oxygen production can become cheaper than the production of the equivalent amount of high pressure air for sufficiently large projects. For projects as small as the present one, advantage has been taken of the economy of scale of large off-site LOX plants.

IX. SUMMARY AND CONCLUSIONS

A field test of an oxygen/diesel fuel, direct contact steam generator has been completed under the United States Department of Energy's Project DEEP STEAM. The field test involved the thermal stimulation of an eight-acre pattern in the tar zone of the Wilmington Oil Field in cooperation with the City of Long Beach and the Long Beach Oil Development Company. An air/diesel downhole steam generator was also tested in an adjacent pattern and is described in a companion report.⁽²⁸⁾ The oxygen/diesel steam generator was operated at ground level because of its less-developed state. Steam and combustion products were delivered to the reservoir through 2022 feet of calcium-silicate insulated tubing.

The objectives of the test included demonstrations of safety, operational ease, reliability and lifetime, investigation of reservoir response, environmental impact, and economics, and comparison on the above points with the air/diesel downhole steam generator. The test was extensively instrumented to provide the required data. A mini-computer was used to record and plot data, to provide warning alarms, and to shut the system down under prescribed emergencies.

Approximately 114 tons of fuel, 371 tons of oxygen, and 2388 tons of coolant water were consumed over a four-month period; this resulted in the injection of 4115 MMBtu, 15130 cold-water-equivalent bbls of steam, and 5.9 MMscf of carbon dioxide. Typically, the combustion efficiency was 95% and the steam quality was 50% at the generator. Thermal efficiency of the insulated delivery system was estimated to be 73% early in the steam injection program and 62% after two months of intermittent use. Evidence of steam leakage both into the tubing insulation and into the tubing/casing annulus was observed. Excluding interruptions not attributable to the oxygen/diesel system, steam was injected 78% of the time. System lifetime was limited by the combustor which initially required rebuilding after only 50-80 hours of operation. A modest development

effort extended this lifetime to 2-3 weeks. A companion report presents the results of metallurgical analyses and recommendations for further improvements.⁽²⁹⁾ Significant further extension of combustor lifetime is believed to be possible. Glow plug lifetime in the oxygen/diesel steam generator was typically only about 24 hours, but this was not a problem since the glow plugs were only required for starting and were easily changed. Also, starting with the pyrophoric triethyl borane was successfully demonstrated.

The field test was terminated because of a change in emphasis of the Department of Energy's enhanced oil energy program, because of the desire of the Long Beach Oil Development Company to install a commercial DSG in the air/diesel injection well, and because of operational limits imposed by the various materials problems.

No statistically-significant production change in the eight-acre oxygen system well pattern occurred during the test nor were any adverse effects on the reservoir character detected. The limited test time and relatively large size of the pattern are believed to be factors in the lack of production response. Except for a possible production change in one well, the same observations have been made with respect to the air/diesel system.⁽²⁸⁾ Therefore, no conclusions regarding which of the two systems is preferred from a technical or economic standpoint can be made based on these tests. Similarly, no conclusive remarks can be made regarding the additive effect of injecting CO₂ with steam. For the conditions of this particular test, one limited observation is possible: the use of trucked-in LOX resulted in less expense than did the on-site production of the equivalent amount of high-pressure air for the air/diesel system.

Gas analyses during the field test showed very low levels of SOX (≤ 1 ppm) in the generator gaseous effluent. Appreciable levels of CO (~5%) were measured at the generator, but produced-gas analyses showed evidence of significant gas scrubbing within the reservoir. Injected gases from the air/diesel unit moved up-dip across the oxygen/diesel pattern and dominated three of its

four production wells.

During the test, on-site briefings were provided to approximately 250 individuals; this represented 60 private concerns, universities or government agencies from the United States and 5 other countries.

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TABLE 1

Oxygen/Diesel Steam Generator Contributors

STEAM AND GENERATOR APPLICATION AND DEVELOPMENT

R.E. ANDRES	B.W. MARSHALL
R.G. CLAY	J.B. MORENO
A.B. DONALDSON*	T.C. PARSONS**
R.C. ELLIS***	C.S. SOTO
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F.G. KING*	W.J. VIGIL

CHEMISTRY AND METALLURGY

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A. L. JENSEN	

SYSTEM HARDWARE SELECTION AND ASSEMBLY

F.B. BRUMLEY	L.L. SANDLIN
R.L. MAXWELL	

H P COMPUTER

P.F. BAHR	N.F. SISK
T.D. DONHAM	

MOD COMP COMPUTER

J.A. BEYELER	H.C. OGDEN
K.B. KIMBALL	D.E. ROMERO
R.J. LONGORIA	R.N. SANDERVILLE
R.J. STANOPIEWICZ	

* NO LONGER WITH SANDIA
** CONTRACT EMPLOYEE
*** CONSULTANT

TABLE 2
Reservoir Characteristics of the
Wilmington Field Tar Zone, City of Long Beach

POROSITY	30-33%
PERMEABILITY	500 md
OIL GRAVITY	12-16° API
VISCOSITY	700 Cp
CURRENT OIL SAT.	55%
CURRENT BHP	900-950 psi
INITIAL TEMPERATURE	115°F
DEPTH (VSS)	2000-2500 ft.
THICKNESS	80-120 ft.

TABLE 3

Typical Oxygen/Diesel Operating Conditions

FUEL	3.45 lb/min
EMULSION WATER	4.08 lb/min
COOLANT WATER	68.0 lb/min
OXYGEN	11.4 lb/min
FIRING RATE	4.11 MMBtu/hr
PRESSURE	1200 psi
TEMPERATURE	550°F
QUALITY	50 %

TABLE 4

Sensitivity Analysis for Calculated Steam Qualities and String Efficiency

		(psi)	(psi)	(°F)	(°F)	(%)	(%)			(%)
Water-Fuel	Oxygen-Fuel	Surface	Downhole	Surface	Downhole	Combustion	Steam Quality			String
<u>Mass Ratio</u>	<u>Mass Ratio</u>	<u>Pressure</u>	<u>Pressure</u>	<u>Temp.</u>	<u>Temp.</u>	<u>Efficiency</u>	<u>Energy</u>	<u>State</u>	<u>Downhole</u>	<u>Efficiency</u>
20.89	3.30	1200.00	1240.00	550.00	520.00	95	50	52	13	68
<u>21.10</u>	3.30	1200.00	1240.00	550.00	520.00	95	48	52	13	69
20.89	3.30	1200.00	1240.00	<u>555.50</u>	520.00	95	49	79	13	68
20.89	3.30	<u>1212.00</u>	1240.00	550.00	520.00	95	50	48	13	68
20.89	<u>3.33</u>	1200.00	1240.00	550.00	520.00	96	51	52	13	68
20.89	3.30	1200.00	1240.00	550.00	<u>525.20</u>	95	50	52	15	71
20.89	3.30	1200.00	<u>1252.00</u>	550.00	520.00	95	50	52	13	68

TABLE 5

Computer-Performed Measurements and Calculations

<u>Variable Name</u>	<u>Description</u>
Tair	Ambient air temperature
Tox	Oxygen temperature at venturi inlet
Toxfire	Oxygen line temperature at steam generator
Tfueld	Diesel oil temperature downstream of high-pressure pump
Th2oin	Water temperature entering combustor head
Th2out	Water temperature leaving combustor head
Tgen	Steam generator body midpoint temperature
Tsteam	Steam temperature at generator outlet
Tsteam dh1	Downhole steam temperature #1
Tsteam dh2	Downhole steam temperature #2
Tcollar-hi	String temperature above second collar
Tcollar	String temperature on second collar
Tcollar-lo	String temperature below second collar
Poxtank	LOX tanker headspace pressure
Poxbnk	Oxygen tube trailer pressure
Poxinlet	Oxygen pressure at venturi inlet
Pdelta	Oxygen venturi differential pressure
Pfueld	Diesel oil pressure downstream of high pressure pump
Ph2o	Water pressure downstream of high pressure pump
Psteam	Steam pressure at generator outlet
Psteamh	Steam pressure at downhole chamber
Mfox l	Oxygen mass flow rate
Mfh2ol	Water mass flow rate
Mfh2oe	Emulsion water mass flow rate
Mffueldl	Diesel oil mass flow rate
Rcry	Relay-point resistance indicating LOX pump on/off
R02f	Ratio of oxygen to fuel mass-flow rates
Qualitye	Energy-balance steam quality at surface
Qualitydh	State-determined downhole steam quality
Totenergy	Steam generator firing rate
Vaporlock	LOX-pump vaporlock-determination parameter

TABLE 6

Computer-Activated Alarms and Shutdowns

<u>Condition</u>	<u>Action</u>
Psteam >1400 psi < 895 Poxtbk >2425 psi <2000 LOX pump vaporlock †Ro2f <2.85	Intermittent alarm, printed message
Toxfire >150°F Tsteam >700°F Tgen >200°F *R02F >3.60 †Qualitye >0.7 †Mfoxl <4 **Mfh2oe <0.8 Mffueldl >1.4 Mffueldl *Mfh2ol <15.5 Mffueldl	Alarm, fuel and oxygen valves closed, printed message
<hr/> *Applied if Mffueldl >0.2 †Applied if Tsteam >300°F **Applied if Tsteam >300°F and time since startup >60 seconds	

TABLE 7

Routine Tasks Requiring Onsite Personnel

- A. Hourly system checks and data logging
 - 1. LOX pump status - on/off, vaporlock?
 - 2. Leak checks - LOX, control air, fuel, water, steam, caustic?
 - 3. Pressures - LOX, O₂, fuel, water, steam?
 - 4. Steam temperature, quality?
 - 5. Flow rates - O₂, fuel, water, caustic?
 - 6. LOX remaining?
 - 7. Generator effluent appearance, pH?
 - 8. Filter status - fuel, water?
 - 9. Other mechanical problems - pump noise, well head vibration, etc?

- B. Daily to weekly system checks, maintenance, and data logging
 - 1. Supply - water tank level?
 - 2. Fuel - tank level?
 - 3. Caustic - tank level?
 - 4. Water softness?
 - 5. LOX, fuel, water softner, and caustic replenishment.
 - 6. Filter changeout.
 - 7. Lubrication.
 - 8. Injected and produced-gas collection and analysis.
 - 9. Production well temperatures and pressures.
 - 10. Computer tape and paper changes.

- C. Randomly-occurring tasks
 - 1. Flow-rate adjustments.
 - 2. System startup or shutdown.

TABLE 8

Oxygen/Diesel System Minor Downtimes
During Steam Injection Period
(2 hrs $\leq$ Downtime $\leq$ 36 hrs)

1. UNEXPLAINED HIGH-TEMP. AUTO-SHUTDOWN.
2. SOFTENER-SERVICE ACCIDENTAL WATER CUTOFF.
3. PLUMBER ACCIDENTAL EMULSION - WATER CUTOFF.
4. LOOSE-WIRE CAUSED AUTO-SHUTDOWN.
5. UNEXPLAINED HIGH-TEMP, AUTO-SHUTDOWN.
6. INJECTION WELL ANNULUS VALVE LEAK.
7. CHANGING COMBUSTOR HEADS .
8. WATER TURBINE METER STOPPED MOMENTARILY .
9. EXPERIMENT TO START DIRECTLY INTO WELL WITHOUT USING AIR.
10. EXPERIMENT TO START DIRECTLY INTO WELL WITH TEB .
11. CRYOPUMP BEARING REPLACEMENT .
12. UNEXPLAINED LOSS-OF-WATER AUTO-SHUTDOWN.
13. STARTUP DELAYED BY LOSS OF DOWNHOLE SIGNALS.
14. FUEL TANK INADVERTANTLY RAN DRY.
15. CHANGING COMBUSTOR HEADS.
16. LEAK AT CAPILLARY TUBE WELL HEAD FEEDTHROUGH.
17. CONTROL AIR COMPRESSOR FAILURE .
18. BROKEN SUPPLY WATER LINE.
19. BROKEN FITTING ON INJECTION WELL ANNULUS.

TABLE 9
Representative Steam Generator
and Well Gas Analyses

<u>GASES</u>	<u>OXYGEN/DIESEL GENERATOR</u>	<u>WELL J-75</u>	
		<u>OCT - NOV</u>	<u>DEC - JAN</u>
CO ₂	88%	3-6%	3-6%
N ₂	0.05	0.4-0.6	0.4-0.6
O ₂	1.7	0	0.7
CO	5.3	0	0.4
H ₂	5.3	0	1.3
H ₂ S	< 10 ppm	2-3000 ppm	1-2000 ppm
SOX	< 1 ppm	?	< 1 ppm
NOX	24-110 ppm	?	1.8-15 ppm
CH ₄	0	87%	87%

TABLE 10

Comparison of Some Capital and Operating Cost
Differences Between the Air/Diesel and Oxygen/Diesel Systems

<u>AIR/DIESEL</u>	<u>CAPITAL</u>	<u>OPERATING</u>
2 ELECTRIC RECIPROCATING COMPRESSORS	\$120,000.00	\$132.00 /d ELECTRIC
1 DIESEL-POWERED SCREW COMPRESSOR	\$ 70,000.00	\$ 343.00/d DIESEL FUEL
	<u>\$190,000.00</u>	<u>\$ 475.00/d</u>
<u>O₂/DIESEL</u>		
2 40,000 SCF TUBE TRAILERS	\$100,000.00	
1 3000 GALLON DEWAR	\$ 30,000.00	\$460.00/d LOX
LOX PUMP	\$ 6,000.00	\$ 3.20/d ELECTRIC
EVAPORATOR	\$ 2,000.00	\$ 0.80/d ELECTRIC
EMULSION-WATER PUMP & INSTR.	\$ 12,000.00	\$ 0.60/d ELECTRIC
	<u>\$150,000.00</u>	<u>\$464.60/d</u>
*OMITTED: EQUIPMENT-REPAIR COSTS		
PRODUCED-GAS CONTAMINATION PENALTY		
ENERGY-LOSS PENALTY		
INSULATED-TUBING COST		

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1981		SYSTEM DESIGN AND DEVELOPMENT AT SANDIA PRELIMINARY TO LONG BEACH F.T.
	JULY	WELL COMPLETION, SYSTEM ASSEMBLY AT LONG BEACH
	AUG.	TRIAL RUNS, SYSTEM DEVELOPMENT
	SEPT.	
	OCT.	SUSTAINED RUNS, COMBUSTOR DEVELOPMENT
	NOV.	STEAM INJECTION, COMBUSTOR DEVELOPMENT
	DEC.	
	JAN.	
1982	FEB.	
	MAR.	

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Figure I.5 Steam Injection-Pressure History

Figure I.6 Downhole Steam Pressure History

Figure I.7 Fuel Pressure History

Figure I.9 Oxygen Regulated Pressure History

Figure I.10 Oxygen Storage-Pressure History

Figure I.11 Steam Temperature History

Figure I.12 Downhole Steam Temperature #1 History

Figure I.13 Downhole Steam Temperature #2 History

Figure I.14 History of Temperature on String 30"
Above Collar on Bottom of Uppermost Joint

Figure I.16 History of Temperature on String 30"
Below Collar on Bottom of Uppermost Joint

Figure I.17 Gaseous-Oxygen Supply-Temperature History

Figure I.18 History of Steam Generator Exterior Temperature

Figure I.19 History of Steam Generator Inlet Water Temperature

Figure I.20 History of Temperature Rise of Water Passing Through Steam Generator Head

Figure I.21 Firing Rate History

Figure I.22 History of Mass Ratio of Oxygen to Fuel

Figure I.23 Energy-Balance-Calculated Steam Quality History

Figure I.24 State-Determined Steam Quality History

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