EXPLOSIVE STIMULATION OF A GEOTHERMAL WELL--GEOFRACT

LA-SUB--93-163

DE93 010758

PIFR-1256

XP9-1358F-1

by

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July 1982

Prepared for

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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CONVERSION FACTORS FOR U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E -10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
British thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
cal (thermochemical)/cm ² §	mega joule/m ²	4.184 000 X E -2
calorie (thermochemical) §	joule (J)	4.184 000
calorie (thermochemical)/g§	joule per kilogram (J/kg)*	4.184 000 X E +3
curie§	giga becquerel (GBq)*	3.700 000 X E +1
degree Celsius†	degree kelvin (K)	T _K = T _C + 273.15
degree (angle)	radian (rad)	1.745 329 X E -2
degree Fahrenheit	degree kelvin (K)	T _K (T°F + 459.67)/1.8
electron volt§	joule (J)	1.602 19 X E -19
erg§	joule (J)	1.000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3.048 000 X E -1
foot-pound-force	joule (J)	1.355 818
(gallon (U.S. liquid)	meter ³ (m ³)	3.785 412 X E -3
inch	meter (m)	2.540 000 X E -2
jerk	joule (J)	1.000 000 X E +9
joule/kilogram (J/kg) (radiation dose absorbed)§	gray (Gy)*	1.000 000
kilotons§	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch ² (ksi)	kilo pascal (kPa)	6.894 757 X E +3
kta ³	newton-second/m ² (N-s/m ²)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E -6
mil	meter (m)	2.540 000 X E -5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E -2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N-m)	1.129 848 X E -1
pound-force/inch	newton/meter (N/m)	1.751 268 X E +2
pound-force/foot ²	kilo pascal (kPa)	4.788 026 X E -2
pound-force/inch ² (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E -1
pound-mass-foot ² (moment of inertia)	kilogram-meter ² (kg-m ²)	4.214 011 X E -2
pound-mass/foot ³	kilogram-meter ³	1.601 846 X E +1
rad (radiation dose absorbed)§	gray (Gy)*	1.000 000 X E -2
roentgen§	coulomb/kilogram (C/kg)	2.579 760 X E -4
shake	second (s)	1.000 000 X E -8
slug	kilogram (kg)	1.459 390 X E +1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*The gray (Gy) is the accepted SI unit equivalent to the energy imparted by ionizing radiation to a mass of energy corresponding to one joule/kilogram.
†The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
‡Temperature may be reported in degree Celsius as well as degree kelvin.
§These units should not be converted in DNA technical reports; however, a parenthetical conversion is permitted at the author's discretion.

FOREWORD

This report was prepared by Physics International Company (PI), 2700 Merced Street, San Leandro, California, 94577, USA, under contract No. XP9-1358F-1 to the University of California, Los Alamos National Laboratory, Los Alamos, New Mexico, 87545. The contract was administered under the technical direction of Dr. Robert J. Hanold who coordinated the activities of the various companies and government agencies assisting in the project and made significant technical contributions.

The author would like to express his appreciation to the Union Oil Company of California, which contributed the well, field support, and the development of the canister that contained the explosives. In particular, I would like to thank Mr. Del Pyle, Mr. Stephen Pye, and Dr. Chris Allen from Union Oil Co. whose tireless efforts contributed to the project's success.

Dr. Eckart W. Schmidt and Mr. Foy McCullough of Rocket Research Co. also provided excellent technical advice regarding the HITEX II explosives they developed and supplied under a separate contract to the Los Alamos National Laboratory. Dr. Arthur M. Spencer of Petroleum Technology Co. provided field support during emplacement of the explosives.

I would also like to thank the following PI personnel for their contributions to the project--Mr. Francis D. Milistefr (Test Engineer), Mr. Patrick M. Creely (Electronics Designer), and Mr. Minoo Mama (Mechanical Engineer).

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SECTION 1

EXECUTIVE SUMMARY

This paper describes the first known explosive stimulation successfully conducted in a geothermal well. Two tests were performed in a 2690-meter-(8826-ft-) deep Union Oil well at the Geysers field in Northern California in December 1981. The heat-resistant process, called GEOFRAC, uses a new, unique, explosive--HITEX II, which is a nondetonable solid at room temperature. Upon melting at a temperature of 177°C (350°F), the HITEX II liquid becomes an explosive that can be safely heated to temperatures greater than 260°C (500°F). These unique properties of the explosive were exploited in the GEOFRAC process through the cooperative efforts of Physics International Company (PI), Rocket Research Company (RRC), Union Oil Company (UO), and the University of California Los Alamos National Laboratories (LANL).

The initial test used 364 kg (800 lb) of explosive placed at a depth of 2256 meters (7403 ft), and successfully demonstrated that the explosive could be safely emplaced using conventional well-head equipment and detonated after 48 hours of exposure to the hot environment of the well on December 4, 1982. Debris from the explosive container, however, caused some plugging of the well.

In the second stimulation test, 5000 kg (11,000 lb) of HITEX II was emplaced at a depth of 1697 meters (5568 ft) using

an alternate configuration to minimize well plugging after detonation. This amount of explosive was contained in a 190-meter- (625-ft-) long aluminum tube to separate it from the well fluids. The explosive was successfully detonated on December 14, 1981 at the scheduled time. Posttest cleanout of the well was minimal for this test, the result of the explosive container configuration change. Flow tests of the well showed that the near-well-bore skin factor was decreased. This improvement in the skin factor was probably caused by the debris plug left in the hole after the initial test. This change in the skin factor would also suggest that no damage occurred to the well bore as a result of the second stimulation test using 5000 kg (11,000 lb) of explosives. No casing damage was observed even though the charge was only 111 meters (365 ft) from the casing shoe. No increase in steam production was observed, suggesting that no additional natural fracture systems were connected over the interval of the well bore treated.

The program objective to demonstrate that HITEX II explosive could be safely emplaced and detonated in a hot geothermal well was successfully accomplished. Further tests are suggested to show the economic utility of the GEOFRAC process in enhancing steam productivity.

SECTION 2

INTRODUCTION

2.1 BACKGROUND

Geothermal energy is a major energy resource for the United States. Only a small fraction of the total geothermal energy potential, however, is currently being used for heating purposes or generating electricity. The exploration and development of geothermal fields is more difficult than natural gas or oil fields because of the high temperature and corrosive nature of geothermal well fluids. Likewise, the use of stimulation techniques such as hydraulic fracturing or explosive fracturing have not been rapidly transferred from fossil-fuel exploration to geothermal-well exploration.

The principal method of stimulating a well to greater productivity is to alter the conditions surrounding the well bore. This alteration can be accomplished by enlarging the well bore or by some other treatment that creates additional fractures or extends existing fractures. These fractures effectively increase the well-bore radius and thus increase the effective permeability of the geologic media. Explosive fracturing creates new fractures because of the rapid pressurization of the well bore during the detonation of the explosives.

The use of explosive or hydraulic stimulation treatments in geothermal wells should prove beneficial in increasing the productivity from these wells, but the hostile environment has hindered the use of many conventional treatment methods. This is particularly true for explosive treatment methods where conventional explosives cannot withstand the high temperatures, and heat-resistant explosives are very expensive for a massive stimulation. The potential usefulness of explosives has long been recognized and discussed (References 1-3) but no known tests have been conducted on an actual well. Recently, however, Rocket Research Company developed a relatively inexpensive, heat-resistant explosive called HITEX II, which was specifically formulated for geothermal wells and other high-temperature applications. The unique features of HITEX II are that it:

- is a safe, nondetonable solid at room temperature
- becomes detonable when it melts at a temperature of 177°C (350°F)
- is stable up to a temperature of 277°C (530°F)
- will not autodetonate at temperatures below 427°C (800°F)
- is easily disposable; it dissolves in water to form a liquid fertilizer.

It is these unique properties that formed the basis for this new explosive stimulation method for geothermal wells that is called GEOFRAC.

2.2 THE GEOFRAC CONCEPT

GEOFRAC is the technique of emplacing HITEX II explosive in a hot geothermal well and detonating it to cause additional fractures in the rock surrounding the well bore, thus increasing well productivity.

The criteria for the development of the concept were that this explosive be safe during emplacement, that conventional well-head equipment be used whenever possible, and that all subsystems be prequalified in tests that simulated the environment of a geothermal well. The technique consists of three basic elements: the explosive, a container to separate the explosive from the well fluids, and a detonator system to ignite the explosive.

The properties of the HITEX II explosive were characterized by RRC under a separate contract from Los Alamos National Laboratories (LANL). Pertinent results of these tests are summarized in Section 3.

The canister used to contain the HITEX II explosive and separate it from the well fluids was developed by Union Oil. Details of the canister design are described in Section 4.

PI, under contract to LANL, developed a shaped-charge firing system that would withstand the high temperatures of the well and ignite the HITEX II explosive at a preset time after emplacement

in the well. Section 5 describes the development of the shaped-charge detonator system and the tests conducted to verify that it would meet the program requirements.

2.3 EMPLACEMENT CONCEPTS

Safety was a primary requirement for the emplacement method. No personnel were to be exposed to any explosives hazard during the time the HITEX II was being lowered into the well. Although this material is essentially a nonexplosive up to temperatures of 177°C (350°F), these temperatures would be exceeded if the well was not cooled during emplacement. The initial concept of injecting air into the well proved ineffective. Water was therefore selected as the cooling medium even though its use could introduce problems of formation spalling, or wall collapse could occur.

The HITEX II was placed in a metal container to separate it from the cooling water and well fluids and to prevent it from entering the formation when it liquifies. Lowering the canister assembly on casing pipe was considered to be advantageous since the detonator system can be wire-line run on the inside of the casing/canister assembly after the canister assembly is safely emplaced at the bottom of the well.

A float assembly connected to the detonator system would keep it from sinking in what eventually would become liquid HITEX II. The wire line could then be disconnected from the detonator float assembly and retrieved. A bridge plug can then

run inside the casing/canister assembly and set in a thick-walled section at the top of the canister. Thus the canister would now effectively be sealed as a self-contained unit.

A release tool located between the canister and casing would be activated and the casing pipe retrieved leaving just the canister assembly in the well. All equipment would then be secured, the water flow stopped, and the well pressurized to drive the remaining water into the formation. The pressurization would then be stopped and the well allowed to produce steam around the canister, raising the internal temperature to melt the HITEX II explosive. At a predetermined time, the detonator system would be set off, and the firing of the shaped charge would generate a jet causing the explosive to detonate. This emplacement technique is illustrated in Figure 1.

An alternate emplacement technique similar to that just described was also considered. In this system the detonator is placed at the bottom of the HITEX II column in the canister. This configuration eliminates the need for the detonator system float assembly and the bridge plug, since the top of the canister can be sealed at the well head before it is lowered into the well. The canister can also be lowered on standard drill pipe--a time saving procedure. The first emplacement technique described was selected for the initial test since the detonator system is not positioned until the HITEX II is at the bottom of the well, and potential problems, including well collapse or bridging, can be safely solved before inserting the detonator system.

Figure 1. GEOFRAC emplacement concept:detonating the top of the HITEX II explosive column.

Also considered was another technique in which the detonator system would be placed on top of the explosive column and allowed to sink to the bottom of the canister as the HITEX II begins to melt. More work would be required to ensure the detonator system would not become lodged part way down the canister before the detonator timing sequence was complete.

To demonstrate the GEOFRAC concept under field conditions, Union Oil provided a test well at the Geysers field. It was decided that the initial test would contain only a small amount of HITEX II to evaluate the emplacement technique. After this initial test, the emplacement technique could be reevaluated and altered prior to conducting a stimulation test using a much larger amount of explosive. The explosive in the second test would be placed slightly above the location in the initial test. The particular well that was selected for testing, the sequence of events for the two tests, and the results achieved are described in Section 6. The conclusions and recommendations from these tests are given in Section 7.

SECTION 3

HITEX II EXPLOSIVE DESCRIPTION

HITEX II is an explosive compound developed by Rocket Research Corporation (RRC). It is especially formulated for use in high-temperature environments typically encountered in geothermal wells. A complete description of the qualification tests conducted under a separate contract from Los Alamos National Laboratories (LANL) specifically for this field demonstration of explosively stimulating a geothermal well are described in Reference 4. Under RRC's contract, the HITEX II was tested extensively to ensure that it would meet the necessary physical and safety requirements. Sufficient HITEX II was manufactured for the various characterization and safety tests and to conduct the two field demonstration tests.

3.1 PHYSICAL AND CHEMICAL CHARACTERISTICS

HITEX II consists of a mixture of nitrate salts. The explosive is manufactured by adding some of the dry ingredients to the mold, which are then melted at a temperature of about 135°C (275°F). The remaining ingredient and water are then added incrementally. The entire mixture is subsequently raised to 190°C (375°F) until fully melted and the water has boiled off. The mixture is then permitted to cool and solidify. The grains are slipped from the molds by removing the bottom plate and reheating until the solid grain drops out.

The cast grains of HITEX II are white at room temperature, but turn colorless when they melt at 177°C (350°F).

The density of solid HITEX II at a temperature of 21°C (70°F) is 1.63 g/cm³. When it melts and becomes liquid, the density decreases to 1.53 g/cm³ between the temperatures of 185 and 204°C (365 and 400°F). Above this temperature, bubbles begin to form as the temperature rises. These bubbles cause a further density decrease to approximately 1.50 g/cm³ between 232 and 260°C (450 and 500°F).

Liquid HITEX II shows a measured detonation velocity of 6394 m/s at 260°C (500°F)--not far off the theoretical velocity, calculated to be 6459 m/s (Reference 5). The heat of explosion is -2844 J/g with an energy release of 864 joules per mole of gas. The critical diameter for sustained detonation was not thoroughly investigated but limited tests suggest that a 6.35-cm (2.5-in.) column is just below the threshold.

Thermal sensitivity tests of HITEX II show that no incipient exotherms occur below 260°C (500°F). A weight loss of less than 1% was measured after the explosive was held at a temperature of 260°C (500°F) for 24 hours. All of the measured characteristics of HITEX II are summarized in Table 1. Figure 2 shows HITEX II grains being prepared for shipment.

Table 1. Physical and chemical characteristics
of HITEX II.

Density	
Solid Grain (21°C)	1.63 g/cm ³
Liquid (185° to 205°C)	1.53 g/cm ³
Liquid (232° to 260°C)	1.50 g/cm ³ (contains bubbles)
Melting Temperature Range	178°C (350°F) to 191°C (375°F)
Color	
Solid (21°C)	White
Liquid (260°C)	Clear
Detonation Velocity (260°C)	6394 m/s (measured) 6459 m/s (calculated)
Heat of Explosion	-2844 J/g
Energy Release	864 J/mol gas

**a) HITEK grains
sealed in polyethylene
bags.**

**b) Grains have been
inserted in cardboard
protective tubes**

**c) Pallets of HITEK II
ready for shipment**

**Figure 2. Photographs of HITEK II explosive grains
being prepared for shipment.**

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3.2 SAFETY TESTS

HITEX II was subjected to a number of safety tests to determine its shipping classification and to provide information about its safe handling. These test results (shown in Table 2) indicate that HITEX II is a very safe material to handle in its solid form and is safer than most explosives when it is in its liquid explosive form. HITEX II was originally classified by the Department of Transportation as a "nitrocarbonitrate" and shipped under an "oxidizer" label. This classification is now obsolete, and HITEX II is expected to be reclassified as a "blasting agent."

3.3 MATERIALS COMPATIBILITY

The compatibility of molten HITEX II was evaluated with other materials that it might contact during emplacement because it is a strong electrolyte comparable to battery acid. These tests were conducted by RRC under contract to Union Oil (Reference 6). The evaluation criteria for determining compatibility or lack of compatibility were weight change of the specimen material, specimen color change, weight change of the explosive, and any exotherms observed during the tests.

Molten HITEX II is compatible [as determined from 24-hour, 260°C (500°F) tests] with 6061 aluminum, 304 CRES stainless steel, Teflon, and an elastomeric material called EPDM Y-267, produced by L'Garde, Inc. K-55 steel with and without tin

Table 2. Results of HITEX II safety tests.

Drop Weight Sensitivity	25 to 171°C	Negative at 524 kg-cm
	191°C	Positive at 140 kg-cm
	260°C	Negative at 16 kg-cm
	260°C	Positive at 26 kg-cm
40-foot drop test (MIL-R-27713)	5°C	Negative
	260°C	Negative
Rifle Bullet (30-06)	21°C	Negative
	260°C	Negative
Electrostatic Discharge	21°C	> 1.26 J, < 5 J
	260°C	> 5 J
Friction Sensitivity	21°C	0.46 GPa at 3 m/s
	260°C	> 0.58 GPa at 3 m/s
Explosion Temperature		Exotherm at 277°C but no explosion up to 427°C
Burn Test (13-kg grain)		Negative
Card gap (#8 cap)	Raw materials	Low order detonation
	Pulverized HITEX II	Negative
	Cast HITEX II	Negative
Detonatability	Up to 142°C	Negative with 0.45-kg composition C-4 booster

coatings, tin, and lead were shown to exhibit excessive reactions. The chemical reaction on bare K-55 steel was accelerated 40 times by galvanic corrosion when K-55 was in contact with aluminum.

Although the number of materials suitable for use with molten HITEX II was shown to be limited, an adequate number exists for fabricating a suitable container and associated hardware.

SECTION 4

EXPLOSIVE CANISTER DEVELOPMENT

The explosive canister development was conducted by Union Oil. This section summarizes their effort. Design requirements were dictated by the characteristics of HITEX II explosive described in the previous section and the environment of a typical geothermal well at the Geysers field where the test demonstration was planned. The design criteria for a typical well is a depth of 2377 meters (7800 ft), an open-hole section diameter of 22.2 cm (8.75 in.), a maximum temperature of 260°C (500°F), and a formation pressure of 3.4 MPa (500 psi). Using these requirements, the canister was designed by coupling sections of pipe to form a long column to contain the explosive. A heavy-wall section of pipe was added above this column in which to set a bridge plug, effectively sealing the canister. The final element of the design was a disconnect joint, which allowed the emplacing pipe to be separated from the canister and retrieved.

4.1 CANISTER BODY DESIGN

The canister was designed using as much commercially available equipment as possible to reduce development costs and maintain compatibility with standard rig equipment. Incompatibility of carbon steel with HITEX II precluded the use of standard steel casing for the body of the canister. Of the suitable material such as stainless steel, aluminum, etc., aluminum was selected because of its lower cost and relative availability. The largest

diameter [(17.78 cm (7.0 in.) O.D. with a 15.24-cm (6.0-in.) I.D.)] was chosen to fill the well bore with the largest amount of HITEK II possible. The longest readily available lengths were 7.32 meters (24 ft). A 13.34-cm (5.25-in.) aluminum retaining ring was staked to the inside diameter of one end of each pipe to prevent the HITEK II grains from falling out. Crush strength tests using NaKCa nitrate, an inert substitute for HITEK II, showed this ring area was adequate to support a weight of 199 kg (438 lb), the amount of explosive contained in one length of aluminum pipe.

The couplings joining the 7.32-meter- (24-ft) sections of aluminum pipe had to provide water-tight seals to prevent liquid HITEK II leaking out, or steam and water leaking into the canister. The top joint in the canister section also had to be capable of supporting not only the canister weight, but also 6,364 kg (14,000 lb) of HITEK II. The total estimated load was 10,454 kg (23,000 lb). Aluminum is not suitable for the coupling material because of the high potential of galling during thread makeup. The relatively large outer diameter that would be required also presents serious problems with rig handling during emplacement. Standard J-55 steel couplings with a protective coating were chosen as substitutes. A Teflon coating was decided on after investigating various coatings for their compatibility with HITEK II. This coating also serves as a lubricant for thread makeup. A standard API modified K-55 coupling with a sealing ring groove was chosen because of its high strength and the extra sealing it would provide. The sealing ring was made of Teflon. This joint configuration was tested at ambient and 260°C (500°F) and found to seal satisfactorily. Because the strength

of aluminum decreases at elevated temperatures, pull tests were also conducted both at ambient and 260°C (500°F). From these tests, a safe load of 36,364 kg (80,000 lb) was demonstrated, providing a safety factor of 3.5 above the anticipated load of 10,454 kg (23,000 lb).

4.2 BRIDGE PLUG/CHECK VALVE JOINT

The top of the canister had two configurations, depending on the emplacement method selected. Both are mentioned in Section 2.3. For the first configuration the detonator system was run inside the canister/casing assembly and a bridge plug was set on top of the canister to prevent water intrusion and allow retrieval of the running casing. A heavy-wall aluminum-pipe section with a 17.8-cm (7.0-in.) O.D. and 11.77-cm (4.654-in.) I.D. was used for this joint to obtain the correct inside diameter for setting a standard bridge plug set.

It was shown during the HITEX II development and qualification test program that significant outgasing occurs at temperatures above 233°C (450°F). Calculations also indicated that a significant amount of pressure could build up inside the canister as the HITEX II was heated. A collar containing eight stainless-steel check valves was installed just below the thick-wall pipe section to solve this potential problem. Setting the check valves to open at a differential pressure of 0.69 MPa (100 psi) precluded significant pressure buildup within the sealed canister. These check valves were tested under simulated well conditions and were found to function properly if they were disassembled and recleaned when received from the manufacturer.

4.3 DISCONNECT TOOL

The final part of the canister configuration was the disconnect tool used to separate it from the running pipe. A J-slot releasing tool was designed with an "O" ring seal to prevent intrusion of water into the canister. This tool was made of carbon steel since it would not contact the explosive once the bridge plug was set in its proper position. The canister configuration for this emplacement technique is shown in Figure 3.

An alternate design to be used if the detonator system is placed in the bottom section of the canister is shown in Figure 4. The significant difference in the alternate design is that a bridge plug and heavy-walled aluminum-pipe section is no longer required. A solid plate incorporating the pressure relief valves welded inside the releasing tool provides a positive top seal. An alternate releasing tool using a left-hand-thread safety joint would also meet canister separation requirements. An attractive feature of this configuration is that the canister could be run in the well on 4-1/2 drill pipe thus reducing the running time in the well. The disadvantage of this technique is that the detonator is in place with the time clocks operating during the time of emplacement. Aborting the test could prove difficult if serious problems occur during canister emplacement. The ability to stop the test was the primary concern with this alternate configuration.

Figure 3. Initial design of the explosive canister.

Figure 4. Alternate design of the explosive canister.

SECTION 5

DETONATOR SYSTEM DEVELOPMENT

PI designed, tested, and developed a detonator system according to the following requirements:

- Cause HITEX II explosive to detonate at a predetermined time up to 48 hours after emplacement.
- Withstand an environment of immersion in molten HITEX II at 6.9-MPa (1000-psi) pressure and 260°C (500°F) temperature for 24 hours minimum, 48 hours desired.
- A maximum outside diameter of 11.43 cm (4.5 in.) to pass through the heavy-wall section of the canister.
- A maximum weight of 227 kg (500 lb) so it could be emplaced on a wire line.
- Maximum reliability of operation and safety.

From early design evaluations, it was determined the detonator components had to be protected from high temperatures and pressures. A pressure vessel and a heat shield (dewar) were selected for this purpose. A shaped charge was considered the best choice to penetrate the protective housing walls and cause the HITEX II to detonate. The shaped charge could be fired with a battery-operated firing unit controlled by an electronic timing circuit. Two completely independent firing systems were incorporated into the design to provide maximum reliability. The shaped

charge itself, because of size constraints, was the only component that could not be duplicated. The individual components are described in more detail in the following subsections.

5.1 SHAPED CHARGE PACKAGE

The maximum interior diameter of only 7.37 cm (2.9 in.) and distance from the explosive required the use of a high-performance, precision shaped charge to ensure sufficient jet energy to penetrate the pressure vessel and initiate the HITEX II. The shaped charge selected was a military unit that uses ~ 0.227 kg (~ 0.5 lb) of explosive, and is suitable for service at 177°C (350°F).

Normally, a single detonator centrally positioned at the end of the shaped charge starts a symmetric detonation on axis. For added reliability, however, two detonators were desired to detonate the shaped charge, and this requirement necessitated the use of a precision initiator charge (PIC) between the shaped charge and the two detonators that are adjacent to one another. The PIC, therefore, is a device that can be detonated off axis at one end and then reshapes the detonation wave so it reemerges axially at the other end as if only one central detonator had been used. The PICs were loaded by Reynolds Industries, Inc., of San Ramon, CA with HNS explosive that has been qualified for use at temperatures up to 260°C (500°F).

RP84 exploding foil detonators, also manufactured by Reynolds Industries, were selected to initiate the PIC. These

also use only HNS explosive and are, therefore, qualified to a similar temperature as the PIC, well above the design goal of 100°C. These detonators require over 2200 A before they will function and cause the explosive to detonate. When they receive a current of this magnitude, sufficient energy is available to vaporize a metal foil, which accelerates a small metal disc. This disc then impacts an HNS pellet, causing it to detonate. Such a detonator is, therefore, quite safe because it is immune to stray voltages and currents.

Two Model FS-34 firing units or capacitor discharge units, (CDU) manufactured by Reynolds Industries, were used to fire the separate detonators. Each firing unit consists of a dc-to-dc high-voltage converter that charges a capacitor when a minimum of 24 volts is applied. A spark gap breaks down when the capacitor reaches 4500 volts (in approximately 10 s) and the capacitor energy is delivered to the detonator via a cable. Similar units have been used successfully under hot conditions. The units were pretested by the manufacturer at a temperature of 100°C for 24 hours. Two separate battery packs supplied 42 volts for charging each firing unit. Based upon recommendations, Eveready E92 Type AAA, sealed, single-cell batteries were selected. These batteries were tested at 100°C (212°F) for 24 hours. No electrolyte leakage occurred nor was the battery voltage degraded below acceptable limits. Twenty-seven of these batteries were soldered and potted together as a unit to form a battery pack.

An electronic clock design was selected as the best method to control the time of firing the shaped charge. The circuit

design uses a crystal controlled oscillator circuit that feeds temperature-stable time pulses to two binary programmable counters. One counter, called the "arming" timer, prevents the other "firing" timer from applying voltage to the firing unit until the arm counter has reached a preset time. After the circuit is "armed," either the time out of the "firing" timer or the closing of a thermal switch will connect the battery power to the firing unit, causing it to charge. The thermal switch is mounted on the circuit board to fire the shaped charge if, after the arming switch has timed out, the interior temperature of the dewar exceeds 100°C (212°F). Exceeding this temperature would cause rapid failure of the batteries. The "arming" timer was set to provide enough time for all emplacement activities to be completed and personnel to be evacuated from the well head. The clock circuit is shown in Figure 5. By individually adjusting the switches, the time out of the clocks could be adjusted from 0 to 51 hours in increments of 0.2 hour.

All electronic components were selected to have temperature ratings of at least 85°C (185°F). Higher ratings would have been desired, but military versions of components capable of operating at temperatures greater than 100°C (212°F) were not available. In general, most of the components rated at 85°C (185°F) will function at temperatures in excess of 100°C (212°F) but their performance does not remain within the guaranteed specification. Four Eveready E91 size AA batteries powered the clock circuits.

The circuit boards were coated with RTV 615 after fabrication to prevent moisture from shorting out or otherwise affecting

NOTES: UNLESS OTHERWISE SPECIFIED

- ALL RESISTORS ARE 1/4 WATT 5% TOL.
- ALL CAPACITORS ARE IN μ DS.

QTY REQ	CODE IDENT	IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	ZONE	ITEM NO
LIST OF MATERIAL							
<p>DESIGNED BY: P. GREENE</p> <p>CHECKED BY: P. GREENE</p> <p>DATE: 11/11/77</p> <p>PROJECT NO: 1903</p> <p>DATE: 11/11/77</p> <p>SCALE: 1:1</p> <p>WEIGHT: 1.00</p> <p>DATE: 11/11/77</p> <p>REVISIONS:</p> <p>1.00: 11/11/77</p>				<p>PHYSICS INTERNATIONAL</p> <p>1700 N. 17TH AVE. SUITE 100 DENVER, CO 80202</p> <p>TELEPHONE: (303) 733-1111</p>			
<p>GEO THERMAL ELECTRONIC CLOCK SCHEMATIC</p>							
<p>CODE IDENT NO: 24616</p> <p>OWN: C</p> <p>PROJECT NO: 1903</p> <p>TYPE: SK</p> <p>SERIAL NO: 117</p> <p>REV: 1</p>				<p>SCALE: 1:1</p> <p>WEIGHT: 1.00</p> <p>DATE: 11/11/77</p>			

Figure 5. Circuit diagram of electronic clock.

the circuits. As an additional precaution, ~ 400 g of desiccant was also placed inside the dewar. A photograph of the mounted components for the electronic clocks are shown in Figure 6.

The temperature of the components placed inside the dewar is dependent on the initial internal temperature, the temperature outside the dewar, and the total heat capacity of all components. A total heat capacity of 18.2 kJ/°K (9.58 BTU/°F) was required to meet the dewar specification that will be discussed later. The explosive and electronic components do not meet the required heat capacity so additional steel thermal masses were added. The desired total heat capacity of the system was achieved in a length of 2.21 meters (7.25 ft). A detailed drawing of the shaped package is shown in Figure 7.

5.2 PRESSURE VESSEL AND DEWAR

The pressure vessel and dewar were designed and fabricated by PDA, Inc., of Santa Anna, CA. Their dewar is called a "thermoshield" and is used to protect logging instruments from heat damage when run in hot wells. The thermoshield is essentially a metal, double-walled container. The space between the inner and outer walls is filled with a proprietary material and the air is evacuated. The open end is filled with a high-temperature fiberglass wool to block heat transfer through this opening. PDA's calculations showed that parts placed inside with a total heat capacity of 18.2 kJ/°K (9.58 BTU/°F) would undergo only a 65°C (117°F) temperature change from ambient with an exterior temperature of 260°C (500°F) for 48 hours. If the initial temperature of the components is 21°C (70°F), the final temperature would

Figure 6. Photograph of two geothermal electronic clock assemblies.

Figure 7. Detail drawing of the shaped charge and associated firing hardware.

only be 86°C (187°F), which allows selection of conventional components for the firing system. Acceptance testing demonstrated that dewar performance agreed with their predictions. The dewar design is shown in Figure 8.

The pressure vessel was designed to withstand an exterior pressure of 6.9 MPa (1000 psi) with a minimum safety factor of 3. The screw cap design incorporated two "O" ring seals, one made from the L'Garde EPDM Y-267 material and the other from Teflon. The body and cap were machined from 304 stainless steel, which is compatible with molten HITEX II. A spring placed in the bottom of the pressure vessel allows space for length changes of the dewar due to differential thermal expansion between the vessel and the dewar. The spring also serves as a shock absorber for the dewar should the detonator system undergo a sudden stop during emplacement. The outside diameter of the pressure vessel was limited to 10.8 cm (4.25 in.), so that it could be emplaced through the X-line running pipe and the heavy-walled aluminum canister section. The design of the pressure vessel is shown in Figure 9. A photograph of the pressure vessel, dewar, thermal masses, and shaped charge components is shown in Figure 10.

In the first emplacement technique, the detonator system is lowered through the X-line pipe into the canister where it rests on the HITEX II. A float assembly was designed to maintain a positive buoyancy and prevent the 116-kg (255-lb) detonator system from sinking partially or completely to the bottom of the canister when the HITEX II melts. The design consisted of two 7.62-meter (25-ft) stainless steel tubes with an outside diameter of 10.2 cm (4.0 in.). Standard stainless-steel weld caps closed

Figure 8. Dewar design details.

Figure 9. Pressure vessel design details.

Figure 10. Photograph of the detonator-system components.

each end of the tubes. The buoyancy requirements necessitated the use of tubing with a wall thickness of only 0.211 cm (0.083 in.). The collapse strength with this wall thickness is only 2.97 MPa (431 psi), significantly below the design requirements of 6.89 MPa (1000 psi). A pressurization port was included in the design so the floats could be prepressurized with nitrogen to 5.52 MPa to overcome this design problem. The internal pressure would increase to 10.75 MPa (1560 psi) when the nitrogen is heated to 260°C (500°F)--well above the design requirement.

The floats and detonator system were coupled together with a stainless swivel joint to provide flexibility during emplacement. Details of the float design are shown in Figure 11, and an overall drawing of the floats and detonator system is shown in Figure 12.

For the alternate emplacement configuration, where the detonator system is located at the bottom of the canister, the floats are no longer needed. The shaped-charge jet in the first emplacement technique is projected through the bottom of the pressure vessel to detonate the HITEX II. In the alternate emplacement configuration, the shaped charge unit is inverted and fires through a modified pressure cap used to seal the chamber. The pressure cap was modified by eliminating the universal joint and the central thickness is thinned to equal the thickness of the pressure vessel bottom.

Figure 11. Detailed drawing of the float assembly.

Figure 12. Drawing of the detonator system and floats.

5.3 VERIFICATION TESTING

A series of tests were conducted to verify design adequacy by simulating the anticipated environment the detonator system would experience during use in a geothermal well. Most tests were conducted as subsystem tests although a final test was performed on the complete system without the explosives.

Several tests were conducted to verify that a detonation wave would transfer from the detonator to the PIC to the shaped charge and that the shaped charge jet would cause molten HITEX II to detonate. The first test used a detonator, PIC, and a small cylinder of LX14 explosive to represent the shaped charge. Detonation transfer between the three explosive components was confirmed by the recovery of parts shown in Figure 13. Detonation transfer was also confirmed by electronic recording of the time-of-arrival of the detonation wave along the cylinder of LX14 explosive. The measured detonation velocity of 8800 m/s is in good agreement with published data.

A shaped charge was heated to 84°C (183°F) in a test configuration that simulated the dewar and pressure vessel to verify the jet would properly form and penetrate the metal parts with sufficient energy. A 7.62-cm- (3.0-in.-) thick piece of armor plate was used as a witness plate where HITEX II would be located. Results showed the armor plate was completely penetrated by the jet, which produced a 0.635-cm (0.25-in.) hole and continued at least 40.6 cm (16 in.) further into the earth beneath. Jet performance appeared to be adequate.

a) Detonation-transfer test setup

b) Aluminum witness plate showing the damage caused by the detonation of the LX-14 explosive

Figure 13. Photographs of the test configuration and recovered witness plate from the detonation-transfer test.

For the final test approximately 8 kg (17.6 lb) of HITEX II was placed in an aluminum container and heated. The chamber was pressurized to 1.38 MPa (200 psi) and the shaped charge fired through the stainless steel lid of the chamber. Figure 14 shows the measured temperatures from thermocouples placed in the HITEX II and on the chamber.

The temperature rose to approximately 185°C (365°F) and remained there for approximately 1 hour until all of the HITEX II was melted. The temperature then increased and was held at 220°C (428°F) for 3 hours before the shaped charge was fired. A witness plate placed beneath the chamber was only bowed and showed no penetration by the jet. A photograph of the test setup and the recovered witness plates are shown in Figure 15.

Tests were also conducted on the electronic clocks to verify they would function at 85 to 100°C (185 to 212°F), that there was sufficient power to maintain them for 48 hours, and to record the timing accuracy. Five circuit boards were operated for 48 hours at ambient temperature [21°C (70°F)] and at 82°C (180°F). During this time, the clock battery voltage was monitored at discrete time intervals to observe the drain on the batteries. The graph shown in Figure 16 summarizes data averaged for the five circuit boards. As can be observed, the hot batteries show a smaller voltage drop during the early-time portion, but the final voltage at the end of 48 hours was very similar to that recorded for the batteries at ambient temperatures. The arming circuit was activated at 24 hours simulating the planned procedure. The

Figure 14. HITEX initiation-test data.

a) Test setup

b) Recovered witness plates

Figure 15. Photograph of the HITEX initiation test and recovered witness plates.

Figure 16. Record of clock-battery voltage versus time at 21°C and 82°C.

temperature was elevated further after 48 hours. The function temperature of all the thermal switches was determined to be at $101 \pm 4^{\circ}\text{C}$ ($214 \pm 7^{\circ}\text{F}$). The Eveready E91 batteries showed no electrolyte leakage or other physical damage.

Timing accuracy of the clock circuits at ambient temperature was about -1 s/hr, with a total spread of ± 1 second for the five boards, after 48 hours. The clocks operate a little faster when heated, finishing a 24-hour time period about 4 seconds earlier than at ambient temperatures.

A final test of the entire detonator system, not including the components containing explosives, was conducted at Los Alamos National Laboratories. Their 9.14-meter- (30-ft-) long vertical autoclave facility verified the pressure vessel and its seals were adequate, the dewar provided sufficient thermal protection to the interior components, and the components continued to function during and after the test. Photographs of the test facility are shown in Figure 17. The test was conducted with water surrounding the two detonator systems at a temperature of 260°C (500°F) and a pressure of 6.9 MPa (1000 psi) for 24 hours. The results of this test are shown in Figure 18. The detonator system was heated and pressurized for 24 hours and then left to cool for 12 hours before it was taken from the autoclave. No water or damage was observed when the components were removed from the dewar, and the maximum temperature recorded by a maximum reading mercurial thermometer and thermal recording strips was

a) LASL autoclave facility

b) Autoclave body and pressure vessel
suspended from lid

c) Autoclave sealed ready for testing

Figure 17. Photographs of the environmental-test setup.

82-4-249

Figure 18. Results of environmental test.

72°C (162°F). The temperature profile was used by PDA to determine if this measured temperature was consistent with predictions. For an internal heat capacity of 18.2 kJ, the final maximum internal temperature was matched exactly as shown in Figure 18. An additional calculation was made to further verify that the detonator system can withstand the anticipated geothermal-well environment. In this calculation, the well's temperature was assumed to be 177°C (350°F) for 14 hours--the time estimated for emplacement. The temperature was then raised to 260°C (500°F) and maintained at that level for 36 hours. Figure 19 indicates a calculated maximum internal temperature of only 88°C (190°F) is reached given an initial temperature of 21°C (70°F) for the components.

Figure 19. Plot of the internal temperature inside the Dewar under maximum predicted well conditions.

SECTION 6

TEST DEMONSTRATION AT THE GEYSERS

The primary objective of the initial test was to demonstrate that a small quantity of HITEK II explosives could be safely emplaced and fired in a geothermal well and, if successful, a second test was to be conducted in the same well for a large scale stimulation. This section describes the selection of the well, the emplacement procedures used for the two tests, and the results obtained.

6.1 WELL DESCRIPTION

The well selected for this test was Well LF-30 which had been completed one year earlier in Union Oil's Lacoma Fame lease. It was selected because it was mechanically sound, its production was somewhat marginal, and it was surrounded by wells with higher average steam-production histories. Figure 20 shows the well's as-drilled configuration. The vertical angle of the well varied from about 18 degrees at the casing shoe to a maximum of 36 degrees near the total depth (T.D.) of 2690 meters (8826 ft). Drilling logs showed steam entries at 1487 meters, 1558 meters, 1672 meters, 1989 meters, and 2112 meters. These locations were suitable for conducting the initial test in the bottom portion of the well, and conducting the main stimulation test at a shallower depth adjacent to the steam entry points.

DATE SPUDDED 9-4-80
DATE COMPLETED 10-29-80

KELLY BUSHING 28 ft
GROUND ELEVATION 3399 ft

Figure 20. Configuration of the as-drilled LF-30 well.

6.2 EMPLACEMENT VALIDATION TEST

A rig was moved on location and the well air-cleaned. A casing log showed the casing to be in good condition. The steam production was killed with a continuous flow of water. A number of bridges (plugs in the well due to formation sloughing), however, obstructed the hole. It took several days to clear the bridges and stabilize the well. During this time the well was sanded back to the desired depth--2256 meters (7403 ft)--to conduct the initial test.

Two canister sections were preloaded with 364 kg (800 lb) of HITEX II grains. The canister assembly included a bullnosed canister section, another canister section loaded with grains of HITEX II, three empty canister sections to house the detonator system and floats, one heavy walled section containing, and the J-slot releasing tool. The assembly was lowered to the bottom of the well using 181 joints of X-line casing. Each pin end of the X-line casing was wrapped with Teflon tape to ensure a positive seal and prevent pipe dope contamination of the explosive.

An 11.4-cm (4.5-in.) gage ring and collar locator was run inside the X-line casing and heavy-walled canister section to make sure the detonator system could be lowered to the bottom. The detonator timing clocks were set for an arm time of 36 hours and a firing time of 48 hours. The detonator system was sealed and attached to the floats, and the entire package was connected to an electric-wire line and run in the hole. The wire line and

cable head had been pretested at high temperatures. The detonator/float assembly was separated from the cable head using an electric motor drive ball release designed by Sandia National Laboratories. G-O International (G-O) then ran and set a Halliburton 11.4 cm (4.5 in.) EZ-Drill™ bridge plug in the heavy-walled section of the canister. Releasing the X-line from the specially constructed J-slot releasing tool proved to be impossible after numerous attempts. To overcome this problem, a G-O high-temperature shaped-charge casing cutter was run inside the X-line and fired, separating the X-line 1-1/2 joints above the J-slot releasing tool. A seismometer located near the rig recorded the functioning of the casing cutter severing the X-line casing. The X-line was retrieved. A bent joint of 17.78-cm (7-in.) casing was installed in the well head to serve as a debris deflector to protect the rig after detonation. These operations were all completed in 23-1/2 hours, well ahead of the 36 hours set on the arming clock.

The water flow into the well was shut off and the well pressurized to drive any water remaining in the well into the formation. After several hours, the air was shut off and the well allowed to produce steam, thus heating and melting the explosive. Detonation occurred close to the preset time of 0300 hours on December 4, 1981. The configuration of the well and the position of the canister is shown in Figure 21.

Following detonation the well vented and died a number of times in the next hour, and then appeared to stay almost dead. A seismometer placed near the rig recorded when the steam flow

Figure 21. Configuration of the canister emplaced in the LF-30 well for the initial test. (Fired on December 4, 1981 at 3:00 a.m.).

was changed from the vent pipe to the muffler, the detonation, and flow fluctuations. The detonation was registered as a 1.2 magnitude earthquake on 10 U.S.G.S. seismometers in the Geysers area.

Several days were spent removing debris from the well and preparing it for the next test. The 1-1/2 joints of X-line casing and the running tool were recovered near the liner hanger at a depth of 414 meters (1357 ft). The ears had been sheared off the running tool. After reaming for some time, the well was cleared to a depth of 1481 meters (4858 ft) where the heavy-wall aluminum canister section with the check valve collar still attached was retrieved. A piece of the standard wall canister that was forced inside the heavy-wall section was also retrieved. These recovered parts are shown in Figure 22. The well was finally cleaned out to 1702 meters (5585 ft) where a debris plug had lodged itself securely in the well, and could not be easily removed with either a bit or mill. This piece of debris is suspected to be the stainless steel pressure vessel of the detonator system. Further attempts to clean out the well to the desired depth of 2257 meters (7403 ft) were discontinued since several producing zones remained above the debris plug. A shot production test was conducted to establish a baseline for comparing the results of the next test.

The test was very successful in demonstrating that the explosive could be safely emplaced and detonated in a hot geothermal well. The problems with the releasing tool and amount of debris left in the well, however, indicated that an alternate emplacement technique would be necessary prior to conducting the main stimulation test.

Figure 22. Photograph of the debris recovered from the first test. These parts are the heavy-wall aluminum canister, steel coupling with check valves, and a piece of crumpled standard-wall canister. A length of the recovered X-line casing is shown in the background.

After careful review of the emplacement method for this test and alternate methods, the configuration in which the detonator system is placed at the bottom of the canister was agreed upon as minimizing the problems just experienced yet retaining the necessary safety requirements. The desirable features of this alternate emplacement configuration are: (1) the detonator package is at the bottom of the well, (2) the floats, heavy-walled aluminum section, and bridge plug are no longer needed and, (3) the amount of aluminum or steel remaining above the HITEX explosive is reduced to just a few meters. The J-slot release tool was replaced with a left-hand-threaded safety joint to improve the method of releasing the canister.

6.3 STIMULATION TEST

Twenty-six aluminum canisters containing 5000 kg (11,000 lb) of HITEX II were transported to the rig pipe rack shown in Figure 23. The bottom bullnose section was set in the wellhead and the detonator system installed. For operational simplicity, the bottom of the bullnose section was filled with HITEX II with just enough space left at the top for the detonator system. The detonator system can easily sink the 4.6 meters (15 ft) to the bottom of this joint when the explosive melts. This scheme was simpler than placing the detonator system at the bottom of the canister and loading the HITEX II grains on top. Successive joints were made up until all of the canisters were connected. The left-hand-threaded safety joint equipped with a sealing plate containing the check valves was attached to the canister and the entire assembly lowered into the well on 11.4 cm (4-1/2 in.) drill pipe. These operations are shown in Figure 24. Figure 25 shows close-up

Figure 23. Photograph of aluminum canisters loaded with HITEX II explosive.

a) Bottom bullnose canister section being lowered into the well head

b) Detonator system being lowered into the canister

c) Power makeup of the aluminum canister joints

d) View of the top length of canister, left-hand-threaded safety joint and connection to drill pipe

Figure 24. Photographs showing various operations during the emplacement of the aluminum canister containing HITEX II explosives.

SEALING RING

a) Inside view at the top of a length of aluminum canister showing the HITEX II explosive and Teflon coated coupling with a Teflon sealing ring

b) Inside view of left-hand-threaded safety joint showing the plate that was welded in and the check valves that were inserted

Figure 25. Photographs of HITEX II explosive loaded into a canister and the interior view of the left-hand-threaded safety joint.

photographs of the HITEX II explosive in a canister and details of the check valves in the safety joint. No problems were encountered in reaching the bottom of the well, releasing at the safety joint, or recovering the drill pipe. The canister was assembled in 4-1/4 hours and only 5 hours were required to emplace it and retrieve the drill pipe. The duration of the operation was well within the 36 hours set on the arm clock. The water flow was shut off, and the well pressurized for several hours and then allowed to produce until the time of detonation of the explosives. The configuration of the well and explosive canister is shown in Figure 26. Well recovery was poor and negligible steam flow was observed out of the deflector pipe at the well head and through the muffler. There was some concern that there would not be sufficient heat to melt the HITEX II.

These fears were put to rest when the 5000 kg of HITEX II detonated at 2145 hours on December 14, 1981. Unfortunately, darkness and a dense fog precluded observing or photographically recording events at the well head, but rocks and debris could be heard venting from the well within a few minutes. The well continued to expel material intermittently with steam for about an hour after detonation. The debris primarily consisted of small chunks of aluminum canister and graywacke rock.

The event was recorded on numerous seismographs surrounding the well site and at stations surrounding the San Francisco Bay Area. The event was calculated to be equivalent to a 2.1 magnitude earthquake on the Richter scale. Close in seismographs showed sufficient detail that it could be determined that the explosive column had been detonated from bottom.

Figure 26. Configuration of the canister emplaced in the LF-30 well for the simulation test. (Fired at 9:45 p.m. on December 14, 1981).

The well cleaned out much easier than expected. The first bridge was encountered at 1460 m (4791 ft) but was easily removed and cleanout continued to 1904 m (6247 ft). Most of the material removed from the well consisted of rock and finely powdered aluminum. Interestingly the solid bridge that remained after the initial test at 1702 m (5583 ft) was dislodged by the force of the detonation and driven 202 m (661 ft) deeper in the well. There was no evidence of any steel debris, even though the releasing tool and 26 collars used to join together the lengths of aluminum pipe were made of steel. Well cleanout was discontinued at this depth after encountering a solid plug. The steam entries at 1988 m and 2112 m (6521 ft and 6927 ft), the original target for the stimulation, remained covered with the solid bridge of fill and debris.

6.4 PRODUCTION RESULTS

Steam production rates, rig flow tests, and pressure buildup tests were analyzed to determine the net effect of the explosive stimulation on LF-30. Stabilized production rates decreased by 37% following the stimulation attempt.

Pressure buildup tests before and after the stimulation show a 34% reduction in the permeability-thickness product (kh). The flow-rate reduction of 37% can be attributed entirely to the reduction in the kh within the accuracy of measurement and analysis. One possible explanation for this decrease in kh is the loss of the lower two steam entries due to the debris plug in the hole following the test shot. The detailed results of steam rate tests are as follows.

Flow Rate Results

The results of the power plant production rates and rig flow tests conducted on LF-30 to help determine the results of the explosive stimulation experiment are listed in Table 3.

Production flow rate A, the steam rate prior to the stimulation, averaged 22,270 kg/hr at 965 kPa (140 psig) well-head pressure. Production flow rate B, the steam rate after the stimulation, stabilized at 14,090 kg/hr (31,000 lb/hr) at 965 kPa (140 psig) well-head pressure. Therefore, steam deliverability has decreased 37%. The direct comparison of the pipeline flow tests furnishes the best estimate of decreased deliverability due to the explosive stimulation because (1) the flow rates appear stable and (2) the same number of off-set wells were producing during each test. The latter minimizes the chance of changing the interference effects from the off-set wells which could affect steam rate.

Figure 27 shows the daily average production rate to the power plant from LF-30. Pipeline flow periods A and B are marked as lines A and B. Also shown are the final flow rates measured by the rig tests following each shot.

Rig Test Results

The results of the rig tests performed after each shot are listed in Table 3 as Rig Test 1 and Rig Test 2. The identical

Figure 27. Production data (1-F-30).

Table 3 Flow rate test data from well LF-30.

Flow Rate (kg/hr)	Wellhead Pressure (kPa)		Remarks
Production flow rate A	22,270	965	Four week flow prior to stimulation; shown as line A in Figure 27.
Production flow rate B	14,090	965	Three week flow following stimulation; shown as line B in Figure 27.
Rig Test #1	20,910	951	Test results followed initial shot.
Rig Test #2	20,910	951	Test results followed stimulation shot.

steam flow rates of 20,910 kg/hr (46,000 lb/hr) at 951 kPa (138 psig) well-head pressure indicates no change in well-head deliverability due to the second stimulation shot.

The identical values of flow rate taken from the rig tests are important because they suggest that:

- (1) The second stimulation shot probably had no effect on the flowrate; therefore, all the decrease in flow was probably due to the initial shot.
- (2) Any change in formation or wellbore characteristics estimated from the buildup tests happened as a result of the initial shot.

The decrease in steam rate following the initial shot was probably due to the loss of the lower two steam entries when the debris plug shut off the lower two steam entries.

Buildup Test Results

Buildup tests were conducted on LF-30 before and after the explosive stimulation experiment. The results of the analyses of Horner plots are listed below.

<u>Buildup Starting Date</u>	<u>Slope MPa²/Cycle</u>	<u>kh (md-m)</u>	<u>Skin</u>	<u>Remarks</u>
11/12/81	2.17	3937	-0.6	Before stimulation experiment.
01/26/82	1.89	2605	-2.4	After stimulation experiment.

The kh product declined from 3937 md-m (12,918 md-ft) to 2605 md-m (8,546 md-ft), a decrease of 34%. As flow rate is directly proportional to kh, the decrease in kh of 34% brought about the 37% flow rate decline as measured by pipeline flow tests A and B. The small variance is within the accuracy of the measurement and analysis of the flow rate and pressure buildup tests.

The decrease in kh and S quite possibly occurred during the initial test shot, which left a debris plug in the hole sealing the lower two steam entries. This conclusion is based on the identical rig test flow rates taken before and after the main test shot.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions from the two tests conducted in the LF-30 geothermal well are:

- Five thousand kg (11,000 lb) of HITEX II explosive can be safely emplaced in a geothermal well using conventional well-head equipment.
- The explosive can be detonated by a shaped-charge detonator system after a 48-hour exposure to the hot environment of the well.
- No casing damage was evident even though the 5000-kg charge was detonated within 111 m (365 ft) of the casing shoe.
- Minimum debris cleanout was encountered when the detonator package was placed at the bottom of the explosive column.
- A measured decrease in the skin factor suggests that no damaging compaction of the rock surrounding the well bore occurred because the near-well-bore permeability was increased.
- No productivity increase of the well was measured from the interval of well bore that was explosively stimulated.
- Additional wells can be stimulated by this process with little or no additional engineering effort or verification tests.

While the primary project objectives to demonstrate that the GEOFRAC process using HITEX II explosives in a geothermal well

were successfully met, the lack of a significant increase in productivity was certainly disappointing. As with any stimulation process, however, additional tests will be required to identify the best method of application and proper geology within the well that is most amenable to this type of treatment to yield an economic benefit.

From these results and conclusions, the following recommendations are made:

- Additional tests should be conducted to statistically evaluate the GEOFRAC process.
- Any future tests should be conducted during routine rig operations or new well development to reduce mobilization costs.

To carry out these recommendations in the most cost-effective manner we suggest that sufficient canister sections and detonator packages be fabricated and preloaded with HITEX II explosive. These assemblies could then be stored at the field location and be rapidly emplaced when candidate wells are identified during the drilling of new wells or workover operations.

While we feel no additional tests are absolutely necessary to further characterize the explosive for similar well conditions, some additional data would add to our knowledge of its full potential and limitations. With this additional data the

process could quite possibly be applied to certain wells without the undesirable requirement of cooling the well with water. Some of the tests which we recommend are to:

- Determine more precisely the temperature at which HITEK II becomes detonatable by the stimulus of a shaped-charge jet.
- Further evaluate the shock sensitivity of HITEK II due to impact or adiabatic compression.
- Study the effect of water on the detonability of the explosive. Quite possibly the container sealing requirements can be reduced, particularly in water dominated systems..
- Conduct additional compatibility tests with HITEK II and various materials.
- Determine more precisely the maximum temperature limitations due to gas evolution, decomposition, and other mechanisms.
- Consider alternate HITEK II compositions that could be used under more severe environmental conditions. Alternate HITEK II compositions may increase the minimum temperature at which it becomes an explosive, further improving its safety features.

By addressing some of these questions and obtaining the answers, the GEOFRAC process can conceivably be extended to a much wider scope of geothermal applications, even quite possibly to the stimulation of oil and gas wells.

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