WELL PENETRATION AND STIMULATION

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ABSTRACT

Two aspects of explosive fracturing--depth of penetration and degree of fracturing were investigated. A study was made of penetrators employing designs other than typical conical shaped charges. Configurations included linear, hemispherical and "dished" designed shaped charges. Through the mechanism of wave shaping as a technique for shock enhancement, fracturing of a host rock was investigated. These two elements, depth of penetration and degree of fracturing, were used as criteria for the design of a single package which generally consists of simultaneously initiated perforators closely followed by a main driver charge(s) which is (are) wave-shaped to cause fracturing in a rock media. The device was successfully field tested in five marginal oil wells and indicates an applicability to geothermal stimulation.

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Explosives have been used in fracturing to generate high pressure shock waves. When initiated, an explosive decomposes by detonation and a radially expanding shock wave is generated which places the host rock in compression--both by the shock wave and by the expanding gases. The compression wave is followed by a tensile reflection which can shatter the rock. While less "brute force" methods such as acidization or hydraulic fracturing tend to produce fractures in a definitive pattern; explosively generated fractures tend to produce a more random and interconnecting system of fractures. The degree of success for explosive fracturing is very dependent on the pressures produced and the positive duration of the overpressure. To improve explosive fracturing, techniques will be necessary to develop and test prototypes designed to enhance the positive duration by at least one order of magnitude.

In general, an explosive device is lowered into a well to a predetermined depth near the producing zone and detonated. One of these techniques achieves penetration through the application of shaped charge explosive devices. The basis for shaped charge action was first noted by Munroe, but little use was made of this effect until 1940. During and after World War II, specialized shaped charges were developed for use against specific military targets to a high level of sophistication. Also, the effectiveness of such directed explosive energy found wide application in various industrial processes. Shaped charges are manufactured to a degree of sophistication such that they are now off-the-shelf stock items. However, the bulk of information available at this moment of these items is relevant to the penetration of some homogeneous* target media in air, with few exceptions. That is, the penetration of a heterogeneous** media such as water, well casing (steel), and concrete has not been studied to the depth that the homogeneous target has. It could be expected that in the case of the heterogeneous target, that when a longitudinal stress wave strikes the boundary between the steel casing and the concrete grout, part of the stress will be transmitted through the concrete and part will be reflected back through the steel well casing. The same conditions will hold true for the stress wave striking the concrete-rock boundary. This "impedence mismatching" was characterized as much as possible from available physical properties of the target materials.

Other available data on penetration of heterogeneous media shows the effect of the liquid layer to be detrimental even though additional confinement of the explosive is available when the test charges are submerged. A reduction in the penetration that can be expected in air by a factor of the order of two has been observed.

In similar fashion, shaped charge penetration of siliceous materials is notably poor. This observed fact has been a major factor limiting the use of shaped charges in such applications as rock drilling, well stimulation, etc. Consequently, the effective use of shaped explosive charges for the penetration of heterogeneous media required the development of specialized configurations of explosive and liner to achieve not only crack initiation, but also propagation. Discussion of two basic approaches that indicate promise in the case of a water-steel target are presented:

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* A homogeneous target is defined as one comprising only one phase, usually a solid or solids, with little or no separation by vapor fluid phases.

**A heterogeneous target is defined as being comprised of two or more phases, interspersed.

The two basic approaches consider first the mechanisms that will permit the reliable penetration of the system directly by the energy focusing characteristic of shaped charges. The second approach will consider mechanisms by which the explosive energy can be coupled to the liquid medium in such fashion that the liquid becomes a primary damage agent, e.g., explosive forming and punching operations using water as a transfer medium and the well-known fact that bubble collapse and/or bubble cycling is normally the primary damage mechanism in the instance of conventional depth charges applied against submarines.

The theory of shaped charge action is based on the control of the detonation wave front,' or wave-shaping. In the case of lined conical cavity charges, a jet or slug is formed from the liner material which is propelled along the axis of the conical cavity at high velocity, of the order of 30,000 feet per second. When this jet impacts a target, e.g., a steel well casing, pressures of the order of 3.75×10^6 psi are created--far in excess of the yield strengths of common materials--and the casing behaves like a liquid. An elementary prediction of the penetration, based on hydrodynamic theory, states that

$$P \propto \ell \sqrt{\frac{\rho_j}{\rho}}$$

in which P is penetration, ρ_j the average density of the jet, ρ the density of the target and ℓ the length of the jet. The reason for the reduction in penetration of a charge fired in, say, water as compared to air, is evident. The rate at which the jet is used up is proportional to $\sqrt{\rho}$. On this basis, the penetration in air, water, and steel is as 1:0.036:0.013 and it appears that water is approximately one-third as difficult for the jet to penetrate as steel.

It is evident that penetration can be improved by a design of a charge that will act to first reduce the amount of liquid in the path of the penetration element--usually a jet or wedge. This is difficult to accomplish with charges that weigh only a few pounds because, at these 120,000-360,000 in. sec.$^{-1}$ velocities (of detonation) the time available for the "special actions" to aid the penetration by "clearing the path" of water is only of the order of ten microseconds or less. Inertia effects, etc., make it difficult to obtain good penetration with simple systems under these conditions.

However, on effect that may prove useful in "clearing a path" for the shaped charge slug is the exploitation of induced cavitation. For example, it was discovered by the German Research Establishment during World War II that as much as thirty percent of the explosive energy of air-dropped devices, e.g., torpedoes, depth charges, and bombs, was lost through "venting" along the cavitated entry path into the water. One general concept is to first initiate an annular ring of explosive or several separate charges simultaneously. Extremely intense, high speed shock waves due to mutual shock reinforcement have been observed in seismic studies using the concept.*** The resulting cavitation path which should develop at velocities in excess 5,000 per second, should materially assist in "clearing a path" to the second target plate for the shaped charge jet. In the above concept, it is not intended (as will be discussed later) to perform perforations by any device other than the shaped charge.

In regard to the water environment explosive forming and depth charge studies have indicated that the water itself can be used very effectively as an energy transfer and focusing medium. The detonation of a spherical charge next to a target tends to emit its energy in an isotropic fashion and the direct energy applied to the target plate may not perform sufficient work on the target plate to produce rupture. However, on collapse, the target itself inhibits the symmetrical collapse of the gas bubble and a significant proportion of the initial explosive energy is thereby directed at a local area of the target. This effect has been studied photographically and target damage was observed to occur during bubble collapse.

The DRI concept, therefore, includes two facets--first, penetration and second, fracturing. Conceptually, the design package may be considered to be cylindrical with linear shaped charges located around the cylinder. The ends of the cylinder may be a conventional explosive or a metalized explosive. The cylinder may be a solid explosive or may have an air or water cavity. Upon initiation, the shaped-charges penetrated the casing and rock formation. Microseconds after the shaped-charges are fired, simultaneous initiation of the main "driver" charge will occur. Through wave-shaping, a high pressure pulse will be driven radially from the axis of the charge. It is expected that this shock enhancement will cause fractures to extend and by placing the rock in alternate compression and tension will cause massive fracturing around the perforations.

Several of these devices were fabricated and field tested in marginal oil wells. Depths to producing zones ranged from 900 feet to 11,000 feet. In all cases production was increased substantially.

We feel that by suitable design for high temperatures, this novel device can be of benefit to the geothermal industry.

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