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APPLIED RESEARCH ON HYDRAULIC DISINTEGRATION OF ROCK FOR RAPID EXCAVATION

(Semi-annual Technical Report)

by

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A method of disintegrating rock at rates suitable for rapid excavation is examined. The method employs high velocity water slugs to generate strong elastic water-hammer type pressure pulses at the instant of impact between the water and the rock. Test slugs of up to one half pound weight with speeds up to 800 ft/sec are projected at a target. The character of the slug at impact is examined with high speed photographs and the character of the delivered pressure pulse is measured with a quartz transducer mounted in a metal target. Tests to date show developed pressures of a useful magnitude and duration. The magnitude approximates that generated by a simple water hammer. Planned tests on a variety of rock samples will evaluate the response and erosive losses of the rock for selected slug firings.

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Semiannual Technical Report

"Applied Research on Hydraulic Disintegration of Rock for Rapid Excavation"

Summary

The subject program intends to establish that high velocity water slugs when repetitively impinged on rock are capable of stressing and disintegrating the rock at rates suitable for use in rapid excavation systems. The damaging stresses are to be achieved by exploiting the "water-hammer" elastic pressure pulse which occurs at the instant of impact of a water slug on a rock face. The use of the high pressure "water-hammer" pulse is attractive because the necessary very high disintegrating pressures (up to 50,000 psi for hardrock) will occur only on the rock and thus permit the pressures within the water launching system to be much smaller than this (2000 to 4000 psi). The latter pressure range, which is fairly modest, can conceivably be generated in a variety of systems for which materials and methods are well within the state-of-the-art. The feasibility of developing the water-hammer principle into a practical system for rapid excavation appears quite good.

The disintegrating action of impacting small water drops based on the water hammer concept has an extensive history in theory and practice relating to the damaging erosion inflicted by condensate water drops on steam turbine blades and rain drops on supersonic aircraft. The current program intends to effectively exploit the known damage potential of these small drops by the use of much larger slugs of water to achieve a rapid rate of rock erosion together with a practical energy input.

The ultimate objective of the program is a tunneling machine involving a nozzle or gun firing compact slugs of water at a continuous high rate. The current program, which is confined to a fundamental laboratory determination of the most effective type of water slug, employs an elementary simulation of the tunneling machine by the use of a specially developed single shot, launcher or gun capable of deliverying full scale slugs of various diameters and lengths with weights up to about 1/2 pound. The velocity of the simulating test slug is also full scale and can range from about 100 to 1000 feet per second.

The research gun or slug generator is powered by compressed air and fires a foamed plastic wadding or sabot of 6 inch diameter containing a frontal cavity which carries the water slug. The sabot is arrested at the gun muzzle and the test water projects on to strike the rock target.

A firing range permitting target stand-off distances of up to 5 feet has been provided. This range is equipped for high-speed still photography of the slug in flight and at impact, and for flight velocity evaluations based on timing of interrupted light beams. Target impact pressures are being evaluated by special test firings involving a steel plate fitted with a flush mounted quartz pressure transducer.

Test firings to date have established that impact pressures approximating a substantial part of the simple water-hammer value can be obtained when firing large slugs of water.

Most of the program to date has been concerned with achieving the necessary means of controlling the slug configuration and evaluating the resulting impact pressures. Some extension of the slug pressure evaluations will be carried out but most of the remainder of the program will be concerned with applying selected water slugs on selected rock targets to establish the feasibility of producing high rates of erosion for use in a rapid excavation system.

An extension proposal has been submitted for funding under the FY 1972 ARPA program. This extension covers research and development studies of methods for continuous high rate production of the preferred water slug established in the current single shot program. Following selection of a method of pulsing a simulating physical test model would be built and tested. In parallel with this development and test program a separate study would be conducted on the use of hydraulic disintegration for size reduction of oversized material produced by primary disintegration at the tunnel face. The latter study relates to eventual use of hydraulic transport in the mucking operation.

I. Introduction

The most common way of disintegrating rock for the purpose of excavation is through the application of local pressure forces which exceed the inherent elastic limits of the rock material. A wide variety of mechanical and explosive means of delivering the necessary forces are available and are successfully employed for excavating rock of low to intermediate strength. However, in the case of stronger rock, the desired rapid rates of excavation cannot be maintained by known practices.

In recent years increasing study has been given to schemes involving the application of disintegrating hydraulic pressure forces directly to the rock structure. Most of these schemes have basically employed a high speed water jet applied to the rock such that a destructive dynamic stagnation type of pressure was maintained for an appreciable time. As an alternate to this approach it is also possible to employ a transient high liquid pressure which is repeated at a high rate. This transient pulse is achieved at the instant of impact of an air-water interface on the rock face. Repetitions of the pulse are generated by firing discrete water slugs at a high rate.

If it is assumed that hard rock may require pressures of the order of 50,000 psi for disintegration and that a stagnation water pressure is given by $P = \frac{\rho}{2x144} V^2$ where P is in Psi and the fluid stream velocity, V, is in fps, then a V, of the order of 3,000 ft/sec would be required to achieve the necessary pressure. Since the generating of a jet velocity of 3,000 ft/sec normally requires a pressure system involving static pressure equal to the stagnation pressure (50,000 psi) very serious problems would be encountered in building and maintaining the necessary pressure generating system with conventional components, materials, and established design practice.

On the other hand a scheme employing the elastic pulse or water hammer pressure relation, $P = \frac{\rho c V}{144}$, where the water density, ρ, is about 2 slugs/ft^3 and the velocity of an elastic water wave, c, is about 5,000 ft/sec permits a pressure of 50,000 psi to be achieved on the rock with a water mass impacting with a velocity of about 700 ft/sec. Since generation of a water velocity of 700 ft/sec requires a static pressure of only about 3,300 psi the system problems of design stress are consistent within known design practice.

The erosive effects of impacting small water drops has been known and studied for over 40 years and the general validity of the water hammer theory of erosion is well documented [1, 2]*. However, these known processes relate to water masses which were well formed and coherent, a condition which occurs when the slug size is small enough to be dominated by interfacial surface tension forces. Such masses do have marked erosive character under high speed impact but their disintegrating influence is micro-scaled and erosive removal occurs through creation of large surface areas with consequent large energy demands per unit volume of eroded material. These energy demands might be greatly reduced if the material removed per impact possessed a substantial volume and relatively small surface area. This is inherently not possible with small drop systems but is conceivably possible through the delivery of larger individual blows via larger individual water masses. It is the objective of this study to establish how large slugs of water can be delivered to a rock mass with an air-water interface sufficiently coherent to generate a strong elastic pressure wave approximating a water-hammer pressure value. It is recognized that the simple water-hammer expression must be adjusted to compensate for (a) the elastic response of the target rock to the impact (b) basic changes in the values of c for both the water and rock under high transient rates of loading and (c) the geometric effects of the frontal configuration of the water slug. These adjustments may be introduced into the equation through the use of a coefficient k. The first phase of this program has been concerned with developing a launching system which could fire slugs of selected dimensions weighing up to 1/2 pound at velocities up to about 1,000 ft/sec with a coherent interfacial front. The second phase of the program will be concerned with evaluating the disintegrating influence of these high-velocity slugs on rock targets of known characteristics.

II. Test Facilities

The first portion of the program was given to the design and development of a single shot gun or launching device. The resulting gun arrangement as shown in Fig. 1 is powered by a compressed air reservoir using

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*Numbers in brackets refer to references on page 12.

plant compressed air at up to 15 psi to launch water slugs of up to 2 in. dia. at velocities up to 1,000 ft/sec. The relatively low and safe air pressure is made possible by accelerating the sabot in a 6 inch diameter barrel of 20 ft length. The general design of the gun follows that of a somewhat similar unit described in Ref.[3]. The test water slug is retained in a frontal cavity in a foamed plastic cylinder which serves as the wadding or sabot of the projectile. The basic length and diameter of the water slug is determined by the cavity provided in the sabot.

The sabot is arrested at the gun muzzle by a structural framing and the test water slug projects on through a limited hole in the arrester. The arrester arrangement is shown in Fig. 2.

The sabot is loaded in to the gun barrel at the breech and the breech is fitted with an expendable thin plastic diaphragm which serves as a pressure barrier between the air reservoir and the gun barrel. Sabot velocity is controlled by selecting the pressure to which the air reservoir is charged before firing. Firing is achieved by rupture of the diaphragm with an electrically controlled firing pin. The loading, firing, and velocity control of the developed system have proven to be quite satisfactory.

The arrester structure which stops the sabot and allows the water slug to project has been fitted to permit attachment of a variety of sleeves, orifices, and extrusion nozzles for exercising control over the diameter and frontal configuration of the air-water interface. The configuration of the projected slug is recorded by high speed still photographs which can be taken at selected points in the variable firing range provided between the arrester and the target. Photo lighting employs a General Radio Co. strobotac model 1538-A which is triggered when the travelling slug interrupts a suitably located light beam. The time interval between this light interruption and the interruption of a second light beam a short distance down range provides input for an electronic timer which permits computation of the slug velocity. The photographic and timing components have in general proven quite satisfactory but substantial difficulties were encountered early in the program because of false triggering due to the indefinite or incoherent front which occurred on the water slug. This will be discussed later.

In order to understand the response of a rock target to the impact load it was considered necessary to first evaluate the pressure characteristics of the blow delivered by the impacting water slug. To this end a target consisting of a flat steel plate was fitted with a flush pressure transducer to provide readout of the delivered transient elastic pressure pulse. A compromise involving physical size, sensitivity, maximum range and ruggedness lead to the selection of a quartz piezoelectric element, housed behind a 0.25 inch diameter stainless steel diaphragm. The calibrated unit with a pressure range up to 70,000 psi was transducer #607C1 as made by Kistler Instrument Corporation.

III. Problems Encountered

It was originally appreciated that delivery of a strong elastic pressure pulse could only be achieved if the air-water interface of the water slug contacted the target face without significant irregularities which might entrap air and otherwise attenuate the pulse. It was also anticipated that the maintenance of a relatively smooth and coherent interface on the water slug might be critically dependent on a balance of viscous, elastic and surface tension effects. A satisfactory balance is known to exist with small water drops moving at low velocity but little was known about the stability of a large interface moving at a high velocity. These concerns were fully justified. The original studies which employed the gun oriented on a horizontal axis were plagued by an inability to stabilize the slug front. This was believed due to a combination of the aerodynamic shear at high velocity which eroded or ablated the slug by shredding away the exterior in drops and mist and by secondary motions imposed on the slug by the complex dynamics of accelerating the slug in the sabot and by the subsequent arresting of the sabot. In addition most of the horizontal firings employed a light frontal plastic diaphragm to retain the water in the sabot cavity. This diaphragm was presumed to rupture and harmlessly shed from the front of the slug in the arresting process. However, photographic studies of the slug in flight suggested that the shedding of the diaphragm was a major disturbance to the coherence of the slug front. Other attempts were made to improve the frontal coherence by adding viscous thickeners to the water but variations of this including viscosities on up to gel conditions failed to produce a satisfactory front although some frontal improvement was observed. Other attempts to improve the front included the use of arrester nozzles which required that the travelling slug be extruded through accelerating or non-accelerating fixed nozzles. These also provided some improvement but did not provide the clean front deemed necessary for a strong elastic impact.

Following the trials with the horizontal orientation the gun was relocated to permit vertical barrel alignment as shown in Fig. 1. This positioning permitted the water charge to rest in the sabot cavity with a horizontal interface which was presumed to remain essentially undisturbed during the sabot acceleration and early phases of sabot arrest. For vertical launches, further modifications were made of the sabot cavity and arresting configurations. These included straight-walled cavities delivering a cylindrical slug of diameter approximately equal to that of the cavity and nozzled cavities delivering an accelerated slug of diameter less than the cavity. Gravitational effects of the horizontal orientation versus those of the vertical orientation proved important to the slug quality in the particular launching device employed for the testing. However, this type of sensitivity would not necessarily exist in other forms of launch devices which may be designed for eventual use.

In conjunction with the photographic studies of slug configuration the later studies have included pressure evaluations for various slug impact conditions. The problem here was to obtain a reasonably accurate graphic time-pressure record of the elastic pressure pulse. An effective breakout of rock requires (a) a pressure of magnitude in excess of the compressive stress limits of the target rock and (b) a duration sufficient to permit penetration of disintegrating forces into the rock far enough to spall large pieces. Understanding the destructive process will require knowledge of both the amplitude and duration of the pulse front. Since the duration was expected to be only a few micro-seconds, pulse recording must necessarily be quite fast. In these experiments the record was made by projecting the water slug at the pressure transducer flush mounted in a metal target and by photo recording an oscilloscope trace of the resulting voltage signal. The principal problem in capturing a meaningful signal was in expanding the time base of the oscilloscope record to sufficiently show the pulse character yet synchronizing the scope sweep to assure that the pulse was on the photo. This proved difficult in many of the earlier shots because poor definition of the slug front prevented close synchronization. Continued improvement in measuring techniques finally supplied pressure records suitable for evaluation.

IV. Results Obtained

A record of the pressure history of an impacting water slug is shown in Fig. 3 for the test conditions noted. The record has been sketched from the original photo, as the oscilloscope trace was too faint to permit satisfactory reproduction. The pressure magnitudes indicated were based on the calibration of the pressure transducer as supplied by the manufacturer. It can be seen that a water-hammer pressure of magnitude much greater than the stagnation pressure can be obtained from the impact of a large water slug.

The coefficient, k, to be applied to the impact pressure ρCV in this case is very close to unity. Analysis of the test results to date have shown that k varies from about 0.2 to 1.0 for slug velocities up to about 600 fps, with the bulk of the data indicating a value of about 0.4. The particularly good record shown in Fig. 3 was selected as evidence that high impact pressures can be attained with a properly generated slug. Theoretical studies [2] indicate that k may range from about 0.5 to 3 depending on the geometric configuration of the slug and the value of the elastic celerities, c, under high rate transient conditions. In the real case discrepancies may arise because the pressure transducer might not be located at the maximum pressure point of the delivered blow and because the transducer, of 0.25 inches diameter, measures only an average pressure over its exposed area.

Further firings will be made in an attempt to better characterize the nature of the elastic pressure pulse as a function of the controllable test variables listed in Fig. 3. However, the attainment of high elastic pressures of the type shown in Fig. 3 justifies proceeding to studies with rock targets.

V. Future Studies

Since the end objective of this program is to obtain high rates of disintegration of a rock target, the foregoing finding on slug generation and the consequent pressure blow must be extended to the disintegration of actual rock targets. To this end, 4 selected rock materials ranging from about 2500 to 50,000 psi compressive strength will be used as target materials. These rocks are to be supplied and characterized by the Twin Cities Mining Research Center as part of the general ARPA program.

The selected rock will be exposed to a programmed series of firings varying primarily in the size, velocity, number and spacing of the impacts. The erosive loss of rock will be evaluated and an attempt will be made to correlate the loss with various characteristics of the rock and of the impacting slug.

LIST OF REFERENCES

[1] Brunton, J. H. "Deformation of Solids by Impact of Liquids at High Speeds," Special Tech. Publication No. 307, American Society for Testing and Materials, 1962.

[2] Heymann, F. J. "High Speed Impact Between a Liquid Drop and a Solid Surface," *Journal of Applied Physics*, December 1969.

[3] Noonan, J. W. and Heath, J. B. R. *NAE Flight Impact Simulator*, National Aeronautical Establishment, National Research Council of Canada, January 1970.

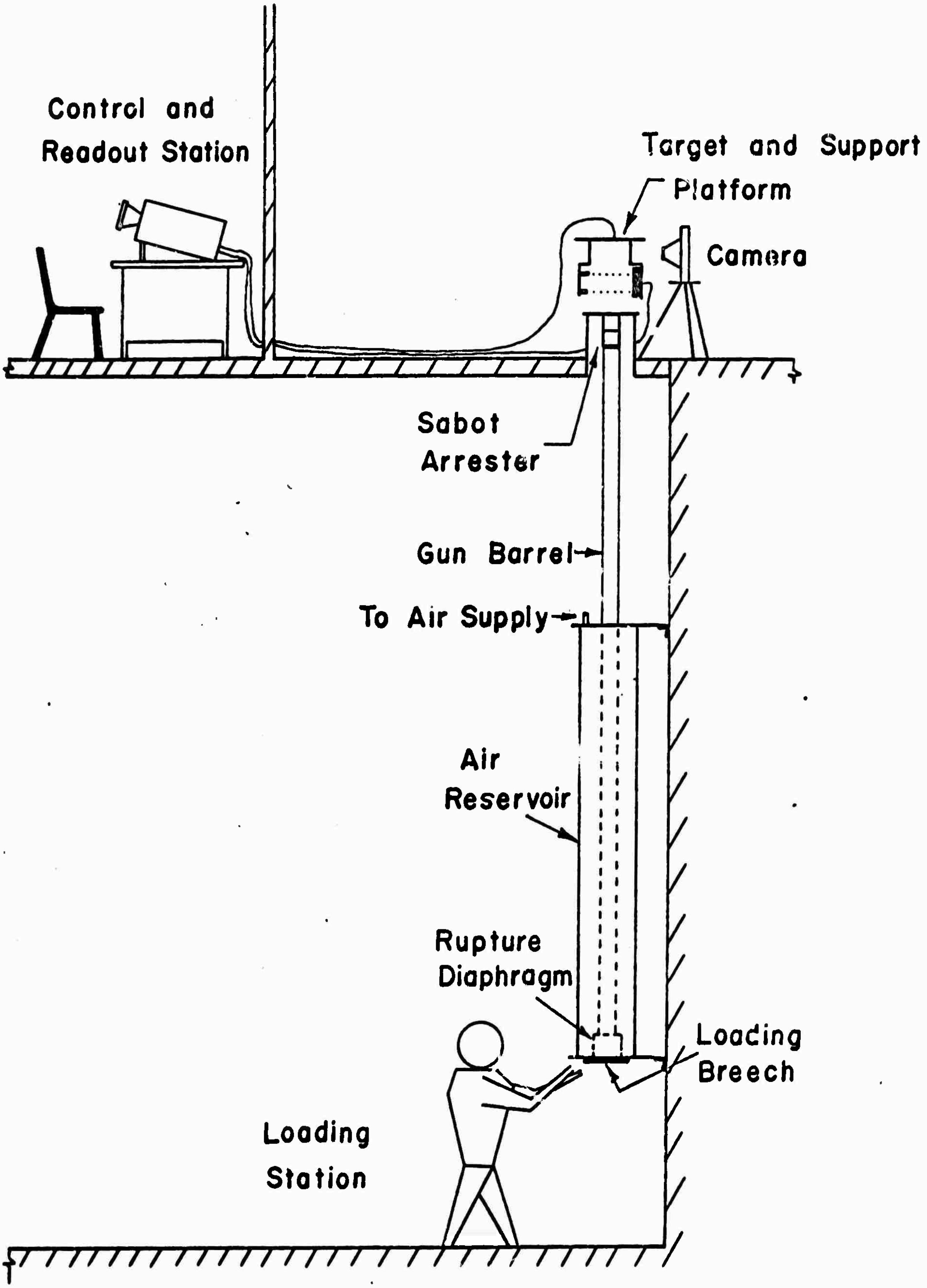

Fig. 1 – Arrangement of the Water Launching Gun and Instrumented Target

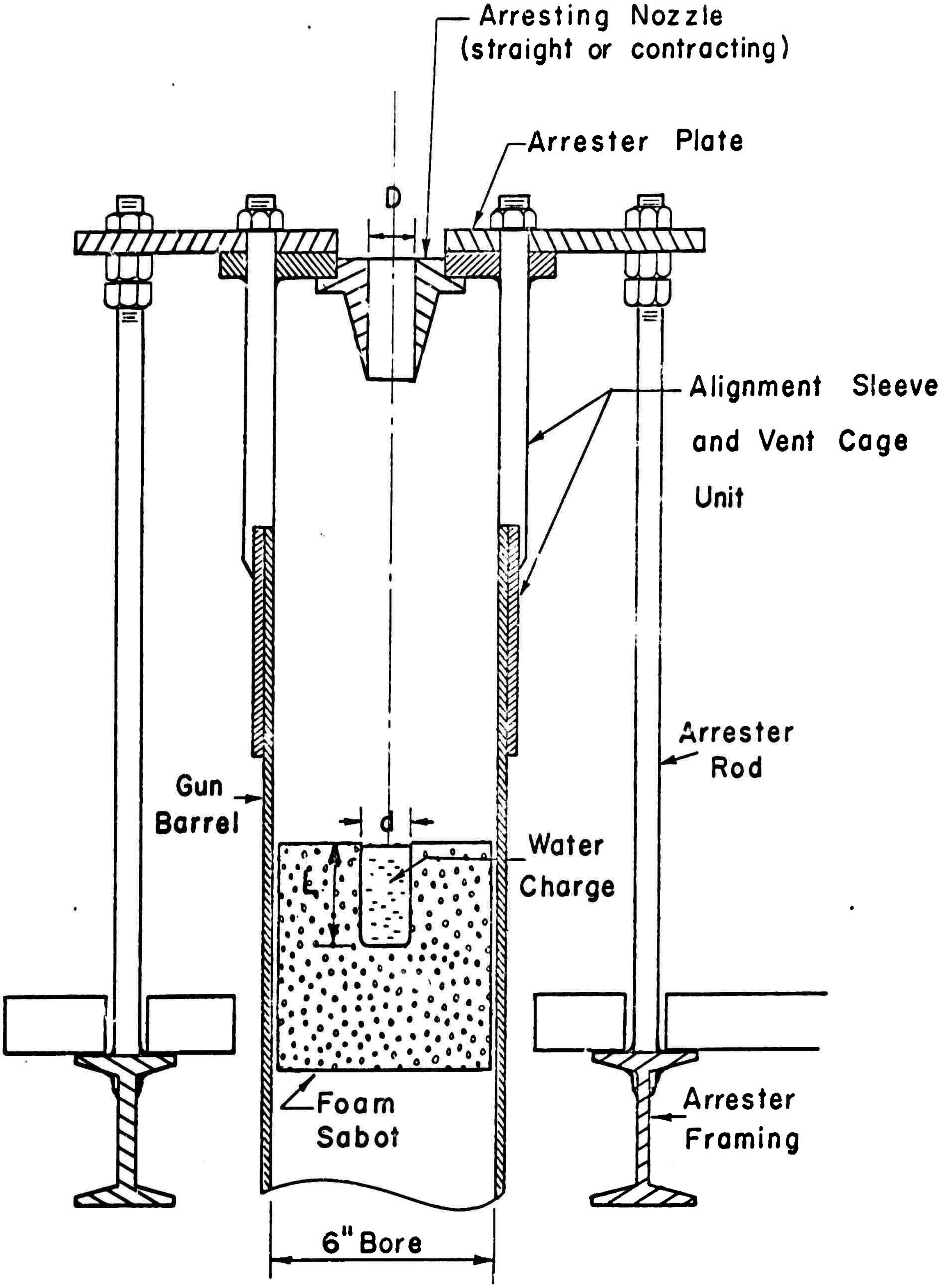

Fig. 2 - Sabot and Arrester Arrangement

Test Conditions

Cavity d = 3.0"
Cavity L = 2.0"
Nozzle D = 2.0"
Slug Vel. = 499 fps
Standoff
Distance = 6D
Transducer
Position: on slug ℄

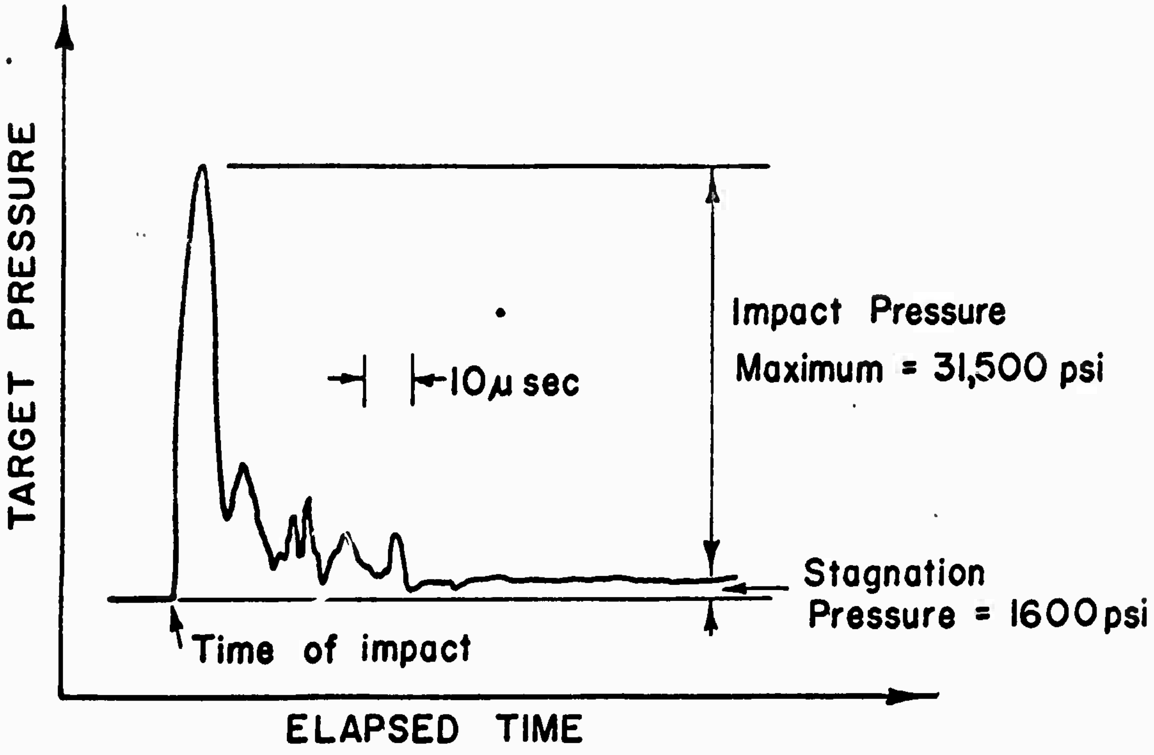

Fig.3 - Measured Pressure History of Impacting Water Slug