STIMULATION RATIONALE

FOR SHALE GAS WELLS

A State-of-the-Art Report

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by

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EXECUTIVE SUMMARY

Despite the very large quantities of gas contained in the Devonian Shales, only a very small percentage can be produced commercially by current production methods. This limited production derives both from the unique reservoir properties of the Devonian shales and the lack of stimulation technologies specifically designed for a shale reservoir.

Since October 1978 Science Applications, Inc. has been conducting a review and evaluation of various shale well stimulation techniques with the objective of defining a rationale for selecting certain treatments given certain reservoir conditions. Although this review and evaluation is ongoing and much more data will be required before a definitive rationale can be presented, the studies to date do allow for many preliminary observations and recommendations.

As shale well production is dominated by the *in situ* natural fracture system, it is imperative that significant efforts be made to quantitatively describe the *in situ* fracture system and its control upon shale well production. As the benefits of various explosive and hydraulic stimulation treatments clearly depend upon the interaction between the induced wellbore fractures and the pre-existing natural fractures, it is equally imperative that increased efforts be devoted to quantitatively understanding the effects of the stimulation treatments. Only by fully integrating fractured reservoir production characteristics with the effects of explosive and hydraulic treatments can a quantitative and supportable stimulation rationale be developed.

For the hydraulic type treatments the use of low-residual-fluid treatments is highly recommended. The lower the initial formation or

reservoir pressure, the more highly the low-residual-fluid treatments may be recommended. The excellent shale well production which is frequently observed with only moderate wellbore enlargement treatments suggests that attempts to extend fractures to greater distances with massive hydraulic treatments may not be warranted. Immediate research efforts should be concentrated upon limiting production damage by fracturing fluids retained in the formation, and upon improving proppant transport and placement so as to maximize fracture conductivity.

The occasionally spectacular production increases resulting from both conventional and displaced explosive treatments suggest that the modest wellbore enlargement resulting from such treatments may provide a viable and cost effective approach to shale well stimulation. In that some, if not all, of the benefits obtained with displaced explosive treatments may be attributed to simple wellbore fracturing, future efforts should be concentrated upon improving wellbore fracturing while minimizing consequent damage rather than upon the displaced explosive technique per se.

In selecting an explosive treatment for application to a shale well, consideration should be given to minimizing mechanical damage to the formation and to selecting an explosive formulation with minimal water generation characteristics. If the well is to be cleaned out following an explosive treatment, it is imperative that this cleanout be done without the aid of water or even a water-based foam. Immediate research efforts should be concentrated upon the mechanisms by which wellbore fractures are induced and propagated, especially in naturally fractured formations, and upon techniques for minimizing mechanical formation damage by explosive/propellant treatments.

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INTRODUCTION

The Devonian shales underlying large portions of the eastern United States contain an enormous quantity of natural gas which has been estimated to be as great as 1450 trillion cubic feet. At present only a small percentage of this gas is being recovered with annual production at less than one trillion cubic feet per year and economically recoverable reserves estimated at 20 to 100 trillion cubic feet. The large disparity between annual production and estimated gas in place derives in part from the unconventional nature of this reservoir rock and in part from the lack of suitable technologies for economically recovering the gas in place. The unconventional reservoir conditions include *in situ* porosities and permeabilities that are largely controlled by natural fracture systems, the production of gas by desorption from organic rich sections of the shale, and the characteristically low reservoir pressures which hinder cleanup after hydraulic stimulation and limit production potential. The technologies which are currently utilized for stimulating and completing shale wells are either very old, empirically developed methods (such as well shooting), or the extension of techniques developed for conventional reservoirs and applied to shale wells on a trial and error basis (such as massive hydraulic fracturing). The development of improved completion and production techniques for Devonian shale wells will require significant research and development efforts on both shale production characteristics and the production modifications effected by conventional and novel stimulation treatments. The ultimate success of these research and development efforts will depend critically upon their integration with each other and with acceptable field practices.

In March 1978 Science Applications, Inc. (SAI) initiated an indepth review of Devonian shale production practices and the research efforts being undertaken to improve them (Young, 1978). This review included a two-day workshop held in Morgantown on May 18-19, 1978. This workshop concluded that Devonian shale production characteristics were unique and poorly understood and that the effects of stimulation treatments in such a unique reservoir were largely unknown. Accordingly the workshop made recommendations that research efforts in these two key areas be increased.

In October 1978, SAI received a task order from METC to initiate the development of a stimulation rationale for Devonian shale wells. Efforts on this task have been largely restricted to: the collection of data on the effects of various stimulation treatments; the organization of, or attendance at, various technical meetings to discuss shale well stimulation technologies; and some technical consideration of the effects of various stimulation treatments upon reservoirs of differing production characteristics. The principal efforts conducted on this task and the important conclusions deriving therefrom are discussed in detail in the following sections.

DEVONIAN SHALE PRODUCTION CHARACTERISTICS

The lack of sophisticated, well-developed technologies for the completion, stimulation and production of Devonian shale wells is largely attributable to the unique production characteristics of this rock. The limited production potential of shale wells as controlled by erratic and unpredictable *in situ* fracture systems and typically low reservoir pressures have not provided a strong economic motive for developing improved recovery methods. The unconventional nature of Devonian shale reservoirs has made the prediction of production enhancement by the application of various conventional practices difficult, thus discouraging efforts to refine these practices for application to shale wells. While a detailed consideration of Devonian shale production characteristics was not included in the efforts undertaken by SAI, the unique production characteristics of Devonian shale must be considered in developing a stimulation rationale; and therefore, the current understanding of shale production characteristics will be reviewed here.

There are two aspects of shale production behavior which would classify the rock as an unconventional reservoir. First, *in situ* permeabilities are most certainly controlled by natural fracture systems which may be highly heterogeneous and anisotropic and whose aerial and stratigraphic extent and interconnectedness is generally unknown. Second, laboratory data on recovered core material indicate that a large fraction of the gas in place may exist in a chemically or physically absorbed state rather than as free gas in the rock. A better understanding of the role that the natural fracture systems play in controlling shale production is critical to the development of improved stimulation technologies and the rationale for their application. The role of gas desorption is critical to the long-term production of shale wells; but it is less important for the development of stimulation technologies and the economics of early production where the production is controlled predominantly by free gas in the natural fracture system. While gas desorption may be vital to estimating accurately total reserves and to meeting this country's future energy needs, it is of lesser importance to the development of a stimulation rationale and will not be considered further here.

The unconventional nature of Devonian shale reservoirs and the role that natural fracture system permeability contributes to this behavior are best demonstrated by considering shale well drilling, stimulation, and completion statistics. Over 40% of all shale wells drilled have no measurable gas flow during initial open hole testing (Smith, et al., 1979). As flows in excess of 5,000 cubic feet per day are generally considered measurable, the production from these wells is indeed quite small. Stimulation of wells with no measurable initial flow, often by simple borehole shooting, results in over 80% of such wells becoming commercial producers. Typically, open flows of over 50,000 cubic feet per day are required to provide a commercially producing well. As conventional borehole shooting can, at best, extend fractures on the order of ten feet from the wellbore, the dramatic increases in productivity when initially dry wells are shot can only be explained by fracture controlled permeability. The heterogeneity of this fracture permeability must be such that a 6 to 8 inch wellbore can fail to intercept significant zones of high permeability and yet a wellbore enlargement of a few feet can provide significant communication with the *in situ* fracture system. These data imply that the fractures controlling shale well production have characteristic spacings greater than one foot but less than 10 feet. The proper determination of *in situ* fracture spacing by the statistical analysis of shot-well production enhancement would require that the stratigraphic distribution of producing zones and variations in joint or fracture characteristics as well as the effective radius of shot wells be known.

Of the 60% of wells with initially measurable production, over 90% of these wells have flows which are subcommercial or marginally commercial, and consequently these wells are stimulated. Over the past ten years about 50% of such wells have been hydraulically stimulated.

The limited wellbore enlargement that can be achieved by explosive means requires that an explosive treatment intercept production characteristics (e.g. fracture systems) which were not intercepted by the initial well. In contrast, hydraulic fracture treatments can provide theoretically effective wellbore radii of several hundred feet, and the modest increases in production imply that the effective fracture length is much less than the predicted fracture length, as is typically the case. The stimulation response of wells with measurable but marginally commercial initial open flows also dictates a heterogeneous production characteristic most likely controlled by the natural fracture system. Only 5% of Devonian shale wells have had initial flows so large that no stimulation treatment was required. The unique feature of these very high initial productivity wells is not that they occur clustered in areas that might be associated with a high productivity reservoir, but rather that they occur interspersed with wells with marginal or no measurable initial production. That one well in 20 will intercept *in situ* characteristics providing high production while its nearest neighbors fail to do so further attests to the large-scale heterogeneity of shale permeabilities as controlled by natural fracture systems.

An effective stimulation rationale for Devonian shale wells must have available to it stimulation techniques capable of effectively communicating with *in situ* fracture systems, modeling methods for predicting the production effects of intersecting natural with induced fracture systems and, finally, statistical, geological, and geophysical exploration means for predicting *in situ* fracture density.

HYDRAULIC STIMULATION TREATMENTS

Until the early 1970's the artificially low prices for natural gas and the consequent marginal economics of Devonian shale production dictated that only conventional explosive stimulation techniques be utilized to improve shale production. With increasing gas prices and economic potential, the more expensive hydraulic treatments began to be considered, tested and evaluated. Initially only conventional water or water/gel treatments with sand as a propping agent were considered. With the inception of the Eastern Gas Shales Project, interest in possibly increasing shale well production even further with massive hydraulic treatments or the use of special fracturing fluids was developed. In general these specialized fluids may be categorized as low residual fluid or energy assisted fluids, such as a nitrogen foam or a cryogenic fluid. The data on enhanced production by conventional hydraulic treatments, massive-hydraulic treatments and low-residual fluid treatments are adequate for drawing some general conclusions on the relative success of these treatments and the rationale for their selection.

Conventional Hydraulic Treatments

In shale well stimulation, conventional hydraulic treatments are characterized as those involving less than 100,000 gallons of water or gelled water as the fracturing fluid. An extensive evaluation of conventional hydraulic treatments was done in comparison with explosive treatments by Yost (1978). In this study, the production decline curves for up to 5 years for comparable explosively and hydraulically stimulated wells were analyzed. While the data presented by Yost indicate that conventional hydraulic treatments would be preferred for shale wells in southern West Virginia and eastern Kentucky, data do not exist to extrapolate this observation to other areas of shale production. Given the significantly higher costs for completing a shale well with a hydraulic stimulation treatment as compared to an explosive treatment, the economic benefits of one treatment compared to the other cannot be fully evaluated at this time. Devonian shale producers are currently employing both conventional explosives and conventional hydraulic treatments in the completion of their wells. In general, their rationale is based upon a continuation of a technique which has proven economically viable in the region and under the conditions in which they are operating.

Massive Hydraulic Treatments

The testing and evaluation of large-scale, massive hydraulic stimulation treatments has been limited to a 3 well program conducted jointly by Columbia Gas Corporation and the Department of Energy (Cremean, et al., 1979). Although the three wells in this program were planned for true massive hydraulic treatment, severe clean-up problems with the first zone treated in well 20401, as indicated in Table 1, resulted in all subsequent treatments being either foam or modified foam types. The results of the Columbia/DOE three well program illustrate that severe cleanup problems can be expected for large-scale treatments in a low-pressure shale reservoir. The cleanup difficulties with these wells, even when a modified foam was used, suggest that fluid retention in even small-scale hydraulic treatments may provide important limitations on production. The large-scale treatments utilizing a nitrogen foam as an energy assist fluid suggest that while the cleanup problem may be significantly reduced with such a fluid, production enhancement warranting the increased cost of such treatments does not occur. Unless it can be demonstrated that the effective length of the fractures developed by large-scale, low residual fluid treatments is sufficiently large and that shale production characteristics would be responsive to such fractures, the economic application of large-scale or massive hydraulic treatments will not be attractive for shale well production.

Low Residual Fluid Treatments

The cleanup problems associated with both conventional and massive size hydraulic treatments in the lower pressure shale reservoirs has caused serious consideration to be given to energy assisted fluids as a fracturing media. Both foam type treatments (utilizing nitrogen and emulsified water) and cryogenic treatments (utilizing water and liquid CO_2) have been tested in shale wells. Cleanup after both types of treatment is facilitated by a gas drive provided by the expanding N_2 or CO_2 introduced into the formation during treatment. Both treatments use less water than conventional water or gelled water stimulations of comparable size. Nitrogen foam treatments have the additional advantage of a high fluid viscosity aiding proppant transport and minimizing fluid leak-off.

TABLE 1 - TREATMENT PARAMETERS
FOR
MASSIVE HYDRAULIC FRACTURING TESTS

WELL	ZONE	TREATMENT TYPE	FLUID VOLUME	SAND WEIGHT	RATE BPM	O.F. BEFORE MCFD	O.F. AFTER MCFD
20401	I-Lower Brown Shale	MHF (Gel/N_2)	517,014 gal	930,000 lb	25	0	103-145
	II-Middle Brown	MOD MHF ($Gel-N_2$/foam)	104,160	322,000	30	0	111
	III-Middle Grey-Upper Brown	MOD MHF ($Gel-N_2$/foam)	100,590	352,000	30	0	80
	IV-Upper Grey	MOD MHF ($Gel-N_2$/foam)	115,290	342,000	25	0	21
20402	I-Middle Grey Upper Urown Upper Grey	foam	131,000	290,000	40	0	139
	II-Lower Brown Lower Grey Middle Brown	foam	181,000	286,000	40	0	145
20403	I-Lower Brown	foam (77%)	234,000	299,000	37	0	110
	II-Middle Brown	foam (81%)	319,750	439,400	40	95	200
	III-Middle Grey-Upper Brown	foam	345,944	340,000	38	103	107
	IV-Upper Brown	foam (80%)	347,000	405,000	40	381	160

Only a minimal number of cryogenic treatments have been attempted in shale wells. On a joint industry/DOE program, Columbia Gas treated two intervals in each of three wells with fluid volumes ranging from 43,560 gal to 139,760 gal. All zones treated had no measurable pre-stimulation flow and the most successfully stimulated zone gave a 370 Mcf per day initial open flow after stimulation. While these cryogenic treatments gave an excellent clean-up and post stimulation production, the high cost of the treatments dictates that they be applied to higher temperature ($>150^{0}$F), and higher *in situ* stress (treatment pressure) reservoirs where foam treatments would be inoperative.

Using foam to create an emulsion in fracturing fluids was introduced in the oil and gas industry approximately six years ago (Blaurer, 1975). The main advantage in using foam is the energy-assist to clean-up provided by the gaseous phase. Fast, efficient clean-up minimizes formation damage due to the short contact time with the fluid and allows the well to be tested and put on production much sooner. Other advantages are high volume efficiency due to low fluid leak-off, good sand transport due to high viscosity in the fracture, and low friction loss in the pipe.

Several factors that limit the use of foam in other areas are not a problem in the Devonian gas shales. Use of foam is limited to temperatures below 150^{0}F and treating pressures below 3000 psi. Because the Devonian shale is a relatively low temperature, low pressure reservoir, these are not serious restrictions. Another problem with foam is that gas leak-off can be high, but because the Devonian shale has a very low matrix permeability, leak-off is not a severe problem.

Limitations in the use of foam fracturing in Devonian Shales have to do with sand concentration and cost effectiveness. Because sand is added to the liquid phase before introduction of the foaming agent, sand concentrations are low. Proppants have been found to be necessary for sustained production in the Devonian Shales. Whether or not the increased cost of foam treatments is justified by increased production will probably depend on the ability to identify reservoirs with sufficient capacity to be exploited by hydraulic fractures (Komar, et al., 1979; Liebenthal, et al., 1979).

EXPLOSIVE STIMULATION TREATMENTS

The explosive stimulation of Devonian shale wells with 80% gel dynamite has been successfully utilized for more than thirty years. The economic success of such conventional explosive well stimulation is related to the small incremental cost of such treatments and the unique production characteristics of Devonian shale. While hydraulic stimulation treatments usually require that the well be cased, cemented, and perforated through the potentially productive section, an explosive treatment is conducted in an open hole, requires no special well preparation, and may be conducted with no surface equipment other than a wireline workover rig. The typical costs for explosive treatments range from one-quarter to one-half of those for a hydraulic treatment. When ultimate production is neither assured nor apt to be spectacular, the lower costs of explosive treatments are especially attractive to the independent operator. As discussed in the preceeding section on hydraulic stimulation treatments, the very large relative increases in production realized with explosive treatments and the consistent elevation of an economically non-productive well to a productive well explain the continued acceptance of conventional explosive stimulation and the interest in improved or novel explosive techniques.

Conventional Explosive Stimulation

Despite the economic, albeit marginal, success of conventional explosive treatments in Devonian shale wells, practically no efforts have been devoted to either understanding the physical benefits of such treatments or attempting to significantly improve the state-of-the-art. Consequently, conventional explosive stimulations are conducted much as they were thirty years ago. The continued success and acceptance of explosive stimulation treatments in shale wells, while such treatments have been completely replaced by hydraulic stimulation techniques in more conventional reservoirs, implies that Devonian shale production is controlled by features which are uniquely responsive to explosively induced fractures. The previously mentioned erratic and wide-ranging initial production behavior of shale wells provides some indication and measure of the unique shale production characteristics. The broad ranges in initial production can only be explained if shale well production is controlled predominantly by a coarsely spaced natural fracture system. Both the frequency of wells with an initial, nonstimulated, commercial production and the occurrences of vertical fractures in shale cores could be utilized to make a statistical estimate of the fracture spacing that controls production. Rough calculations indicate that the production controlling fractures must have spacing on the order of three meters (10 feet) in that such fractures are certainly very coarsely spaced compared to wellbore diameters. Thus, the drilled shale well has a low probability of intersecting significantly the production controlling fractures but a minimal enlargement of the effective wellbore radius, such as effected by conventional explosive stimulation, has an excellent probability of intersecting adequately the natural fracture system.

While conventional explosive stimulation treatments most certainly generate wellbore fractures which provide an effective wellbore radius of a few meters, these treatments could cause significant wellbore damage in terms of permanent non-elastic deformation of the rock around the wellbore and in terms of fracture-plugging fines. Efforts to understand the explosive stimulation process, with the goal to minimize wellbore damage and to maximize effective wellbore fractures, could yield significantly improved benefits for explosive-type stimulation treatments. The current practice of using four inch diameter explosive charges in a six or seven inch diameter open hole probably represents the empirical development of a technique for minimizing wellbore damage. If the wellbore were completely loaded with explosives, the peak stresses experienced by the rock in contact with the explosives would exceed by several orders of magnitude the compressive and crushing strengths of the rock. By slightly decoupling the explosive charge from the wellbore wall, the peak stresses applied to the rock are significantly reduced such that the majority of rock damage involves tensile fracturing caused by the explosively generated gases. Although research efforts could be effectively utilized to define the ideal explosive decoupling factor for a given set of rock properties and natural fracture spacing, it would be more beneficial to consider the development and application of explosives with lower detonation pressures and greater gas generating characteristics. An explosive of this type, du Pont's EL-836, does display lower detonation pressures and high hydrogen gas generation and has been proposed for well stimulation purposes.

Displaced Explosive Stimulation Techniques

One important variant of the explosive stimulation techniques involves displacing a low-viscosity high-sensitive explosive into the formation prior to detonation. Displacement of an explosive into the formation allows for a greater quantity of explosive to be utilized in a stimulation treatment and supposedly provides a better stimulation as the explosive is detonated in the induced and natural fracture system in which it has been injected. The displaced explosive technique has been developed and field tested by several companies, most notably the Petroleum Technology Corporation (PTC), the Talley Frac Corporation, and Gerhart Owens. The Talley and PTC techniques are only utilized in open holes where some residual quantity of explosive remains and is detonated. The Gerhart Owens process is designed to be utilized in a cased hole with a cement plug completely filling the wellbore in the vicinity of the displaced explosive so as to minimize damage to the casing. Although each of these three techniques, as well as several other comparable methods, have been tested in numerous wells, none of them is commercially accepted at present.

Only the PTC Astrofrac process has been tested in Devonian shale wells. The results of several PTC experiments over a period of six years are summarized by Schott and Nuckols (1979) and have been documented in detail by Beckelman and Spencer (1979). While the PTC wells gave impressive initial open flows after stimulation, averaging 314 MCF, these high flows were not sustained, supposedly due to well cleanup problems. In addition, many of the wells stimulated by the PTC Astrofrac process experienced operational difficulties wherein the explosive detonated prematurely and prior to its complete displacement into a fracture system around the wellbore. Thus some of the enhanced production may have been caused by the effects of explosive detonation in a fully loaded wellbore. As noted by Schott and Nuckols, it is also possible that significant fracturing was developed by the explosive gases pressurizing the wellbore in a region between where the explosive was detonated and a containment tamp was placed. In addition to the unknown physical effects, the displaced explosive techniques are hindered by many operational and technical difficulties. In order that the explosive might have a reasonable probability of detonating in the thin fractures into which it has been injected, the explosive formulation must be quite sensitive. This sensitivity requires that either extreme explosive handling precautions be taken on the surface or that the explosive formulation be mixed downhole (as in the PTC Astrofrac technique) with a concordant complication of the downhole engineering and hardware. As has been documented by a series of tests at Sandia (Neel, et al., 1979) even the explosive formulations designed for detonation in fractures do not perform such that detonation can be assured. Any delays between the displacement of the explosive into the formation and its detonation could result in the partial reclosing of the explosive filled fractures with a concordant loss in detonability. The inability to assure detonation or even deflagration of the explosive displaced into fractures is a serious detriment to the viability of the displaced explosive techniques.

Tailored-Pulse Loading

Because of the inherent low permeability of Devonian gas shale, any stimulation technique applied to it must entail some in-formation fracturing. A principle objective of explosive techniques has been the formation of multiple fractures and/or extending natural fractures by loading the rock dynamically. Tailored-pulse-loading represents a stimulation technique which has been proposed to optimize the fracture formation and growth. The desired result is to create cracks of adequate extent in preferred directions so as to intersect as many gas bearing natural fractures as possible, without the wellbore damage typically associated with explosive borehole shooting. A detailed knowledge of the relationships between the processes controlling rock fracture and the stress history of the dynamic loading is a necessary requirement in efforts to optimize the explosive stimulation pressure-time history. Much recent research has been directed towards an understanding of the stimulation phenomenon and several stimulation processes have been developed to quantify and demonstrate the pulse tailoring concept.

The optimized pulse would avoid limitations inherent in both hydraulic fracturing and explosive fracturing. Hydraulic fractures, which are initiated and propagated at pressures that are slightly higher than the minimum *in situ* stress and for pumping times that are on the order of hundreds of seconds, typically produce only a single pair of fractures where orientation is aligned with the *in situ* stresses. Explosive detonations, which usually have peak pressures that are orders of magnitude above the *in situ* stresses and occur in microseconds, often cause considerable borehole crushing and leave a residual compressive stress zone around the wellbore. The wellbore damage and stress cage will often seal off any cracks that are formed further from the wellbore. A tailored-pulse would incorporate the benefits of hydraulic and explosive fracturing by imparting a controlled pressure load such that: 1) the peak radial stress is below the flow stress of the rock; 2) the peak hoop stress is above the tensile strength of the rock; 3) the initial loading rate is large enough to initiate multiple fractures; and 4) the duration of the pulse and the permanent gases generated by the explosive or propellant are sufficient to extend the multiple fractures for relatively long distances.

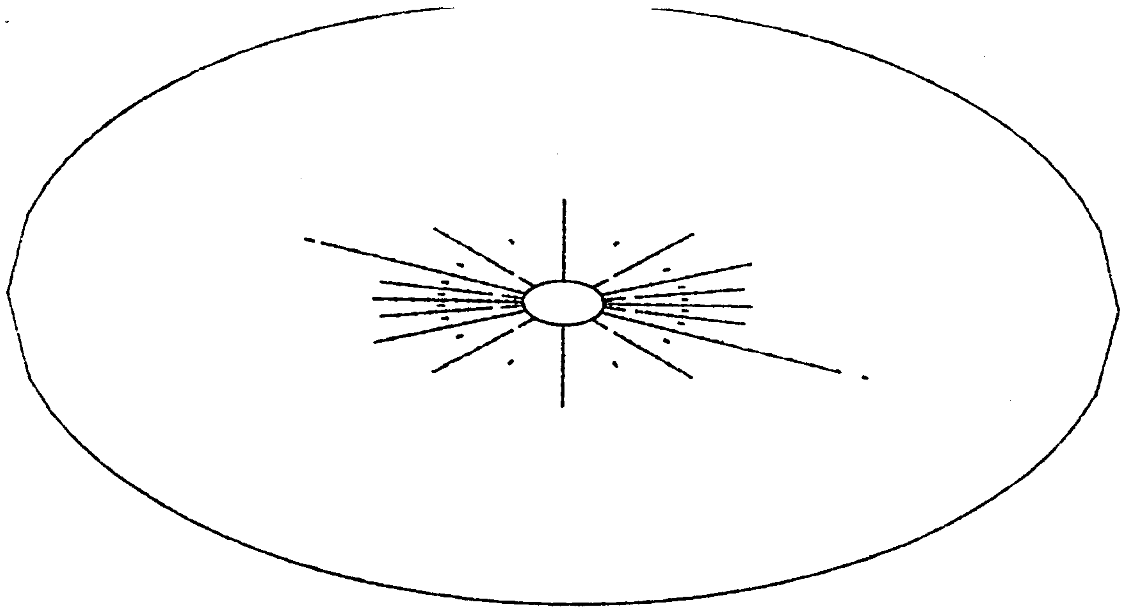
The initial efforts on tailoring the borehole pressure pulse were carried out by Physics International and have resulted in the Dynafrac process (Moore, et al., 1977). Subsequent efforts have been performed by Sandia Laboratories (Gas-Frac; Warpinski, et al., 1979) and Kinetech Corporation (Kinefrac; Fitzgerald and Anderson, 1978). The Dynafrac process uses a short rise time explosive pulse to initiate multiple fractures with a superimposed slow burn-rate propellant pulse (as the explosive pulse decays) to extend the fractures. Kinefrac and Gas-Frac use deflagrating charges (propellants) with loading rates slower than explosives but large enough to initiate multiple fractures. Both are high gas generators with low enough peak amplitudes to minimize borehole crushing and stress cage development. Abundant gas generation maintains the pulse long enough to permit the high pressure gases in the borehole to enter and extend the created multiple fractures. A buffering fluid (water) is employed in the Kinefrac and Dynafrac processes to provide the desired loading rates while restricting peak pressures to below those which cause borehole damage by crushing or shear deformation of the rock.

Analytical, numerical, and experimental programs are currently being conducted to evaluate the potential for multiple fracture development and the influence of tailored-pulse-loading. SRI International and Science Applications, Inc. (SAI) are currently involved in numerical simulations (using finite-difference calculational techniques) of the above mentioned processes to cooperatively evaluate the stimulation treatments on the fracture development that their fracture models compute. The SRI International NAG-FRAG fracture model (Shockey, et al., 1976) uses a tensile stress-dependent criterion for microflow activation and coalescence to describe crack development. The influence of various hypothetical pulse-tailored pressure profiles, in numerical borehole models, has been shown to have a significant influence on the computed fracture distribution (McHugh, et al., 1978). SAI's CAVS*fracture model uses a tensile stress criterion to define fracture initiation and propagation and describes the compatibility of the stress tensor adjustments as cracks open and close in three orthogonal directions (Maxwell, 1979). The influence of the rock's yielding properties and of crack propping and internal pressurization have been described (Barbour, et al., 1980). The effects of anisotropic *in situ* stress field and existence of preexisting fractures is currently being investigated by SAI. The University of Maryland (Fourney and Barker, 1979), (Fourney, et al., 1980), and SRI International (McHugh, 1980) are currently involved in laboratory experimental programs to establish the influence of tailored-pulse loading on the fracture development in borehole models in polymers and rock. Currently under investigation are the influences of anisotropic stress fields and crack pressurization.

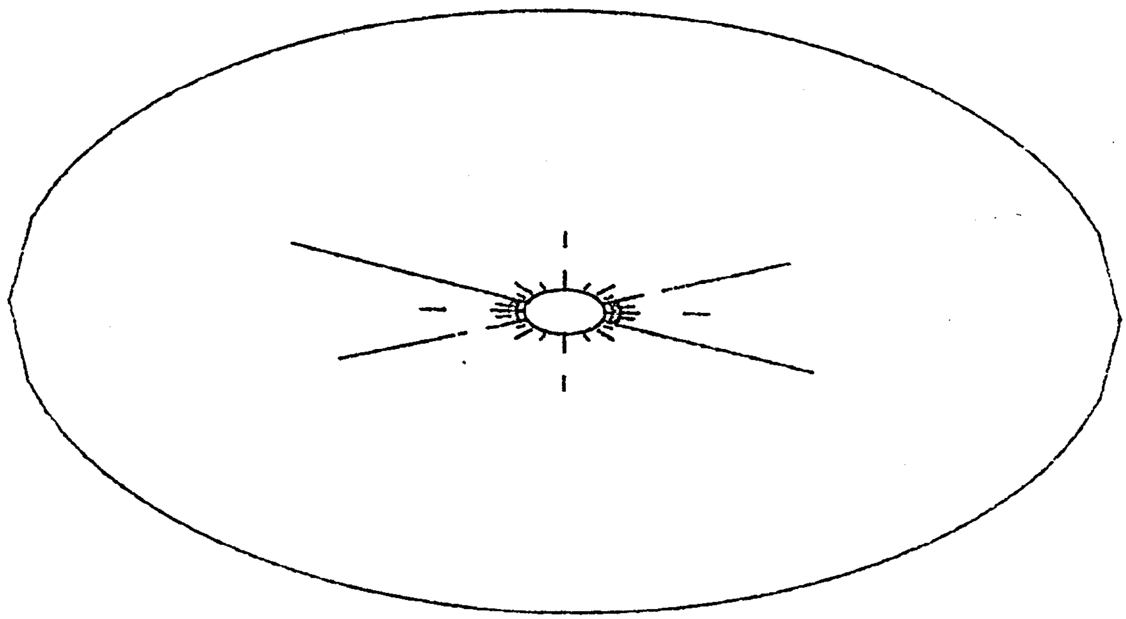
*Crack And Void Strain

Results of one-dimensional cylindrical geometry numerical calculations using SAI's CAVS tensile failure model have been used to evaluate the sensitivity of fracture development around an explosively loaded wellbore upon 1) rock mass properties, 2) crack propping, and 3) crack internal pressurization. The nature of the stimulating pressure profile and fracture pressure profile as related to the rock yielding properties can significantly modify the fracture pattern around a borehole. The rock yielding causes stress redistributions which can severely limit fracture growth. Figure 1 shows the effect of three yield surfaces for the modeled ash-fall tuff subjected to the unaugmented Dynafrac process. Figure 2 shows the three yield surfaces utilized in the calculations giving the results shown in Figure 1. The lower yield strength models illustrate the detrimental effect of wellbore yielding and stress redistribution, with the length of fractures into the formation being severely reduced. Without a propping mechanism to hold cracks open once they are created, explosively induced fractures could have such low conductivities as to seriously limit production potential. The once opened cracks will reclose in response to compressive hoop stresses that redevelop after the hoop tensile stress wave passes. A "skip-zone" of reclosed cracks often develops as shown in Figure 3.

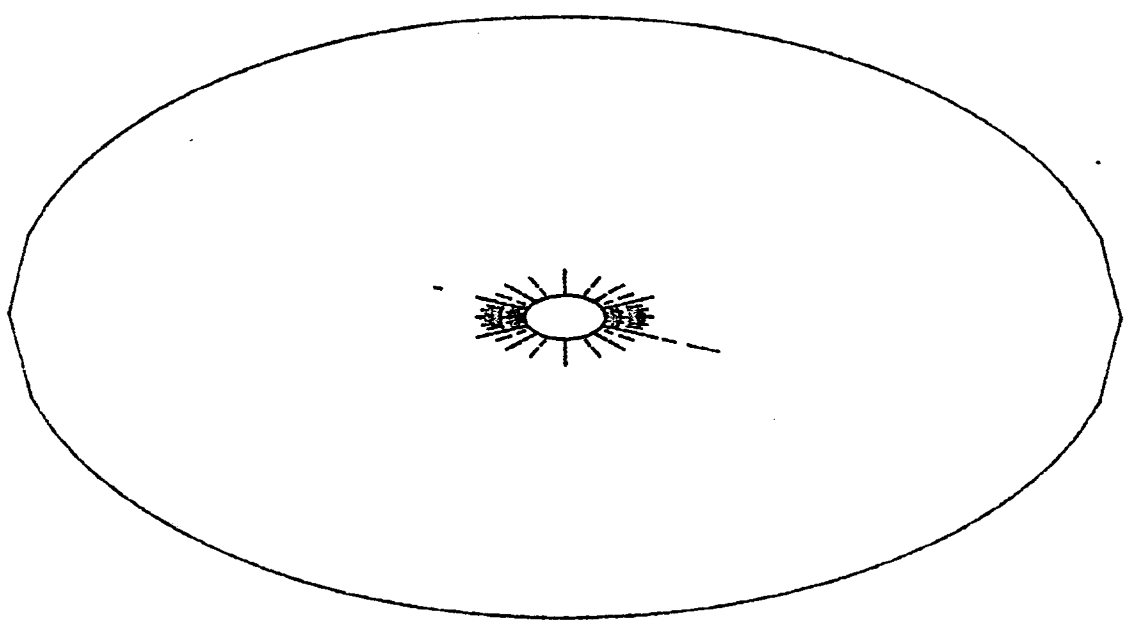
The Multi-Frac Test Series (Schmidt, et al., 1979), has been recently completed at the DOE Nevada Test Site in an ash-fall tuff formation. The purpose of these tests has been: 1) to evaluate the characteristics of five tailored-pulse fracturing concepts -- Dynafrac, Augmented Dynafrac, Kinefrac, multiple firings of Kinefrac and Gas Frac, and 2) to provide inputs for modeling efforts (experimental and numerical) which are necessary if such concepts are to be applied effectively to particular reservoirs, such as the Devonian shale.



1 A) BASELINE YIELD



1 B) YIELD #1



1 C) YIELD #2

Figure 1. Fracture Plots for Three Yield Models (Outside Boundary = 100cm).

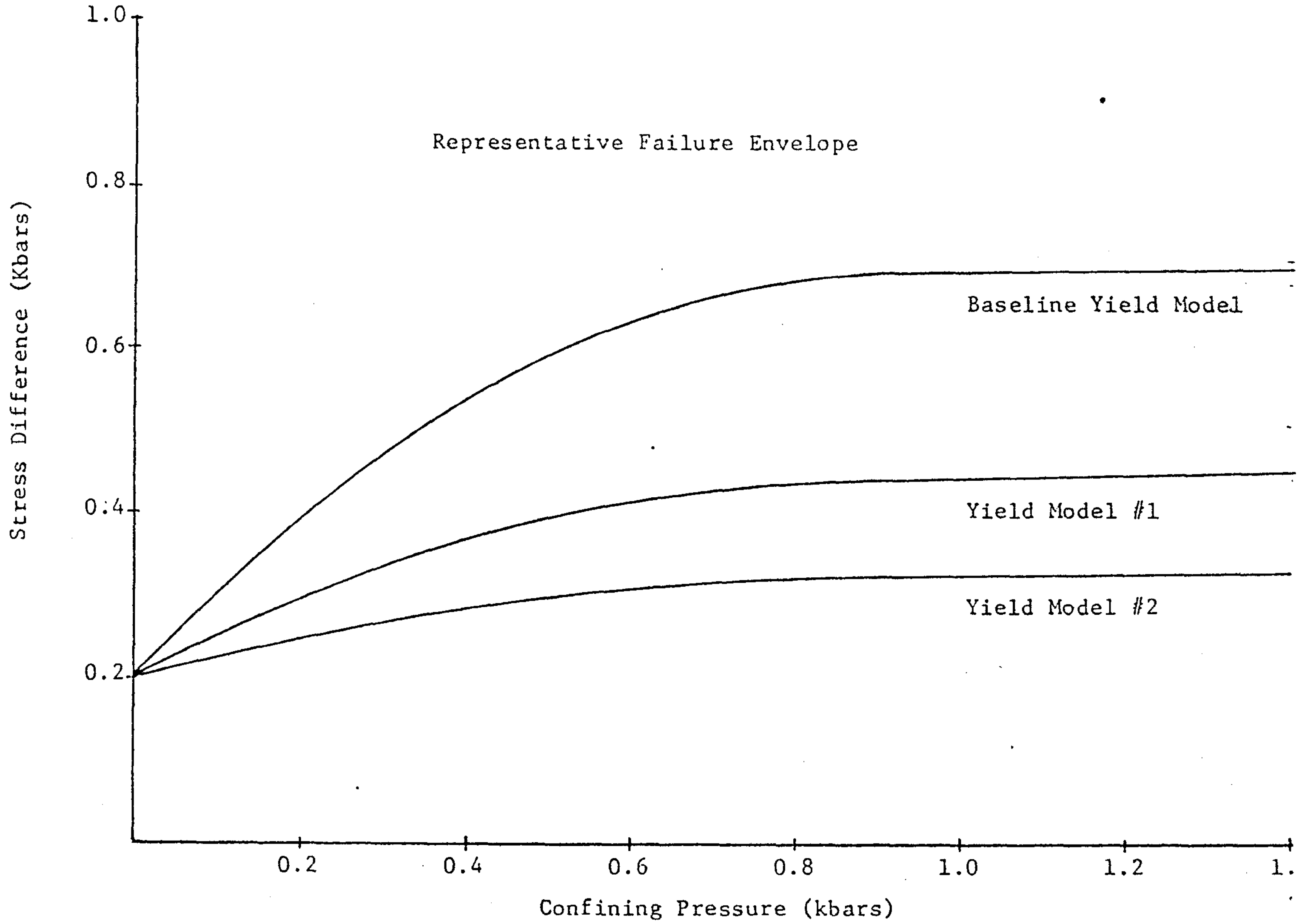


Figure 2. Ash-Fall Tuff Yield Models.

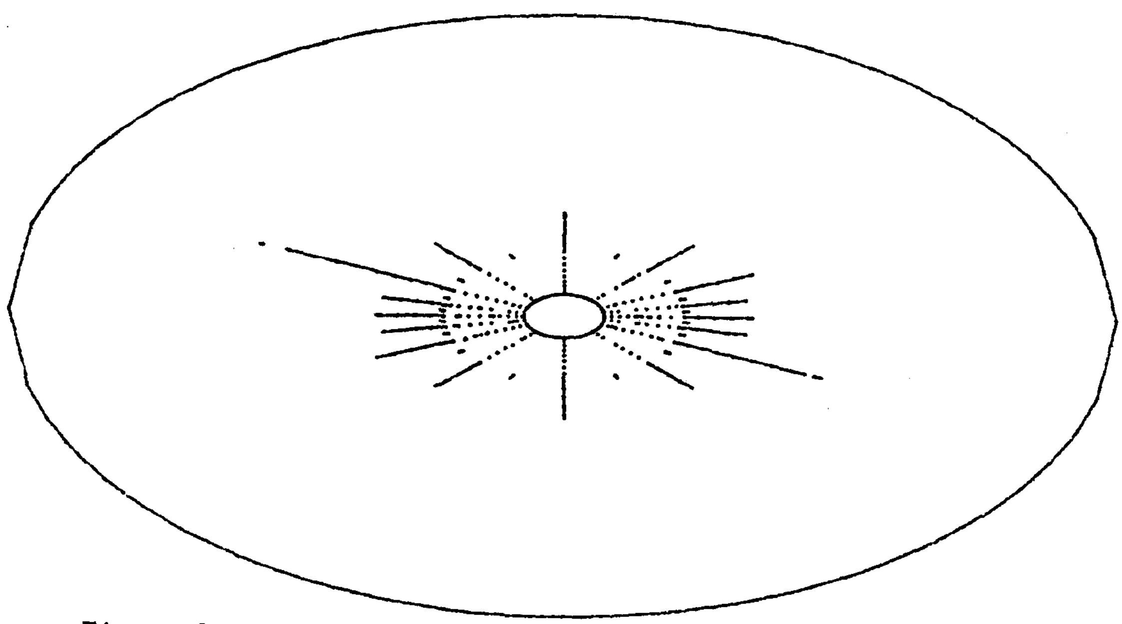


Figure 3. FRACTURE PLOT WITHOUT CRACK PROPPING
(Dotted Portion Represents Closed Cracks)

CONCLUSIONS AND RECOMMENDATIONS

There is not yet a sufficient data base on either Devonian shale production characteristics or the effects of explosive and hydraulic stimulation treatments upon which to base a quantative stimulation rationale for shale wells (Komar, 1978). There is adequate data, however, to support observations on the potential merits of the various explosive and hydraulic stimulation treatments and to predict which types of treatments are apt to be most effective under certain production conditions. Most importantly, the increased understanding of shale production characteristics and stimulation treatment effects gained during this study provides a foundation for defining the additional research and field testing efforts required to develop a firmly based stimulation rationale for shale wells.

All of the studies on Devonian shale production characteristics conducted to date agree and confirm that shale well production is fundamentally controlled by the *in situ* natural fracture system. While some of these studies (Kuuskraa, et al., 1978; Ford, 1979) conclude that the integrated effect of the *in situ* fracture system is to give shale wells conventional "blanket sand" production characteristics; more recent studies (Smith, et al., 1979; McCarthy, et al., 1979) argue that naturally fractured shale reservoirs do not display conventional production characteristics. Certainly, the many fold increases in production observed with conventional wellbore shooting and small scale hydraulic stimulation treatments attest to the heterogeneous characteristics of shale production on the scale of initially drilled wellbore diameters and even on the scale of the effective radii of stimulation treatments.

As shale well production is dominated by the *in situ* natural fracture system, it is imperative that significant efforts be made to quantitatively describe the *in situ* fracture system and its control upon shale well production. As the benefits of various explosive and hydraulic stimulation treatments clearly depend upon the interaction between the induced wellbore fractures and the pre-existing natural fractures, it is equally imperative that increased efforts be devoted to quantitatively understanding the effects of the stimulation treatments. Only by fully integrating fractured reservoir production characteristics with the effects of explosive and hydraulic treatments can a quantitative and supportable stimulation rationale be developed.

Although the data base and the integrating physical models are far from adequate, it is possible to make specific recommendations on the applicability of various stimulation treatments to shale wells. The experience and data on both hydraulically and explosively stimulated wells suggest that formation damage and usually related cleanup problems are a major concern.

For the hydraulic type treatments the use of low-residual-fluid treatments is highly recommended. The lower the initial formation or reservoir pressure, the more highly the low-residual-fluid treatments may be recommended. The excellent shale well production which is frequently observed with only moderate wellbore enlargement treatments suggests that attempts to extend fractures to greater distances with massive hydraulic treatments may not be warranted. Immediate research efforts should be concentrated upon limiting production damage by fracturing fluids retained in the formation, and upon improving proppant transport and placement so as to maximize fracture conductivity.

The occasionally spectacular production increases resulting from both conventional and displaced explosive treatments suggest that the modest wellbore enlargement resulting from such treatments may provide a viable and cost effective approach to shale well stimulation. In that some, if not all, of the benefits obtained with displaced explosive treatments may be attributed to simple wellbore fracturing, future efforts should be concentrated upon improving wellbore fracturing while minimizing consequent damage rather than upon the displaced explosive technique per se.

In selecting an explosive treatment for application to a shale well, consideration should be given to minimizing mechanical damage to the formation and to selecting an explosive formulation with minimal water generation characteristics. If the well is to be cleaned out following an explosive treatment, it is imperative that this cleanout be done without the aid of water or even a water-based foam. Immediate research efforts should be concentrated upon the mechanisms by which wellbore fractures are induced and propagated, especially in naturally fractured formations, and upon techniques for minimizing mechanical formation damage by explosive/propellant treatments.

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