Novel Concepts for Unconventional Gas Development of Gas Resources in Gas Shales, Tight Sands and Coalbeds

Public Version

Final Report

RPSEA Subcontract 07122-7

February 19, 2009

By:

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Novel Concepts for Unconventional Gas Development of Gas Resources in Gas Shales, Tight Sands and Coalbeds

Final Report with Confidential Information Removed

Restricted Data Notice and Patent Waver

"The data contained in Appendix C and D of the full report and the accompanying spreadsheet "Model of Bowstring saw 8 for RPSEA.xls", have been submitted in confidence and contain trade secrets or proprietary information, and such data shall be used or disclosed only for valuation purposes. RPSEA shall have the right to use or disclose the data herein to the extent provided in the award. During the course of performance of RPSEA contract 07122-7 Novel Concepts for Unconventional Gas Development in Shales, Tight Sand, and Coal beds, Contractor has made inventions and improvements to concepts and has filed a provisional patent application covering the inventions in the body of the report and intends to file for US and foreign patents on these concept as well as those in Appendix C and D. Contractor requests that the technical details of the report on pages 15-29(as well as Appendix C and D) be held confidential not be published as this could hinder efforts to obtain optimal patent protection. Contractor has made a confidential invention disclosure to the contracting officer and advised contracting officer that contractor has elected to claim rights to inventions described herein as per (DEARS) provision 952.227-11 NOTICE OF RIGHTS TO REQUEST PATENT WAIVER, and our subcontract 07122-7, mod 002.

----All confidential information has been removed from this copy---

Subcontract 07122-7

Unconventional Onshore Program

Research Partnership to Secure Energy for America

<u>Executive Summary</u>

Carter Technologies Co of Sugar Land, Texas is a technology developer in the field of underground engineering and modification of subterranean formations for environmental and energy applications. The project director and principal investigator for this work, Ernest Carter, is a Texas Professional Engineer, with over 25 years of experience in underground engineering, grouting and design of down hole tools for well completion.

The project is titled: Novel Concepts for Unconventional Gas Development Shales, Tight Sands and Coalbeds.

Current methods of horizontal drilling and fracturing experience rapid production declines and leave as much as 90% of the gas in place. Hydraulic fracturing techniques have been successful in the Barnett shale but are expensive and may consume up to 4 millions gallons of water each. There are also many different shale formations in the United States such as the New Albany shale that also have gas but have not responded as well to existing technology. Clay rich shales such as the Caney do not respond to fracture stimulation as well as the more brittle silica rich shales of the Barnett.

The project objective was to develop an alternative method of formation stimulation to increase the net production of gas from shale while reducing the environmental impact due to the amount of water required. The project has been an outstanding success and produced at least one new method of formation stimulation that may be able to connect hundreds of thousands of square feet of the formation face directly to the well bore. Over a dozen new concepts were evaluated including one promising method that appears to be able to cut 100 foot deep slots all along a 2500 foot long horizontal well. The method appears to have a low capital cost and be sufficiently robust to withstand the rigors of the down hole drilling environment.

The preferred method uses a downhole cable saw to cut a pathway or “slot” into the formation all along the length of a horizontal lateral well bore within a shale formation. Theory indicates that these slots may also reduce production decline, reduce the effects of formation damage, and allow a larger percentage of the in-place gas to be recovered compared to conventional completions.

The computer model developed during the work indicates that the deep longitudinal slots can produce 50 to 100 times as much surface area as a horizontal well alone. These slots may be thought of as steerable oriented fractures. They are over an inch wide, and thus more resistant to plugging than a hydro-facture. They can be left open or packed with sand or pea gravel. Since their size and position are controlled, rather than random, they can be placed in a grid or pattern to maximize production from a given well or lease acreage. In future work we plan to evaluate performing additional fracturing activities from the high surface area slots.

Collaborative associates for the project have included M-I LLC, a Smith/Schlumberger Company, Smith International, and professors Peter Valco from Texas A&M University and Younane Abousleiman from the University of Oklahoma.

Introduction

It is known that shale rock formations often contain large volumes of natural gas but the relatively low permeability of these formations sometimes limits the recovery flow rate of the gas to non-economic quantities while leaving behind significant unrecovered gas. The low permeability of the rock near the well bore prevents the rest of the formation from being exposed to significant pressure drop from the well bore.

This problem has previously been addressed by drilling holes that turn horizontal at depth and travel within the relatively thin shale formation layer. Electronic tools run within the drill pipe are able to track the position and progress of the hole and its proximity to the shale formation layer interface. Hydraulic fracturing is then used to increase the surface area of these wells by fracturing at intervals along the horizontal well, but it is difficult to control the direction or orientation of such fractures.

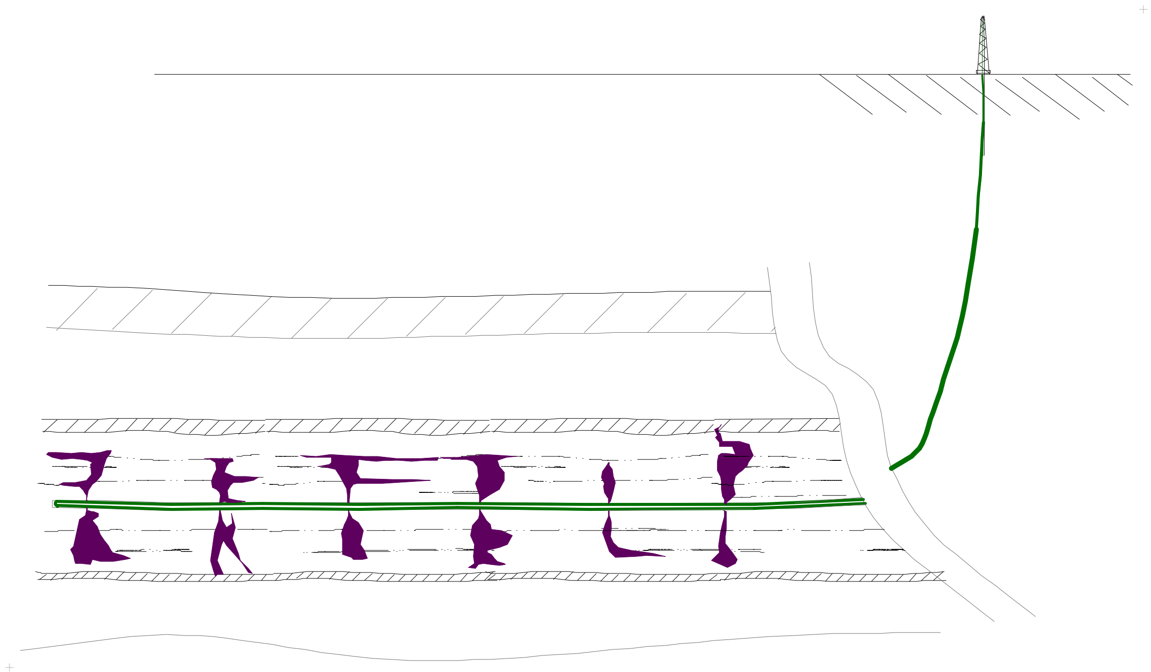

Figure 1, Conventional horizontal well with multiple fractures.

This lack of control may lead to un-even and incomplete recovery of gas from the leased formation. Large areas of the formation may remain too far away from the fractures for effective gas production. Fracturing the wells too vigorously may also risk creating flow paths to adjacent formation layers containing water. Water from an adjacent formation layer entering the well can reduce the flow of gas to the surface. Large volumes of water are required for the fracturing process and the water use and disposal may become an environmental problem. The true extent and geometry of these fractures is never known in spite of extensive simulation and even modern micro-seismic study, but it seems likely that the fractures access only a fraction of the 3 dimensional volume within a lease area.

The objective of the present work is to develop new stimulation concepts that provide a cost effective means of increasing the amount of gas that may be economically recovered from a given lease acreage area of a subterranean formation, while minimizing the cost and environmental impact. A further objective is to maximize the total recovery of gas from a given area by accessing a larger percentage of the total reservoir volume. If successful, the methods would also have application in increasing production of oil or gas in many types of formation including shale, tight sands and coal beds.

Summary of Technical Approach

The preferred method will comprise means to form deep longitudinal cuts from and along a conventional horizontally drilled borehole within a gas producing formation at great depth. These galleries are mechanically cut with specific dimensions to provide a vastly increased surface area compared to the well bore alone. Means are sought to cut sideways, upward, and even downward from a horizontal borehole or at various angles. Unlike the thin and random cracks formed by hydraulic fracturing techniques, these cuts would be much wider and may not require filling with sand to keep them open. Cuts may be made substantially vertical to minimize collapse forces due to overburden subsidence.

These vertical cuts may form planar surfaces tens of thousands of square feet in size and have much higher conductivity than fractures. The surface of a slot may experience the same depth of formation damage due to water clay swelling as the wellbore but due to its planar geometry the flow reduction would be far less than the radial flow reduction into a round bore hole with the same depth of formation damage.

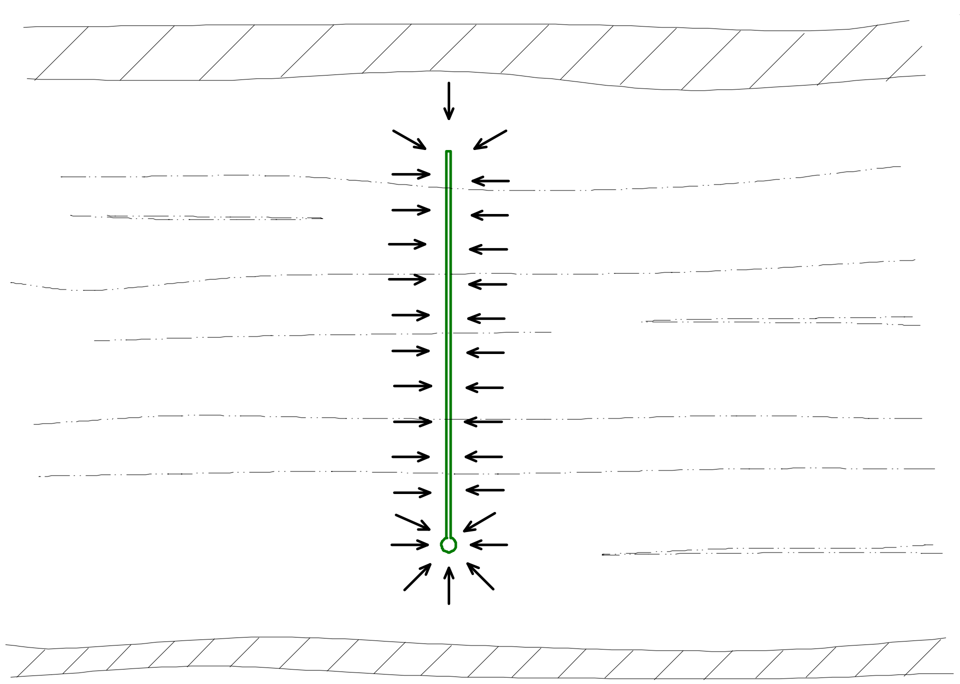

Figure 2, Vertical slot all along a horizontal lateral, within a gas shale

Multiple horizontal boreholes may be created that are substantially parallel and the present invention may be used to form substantially parallel vertical planar cuts from said parallel horizontal boreholes. Alternately, the cuts may spiral out in multiple directions from a common vertical borehole. The greatly increased surface area from these cuts will allow increased gas production from low or high permeability formations. An extension of these concepts could allow a radial array of thin horizontal arc cuts to be formed from a single well location. Since the cut is over an inch wide it should be possible to fill it with a much larger size of sand particles resulting in vastly increased conductivity compared to traditional propped fractures.

While it may be possible for the cut slots to compete favorably with conventional fracturing, it is also inevitable that fracturing would then be tested on the slots. If the substantial planar cuts can in fact be constructed, it may then be possible to develop a secondary stimulation method based on fracturing. A large subterranean planar gallery may respond very differently to fracturing techniques especially those that allow a very rapid pressure rise such that the central parts of the plane experience high pressure before the edges. Tuning of the pressure pulse may allow creation of multiple fractures perpendicular to the plane of the cut. This work on secondary fracturing is of significant interest but has not been modeled in the currently funded project because its feasibility is entirely dependent on successful construction of the slots. Significantly development of slot construction methods was done during this preliminary 6 month study but significant research remains before they can be field tested.

Project Objectives

The project objective was to prepare a preliminary study of novel methods of formation stimulation to increase the production of large amounts of gas in shale, tight sands, and coal bed formations not currently deemed economic. Specifically the method of stimulation is cutting of a deep slot from a horizontal borehole deep into the formation.

Gas shale is though to have the most significant potential for improvement. Shale formations have been found to contain vast amounts of natural gas but the low permeability of the formation limits economic production of these resources. It was proposed that if a large surface area slot could be opened up along the well bore that the gas would flow faster and a greater percentage of the in-place gas could be produced. If feasible this method might reduce the need for massive hydraulic fracturing along with its expense and water resource issues. The large surface area galleries created by the slot could also be used to facilitate new types of fracturing technology. The goal was to develop and model at least one workable method to the point that it could be evaluated by a potential licensee, and sufficient to attract additional funding from RPSEA for a full scale development of the idea.

The project would perform new creative design work based on the principal investigator's experience in cutting underground pathways and modifying formation permeability. The work utilized patented and public domain concepts as well as novel methods previously conceived by the principal investigator. Where appropriate, additional patent documents have been filed to protect the inventions described in this report. Microsoft Excel computer modeling tools were to be created to evaluate mechanical slot cutting friction loads and size in various formations. The project was to be a preliminary "paper" design study to originate and develop novel concepts. The work would all be performed in the researcher's offices had no field-testing of any kind so it was not expected to result in any "proven" methods, but only concepts for further study.

Concept and design drawings were prepared for a number of different approaches. Over a dozen different approaches were evaluated with concept drawings. See **Appendix D**. Concepts were judged on mechanical feasibility, mechanical robustness, cuttings management, cost, productivity, and overall reliability. The successful project would develop data for a phase-two draft proposal for further work in cooperation with one or more production or service companies.

Promising methods of forming mechanically prepared infiltration galeries, (or slots), and formation sawing techniques were evaluated and numerically modeled. The work was focused on the methods of actually cutting the slots while leaving the task of evaluating potential for advanced fracture propagation and propping concepts to future work. The task of determining the desirability or benefit of cutting slots was specifically outside the scope of this work but preliminary opinions from collaborating experts have not cast any doubt on the initial assumption that deep slots may be comparable to fracturing for shale, tight sands and coal beds.

The mechanical slot stimulation methods rely less on knowledge of the natural fracture systems and therefore may be applicable to formations with limited geologic data. If successful, this will open up economic production in tight formations that do not respond to conventional hydraulic fracturing stimulation or for which there is insufficient data to design a fracturing treatment. The preferred method evaluated appears to be relatively low in capital cost and should increase the reach of small production companies. Since these methods do not require as much formation data to be successful, this tends to make the process more attractive for wildcat operators and may open new fields more rapidly.

Existing Technology Web Search

A technology status assessment was performed to identify potentially useful concepts. An internet based review of current technology and the characteristics of known shale gas formations was performed. The published fracturing technologies of Halliburton and Schlumberger were reviewed. The state of the art was found to include horizontal laterals spaced evenly apart with fracture events initiated at intervals down the horizontal length. A web search was also performed looking for any patents on abrasive cable cutting of subterranean formations. Several patents were found that proposed constructing a cut from a pair of holes which intersect, or a wire saw cutting upward from a U shaped hole. Others propose use of an endless loop or rope, chain, or cable to saw undercut a formation or mine coal. Most of the methods either neglect the effects of friction or propose placing pulleys deep in the ground to direct the sawing action.

Another factor they have in common is the requirement to have a hole that comes back to surface at a two points so that the cable can be pulled from either side to reciprocate it.

One recent patent application was found describing a fanciful but highly challenging concept of drilling two roughly parallel holes that intersect at depth and threading and reciprocating a length of diamond wire saw cable around the intersection point to cut a slot between the two bore holes. Friction factors and cable flexibility would preclude this.

A review was also made of mining machine rock cutters and tunnel boring machine rock picks and conical rotating cutters as well as a brief study of the history of oil well drill bit development and diamond wire saw technology.

Initial Concepts

The project began by brainstorming for new concepts. The immediate objective was limited to methods of forming an extended slot within a relatively thin shale layer. In conventional drilling the weight of the pipe in the hole above produces extreme force on the drill bit and circulation of mud removes both heat and formation cuttings. A tool cutting laterally away from a borehole would not have this force available. A list was made of all physical methods which might be used to produce cutting force normal to the well bore in a horizontal bore. Ways to generate this lateral force include:

- Local weight of the pipe in a horizontal bore bearing against bottom side of hole
- Buoyancy of the pipe causing it to bear against upper side of hole
- Inertial momentum from a pipe bouncing up and down in horizontal bore
- Any of the above augmented by rotation or reciprocation of tool
- Curved tool cutting surfaces digging into formation due to rotation or reciprocation
- Reaction thrust from water jet nozzles
- Bending moment on drill tools in a curved hole
- Tensile force causing pipe to bear against inside hole radius

- V shaped hole allowing a loop of cable to cut upward between two surface points
- U shaped hole allowing a loop of cable to cut downward between adjacent holes
- Intersecting holes with tensioned cutting means between

Evaluation Criteria for the novel concepts studied included the cutting force available since this would determine the maximum production rate and thus affect the cost. The width of the cut to be formed is also a similar factor in that a 12 inch wide cut would require 12 times as much cutting energy and produce 12 times the volume of cuttings as a 1 inch wide cut. A wider cut width could be useful if the residual horizontal stress tend to elastically close up a narrow cut. Unlike a round borehole which is supported by the structural properties of the rock, a very large planar cut may allow the rock to elastically close the cut some distance away from the edges if there is horizontal compressive stress in the rock. The magnitude of native horizontal stress in shale formations is unknown. In personal communications with several "experts" no consensus was reached on the magnitude of this stress or even if it exists. For mechanical design purposes it was determined to assume that a vertical cut would tend to at least partially close up after the cut was advanced several meters and thus the cutting apparatus might not be able to freely traverse the pathway again.

Cuttings removal is a critical feature of any drilling technology. The circulation of drilling fluid carries away both cuttings and heat while lubricating the mechanical contact points. However once a cut extends substantially far away from the original borehole, it becomes more difficult to generate fluid flow within the cut due to its greater cross section. Cutting larger chips saves energy but makes chip removal harder. The cutting surfaces may heat up and soften, or the tool may become stuck in a mass of cuttings. This problem may be addressed by thicker mud, mechanical action, or forming a relatively thin cut vertically upward to allow gravity movement of cuttings back to the larger borehole to be swept out by fluid circulation.

Mechanical wear on drilling systems is important. In deep holes tripping in and out of the hole is costly and so the tools should last long enough to cut the entire slot before wearing out. Tools are made with various kinds of hard facing metal or even diamond abrasives as in wire saws used in the stone cutting industry.

Equipment and tool costs must be within economic limits of the increase in well productivity. Fracturing technology makes use of external power sources in the form of many diesel powered pump trucks. This is a major capital investment and limits the work to special service companies which can charge a premium based on the production improvement. However it may be possible to operate a slot cutting system with the drilling equipment of a standard drill rig. The rigs generally have the ability to raise and lower very heavy weights of drill pipe and to rotate the pipe with considerable power. Also the rig generally has mud pumps that can circulate drilling fluids at pressures several thousand psi more than the downhole pressure. However, use of the rig power to run the cutting tools will tie up the rig for additional days and this cost must also be considered. Compatibility with rig systems is needed to avoid excess costs of modifications and damage to drilling and fluids control equipment.

Water and drilling fluids must be recycled to avoid wasting resources. The mud recycling technology currently available is able to remove both fine and coarse particles from the mud and re-use it indefinitely. MI drilling fluids has suitable equipment.

Concept development work began with sketches of 12+ different methods to be considered. These concepts included Jetting systems, Rotating cutters, Reciprocating cutters, Cable saw systems, Elastic Cable stretch systems, Pressure driven Auto-stroke cable saw systems, Cable anchor-spring loaded systems, and various Pipe driven cable saw concepts. A more detailed discussion of the other concepts initially considered is quite lengthy and is included in **Appendix D** of this report.

The project included a specific task to evaluate using high pressure water jets to cut through the rock. A previous invention of the PI called the “Soil Saw” used this technology to cut and form a 12 inch wide cutoff wall in soil at rates of up to 100 square feet per minute. The machine used two large Halliburton Frac pumps to power 72 jets orifices locating on a reciprocating beam. The jets liquefied the soil and sunk into the earth on its free end and traveled horizontally using a large tracked machine. In an underwater environment, the powerful jets lose energy rapidly with the square of the distance so 95 percent of the energy is dissipated after a foot or two. Therefore it is required that the jets be continually moved into the face of the cut. Sketches were made of two similar devices that would be reciprocated within a portion of the hole. The weight of the pipe provided the driving force to push tool against the face of the cut.

Drawbacks to this jetting tool included the need for many high pressure pumps to support its action. Another factor is that rock does not cut as easily as coal or soil and production rates would be reduced. The differential pressure across the jets is reduced at depth by the hydrostatic head of the fluid in the hole so at ambient downhole pressure, the pump pressures would require Halliburton style intensifier equipment which is costly. For these reasons it was decided not to pursue the jetting technology for shale gas but to focus on the leading mechanical concepts.

Results: Two Leading Concepts

Two different concepts were judged to be most promising for near term development. The "**Rotating Cutter Tool**" uses cutting teeth on a heavy rotating drill pipe to cut a nominally 6 to 12 inch wide cut downward from a substantially horizontal bore. The relatively wide cut made by this class of tool is expected to make it far less cost effective. The tool is made of heavy steel and is mechanically robust. Costs are relatively high compared to the other method since at least 300 feet of these special tools would be needed for a full scale application. It appears to be technically feasible so it should continue to be studied. In an attempt to avoid reader confusion the details of the Rotating Cutter Tool are described fully in **Appendix A.**

The Bow String Cable Saw concept technical description is part of the confidential information not included in this version of the report.

Conclusions

The Bow String Cable Saw method appears to meet the previously described project objectives and may do so in a cost effective manner. The method is mechanically simple and robust. Operation and control does not appear to be too complex. Potential for getting stuck in the hole seems small due to the inherently lower friction on the pull. It seems probable that well surface area can be increased by a factor of 50 to 100 times and that the planar slot will suffer far less influx degradation due to formation damage compared to a wellbore that draws from a radial pattern. The proposal objectives have been satisfied in that at least one method has been advanced to an engineering level sufficient for others to evaluate its merits. Considerably more engineering work will be required in the next phase to bring the method to a sufficiently marketable status that it can be tested in major shale gas producing areas. The idea has received a surprisingly level of enthusiasm from our industrial partners and one gas producer has indicated a desire to try it out in some low cost shallow wells this summer.

APPENDIX B

Letters of Interest or Support

The University of Oklahoma
POROMECHANICS INSTITUTE

February 16, 2009

Ernie Carter, President
Carter Technologies Co.
9702 Garden Row Drive
Sugar Land, TX 77478

Dear Mr. Carter:

I have reviewed your slot cutting concepts for stimulation of gas shale formations and I am very interested in working with you on development of this technique. I believe that if you are able to cut slots of the magnitude we discussed that it will produce a significant production increase in gas shale as well as certain other types of formations. Please keep me informed and we will continue an informal collaboration as you continue development. When you are ready, I can help arrange contacts with companies that may be interested in licensing your invention.

Our special expertise in poromechanics may be useful in evaluating the potential of the longitudinal slots you hope to be able to produce. My department has student researchers that may be able to perform specific research tasks for the work if you have funding available. We may be able to help you with the question of whether these slots would need to be filled with proppant or left open. Stability of the hole and experimental verification of friction and cutting rates are other areas that could be studied.

Very truly yours,

Dr. Younane N. Abousleiman
Larry W. Brummett/ONEOK Chair & Professor
Director, PoroMechanics Institute
School of Geology and Geophysics

Sarkeys Energy Center, Suite P119, 100 East Boyd Street, Norman, Oklahoma 73019-1014 PHONE (405) 325-2900 FAX: (405) 325-7491

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February 18, 2009

Ernest E. Carter
Carter Technologies Co
9702 Garden Row Drive
Sugar Land, Texas 77478

RE: Gas Shale Stimulation

Dear Mr. Carter,

Thank you very much for the extremely well done presentation of your novel concepts for increasing gas production from low-permeability shale formations. Both slot cutting techniques are quite innovative and exciting ideas that may very well allow the economic recovery of large amounts of previously unavailable natural gas.

Our corporate parent, Smith International Inc. was also very interested in your ideas and your presentation has generated considerable enthusiasm among their engineering staff as well as management.

We look forward to working closely with you in the development and future utilization of your techniques and continuing our mutually beneficial relationship.

Best regards,

Jim Thomason
Senior Manager – Business Development

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TEXAS A&M
THE HAROLD VANCE DEPARTMENT OF
PETROLEUM ENGINEERING

Peter P. Valkó, "L.F. Peterson" endowed professor
office: 501K Richardson Building
mail: 3116 TAMU, College Station TX 77843 (USA)
phone: (USA)-(979)-862 2757
fax: (USA)-(979)-862 1272
web: http://www.pe.tamu.edu/valko/
email: p-valko@tamu.edu

Ernie Carter, President
Carter Technologies Co.
9702 Garden Row Drive
Sugar Land, TX 77478

Dear Ernie,

February 19, 2009

This letter is to express my interest in the idea you are currently developing to increase the productivity of hydrocarbon producing wells by using cable cutting technology.

I am convinced that the technology has great potential. If a slot of reasonable length and height – commensurate to the one we attempt to realize by hydraulic fracturing – can be created and kept open afterwards, the advantages would be numerous. To mention just a few:

i) In contrast to hydraulic fracturing, the created geometry would be well defined.
ii) In contrast to hydraulic fracturing, the conductivity within the created object could be much higher – practically infinite.

Our group has the necessary knowledge to forecast production from various well/slot configurations of practically any complexity. We have graduate students ready to carry out optimization once the technical constraints and the costs associated with the technology are known.

Looking forward to working with you,

Peter Valkó

3116 TAMU, 507 Richardson Building, College Station, Texas 77843-3116
(979) 845-2241 – FAX (979) 845-1307 – http://www.pe.tamu.edu

SMITH SERVICES

Carter Technologies Co.
Underground Engineering and Grouting Technology
Sugar Land
Texas

Smith International Inc.
16740 Hardy Street
Houston,
Texas 77032

Dear Ernie,

I wanted to take this opportunity to thank you for explaining your novel concept for formation stimulation in unconventional gas development shale, tight sand and Coal beds. The use of existing technology coupled with the wire rope in the reciprocating mode to cut 1-2 inch paths selectively in the formation has potential for significantly improving production from reservoirs by exposing a greater surface area. We would be extremely interested in learning more about the successes of this system when you have completed the initial test runs.

If there is any information that we can provide you in support of your quest to bring this concept to a reality please do not hesitate to ask.

Yours sincerely

Malcolm Perschke
Director of Engineering
Completion Systems
Smith International Inc.

APPENDIX C

Valco Computer Model

A computer model developed by Dr. Peter Valco to evaluate fracture potential was applied to the hole geometry of a well completed with a slot. Following are the output charts from the model. No independent evaluation of the model assumptions or conclusions was performed.

e1

Needs

BoxInBox ufun, pDelD, puD

Multiple Sources

Mult Box with Inf Cond Connection

N1A Large thickness, isotropic

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In[373]:= hl = {25.1, 89.5, 177.6, 283.4, 395.4, 510.6, 601.5, 612.8, 494.8, 201.4};
          dw = {0, 25, 115, 292, 595, 971, 1482, 2083, 3211, 3392};
          db = {9073, 9227, 9400, 9559, 9661, 9651, 9454, 8985, 8168, 6961};
          onevec = 1 + 0 hl;

In[377]:= cx = dw + hl / 2; cy = 1000 onevec; cz = 10 000 - db + 30;
          wx = hl / 2; wy = 1 / 12 onevec; wz = 30 onevec ;
          sources = {cx, cy, cz, wx, wy, wz}';

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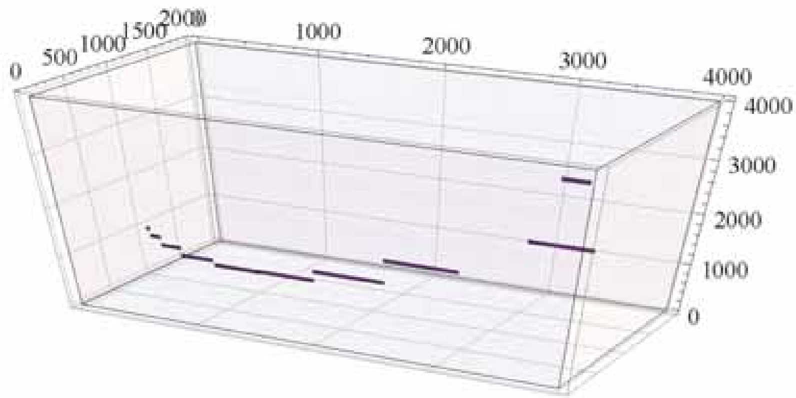

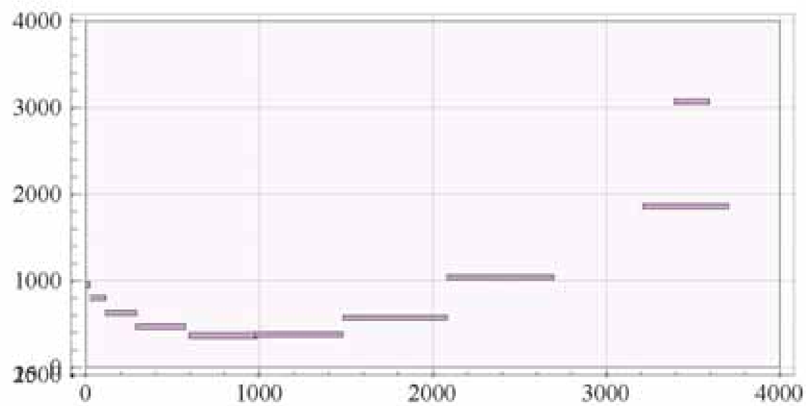


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Timing[{JDTabHoriWell, kh} =
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Out[187]= {2.792, 0.124481}

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  , Frame → All, BaseStyle → {FontSize → 16}] // Print
```

Productivity wrt	
Vert well	Hori well
1.49447	1.49447

- **Comment**

The results show that in an isotropic reservoir with thickness so large, the advantage of the cable-cut slot over vertical/horizontal well is moderate. (Reference vertical well is perforated all 4000 ft and rw = 0.3 ft .
Reference horizontal well is drilled and perforated all 4000 ft and rw = 0.3 ft .)

N1 B Large thickness, Vertical anisotropy

```
In[189]:= resbox = {4000, 2000, 4000, 1, 1, 0.1};

In[190]:= hl = {25.1, 89.5, 177.6, 283.4, 395.4, 510.6, 601.5, 612.8, 494.8, 201.4};
dw = {0, 25, 115, 292, 595, 971, 1482, 2083, 3211, 3392};
db = {9073, 9227, 9400, 9559, 9661, 9651, 9454, 8985, 8168, 6961};
onevec = 1 + 0 hl;

In[194]:= cx = dw + hl / 2; cy = 1000 onevec; cz = 10 000 - db + 30;
wx = hl / 2; wy = 1 / 12 onevec; wz = 30 onevec ;
sources = {cx, cy, cz, wx, wy, wz}';
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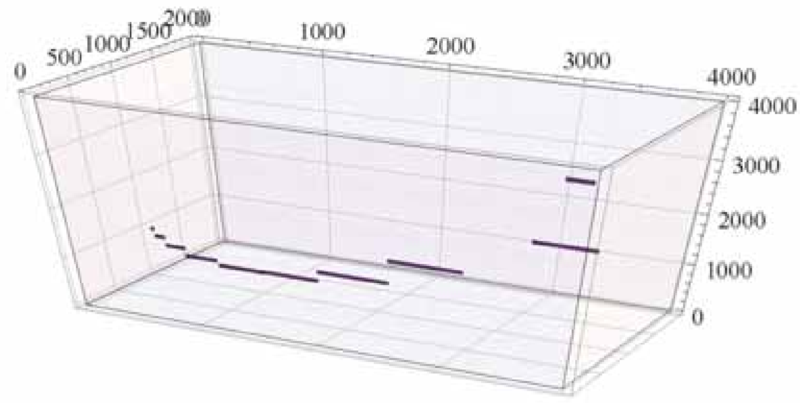
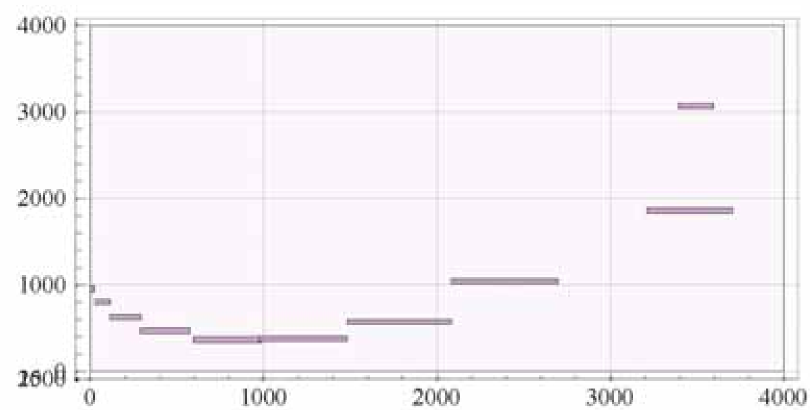
    Show[gr, AspectRatio → 1 / 2, ImageSize → 600, ImagePadding → 60] // Print;
    Show[gr, AspectRatio → 1 / 2, ImageSize → 600,
      ViewPoint → {0, -Infinity, 0}, ImagePadding → 60] // Print;
```






```
In[400]:= {Total[hl] 60, "sqft"}
Out[400]= {203 526., sqft}
```

```
In[401]:= tDTab = 10^Range[-12, 2, 1/4]; w = 1.444 0.3;

          Timing[{JDTab, kh} = MultBoxInfCond[resbox, sources, tDTab][[{5, 7}]]; JDTab // Last]
          Timing[{JDTabVertWell, kh} =
            MultBoxInfCond[resbox, {{2000, 1000, 2000, w, w, 2000}}, tDTab][[{5, 7}]];
           JDTabVertWell // Last]
          Timing[{JDTabHoriWell, kh} =
            MultBoxInfCond[resbox, {{2000, 1000, 2000, 2000, w, w}}, tDTab][[{5, 7}]];
           JDTabHoriWell // Last]

Out[402]= {12.215, 0.0637638}

Out[403]= {0.187, 0.124447}

Out[404]= {0.203, 0.0329997}

In[405]:= Grid[
            {{"Productivity wrt", SpanFromLeft},
             {"Vert well", "Hori well"}, {Last[JDTab]/Last[JDTabVertWell], Last[JDTab]/Last[JDTabHoriWell]}}
            , Frame -> All, BaseStyle -> {FontSize -> 16}] // Print
```

Productivity wrt	
Vert well	Hori well
0.512376	1.93225

- **Comment**

The results show that in an anisotropic reservoir with thickness so large, the best thing to do is to drill a vertical well.

N2 A Moderate thickness, isotropic

```
In[406]:= {(hl // Total) 60, "sqft"}

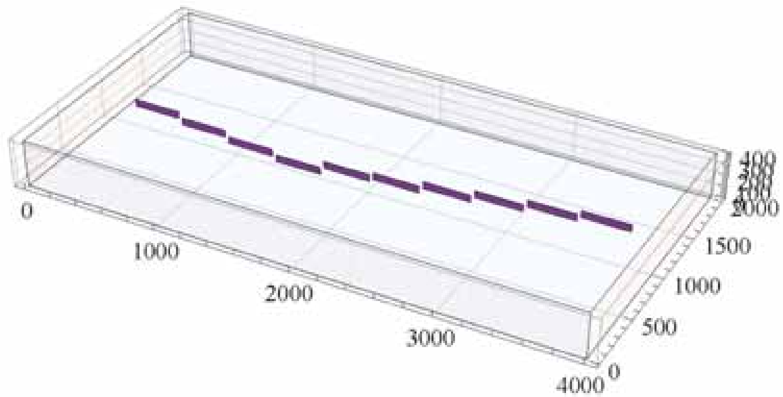
Out[406]= {203526., sqft}

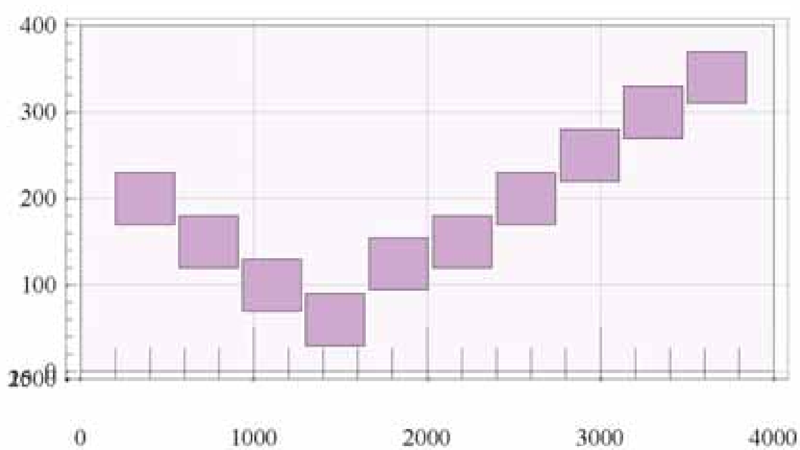
In[407]:= resbox = {4000, 2000, 400, 1, 1, 1};

In[408]:= hl = Table[340, {10}];
          dw = Range[200, 3500, (3500 - 200)/9];
          db = { 9800, 9850, 9900, 9940, 9875, 9850, 9800, 9750, 9700, 9660};
          onevec = 1 + 0 hl;

In[412]:= cx = dw + hl / 2; cy = 1000 onevec; cz = 10000 - db;
          wx = hl / 2; wy = 1 / 12 onevec; wz = 30 onevec ;
          sources = {cx, cy, cz, wx, wy, wz}';
```

```
In[415]:= gr = Graphics3D[{Opacity[0.05],
       Cuboid[{0, 0, 0}, resbox[[{1, 2, 3}]]],
       Opacity[1],
       Map[Cuboid, {{cx - wx, cy - wy, cz - wz}', {cx + wx, cy + wy, cz + wz}'}']
      }
      , Axes → True,
      FaceGrids → {{-1, 0, 0}, {0, 0, -1}, {0, 1, 0}}, {BaseStyle → FontSize → 16}];
    Show[gr, AspectRatio → 1 / 2, ImageSize → 600, ImagePadding → 60] // Print;
    Show[gr, AspectRatio → 1 / 2, ImageSize → 600,
      ViewPoint → {0, -Infinity, 0}, ImagePadding → 60] // Print;
```






```
{Total[hl] 60, "sqft"}
{204 000, sqft}
```

```
In[419]:= tDTab = 10^Range[-12, 2, 1/4]; w = 1.444  0.3;

  Timing[{JDTab, kh} = MultBoxInfCond[resbox, sources, tDTab][[{5, 7}]]; JDTab // Last]
  Timing[{JDTabVertWell, kh} =
     MultBoxInfCond[resbox, {{2000, 1000, 200, w, w, 200}}, tDTab][[{5, 7}]];
    JDTabVertWell // Last]
  Timing[{JDTabHoriWell, kh} =
     MultBoxInfCond[resbox, {{2000, 1000, 200, 1700, w, w}}, tDTab][[{5, 7}]];
    JDTabHoriWell // Last]
Out[420]= {235.92, 1.98495}
Out[421]= {2.49, 0.124504}
Out[422]= {3.464, 0.965964}
In[423]:= Grid[
    {{"Productivity wrt", SpanFromLeft},
     {"Vert well", "Hori well"}, {Last[JDTab]/Last[JDTabVertWell], Last[JDTab]/Last[JDTabHoriWell]}}
    , Frame -> All, BaseStyle -> {FontSize -> 16}] // Print
```

Productivity wrt	
Vert well	Hori well
15.9429	2.05489

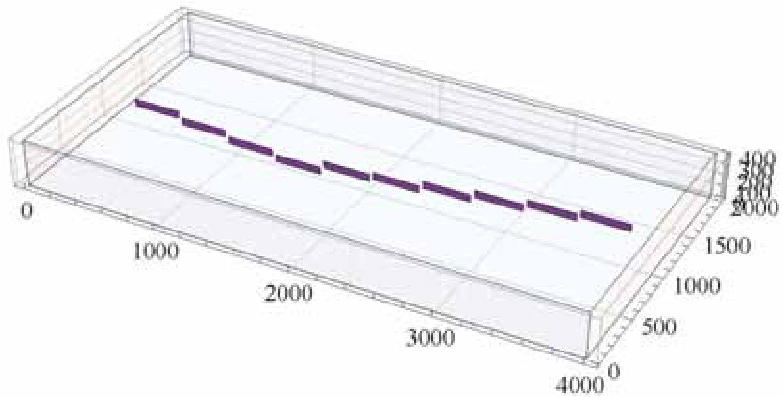
- **Comment**

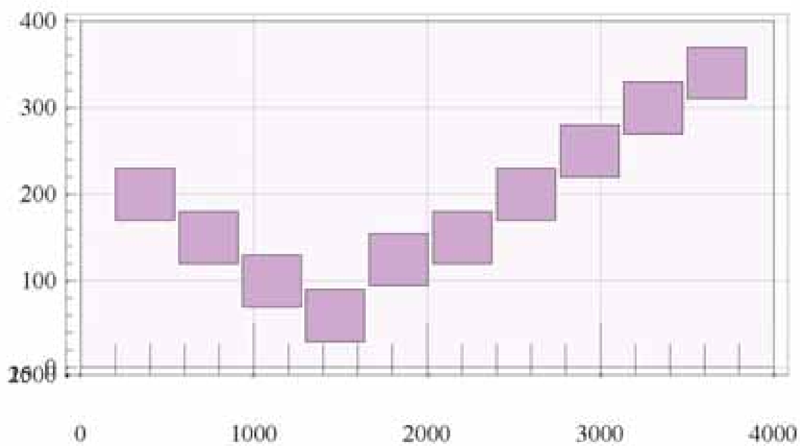
The results show that in an isotropic reservoir with thickness much less, the advantage of the cable-cut slot is enourmous wrt the vertical well and substantial wrt the horizontal well.

N2 B Moderate thickness, vertical anisotropy

```
In[424]:= resbox = {4000, 2000, 400, 1, 1, 0.1};
In[425]:= hl = Table[340, {10}];
  dw = Range[200, 3500, (3500 - 200)/9];
  db = { 9800, 9850, 9900, 9940, 9875, 9850, 9800, 9750, 9700, 9660};
  onevec = 1 + 0 hl;
In[429]:= cx = dw + hl / 2; cy = 1000 onevec; cz = 10 000 - db;
  wx = hl / 2; wy = 1 / 12 onevec; wz = 30 onevec ;
  sources = {cx, cy, cz, wx, wy, wz}';
```

```
In[432]:= gr = Graphics3D[{Opacity[0.05],
      Cuboid[{0, 0, 0}, resbox[[{1, 2, 3}]]],
      Opacity[1],
      Map[Cuboid, {{cx - wx, cy - wy, cz - wz}', {cx + wx, cy + wy, cz + wz}'}']
     }
     , Axes → True,
     FaceGrids → {{-1, 0, 0}, {0, 0, -1}, {0, 1, 0}}, {BaseStyle → FontSize → 16}];
   Show[gr, AspectRatio → 1 / 2, ImageSize → 600, ImagePadding → 60] // Print;
   Show[gr, AspectRatio → 1 / 2, ImageSize → 600,
     ViewPoint → {0, -Infinity, 0}, ImagePadding → 60] // Print;
```






```
In[435]:= {Total[hl] 60, "sqft"}
Out[435]= {204 000, sqft}
```

```
In[436]:= tDTab = 10^Range[-12, 2, 1/4]; w = 1.444 0.3;

          Timing[{JDTab, kh} = MultBoxInfCond[resbox, sources, tDTab][[{5, 7}]]; JDTab // Last]
          Timing[{JDTabVertWell, kh} =
            MultBoxInfCond[resbox, {{2000, 1000, 200, w, w, 200}}, tDTab][[{5, 7}]];
           JDTabVertWell // Last]
          Timing[{JDTabHoriWell, kh} =
            MultBoxInfCond[resbox, {{2000, 1000, 200, 1700, w, w}}, tDTab][[{5, 7}]];
           JDTabHoriWell // Last]

Out[437]= {13.9, 1.08104}

Out[438]= {0.203, 0.124497}

Out[439]= {0.234, 0.39246}

In[440]:= Grid[
            {{"Productivity wrt", SpanFromLeft},
             {"Vert well", "Hori well"}, {Last[JDTab]/Last[JDTabVertWell], Last[JDTab]/Last[JDTabHoriWell]}}
            , Frame -> All, BaseStyle -> {FontSize -> 16}] // Print
```

Productivity wrt	
Vert well	Hori well
8.68331	2.75453

- **Comment**

The results show that in an anisotropic reservoir with moderate thickness, the advantage of the cable-cut slot is more significant wrt the horizontal well.

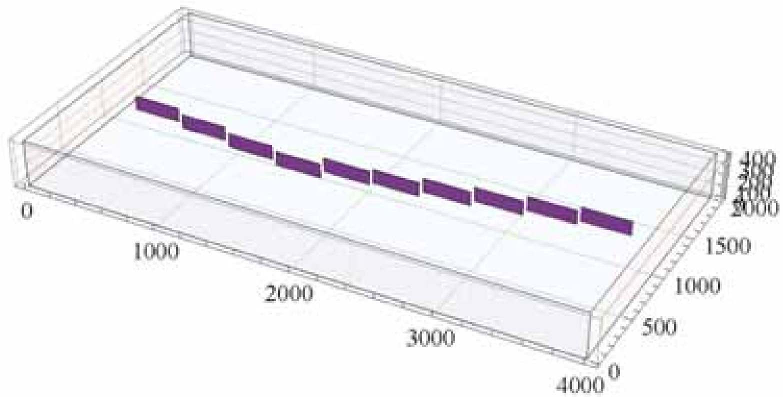
N2 C Moderate thickness, Vertical anisotropy - slot height increased to 120 ft

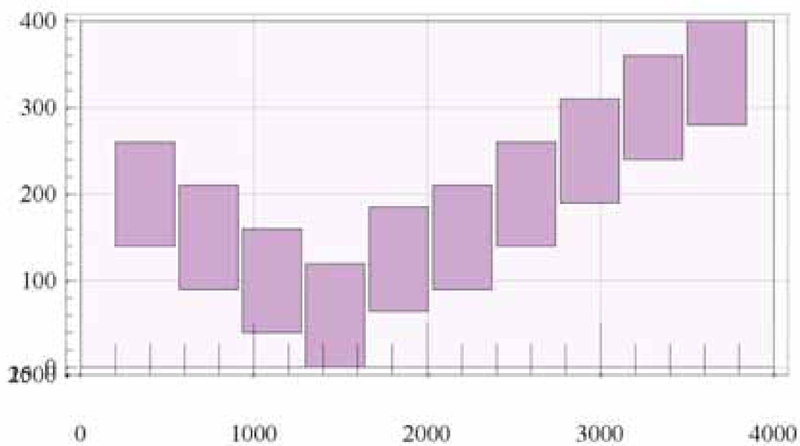
```
In[441]:= resbox = {4000, 2000, 400, 1, 1, 0.1};

In[442]:= hl = Table[340, {10}];
          dw = Range[200, 3500, (3500 - 200)/9];
          db = { 9800, 9850, 9900, 9940, 9875, 9850, 9800, 9750, 9700, 9660};
          onevec = 1 + 0 hl;

In[446]:= cx = dw + hl / 2; cy = 1000 onevec; cz = 10000 - db;
          wx = hl / 2; wy = 1 / 12 onevec; wz = 60 onevec ;
          sources = {cx, cy, cz, wx, wy, wz}';
```

```
In[449]:= gr = Graphics3D[{Opacity[0.05],
      Cuboid[{0, 0, 0}, resbox[[{1, 2, 3}]]],
      Opacity[1],
      Map[Cuboid, {{cx - wx, cy - wy, cz - wz}', {cx + wx, cy + wy, cz + wz}'}']
     }
     , Axes → True,
     FaceGrids → {{-1, 0, 0}, {0, 0, -1}, {0, 1, 0}}, {BaseStyle → FontSize → 16}];
  Show[gr, AspectRatio → 1 / 2, ImageSize → 600, ImagePadding → 60] // Print;
  Show[gr, AspectRatio → 1 / 2, ImageSize → 600,
     ViewPoint → {0, -Infinity, 0}, ImagePadding → 60] // Print;
```






```
In[452]:= {Total[hl] 120, "sqft"}
Out[452]= {408 000, sqft}
```

```
In[453]:= tDTab = 10^Range[-12, 2, 1/4]; w = 1.444  0.3;

          Timing[{JDTab, kh} = MultBoxInfCond[resbox, sources, tDTab][[{5, 7}]]; JDTab // Last]
          Timing[{JDTabVertWell, kh} =
            MultBoxInfCond[resbox, {{2000, 1000, 200, w, w, 200}}, tDTab][[{5, 7}]];
           JDTabVertWell // Last]
          Timing[{JDTabHoriWell, kh} =
            MultBoxInfCond[resbox, {{2000, 1000, 200, 1700, w, w}}, tDTab][[{5, 7}]];
           JDTabHoriWell // Last]

Out[454]= {14.024, 1.4561}

Out[455]= {0.203, 0.124497}

Out[456]= {0.234, 0.39246}

In[457]:= Grid[
            {{"Productivity wrt", SpanFromLeft},
             {"Vert well", "Hori well"}, {Last[JDTab]/Last[JDTabVertWell], Last[JDTab]/Last[JDTabHoriWell]}}
            , Frame -> All, BaseStyle -> {FontSize -> 16}] // Print
```

Productivity wrt	
Vert well	Hori well
11.6959	3.7102

- **Comment**

The results show that in an anisotropic reservoir with moderate thickness, the increase in slot height has an additional advantage.