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Effective Secondary Recovery Stimulation Using Solid Propellant Technology for Tight Sand Development in Sirikit Oil Field, Thailand

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Abstract

The Sirikit Field, a mature onshore field operated by PTTEP in northern Thailand, derives production from sandstone reservoirs. While production from many of the shallow pays have been well-developed and optimized, comparatively few of the deeper and tighter sands have been similarly produced. Various methodologies have been trialed to enhance production from these tight sands and an examination of results will be presented in the context of geology, engineering and economics.
This field, like most in the world, was produced initially by primary recovery (natural flow and various artificial lift mechanisms). Later in the development phase, secondary recovery (waterflooding) was implemented in the Sirikit Main area with the aim of improving production from the shallower, higher permeability, reservoirs. The deeper, lower permeability, sands have not undergone secondary recovery. It is foreseen that the vast majority of STOIIP can be extracted from these tight sands and will ultimately be the future of Sirikit long term production.

Several secondary recovery methods were evaluated. Waterflooding was ruled out as an option due to poor reservoir properties which were not favorable for flooding displacement as well as a high injection pressure requirement. The focus then became well stimulation as the main strategy to enhance production from these tight reservoirs. Initial well stimulation technology was the use of larger size perforation guns for the low porosity sands in order to improve reservoir penetration and overcome damage zones. Analysis after field trials showed that the deep penetration perforations had insignificant production improvement. Consequently, solid-propellant technology, which is capable of creating near wellbore fractures, was field trialed. Two types of solid-propellant were tested: "regressive" burning propellant and "progressive" burning propellant. The "regressive" burning propellant results were inconclusive; however, the "progressive" burning propellant results showed clear improvements in production. Moreover, in order to create deeper fractures, "hydraulic fracturing", which requires higher investment, was tested in parallel to the smaller scale investment perforation guns and solid-propellant; however, the results were no better than the "progressive" burning propellant. Consequently, the "progressive" burning propellant provided the positive results at the best economics.

Different well stimulation technologies may be appropriate for varying geologic, engineering and economic conditions. For tight or damaged reservoirs, progressively burning propellant may prove to be the most efficient and cost effective technology for secondary recovery.

Solid Propellant Technology

In the industry, there are generally three main methods of stimulating a well with pressurization: explosives, hydraulic fracturing, and solid propellant. The first two are common where explosives are the general perforation guns use while the hydraulic fracturing had been implemented in some candidate wells since 2012. For the last one, solid propellant, it is considered to be an interesting method for this field. This solid propellant here is fundamentally military derived technology which has been applied in oil and gas industry for over 40 years. The concept is that the propellant burning rates and pressure-time profiles are different from the explosives and hydraulic fracturing, so that it can create multiple fractures that are not governed by in-situ stresses. It is claimed that the propellants will not be detonated, but will be progressively burned at the designed rates so that the rock will be in tension rather than compression and at sufficiently rapid rates that single bi-wing fracture cannot hold all the high pressure gas and multiple fractures are generated, see **Figure 1**. The pressure-time profile which is different from the explosive and hydraulic fracturing is shown in **Figure 2**.

There are several applications of this propellant technique ranging from by-passing the skin or damage zone, pre acid job improvement, and several other useful applications. However, in this paper, it is aimed to not only by-pass the damage zone but also enhance the permeability around the wellbore.

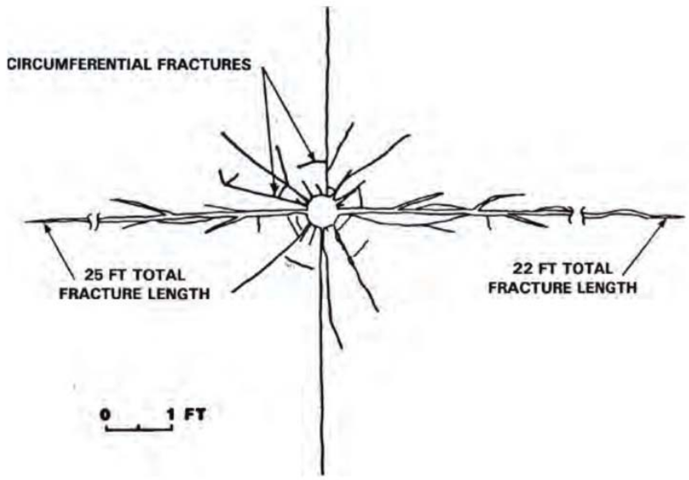

Figure 1: Typical fracture pattern produced by "Progressive" burning propellant gun in underground experiment (Reference: *www.thegasgun.com*)

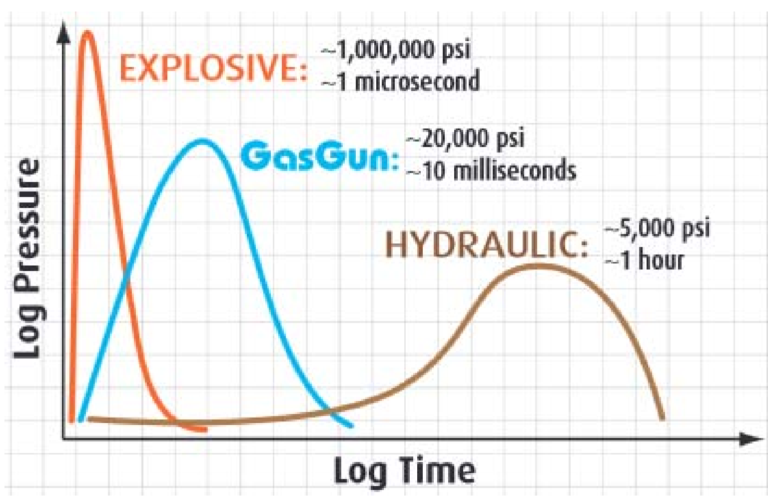

Figure 2: Pressure time profiles of three stimulation methods (Reference: *www.thegasgun.com*)

The "progressive" solid-propellant technology was developed by Sandia National Laboratories' scientists back in 1970s. It was later implemented in several actual field operations and the most common applications in oil and gas industries are shown below.

Applications	Descriptions
Close Water Contact	- Minimal Fracture Growth - Fractures stay in pay zone
Horizontal well	- Cost effectively stimulate long interval - Minimal onsite equipment - Environmentally friendly
Injection well	- Increase injection and withdrawal rates - Bypass nearbore damage

	- Reduce injection pressures
Naturally Fractured	- Significantly improve formation drainage - Multiple fractures intersect natural fractures
Nearbore Damage	- Remove skin from perforators, drilling, cement, etc - Fractures created at every perforation tunnel
Open Hole	- Zone isolation achieved without packers - No adverse effects to borehole integrity - Fractures not dominated by earth stresses
Pre-acid	- Improve effectiveness of spotting acid - Break down formation/reduce treating pressures
Pre-Frac	- Reduce tortuosity & resulting screen-outs - Break down formation/reduce treating pressures

Reference: *www.thegasgun.com*

The gun sizes selected to be applied during trial phase are 3-3/8” and 2” gun system. The smaller size gun will be applied with the existing wells as it needs to be able to pass through 2 7/8” tubing restriction while the bigger size gun will be used with on-rig perforations before the completion of production tubing.

Note that 4” gun is one of the gun sizes that is suitable for on-rig perforation as it is the appropriate gun size for 7” casing which is the normal casing size this field. However, due to very high cost and its weight which will require higher trips for the run, it was decided to be neglected from this trial phase.

Figure 3: 2” Gun, 3.375” Gun, and 4” Gun (Reference: *www.thegasgun.com*)

The ”progressive” burning propellant gun tool is fired in the same manner as perforating guns, and complies with The American Petroleum Institute’s Recommended Practices for Oilfield Explosives Safety (API RP-67), and company policies and procedures for explosive safety.

Well Candidate Screening and Tool Size Selection

According to the inconclusive results of the first trial on "regressive" burning propellant in 2014 and the recommendations that another solid propellant gun trial should be performed in the areas with available flowlines and artificial lifts, candidates in flowstation were, therefore selected, the workflows for candidate screening as illustrated in **Figure 4**

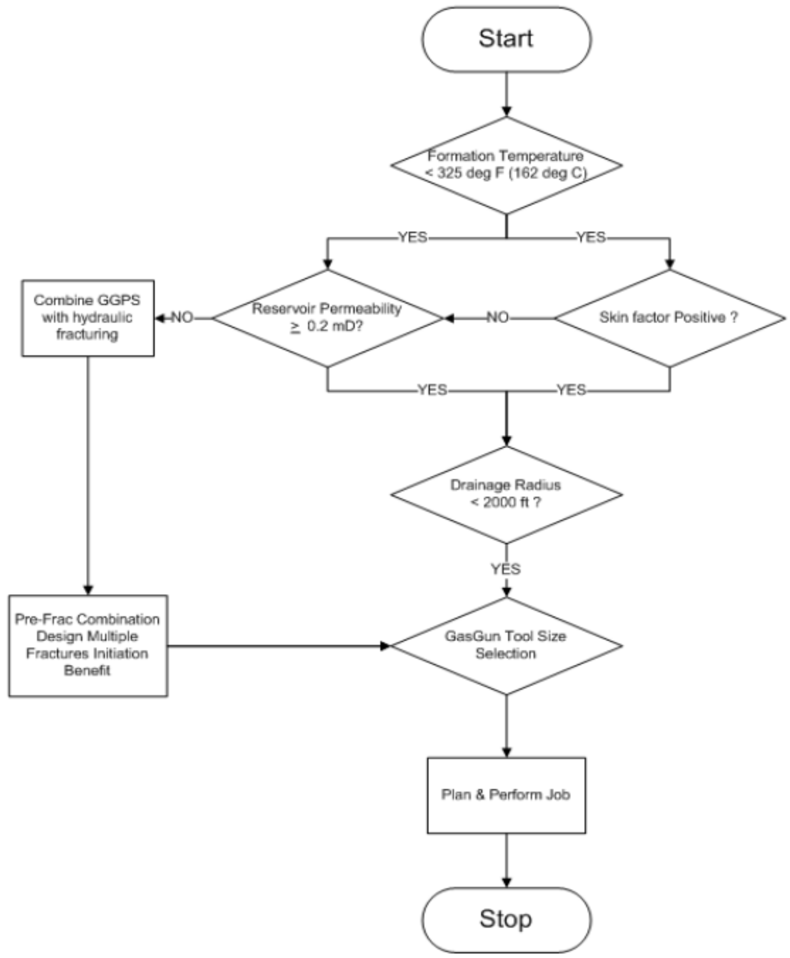

Figure 4: Screening workflow for candidate selection

Table 1 summarizes general information of five selected candidates for this trial phase.

Well Name	Well#A	Well#B	Well#C	Well#D	Well#E
Well type	New well	New well	New well	Existing well	Existing well
Casing x Hole sizes, inches	7"x8-1/2"	7"x8-1/2"	7"x8-1/2"	7"x8-1/2"	7"x8-1/2"
Formation	P	L	L	P	M
Depth, mTVDss	1,906	2,950	2,876	1,841	2,244
Porosity, %	13	9	10	14	19
Permeability, mD	2.56	0.16	0.2-1	12.8	1.7
Bottomhole temperature, degC	98	123	118	101	109
Bottomhole pressure, psi	2,253	4,700	4,570	2,240	4,140

With the applications of progressive burning propellant gun, it is expected to mainly reduce skin factor around wellbore and increase nearby well permeability caused by mini-fracturing; therefore, it is planned to be executed in low permeability reservoirs to enhance the oil production in these tight sands. The proposed treating intervals for individual wells were initially determined based on petrophysical results using porosity cut-off or using VShale cut-off. However, the actual treating intervals were slightly different from the proposed ones because of the limitation in the length of gun carriers and the optimization in the wireline run.

Given workflow for gun size selection as shown in **Figure 5**, there are two sizes of progressive burning propellant gun considered at this stage; 3-3/8" and 2" where the bigger size will be utilized on-rig and will be applied to the newly drilled wells or workover wells while the smaller size of 2" will be practical for the existing wells without workover. The first batch is the 3-3/8" GasGun where they were performed on 3 wells, Well#A,Well#B,and Well#C during early November 2015. The second batch is the 2" GasGun which were done in Q1 and Q2 2016 on two wells which are Well#D and Well#E. Most of the well candidates are all in the main production area except Well#C which is in theremote area.

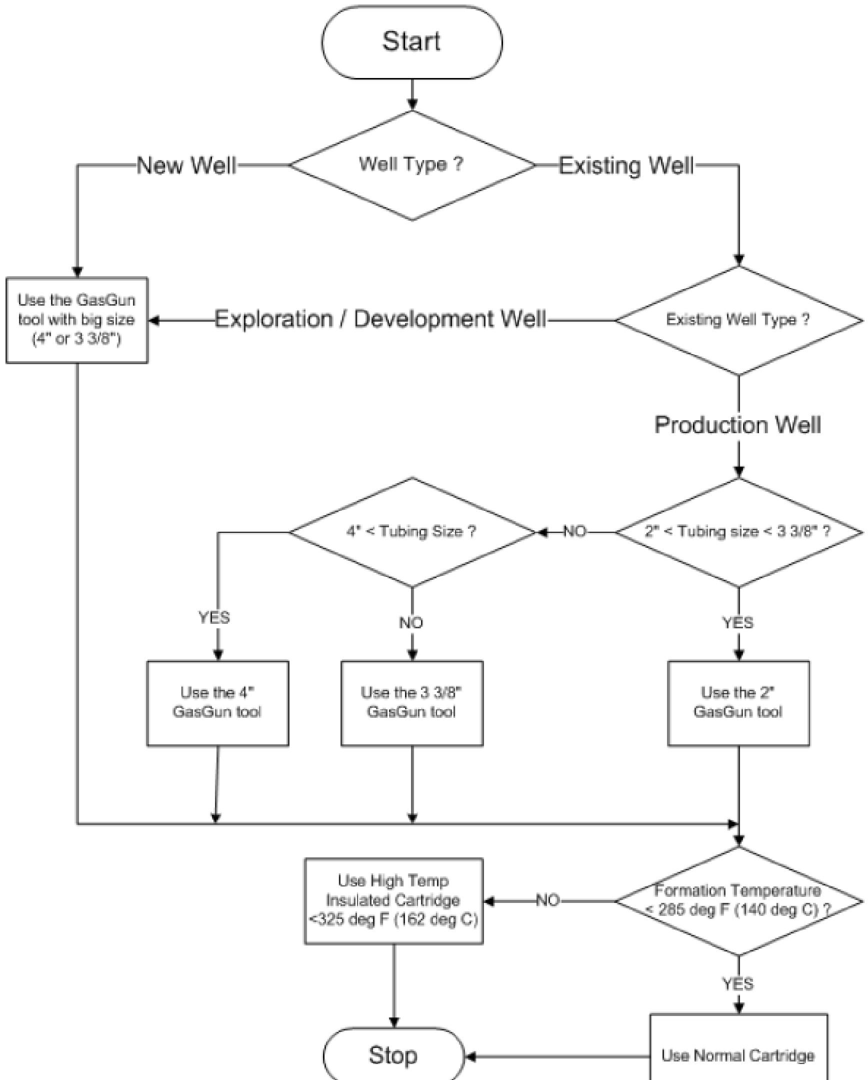

Figure 5: Workflow for gun size selection

In order to determine the economic benefit of the pilot project, the production improvement was studied. Firstly, the pre-fracture estimate (PFE) workflow as shown in **Figures 6 and 7** was carried out to determine fracture length and PI improvement using the latest AI algorithms for predictive analytics.

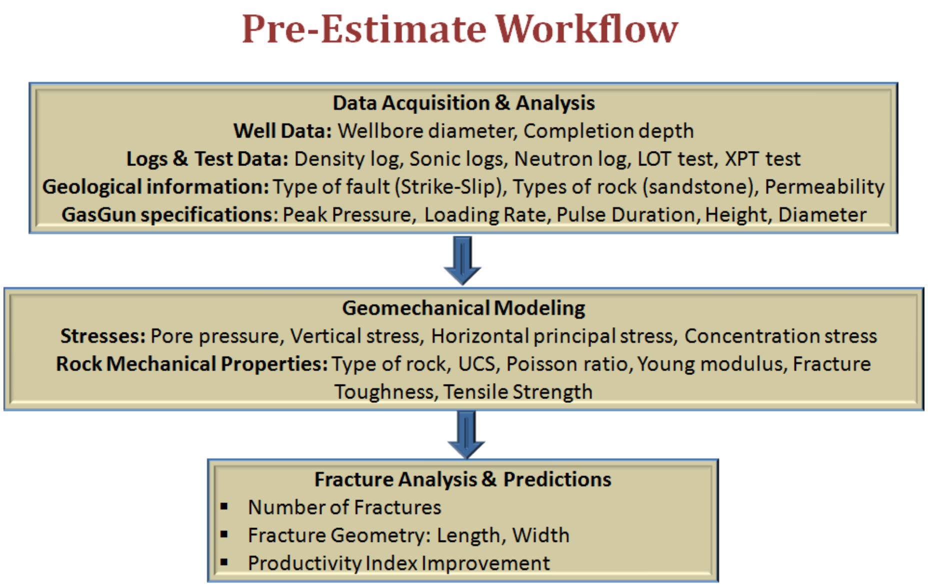

Figure 6: Workflow for pre-fracture estimation

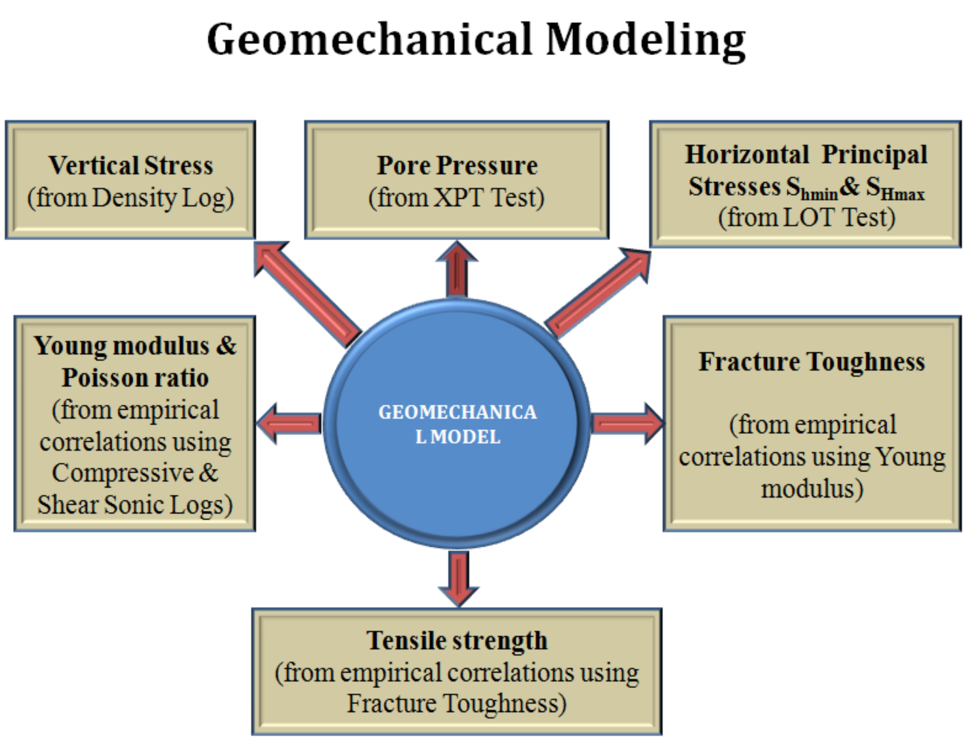

Figure 7: Geomechanical Modeling

The geomechanical data required for pre-fracture estimation was provided as shown in **Table 2**. Since most of data properties were not available, empirical correlation was used to estimate these properties with much less reliable results. Minimum horizontal and maximum horizontal stress values were determined from formation leak-off test (LOT) at a specific depth in the well. Young's modulus and Poisson ratio were calculated based on sonic log of Well#A using empirical formulas. Fracture toughness was calcualted from empirical correlation using Young's Modulus of Well#A. Tensile strength was calculated from empirical correlation using Fracture toughness of Well#A. These three estimated values were also used for the other well candidates, if not available.

Table 2: The geomechanic data of selected candidates used in pre-fracture estimation (PFE)

Well Name	Well#A	Well#B	Well#C	Well#D	Well#E
Minimum Horizontal Stress, psi	5442	6805	5944	5256	No PFE conducted for this well since 2" GasGun was provided by Vause
Maximum Horizontal Stress, psi	9897	10700	6844	9559	
Pore Pressure, psi	2715	4600	4570	2683	
Young's Modulus, MPa	18000	18000	18000	18000	
Poisson ratio	0.27	0.27	0.3	0.27	
Fracture toughness (Mpa.m$^{1/2}$)	0.25-1.1	0.25-1.1	0.25-1.1	0.25-1.1	
Tensile Strength (Mpa)	3.19-7.75	3.19-7.75	3.19-7.75	3.19-7.75	

Finally, fracture analysis and prediction was using simulation software of high energy gas fracturing with MATLAB The main input data in the software consisted of well characteristics (wellbore, perforation depth),gun specifications (peak pressure, loading rate,height,diameter), reservoir characteristics (reservoir permeability, reservoir radius), geomechanical characteristics (minimum and maximum horizontal stresses, pore pressure),and rock properties (Young's Modulus, Poisson ration, tensile strength, fracture toughness, bulk density). Artificial intelligence algorithms were established to intelligently predict future outcomes. **Table 3** shows example of pre fracture estimation (PFE) results on Well#A. There are three cases (Worst, Medium, and High) for two different gun sizes (2" and 3-3/8"). The 3-3/8" gun can improve the PI between 3.44 – 5.14 times with fracture length of 3.73 – 7.66 meters. For the 2" gun, the PI improvement ranges from 2.55 – 3.80 times with 1.96 – 4.51 meters fracture lengths. The example of estimated fracture geometry using 3-3/8" gun for worst case scenario is illustrated in **Figure 8**.

Table 3: Pilot Pre-Estimation Results of Well#A

Case	Fracture Toughness (Mpa.m-1/2)	Tensile Strength (MPa)	Fracture Length (m)		PI Improvement J_{after}/J_{before}	
			Gun size 3.375 in	Gun size 2 in	Gun size 3.375 in	Gun size 2 in
Worst case	1.10	7.75	3.73	1.96	3.44	2.55
Medium Case	0.68	5.50	4.84	2.68	3.95	2.93
High Case	0.25	3.19	7.66	4.51	5.14	3.80

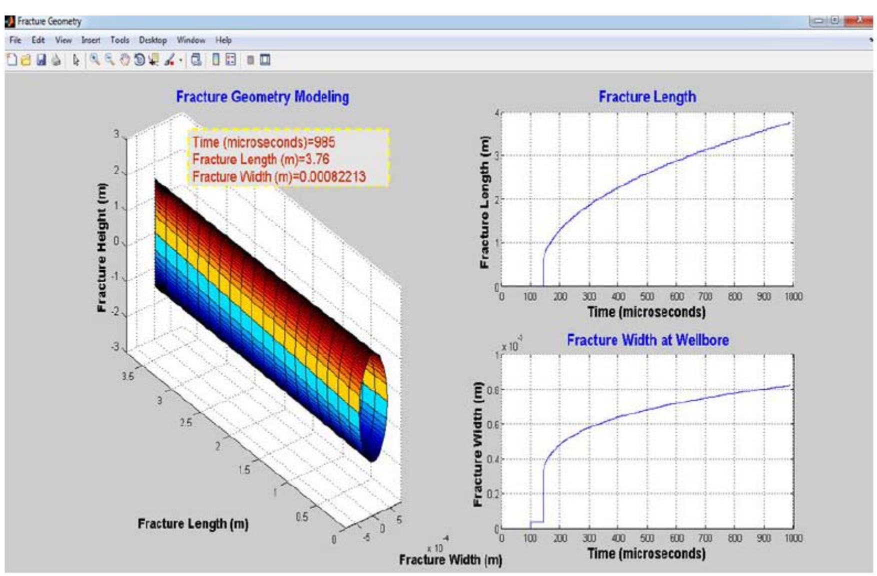

Figure 8: Simulation of High Energy Gas Fracturing with MATLAB

Table 4 shows sensitivity of permeability of reservoir properties on the PI improvement. The sensitivity shows that the permeability plays an important role on the PI improvement. The lower permeability formation tends to have higher PI improvement.

Table 4: Sensitivity Study for permeability of Well#A

k (mD)	PI Improvement J_{after}/J_{before}
0.01	**4.38**
0.05	**4.36**
0.1	**4.35**
0.5	**4.23**
1	**4.09**
5	**3.39**
10	**2.96**
50	**2.22**
100	**2.06**

- **Gun size: 3.375 in**
- **Medium case**

Secondly, Nodal analysis commercial software was also used to simulate the advantage of progressive burning propellant gun and compare with the result of pre fracture estimation (PFE). However, due to the limitation of the software, the effect of progressive burning propellant gun was assumed to help increase the perforation penetration. Therefore, the Karakas and Tariq skin model was selected to simulate the effect of long perforation penetration. The fracture length is one of inputs in the model. In addition, Cinco/ Martin-Bronz model was used to model additional skin from deviation/ partial penetration. Then the production rates and well productivity index (PI) improvement factors are calculated using Nodal analysis commercial software and cross-checked with the numerical network model. Then the calculated initial rate was use to estimate reserves using decline curve analysis (DCA) concept, with decline rate analog from nearby producing wells. Finally, reserves from progressive burning propellant gun cases are used to calculate the incremental Net Present Value (NPV).

Excluding progressive burning propellant gun effect, the production rates of normal perforation gun cases were estimated using two skin model assumptions which are entering skin by hand and Karakas and Tariq model. For stimulation cases, there are two cases which are 2” and 3-3/8” guns. By using Karakas and Tariq skin model, the production rates can be calculated and all calculation results are shown in **Table 5** below.

Table 5: Production Gain Estimation and Economic Analysis of Well#A

Case	Skin Model	Penetration Length (m)	PI (STB/d/psi)	PI Improvement	Liquid Rate (BPD)	Reserves (MSTB)
3-3/8” Normal Gun	Karakas+Tariq	0.508	0.0609		73	10.93
2” GasGun	Karakas+Tariq	2.68	0.0827	1.359	98	14.71
3-3/8” GasGun	Karakas+Tariq	4.84	0.1040	1.708	122	18.31

Field Operational Trial Results

The operations started in Q3 2015 and lasted to Q2 2016. 1st batch wells were perforated with normal guns and then followed by progressive burning propellant gun before production and well tests were performed. Important parameters such as Skin and Kh were obtained from Flow Build Ups (FBUs) and Pressure Transient Analyse (PTA). Only Well#B was unable to unload the well after several attempts, so the welltest was cancelled. Moreover, Well#A showed an undesirable performance after a long shut-in for FBU, which was suspected to be due to the closing of created multilateral fractures. As a result, 2nd batch wells approaches were planned differently. As the wells are existing wells and were put on production before progressive burning propellant gun were later perforated. The production tests are possible both before and after progressive burning propellant gun perforations. Team, then, planned the well tests in order to avoid the unappealing performance due to closing fractures, and secondly, to obtain Skin and kh of formation.

The first batch of the trail with 3-3/8” gun, the 3 new wells showed both positive and negative results. Well#A and Well#C showed the appealing performance with 4.5 and 1.6 Fold of Increase (FOI), respectively. Both of these wells, the flow build-up (FBU) tests were done and Pressure Transient Analyses (PTA) were interpreted. Conversely, Well#B showed unsuccessful effort to enhance the performance by progressive” burning propellant gun. The formation is believed to be very tight confirmed by Fast Gauge and fractures are not anticipated to be created.

The second batch, 2” progressive burning propellant gun, the results are positive in both wells. The performance comparison strategy is that the production tests and Pressure Transient Analyses (PTA) were performed before to identify the necessary reservoir parameters such as original permeability and skin. Then, later the wells were perforated by progressive burning propellant gun followed by production tests. The production tests after would be used to identify new permeability and/or skin.

Table 6 summarizes the production performance of both sets of wells including the initial gain. The final results shown in the table below show a range of FOI from zero to 4.5 times. The FOIs in the new wells (1st batch) tend to be higher than the existing wells (2nd batch). This could be due to the larger gun size and the less depleted reservoirs.

Table 6: Summary of Production Performance

Production	1st batch	1st batch	1st batch	2nd batch	2nd batch
Well Name	**Well#A**	**Well#B**	**Well#C**	**Well#D**	**Well#E**
Formation	P	L	L	P	M
GasGun Size, inch	3 3/8"	3 3/8"	3 3/8"	2"	2"
Estimate conventional, bpd	73	68	66	125	42
Actual Gas gun, bpd	300	3	105	167	53
Difference, bpd	234	-65	39	42	11
Fold of Increase, times	**4.5**	**Nil**	**1.6**	**1.3**	**1.3**

To evaluate the performance of progressive burning propellant gun application, pressure data measured during and after the job was required. In order to observe and verify on the created and extended fractures, the FastGuage with high resolution of pressure and temperature was installed at the bottom most of the Gun carrier to detect the pressure behavior generated during perforation. It should be noted that there are many variables that influence the measured pressure and also the actual pressure generated by the GasGun system. Examples include reservoir permeability, porosity, and rock stresses. There are variables that change with each run and cannot be easily measured such as tool length, skin damage at each perforation, exact positioning of the gun relative to the perforations (+/- error in wireline placement of tool across perforations), gun orientation relative to the perforations, and other items. **Figure 9** shows an example of pressure-time profiles during perforating progressive burning propellant gun on Well#A.

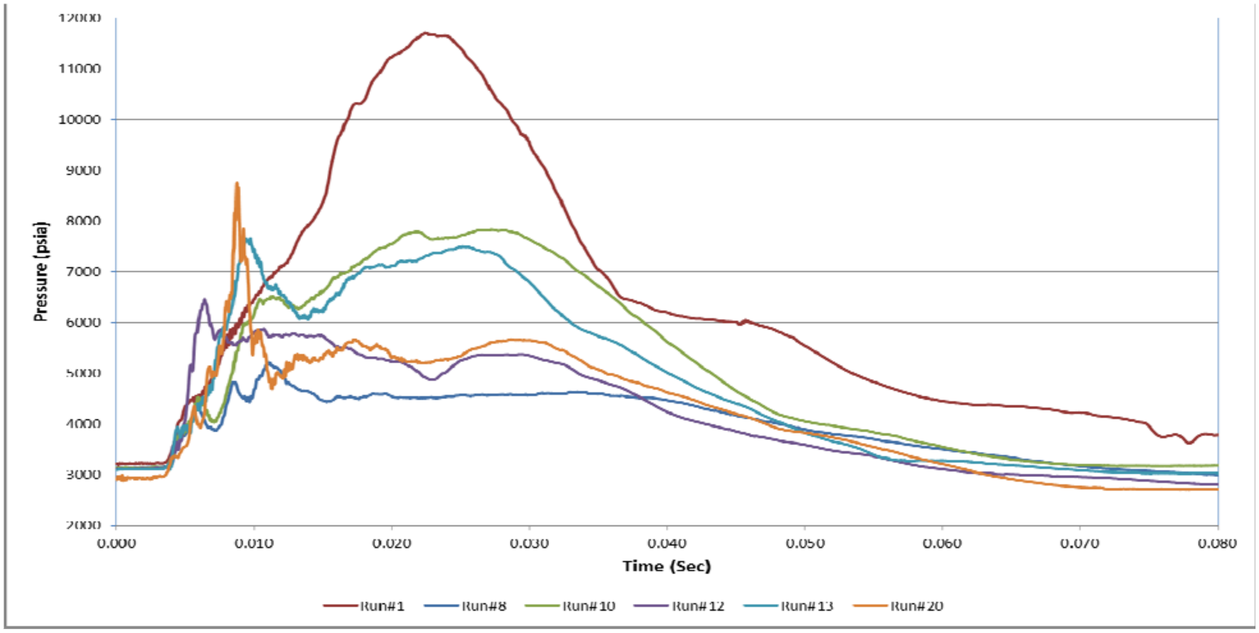

Figure 9: Well#A Pressure-Time Profile

Regarding the generated pressure, it is clearly shown that progressive burning propellant gun is capable of generating sufficient pressure to fracture the formation; maximum generated pressure was 11,713 psi. That pressure could be sustained for 20-35 milliseconds which is higher than theoretical figure of 10 milliseconds. Run #1 represented the first run of the job program and the deepest of the runs. Compared to subsequent runs including Runs #8, #10, #12, #13, and #20, we observe the following: 1.) Multiple fracture generation signatures represented by the rise and fall of the initial pressure profile; 2.) No peak pressure at the earliest stage of all runs which is consistent to the expected pressure profile shape that allows no damage to the casing or formation; 3.) Higher peak pressures for the runs that are deeper in general (this is also related to the specific rock stresses and properties of the particular rock at the particular depth), but in general we are seeing the deeper formation showing a higher peak pressure correlating to higher stresses on the rock for being deeper. With different runs, different fracture pressures are observed and this implied that in general there will be higher peak pressures with the deeper runs.

Table 7 summarizes the result of Fast Gauge measurement on all 5 candidates. For the well with high initial wellbore pressure prior to gun detonation, i.e. Well#B and Well#C, the peak pressure during the propellant burn is also high. The required breakdown pressure has a noticeable effect on the peak pressure. The higher the breakdown pressure is, the higher peak pressure is. With the highest peak pressure observed, it indicated that the formation in Well#B is significantly tight compared to those of the other well candidates. Moreover, time of wellbore breakdown occurring since the propellant combustion begins until high pressure discipates was clearly observed to be longer in 3-3/8" than 2" gun type due to more propellant loaded and narrower annular spacing between gun and casing. The average fracture length obtained from post fracture analysis (PFA) after calibrated burning fracture propagation equations against Fast Gauge data was somewhat consistent to one from pre fracture estimation (PFE).

Table 7: Result of Fast Gauge measurement on all candidates.

Production	**1st batch**	**1st batch**	**1st batch**	**2nd batch**	**2nd batch**
Well Name	**Well#A**	**Well#B**	**Well#C**	**Well#D**	**Well#E**
Peak Pressure, psi	5,200 – 11,700	12,800 – 28,800	8,900 – 9,400	2,000 – 3,800	3,600 – 4,200
Time of wellbore breakdown, ms	20 - 35	10 – 20	10 – 20	5 – 10	5 – 10
Average fracture length, m	3.61	N/A	2.35	1.82	N/A

Pressure Transient Analyses (PTA) were performed and the result showed that the skin is likely changing, which indicates using the progressive" burning propellant gun effectively bypasses near wellbore damage but has no effect to permeability as observed on Well#D and Well#E where flow build-up pressure surveys (FBU) were conducted before and after. However, there are some uncertainties in well testing interpretation, those can be addressed as below.

- Multi-layer reservoirs and depleted reservoirs, this leads to two major uncertainties; firstly, the producing fluids are not from a single layer of reservoir. Secondly, the pressures are depleted to different degrees and some are anticipated to be below the bubble point pressure already which leads to multiphase flow in the well.
- High Gas Production (multiphase flow), as mentioned earlier, some of the sands are depleted and went below the bubble point pressure. The gas production was high and would interfere with the interpretation results.
- Progressive burning propellant gun is not performed in all perforation intervals, additionally, as only sands with permeability lower than 1 md were selected to be perforated. This means that not all sands were enhanced and we cannot distinguish the flow contribution

Table 8: Results of Pressure Transient Analysis on all 5 candidates.

Well	Permeability, md Before	Skin Factor Before	Permeability, md After	Skin Factor After	Interpreted Well Test Model
Well#A			0.13 (k outer) 2.6 (k inner)	5	Radial Composite with 12 – 15 meters inner boundary
Well#B			-	-	*Well Testing was cancelled*
Well#C			0.63-0.64	0.009-0.05	Closed Boundary
Well#D	12.9	10	12.9	5	Closed Boundary – Channel + Faults
Well#E	1.7	5	1.7	3	Use Nodal Analysis Commercial Software

In conclusion, it can be summarized as follows:

- Most of the wells show considerable gains from Progressive” burning propellant gun. The Fold of Increase (FOI) from Well#A, Well#C, Well#D, and Well#E varies from 1.3 to 4.1 times.
- Only Well#B shows no Gain. The interpreted permeability showed that it was comparatively lower than prognoses. This is considered as no gain from progressive burning propellant gun.
- With above new initial rate promotes by progressive burning propellant gun, the reserves gain are estimated. In order to accurately compare the effect of Progressive” burning propellant gun in tight reservoir, two production tests and two FBUs must be performed right before and after. Two FBUs will give us more confidence in reservoir properties and data analysis. Moreover, Gun equipment must be ready for the operation once the first FBU was completed to avoid the reservoir depletion as encountered in

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Nomenclature

APB	=	Annula program budget
EUR	=	Estimated ultimate recovery
Di	=	Initial decline rate
FBU	=	Flow and build-up
FOI	=	Fold of increase
Kh	=	Permeability-thickness product
LOT	=	Leak-off test
NPV	=	Net present value
PBU	=	Pressure build-up
PFE	=	Pre-frac estimate
PFA	=	Post-frac analysis
PTA	=	Pressure transient analysis
Qi	=	Initial rate
STOIIP	=	Stock tank oil initially in-place

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