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An Innovative Perforating Technique of Multiple Gun Sizes for Multiple Casing Sizes in Single Run

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Abstract

In certain cases, multiple production casing sizes are used across formations of the same pressure regime especially in vertical or slightly deviated wells with long pay sections. The normal perforation practice would be to use a smaller gun size to perforate the smaller lower casing section before making another perforating run with bigger gun size to perforate the upper casing. Such perforating technique not only adds cost and time to the completion program but also reduces the efficiency of the perforation tunnels due to damage caused by the completion fluids in the wellbore between the two perforation runs. In addition, underbalanced perforation can only be performed on the first perforating run. Isolation of the first zone would be required to create under-balance for the second run, thus adding cost and complexity to the operations. Furthermore, multiple perforation runs in a well tends to damage the existing perforations due to pressure surges created in the subsequent runs. These pressure surges generally pack wellbore solids into the existing perforation tunnels.

This paper describes in greater details the innovative technique of perforating with multiple gun sizes across multiple casing sizes in a single run. It discusses the engineering design and considerations involved which allows the application of this new technique safely without imposing additional risks to the perforating operation. This technique provides the operators with a viable option that is more economical and efficient compared to conventional practices of perforating across different sizes of casing using multiple runs.

The key areas of concern when designing the perforating technique with two guns sizes are the combined detonation pressures and the shock waves effects from both gun sizes on the perforation string. Both of these factors were carefully calculated for the specific environment in which the guns to be run. From these engineering calculations, a suitable gun string can be design to stand the explosive effect resulted during perforation. Based on the detonation pressure, suitable gun adaptor is designed using appropriate alloy to stand the ballistic effect during the perforation. This gun adaptor allows instantaneous ballistic transfer between the two gun sizes. The use of reactive liner perforating shaped charges also reduces the damage on the perforation tunnels as well as eliminating the limitation due to wellbore and reservoir conditions.

This innovative perforating technique of running multiple gun sizes in a single run was applied successfully in a gas well in Pakistan. The pay zone was completed with 7 in. liner and 5 in. liner. The operator was initially considering either to perforate the well using wireline conveyed perforation or using shoot and pull technique with tubing conveyed perforation with one gun sizes at a time. However, both methods involve long and costly operations. Considering all the above challenges, the new perforating technique was recommended. The perforating string consisted of 82 m of 3-1/8 in. and 91 m of 4-1/2 in. guns which were run in tandem. The overall operation only took place in 24 hours which saved the cost and rig time for the operation. The spent guns were retrieved in good condition with all charges fired. The post production result indicated excellent well productivity with total calculated skin of negative 3.

This paper makes three major technical contributions to knowledge of the petroleum industry. Firstly, it documents successful application of this technique to connect multiple gun sizes in a single run. Secondly, it describes the design considerations involved as well as the calculation required to safely design the multiple gun sizes perforation string. Thirdly, it identifies a technique of perforating multiple casing sizes without exposing the earlier perforation to risks of formation damage by shooting the entire interval in one go without having to use the smaller sized gun in larger casing size.

This novel technique ensures that the objectives of the perforation were safely met. The well production target was achieved and a new technique was proven to perforate two different casing sizes in a single run with the largest possible gun size used in each casing.

Introduction

In cased and perforated completion, the well is typically drilled and completed using uniform size liner/casing across each producing zone (Type A completion as shown in **Fig. 1**). This is the most common completion as it is the simplest with minimum cost. Unfortunately, in some exceptional cases, multiple casing sizes (Type B completion as shown in **Fig. 2**) have

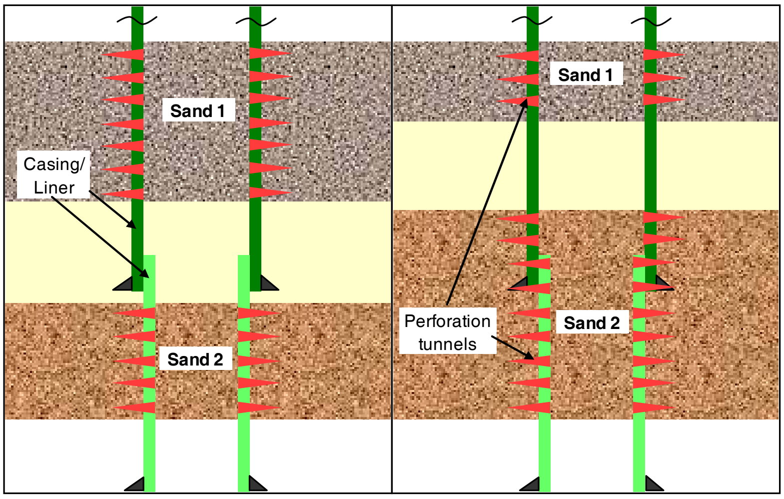

Fig. 1 – Type A Completion (Typical) **Fig. 2 – Type B Completion**

to be use to case a single zone due to formation limitations or operational complications encountered during drilling. When well is completed as Type B completion, the conventional method for perforating the zone which is cased with 2 sizes of casing/liner can either be one of the following options:

- Option 1 – Perforate lower/smaller casing section using a smaller gun size. Then on a separate run, perforate the upper/bigger casing section using a bigger gun size.
- Option 2 – Perforate both casing sections simultaneously in a single run using gun which can fit through the smallest casing size.

In Option 1, the main advantage is that the perforation tunnels geometry can be optimized by selecting the appropriate gun size which suits the casing size. Unfortunately, it requires separate run for each gun size used. This will result in additional operation time and cost to the well. Additionally, underbalanced perforation can only be done on the first perforating run. Subsequent run will require isolation of the existing perforations from the first run to create necessary underbalanced for the second perforation. This adds complexity and cost to the operation. Further complication such as to cure well losses in the initial perforation may be encountered which will not only adding cost and time but can also have detriment effect on the initial perforation due to exposures to kill fluid used. Even if without the effect from the kill fluid, the first perforation tunnels can be damaged due to the pressure surges effect from the second perforation as it will pack wellbore solids into the existing perforation tunnels.

Option 1 perforation method can be conveyed using either wireline or tubing. However, using wireline conveyance method may require more number of runs compared to tubing conveyed perforation method. In a thin layer formation with shorter interval length, wireline perforation runs may be more economical than tubing conveyed runs however the more perforation runs made the higher potential of exposing the existing perforations to potential damage from the subsequent runs as described earlier. For this reason, tubing conveyed perforation method is normally preferred to deliver more efficient perforation tunnels.

Option 2 can only be carried out using tubing conveyed perforation method. Option 2 maybe considered if the perforation intervals across the smaller casing section is much longer than the upper casing section. In Option 2, even though the perforation tunnels of the bigger casing section cannot be optimized using a bigger gun size, the operation will only require a single perforation run which will reduce the cost and operation time as well as the complexity. Potential damage to the perforation from pressure surges, kill fluid and loss control material can be minimize as compared to Option 1.

The ideal perforation solution for Type B completion is to be able to perforate in a single perforation run using multiple gun sizes suited for the each casing size. This will ensure that the perforation tunnels geometry are not sacrificed through the use of smaller size guns or through damages induced from multiple perforating runs and at the same time reducing the cost and time to the operation. The following sections of this paper will describe in details on how the innovative perforating technique of running multiple gun sizes in a single run was successfully design and applied in a field operation in Pakistan.

Technical Description

Tubing conveyed perforation is the only method that can deploy multiple gun sections and sizes in a single run. Hollow-carrier steel shaped charge gun is the type of gun mostly used when perforating with tubing. During perforation, the detonation of explosive shaped charges results in rapid emission of gas, building up rapidly to ultra-high pressures and to the generation of intense shock waves. The magnitude of detonation pressure can approach 4 x 10^6 psi which only takes place in less than 100 microseconds (Bell and Shore 1964). Only part of the energy liberated in the explosion is expended in converting the shaped-charge liner into a high-speed penetrating jet which creates the perforation tunnels; the remainder generates shock wave forces which are absorbed by the casing, gun carriers, fluid in the hole and the formation. Most of the explosive shock is absorb by the heavy-walled steel carrier rather than the casing; eliminating the risk of casing deformation (Bell and Shore 1964; Godfrey and Methven 1970).

In normal perforation gun string with single size guns, the detonation pressure and shock wave generated create forces which are distributed uniformly across the perforating string. When multiple gun sizes are used, additional offset areas (shown in **Fig. 3**) due to the difference of outer diameter (OD) of the guns will be introduced in the gun string. Even though the horizontal acting forces will be balanced similar to single size gun string, the vertical forces will be affected by the offset areas on the multiple gun size string as shown in Fig. 3. The effect of high detonating pressure and shock waves acting on the offset areas will create additional upward acting force on the string. It is critical to calculate the net lifting forces on the string to ensure that it is less than the weight of the string. This is to avoid the string from lifting upward during detonation which can create catastrophic incident.

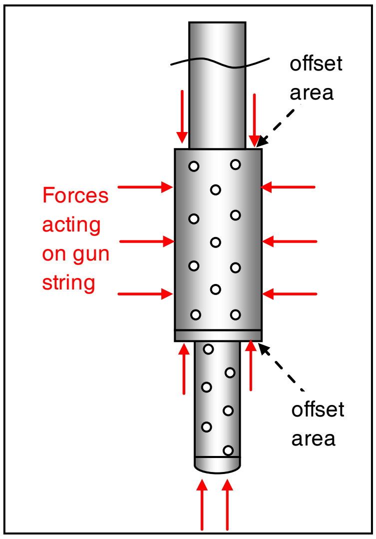

Fig. 3 – Forces acting on gun string during detonation

The net lifting force on the string is determined by first calculating all the net offset areas along the string (at each point where the OD of the tool changes) where pressure will be acting upon. Then, the product of net offset areas with the combined detonation pressure from all the charges is the lifting force acting on the string during detonation. The detonation pressure of each gun sizes is normally known from manufacture laboratory testing.

In reality, hydrostatic pressure and reservoir pressure will also contribute to the overall pressure effect acting on the gun string. However, the magnitude of detonation pressure is much higher than the hydrostatic pressure and reservoir pressure, so the combined detonation pressure from all charges is used in calculating the lifting force. Even though the detonation pressure effect will only occur in microseconds, it is used in the design calculation as a conservative approach that represent the worst case scenario when the highest lifting force may act on the string during perforation. The effect of the additional lifting forces can be reduce by increasing the weight of the major string (tubing or drill pipe section) by adding drill collars or using heavier tubing.

Once the detonating pressure and the offset areas effect are addressed, the design of adaptor which will connect the two gun sizes has to be considered. The adaptor metallurgy must have sufficient yield strength to withstand the detonation pressure and shock wave effect of the explosives. The same material used in adaptor which is used to connect same size gun sections is used. The adaptor is designed to accommodate installation of primacord and booster similar to standard gun adaptors which will allow instantaneous ballistic transfer when the firing head is activated. In this way, both gun sizes are activated simultaneously.

The effectiveness of perforating across concentric casing section is also looked at. The reduced effective penetration of the perforation tunnels in concentric casing is simulated using gun performance analysis software to ensure that the penetration depth will still be acceptable to connect to the reservoir. The perforation string is designed so that perforation will not occur at liner hanger depth to avoid from damaging it. Nevertheless, the integrity of the liner hanger prior to perforation is not a requirement to execute the multiple gun sizes technique as it will only affect the type of firing head which can be used for activating the guns.

From the operation safety standpoint, the standard precautions and procedures when running single gun size string are still applicable for the multiple gun sizes technique. The only operational limitation for this technique is that the deployment of multiple gun sizes can only be carried out in an overbalanced well condition. Underbalanced deployment of multiple gun sizes will require complex lubricator design to accommodate both gun sizes. This will add additional cost to the operation.

Since underbalance condition will add complexity to the perforation operation, reactive liner perforating system is chosen as the best shaped charge gun system for this technique as it does not depend on static or dynamic underbalance in creating clean and deep perforation tunnels. By virtue of having no crushed zone and no compacted fill, the perforation tunnels created by reactive liner perforation provide an excellent connection to the reservoir and deliver improved flow performance relative to conventional charges. This is important in achieving optimum perforation geometry and flow performance through debris-free tunnels. In addition, the reactive liner perforating technology has proven to deliver incredible perforating efficiency, superior productivity, enhance injectivity, and dramatic improvements in stimulation parameters and performance (Bell et al. 2009).

Field Application

The innovative perforating technique of multiple gun sizes for multiple casing sizes in single run was first executed in Salsabil gas and condensate field in Pakistan in Novemeber 2008. The well was initially designed to be completed with 7 in. 29 lbm/ft liner across its pay zone. Unfortunately, due to limitation of the rig's hook load during drilling operation, only half of the pay was cased with 7 in. liner. The remaining zone was further drilled with 6 in. drilling bit and cased with 5 in. 18 lbm/ft liner. The perforations intervals and the simplified well sketch are shown in **Fig.4**. The zone of interest was Chiltan limestone formation. The gross perforation interval was 306 m. The net perforation interval was 173 m with 91 m in the 7 in. liner section and 82 m in the 5 in. liner section.

		Perforation Intervals m MD	Thickness m
Chiltan Top	3200 m MD		
		3215-3218	3
		3225-3230	5
		3275-3277	2
		3281-3286	5
		3289-3304	15
		3318-3326	8
		3328-3347	19
		3351-3358	7
		3366-3370	4
		3372-3381	9
		3385-3390	5
		3399-3402	3
		3410-3414	4
		3420-3443	23
		3448-3466	18
		3470-3476	6
		3480-3495	15
		3497-3500	3
		3502-3521	19
Chiltan Bottom	3667 m MD		
		Net Perforations	173

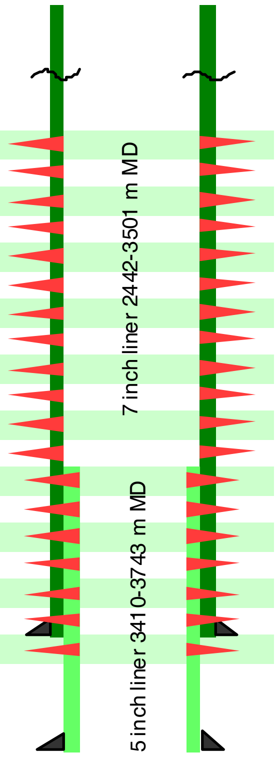

Fig. 4 – Perforation Intervals and Well Schematic

Wireline conveyed perforation method was initially evaluated to perforate Chiltan zone. Since wireline can only convey one gun or max two guns at a time, the total number of runs required will be 21-43 runs. This was estimated to take approximately 5-10 days assuming no operation complication encountered during the wireline perforation. Since the rig was already behind its schedule due to complications encountered when drilling the well, perforating for 5-10 days with wireline was not acceptable. In addition, running multiple runs perforation induced damage to the perforation tunnels.

Using conventional tubing conveyed perforation method with single gun size each run was also evaluated. Even though the number of runs will be less than wireline operation, the overall operation of running two independent perforation runs was estimated to take minimum 48 hours. Given the fact that the zone had tendency for losses after perforations, additional time may be required to cure the losses before running to perforate on the second run.

Considering all the challenges above, the new perforating technique of running multiple gun sizes string in a single perforation run was the perfect solution that would greatly benefit this well. Reactive liner shaped charge system was used in both casing sections based on the technique design consideration as discussed earlier. 4-5/8 in. diameter with 22.7 grams charges at density of 12 shot/ft (spf) and 45-degree phasing was selected to be used to perforate 7 in. liner section. 3-1/8 in. diameter with 22.7 grams charges at density of 6 spf and 60-degree phasing was used for the 5 in. liner section. Both guns sizes were evaluated to give optimum perforation tunnel penetrations depth and hole sizes. The gun swelling effect post-perforation was also verified to ensure that the guns can be used safely without any chance of getting stuck. Another added advantage was that both gun sizes carries same amount of charges (22.7 gram), which could create perforation tunnels geometry with almost similar production performance in both liner sections.

The complete gun string diagram which was used during the operation is shown in **Appendix A**. The well was filled with 8.7 lbm/gal mud to create hydrostatic cushion equivalent to 4,768 psi. Mechanical firing head activated with slickline drop bar was used to activate the perforation guns. The liner hanger of the well was unable to hold pressure during pressure test so the use of hydraulic pressure activated firing head was not possible in this application. Radioactive marker was installed for depth correlation. Accurate depth correlation was critical not only to ensure correct zone was perforated but also to ensure that guns were not position across liner hanger. Debris sub or circulation sub was installed to allow circulation in the string when required. Shoot and pull tubing conveyed perforation method was applied in this field application.

Standard perforation safety precautions were applied during the operation. Gun loading sheet diagrams were designed to ensure correct order of guns and tools were deployed. The example of the gun loading sheet is shown in **Appendix B**. The following are the deployment and perforating procedures used during the job execution.

Gun Deployment Procedures

1. Conduct pre-job safety meeting prior picking up guns.
2. Ensure the well is in overbalance condition.
3. Change to 2-7/8 in. elevator.
4. Pick up the gun 1 and run in hole. Put a 3-1/8 in. safety clamp on it and hold it with 3-1/8 in. slips.
5. Run all 3-1/8 in. guns.
6. Make up 3-1/8 in. x 4-5/8 in. adaptor to the top sub of 3-1/8 in. guns.
7. Pick up 4-5/8 in. guns and run in hole as per diagram. Use safety clamp and proper slip.
8. Pick up safety spacer, connect it to last gun, run in hole and put a safety clamp on it.
9. Connect a mechanical impact firing head assembly.
10. Connect two 2-7/8 in. EUE tubing joint, debris sub, by using 2-7/8 in. slips.
11. Connect one joint of 2-7/8 in. EUE tubing above debris sub.
12. Connect crossover to 3-1/2 in. IF box and run in hole first stand of drill collar of length 27.63 m.
13. Connect radioactive marker sub and run in hole remaining 04 stand of drill collar and 27 joints of heavy weight drill pipes as per tally.
14. Connect cross over to 3-1/2 in. PH6 tubing.
15. Run in hole 97 stands of 3-1/2 in. PH6 tubing followed by crossover to 3-1/2 in. PH6 as per string diagram and proceed with the perforation procedure.

Perforating Procedures – Shoot and Pull

1. After completing running in hole with tubing, performs Gamma Ray CCL depth correlation and space out.
2. Rig up flow head and slick line pressure control equipment.
3. Start running in hole with slick line with 1.25 in. drop bar. Tag debris sub and then tag firing head and jar down to fire the guns.
   Note:
   - Stop trip tank running before firing the guns and check the wellbore level after firing the guns to get loss or gain after firing.
   - Monitor tubing annulus pressure for any loss or gain during operation.
   - Keep 50 psi pressure in the system to confirm the firing of the guns as well as to minimize shock waves impact.
4. Observe well and pull out slickline to surface.
5. Rig down slick line equipments.
6. Continue to observe well behavior. Reverse circulate one tubing volume. Observe the well and pull out of hole perforation string.

The entire perforation operation only took place in 24 hours which was less than conventional tubing conveyed perforation with single size gun runs or wireline perforation. This novel technique saved the cost and rig operation time as anticipated. Once the perforation gun string was pulled out of hole, the spent guns were inspected to be in good condition with all charges fired. Furthermore, the post production evaluation revealed total skin of negative 3 with estimated absolute open flow of 60 MMscf/D which was 3 times more compared to adjacent well from the same formation. It was believed the excellent well productivity was contributed by the use of reactive liner perforating technology combined with the multiple gun sizes enabling largest gun OD to be run in single run perforation technique which minimize the possibility of damaging the perforation tunnels.

Lesson Learned and Recommendations

Even though it is not common to encounter well completion Type B (Refer to **Fig. 1**) where perforation interval of the same formation run across two different sizes of casing, the current conventional perforation technique can easily be improved using multiple gun sizes string by applying proper design consideration and calculation as described in earlier sections. The successful application of the technique of running multiple gun sizes in single perforation run proved that this technique can be done without imposing additional cost and complexity to the conventional operations. In fact, the added advantage of creating clean and undamaged perforation tunnels is something which every operator desires for their wells.

The used of reactive perforation shaped charge reduces the limitation of the multiple gun sizes perforating technique as it eliminate the concern on wellbore and reservoir conditions which normally will affect the perforation performance of conventional charges.

Conclusions

The introduction of new perforating technique of multiple gun sizes for multiple casing sizes in single run offers an improved perforating technique compared to conventional perforation run using single size gun. The advantage of the technique not only saved cost and time to the perforating operation but also minimized the damaged induced to the perforation tunnels. Proper design considerations such as calculating the effect of detonation pressure and shock waves on the string, selecting suitable material for adaptor that allows simultaneous end-to-end detonation of both gun sizes, and choosing the proper type of shaped charge gun should be made prior to applying this technique. The field application proved that this technique can be done safely and successfully.

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Nomenclature

BHA	*bottom hole assembly*
CCL	*casing collar locator*
in	*inch*
lbm/ft	*pound per foot*
lbm/gal	*pound per gallon*
m	*meter*
MD	*measured depth*
MMscf/D	*million standard cubic feet per day*
OD	*outer diameter*
psi	*pound per square inch*
RA	*radioactive*
shots/ft	*shots per foot*
spf	*shots per foot*
TCP	*tubing conveyed perforation*

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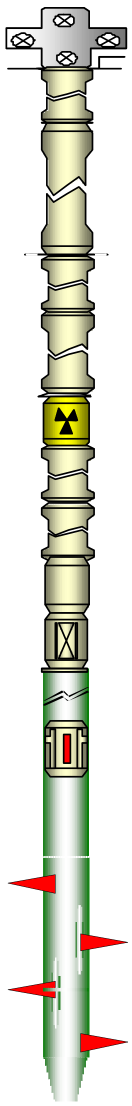
Appendix A

TCP SHOOT & PULL STRING DIAGRAM

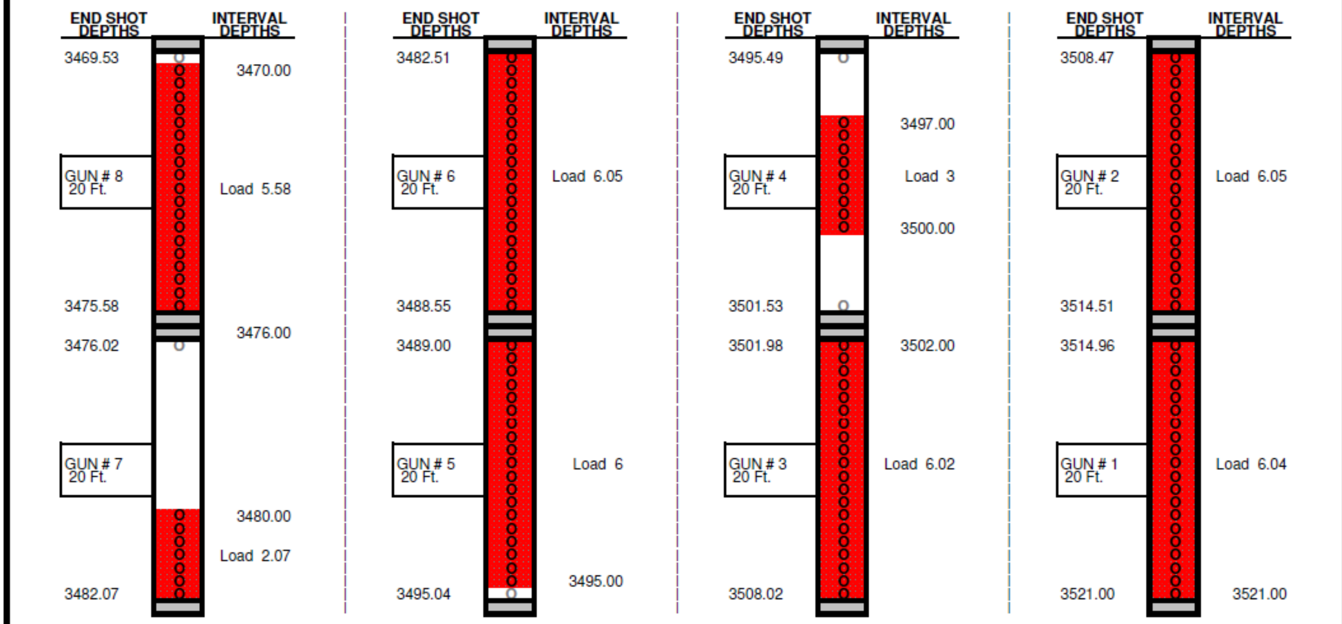


Description	O.D.(in.)	I.D.(in.)	Box	Pin	Length (m)	Depth (m)	Depth (ft)
Flowhead	****		****			-0.24	-1
Cross Over	3.50	2.765	3-1/2 in. IF	3-1/2 in. PH6	0.240	-0.24	-1
3.5 in. PH6 Tubing up to surface (97 Stands + One single + 0.82 m Pup Joint)	3.50	2.765	3-1/2 in. PH6	3-1/2 in. PH6	2792.755	0.00	0
Cross Over	5.00	2.2	3-1/2 in. PH6	3-1/2 in. IF	0.330	2792.76	9163
4-3/4 in. Drill Collar (4 stands) + 27 Joints of Heavy weight drill pipes	4.75	2	3-1/2 in. IF	3-1/2 in. IF	361.360	2793.09	9164
Radioactive (RA) MARKER	4.75	2.25	3-1/2 in. IF	3-1/2 in. IF	0.165	3154.45	10350
4-3/4 in. one Stand of Drill Collar	4.75	2	3-1/2 in. IF	3-1/2 in. IF	27.630	3154.61	10350
Cross Over	4.75	2.44	3-1/2 in. IF	2-7/8 in. EUE	0.355	3182.24	10441
01 x 2-7/8 in. EUE Tubing Joint	3.68	2.44	2-7/8 in. EUE	2-7/8 in. EUE	9.585	3182.60	10442
Debris Sub (Flow area 4.9 in^2)	3.68	2.44	2-7/8 in. EUE	2-7/8 in. EUE	0.165	3192.18	10474
02 x 2-7/8 in. EUE Tubing Joints	3.68	2.44	2-7/8 in. EUE	2-7/8 in. EUE	19.120	3192.35	10474
Mechanical Firing Head	3.68	1.39	2-7/8 in. EUE	2.75 in. DIA.- 6P ACME-2G	0.950	3211.47	10537
Safety Spacer	4.62	N/A	2.75 in. DIA.- 6P ACME-2G	3-15/16 in. DIA.- 6P ACME-2G	2.585	3212.42	10540
4-5/8 in. 91 m Gun Loaded with Reactive Charges **Top Shot**	4.62	N/A	3-15/16 in. DIA.- 6P ACME-2G	3-15/16 in. DIA.- 6P ACME-2G	179.000	3215.00	10548
Adaptor 3-1/8 in. to 4-5/8 in. Gun system	4.50		3-15/16 in. DIA.- 6P ACME-2G	2.75 in. DIA.- 6P ACME-2G			
3-1/8 in. 82 m Gun loaded with Reactive Charges	3.13	N/A	2.75 in. DIA.- 6P ACME-2G	2.75 in. DIA.- 6P ACME-2G	127.000	3394.00	11136
Bottom Nose **Bottom Shot**	3.13	N/A	2.75 in. DIA.- 6P ACME-2G	Blank	0.135	3521.00	11552
						3521.14	11553

NOTE:-

RA TO TOP SHOT 60.37 meter
RA Marker Depth 3154.63 meter
BHA Length 728.38 meter
Result:
Found RA at 3143 m . Add one Pup joint of 0.82 & One single after correlation.

Appendix B



ALL LENGTHS IN METERS

SUM OF PERF INTERVALS = 91 METERS

3 1/8" in. 6 SPF GUNS

INTERVALS	8	7	6		5	4	3		2	1
TOP DEPTH	3399.00	3410.00	3420.00		3448.00	3470.00	3480.00		3497.00	3502.00
BOT. DEPTH	3402.00	3414.00	3443.00		3466.00	3476.00	3495.00		3500.00	3521.00

LENGTH	METERS
Top Adaptor	
Bottom Adaptor	0.08
End to 1st Shot	0.18
End Shot-Shot	0.44
Top to Bot. Shot	6.05
TOTAL GUN	6.49

TOTAL LENGTH LOADED	85.69	METERS
CORD LENGTH (ADVISED)	200	METERS

TOTAL CHARGES	1687	LOADED AT 6 SPF
TOTAL BOOSTERS	40	WITH SINGLE FIRING HEAD

GUN LOADING SHEET #1