



Society of Petroleum Engineers

SPE-199200-MS

Knowledge and Experiences Combined under One Hood: Lessons Learned from Peninsular Malaysia Well Abandonment Campaign

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This paper was prepared for presentation at the SPE Symposium: Decommissioning and Abandonment held in Kuala Lumpur, Malaysia, 3 - 4 December 2019.

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Abstract

Operators, regulators, industry experts and service providers had lately landed onto a common ground on the needs for a strategic late field life management focusing on well abandonment planning and execution. With increased number of depleted well strings after exhaustive attempts to unlock the remaining well potential, this topic is gaining a spotlight day by day which triggers the industry to spare their attention to find the best solutions in getting the most out of the campaign. This paper will highlight the practical experiences and capture the lessons learned obtained while executing well abandonment campaign in Peninsular Malaysia waters demonstrating a quick learning curve and agile workflow in achieving a safe and world class project execution. Some best practices will be also proposed to strengthen the technical assurance, project governance as well as enhancing the safety features.

Lessons learned gained are categorized under seven lenses namely cap rock identification and subsurface study, governance model, well and equipment preparation, perforation and cementing operation, cement bond logging and casing integrity evaluation, HSE related matters and also special topics where few examples and case studies will be presented for each. New insights, interpretation and efforts to improve the operational efficiency have led to the birth of new technology deployment, increased industrial networking for knowledge sharing and also integrated project management for cost optimization. As each abandonment campaign is unique in terms of threats and challenges, different approaches will be required to abandon the wells safely which steer the operators to be high on the learning curve and subsequently promote greater industrial collaboration.

In essence, the lessons learned and insights gained throughout abandonment campaigns will keep accumulating with time to feed into the knowledge and experience vault. With proper project documentation, many success cases and best practices can be emulated both from technical and commercial point of view.

Introduction

Well abandonment is a unique subject, which is getting more attention both from operator and regulator point of view. Any field development project which normally takes 6 months to one year before final investment decision phase, should take into consideration well plug and abandonment program both in the schedule and costing exercise. In Malaysia, requirement to abandon the well starts as early as during idle well screening

for each of the producing field. For brown fields approaching towards the end of economic life or end of field operating life, final full field review (FFR) study will be required to exhaust the remaining hydrocarbon potential in the field. **Table 1** shows example of tabulation of remaining hydrocarbon potential in a typical brown field asset.

Table 1—Brown field remaining hydrocarbon potential screening

Reservoir	Oil STOIP (MMSTB)			Log interval (m MDDF)	Log Perm (mD)
	P90	P50	P10		
I-35	0.2	0.35	0.52	NL-A6: 1314.5-1319	29.8-126
I-70	0.1	0.15	0.21	NL-A5: 1697.5-1705 NL-A6: 1429-1432	42.4-212 5.2-25.3
I-60	0.28	0.5	0.95	NL-1: 1375-1380 NL-A3-ST2: 1645-1655	3.08-22 23.6-100
I-66	0.11	0.25	1.09	NL-A3-ST2: 1670-1674	162.5-540.6
I-80	0.28	0.54	1.18	NL-A5: risk of GOC NL-A6: 1486.5-1490 (risk of OWC)	90-127.8
I-110	0.28	0.54	1.53	NL-2: 1528-1531 NL-A2: 1595-1606 NL-A6: already perf	4.8-19.7 49.7-122 13.5-67.8
TOTAL	1.25	2.33	5.48		
I-66	0.28	0.38	0.5	PU-A1: 2023-2036 PU-A5: 2190-2206	31-607 41.2-558
J-60	0.22	0.27	0.32	PU-A5: 2730-2740	35.4-440
TOTAL	0.5	0.65	0.82		
J-30	0.44		0.75	PE-A6: 2060-2073	40-200
TOTAL	2.19	2.98	7.05		

Those idle strings status will need to have maturation plans to be revived or reactivated such as for add perf job, chemical stimulation, water injector conversion, work-over candidate or as a slot donor for infill drilling campaign. For those strings or wells which are totally depleted and do not have any remaining hydrocarbon potential to be exploited will need to be abandoned after getting approval and abandonment certificate from the regulatory body. The abandonment program will need to be executed within three years after getting the approval. Globally, there are several methods or approaches to abandon a well namely bull heading and zonal isolation, cap rock restoration, cut and pull casing, risk-based abandonment, perf-wash-cement (PWC) technique and rigless or in-situ well abandonment. In Malaysia the two most common approaches for well abandonment include zonal isolation and rig-assisted cap rock restoration with PWC. **Figure 1** shows the typical workflow starting from entering the well, logging for cement bond, PWC remedial job wherever required and setting the final surface plug before moving to the next job.

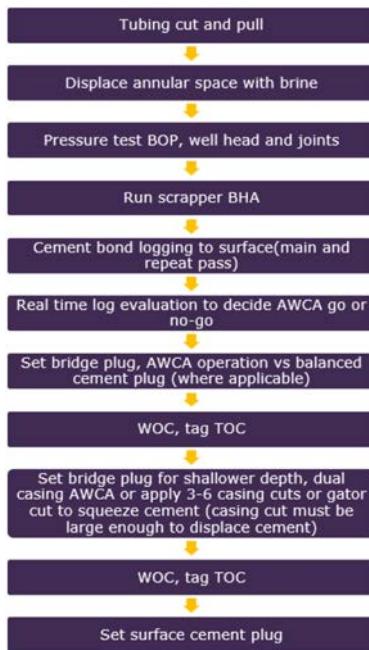


Figure 1—Typical well abandonment workflow

This paper will highlight several best practices and lessons learned in seven key operational areas given in the following paragraphs.

Cap rock identification and subsurface study

Identifying competent cap rock starts with the observation from the log data at the zone of interest where this cap rock must be impermeable, able to prevent cross flow between multiple reservoirs and able to withstand reservoir pressure from below. Figure 2 shows example of competent cap rock interval.

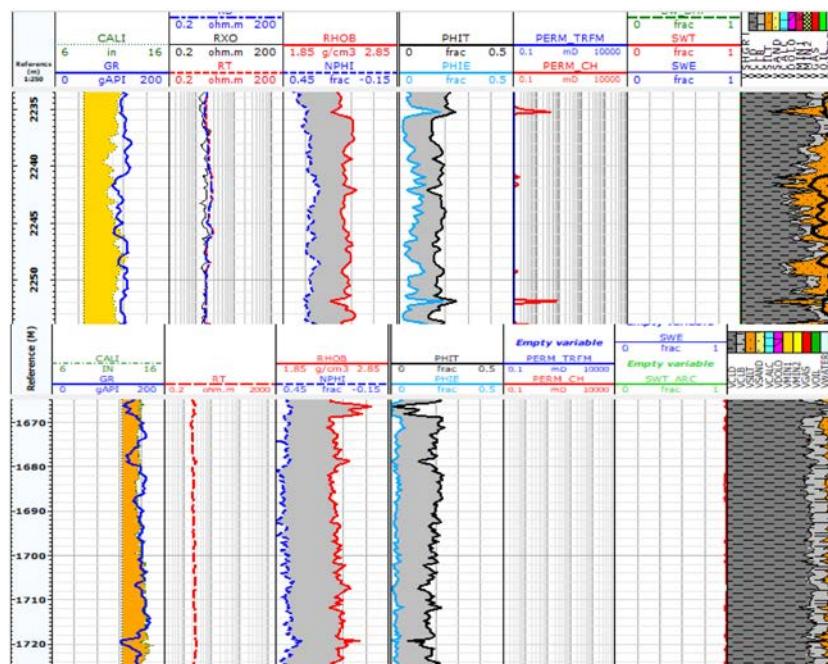


Figure 2—Example of competent cap rock interval

The cap rock interval should be laterally continuous across the field wide and should cap similar reservoir accumulation. However, caution should be exercised for stratigraphic reservoirs, which are drained from only few wells. In this scenario, well by well cap rock evaluation is exercised to determine the exception. Knowing only the competent cap rock interval may not be sufficient as reservoir barrier without the assessment of cap rock strength. Fluid pressure and minimum plug setting depth in the wellbore should comply to the cap rock strength limit as illustrated in Figure 3.

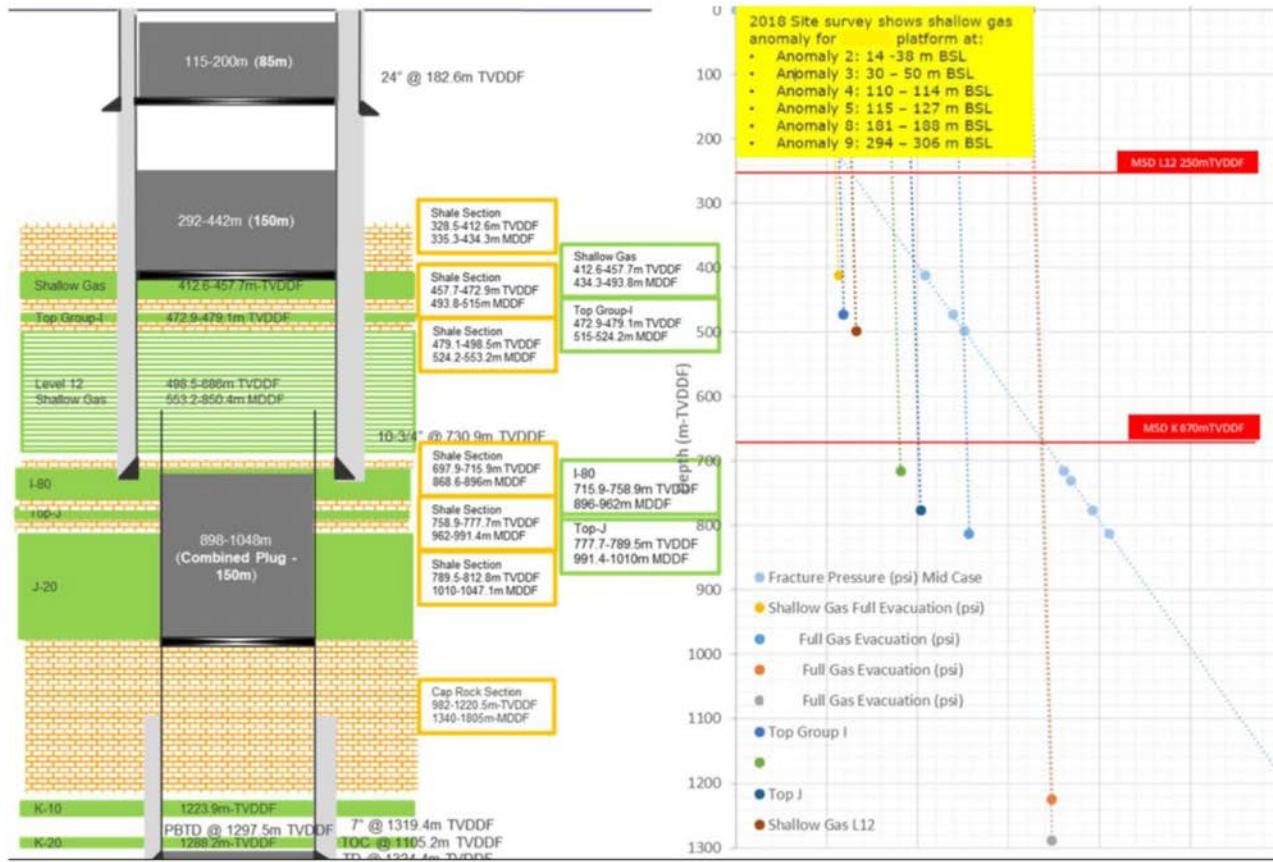


Figure 3—Pressure plot to determine fracture gradient and minimum plug setting depth in the wellbore

The intersection between fluid gradient line assumed as gas as worst case scenario and the fracture gradient line determines the minimum plug setting depth. The fracture gradient line is compared with leak-off test (LOT) value during drilling operation. Alternatively, if geomechanics study are available the results should be used to guide the pressure plot design.

Governance

Each abandonment project is unique and often called for specific and fit-for-purpose governance model as well as contract arrangement. From casing and cement bond evaluation point of view, specific criteria and logging requirement need to be outlined at the beginning of contract initiation. Figure 4 shows example of cement bond logging criteria to meet the abandonment objectives.

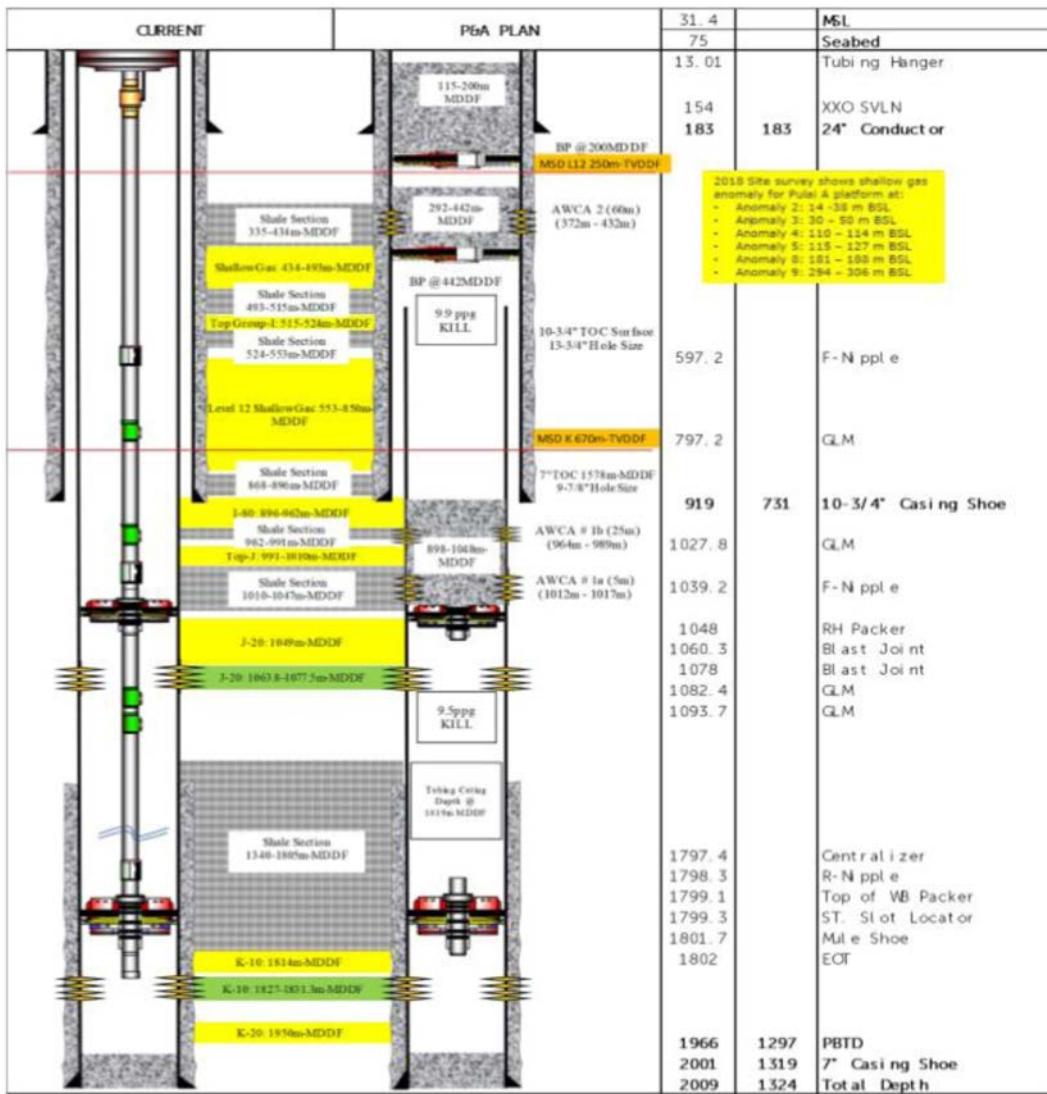


Figure 4—PWC intervals with casing cut and pull scenario

Well and equipment preparation

Prior to abandonment job execution, well and equipment readiness will be tracked and monitored as standard practice. Wireline unit, logging tools and other well abandonment equipment will be inspected according to specific operational checklist for assurance prior to job execution. Table 3 shows inspection checklist for wireline unit and cement bond logging tools. Prior to abandonment each well needs to be killed, wellbore displaced with brine and conditioned with all the tubulars and well head properly tested for leaks and other integrity issue. Tubing will be cut and retrieved if any cement bond logging is planned to be acquired. For wells with historical sustained annulus pressure (SAP) issue, the annulus section needs to be vented and monitored throughout the operation.

Table 2—Cement bond logging criteria for well abandonment

No	Item	Key Specifications	CONTRACTOR's Response
8	Downhole Logging including logging equipment and/or sensors and/or accessories	<p>Compatibility test with any e-line conveyance services to be witnessed by COMPANY representative prior to job execution</p> <p>CONTRACTOR to provide ultrasonic cement evaluation tools i.e. USIT, CAST or equivalent. The ultrasonic cement evaluation tools run shall run in tandem with CBL-VDL or equivalent and GR/CCL.</p> <p>CONTRACTOR to provide available leak detection tools which is capable of giving quantitative and/or semi-quantitative solution inside single tubing and/or single casing and/or behind multiple tubing/casing layers. Service to include GR-CCL by contractor</p> <p>Downhole logging services cost is inclusive of pre-job modelling and job proposal by contractor</p>	
9	Data interpretation and delivery package	<p>The quick look interpretation (and presentation) should be within 3 hours (including of when logged during weekend).</p> <p>Basic Interpretation Suite to include</p> <ol style="list-style-type: none"> 1. Cement quality 2. Well leak detection 3. Top of Cement (TOC) <p>Bidder to specify Advanced Interpretation Suite specifications.</p>	

Table 3—Wireline unit and cement bond logging tools checklist

SURFACE LOGGING UNIT			
Unit Serial Number	YES	NO	
Load test and MPI test certificate still valid	YES	NO	
Electronic check/diagnostics done for surface acquisition system?	YES	NO	
*Purge system is in good condition	YES	NO	Cabin pressure should hold 1-2 bar
*Alarm for Purge system is in good condition	YES	NO	if cabin not holding pressure
*Shut down system working if cabin pressure not holding	YES	NO	
Unit able to send power for logging and perforation job?	YES	NO	power up telemetry tool, power up GR/CCL tool and simulate perforation
verify the tension device system is working	YES	NO	calibration should valid 1 month
verify the depth device system is working	YES	NO	calibration should valid 6 month
Equipment inside the unit is working ie, monitor, air conditioner	YES	NO	
STANDARD LOGGING CABLE			
Equipment Serial Number	YES	NO	
Does the cable was splice?	YES	NO	
Load test and MPI test certificate still valid	YES	NO	
Cable pass the Ductility test?	YES	NO	
Cable length is sufficient for the job?	YES	NO	
Cable type is suitable for the job?	YES	NO	
PORTABLE ELECTRIC POWER GENERATOR			
Equipment Serial Number	YES	NO	
Load test and MPI test certificate still valid for the bracket	YES	NO	
Generator having good maintenance history	YES	NO	Check the generator maintenance history
Turn on the generator and verified the output using a multimeter	YES	NO	to check sufficient power could be generated to power up unit or tools if required
CEMENT BOND LOG TOOL			
Tool Serial Number	YES	NO	
Electronic Tool check/diagnostics done?	YES	NO	
Is the tool normalized? Normalization date <6 months?	YES	NO	
Oil level in the tool confirmed to be full?	YES	NO	
Tool rated for the expected BHT	YES	NO	
Accessories of the tool suitable for casing size(e.g PPC / centralizer)?	YES	NO	
Receiver check done? (using steel tank or steel truft)	YES	NO	Should read 57us/ft or 52mV
Centralizers confirmed to be in good shape	YES	NO	
ULTRASONIC IMAGING TOOL (CEMENT/CASING MAPPING)			
Tool Serial Number	YES	NO	
Tool rated for the expected BHT	YES	NO	
Ultrasonic subs used is for dedicated casing size?	YES	NO	
Accessories of the tool complete for hole size(e.g centralizer)?	YES	NO	
Centralizers confirmed to be in good shape	YES	NO	
station log done inside presurized water tank?	YES	NO	
CASING COLLAR LOCATER			
Tool Serial Number	YES	NO	
Check CCL signal in depth log simulation	YES	NO	should see high deflection when metal near to the magnet.

Perforation and cementing

In some abandonment projects, the first casing layer is intended to be cut and pulled mainly to enable cement bond logging across the second casing layers. In this case single casing perf-wash-cement (PWC) perforation is planned as remedy in case cement bond quality behind the casing does not meet acceptable criteria. It is observed that in few occasions the casing could not be cut and retrieved to the surface due to cement grouting at the wellhead area. All these records need to be properly stored and documented. In case of casing could not be retrieved, dual casing PWC operation is planned. Based on the jobs conducted to date, single casing PWC is the best approach for cement remedial with 18 shot per foot density and double perforation. An alternative to dual casing PWC is to conduct multiple casing cuts using a specially design blade and cutter which creates bigger holes for cement displacement and allows deeper cement penetration behind the casing into the annulus B area. **Figure 4** illustrates casing cut and pull scenario.

Cement recipe for well abandonment purpose also needs to follow certain design to minimize damage and gas contamination given the degradation of cement quality with time. **Table 4** presents the typical cement recipe design for abandonment purpose.

Table 4—Cement recipe and rheology design for well abandonment

Job Type	Plug	Depth	950.0 m	TVD	775.5 m		
BHST	144 degF	BHCT	117 degF	BHP	2000 psi		
Starting Temp.	81 degF	Time to Temp.	00:05 hr:min	Heating Rate	7.20 degF/min		
Starting Pressure	50 psi	Time to Pressure	00:05 hr:min	Schedule	()		
Composition							
Slurry Density	15.00 lb/gal	Yield	1.28 ft ³ /sk	Mix Fluid	5.800 gal/sk		
Solid Vol. Fraction	39.6 %	Porosity	60.4 %	Slurry type	Conventional		
Code	Concentration	Sack Reference	Component	Blend Density	Lot Number		
SLAG		94 lb	Blend	2.9600 SG	KMN Sample		
Sea water	5.075 gal/sk		Base Fluid		Rig Sample		
D047	0.020 gal/sk		Antifoam		6302018		
D500	0.550 gal/sk		GASBLOK LT		CY70563048		
D145A	0.090 gal/sk		Dispersant		704247		
D081	0.065 gal/sk		Retarder		CP170206		
Rheology							
Temperature	81 degF			117 degF			
(rpm)	Up (deg)	Down (deg)	Average (deg)	Up (deg)	Down (deg)		
300	62.0	62.0	62.0	72.0	72.0		
200	47.0	47.0	47.0	51.0	52.0		
100	32.0	31.0	31.5	36.0	35.0		
60	23.0	23.0	23.0	28.0	28.0		
30	18.0	17.0	17.5	24.0	23.0		
6	13.0	14.0	13.5	15.0	15.0		
3	11.0	11.0	11.0	12.0	12.0		
10 sec Gel	14 deg - 14.94 lbf/100ft ²			15 deg - 16.01 lbf/100ft ²			
10 min Gel	25 deg - 26.68 lbf/100ft ²			30 deg - 32.02 lbf/100ft ²			
1 min Stirring	19 deg - 20.28 lbf/100ft ²			19 deg - 20.28 lbf/100ft ²			
Rheo. computed	Viscosity : 49.452 cP Yield Point : 13.36 lbf/100ft ²			Viscosity : 53.699 cP Yield Point : 17.46 lbf/100ft ²			
Thickening Time							
Consistency	Time						
40 Bc	07:18 hr:min						
70 Bc	07:42 hr:min						
100 Bc	07:53 hr:min						
Free Fluid							
0.0 mL/250mL in 2 hrs							
At 81 degF and 0 deg incl							
Sedimentation : None							
Fluid Loss							
API Fluid Loss 48 mL							
In 30.00 min at 117 degF and 1000 psi							

Cementing job should follow the best practices while mixing, pumping, displacing, hardening and pressure testing to achieve the best cement placement qualified as a barrier along the wellbore. [Table 5](#) outlines some of the best practices to emulate.

Table 5—Cementing operation best practices

Activity	Best practices
Fit for purpose cement recipe	The best cement recipe must not have free water, has stable density reading, sufficient amount of retarders and expanders and appropriate control on the fluid loss rate. Adding the gas block materials in the recipe is also recommended to reduce cement permeability for gas migration
Centralization	Ideally, each casing joint should be run together with a centralizer to ensure proper stand-off from the borehole while pumping for cement displacement
Hole conditioning	Hole condition and mud properties used during open hole drilling are critical to design the cement primary volume, excess volume and also type of cement to be used. Conditioning the well prior to the cementing operation is also critical to minimize mud channeling occurrences
Mixing cement	Cement slurry is best mixed at the right downhole temperature obtained from the downhole sensor. Design of setting time, thickening time and compressive strength should be based on the representative downhole condition
Pumping and displacement	To achieve minimum mud contamination during cementing, use a series of spacers and flushes pumped at maximum rate without breaking the formation. Casing should be rotated and reciprocated while pumping to further displace the mud. In a long wellbore interval or highly deviated well, it is a good practice to apply multi-stage cementing operation to achieve the maximum displacement and cement coverage around the annulus area
Pressure condition	While waiting for cement to harden and set, usually 200-300 psi pressure lock is applied from surface

Cement bond logging and casing integrity evaluation

The most critical element in well abandonment is cement and casing integrity evaluation to qualify cement as barrier and to determine source of leaks and pinholes respectively. There are different type of cement bond logging tools commercially available. Best practice in well abandonment is to run a combination of acoustic and ultrasonic cement bond tools with the objective to evaluate cement to casing and cement to formation bonds. In wells with severe SAP occurrence, it is recommended to diagnose the issue via casing integrity and well leak detection logging to point out the source. The common practice is to establish 80% cement coverage and 80% bond index to qualify as a good bond. Below this cut-off will require cement remedial job accordingly. [Figure 5](#) illustrates the decision tree for PWC operation following cement bond logging results, while [Figure 6](#) shows example of log results which require and not requiring remedial job respectively.

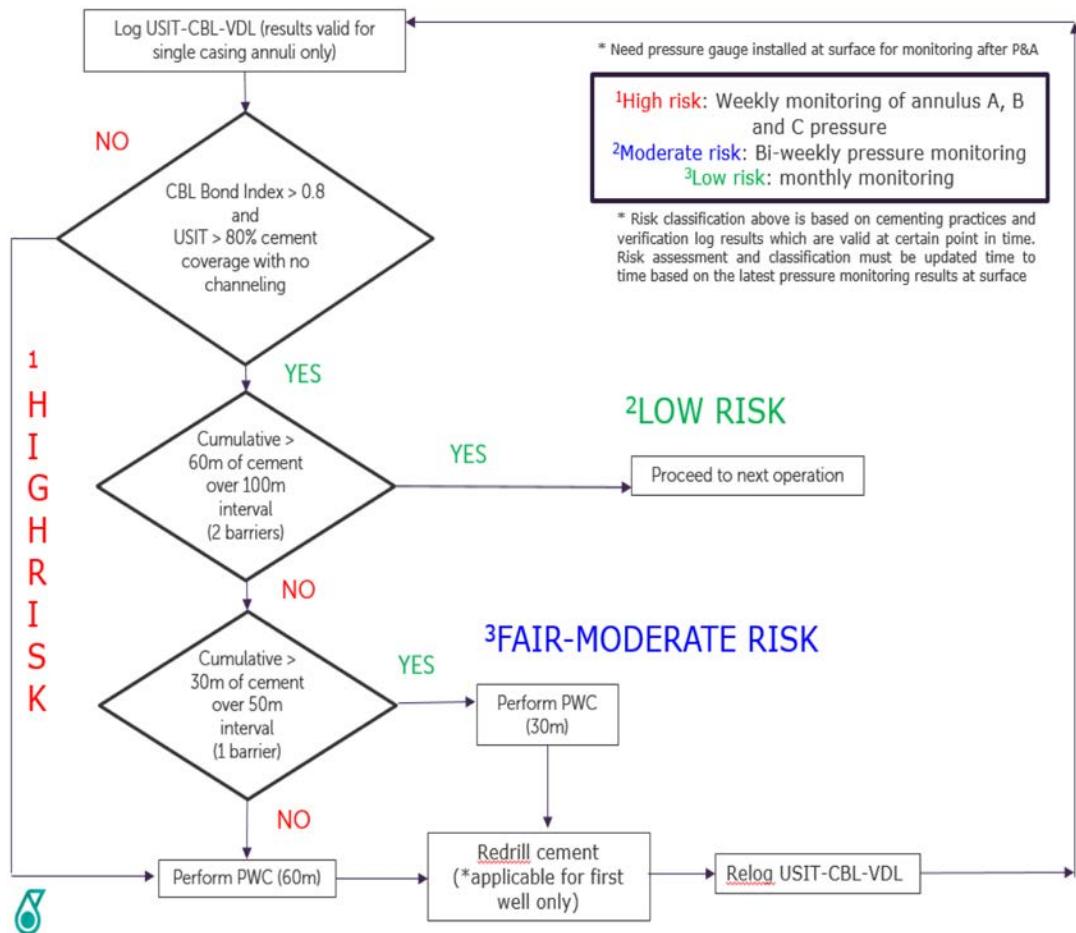


Figure 5—PWC decision tree following cement bond logging results

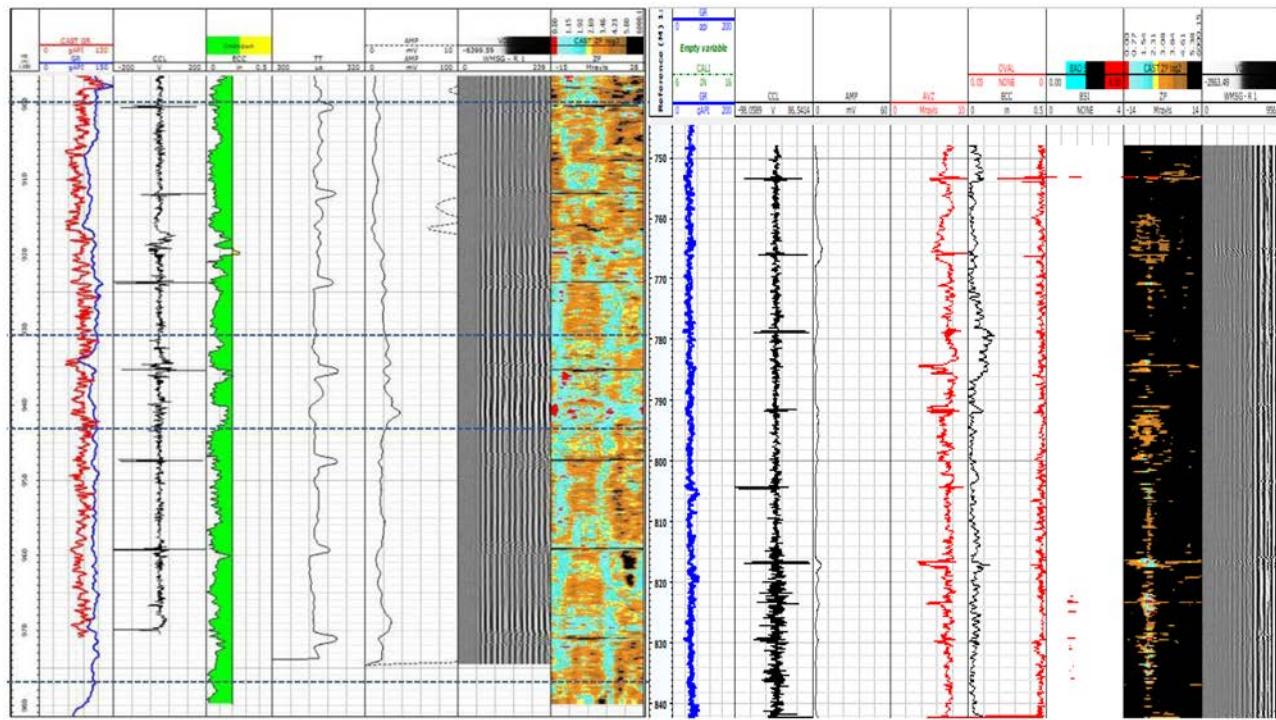


Figure 6—Log examples showing PWC is required (left) and PWC is not required (right)

It is also worth to highlight the hierarchy of cement bond evaluation given as following:

To evaluate the effectiveness of PWC remedial operation, the best practice is to redrill the cement and relog the interval with poor cement bond prior to PWC. Figure 8 shows the redrill parameters and comparison of cement bond quality before and after the PWC, which shows significant improvement.

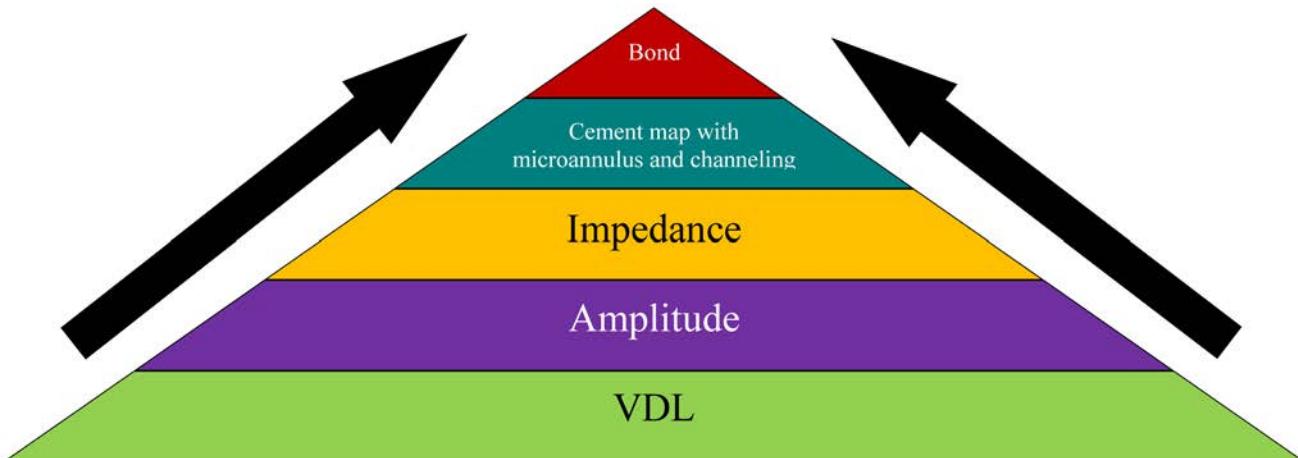


Figure 7—Data hierarchy (in the order of evaluation sequence) to determine cement bond quality

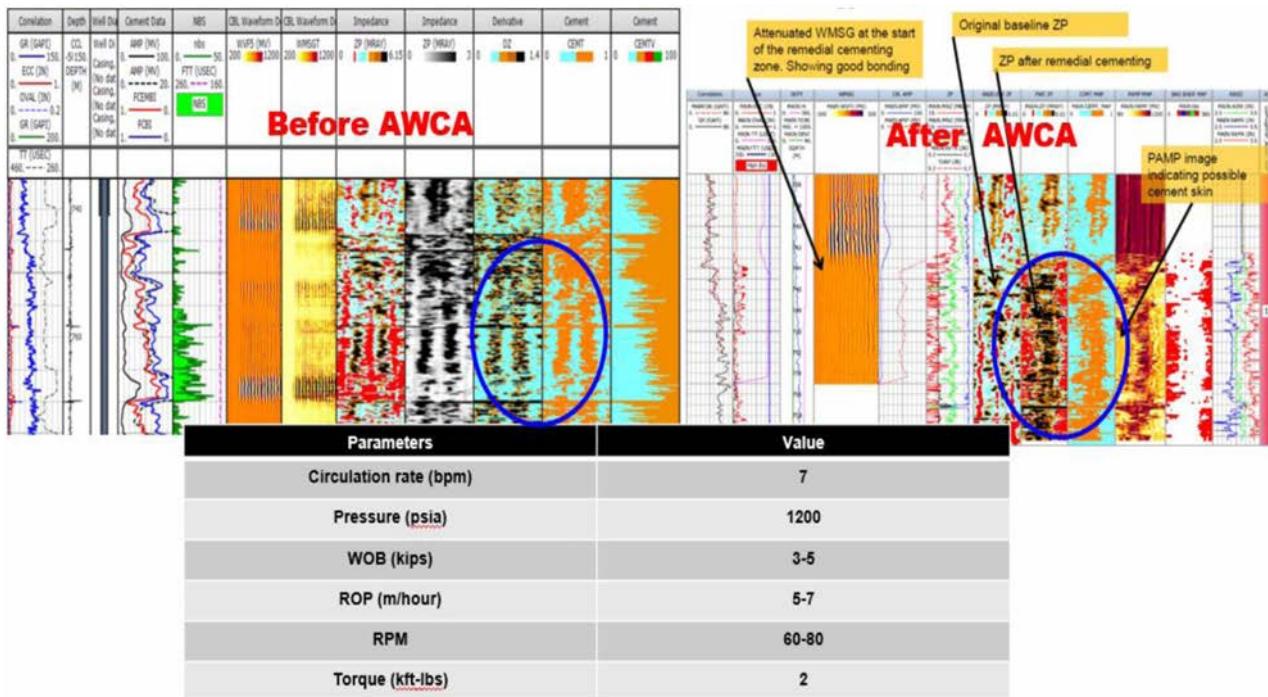
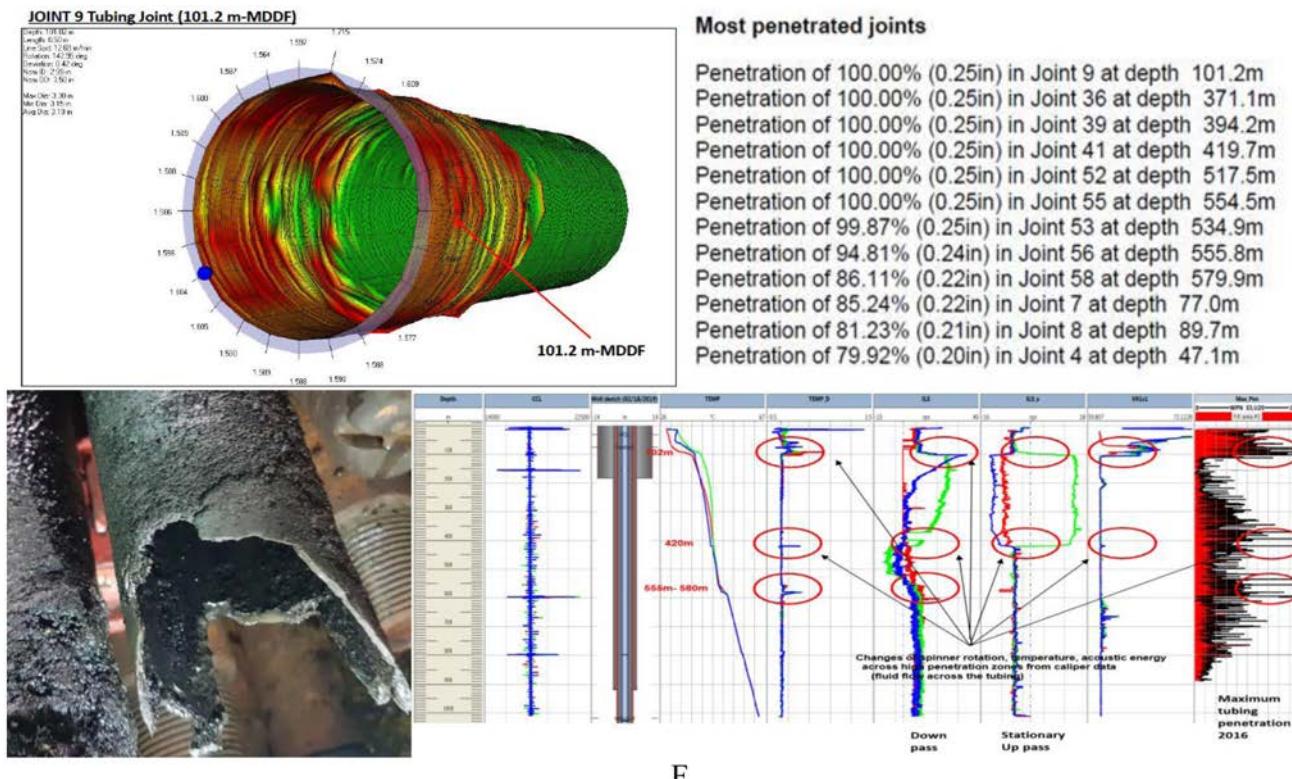


Figure 8—Cement redrill parameters and log comparison before and after PWC

Casing integrity is of utmost importance if there is plan to retrieve the tubulars to surface. Figure 9 shows example of bad casing and tubing condition based on the ultrasonic and mechanical caliper logs which pose a high risk for the retrieval job.

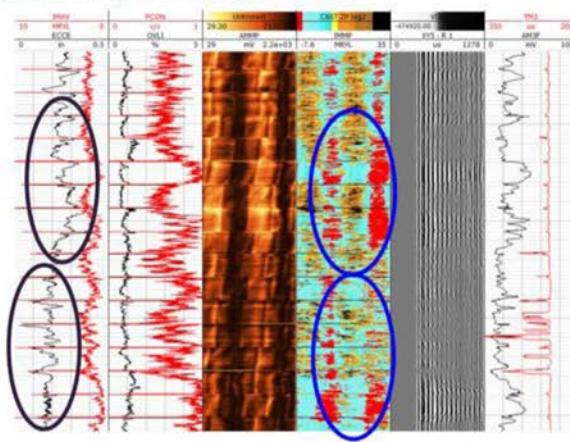


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Figure 9—Tubing leaks based on mechanical caliper and ultrasonic diagnostic survey

A proper QAQC of the acquired cement bond logs are also critical to give the real time answer on cement bond quality and to decide whether or not PWC is required as remedial work. Pre job planning using the tool planner should be properly conducted, ensuring the correct amount and placement of centralizers along the tool string, including temperature sensor in the tool string for cement hardening time design and also choosing the correct free pipe interval in the well as calibration for cement bond log evaluation. Figure 10 shows the consequences of violating these rules.

Severe casing eccentrication will generate 'pseudo' gas effect



Trapped gas affecting CBL free pipe calibration

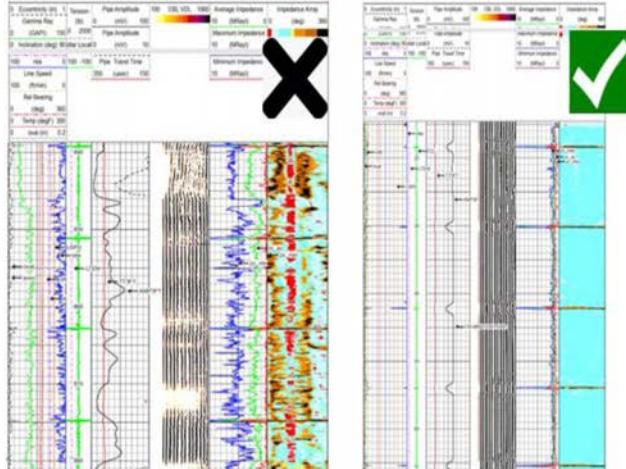


Figure 10—Inaccurate log evaluation resulting from wrong free pipe calibration and insufficient tool centralization

HSE

There are three HSE elements observed throughout the well abandonment execution campaign. First is technologically enhanced naturally occurring radioactive materials (TENORM) requirement for the retrieved tubulars which need to comply to specific limit of 0.50 uSv/hour or 0.30 mSv/year for waste disposal. Second is the safety handling of perforation charges and live gun loading as well as deployment in the wellbore. **Table 6** outlines some of the safety checklist. Third is the handling of carbon monoxide (CO), carbon dioxide (CO₂) and H₂S gases as byproduct of perforation and also originating from the reservoir itself. Special venting lines and protective personal equipment need to be adorned for H₂S handling and testing at the surface.

Table 6—Explosives handling, gun loading and deployment safety checklist

ITEMS	CHECKLIST (reference: CONTRACTOR'S TECHNICAL PRESENTATION, SOPs AND TECHNICAL GUIDELINES)	Available	litv	Quality
8.00	Explosives handling and gun loading safety			
8.01	Never load a tube strip with perforating charges with prima cord still attached to the main roll. Cut length and remove cord roll from the loading area			
8.02	Load the charges in top-down sequence. Attach booster to the bottom most gun. 3 types of gun loading style: external wrap, centralized and internal weave			
8.03	To observe gun and tandem receiving specific measurement for safe operation			
8.04	Voltage between wellhead, rig and wireline unit less than 250mV before installing clamps. Ground clamp should read less than 0.5 ohmm. If voltage exceeds 250 mV but less than 5V before installing clamps use of radio silence equipment is mandatory. If voltage is greater than 5V use TCP or decline the job			
8.05	Check gun/explosive device for trapped pressure and bleed-off as required post job			
8.06	Do not pressure test lubricator with explosive device inside			
8.07	Loose explosive powder needs to be washed off with gentle stream of water, filtered and stored into anti-static plastic bag before disposal			
8.08	Do not store sparking metal tools in the explosive magazines			
8.09	Use only battery-operated flashlight if required in magazines area. Do not use extension cords or exposed light bulbs as light sources			
8.10	All explosives must not be exposed to shock, vibration, heat, impact, confining pressure or any detonating sources			
8.11	Smoking, open flames, RF transmitting device and spark-producing devices must not be used in the magazines and around gun loading area			
8.12	Boxes fo explosives must be covered by water and flame-resistant tarpaulin when transported in open vehicle			
8.13	Detonator, booster, shape charges and detonating cord must be stored separately in an approved magazine			
8.14	A vehicle transporting the explosives must have the engine shut-off when refueling			
8.15	All perforating assemblies must be supported at least every 3 ft along the length of assembly			
8.16	Assemblies longer than 11 ft must be secured at both ends and in the middle			
8.17	For rough or long journey on rough roads use an air-ride suspension system where possible			
8.18	Stop all surface-related operations during electrical storms (lightning, snow, sand, dust) within 10 miles of explosives operation			
8.19	Loaded perforating guns not in immediate use are to be placed out of direct line of fire from the arming area			
8.20	Well-site loading or unloading of explosives must be conducted in a designated area located at least 50 feet away from sources of heat, welding operations, out of direct line of fire and behind a metal barrier			
9.00	Gun Arming safety			
9.01	Stop all welding (electric and gas)			
9.02	Shut down electrically-powered cathodic protection system			
9.03	Install grounding cable to the logging unit, rig structure, well head and pipe racks on which the guns are to be armed in the vicinity of wireline operation			
9.04	Connect cable head to GR, CCL, sinker bar and other accessories. Complete insulation and continuity test			
9.05	The arming area must not be in the dog house or other area where there are electrical sockets			
9.06	Gun must always be electrically armed before ballistically armed. For gun disarming, ballistically disarmed first then electrically			
9.07	Barricade arming area and post 'danger-explosives' sign			
9.08	All unnecessary panels turned off, switch on the perforating panels in SAFE mode, all power supplies are at zero-power position and logging unit has been vacated by non-essential personnel			
9.09	Secure a detonator safety shield at the bottom of gun assembly			
9.10	Position safety shield so that it will not contact other explosives, remain clear of blast area as much as possible, do not hold safety shield in hand while testing/ connecting the detonator			
9.11	Do not pull the leads of detonator, detonator being tested must be contained in the safety shield			
9.12	Gun system arming procedures can be divided into 2: gun connected to cablehead/CCL prior to connecting the detonator and gun connected to the detonator before cablehead/CCL			
9.13	Use only an approved detonating cord cutter to cut the detonating cord to the correct length			
9.14	If electrical hoist system is used to pick up the gun assembly check for stray voltage between hoist cable and ground before using it on the gun			
9.15	Radio silence need to be requested while arming the gun until the gun is lowered 60m below the seabed or downhole safety valve. Similarly after the job the gun cannot be POOH to surface until radio silence condition is granted			
9.16	A 'hang-fire' gun (delayed detonation) is undergoing thermal event (temperature>100 degC) must not be handled. Keep the surrounding area 15m radius of the gun clear of all personnel to protect from delayed shape charge detonation, check gun temperature every 2-hour interval at a safe distance, once the gun and explosives had cooled down, carefully disarmed them			

Special topics

Other than operational best practices, there are few impactful insights which could be extracted from the recent well abandonment campaign. Shale by nature is a ductile formation and some regions have demonstrated the occurrence of creepy shale which has the potential to be the natural well barrier when it creeps and improves the bonding with formation as well as casing. **Figure 11** shows example of creeping shale observed from the logs.

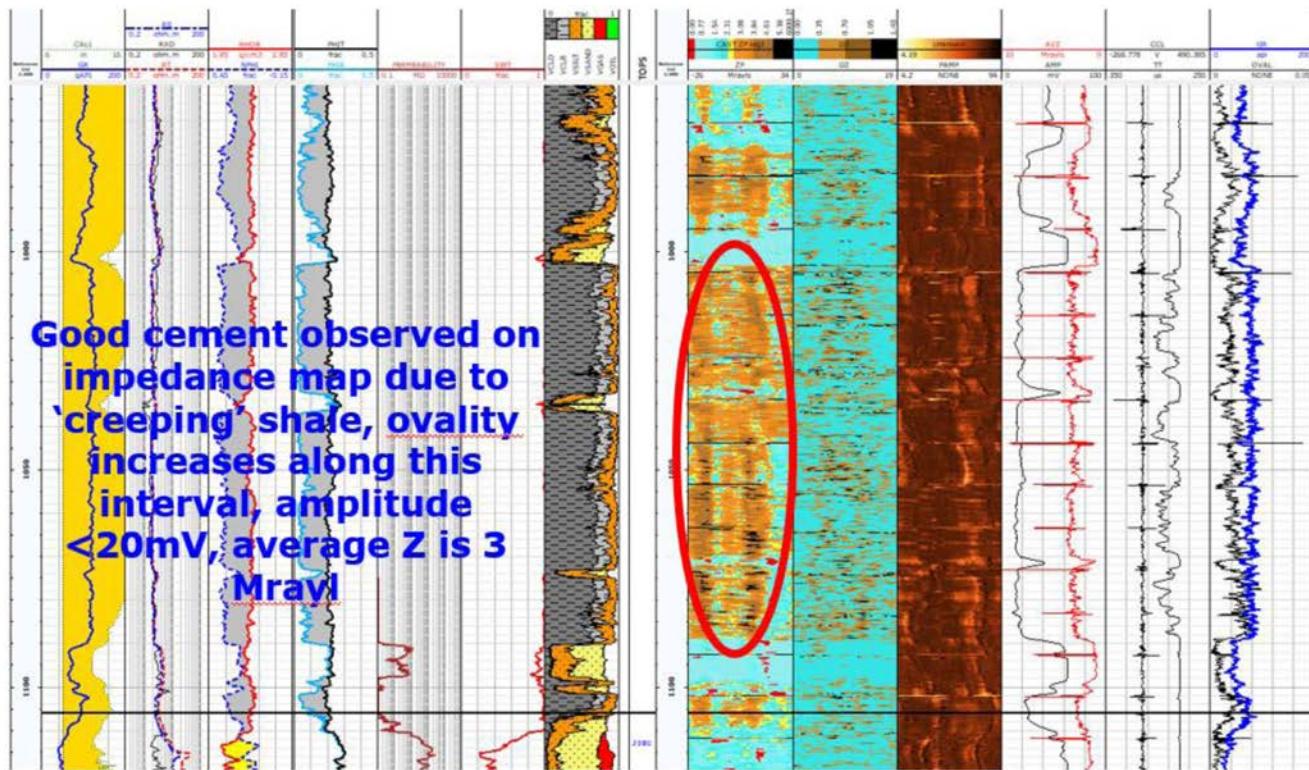


Figure 11—Example of creeping shale from logs

Another interesting finding from all the newly acquired cement bond logs is gas detection both at shallow zone as well as from deeper reservoir migrating up through the poor cement bond behind casing. This is the value-added information could be obtained by running cement bond evaluation logs instead of additional pulsed neutron logging for gas detection. Figure 12 illustrates this example.

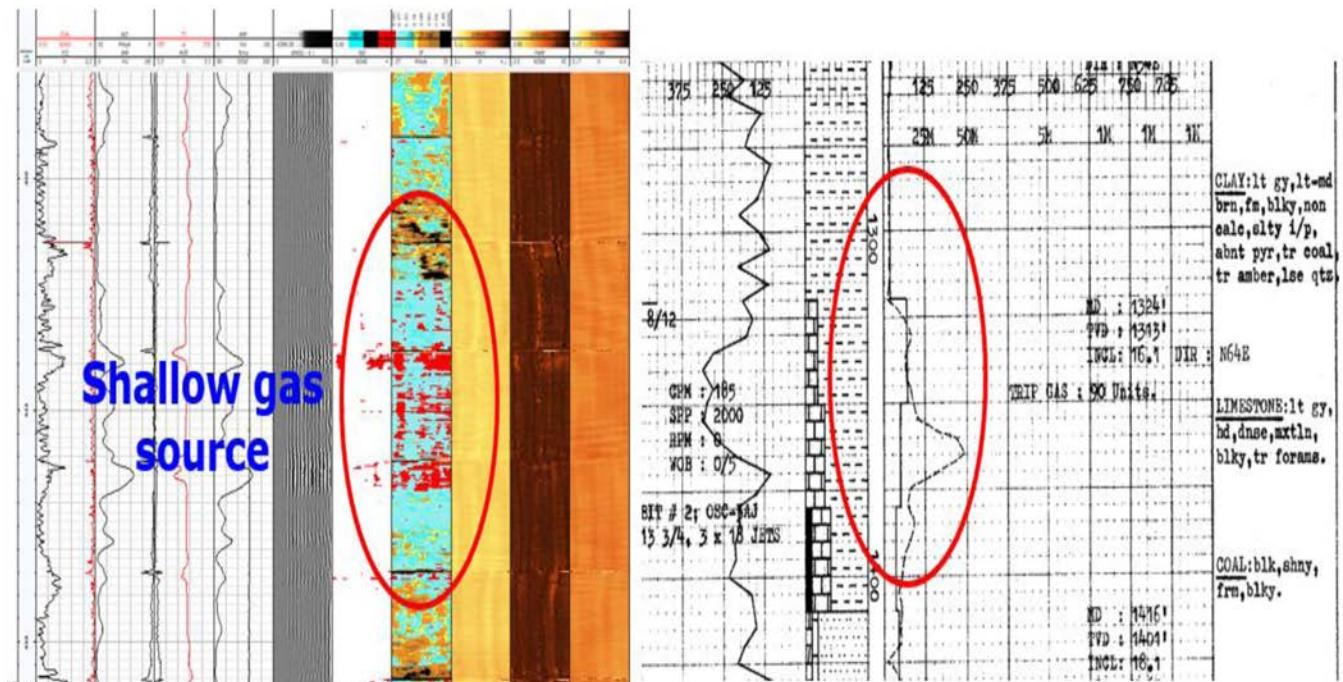


Figure 12—Gas detection from cement bond logging acquisition

In terms of technology, due to high operational cost involved in rig-assisted job execution, an alternative rigless well abandonment approach with in-situ cap rock melting as zonal isolation and well barrier element seems to be a feasible option to minimize the rig cost. New technology to evaluate cement bond behind dual or multiple casing layers is also under development in which if it is proven, could further eliminate casing cut and pull operation which leads to significant rig time saving. Figure 13 demonstrates the new technology conceptual idea.

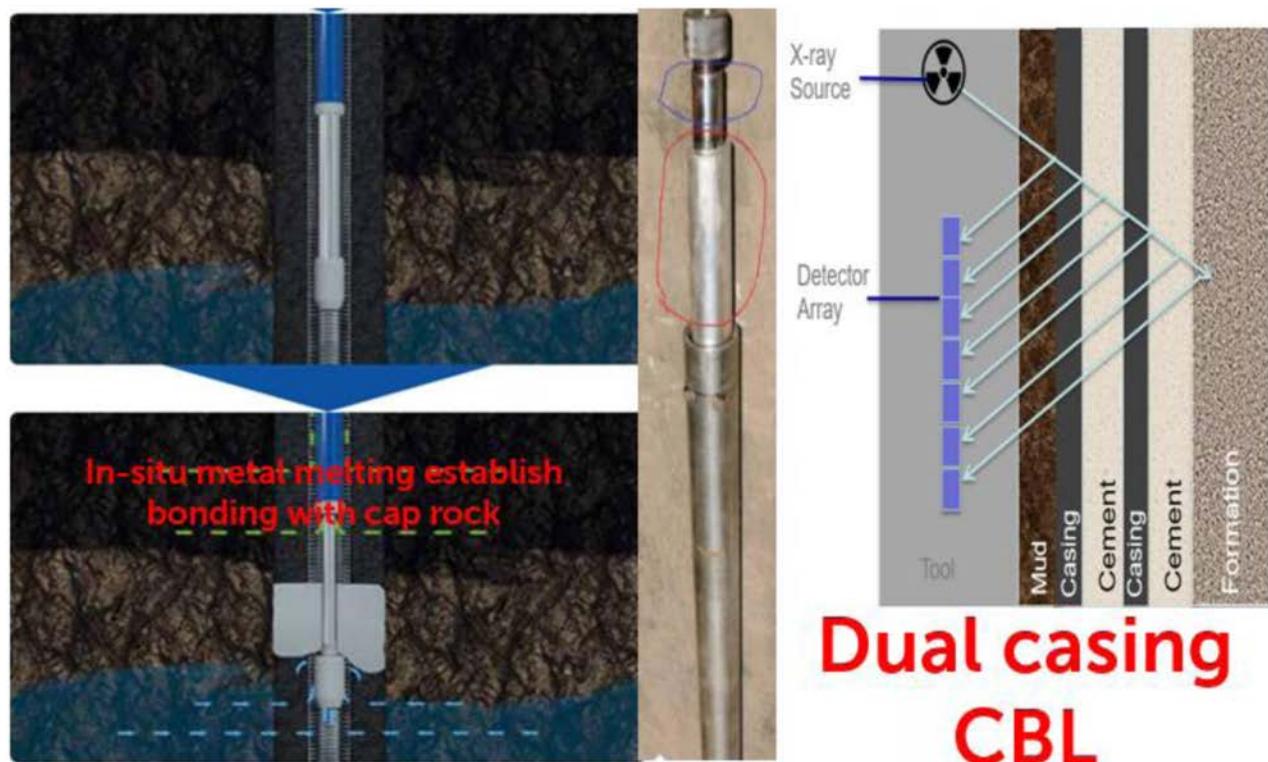


Figure 13—New zonal isolation technique and multiple casing cement bond logging technology

Conclusion

In a nutshell, all the lessons learned and best practices gathered in various aspects from the recent well abandonment campaign could be potentially replicated to other projects with similar well profile and requirement. No one design will fit for all, however with the technical know-how and experiences accumulated throughout the project execution, they will certainly contribute to improved operational efficiency and cost optimization as well as generating a blueprint for future well abandonment projects.

Acknowledgement

The author wish to thank you PETRONAS Carigali Sdn Bhd, technical and management team for the support and approval to present and publish this manuscript.

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