Propellant Perforation for a Depleted Carbonate Subsea Gas Well – Malampaya

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Agenda

- Malampaya Asset - Overview
- Malampaya Phase 2 Project – Overview
- Well Performance: Expected vs. Actual
- STIMGUN Selection
- Process Safety Due Diligence
  - Modeling Studies – Static & Dynamic
  - Yard Visit
  - Connector Test
- Operational Overview
- Conclusions & Project Learning's
1.0 Malampaya Asset

Overview
Malampaya Asset

Malampaya Deep water Gas to Power Project

Reservoir: Deep water, gas carbonate
Wells: 7 subsea wells in 820m water
Flowlines: 2 x 28km CRA flowlines
Platform: Concrete gravity base platform in 43m water, offshore dehydration, continuous MeOH injection, 2x26 MW gas turbine driven export compressors, condensate stabilized offshore stored in the gravity base structure, export via CALM buoy, remote control from Onshore Gas Plant
Pipeline: 504 km 24” gas export pipeline
Gas plant: Onshore treatment plant uses amine process to sweeten and mole sieves to dehydrate the landed sour gas. Currently operating in Dry Gas Mode (i.e. low H₂S)
Customers: Gas sold to 3 power stations (design 2700 MW)
Capacity: 528 MMscf/d of gas
32,800 bbl/d of condensate
SC-38 Stakeholders – Joint Venture

- **Government of the Republic of the Philippines (DoE)**
- **Philippines National Oil Company (PNOC) (Philippines)**
- **Shell Petroleum N.V. (Netherlands)**
  - **100%**
  - Shell Philippines Exploration B.V. (Netherlands)
  - **45% undivided interest** Operator
- **Chevron (USA)**
  - **100% indirectly**
  - Chevron Malampaya LLC (Philippines)
  - **45% undivided interest**
- **PNOC – Exploration Corporation (Philippines)**
  - **10% undivided interest**

**Service Contract 38**
Subsea to SWP to onshore...

- Gas dehydration
- Gas dewpointing
- Condensate stabilisation
- Export compression
- Depletion compression

Upstream:
- Catenary Anchored Leg Mooring (CALM) buoy for tanker loading of condensate
- Sulphur Recovery
- H2S removal
- Metering
- Supply base

Downstream:
- Batangas
- Power Stations
- Alternative Fuel

- 28 km
- 504 km

- 3rd flowline (2021)
- Subsea manifold
- 2 x 15" CRA wet gas
- 5 Development wells
- 4 Additional development wells (2009)

- 24" Dry gas pipeline

Water depth (m):
- Platform Location
- South of Mindoro
- Manila Trench

KP position (km):
- 0
- 100
- 200
- 300
- 400
- 500

Graphs and charts showing water depth and KP position.
**Discovery & Appraisal**
- Discovery: 1989, CA-1 (Occidental)
- Gas Appraisal: 1992-94, 4 MP wells
- Oil Rim Appraisal 2002: MA-10

**Development Phase 1 (MP1)**
- 5 MP wells & subsea production system, Platform, pipeline and onshore gas plant (on-stream 2001)

**Asset Integrity (AI) (2010)**

**Phase 2 (MP2)**
- MP Infill: 2 wells (2013)

**Phase 3 (MP3)**
- Depletion Compression (2015)
MALAMPAYA RESERVOIR CHARACTERISTICS

- Carbonate – vugs, karsts, fractures – Heterogeneous
- Average Porosity 18%
- Average Matrix Permeability 250-350 mD/ Effective Perm2 D
- Poor Aquifer/Depletion Drive
- Reservoir Temperature 115 deg C
Reservoir Pressure declined by a third in 10 years.

- Biggest subsurface challenge – drilling in a highly fractured depleted carbonate.
MP2 Overview

Status Update
Malampaya Subsea System Layout

5 Development Wells
Each ~100 MMscf/day
- Max. Deviation 49.1°
- Design Life 20 yrs
- Cased & Perforated
- Long Liner Flow Design
  - 7” Liner
  - 9-5/8” Liner
- Zero Intervention Philosophy
- Thru Tubing Perforation
  - 2” CT N₂ for unloading if req
- Stimulation: STIMGUN
- Tubing: 7” X 9-5/8” X 7”
- TR-SCSSSV 7”
- Surveillance: PDHG
Gun Selection

- 200 m of perforation length per well
- 7” Liner Cased & Perforated Completion
- 3-3/8” OD STIMGUN was shortlisted
  - Min ID of Tubing hanger at subsea tree was 5.12”
- Standard 6 SPF shot density, 60 deg phasing
- Deep Penetrating HMX charges

Figure 1 – StimGun™ assembly: The perforating event ignites an outer propellant sleeve as it perforates the casing and formation.

Figure 2 – Gas expansion of the burning propellant sleeve as the formation is fractured.
3.0

Well Performance: Expected vs. Actual

Overview
Drilled reservoir section with total losses indicating a highly fractured carbonate as expected. Fractures observed on Image logs.

Reservoir quality more heterogeneous than the nearest offset well.

High perm zones observed from log data.

Perforation interval optimized by lowering 15 m to connect to deeper high perm zones.
Well Testing Overview

- Estimated 150 MMscf/day demonstrated
- Clean up criteria achieved
- Final Salinity 235 ppm and 0% BSW solids
- ~200 ft flare – Weather favourable
- Dual Separator mode on the rig flowed to 120 MMscf/day (measured) - STABLE flow
Expected IPR vs. Actual Flow Performance

- Benefit of near well bore stimulation & thick high perm reservoir sections
STIMGUN Selection
Why did we need some form of Stimulation? Uncertainty Space -> Low Productivity -> Non-Deliverability

- Reservoir Pressure depleted by 1/3rd from virgin pressure
- Huge drilling & cementing losses expected
- Presence of Karsts
- Could expect thick damage zone around the wellbore that could go beyond depth of penetration offered by conventional perforations
- Large uncertainty in (Permeability) Prognosis – Carbonates - Expect surprises!
- Inefficient clean-up due to insufficient delta P or deeper invasion in high perm zones leading to a turbulent drainage pattern into the wellbore
- Zero Intervention Philosophy - Well Completion Design
  - No interventions preferred for stimulation(acid jobs) in retrospect if wells do not flow at expected capacity
- Insurance against non-deliverability of wells due to formation damage
  - 100 MMSUD CAPEX per well
  - JV contributes to 40% of the Philippines Luzon Island’s power grid
What we needed?

- Some near wellbore stimulation to bypass any potential damage zone
- Not expecting new fracture generation as the reservoir was already fractured
- Propellant loading could be kept modest to achieve this objective
Acid Jobs vs. Propellant Assisted Perforation

- Complete stimulation of the reservoir section is very difficult to achieve using acid diversion techniques in a karstic environment due to the large variability in the permeability.

- Technology Solution: Propellant-assisted perforating technique - Stimulation with Perforation – STIMGUN

- Propellant-assisted perforating was considered as it achieves effective stimulation diversion equally across the entire perforated interval.

- Additionally, its usage eliminates the need for conventional, separate acid stimulation saving rig time and costs while reducing HS&E risks.
5.0 Due Diligence - MODELING for Malampaya Perforation Jobs
Overview
Perforation Modeling Objectives

- Can the 1.75” CT work for MP2 wells or do we need 2” CT?
- Do we need drag reducers or not?
- Does it take all the loadings (static) in worst case scenario – fluid inside CT and gas in well after perforation?
- How does the system react under dynamic pressure conditions in worst case scenario – uncemented liner with all the cement lost to the formation?
- What are the differential pressures expected across the packer and liner hanger in an Uncemented Liner scenario?
- Any coil collapse risks?
5.1 COIL MODELING for Malampaya Wells

Overview
## CIRCA Modeling – Static Loading – Coil Modeling Result

<table>
<thead>
<tr>
<th>Well</th>
<th>Malampaya</th>
<th>2.00&quot; GT-90</th>
<th>Without Drag Reducers</th>
<th>With Drag Reducers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CT String OD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gun Spec:</strong> 3-3/8&quot; Stimgun</td>
<td>Length (m) / Type</td>
<td>160 m</td>
<td>220 m</td>
<td></td>
</tr>
<tr>
<td><strong>Unperforated</strong></td>
<td>RIH Fluid in CT and Well</td>
<td>Feasible</td>
<td>Feasible</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POOH Fluid in CT and Well</td>
<td>Feasible</td>
<td>Feasible</td>
<td></td>
</tr>
<tr>
<td><strong>Perforated</strong></td>
<td>POOH Gas in CT and Gas in Well</td>
<td>Feasible</td>
<td>Feasible</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POOH Fluid in CT and Gas in Well</td>
<td>Not Feasible</td>
<td>Not Feasible</td>
<td></td>
</tr>
</tbody>
</table>

### Well MA

<table>
<thead>
<tr>
<th>CT OD</th>
<th>Conventional Gun Size</th>
<th>CT Grade</th>
<th>Maximum Gun Length (m) Possible with Gas in CT / Gas in Completion Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>2&quot;</td>
<td>3-3/8&quot;</td>
<td>GT-90</td>
<td>No Drag Reducers 160</td>
</tr>
</tbody>
</table>
CERBERUS Coil modeling for Well: In-house by Shell, Miri

In-house Coil modeling done for the higher inclination well apart from vendor’s modeling – No Static showstoppers (RIH/POOH) for 2” CT
5.2
PULSFRAC MODELING for Malampaya Wells
Overview
Biggest Uncertainty

- Quality of cement behind the 7” liner

*Figure 2 – Gas expansion of the burning propellant sleeve as the formation is fractured.*

- Model the Worst Case Scenario: Assume complete loss of cement to the depleted reservoir
StimGun is loaded at 30% coverage, burn is complete.

There is no fracturing but a surge effect has reduced the initial skin from +4.2 to zero.
Lack of reservoir pressure means no fracturing.

There is no “push back” from the formation, therefore pressure does not build up in the wellbore.

30% coverage does not provide enough energy to promote fracturing.

This is a result of the formation pressure allowing the gas to feed into the reservoir rather than building up in the wellbore.
# Pressure Differentials across Packer & Liner Hanger

## Packer

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.355 inch</td>
<td></td>
</tr>
<tr>
<td>7 inch</td>
<td></td>
</tr>
<tr>
<td>1.21E-02 sq.m</td>
<td></td>
</tr>
</tbody>
</table>

### Maximum dP Packer
- Value: 37 MPa
- Unit: PULSFRAC modeling

### Maximum Force Upwards
- Value: 447253 N
- Unit: 72%

### Packer Rating
- Value: 7500 psi
- Unit: 517 bar

### Differential Pressure
- Value: 52 MPa
- Unit: 625 kN

## Liner Hanger

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.355 inch</td>
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</tr>
</tbody>
</table>

### Maximum dP Liner Hanger
- Value: 47 MPa
- Unit: PULSFRAC modeling

### Maximum Force Upwards
- Value: 568132 N
- Unit: 568 kN

### Liner Hanger Seal Rating
- Value: 10000 psi
- Unit: 690 bar

### Differential Pressure
- Value: 69 MPa
- Unit: 834 kN

### Weight of Liner Hanger
- Value: 358 m^2 43.16 kg/m^3 * g

### Force downwards
- Value: 151423 N
- Unit: 151 kN

### Net Force on LH Upwards
- Value: 417 kN
- Unit: 50%
5.3 Labuan Yard Visit

Personal checks
Vendor Yard, Labuan, Malaysia

3-3/8” gun carriers
Vendor Yard, Labuan, Malaysia

Propellant sleeve
5.4
Connector Pull out Test

Baker
Sarawak well had a CT Connector failure in 2007 during a STIMGUN Job

Gun movement kick on the connector presents a dynamic load.

CT connector could be the weakest link and could fail before the coiled tubing.

Static load limit from coil modeling not acceptable.

To find out the pull out force from Coil Tubing Connector from vendor

2.88” OD Grapple Connector was used

Conducted in December 2012 in Houston at vendor’s facility

New 2” Tapered CTU (wall thickness 0.156” to 0.125”) used – which was planned for MP2 jobs
Conclusion: 2” Coil (which we used) was weak point. 2.88” CT connector passed the test.
6.0

Operational Overview

Learning From Incident LFI-PTW-I-D-201304
MP2 Perforation Jobs - Overview

- All charges on all guns fired on visual inspection.
- No H$_2$S content reported on gun POOH.
- Wells unloaded completely to gas in less than 24 hrs without any need for N$_2$ lifting via CT (back up Well Unloading Plan).
- Malampaya Well Test separators were opened in Labuan and found no debris at all. Confirms that the propellant was completely burnt.
- Fast Downhole Gauges were used at bottom of perforation gun successfully in both the wells to collect high frequency pressure and temperature data and the data was recovered for Post Job PULSFRAC Analysis.

- On one of the wells- Dropped Incident 70 kg dropped 10 m to rig floor.
Dropped Object

- X/over
- CCL
- Primary Firing head
- Connection to TCP
- Top
- Bottom
- A2 connector (Backed out)
- A1 connector
- 2 7/8” ACME thread Protector removed
Dropped Object Incident

- Occurred in the process of making up the Telecoil/firing head assembly onto the deployed TCP gun assembly
- Firing assembly released at an ‘A2’ Wireline connector and dropped 10 m to the rig floor.
- Weighed 70 kg and measured 2.2 m X 3.375”
- Drop event was in a controlled “RED” zone, which was barriered off
- Luckily, no crew was in the “RED” zone.
‘A2’ wireline connector was used in the firing head assembly
- Torque by hand and has no form of secondary lock mechanism
- Wireline connector typically used in a TCP toolstring
- Removing the protector introduced left-hand rotation into the assembly which resulted in the ‘A2’ connection backing off
- Assembly was inside the CT BOP and riser
- The reason for the wireline connection was related to the Tele-coil being included in the BHA, which is an unusual application for the vendor and hence different product groups of vendor working together to make a workable BHA: wireline (for the telecoil), CT, TCP and the telecoil group.
- Interface management between different groups of vendor needed more focus
Lessons Learnt

- Insufficient DROPS awareness of business partners
- Needs to be sufficient focus on technical and organizational integration across product lines when planning and executing unique and complex rig-ups
- Dedicated Meeting recommended for focus on Vendor Interface Management after CWOP workshop

Vendor

- A2 Wireline Connector Design Modification – Engineering in progress
  - Flipping the design to prevent water ingress into the connector
  - Additional key at bottom to lock the rotation of the assembly
- DROPS Bow-Tie Campaigns
A2 Connector Modification – Work in Progress by Vendor

Action:
A2 connections tool redesign for this type of Telecoil application

Status
Project approved and preliminary design completed. Currently under engineering review.
2 major changes – flipped the connector and added a key to prevent rotation. Release expected in late Q4.
Conclusions

- Stimulation was deemed necessary for Malampaya wells given the depleted reservoir and total losses scenario expected – 1 MM USD as insurance for 200 MM USD Subsea campaign for both wells.

- STIMGUN was selected based on optimization of rig time, ineffectiveness of acid jobs in a karstified, fractured carbonate and Process Safety considerations.

- 2” CT collapse risk mitigation:
  - Moderate propellant loading to 30%
  - Overbalance Perforation preferred to make system stiffer
  - Seawater + MEG mixture inside and outside coil (for hydrate prevention)
  - N2 lift contingency as well unloading plan if need be.

- 200 m Perforation guns perforated successfully with 30% propellant loading.

- Better inflow performance than expected: Benefit of near well bore stimulation & thick high perm reservoir sections.
Malampaya Perforation Design - Project Learning’s

- Always work very closely with vendor and do not assume
- GIGO modeling – Incorrect Assumptions – Wrong Interpretations – Fatality
- Get PTE/SME steer early into the Project to ensure all risks are completely assessed
- Static conditions modeling is not adequate – CIRCA, Cerebrus models
- Detailed dynamic analysis of actual BHA(Perforation) should be modeled including the accurate spacer lengths, blank section to assess the impact of pressure surges/dynamic UB
- PULSFRAC Modeling: Always update the models after drilling the reservoir section with actual LWD based reservoir quality info to see how the dynamic perforation wave impacts the bottom hole assembly and completion components and how much energy gets absorbed by the formation
Malampaya Perforation Design - Project Learning’s

- Check for differential pressures across packer and liner hanger components
- 12.8m spacer sub chosen for MP2 wells to ensure Top Shot below the Rotary for Operations Personnel Safety while RIH
- Ensure proper MOC is followed and take vendors along in all the discussions
- Time consuming Finite element modeling work in PULSFRAC
- Frequent crashes of servers – take snapshots frequently when doing PULSFRAC
- As a single operated asset in the Philippines, the operator Shell effectively leveraged on its global resources & expertise, e.g. global technology centers in India, Europe and US, and operations teams in the region. A degree of collaborative virtual working is essential for success in today’s world.
Presenter’s Info

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- Organization: Shell Projects & Technology
- Role: Production Technologist
- Location: Shell Technology Centre Bangalore, India
MA 11 Data Matching

- Some difficulty in getting the original files to match
- When we only looked at the Darcy plus perm area in the lower part of the interval we got a very good pressure layover.
- The propellant burned slowly due to the lack of confinement in the wellbore, the gas was flushed into the rock almost as fast as it was produced.
- There was probably more of a “washing effect” due to the high velocity froth being injected at very high rate into the reservoir.
MA12 Recorder Run – Lower Section

File Name: Copy of ma12 recorder run revised skin.pul
Run Date: 10/29/2013
View Date: 17/11/2013
Cutoff Time: None
Stop Time: 1.500000
Run Time: 1.500000

Notes: Increase Skin thickness .3m to 1m. Reduce skin perm from 50% to 20%. To measure impact on reflected wave.
MA12 Recorder Run – AVI Simulation Run
MA12 Recorder Run – Recorder data