Outline

- Kraken overview
- Artificial lift challenges
- Artificial lift selection
- Viscosity corrections
- Pump design optimisation
- Completion design
- Production infrastructure
- Summary
Introduction

Located in Block 9/2b
- Discovered 1985
- 400 km NE of Aberdeen
- 380 ft water depth
- Licensees: EnQuest, Cairn Energy, First Oil

Adjacent Heavy Oil Developments
- Bentley (Xcite)
- Bressay (Statoil)
- Mariner (Statoil)

Closest Field Analogue
- Mariner (Heimdal-III)
Reservoir & PVT

**Rock Quality**
- High porosity (>30%)
- High permeability (3-8 Darcies)
- Unconsolidated

**Formation**
- Heimdal-III sands (Palaeocene)
- 11 km x 1.5 km
- Relatively thin sands (30-120’, average 50’)
- High $K_v / K_h$
- No underlying aquifer (underlain by shale)
- High N:G (75-98%, average 90%)
- Low reservoir pressure (1742 psia)
- Shallow reservoir (3900 ft TVD-SS)
- Cool (108°F)

**Fluids – 3 PVT regions**
Key Artificial Lift Considerations

- Normally pressured, shallow reservoir – 3900 ft TVDSS
- Relatively high viscosity – 78 to 161 cP at reservoir conditions
- Low GORs – 85 to 147 scf/stb
- High drawdowns and offtake rates required for economics
- 5:1 increase in PI from initial dry oil conditions to late-life high watercut
- Preference for FPSO-based subsea development due to multiple drill centres required (4)
Typical Trends in Pressure, PI, Watercut

- High initial drawdowns
- Initially stable PI at 0% watercut, BHP constrained
- Rapid rise in PI as watercut develops
- Well becomes rate constrained at high watercut
- Drawdown diminishing with time
Effect of Temperature on Oil Viscosity

\[ T_{\text{RES}} : 42^\circ \text{C} \]

\[ T_{\text{seabed}} : 5^\circ \text{C} \]

Conclusion: need to retain heat in the system.
HSP - Principle of Operation

[Diagram showing the principle of operation of HSP, illustrating components such as CYCLONE, SEPARATOR SYSTEM, POWER FLUID PUMP, POWER FLUID SUPPLY, PRODUCED FLUID, COMMINGLED RETURN FLUID, CONTROL CHoke VALVE, TURBINE, PUMP, TURBINE EXHAUST PUMP DISCHARGE, and RESERVOIR FLOW.]

[Diagram comparison between OPEN LOOP and CLOSED LOOP configurations, highlighting differences in fluid flow paths and return systems.]
# Comparison of Artificial Lift Options

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**HSP:**
- Addresses flow assurance concerns
- Satisfies life-of-field performance requirements
- Excellent and well documented track record in analogue application
- SELECTED FOR DEVELOPMENT
Comparison of Artificial Lift Options

- **Gas Lift**
  - Not a contender – high lift rates required – little solution gas available.

- **ESP**s – feasible option but:
  - Sizing studies showed a single ESP design could not be used for life of field
  - Diluent injection below the pump or at the wellhead may be needed (or heating system) for startup
  - Very high number of power cables to accommodate in a FPSO swivel system

- **HSPs & Jet Pumps**
  - Overcome some of the key flow assurance issues presented by the high crude viscosity
  - Heated power fluid can be used to reduce fluid viscosity (and also pre-heat pipelines)
  - Both have similar efficiency, but at lower PI HSPs more efficient.
  - Track record of HSPs in subsea applications now much greater than jet pumps – over 45 HSPs installed in Captain
  - Downside – more fluids to handle topsides + additional pumps to provide power fluid.

**Final selection in favour of HSPs, based on:**

- Ability to deliver the required drawdowns and liquid rates
- “In-built” management of high crude oil and emulsion viscosities
- Expected high reliability – essential in subsea to minimise field OPEX
Key HSP Design Features

- **Ultimate Wear & Corrosion Resistance for Maximum Life**
  - Super Duplex, Nickel & Cobalt Alloys and Ceramic Bearings

- **Elimination of Mechanical Seal / Protector**
  - Simple throttle bush isolates between turbine and pump

- **Self-Regulating Turbine Thrust Balance**
  - Hydrostatic ceramic drum utilises clean feed from turbine

- **Robust Drive with Unrivalled Operating Window**
  - Compact, high speed, multistage water driven turbine

- **Low Inertia, High Precision One Piece Shaft**
  - Shop assembled integrated unit with no couplings

- **Ultra long Life Hydrostatic Ceramic Bearings**
  - Non-contacting for low wear utilising clean turbine feed

- **Class leading Performance to 75% Free Gas Level Continuously**
  - Patented multiphase pump stage design

- **Power Delivery via Simple Industry Standard Tubular Thread Connections**

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Circulation & Pre-heating Functionality

• **Flushing** – Following the shutdown, flow lines can be flushed with water to displace the hydrocarbons.

• **Pre-heating** – Hot water can be circulated in the flow lines to pre-heat all exposed subsea metalwork and mitigate any viscosity related issues.
Effect of Viscosity on Pump Design

- Oil viscosity higher than in earlier HSP applications
- Important to predict impact of high viscosity on:
  - Pump sizing – no. of pump/turbine stages
  - Power water pressure and rate requirements (facility design)
- Industry corrections unsuitable for axial flow pumps
- Conclusion: needed to perform flow loop tests to:
  - obtain corrections to head, capacity and power for viscosity & speed effects
  - assess fluid temperature rise across each stage & pump performance
  - refine stage-by-stage models of pump hydraulic performance
  - refine HSP modelling within proprietary nodal analysis
Flow Loop Testing – Sample Output

- Used to generate corrections for Head, Capacity as a function of:
  - Viscosity
  - % Best Efficiency Flowrate
  - rpm

- Used to validate predictions of temperature rise based on efficiency
Impact of P/T Variation on Viscosity and Head Correction

Original Image © Clyde Union Ltd
Selected a pump/turbine combination to maximise production within constraints:

- Represents significantly higher head and power requirements than for Captain HSPs
  - Final pump design > 24 x TP145AH stages (7 more)
  - Final turbine design > 18 x T60C – (7 fewer)
- Larger OD T60C turbine blade allows higher HHP to be generated with slight increase in PW supply pressure – more power fluid
Range of HSP Operation

Illustrates flexibility of HSP over life-of-field conditions from:
- Early, dry oil / low PI
- Late, high watercut / high PI
Completion Design

- No requirement for free flow facility – no free gas cap, normally pressured
- Significant well cost saving if 10 ¾” casing could be used instead of 11 ¾”
- Needed to confirm frictional pressure loss in annulus across clamps acceptable

**Conclusion**  > frictional pressures loss small, but not insignificant ~ 50 psi
Modelling Flow in Annulus around Clamps

- Concern that higher velocities could induce vortex shedding around clamps:
  - Depending on frequency, could cause excitation of control lines, inducing stress and mechanical damage
  - CFD analysis carried out to investigate flow behaviour

**Conclusion** > at the predicted frequency for vortex shedding, fatigue life of control lines effectively infinite – no issues
FPSO Design Capacities

- Peak Liquids Production: 460 mbd
- Oil Production: 80 mbd
- Water Production: 275 mbd
- Gas Production: 20 MMscf/d
- Water Injection: 275 mbd
- Power Water: 225 mbd
Summary

- HSP selected as the optimal solution for Kraken based on performance, operability and expected reliability
- Mitigates many of the flow assurance issues which high viscosity fluids would otherwise present in a subsea context
- Kraken HSP a significant uprating of existing design - addresses higher head and power requirements
- Completion design builds on the lessons learned on Captain, and simplifies where appropriate
- Subsea and topsides infrastructure has been designed around the requirements of the HSP
Acknowledgements

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