Oil & Gas Authority

Polymer Enhanced Oil Recovery

Industry lessons learned

October 2017

Foreword

The Oil and Gas Authority's (OGA) Enhanced Oil Recovery (EOR) Strategy[1] sets out a high-level overview of the long-term benefits of EOR and the expected role it has in support of maximising economic recovery (MER) from the UK. The accompanying document, the EOR Delivery Programme[2], set out the framework for EOR implementation in the UK, a method which is not yet mainstream in the UK.

If industry is to deliver on the OGA target of 250 million barrels of incremental reserves by 2021, more help and support is needed to provide industry with a balanced perspective on the benefits and complexities of implementing the technology. In the case of this report, it is polymer EOR.

The question was how best to do this. It is widely acknowledged that for a mature basin like the North Sea, success in polymer EOR has the potential to increase recovery, extend field life, create and maintain jobs, help stimulate field redevelopments and defer decommissioning activities. However, there is currently a wide range of understanding of polymer EOR technology among operators. It was concluded that a sharing of lessons learned by those operators who are active in this space was a good place to start.

This resulted in a call to action and formation of a joint industry task group in late 2016, which comprised four operators; BP, Chevron, Shell and Statoil. Over the last year, the task group has compiled the key lessons learned from decades of experience into a single document, to help inform other operators in the UK who are considering polymer EOR as part of their future field development plans.

The aim is to help companies considering future polymer EOR projects to move quickly up the learning curve and to understand the value these projects can add to their assets.

It is important to understand that the duration of the polymer EOR roadmap can be long and sufficient time must be allowed for success. It can be advantageous to actively work polymer EOR very early into a field's development timeline.

We thank those who have contributed to this document and hope you find these lessons useful.

Richard Hinkley
Industry Lead, Chevron North Sea Limited

Glenn Brown
EOR Manager, OGA

[1] https://www.ogauthority.co.uk/news-publications/publications/2016/enhanced-oil-recovery-strategy/

[2] https://www.ogauthority.co.uk/news-publications/publications/2016/eor-delivery-programme/

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Executive summary

There is a wide range of understanding of polymer EOR technology among operators in the UK.

If industry is to deliver on the OGA EOR ambition of 250 million barrels of incremental reserves by 2021, more help and support is needed to provide industry with a balanced perspective on the benefits, and complexities, of implementing the technology. This was the primary focus for the task group.

Data gathered from the OGA's 2016 Stewardship Survey show that there are six fields where there are plans to implement polymer EOR, potentially delivering some 194 million barrels of incremental reserves. This represents an incremental recovery factor of 5%.

These projects include the Chevron-operated Captain EOR in the Outer Moray Firth and BP-operated Quad 204 development in the Atlantic Margin. Both examples offer a rich source of lessons for other operators looking to frame and execute activity in polymer EOR.

Key lessons learned

The polymer EOR task group has reflected on all the lessons learned over a decade of implementing polymer EOR in the UK and consolidated them into eight lessons:

1. Importance of utilising a roadmap, process-based approach with a progressive ramp-up and staged expansion of polymer EOR, focused on pilots and brownfield scopes. This enables key uncertainties to be progressively mitigated before committing to the high cost of full field implementation. It begins with detailed laboratory experiments to get the polymer basis of design and compatibility established early.

2. It is important to understand that the duration of the polymer EOR roadmap can be long and sufficient time must be allowed for a successful outcome. The need to actively work polymer EOR very early in the field's development's timeline is essential.

3. There are certain conditions that will make polymer EOR very difficult to execute in a manner consistent with the OGA ambition target. If the asset is either a subsea development, has large distances between wells, or relies on surface water discharge, then the application of EOR will be more difficult. If a polymer EOR project is under consideration, the potential implications of these development choices need careful consideration.

4. There is a good business case for EOR. It is important to look long term when considering the technology and understand the benefits. Late life incremental barrels provide the opportunity to manage long term cost structure, cash margins, and extend asset life.

5. It is widely recognised that the supply chain has excellent competency in EOR, but there is an opportunity to standardise a suite of experiments that should be consistently applied and available to all, to assess the compatibility and polymer selection. API RP 63 provides methods for evaluating polymers but it is out of date. Over time, the industry has revised methods to improve efficiency and address observed differences in performance between the laboratory and pilot. A new set of standard tests could accelerate product screening and reduce project evaluation time and cost.

6. Polymer injectivity must be sustainable long-term if incremental oil recovery targets are to be realised. There is a risk that polymer injection can cause deterioration of injectivity relative to water injection. Understanding and mitigating this risk must be a high priority, early in the project de-risking process.

7. It should not be expected that all EOR uncertainties can be resolved in a single pilot. Plan for multiple pilots to de-risk a project (as noted by the Captain Field case study). Make sure pilots are planned appropriately, with clear expectations and expected lessons and these are openly communicated to decision makers.

8. Any EOR deployment needs to consider the end-to-end learning and attention needs to be paid on polymer returns through the production system, early, so the production efficiency impacts are fully understood and built into the economics. Back-produced polymer can be managed, but needs early attention.

9. There are regulatory requirements on polymers that need to be fully considered, early, to avoid surprises.

By focusing attention to these areas of learning, it will be possible for other operators considering EOR to avoid the pitfalls identified by others who have managed EOR projects for many years. It will help improve the framing, business case and ultimately execution of EOR in delivering on MER UK expectations.

1. Joint industry task group

The EOR task group was established to bring together industry leaders in polymer EOR, noting that the best way to promote polymer EOR is to have evidence that others have managed to apply the technology and create value.

The purposes of the task group include:

- Grow industry capabilities that address principal barriers towards implementation of the EOR Strategy and associated Delivery Programme
- Focus on MER UK, not individual owner positions; leverage the best practices from operators currently investing in polymer EOR
- Collaboration and partnership through a series of six OGA workshops; a place to meet in small groups and learn from other operators
- Respect the intellectual property (IP) of companies by focusing on sharing non-confidential information

The activities in the EOR Delivery Programme are being monitored by a joint industry task group made up of members from BP, Chevron, OGA, Shell and Statoil and reviewed annually by the MER UK Asset Stewardship Task Force.

Terms of reference and charter

The task group has collated a set of guiding principles using industry expertise, best practices and lessons learned in the area of polymer EOR.

This work also addressed some of the barriers to implementing the EOR Strategy and Delivery Programme and identified the following as focus areas for collaboration:

- **Polymer project de-risking**
- **Polymer EOR injectivity**
- **Polymer testing standardisation**
- **Impact on operations from produced polymer**
- **HSE considerations for polymer EOR**

Through collaboration in the above areas, the task group seeks to:

- Publish a polymer EOR Starter Pack, including industry lessons learned and recommendations that assist UK operators to identify and evaluate EOR and accelerate their capabilities to address key issues and mitigations (this document)
- Establish an industry-led forum to discuss polymer EOR focus areas, risks, issues and mitigations

2. How does polymer EOR work?

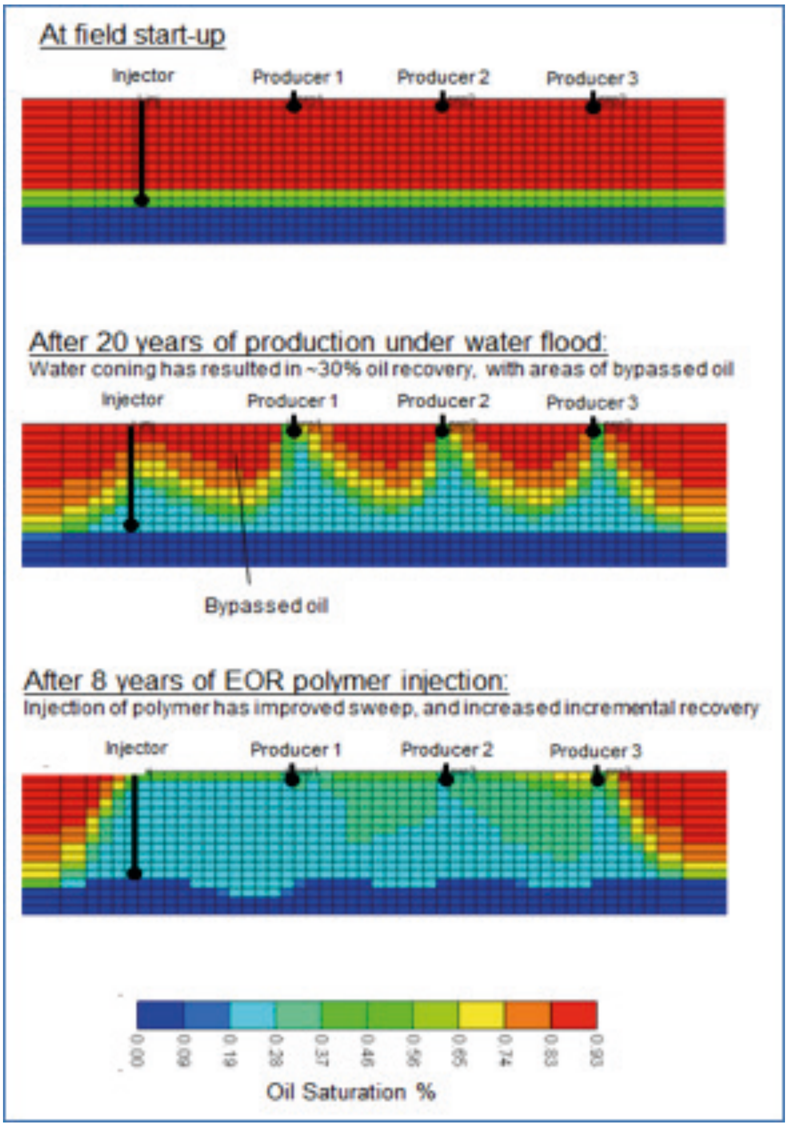
In an offshore reservoir, polymer EOR is designed to improve the sweep of existing water flood systems.

In traditional water flood systems, water is pumped through injector wells to push oil towards production wells. In many reservoirs, the water flood narrows its course between the injector wells and the producers. This results in 'coning' or 'fingering' patterns whereby potentially large volumes of oil-saturated rock are bypassed by the water flood and the oil therein is not recovered.

To improve water flood sweep efficiency, an operator can increase the viscosity of injected water with polymers. This reduces the tendency of water to bypass or finger through oil, thereby sweeping more oil toward production wells to significantly improve recovery.

Two most commonly used types of polymers are synthetic (typically characterised as a partially hydrolysed polyacrylamide or HPAM) and biopolymers. Currently, synthetic polymers are the most widely deployed technology solution.

Figure 1: An example of polymer EOR injection profiles



3. Link to the OGA EOR Strategy

EOR Strategy and Delivery Programme

OGA's Enhanced Oil Recovery (EOR) Strategy sets out a high-level overview of UK EOR opportunities. The importance of encouraging industry uptake of EOR was outlined in the Wood Maximising Recovery review and subsequently EOR is an integral theme of the MER UK Asset Stewardship Task Force.

The EOR Delivery Programme builds on the EOR Strategy and describes in more detail how and when the near-term priority areas in EOR will be delivered. The objective of Element 2 of the EOR Delivery Programme is to ensure EOR opportunities are identified early enough in the field life cycle to maximise economic recovery and therefore focus on progressing future EOR projects. The relevant activities defined are:

Introduce early EOR screening for regulatory approval in draft FDPs

- EOR screening is part of the regulatory approval process in FDPs
- There's an obligation for operators to justify why EOR is not being used
- The OGA will ensure that in preparation of FDPs, the appropriate level of EOR modelling/screening has been completed and future EOR forecasts presented

Promote the progression of high-graded EOR resource opportunities

- Ensure operators maximise EOR benefits and economics
- Support EOR to identify barriers to deployment and help provide mitigations
- Support and encourage EOR in heavy oil fields

OGA Asset Stewardship Expectations

The OGA Asset Stewardship Expectations encourage the assessment of EOR. In consultation with the industry, the OGA has developed stewardship expectations across the oil and gas lifecycle, for operators and licensees. These expectations are aligned with the MER UK Strategy supporting obligations and are designed to help achieve consistent stewardship performance.

Relevant to the polymer EOR work described in this document is the Section 2.1 "Reservoir, wells and plant technical limits" of the Implementation Guide for SE-06 – Production Optimisation which states a requirement to have technical limit processes in place for reservoir, wells and plant:

- Understand the recovery technical limit and current predicted recovery, and then evaluate and select future recovery options (new wells, improved oil recovery, enhanced oil recovery) to maximise economic recovery.
- Identify the associated technology and/or production strategies required to maximise economic recovery.

4. Size of the prize

There are three sources of data: what is published, what is estimated from screening studies and what is submitted to the OGA as part of the annual UKCS Asset Stewardship Survey.

Asset Stewardship returns

The objective of Element 1 of the EOR Delivery Programme is to ensure current EOR projects are progressed in line with their Field Development Plans (FDPs).

The OGA's ambition is to drive economic development of 250 million barrels of incremental reserves, primarily through polymer EOR. It is also to create an environment where operators and the supply chain work together to support existing projects to ensure readiness for future projects and to drive risk reduction via technical and economic improvement.

Data from the 2016 UKCS Asset Stewardship Survey show six fields have reported total incremental polymer EOR reserves with an estimated volume of 194 million barrels. This represents an average polymer EOR % Stock Tank Oil Initially In Place (STOIIP) of 4.7%. The average water flood recovery of these fields is 29.8%.

This demonstrates good progress of operators towards the OGA ambition.

Beyond the survey results, there are another four fields (primarily in Quad 9) where the OGA has estimated that a total of 258 million barrels represents a further potential polymer EOR % STOIIP of 5.4%. The average water flood recovery is 22.1%.

These results are summarised in the table below:

Polymer EOR Information		Number of fields	Estimated STOIIP (mmbbls)	Waterflood base case (mmbbls)	Polymer EOR (mmbbls)	Waterflood % STOIIP	Polymer EOR (% STOIIP)
Tranche 1	2016 Stewardship Survey data	6	4128	1230	**194**	29.8	4.7
Tranche 2	OGA future potential	4	4784	1055	**258**	22.1	5.4
Trance 1+2	**All polymer EOR**	**10**	**8912**	**2286**	**452**	**25.6**	**5.1**

Previously published PILOT EOR studies

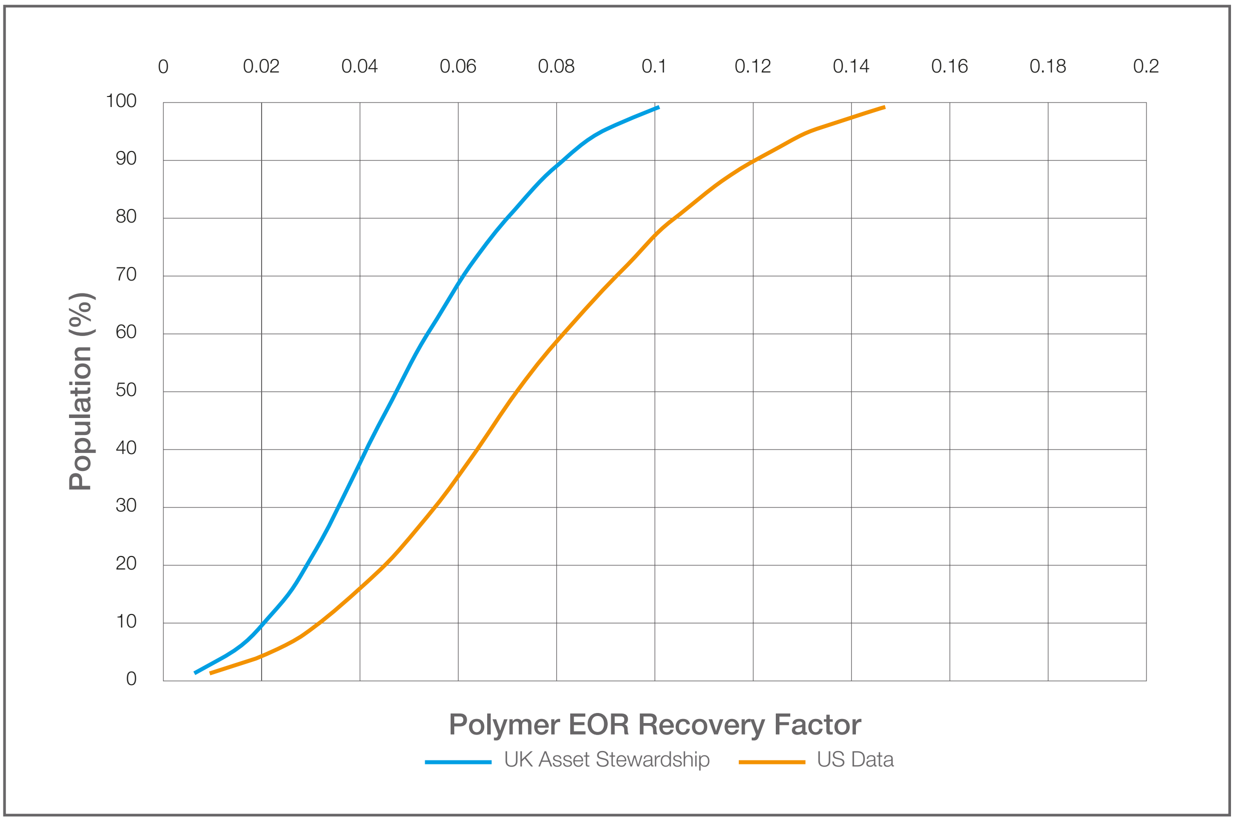
In 2014, the PILOT EOR Workgroup made significant progress in raising awareness of EOR in the North Sea and stimulating industry cooperation in EOR technologies. The PILOT EOR Workgroup's work was summarised in SPE 172017 "Maximising Enhanced Oil Recovery Opportunities in UKCS through collaboration".

Benchmarking UKCS Asset Stewardship Survey with US published data

A number of USA onshore polymer projects have been summarised in SPE – 174541 – Status of Polymer-Flooding Technology. These USA data have been plotted in orange in the figure below. The potential UKCS polymer EOR project portfolio is shown in blue. It can be seen that the UK data are more conservative than the USA data. The estimated recovery factor for the 10 UKCS offshore polymer projects ranged from 1% to 11%.

The UKCS offshore operating environment, wider well spacing, increased polymer supply costs all play a role in impacting the potential polymer EOR prize. The estimated UKCS polymer EOR prize may increase as new projects are identified and offshore polymer EOR technology is developed and successfully deployed. The lessons learned from this work will also play a role of increasing the prize.

Figure 2: Incremental oil recovery (potential UKCS polymer projects compared to US projects)



5. Current and planned polymer projects

Currently there are some significant polymer EOR projects under development in the UK, highlighting the possible benefits for EOR to late life, mature assets and new developments.

Captain

The Captain Field is situated in the Outer Moray Firth, in water depths of roughly 346 feet (105.5 m). Discovered in 1977 in Block 13/22a, the Captain Field achieved first production in March 1997 and reached peak production of around 100,000 barrels a day. The basis of design was long horizontal producer and injector pairs and water flood from day one with no surface water discharge. The average distance between wells in Captain is around 250m. The current recovery factor is around 30%.

The Captain EOR project is designed to increase field recovery by injecting polymer solution into the Captain reservoir. A synthetic HPAM polymer is being used for the project and the proposed brownfield expansion will be centred on the existing Captain infrastructure, located in a segment of the field supported by the existing platform area.

In total, polymer was injected into four wells to get the confidence to proceed with stage 1 of the project. The expected incremental recovery from EOR, on a sector basis, is around 5%.

Key to success has been an expanded pilot programme between 2010 and 2017 that has been used to validate the incremental recovery factor, polymer quality, supply chain logistics, and long term operability and integrated with base business.

Part of Captain's EOR success is due to the optimum configuration of the field, with respect to:

- **Reservoir:** High quality porosity and permeability sandstone that is laterally extensive
- **Fluid properties:** Heavy oil (18o API, 85cP) that benefits from changes in mobility ratio between oil and the introduction of polymer solution
- **Well configuration:** Average distance between wells is around 250m, which means the lag time between injection and production response is only a few months, instead of years, enabling performance enhancements to be made as required
- **Water production:** There is no surface discharge of water introducing environmental risks
- **Runway:** Sufficient time remaining ahead of decommissioning to get sufficient incremental recovery that delivers a strong, economic project

The initial expansion phase is expected to include at least six long reach horizontal injection wells drilled in Area A. This initial brownfield expansion will likely include bulk provision of chemicals and facilities modification on the existing Captain wellhead protector platform, the installation of new polymer mixing equipment to expand processing capacity that will tie-in to the pre-existing injection system and polymer storage facilities.

The full field expansion of EOR will be dependent on the success of stage 1.

Quad 204 (Schiehallion Area)

The BP operated Schiehallion and Loyal fields are located 175km west of the Shetland Isles in around 400m water depth. The fields have been on production since 1998 and achieved a plateau rate of approximately 120,000 barrels per day.

All wells have subsea wellheads and are tied back to an FPSO through flowlines and risers via five drill centres. In 2006 BP and its license partners embarked on the Quad 204 project to re-develop the greater Schiehallion area through investment in a replacement FPSO, improved subsea infrastructure, well interventions and a significant infill well programme.

Provision for a potential future polymer EOR scheme was made in the design of the new FPSO, the Glen Lyon. Production from the Schiehallion field restarted in May 2017 following a four-year production shut down.

- **Reservoir:** Palaeocene turbidite sandstone channels, cross-cut by faults
- **Fluid properties:** Medium Oil (26o API and 1.5 to 4cP)
- **Well configuration:** Typical distance between producer and injector pairs is approximately 1 to 1.5km meaning there is a residence time of a few years. All wells have subsea wellheads and are tied back to the FPSO through flowlines and risers via five drill centres
- **Water production:** All produced water is reinjected under normal operating conditions

A polymer flood, utilising an acrylamide-based polymer (HPAM), is currently being evaluated. Polymer flooding seeks to improve oil displacement efficiency by increasing the viscosity of the injected water-flood. A more viscous flood gives a lower mobility ratio of injected brine to displaced oil, improving local, areal and vertical sweep efficiency and increasing oil recovery.

Four primary issues relating to the success of a polymer flood in Schiehallion and Loyal are:

- **Thermal degradation:** Loss of viscosity in the reservoir
- **Shear degradation:** Loss of viscosity due to pressure drop across subsea chokes
- **Injectivity:** Reduction in injection rates on switching from water to polymer
- **Produced polymer:** Impact of back-produced polymer on efficacy of water handling equipment

A further consideration is the adverse weather conditions west of Shetland which makes the deployment of a liquid, rather than a powder polymer the only practical choice. If the polymer flooding scheme is sanctioned, the Schiehallion area will be one of the first full-field offshore schemes utilising this technology.

Mariner

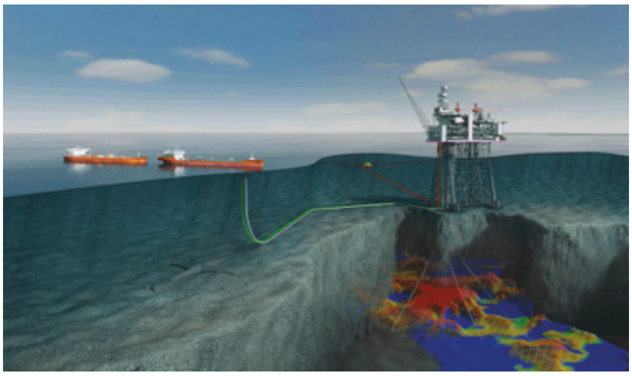
Discovered in 1981 on the East Shetland Platform, approximately 150 kilometres east of the Shetland Islands, the Mariner field has been subject to several development studies by different operators. Statoil was the first company to put forward a development concept that will fully address the complexities of this field. The Mariner field is operated by Statoil on behalf of joint venture partners JX Nippon, Siccar Point Energy and Dyas.

The chosen concept includes a production, drilling and quarters (PDQ) platform based on a steel jacket, Mariner A, with a floating storage unit (FSU), Mariner B. Drilling will be carried out from the Mariner A drilling rig, with a jack-up rig assisting for the first few years.

The development of the Mariner field will contribute more than 250 mmbbls reserves with average plateau production of around 55,000 barrels per day. The field will provide a long production period of over 30 years. Production is expected to commence in H2 2018.

Reservoir: The Mariner oil field consists of two shallow reservoir sections: the deeper, Maureen formation at 1,492m and the shallower Heimdal reservoir at 1,227m.

- Maureen: Deep water turbidites, high porosity multi-Darcy sand with good connectivity
- Heimdal: Deep water channels and re-mobilised sand injectites, high porosity and high permeability (>10 D) poorly consolidated isolated sand bodies



Fluid properties: Heavy oil with API gravities of 14 and 12 and viscosities at reservoir conditions of 67 cP and 508 cP, respectively for Maureen and Heimdal.

Well configuration: Horizontal producers and highly deviated water injectors.

- Maureen: Peripheral water flooding with ~ 800-1200m distance between injectors and producers
- Heimdal: Wells targeting individual mapped geobodies with ~ 150-200m distance between injectors and producers

Water production:
Produced water and additional make-up water from a dedicated water producer will be injected into the reservoir for pressure support and voidage replacement.

Detailed screening work of various EOR methods revealed that the polymer flooding can be the most promising EOR method for Mariner to enhance oil recovery. Polymer is used to increase the viscosity of the injection water to improve sweep, reduce water production and improve recovery.

Fine scale reservoir modelling and simulation work demonstrated that the high mobile oil saturation, degree of reservoir heterogeneity, reservoir temperature, water salinity and free potential for cross flow in Mariner reservoirs also promote the potential for polymer flooding.

A project to mature polymer flooding for Mariner will progress in parallel with the main field development work. The polymer flooding project has been matured to technical feasibility (DG1) level.

6. Benefits of polymer EOR

Business potential of polymer EOR

Many different value drivers should be considered in the business potential for polymer EOR development, including employment opportunities, development of capabilities and development of a supply chain with export potential.

In order to create a sustainable and profitable EOR industry, it is important that EOR projects are economic and competitive. Although economic and competitive projects are a pre-requisite for industry to invest and develop, there can be multiple aspects that drive this value:

- Delivering higher recovery
- Adding reserves to lower cost per barrel in mature assets
- Potential to extend field life
- Accelerate production within technical limits of facilities
- Optimise water production and management
- Lower water handling associated cost
- Creating ullage in existing facilities to pursue other development opportunities
- Strategic value of being recognised as a competent operator with successful polymer flood capabilities

Delivering higher recovery

To enable polymer EOR projects to proceed, reliable estimates of operational performance and incremental recovery ranges are required. Laboratory tests, yard and field trials and pilots can help validate these predictions. This report outlines a roadmap of activities that every operator considering the application of polymer EOR can use to improve outcome predictions and manage expectations.

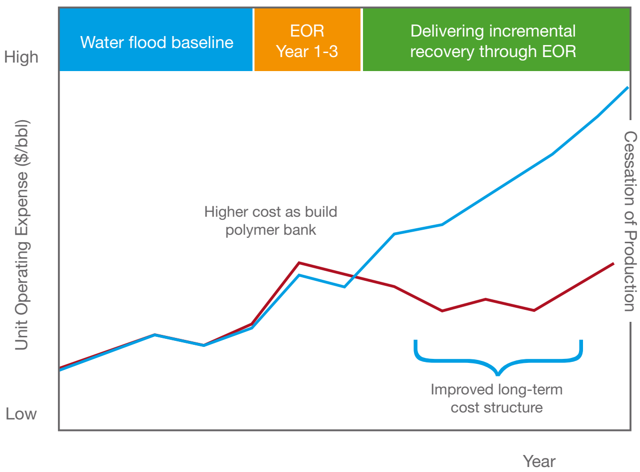
Optimise water production and management

Execution of EOR requires less injection fluid, which can either (i) enable Integrated Production System Optimisation (IPSO) (such as new water flood in a different segment of the field), or lower water production rate, which in turn can lower plant operating costs and lower emissions on CO2/tonne basis.

Potential to extend late life assets

While it is true that the cost of a barrel of polymer solution is higher than the cost of normal water, these costs are more than offset by incremental oil production, which means that costs on a $ per barrel basis can be successfully managed over the long term. Late life incremental barrels provide the opportunity to manage long term cost structure and extend asset life, as outlined in the generic schematic below:

Figure 3: Example of the long-term benefit for EOR. By delivering more incremental oil, the additional cost of polymer injection and facility operating cost results in a $ per barrel cost that is more sustainable, with potential to defer COP.



Improving economics of polymer EOR

It was beyond the scope of the EOR task group to consolidate lessons learned related to the economic viability of EOR for individual assets, other than to summarise that projects currently under execution in the UK have a favourable value proposition.
More information is available within SPE Paper 175470 by Kemp and Stephen entitled “The Economics of EOR Schemes in the UK Continental Shelf (UKCS)”, which provides a detailed analysis of the economics aspects of EOR including two polymer EOR cases.

7. Key focus areas for collaboration

The EOR task group prioritised five polymer EOR activities:

Polymer EOR project de-risking

Build industry capability to de-risk EOR projects by identifying options to mitigate or manage risks associated with pilot and full-scale EOR deployment. Focus areas will be injectivity, subsurface uncertainty, logistics, capital and operating costs, operational issues, production efficiency and HSE. This work will result in recommendations for managing risks, reducing costs and improving project economics in combination with appropriate incentives.

Polymer EOR injectivity

Understand injectivity loss during polymer injection and provide robust de-risking strategies. Injectivity loss and subsequent reduced throughput is one of the main risks in polymer injection and early consideration as part of a de-risking strategy is recommended. It can erode the value of the polymer and put base water flood performance at risk. The underlying reasons for changes in injectivity during offshore EOR polymer injection and the likelihood of injectivity problems occurring should be evaluated and calibrated to industry experience along with appropriate de-risking strategies for prevention, mitigation and remediation.

Polymer EOR testing and standardisation

Develop standardised tests of polymer products for EOR, allowing fair and consistent comparisons to be made and providing consistent onsite QA/QC criteria. API RP 63 provides methods for evaluating polymers but it is out of date. Industry practitioners have revised methods to improve efficiency and to address observed differences in performance between laboratory studies and deployment at scale. Original procedures were developed for conventional polymers and are not necessarily suitable to evaluate the extensive array of today's new polymer chemistries. A new set of standard tests could accelerate product screening, reduce project evaluation time and cost, consistently assess impact on produced fluids and enable cross-industry exchange.

Health, safety and environmental considerations for polymer EOR

Establish knowledge in relation to persistence and degradation of polymers in the marine environment and thereby obtain a more complete understanding of environmental risk. Standard biodegradation tests indicate very low biodegradation, but it is important to study other potential types of degradation such as biological, chemical and physical degradation (such as via UV radiation and oxygen radicals) in the marine environment. This work can enable acceptable standards and thresholds for disposal to be determined.

Impact on operations from produced polymer production

It's important to understand and mitigate risks associated with produced polymer in the production facilities. Once polymer breaks through into the producing wells, both the produced water quality and processing may be impacted (including separation efficiency, water treatment, polymer precipitation at elevated temperatures). Understand impact mechanism and develop standardised methods for mitigating these risks.

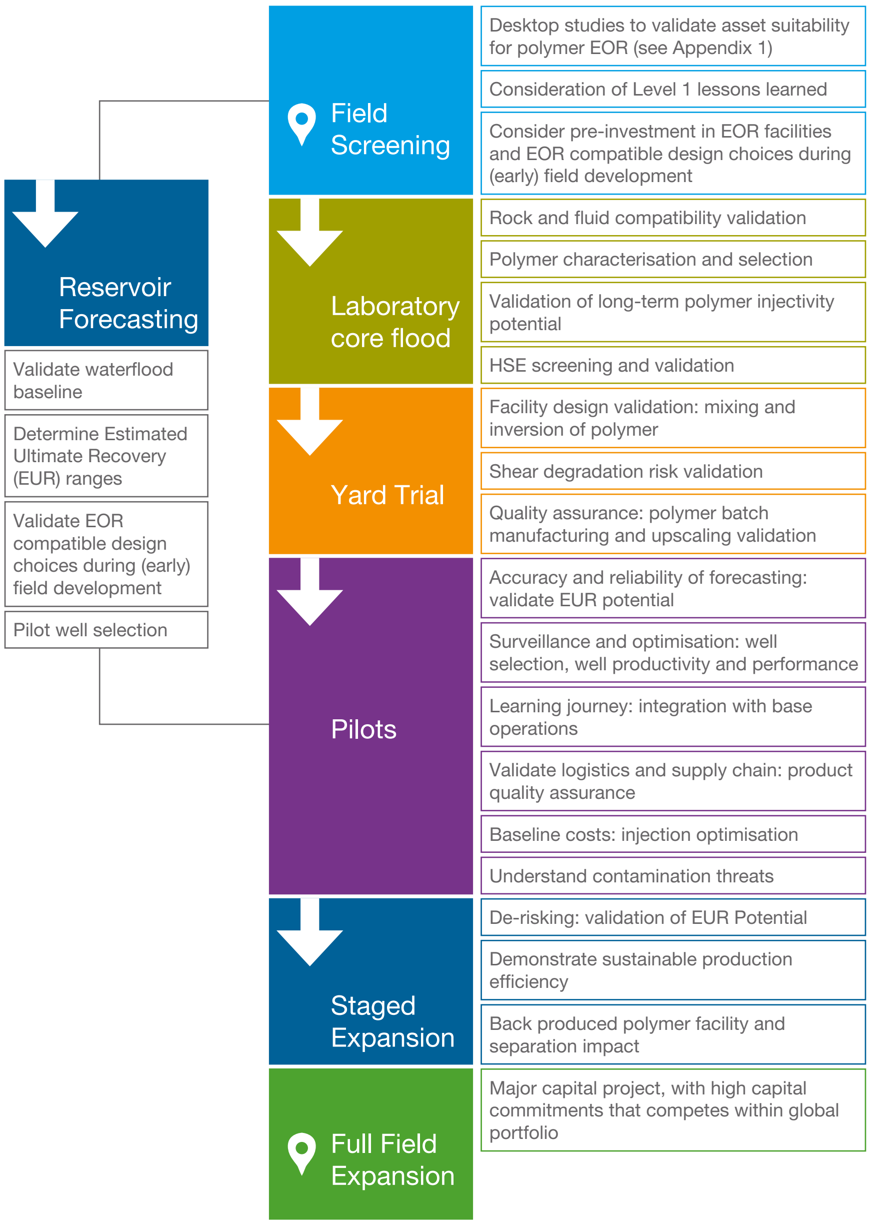
8. Roadmap to implementation

One of the key lessons learned from the EOR task group, is the acknowledgement for the need of a roadmap to implementation for polymer EOR.

This roadmap can assist operators to identify and evaluate polymer EOR opportunities and to accelerate their capabilities by addressing key issues and developing potential mitigations.

The Polymer EOR industry roadmap is outlined below. This outline roadmap for polymer EOR represents a generally accepted view of the multiple stages that a successful EOR project has to go through to mature from screening of the field through full field expansion.

Figure 4: Outline roadmap for polymer EOR



Polymer EOR competency

It is often the view that the technical expertise required to develop and manage a polymer EOR flood limits its application. It is true that there is a significant level of technology development and intellectual property associated with developing bespoke chemical formulations that are tailored to specific reservoir conditions.

While this expertise resides primarily within the operating companies involved, there is also significant expertise within the supply chain to support the deployment of EOR.

Suppliers are in a position to leverage their experience working across existing projects as well as transferring relevant expertise from elsewhere such as water treatment and paper manufacturing.

At the same time, reservoir management techniques continue to improve, particularly in simulation workflows, to better characterise the incremental recovery to build a business case.

Field polymer EOR screening

Early screening of a field's potential for polymer EOR is important as it can influence pre-investment decisions to enable future implementation of an EOR scheme.

The objective is to understand the portfolio of EOR opportunities based on specific field/asset characteristics that are deemed favourable for effective polymer EOR implementation. Not all fields have favourable characteristics for EOR and some fields can therefore be eliminated from consideration.

The technical screening allows an early identification of EOR so efforts can be allocated to focus on the where there could be a potential impact. This will also enable potential pre-investments in EOR facilities and EOR compatible choices being made during (early) field development and execution. Appendix 1 provides more information on criteria for polymer EOR screening.

Laboratory screening

The objective is to select and/or develop the right polymer package for the specific field characteristics at hand. Chemical screening should consider factors such as chemical stability along the supply chain from manufacturer to the reservoir, chemical integrity within the reservoir, facility complexity, operational robustness, supply chain reliability and commercial viability.

Yard testing

The objective is to prove the chemical's operational performance under representative facility arrangements and under varying operational conditions before taking the product to the field.

Pilot

The objective of pilots is to resolve key uncertainties associated with the specific project, gain early operational experience in the field and to de-risk key components of the project that are barriers to full field implementation. Typically, the main driver for pilots is value of information.

Early production system

Early production systems can help prove early commerciality of the EOR application under field conditions whilst further de-risking expansion and/or full field application. Early production systems can be leveraged to enable a staged development approach, accelerating polymer related production whilst maturing larger scale field expansion projects.

Field expansion

The objective is to leverage experience, knowledge and lessons learned that were gained along the EOR roadmap to maximise economic recovery of the field using the EOR recovery mechanism. This MER objective can be achieved through different approaches, varying from only a partial field development, a staged development approach or a full field implementation.

9. Industry lessons learned

More than any other type of EOR, polymer flooding is a bespoke process that needs to be optimised for the individual assets and there are some potential pitfalls that need careful consideration. The EOR task group have laid out the lessons learned using a level 1-3 system to help inform other operators:

- Level 1 is considered to inform a go/no-go decision for EOR
- Level 2 is a summary of work scopes that would be needed to optimise an EOR decision
- Level 3 are the specific lessons learned for each category

Level 1 considerations

There are three criteria that were considered to have a significant influence on the realistic and pragmatic expectations from EOR. It is not meant to portray these factors as showstoppers, but instead should highlight the need for a feasible technical solution before proceeding too far along the EOR roadmap.

Observation	Lessons learned
Subsea development	The potential shearing of polymer through subsea choke reduces viscosity to a level where it can be rendered ineffective (see level 3 summary). Mitigations would require either (i) overdosing (ii) injection downstream of the subsea chokes, or (iii) deployment of new technology associated with delayed action polymers.
Well configuration and spacing	Retention time for the polymer within the reservoir. The wider the well spacing the greater the lag time between injection and oil recovery. This will mean that the risked cost of capital will be higher on consumables (due to the lag time) and more time to validate EUR as part of the roadmap. There is also the risk that the polymer can deteriorate in-situ due to chemical or thermal attack, leading to loss of viscosity and erosion of incremental benefit. Both of these effects will impact the business case for EOR implementation.
Surface water discharge	Managing environmental risks (see level 3 summary).

Level 2 considerations

There are many technical hurdles in the deployment of EOR and the highest-ranking areas have been mapped to a process flow diagram summarised in the table below (courtesy of Quad 204 partnership).

PFD Element	Level 2 focus areas to make polymer EOR a success				
Polymer Supply	Minimising batch variation	Design and operability of emulsion storage	Optimised transportation route	Optimising and importance of vendor selection	
Injection Facilities	Effective emulsion inversion		Produced water specs	Acceptable emulsion filtration	Polymer QA
Subsea Infrastructure	Mitigation for mechanical, or choke degradation				
Injectors/ Producers	Minimising well bore damage and maintaining injectivity	Material compatibility			
Reservoir	Understand shearing at sand face	What is the adsorption/ RF/RRF	Fracture growth impact	Long-term polymer stability	Deliver incremental oil
Production Facilities	Managing back-produced polymer	Production chemistry compatibility	Risk of heating/ precipitation		
Production Facilities	Polymer/ produced water discharge	Refinery impact/crude value	Off-spec polymer disposal		

Level 3 polymer EOR focus area objectives opportunities/challenges and lessons

Below is a summary of the lessons learned that were collated from the six EOR task group working sessions for each of the Level 2 focus items.

1. Polymer characterisation and selection

Objective: To provide guidance on testing methods to inform polymer selection

Key lessons learned:

Observation	Lessons Learned
The API RP63 standard to characterise polymer rheology is not accurate/ reproducible enough for low viscosity floods currently being evaluated.	Use of modern low shear rheometers (such as the Anton Parr MCR302 with a double gap adaptor) to allow accurate viscosity vs. shear curves to be measured. Target viscosities should be those on the lower Newtonian plateau, which are representative to the low shear regime deep in the reservoir.
Poor inversion of some (liquid) emulsion polymers can impact well injectivity.	Emulsion polymer inversion is a function of variables such as injection water salinity and temperature. Before field trialling, large-scale yard trials demonstrating full inversion should be performed. Complete inversion of fluids can be demonstrated using core flood injectivity tests.
Laboratory testing can fail if emulsion polymers are not fully inverted. The high shear regimes required to invert emulsion polymers, cannot be replicated in the laboratory.	For early laboratory studies, to ensure full polymer inversion, it is advised to request polymer vendors to supply emulsion polymer fully inverted in the brine of interest. Alternatively, full polymer inversion can be checked by measuring inverted solution viscosity build-up with time. The viscosity of the final time-step should then be re-measured after dosing additional surfactant.
Polymer may thermally degrade in relatively low temperature reservoirs, when reservoir residence times are long, for example offshore polymer deployment, where well spacing is large.	Laboratory tests can address the risk, when done with understanding. Options include sample preparation and storage in a high specification anaerobic glove box or sample preparation in said anaerobic glove box followed by use of bombs for long term storage.

Observation	Lessons Learned
Polymer thermal stability for the project may be unknown in the early project stages as an accelerated thermal stability test has not yet been identified.	These long duration tests must be identified in the project schedule.
Concerns over polymer thermal stability can result in a high OPEX cost in over-specifying the polymer.	Laboratory testing should include standard polymers and more thermally stable polymers.
The API RP63 standard to measure polymer filtration ratios is not stringent enough to assess injectivity risk.	Filter ratio test with finer filters and larger volumes can be designed for screening tests. Injectivity risk is better assessed with long term core injectivity tests cores (>1000pore volumes). This test is under matrix injection and should use synthetic brines, as the solids in produced fluids may plug the core without polymer present.
Obtaining the laboratory polymer measurements required as input parameters for reservoir model to estimate likely incremental oil. These include polymer adsorption to rock, Resistance Factors (RF) and Residual Resistance Factors (RRF).	Tests can be done in-house using company proprietary methods. Test can be out-sourced to competent laboratories. Venture partners should reach agreement on test protocols ahead of testing.

2. Shear degradation

Objective: To prevent and/or minimise viscosity loss of injection fluid due to shear degradation

Key lessons learned:

Observation	Mitigations/recommendations
Shear degradation when injecting into the reservoir.	Shear degradation in the near-wellbore area may be significant. It has to be quantified in order to prevent excessive degradation of polymers.
Shear degradation throughout facilities at any point where the pressure undergoes significant change.	Where subsea infrastructure is already in place, a delayed action polymer may offer a chemical solution to shear degradation. Solutions such as surface overdosing would add a long term operating cost burden and may exacerbate produced liquid processing issues. An alternative solution can be to inject polymer downstream of restrictions (usually injection chokes) which can offer the additional benefit of polymer optimisation on a well by well basis.
Shear degradation throughout facilities at any point where the pressure undergoes significant change.	Considering the removal of shear points from polymer injection system design, where possible, is important.

3. Project definition and design

Objective: Clearly define scope, objectives, uncertainties, risks and value criteria for the EOR project so that development and implementation activities can be efficiently aligned

Key lessons learned:

Observation	Lessons Learned
Performing pilot activities in isolation of an overarching project roadmap may not effectively enable timely EOR project maturation.	Start with the view of an overarching EOR project implementation in mind and ensure pilot activities are fully integrated. Consider progressing the overarching EOR project in parallel to pilot activities to accelerate project timelines.
There is no one-size-fits-all EOR solution.	Polymer flood design needs to be tailored to specific field attributes and risk profiles. Ensure a structured and well thought development approach with early sensitivity work on polymer slug design parameters and timely project de-risking.

4. Pilot and de-risking strategy

Objective: Develop a pilot strategy that addresses key uncertainties and risks in a timely manner to mature further field expansion

Key lessons learned:

Observation	Lessons Learned
Project uncertainties and risks are often considered too big to commit to an early full field project sanctioning.	Start with early risk and uncertainty identification and definition to establish a learning plan and associated piloting strategy. Consider resolution alternatives (yard testing, field injectivity and/or pilot/EPS strategies) and clearly define test/pilot objectives. Consider facility pilots (for example spiking production side with produced polymer). Consider a staged development approach with specific learning objectives for each stage.

5. Injectivity assessment and management

Objective: To prevent and/or minimise injectivity loss due to polymer injection

Key lessons learned:

Observation	Lessons Learned
Polymer impact on injectivity can be highly variable between wells.	1. Consider multiple injectivity tests within a field and of sufficient duration to allow any potential problems to be identified. 2. If injection is proposed into a new area within a field, where permeability could be lower, then this strengthens the case for additional injectivity testing.
Fracture growth as a result of polymer injection, has the potential to improve or reduce sweep efficiency.	1. The impact of potential loss of injectivity with time needs to be carefully modelled. 2. Models should be calibrated with a high level of baseline well surveillance (e.g. ILT, multi rate tests, PFO).
Unexpected outcomes are commonly observed.	1. Injection tests and piloting are essential to obtain practical experience. 2. Mechanisms other than polymer rheology and polymer adsorption can contribute to injectivity loss. 3. Surfactant/oil packages can influence injectivity.
Lab measurements of injectivity may not correlate well with actual field performance.	1. Lab filtration ratio tests may be useful if correlated to field core tests. 2. If production water (PW) mixing is proposed, then care should be taken to conduct injectivity tests with a representative PW composition. 3. Injectivity assessment should be a primary objective during the early stages of piloting.

Observation	Lessons Learned
Rigorous QC of polymer.	1. Vigilance at all points in supply chain to ensure polymer products are within agreed tolerances. 2. A "no change point" is recommended where the polymer specification is fixed, typically after the pilot phase and prior to scale up. 3. If using an emulsion type polymer, QC of the polymer inversion is advisable.
Injection pressure limits in field may heavily restrict the injection rate.	A robust understanding of constraining pressure/ geomechanics issues is recommended e.g. sand/shale fracture pressures, prevailing minimum stress direction. Delayed action polymers may enable sustained injectivity.
Polymer damage by gels and adsorbed polymer builds up a skin that can be removed chemically.	1. Understand the key reason for injectivity loss is highly recommended. 2. Various chemicals can be used for cleaning up polymer damage. Selection through lab work is advisable. 3. Placement of the chemicals for treatment is of key importance.

6. Water flood and EOR design, surveillance and optimisation

Objective: Provide reliable information to make high quality development decisions and maximise economic recovery by optimising capital allocation and minimising operating cost

Key lessons learned:

Observation	Lessons Learned
What is the optimum timing for polymer flood implementation?	Trade-off between early implementation with limited understanding of water flood baseline performance v. late implementation with potential value erosion within life of field. Ensure there is a robust waterflood baseline to validate the EUR potential. Ensure life-of-field studies are current and understood to validate the runway for EOR on late life assets.
Uncertainty in flow measurements may lead to unreliable data.	Flow measurements can be highly fluid-specific. Since suppliers often have a limited capability to perform tests with real crude systems, it is not always possible to rely on supplier-provided instruments. Ensure there is a rigorous sampling program, on-site, to validate metering results.
A detailed understanding of the interaction between injector/producer and the reservoir is important to understand the subsurface.	Extensive monitoring prior, during and after polymer injection is essential in order to understand the effect of polymers on oil displacement. Ensure there is a good, robust production logging (PLT) program that includes a water flood baseline, to measure polymer injection performance.
Project uncertainties and risks are often considered too big to commit to an early full field project sanctioning.	Establish a 'learning journey' that is tied to a staged roadmap, that has very clear expectations and objectives at each stage of the project (via an uncertainty management plan) to de-risk the project. Ensure management endorsement of the learning journey.
Pattern by pattern variations were observed, including modestly responding producers on polymer. Polymer injection allocation can be optimised.	Upscaling of pattern or sector polymer performance is enabled by: • Understanding water flood is important for understanding Polymer EOR performance. • Simulation forecasts of polymer flood can be used when water flood is understood.

7. Facility design

Objective: Design polymer compatible facilities to most economically apply chemical EOR

Key lessons learned:

Observation	Lessons Learned
Storage issues with neat polymer product, including skins, clumping and settling to be mitigated.	Careful testing using physical models is needed to avoid design flaws. Ensure there is sufficient agitation and re-circulation, with clear standard operating procedures, to avoid any settling-out issues of the polymer in the storage system.
EOR facility installation as part of initial FID enables timely implementation.	It's recommended to screen asset/reservoir potential for EOR prior to Field Development Plan submission. Consider integrating pilot facilities into facility design to accommodate future EOR application and maintain accordingly. Seek to retain flexibility through the early field development decisions. For example, consider the wet vs. dry trees and well spacing decisions with potential future EOR in mind.

8. Operations and logistics

Objective: Ensure safe and efficient operations and maintain chemical product quality from the manufacturer to the wellhead

Key lessons learned:

Observation	Lessons Learned
1. It's important to monitor product quality to ensure injected polymer in line with product specifications.	1. Polymer emulsions are subject to aging and therefore have a limited shelf life. 2. Agree testing protocols with vendors and third party labs for consistency. Ensure routine sampling.
2. Custody transfer of polymer from supplier to operator.	1. Conduct rigorous product testing to ensure product quality is maintained from plant to well. 2. Ensure polymer quality if monitored and regularly reviewed by independent 3rd party to ensure quality of product, particularly viscosity.
3. For a HPAM polymer, any water ingress, including the evaporation and condensation cycle in storage tanks can cause filter blockages and lead to frequent requirements for filter change outs.	Avoid any form of water ingress, install duplex filters and consider auto-filtration devices.

9. Back-produced polymer

Objective: To avoid and/or ensure safe and efficient handling of polymer that is produced from wells, following breakthrough

Once the polymer breaks through into the producing wells, the produced water quality and processing may be impacted (including separation efficiency, polymer precipitation at elevated temperatures).

Key lessons learned:

Observation	Lessons Learned
1. Produced polymer impact on well productivity.	Investigate the impact of potential reduced well productivity on the EOR value. Investigate options for productivity restoration in case productivity decline would take place.
2. Produced polymer impact on well performance (e.g. artificial lift).	Back-produced polymer may impact ESP performance. It's recommended that mitigation options are developed and ready to be implemented.
3. Produced polymer impact on facilities (e.g. heat exchanger).	Polymer precipitation and fouling from back-produced polymer can have a detrimental impact on production efficiency. Fouling in heat exchangers is a primary root cause. It's recommended that mitigation options are developed; engineer a solution that avoids selection of a heat exchanger that is prone to fouling, develop operational plans for mechanical intervention and isolation and plan for use of chemical demulsifiers.
4. Produced polymer impact on separation (e.g. separator process).	The effect of emulsion breakers is fluid-specific so testing is essential to prevent processing problems. De-risk the effect of polymer in the water on bulk separation with physical tests for the field specific conditions. Assure safe limits can be obtained and mitigation through dilution with water from other producers is feasible. Reduce the number of polymer injectors, duration of injection and polymer concentration if so required.
5. Back-produced polymers may have a significant detrimental effect on water treatment units.	Efficiency of water treatment units may be increased by: mechanical degradation, chemical degradation, water treatment chemicals or modification of equipment.

10. Health, safety and environment considerations

Objective: Ensure that offshore polymer projects are executed within the boundaries set by regulatory authorities with respect to HSE

Key lessons learned:

Observation	Lessons Learned
1. HPAM is not classified as toxic and does not bio-accumulate. However, it does not pass the standard OECD 306 biodegradation test. Due to this failure, HPAM has a level-4 substitution warning on UKCS while it is classified as a "red" chemical in Norway. **2. Regulations differ from country to country.**	1. Early interaction with relevant regulatory authorities is essential in order to ensure full compliance. 2. Due to the classification of HPAM, the base case for any polymer EOR project should be that water containing potential traces of polymers should be re-injected. 3. As part of a discharge permit application, documentation of potential effects of polymers in the natural environment is required. 4. Standard biodegradation tests (OECD 306 and 308) indicate very low biodegradation, but it is important to study other potential types of degradation such as biological, chemical and physical degradation (e.g. via UV radiation and oxygen radicals) in the marine environment. This work can enable acceptable standards and thresholds for disposal to be determined.

10. Polymer EOR workshop

A complete set of presentations from the six polymer forums is available to those who would like more information on the lessons learned. The packs contain details of the each of the five polymer EOR activity areas which are seen as the most important areas for the UKCS and outline many useful lessons learned for:

- Polymer EOR project de-risking
- Impact on operations from produced polymer production
- Polymer EOR injectivity
- Polymer EOR testing and standardisation
- HSE considerations for polymer EOR

Please contact EOR Manager, Glenn Brown (Glenn.Brown@ogauthority.co.uk) for more information.

11. Polymer EOR – workshop references

The polymer EOR references captured during the workshops are shown below.

1. Polymer EOR project de-risking

Focus areas on injectivity, subsurface uncertainty, logistics, capital and operating costs, operational issues, production efficiency and HSE.

Focus areas arising from the problem statement	Key references captured
1. Build capability to mitigate or manage risks: Injectivity (see separate problem statement)	SPE – 170104 – The polymer in polymer flooding: Is its value overestimated? SPE – 13603-PA – Improving Polymer Injectivity at West Coyote Field, California SPE – 179696-M – Evaluation of Innovative Associative Polymers for Low Concentration Polymer Flooding SPE – 20060 Dos Cuadras Offshore Polymer Flood
2. Build capability to mitigate or manage risks: Subsurface Uncertainty	SPE – 129177 – Polymer Injection in a Heavy Oil Reservoir under Strong Bottom Water Drive SPE – 154620 – EOR Field Management Through Well-Planned Surveillance SPE – 183535 – Implementing Fiber Optics Distributed Sensing as a Key Surveillance Tool SPE – 17395 – Performance and Operation of a Successful Polymer Flood in the Sleepy Hollow Reagan SPE – 18974 – J-Sand Polymer Flood Perf. Review SPE – 153161 – Thermal stability of Scleroglucan at realistic reservoir conditions SPE – 170007-MS – Optimizing Field Development of Greenfield Polymer Floods Using Experimental Design SPE – 9794-MS – Performance Of Deutsche Texaco Ag's Oerrel And Hankensbuettel Polymer Floods SPE – 17631 – Numerical Simulation for Planning and Evaluation of Polymer Flood Process: Field Analysis SPE – 17675 – Preconditioning Concepts in Polymer Flooding in High Salinity Reservoirs: Laboratory Investigations and Case History SPE – 24118 – Performance Analyses of Several Polyacrylamide Floods in North German Oil Fields SPE – 124001-MS – Oil-Recovery Predictions for Surfactant Polymer Flooding J. Petr. Sc. Eng. vol122, 2014 – Literature review of implemented polymer field projects

Focus areas arising from the problem statement	Key references captured
3. Build capability to mitigate or manage risks: Logistics	SPE – 155116 – Surface and Subsurface Requirements for Successful Implementation of Offshore Chemical Enhanced Oil Recovery
4. Build capability to mitigate or manage risks: Operational Issues	SPE – 169746 – Optimization of polymer flood SPE – 155116 – Surface and Subsurface Requirements for Successful Implementation of Offshore Chemical Enhanced Oil Recovery SPE – 15652 – Molecular Degradation, Injectivity, and Elastic Properties of Polymer Solutions SPE – 169722 – Design of Horizontal Polymer Injectors Requiring Conformance and Sand Control SPE – 14658 – Polymer Flood Operations: East Texas Field SPE – 8380-MS – Skull Creek Newcastle Sand Unit – A Successful Polymer Flood Field
5. Build capability to mitigate or manage risks: Impact on operations from produced polymer	
6. Build capability to mitigate or manage risks: HSE (see separate problem statement)	
7. Provide Recommendations: to reduce uncertainties	SPE – 18092 – Evaluation of a Pilot Polymer Flood in the Marmul Field, Oman SPE – 167377 – Full field polymer history match EAGE IOR 2015 – Quantifying Viscous Cross-flow and its Impact on Tertiary Polymer Flooding in Heterogeneous Reservoirs SPE – 178593 – Modelling viscosity and mechanical degradation of polyacrylamide solutions in porous media
8. Provide Recommendations: to manage risks	IPTC 17342 – Low-Salinity Polymer Flooding: Improving Polymer Flooding Technical Feasibility and Economics by Using Low-Salinity Make-up Brine
9. Provide Recommendations: to improve project economics with appropriate incentives	SPE – 13603-PA – Improving Polymer Injectivity at West Coyote Field, California EAGE IOR 2017 – Polymer “viscoelastic effect”; Does it reduce residual oil saturation?

2. Polymer EOR injectivity

Understand injectivity loss during polymer injection and provide robust de-risking strategies.

Focus areas arising from the problem statement	Key references captured
1. Understand Causes of Injectivity Loss: Recognise the underlying reasons for injectivity loss and the likelihood of occurrence. Loss mechanisms might be related to: **(a) Water quality control,** **(b) Polymer quality control** **(c) Polymer rheology** **(d) Polymer interaction with reservoir (e.g. adsorption).**	SPE – 144164 – Planning for Increased Production Through Integrated Well and Reservoir Surveillance in the Oman EOR Developments SPE – 175383 – Injectivity Loss in Polymer Floods: Causes, Preventions and Mitigations; SPE – 179694 – Radial and Linear Polymer Flow – Influence on Injectivity SPE – 174665 – Mechanistic Simulation of Polymer Injectivity in Field Tests SPE – 179657-MS – Permeability Reduction Due to use of Liquid Polymers and Development of Remediation Options SPE – 39694-MS – Polymer Transport and Rheological Properties for Polymer Flooding in the North Sea
2. Understand Consequences of Injectivity Loss: Define impact of injectivity loss. Impact might be related to: **(a) Reduced throughput / voidage** **(b) Fracture growth / conformance.**	SPE – 175383 – Injectivity Loss in Polymer Floods: Causes, Preventions and Mitigations SPE – 181582 – De-risking Polymer Flooding of High Viscosity Oil Clastic Reservoirs – A Polymer Trial in Oman SPE – 160967 – Fracture growth in polymer flood

Focus areas arising from the problem statement	Key references captured
3. Provide appropriate Prevention Strategies: Strategies to prevent the injectivity loss happening and including recommendations for QA/QC protocols (e.g. water and polymer quality).	SPE – 175383 – Injectivity Loss in Polymer Floods: Causes, Preventions and Mitigations EAGE 2017 B05 – Polymer injectivity de-risking in low perm West Salym EOR pilot SPE – 121840 – Polymer Flooding in Unconsolidated-Sand Formations: Fracturing and Geomechanical Considerations SPE – 175349 – Selecting the optimum water flood concept SPE – 14948 – The nature of polymer plugging and a wellbore treatment to minimize It SPE – 20243 – Formation damage from polymer solutions: Factors governing injectivity SPE – 21018 – Measurements of polysaccharide polymer properties in porous media SPE/DOE – 17395 – Performance and Operation of a Successful Polymer Flood in the Sleepy Hollow Reagan Unit EAGE 2016 – Degradation of synthetic polymers during radial injection in a sandstone EAGE IOR 2017 – Qualifying an 'Emulsion' Polymer for Field Use – Lab scale Assessments on Adsorption and Injectivity
4. Provide appropriate Mitigation and Remediation Strategies: Strategies to mitigate and restore the effects of injectivity decline if/when it occurs (e.g. pressure and rate controls).	SPE – 175383 – Injectivity Loss in Polymer Floods: Causes, Preventions and Mitigations ECMOR XV 2016 – Flow Diagnostics for Optimal Polymer Injection Strategies

3. Polymer standard testing

The aim is to develop standard tests of polymer products for EOR projects, allowing fair and consistent comparisons to be made and providing in consistent onsite QA/QC criteria.

Focus areas arising from the problem statement	Key references captured
1. Polymer Supply – Batch variation standard tests – supplied concentration, molecular weight distribution, filtration ratio tests, viscoelasticity	SPE – 12652 – Quantification of Viscoelastic Effects of Polyacrylamide Solutions SPE – 169681 – A Systematic Study of the Polymer Visco-Elastic Effect on Residual Oil Saturation by Core Flooding SPE/DOE – 17395 – Performance and Operation of a Successful Polymer Flood in the Sleepy Hollow Reagan Unit
2. Polymer Supply – Emulsion storage tests – temperature stability, formation of condensation gels, clinage, rheology	SPE – 11504 – Design of a Pilot Polymer Flood in the Marmul Field, Oman EAGE – 31683 – Enhanced Polymer Flooding: Reservoir Triggering Improves Injectivity and Eliminates Shear Degradation
3. Injection Facilities – Emulsion inversion test – lab inversion, yard flow loop inversion, in-field performance	EAGE – 31683 – Enhanced Polymer Flooding: Reservoir Triggering Improves Injectivity and Eliminates Shear Degradation
4. Injection Facilities – Assessments of the impact of contaminants commonly found in produced water or treated seawater on polymer properties and injectivity. Contaminants to include corrosion products, suspended solids, residual production chemicals, biomass, returned polymer, etc	SPE – 144164 – Planning for Increased Production Through Integrated Well and Reservoir Surveillance in the Oman EOR Developments
5. Injection Facilities – Unplanned shut-down – rheology operating envelope of mother solutions and dilute solutions	SPE/DOE – 9781 – Sloss Micellar/Polymer Flood Post Test Evaluation Well
6. Subsea – Shear degradation tests (pumps and chokes) (1) flow loop with scaled choke, (2) pressure drop over an orifice, (3) shear through a capillary, (4) In field performance	SPE – 4748 – The Behaviour of Polymers in Porous Media EAGE – 31683 – Enhanced Polymer Flooding: Reservoir Triggering Improves Injectivity and Eliminates Shear Degradation
7. Reservoir – Adsorption – reversible and irreversible polymer adsorption by dynamic core floods	SPE – 4026 – Analysis of Factors Influencing Mobility and Adsorption in the Flow of Polymer Solution Through Porous Media SPE – 18090 – Transport mechanisms of Xanthan biopolymer solutions in porous media EAGE 2017 – B15 Qualifying and emulsion polymer for field use – lab-scale assessment on adsorption and injectivity

Focus areas arising from the problem statement	Key references captured
8. Reservoir – RF/ RRF – reduced and reservoir condition core floods	SPE – 4026 – Analysis of Factors Influencing Mobility and Adsorption in the Flow of Polymer Solution Through Porous Media SPE – 175380 – Simultaneous Sorption and Mechanical Entrapment During Polymer Flow Through Porous Media SPE – 9408 – Steady-state measurements of relative permeability for polymer/oil systems EAGE 2015 – Polymer Flooding for EOR in the Schiehallion Field – Porous Flow Rheological Studies of High Molecular Weight Polymers
9. Reservoir – Polymer stability – anaerobic stability studies at various temperatures with reservoir fluids	SPE – 141497 – Pushing the envelope for polymer flooding towards high-temperature and high-salinity reservoirs with polyacrylamide based ter-polymers OTC – 25817 – Evaluation of the Potential of High-Temperature, Low-Salinity Polymer Flood for the Gao-30 Reservoir in the Huabei Oilfield, China: Experimental and Reservoir Simulation Results SPE – 20237 – Thermal Stability of Scleroglucan at Realistic Reservoir Conditions SPE – 14232 – Chemical stability of polyacrylamide under simulated field conditions SPE – 9300 – Polymer flooding in North Sea reservoirs EAGE – 31683 – Enhanced Polymer Flooding: Reservoir Triggering Improves Injectivity and Eliminates Shear Degradation SPE/DOE – 9781 – Sloss Micellar/Polymer Flood Post Test Evaluation Well
10. Production Facilities – Returned polymer – impact on oil-water separation and produced water treatment. Contact plate adhesion (heater fouling)	SPE – 13033 – Hydrolysis and Precipitation of Polyacrylamides in Hard Brines at Elevated Temperatures NEL Produced Water Workshop (2015) – Polymer Flood Produced Fluid Separation
11. Production Facilities – Production chemistry compatibility – chemical compatibility tests with metals, elastomers etc.	

4. Polymer EOR HSE

The persistence and degradation of polymers in the marine environment and impact on environmental risk.

Focus areas arising from the problem statement	Key references captured
1. Understanding of current standard biodegradation tests – OECD 306, 308, CEFAS	
2. Fate of the polymer in the marine environment and potential effect of polymers on marine organisms	
3. Understanding of UK offshore approvals process – HPAM polymer substitution warning	
4. Study biological degradation in the marine environment	
5. Study chemical and physical degradation the marine environment	
6. Guidelines for Polymer Produced Water discharge and off-spec polymer disposal	SPE – 155116 – Surface and Subsurface Requirements for Successful Implementation of Offshore Chemical Enhanced Oil Recovery
7. Propose acceptable standards and thresholds – for disposal to be determined	

5. Impact on operations from produced polymer

Understanding produced polymer impact on operations.

Focus areas arising from the problem statement	Key references captured
1. Produced polymer impact on well productivity	SPE – 169714 – Solvent Stimulation to Restore Productivity of Polymer pattern producer wells – A case study SPE/DOE – 17395 – Performance and Operation of a Successful Polymer
2. Produced polymer impact on well performance (e.g. artificial lift)	
3. Produced polymer impact on facilities (e.g. heat exchanger)	SPE169718 – On Crude Dehydration Due To Back Production Of Polymer SPE13033 – Hydrolysis and Precipitation of Polyacrylamides in Hard Brines at Elevated Temperatures
4. Produced polymer impact on separation (e.g. separator process)	SPE169718 – On Crude Dehydration Due To Back Production Of Polymer
5. Produced polymer impact on water treatment (e.g. hydrocyclones)	NEL Produced Water Workshop (2015) – Polymer Flood Produced Fluid Separation TEKNA Produced water management 2017 – Treatment of produced water from polymer flooded reservoirs NEL Produced water Workshop (2017) – produced water treatment from polymer flooded reservoirs
6. Produced polymer impact on crude oil quality and/or downstream operations	SPE – 169718 – On Crude Dehydration Due To Back Production Of Polymer

12. Appendix 1 – polymer EOR screening

A number of references are available which can be used to identify whether polymer EOR is applicable. **SPE – 174541 – Status of Polymer-Flooding Technology – James J. Sheng et al** provides a complete summary of Polymer EOR Technical Screening Criteria. Table 1 is shown below to give an idea of the important field parameters.

Proposed by	k (md)	T_r (°C)	Formation-water-salinity (TDS, ppm)	Divalent (ppm)	Lithology	Clay	μ_o (cp)	S_o (fraction)	Aquifer	Gas Cap	API Gravity	Depth (ft)
NPC 1976	≥20	≤93.3			NC		≤200	$(S_o-S_{or})>0.1$	None to minor	None to minor		
Brashear and Kuuskraa 1978	>20	<93.3	50,000	1,000	Sandstone	Low	<20	>0.25	None to week	None to week	>15	NC
Chang 1978	>20	<93.3			Sandstone preferred		<200	$(S_o-S_{or})>0.1$	None	None		
Carcoana 1982	>50	<80	Low	Low	Sandstone		50–80	>0.3	Weak	Week	25-35	<6,561
NPC 1984**	>10	<121	<200,000		Sandstone and carbonate		<150					
Goodlett et al. 1986	>20	<93.3	100,000		Sandstone preferred		100	$(S_o-S_{or})>0.1$			>25	<9,000
Taber et al. (1997a,b)	>10	<93.3			Sandstone preferred		$10<\mu_o<150$	>0.5			>15	<9,000
Al-Bahar et al. 2004	>50	<70	100,000	1000	Sandstone	Low	<150	0.6	None	None		
Dickson et al. 2010	>100 if $10<\mu_o<100$ >1,000 if $100<\mu_o<1,000$ cP	<76.7	<1,000 if $10<\mu_o<10$ < 3,000 if $100<\mu_o<1,000$ cP				$10<\mu_o<1,000$	> 0.3			>15	800–9,000
Limited projects (Al-Adasani and Bai 2011)	834.1	75			Sandstone		123.2	0.64			26.5	4,221.9
Saleh et al. 2014a	>10	<98.9			Sandstone and carbonate		<5,000	>0.21			>12	
Saleh et al. 2014b	139	43.9	6,500				5					
Polymer projects	116.0	46.1	20,500 (39,750*)	110 (326*)	Majority sandstone	Low	9.15	0.52	Generally none	Generally none	32	3,486
Proposed in this paper	50	<93.3	<50,000	<100	Sandstone	Low	<150	$(S_o-S_{or})>0.1$	Weak	Weak	NC	NC

In the table, μ_o is the oil viscosity, S_o is the oil saturation before ASP, T_r is the reservoir temperature, NC means not critical.
*TDS and divalents before polymer flooding.
**Proposed for advanced technology

Table 1—Summary of screening criteria for polymer flooding.

Oil & Gas Authority

Oil and Gas Authority is a limited company registered in England and Wales with registered number 09666504 and
VAT registered number 249433979. Our registered office is at 21 Bloomsbury Street, London, United Kingdom, WC1B 3HF

www.ogauthority.co.uk