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Subsea Capping Stack Design and Operability Assessment

Acknowledgements

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IOGP's Subsea Well Response and Source Control Subcommittee (SWRSC) was formed in 2017 under the leadership and guidance of the WEC. SWRSC aims to be a centralised source of industry knowledge and shared experience in subsea well response and source control, to support IOGP member organisations and the broader E&P industry engaged in subsea activity, and to provide a forum for industry to identify technical areas where further development may be warranted.

Trendsetter Engineering, which has been involved in the design and development of most capping stacks that are currently available in today's market. Their engineering expertise has been instrumental in preparing this report.

The WEC wishes to thank members of the American Petroleum Institute's Committees for API RP 17W - Recommended Practice for Subsea Capping Stacks, and API Standard 53 - Blowout Prevention Equipment Systems for Drilling Wells, who were involved in the reviews of this report.

Front cover photography courtesy of Oil Spill Response Limited.

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Revision history

VERSION	DATE	AMENDMENTS
1.0	February 2020	First release

Contents

Scope

This report was developed to share the design basis of capping stack solutions with industry, regulators, and other stakeholders. It aims to provide confidence that capping stacks can be reliably deployed and function as designed. This report shares a catalogue of practical deployments and provides insights into the technical boundary assumptions, design choices, and capabilities. The report also highlights a recommended way forward to provide engineering assurance of steps to be taken when well requirements exceed capping stack designs.

Topics addressed in this document include:

- Consideration of identified risks, engineering requirements, and functional requirements that went into the capping stack's basis of design
- Description of key components that constitute a capping stack and its ability to latch onto a BOP or wellhead and be shut-in
- Equipment commonality with other BOP and subsea equipment
- Explanation of the rationale between different capping stack configurations
- Valve sizing and considerations
- The role of CFD (Computational Fluid Dynamics) analysis in the design brief, and understanding landing stability and erosion
- Offset installation methods
- Rigging, equipment and deployment strategies
- A catalogue of physical deployment activities

Topics not addressed in this document include:

- Preparatory activities to receive a subsea capping stack such as debris removal or wellhead straightening
- Flowback through a subsea containment system where the well cannot be shut-in

Foreword

"Well Source Control" is a generic term for all activities related to the direct intervention in a well that has experienced loss of containment with the intent to halt or control the release of hydrocarbons to the environment. Prior to the 2010 *Deepwater Horizon* incident, and for deepwater projects, the primary source control response option for most industry participants was to rely on relief wells. Historically, subsea remedial source control activities were limited, due to a lack of specialised equipment tailored for the demanding environment. After *Deepwater Horizon*, that changed, and though a relief well should always be part of the source control response plan, installation of a capping stack is the preferred method to stop the flow.

Following the *Deepwater Horizon* response, the industry led and funded several major engineering projects to advance subsea capping stack technology and produced several equipment packages for source control solutions that are today strategically located around the world. The equipment list includes:

- Capping stacks with diverter spools and chokes (valve and ram-based)
- Containment systems (for producing back to surface where a well cannot be shut-in)
- Offset Installation Equipment (for handling a capping stack where there is no vertical access)
- Source control support equipment such as ROV tools, accumulators, pipe shears, subsea dispersant injection system, etc.

During their development, response equipment and systems were risk assessed, and tested via 'table top' exercises and offshore deployments. Design briefs focused on using known reliable technologies that were further supported with advanced computational methods. To promote consistency in design methodology and clarify recommended performance standards, API RP 17W - Recommended Practice for Subsea Capping Stacks, was developed and released in 2014. Knowledge was shared across the industry and as the new equipment packages became physically available, a range of full-scale exercises were conducted which included loading heavy-lift aircraft and vessels with the equipment and deploying it on abandoned wells.

This report looks back at how today's systems were engineered and developed. It explains the design briefs, the careful forethought, and some insights behind the rationale of different stack designs.

As this report will show, capping stack designers considered most of the industry's global operational requirements. However, there could be specific situations where a well's discharge performance may exceed the stated design brief. Most capping stacks have the capability to handle higher than stated flow rates, and some have already gone through an upward revision process, as shown in Appendix 2. In cases where the stated design brief can potentially be exceeded, the interested party may need to go through some additional engineering steps that consider specifics to further validate its use. This report outlines what those steps and workflow entail.

At its conclusion, it is expected that readers will have:

- Confidence that capping stacks can be deployed and work as intended
- Awareness for areas of residual risk
- Adequate technical insight towards their chosen capping solution
- Understanding what can be done should their specific needs go beyond the stated design brief.

And finally, this report presents a summary of physical activities that have been conducted to verify that logistical and deployment assumptions are correct.

1. Evaluating Risk and Defining Functional Requirements

The use of a capping stack to control a flowing well has been part of the industry's response tool kit for some time. Prior to the *Deepwater Horizon* incident, that use for the most part had been confined to surface applications. The capping stacks themselves were typically full-bore BOP blind rams, which would later have flanges and intervention adapters installed to either shut-in the well while a relief well was being drilled, or to have intervention equipment rigged up to stop the flow. Overall, this response tactic worked and continues to be commonly used for surface offshore and land applications. Surface capping stacks inspired the capping stack that was later installed on the Macondo well (the site of the *Deepwater Horizon* incident).

Figure 1: A single blind ram capping stack is prepared for installation over a high rate gas well. The capping stack lies above a diverter spool with outlet valves installed.
Reproduced courtesy of Wild Well Control.

Figure 2: The capping stack installed over the incident well with hydraulic lines installed and well shut in. *Reproduced courtesy of Wild Well Control.*

Immediately after the Deepwater Horizon incident, the US government temporarily suspended drilling operations in the Gulf of Mexico. At this time, the industry sought to develop reliable well control solutions using proven equipment and technologies. The conditions during the *Deepwater Horizon* event and after established an understanding that high flow potential, blowout loads and/or narrow pore pressure and fracture gradient margins could impact shut-in reliability and/or well integrity creating the need for the introduction of a diverter spool and chokes.

With the United States offshore industry effectively shut down until Operators could prove they had access to capping stacks that could be used on their wells, time was critical. It was essential that readily available and field-proven equipment be used. In order to meet the requirements for a foreseeable worst case discharge scenario, the capping stacks had to, at a minimum, be capable of diverting at least 100 kbopd with a GOR of 680 scf/stb, be operable in in up to 3,000m of water, and, to accommodate sour service conditions, be NACE MR0175 Region 2 compliant. The stacks used at this time can be described, for the purposes of this discussion, as the first series of capping stacks.

The second series of capping stacks that followed were developed around three years after the *Deepwater Horizon* incident. These followed similar principles as the first series, but had the advantage of being developed as measured engineering projects. Expanded project times allowed for a better understanding of well capping options, potential limitations, maturing of engineering, and manufacturing of optimal componentry.

As the second series of capping stacks were developed, API RP17W - Recommended Practice for Subsea Capping Stacks was created as a way of formally documenting capping stack design concepts.

The third series of capping stacks that have recently been built or are being developed have taken a different design approach to the first two series. Like other series, proven equipment and technologies have been used in their creation. They differ by being valve-based, which in turn results in being smaller, lighter, and more modular. The valves that are used are common to those of Subsea Production Trees and other hydrocarbon production valves. Like ram options, valves are also routinely used in surface source and general pressure control applications. The significant weight reductions when compared to alternatives with the same pressure rating may require less onerous logistical support when mobilising. Weight reduction makes a significant difference in certain situations where conductor integrity may be in doubt, or in the 20,000psi technology space.

One of the implications with the valve-based stacks is the reduced bore size that is needed to accommodate the valves. In certain situations, the reduced bore size, combined with a lighter capping stack, can make it less stable or more susceptible to uplift forces upon installation; if considering a valve based capping stack, landing should be evaluated. The restriction presented through the smaller bore generates a higher pressure change across the capping stack acting as a choke, creating higher uplift forces during landing. This may impact the stacks ability to land in very high flow rate situations. CFD (Computational Fluid Dynamics) analysis should be used to assess capping stack landing capabilities. As it stands today, there are no 18-3/4" 10,000psi (or higher) rated valves. Such valve designs would likely be excessively large and prohibitive from a capping stack size and weight limitation.

With the three series of subsea capping stacks described above, the industry has a complete tool kit to address nearly all foreseeable situations. Each series has a role, has been developed to address a specific design brief, and each can present advantages as well as disadvantages.

1.1 Worst Case Discharge Rates

During the time of development, the second series of capping stacks generally followed the design brief as presented in IOGP Report 464 - *The Global Industry Response Group Capping and Containment recommendations*. These performance characteristics covered 85 to 90 percent of the industry's subsea response needs at the time and largely revolved around a global evaluation of Worst-Case Discharge, as defined at the time by the United States Bureau of Ocean Energy Management Regulation and Enforcement, and later clarified by the Society of Petroleum Engineers.

This report also points out that the remainder of wells that exceeded the 100kbopd threshold exceeded that rate considerably. Attempting to capture those outliers in a catch-all at the time was deemed not appropriate.

Within the capping stack design, the flow limitation is determined by the ability to handle diverted flow (flow through the wing valves and chokes). Many of the capping stacks available today have gone through additional engineering qualification or upgrade to their flow outlets and can handle far in excess of 100kbopd.

1.2 Capping Stack Components and Technology Readiness

To follow is a Technology Readiness Level (TRL) assessment. The assessment considers the components that may be considered important for connecting, shutting in and maintaining pressure integrity. In describing TRL, nine field matrixes are used that considers the spectrum of known and proven through to new and unproven. The assessment considers both the technology status and its application in the context of a subsea capping situations.

Table 1: Technology Classification Matrix

Application Area	Technology Readiness Level		
	Proven	**Limited Field History**	**New or Unproven**
Known	1	2	3
Limited Knowledge	2	3	4
New	3	4	4

1: No new technical uncertainties (proven technology)
2: New technical uncertainties
3: New technical challenges
4: Demanding new challenges

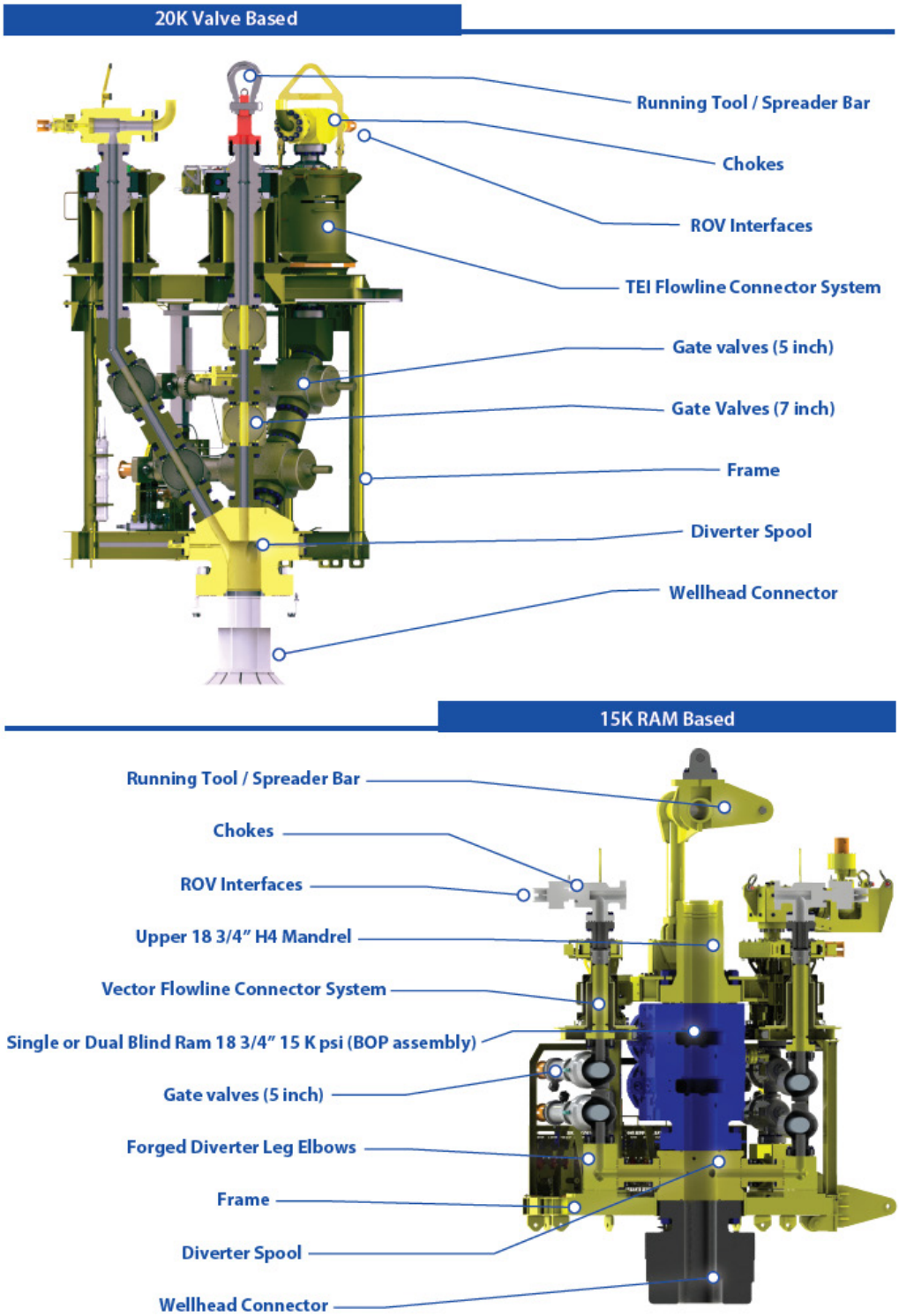


Figure 3: Sectional views with equipment components for a 20k psi valve based capping stack and a 15k psi ram based capping stack. *Reproduced courtesy of Trendsetter Engineering.*

Table 2: Technology Classification Matrix

ID	Component	Application Area			Technology			Tech. Class
		Known	Limited Knowledge	New	Proven	Limited Field History	New or Unproven	
1	Adaptor Spool	X			X			1
2	Wellhead Connector (when used in flowing conditions)		X		X			2
3	Spacer Spool	X			X			1
4	Diverter Spool	X			X			1
5	Gate Valves (5in)	X			X			1
6	Gate Valves (7in)	X			X			1
7	Forged Diverter Leg Elbows	X			X			1
8	TEI/Vector Flowline Connector System	X			X			1
9	Chokes	X			X			1
10	Single or Dual Blind Ram 18 3/4" 15K psi (BOP assembly)		X		X			2
11	Running Tool / Spreader Bar	X			X			1
12	Subsea Accumulator Module	X			X			1
13	ROV Interfaces	X			X			1
14	MQC plates	X			X			1
15	PP/PT Sensors	X			X			1
16	Upper 18 3/4" H4 Mandrel	X			X			1
17	Upper 18 3/4" 15K H4 Test Cap	X			X			1
18	Frame	X			X			1
19	Test Stand	X			X			1
20	Chemical Injection Valve	X			X			1
21	Small Bore Tubing	X			X			1
22	SS valve actuators	X			X			1

As shown in Table 2, all but two components reside in the known-proven field. The two that do not are both proven technologies that have limited application history in the context of subsea capping – or more specially, application in a high flow rate situation.

Wellhead connectors are a proven technology, but there is limited history of their application when landed over and made up to a flowing wellbore. The risk has to do with unseating the gasket, sealing surface damage at either end of the connection, or actual gasket damage sustained while landing due to erosion from a high solids content flow. Another risk is potential hydrate formation around the gasket that can interfere with the connector's ability to lock and seal.

CFD analysis is used to evaluate erosion risk. Hydrate formation is mitigated by introducing chemical (methanol) wash ports on the connector. Methanol wash ports are a non-standard feature that needs to be specified. For occasions where an alternate connector from that provided by the OEM is needed, care should be taken when sourcing to ensure the type of connector used features methanol wash ports.

BOP blind shear rams are extensively qualified and used throughout industry. API Specification 16A governs the design and testing of blind shear rams, and API Standard 53 governs performance characteristics and operational testing. While both these API documents specify pressure testing, they do not specifically address design criteria, qualification or closing under flowing conditions.

When resolving surface blowouts, the industry has successfully used blind rams to cap and seal wells on several occasions. Experience shows that in nearly all circumstances, the primary blind ram has functioned effectively and shut in the well. The capping stack used to secure the Macondo well, for example, had a single blind shear ram. Subsea capping stacks more generally use blind shear rams. Apart from their ability to shear pipe, the design of the blind shear ram is such that the elastomer sealing area is protected from flow by the shearing blade which improves reliability.

From an engineering perspective, the point of concern when considering blind shear rams has to do with a possibility of eroding ram elastomers or sealing areas within bonnet pockets. API Standard 53 considers this risk and mandates that subsea rams must close in 45 seconds. Taking consideration of uncertain flowing conditions and to further reduce risk, subsea capping stack designs have taken the additional precautions of including multiple rams, a diverter spool with chokes, and a shut-in procedure.

- The diverter spool is located under the first ram and features two to five outlets and chokes. This design feature is to allow for as much flow as possible to be diverted through the diverter spool while the lower ram is closed and reduce erosion risks.
- Multiple rams in the system gives the advantage of allowing the first ram to be closed, and if the flow rate is such that it leaks, it would act as an effective tool for slowing down and regulating much of the flow while the second ram is closed.
- After the second ram is closed, the chokes may be staged down in a controlled way so that well integrity can be validated before being fully closed.

In summary, although there is limited field experience of capping and sealing on a subsea well, surface applications indicate a very high chance of success with a single blind ram; Macondo was capped and shut-in with a single ram and all but the original capping stack used on the Macondo well have a diverter spool and multiple rams, introducing at least three levels of redundancy within the systems design, which is recommended in API RP 17W.

1.3 Failure Mode Analysis

During the design stage, each capping stack will have undergone a Failure Mode, Effects and Criticality Analysis (FMECA). The assessment is used to identify critical factors that influence the ability of a capping stack to effectively function as intended while it is being stored, installed, or operated. Appendix A presents a summary FMECA that is applicable for most of the capping stacks that are in service today. Each capping stack's formal FMECA will go a step further than the provided summary and evaluate consequence severity and likelihood which will be translated into a low, moderate or high risk.

FMECA information for a given stack may be obtained by the provider. Meanwhile, the presented information shares with readers the key risks and mitigations associated with capping stacks. It is intended to be informative and give an overview of the broad considerations that have gone into the design, reliability, storage, and maintenance of a capping stack.

2. Response Time Model

It is important to note that not all incidents will be the same. There are many factors that could influence the scenario and affect the response time. It is therefore important to develop time estimates, or response time models, for each operating area highlighting critical path items and providing mitigations. It is often assumed that the Capping Stack is the critical path item, but multiple IOGP Member drills and exercises have shown that this is rarely the case. The exercises have found the typical critical path activities vary from one location to the next and are often associated with the factors listed below:

- Access to site survey equipment
- Availability of subsea intervention or construction vessel
- Importation processes or ambiguities
- Personnel visa/immigration issues
- Regulatory permitting, inspections or other activities
- Amount of debris at the well location.
- Complexity of debris removal
- Landing rights for aircraft and tarmac length for heavy aircraft
- Road infrastructure or routing limitations such as bridges and trucking contractor
- Quayside depth and infrastructure or staging area
- Crane access and specification
- Visibility
- Limited vertical access to well due to plume, or surface issues such as Volatile Organic Compounds (VOC)
- Metocean conditions
- Subsea infrastructure
- Availability of human resources

IOGP, in collaboration with NOPSEMA and Oil Spill Response Limited (OSRL), has developed a Response Time Model (RTM) that can be used to evaluate response options, understand critical path activities and/or the risks to critical path activities, and promote global consistency for subsea well response planning across the industry and beyond. While the RTM Toolkit was developed for use by an upstream operating company to predict an estimated response timeline for capping a subsea well blowout, it may be of interest to other groups as well. IOGP Report 592 - *Subsea Capping Response Time Model Toolkit User Guide* is available to download from the IOGP Bookstore and contains guidance on using the RTM, as well as the RTM Toolkit itself (available in multiple formats).

3. API RP 17W and the role of Computational Fluid Dynamics (CFD)

API RP 17W - Recommended Practice for Subsea Capping Stacks is a document developed by industry experts that provides recommended practices for the design, manufacture, and use of subsea capping stacks. API RP 17W points readers in the right direction for relevant API standards and specifications that apply for the design of specific components.

In addition, there are parts of API RP 17W that consider the operating conditions that a capping stack may be expected to reliably function under, and to that end, provides some areas of specific recommended practice.

API RP 17W also recommends that the subsea capping stack be suitable for the well conditions where it may be used. This is to ensure that reliable deployment, landing, and operability be verified by Computational Fluid Dynamics (CFD) modelling, flow analysis, structural assessments of the wellhead system to withstand the subsea capping loads, and well integrity assessment to handle shut-in and flowing wellbore pressures.

The following engineering design recommendations and activities are excerpted from API RP 17W - Recommended Practice for Subsea Capping Stacks:

1) Temperature: Classification per API SPEC 6A of U [-18° C (0° F) to 121° C (250° F)].
2) Because flow from an incident well may have high concentrations of solids, subsea capping stack designs should be analysed using CFD analysis to determine reliability through areas of high erosion.
3) Where areas of high erosion are identified, capping stacks should incorporate available technologies to reduce the erosion effects.
4) High-quality, reliable and field-proven components: Capable of withstanding extended periods of exposure to elements, surface preservation and frequent surface testing.
5) Containment: Be able to withstand 6 months of continuous flowing sandy service conditions.
6) Bore size: The capping stack bore size should depend primarily on the ability to be installed and landed. A CFD landing analysis should be completed to determine the capping stacks uplift and landing stability.
7) Erosion: In a blowout situation, solids may be included in the flowing fluids and lead to erosion of critical components. Devices used to shut off flow shall be designed to mitigate the effects of erosion and conform to API STD 6AV1 (which relates to valves).
8) Primary bore closure: Where a ram is used in the vertical bore as the closure device, it should be qualified to close on the maximum flow defined by the capping stack basis of design. In the absence of a qualified ram, a second vertical bore closure device should be included. Rams should be in conformance with API SPEC 16A and API STD 53.
9) Secondary bore closure: To protect against gas migration past or permeating through ram packing elements, a second valve based vertical bore closure device should be used. This may later be installed as a valve that mates with the top of the capping stack hub or interface.
10) Fail safe: Capping stack valves should be designed to fail as-is or fail open.

3.1 Computational Fluid Dynamics (CFD) Analysis

CFD analysis is typically used to assess conditions in four key areas of a response. They are:

1) Analysis of capping stack landing on a flowing well to understand uplift and impact of flow on the capping stack during approach and landing.
2) Analysis of the oil and gas plume behaviour in the water column and impact from ocean currents. This may also include assessment of gas absorption rates in the water column during gas travel to surface.
3) Analysis of the surface plume (in shallow water) to understand impact on vertical access to the well and vessel's ability to work at the source.
4) Analysis of surface gas dispersion to understand VOC and Lower Explosive Limit (LEL) levels at the source and how metocean conditions impact the VOC and LEL levels and the ability of the responders to work at the source.

Modelling oil and gas flow is complicated and requires expertise, experience, and considerable computer resources. Experience suggests capping stack landing analysis may take one to two weeks or longer to complete. The more complex analysis of surface gas dispersion may require considerably more time and computer resources to achieve credible results.

CFD is an important part of the engineering tool kit, and has been used in oil and gas and other industries for some time. It is an important workflow for providing confidence toward reliable deployment of a capping stack and analysis of surface conditions. Care must be taken when programming the models. The experience level of the modelling personnel should be evaluated. Models themselves are sensitive to parameters such as the internal dimensions, shapes of the capping stack and importantly, how the model mesh is constructed. Generally, the finer the mesh the more credible results are obtained. A finer mesh also requires more computational resources. Mesh design has not been standardised and work is ongoing within IOGP to further study CFD practices and develop a recommended practice guideline.

3.2 CFD Analysis - Landing

CFD analysis is used to evaluate and understand impacts of landing a capping stack on a flowing well. The models typically predict how the capping stack behave as it is moved into the incident well flow path and progressively lowered until land-out. CFD analysis has also been used to predict how a stack would behave if landed over an inclined wellhead. Analysis is the best way to provide confidence that when landing in a dynamic environment that the capping stack will be stable. The results of the analysis may be used to assess the deployment scheme and rigging to achieve stability.

3.3 CFD Analysis - Oil and Gas Plume in Water Column

In deep and shallow water wells, ocean currents may impact the shape and the extent of the plume through the water column and at surface. Deepwater wells do not necessarily exhibit surface plume issues. Oil and gas concentrates at surface may be impacted by the current profile in the water column. How plumes are formed and how they impact surface response and a vessels vertical access must be assessed on a case-by-case basis and depend on oil and gas flow rate, hydrocarbon properties, water depth, and metocean conditions.

3.4 CFD Analysis - Surface Plume Effects

The surface plume or "boil" is normally a shallow water effect. There are several examples of shallow water blowouts where the surface plume is substantial and prevents vertical access and vessels ability to work at the source. Analysis and videos confirm severe plume effects where elevation difference between "calm waters" and the plume may be several feet. Modelling also show strong surface currents in the plume, generated by the flow of oil and gas.

3.5 CFD Analysis - Surface Gas Dispersion

The surface gas dispersion and associated gas concentrations (VOC and LEL) can also be modelled using CFD analysis. LEL (Lower Explosive Limit) and UEL (Upper Explosive Limit) describes the lower concentration boundaries for which a hydrocarbon rich mixture will burn. In the case of methane, the LEL is 4.4% (44,000ppm,) and UEL is 16.5% (165,000ppm). Actual LEL and UEL values are subject to hydrocarbon mix and can vary. Modelers will often consider a fraction of the LEL when preparing models as a way building a safety margin into the results. The mesh must be carefully defined to allow analysis of gas concentrations based on metocean (wind, wave, current profile) conditions at the site.

Previous analysis and research shows that gas absorption rates in the water column can be as high as 40% to 50%[1], which depends on water depth, water temperature, and gas composition. That means initial gas release at surface may range from 50% to 60%. The analysis is complex and requires input from researchers who have studied gas absorption in the water column.

With high VOC levels and surface plume issues, capping stack installation method will be through use of the OIE (Offset Installation Equipment) or other offset installation methods.

[1] French-McKay D, Crowley D, and McStay L. "Sensitivity of modeled oil fate and exposure from a subsea blowout to oil droplet sizes, depth, dispersant use and degradation rates". Marine Pollution Bulletin 146 (2019). p.779-793.

4. Capping Stack Deployment

In many ways, deployment of a capping stack is analogous to the deployment of subsea equipment that is conveyed either on wire via a heave compensated crane, or mechanically using a riser or drill pipe that is compensated by the derrick of the Drilling Unit (MODU). The key considerations are capping stack weight, metocean conditions, and ability of the deployment vessel to deliver the load to the seabed while heave compensating the load.

Four circumstances that may impact capping stack deployment are:

1) Landing on an inclined wellhead.
2) Landing on a flowing well causing uplift and instability.
3) Damage to the BOP or Wellhead connector seal face areas due to debris.
4) In the case of shallow water situations: being unable to gain vertical access from surface due to hydrocarbon plume or gas boil.

4.1 Wellhead Inclination

Wellhead inclination can be managed through a range of techniques listed below. The application of wellhead straightening devices with subsea capping stack installation should be carefully analysed with regards to structural strength and remaining load capacity of the wellhead.

1) Use of high angle release connectors. The benefit may be limited since the cap must be centre lined with the hub during landing to minimise possibility of damage to the ring gasket. Conductor structural capacity should also be re-evaluated if the conductor inclination exceeds approximately 9 degrees. Some studies have indicated a notable degradation in conductor stability at high inclinations. This is situation specific and should be individually evaluated.
2) Deflection rigging equipment, or spreader bar to incline the capping stack and line up with the inclined hub.
3) Wellhead straightening devices. These come in different forms, but in principle, large suction or drill-in piles are installed near the inclined well and used as anchors. Rigging and winch equipment is made up to the anchor and around the inclined conductor or wellhead to allow the wellhead and conductor system to be pulled into a more vertical position and be secured. A minimum of two anchoring points is required for stability.

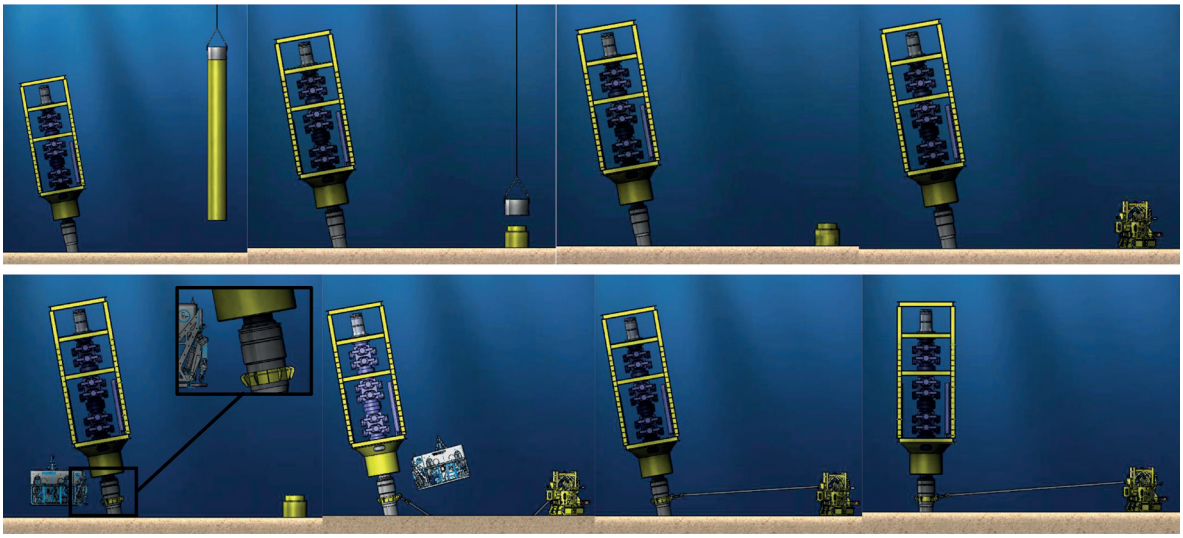


Figure 4: An example of a well straightening concept. This concept involves installing a subsea pile with a winch that is hydraulically actuated by an ROV.

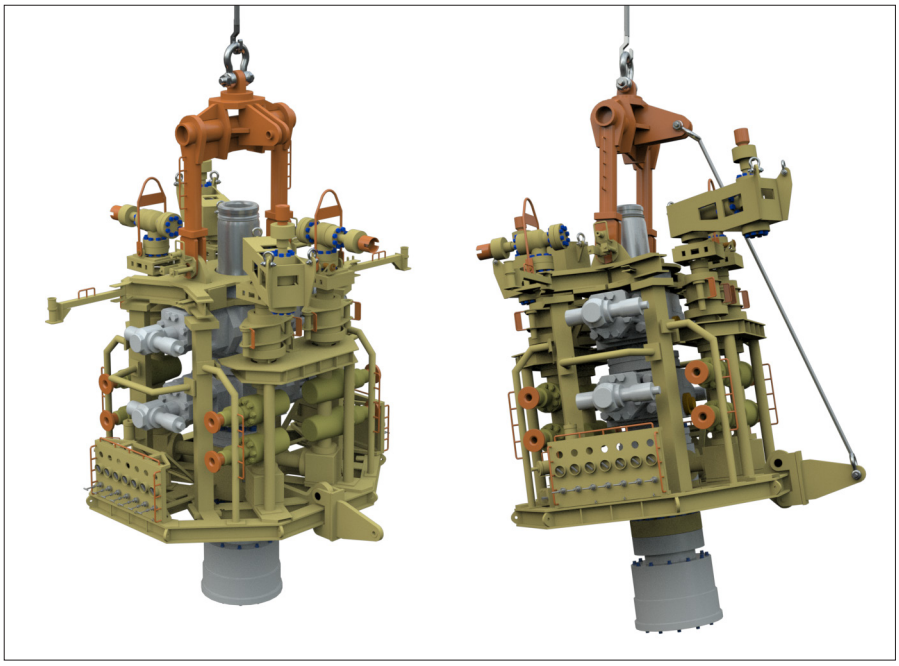


Figure 5: Alternative method for landing a capping stack on an inclined BOP.

4.2 Damage to Seal Faces

Scratching or gauging of the seal face of the BOP or Wellhead mandrel may compromise the ability of the capping stack connector to form an adequate seal. In such an event, the planned contingency is to pull the capping stack and install an alternate gasket design with an elastomeric (resilient) seal preparation. If this does not work, alternative gaskets with softer metals may be applied. The risk with the resilient seal gaskets is the potential for elastomer to dislodge from the flowing wellbores discharge. As this is considered a low risk event, the base case is to run the conventional metal to metal seal.

4.3 Restricted Vertical Access and Offset Installation

In shallow water situations where the hydrocarbon plume or gas boil cover the flowing well location, it may not be possible for a vessel to access the vertical position to deploy the capping stack. In consideration of this, the industry has a range of offset installation or deployment tactics that have been developed. The three most common deployment strategies are:

1) Tandem deployment using two or more anchor handling vessels as illustrated in Figure 6. Understanding how the capping stack will respond in the plume is important and should be modelled with CFD.

2) A Heave Compensated Landing System (HCLS). A system originally developed to install subsea trees, HCLS works by lowering the capping stack into the water column and, at a pre-determined depth, buoyancy modules are connected by wire rigging which can be arranged to make the capping stack neutrally or positively buoyed. From this point, techniques vary depending on specifics, but one method involves installing suction piles around the incident well that are configured to receive rigging equipment. Rigging equipment is then installed and connected to the capping stack and the stack winched into position and landed. One of the considerations with this approach is understanding how the buoyancy modules and stack will behave in the plume. This can be evaluated with CFD.

3) Limited to the OSRL (Oil Spill Response Limited) consortium, the Offset Installation Equipment (OIE) is another option. This is a deployment frame that was purpose built for installing capping stacks in "shallow water" situations where vertical access may be hindered. The system follows a similar concept to the HCLS but uses four buoyancy modules that are built into a frame. The capping stack is located in the centre of the frame and hung on a connector that can be articulated to position and land the capping stack. By having the capping stack located in the centre of the frame, the buoyancy modules can be kept out of the plume and create a more stable platform. To help stabilise and position the system, drag chains and anchoring methods are used. Consideration needs to be given to local seabed infrastructure that may interact with the OIE drag chains or anchors. The system has been extensively engineered and exercised to land a capping stack on an abandoned well. The demonstration exercise also included landing the capping stack at a 10 degree inclination. The system is very large and must be disassembled, transported, then reassembled on site if mobilised by air. One of the considerations if choosing this system is how it would be staged offshore and where or how to position the towing wires.

Notwithstanding the above strategies, there can be specific "shallow water" situations that involve high rate gas wells in combination with adjacent seabed infrastructure that creates its own unique set of vertical access and offset installation challenges. These types of situations require careful consideration and evaluation for how to deploy and land the capping stack.

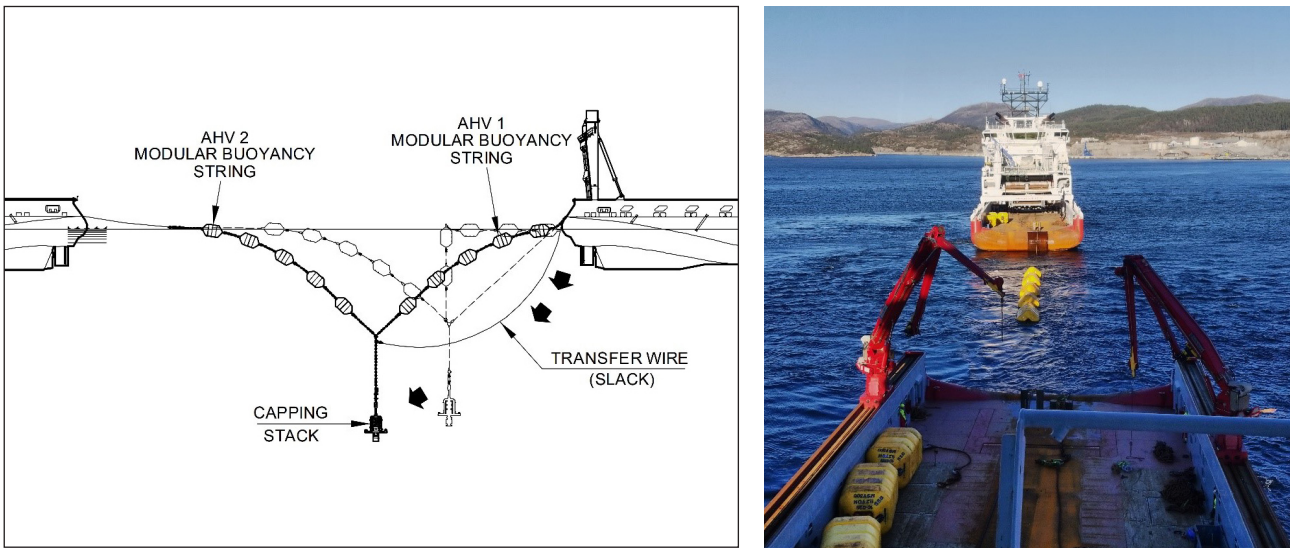


Figure 6: A schematic of the tandem deployment method (left) and a photograph of the test deployment setup that was carried out in Norway. The Norway exercise involved lowering a capping stack into the water using this method. *Reproduced courtesy of InterMoor.*

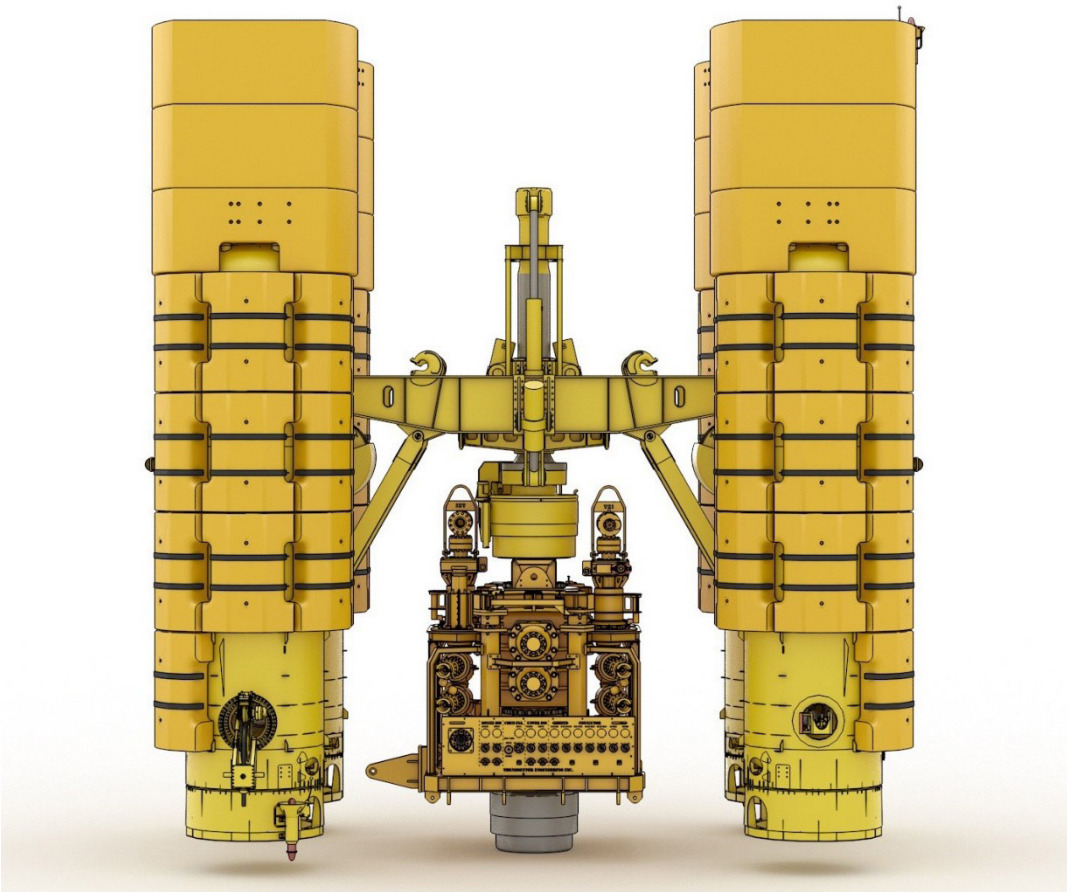


Figure 7: A rendering of the OSRL Offset Installation Equipment. The rendering illustrates the four buoyancy modules that surround the capping stack. The capping stack is held with a connector and articulated arm that allows it to be rotated and tilted to land on a flowing well. *Reproduced courtesy of Oil Spill Response Limited.*

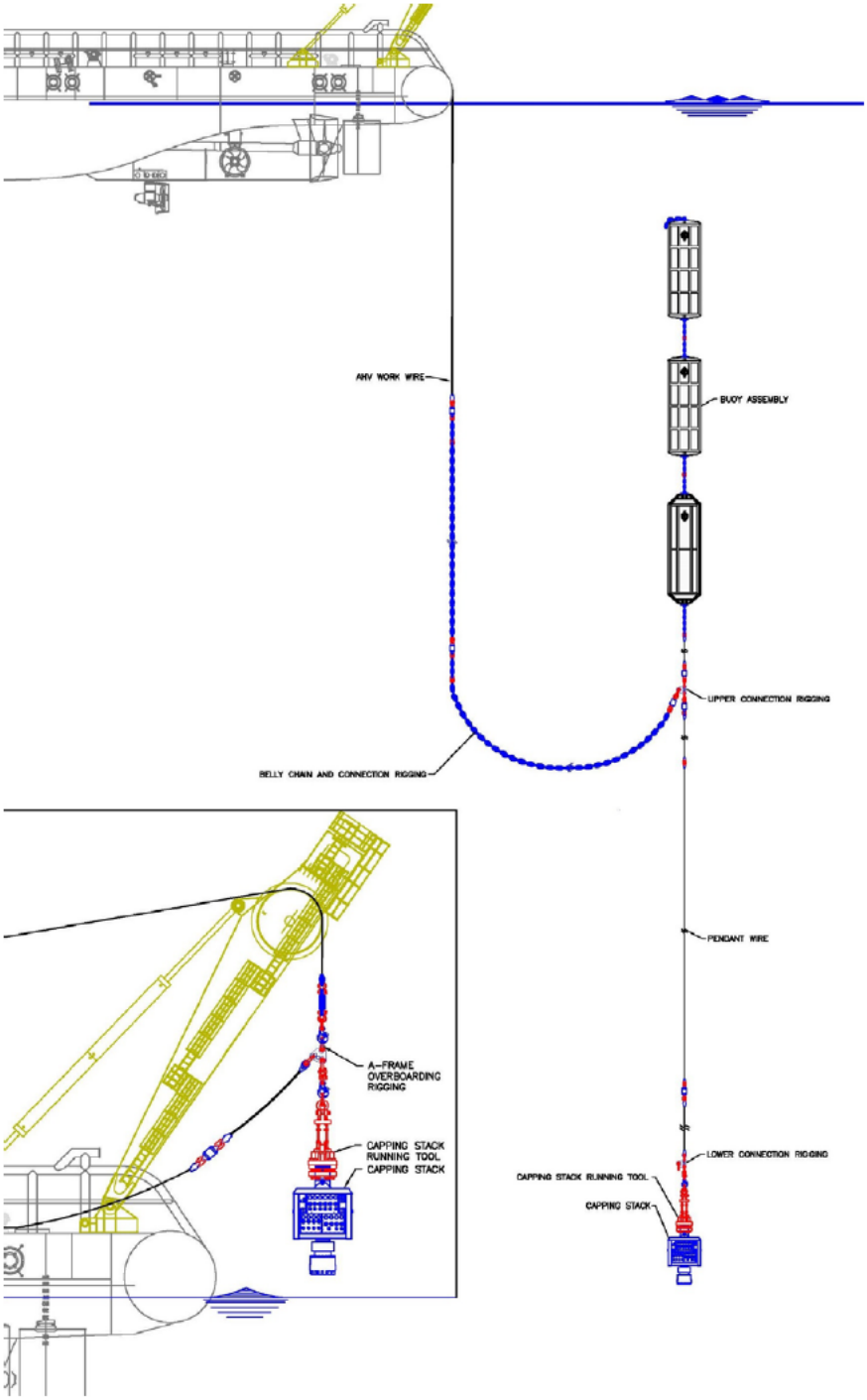


Figure 8: The Heave Compensated Landing System. *Reproduced courtesy of Delmar Systems.*

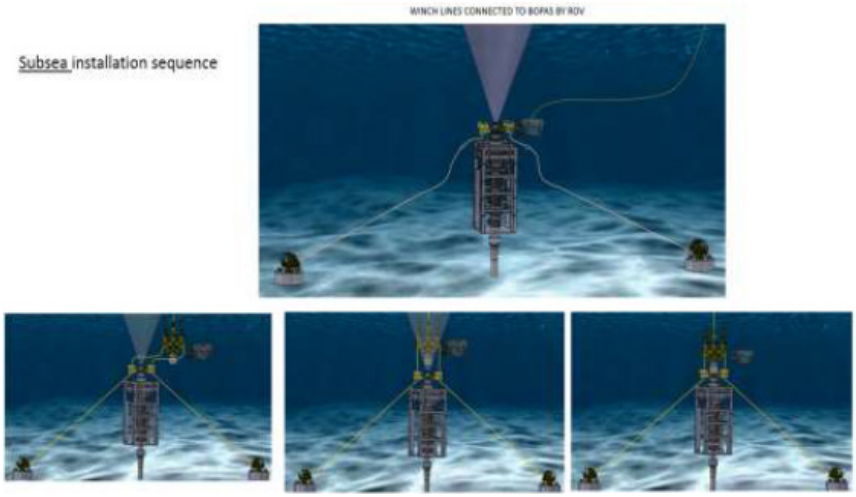


Figure 9: One type of winch positioning system. *Reproduced courtesy of Trendsetter Engineering.*

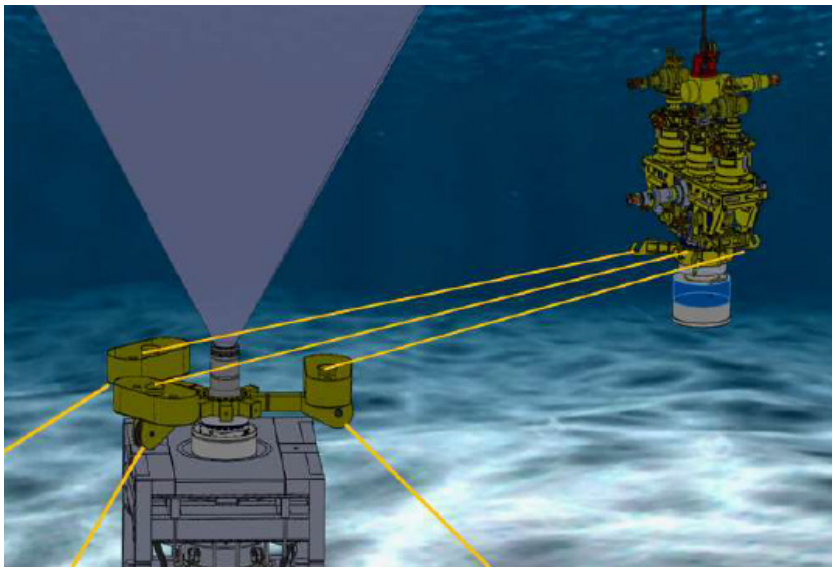


Figure 10: One type of winch positioning system. *Reproduced courtesy of Trendsetter Engineering.*

5. Catalogue of Physical Deployments

Since the *Deepwater Horizon* incident in 2010, Industry has carried out multiple physical deployments of capping stacks and critical source control equipment to demonstrate readiness and suitability. A summary of major activities is presented below:

Equipment Type	Deployment Date	Detail
Subsea Dispersant System	2012 / 2013	System deployed from Norway to Angola in support of an operator exercise.
	2019	System mobilised from Houston to Nigeria and physically deployed to a depth of approximately 1200m. Used to pump red dye as part of a deployment exercise.
OIE – Offset Installation Equipment	2017	System mobilised from storage base, loaded onto vessel, function tested subsea including landing of dummy cap on vertical and inclined wellheads.
Capping Stack	2012	Stack was loaded and sea fastened onto vessel and deployed onto dummy wellhead in 6900ft WD. Stack was then successfully pressure and function tested, then recovered to surface. Exercise validated all anticipated timelines.
	2012 & 2015	Stack was loaded and sea fastened onto vessel and kept in field during the drilling season. Stack was also deployed overboard and ROV surveys of the stack and panels were performed. Stack then recovered to deck, sea fastened, and pressure tested.
	2013	Stack loaded and sea fastened onto deployment vessel and mobilized offshore. Cap deployed on wire to ~5000ft WD and landed out on dummy wellhead. Stack fully function and pressure tested using ROV. Simulated soft shut-in procedure. Stack successfully recovered to surface.
	2017	Stack mobilised from storage facility onto vessel, deployed subsea, function tested and retrieved successfully to surface.
	2018	Fully assembled 15ksi capping stack successfully loaded on Antonov -124 aircraft including take-off and landing - see Fig 11 below
	Annual	Stacks typically moved from storage to quayside as part of annual maintenance programs.
Debris Clearance Packages	2012 - 2019	Multiple mobilisations from storage bases to locations round the world in support of exercises and actual events.
Shears	2009 – 2011	2500 shears physically deployed and used for cutting platform jacket legs in US Gulf of Mexico decommissioning activities.
	2010	2500 shears physically deployed and used for cutting the riser on the Macondo event.
	2009 – 2011	660 shears physically deployed and used for cutting subsea pipeline and multi-string wells on hurricane damaged platform projects.
Subsea Emergency Response System (SERS) – Capping Stack	2019	System specially designed to intervene in a drilling and production scenario. System mobilized from storage base in Congo, loaded onto vessel, landed on subsea wellhead (approximate depth 1200m) with all valves being functioned by ROV.

Figure 11: Air Freight Capping Stack Test Flight on AN-124 in 2018. *Reproduced courtesy of Oil Spill Response Limited.*

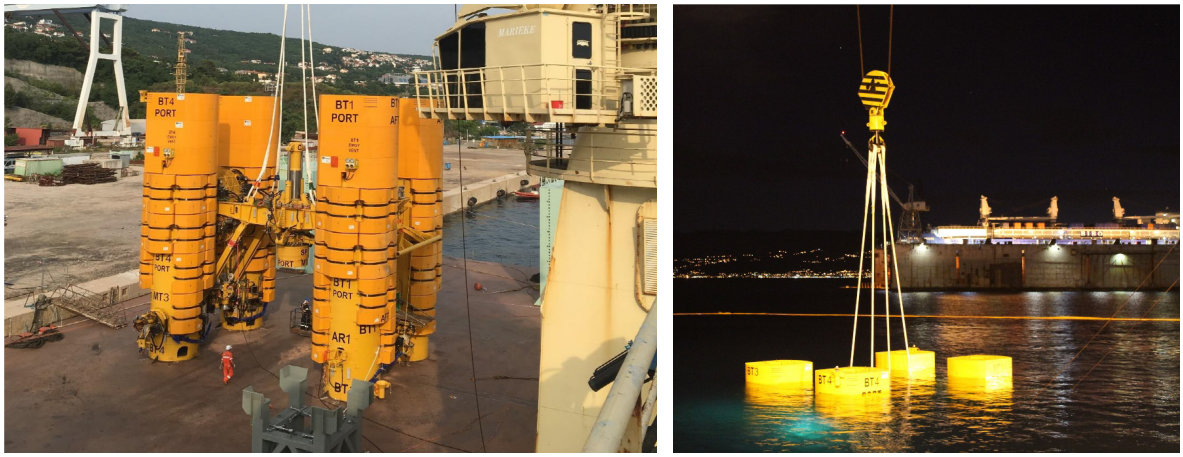


Figure 12: Some photographs of the OSRL Consortium's OIE equipment during its Site Inspection and Testing in 2017. To gain an appreciation of size, note the person standing slightly off the left-hand buoyancy module. The photo to the right is the OIE being lowered into the sea to later land a capping stack on an abandoned well. *Reproduced courtesy of Oil Spill Response Limited.*

6. When a stated design brief has been exceeded

Though most of the capping stacks available today had an initial design brief of handling up to 100kbopd, most can support much higher flow rates. In most situations, fluid handling capacity is governed by internal capacities, the diverter spool, elbows, lengths of flow paths and chokes. It is also governed by Containment assumptions. It is also governed by flow assurance considerations for a containment system (similar to a temporary production system). A potential workflow is shared below for situations where an estimated worst case discharge potential exceeds the stated design limits.

1) Evaluate the flow capacity information in Appendix 2. It may be the capping stack in question has already been revised beyond 100kbopd.
2) In addition to the analysis in Step 1, model WCCD (Worst Case Credible Discharge) flow rate. The WCCD is typically less than the WCD (Worst Case Discharge) number due to decline in flowrate over time. Another variant is WCCD modelling is use of choking flow on the capping stack to limit discharge volumes. This is an important number for well planning and 'oil into the water' calculations. It is also important for assessing capping stack use and possible integration with containment systems available from the providers. Evaluations and assessment through flow assurance may show that production is limited by surface processing systems rather than the flow-through capabilities of flow-lines and piping of the containment system.
3) Evaluate the flow potential with the capping stack provider and decide if it is necessary to complete an additional erosion study. If performing additional erosion study work, consider the recommendations as provided in API RP 17W.
4) As erosion studies have a high sensitivity to gas rate and solids, it may be prudent to revalidate the fluid characteristics that were assumed when designing the capping stack. Are those characteristics assumed during design representative of the conditions that could be expected in the area of operation?
5) An independent third party review and engineering validation of the engineering work completed above.

Conclusions

All subsea capping stacks have been developed to address a specific design brief and to work as intended. Their design includes redundancy features that further assure reliable operability. Within the response tool kit, the industry has access to a range of capping stack choices: which of these is best depends on the capping stacks operational envelope and application specifics. Irrespective of choice, all capping stacks have been constructed with proven components and can be reliably deployed using proven methods. The *Deepwater Horizon* incident is the only data point available to the industry for benchmarking subsea capping stack installation and performance. Practically, it is not possible to perform a full-scale exercise where a capping stack is deployed to depth and landed on a flowing wellbore. Static landings have been performed and continue to be performed every time a BOP or subsea Christmas Tree is deployed.

CFD is an established engineering tool used in a range of industries to model dynamic flow situations. As detailed in IOGP Report 594, CFD plays an important role in capping stack design, selection, uplift modelling, and deployment strategy.

Though confidence in design and deployment reliability is high, some specific areas of risk that may affect deployment are:

1) Damage to the gasket or sealing areas of the capping stack and the in situ connecting area. The damage may be due to factors such as solids in the wellbore, debris scratching, or other complications.
2) Excessive metocean conditions that exceed the heave compensation limits of the deployment system. Care needs to be taken when choosing the response vessel to ensure it has adequate crane capacity and heave compensation for the intended conditions.
3) An inability to land on a wellhead that is excessively inclined.
4) Shallow water situations, and more specifically those that involve high rate gas wells in combination with adjacent seabed infrastructure, create their own unique set of vertical access and offset installation challenges, which requires careful consideration and evaluation.
5) Modelling expertise and standardisation of modelling methods for CFD practitioners in the area of subsea source control. There are no publications within industry for how to perform a landing analysis. However, extensive analyses of flow cases have been performed by the industry. These show a self-centring effect during approach and landing, an effect observed during Macondo. IOGP is studying the topic further with the intention of providing a guidance document on CFD analysis.

Appendix 1: Failure Mode Analysis

The summary table that follows generalises and summarises some of the information contained within the Failure Mode, Effects and Criticality Analysis (FMECA) that has been completed for individual capping stacks that are available today.

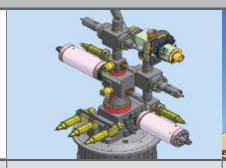
Assembly/ Component	Item Function	Failure Mode Category	Potential Failure Mode	Failure Mechanism	Failure Consequence	Safeguard/ Current Controls
Capping Stack System	Wellbore Containment System	Installation	Unable to land Capping Stack due to stability of stack over plume	Thrust force exceeded design limit Water column turbidity around the well and capping stack	Unable to land stack at well location Wellhead or seal face damage Uncontrolled Discharge Capping stack equipment (collision) damage	Landing analysis performed at specified worst case discharge properties Snubbing procedures to aid stack landing Landing procedures
			Well integrity compromised	Shut in sequence not implemented	Major damage of well bore system	Soft shut-in procedure Active pressure temperature monitoring
			Physical Damage	Dropped object	Partial Loss of functionality	Grating on top of frame Offshore handling procedures
			Unable to land Capping Stack	Stuck Objects in any bore (from plume)	Delay Operation	Injection of hydrate inhibitors during deployment; debris removal plans
		Storage	Elastomer and Paint Degradation	UV rays (External Storage)	CP system can be compromised due to inadequate coating performance	UV protectant coating system; Periodic Maintenance Storing indoors
		Operation	Structural damage to capping stack	Operational loads exceed design and safety factor parameters	Loss of containment and/or functionality	Operation Philosophy Design per Industry Standards and Codes applicable to Project requirements (e.g., API RP 17W)
Wellhead Connector	Interface to Wellhead. Interfaces to diverter spool Supports CS weight & bending moments Contains flow	Installation	Failure to seal between WH & WH connector	Debris ingress during running Scratching or gauging of the sealing area due to debris Seal retainer failure Seal damage or degradation Re-use of testing gasket	Potential damage of the WH and loss of integrity and loss of containment Unable to use capping stack for operation	Suitable material selection for wellhead connector Seal retainer mechanism testing; Operation Philosophy Maintenance and testing prior to installation Alternate gasket types (resilient seals, softer metallurgy) Deployment procedures ROV survey cleaning etc Procedures and witnessing for gasket change out

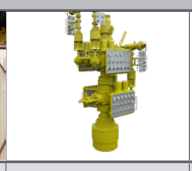
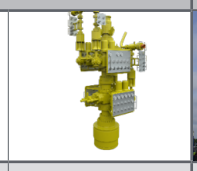
Assembly/ Component	Item Function	Failure Mode Category	Potential Failure Mode	Failure Mechanism	Failure Consequence	Safeguard/ Current Controls
			Fail to Lock or Unlock Connector	Loss of Hydraulics Hydrates formation Debris	Discharge around WH and loss of integrity Retrieve capping stack and delay in successful capping operation	Minimise exposure of hydraulic lines to flow Operation philosophy; Methanol Injection
			During landing due to misalignment on wellhead connector fail to lock	Wellhead inclination is more than permitted by design	Latch and lock on inclined wellhead Unable to land stack	Operation philosophy WH straightening procedures Inclination rigging
		Operation	Failure to operate primary unlock mechanism	Failure to operate primary unlock mechanism	Failure to unlock WH connector Inability to recover the capping stack assembly	MeOH wash Separate hydraulic control lines for primary unlock and secondary unlock Secondary unlock
			Failure to operate secondary unlock mechanism	Mechanical failure (common cause to primary and secondary unlocking mechanism)	Failure to unlock WH connector Inability to recover the capping stack assembly	None
			Failure to access MeOH wash line	Clogged line Loss of Hydraulic function	Hydrate formation and then lead to failure to unlock or lock WH connector	Secondary line
		Storage	Failure to seal/ hold pressure inside WH connector	Non-metallic Seal degradation	Scheduled delay	Pre-deployment check Maintenance procedures Spare seals
Blind Shear Rams	To shut in and isolate main bore Barrier to wellbore fluid	Operation	Ram blocks or ram seals eroding under flowing conditions during shut in Inability to close the blind shear ram fast enough	Erosion of seal face Debris preventing effective closure	Inability to shut in and seal Round trip of capping stack to re-dress	Multiple shear rams and sequential closing sequence Sufficient hydraulic power to close the blind shear ram within closure time Soft shut in procedures where flow is diverted through outlets while closing the blind shear ram
		Storage	Elastomer and hydraulic fluid degradation Seal surface degradation	Inappropriate storage and exposure to environmental elements	Complete re-dress when required on demand	Maintenance activities Pre-deployment checks Storage conditions (warehousing, climate control)

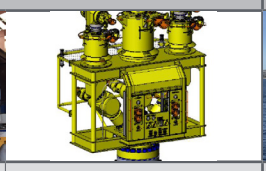
Assembly/ Component	Item Function	Failure Mode Category	Potential Failure Mode	Failure Mechanism	Failure Consequence	Safeguard/ Current Controls
Gate Valve	Flow Isolation Barrier to wellbore fluid	Installation	Failure to operate valve	Stuck object/debris in bore. Insufficient torque Mechanical damage due to over torque Class 4 end effector/ bucket is damaged	No barrier Inability to open or close gate valve	Operating procedures for not over torqueing Spare valve for centre bore & choke to reduce flow on the side outlets
		Storage	Compensator Failure (hydraulic valves only)	Inadequate volume of Fluid due to leakage due to thermal cycling	Potential damage to actuator mechanism/ sea water ingress	Relief Valves/ Maintenance Procedures Visual Inspection Mechanical override where equipped
Choke	Control Flow. Provide soft shut-in capability Sacrificial unit to safely cap well Contains flow	Installation	Failure to operate	Damage top Trim due to impact	Compromised soft shut-in	Retrievable choke Operational Philosophy
		Operation	Failure to operate	Limited accessibility via ROV (in the plume zone)	Loss of soft shut-in; Potential well integrity issues	Up-spouts to divert plume Operational Philosophy
				Damaged ROV interface Damaged gearbox	Compromised soft shut-in	Retrievable choke Operational Philosophy
				Stuck object in the bore	Compromised soft shut-in	Retrievable choke Operational Philosophy
			Failure to indicate choke position	Damaged visual indicator due to excessive impact force	Reduced functionality of choke Delay in choke operations	ROV tool: Count number of turns on torque tool to approximate choke position
Spools	Pressure containing. Divert Flow Provide Interface to PT/TT sensors Provide Interface to Wellhead connector Provide support to frame Provides support to spool Provides access to centre bore	Installation	Flow outlets clogged	Hydrates	Difficulty in landing capping stack	Chemical injection access lines provided for injecting hydrate inhibitors via ROV Deployment philosophy Operational philosophy
		Operation	Compromised structural integrity	Erosion	Loss of Containment/ Major Leakage	Erosion Analysis (CFD) review using project conditions NACE MR0175 cladding
			Compromised process piping integrity	Corrosion due to process fluid	Loss of Containment/ Major Leakage	NACE MR0175 overlay in body
			Compromised structural integrity	Corrosion due to seawater	Possible loss of containment	Use of coatings 3 coat epoxy and CP from the capping stack
Component Flange Sealing Surface	Pressure containing	Mobilisation assembly or re-config'n	Damage in the sealing surface	Excessive deflection due to inadequate preload	Loss of Containment/ leakage	Assembly procedure Pre-deployment check Crane operation and Operator competency

Assembly/ Component	Item Function	Failure Mode Category	Potential Failure Mode	Failure Mechanism	Failure Consequence	Safeguard/ Current Controls
Chemical Injection Valve (Flow Outlet Panels)	Facilitate injection of chemicals into production bore – Diverter Spool (Valve A & B) Contains flow from diverter.	Operation	Fail to operate	Not enough torque from mechanical tool	Risk of hydrate formation	ROV Class 2 torque tool Continuous pumping of methanol Operating procedure
			Fail to seal at the gate	Damaged seal (gate) surface	Loss of secondary barrier Unable to check bore pressure depending on valve A or valve B functionality Small leak from stack.	Dual redundancy Dummy hot stab can be pressure barrier
Small Bore Tubing	Conduit for chemical/ dispersant supply.	Operation	Tubing leaks	Debris from plume Over stressed bends	Reduced functionality Leakage to environment	Protect tubing (routed in frame) Hydro test Minimise bends (minimum bending radius 10D) ASME B31.3 process piping design

Appendix 2: Individual Capping Stack Design Briefs

	Oil Spill Response					
Summary of Capabilities						
Location / Status	**Norway, Stavanger / Ready**	**Brazil, Angra dos Reis / Ready**	**South Africa, Saldanha / Ready**	**Singapore, Loyang / Ready**	**United Kingdom, Aberdeen / Ready (OSPRAG)**	**Italy, Trieste / Under Commissioning**
Pressure Rating	15k psi	15k psi	10k psi	10k psi	15k psi	n/a
Seal Elements	2 x 18-3/4" Rams	2 x 18-3/4" Rams	2 x 7-1/16" Gate Valve	2 x 7-1/16" Gate Valve	2 x 5 1/8" Gate Valve	N/A
Connector Profile OD	27"	27"	27"	27"	27"	N/A
Hub Profile	HCH4 or HC	HCH4 or HC	HCH4 or HC	HCH4 or HC	H4	N/A
Water Depth (m)	3,000	3,000	3,000	3,000	3,000	75 - 600
Stack Weight	~102mT	~102mT	~83 mT	~83 mT	~43 mT	236 mT
Footprint	16' x 13' x 28' to top of shackle	16' x 13' x 28' to top of shackle	16' x 13' x 28' to top of shackle	16' x 13' x 28' to top of shackle	13' x 13' x 15'	
Diverter Spool Outlets	4 x Outlets w/ 2 x 5-1/8" 15k PSI Gate Valves per outlet	4 x Outlets w/ 2 x 5-1/8" 15k PSI Gate Valves per outlet	4 x Outlets w/ 2 x 5-1/8" 15k PSI Gate Valves per outlet	4 x Outlets w/ 2 x 5-1/8" 15k PSI Gate Valves per outlet	1 x 5 1/8" Outlets	N/A
# Chokes / Flow	Three / 100,000bpd	Three / 100,000bpd	Three / 100,000bpd	Three / 100,000bpd	One / 75,000bpd	N/A
Deployment	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Wire
Operation	ROV (manual or hydraulic - hot stabs)	ROV (manual or hydraulic - hot stabs)	ROV (manual or hydraulic - hot stabs)	ROV (manual or hydraulic - hot stabs)	ROV, hydraulic	ROV
Design Temp degF = (degC x1.8)+32	minus 2 deg C to 150 deg C (302 deg F) - Operational minus 20 deg C to 40 deg C - Storage	minus 2 deg C to 150 deg C (302 deg F) - Operational minus 20 deg C to 40 deg C - Storage	minus 2 deg C to 150 deg C (302 deg F) - Operational minus 20 deg C to 40 deg C - Storage	minus 2 deg C to 150 deg C (302 deg F) - Operational minus 20 deg C to 40 deg C - Storage	250 deg F	minus 20 deg C to 50 deg C (Air) minus 2 deg C to 50 deg C (Water)
Manufacturer	Trendsetter	Trendsetter	Trendsetter	Trendsetter	Cameron	Saipem
Transportation Options / Scope	Sea or Air Stored and maintained fully assembled, can be air-freighted in fully assembled state without losing/reducing pressure integrity, to arrive in ready-to-use condition	Sea or Air Stored and maintained fully assembled, can be air-freighted in fully assembled state without losing/reducing pressure integrity, to arrive in ready-to-use condition	Sea or Air Stored and maintained fully assembled, can be air-freighted in fully assembled state without losing/reducing pressure integrity, to arrive in ready-to-use condition	Sea or Air Stored and maintained fully assembled, can be air-freighted in fully assembled state without losing/reducing pressure integrity, to arrive in ready-to-use condition	Sea	Sea or Air Stored and maintained in partial assembly. Will be fully assembed for mobilization at storage site. Must be disassembled then reassembled at well site for sea or airfreight shipment. Installation at sea requires 5 vessels (one must be a heavy lift vessel)
API RP 17W Compliant	Comparing a total of 87 requirements, an analysis performed by the OEM (TEI) confirmed that the OSRL capping stacks meet the intent of API RP 17W. The 4 requirements not met were not considered to be critical to Cat 1 or Cat 2 operational requirements.	Comparing a total of 87 requirements, an analysis performed by the OEM (TEI) confirmed that the OSRL capping stacks meet the intent of API RP 17W. The 4 requirements not met were not considered to be critical to Cat 1 or Cat 2 operational requirements.	Comparing a total of 87 requirements, an analysis performed by the OEM (TEI) confirmed that the OSRL capping stacks meet the intent of API RP 17W. The 4 requirements not met were not considered to be critical to Cat 1 or Cat 2 operational requirements.	Comparing a total of 87 requirements, an analysis performed by the OEM (TEI) confirmed that the OSRL capping stacks meet the intent of API RP 17W. The 4 requirements not met were not considered to be critical to Cat 1 or Cat 2 operational requirements.	No	n/a
Miscellaneous Comments					No ability to inject any fluid	

	Wild Well Control				Marine Well Containment Company		
Summary of Capabilities							
Location / Status	United Kingdom, Aberdeen / Ready	Singapore / Ready	United Kingdom, Montrose / Storage	United Kingdom, Montrose / Storage	USA, Ingleside (US Waters Only) / Ready	USA, Ingleside (US Waters Only) / Ready	USA, Ingleside (US Waters Only) / Ready
Pressure Rating	15k psi	15k psi	10k psi	15k psi	15k psi	15k psi	10k psi
Seal Elements	3 x 18-3/4"" Rams (blind or shear)	2 x 18-3/4"" Rams (blind or shear)	2 x 13 5/8"" Rams (blind or shear)	2 x 13 5/8"" Rams (blind or shear)	2 x 18-3/4" Blind Rams	1 x 18-3/4" Blind Ram	7-1/16" Dual Blind Ram
Connector Profile OD	27"	27"	27"	27"	27" or 30"	27" or 30"	27" or 30"
Hub Profile	H4 or HC	H4 or HC	H4 or HC	H4 or HC	H4 or HC	H4 or HC	H4 or HC
Water Depth (m)	3,800	3,800	3,000	3,000	3,000	3,000	3,000
Stack Weight	100 mT	110 mT w/ connectors & spreader bar	Weight with 2 Modules, 60 mT	Weight with 2 Modules, 70 mT	~170 MT w/ connectors and H4	~100 MT w/ connectors and H4	~40 MT w/ connectors and H4
Footprint	20' x 20'	20' x 20'	20' x 20'	20' x 20'	27' x 21' x 21' to 32.5' x 21' x 21' based on configuration (secondary containment cap installed)	22' x 16' x 16' (secondary containment cap installed)	18' x 9' x 9'
Diverter Spool Outlets	4 x 4-1/16" 15k PSI Outlets	4 x Outlets w/ 2 x 5-1/8" 15k PSI Gate Valves per outlet	BOP Side Outlets, 2x 3-1/16"" Dual Block Gate Valves	BOP Side Outlets, 2x 3-1/16"" Dual Block Gate Valves	4 x 5 1/8" Outlets	4 x Outlets w/ 1 x 5-1/8" 15k psi Gate Valves and 1 x 5-1/8" ball valve per outlet	2 x Outlets w/ 1 x 5-1/8" 10k psi Gate Valves per outlet
# Chokes / Flow	Two P25 Manual Chokes / 100,000bpd	2x 5-1/8" 15k CC40HP Choke / 150,000bpd	2x 3-3/16" 10k CC40HP Choke/350,000 bpd	2x 3-3/16" 10K CC40HP Choke/350,000 bpd	Four / Site and condition specific, seek advice	Two / Site and condition specific, seek advice	Two / Site and condition specific, seek advice
Deployment	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire
Operation	ROV (hydraulic and manual)	ROV (hydraulic and manual)	ROV	ROV	Umbilical or ROV	ROV	ROV
Design Temp degF = (degC x1.8)+32	API 16A, T-20/250	API 16A, T-20/250	API 16A, T-20/250	API 16A, T-20/250	250 deg F @ 15k PSI	350 deg F @ 15k PSI	300 deg F @ 10k PSI
Manufacturer	Cameron	Trendsetter	Cameron	Cameron	Aker	Trendsetter	Trendsetter
Transportation Options / Scope	Sea or Air, stored crated for air freight	Sea or Air, stored crated for air freight	Sea or Air, Stored assembled	Sea or Air	Sea Stored assembled	Sea Stored assembled	Sea Stored assembled
API RP 17W Compliant	No	No	No	No	No	No	No
Miscellaneous Comments			Available to Clients only in the North Sea Region. Subject to a separate membership agreement than the 18-3/4" systems	System will be completely recertified and operational Q4 2019. Not included in any consortium option at present			

	HWCG			PSW	Boots & Coots
Summary of Capabilities					
Location / Status	USA, Ingleside (US Waters Only) / Ready	USA, Ingleside (US Waters Only) / Ready	USA, TBC (US Waters Only) / Pending	Norway, Mongstad / Ready	USA, Houston / Ready
Pressure Rating	10k psi	15k psi	20k psi	10k psi	15k psi
Seal Elements	2 x 13-5/8" BSR Rams	2 x 18-3/4" Rams	1 x 5 1/8" Gate Valve per outlet 3 x 5 1/8" outlets 1 x 7" center bore valve	18 ¾" Dual BSR	2 x 5-1/8" Outer Gate Valves 1 x 7-1/16" Central Gate Valve
Connector Profile OD	27"	27"	30"	27"	27"
Hub Profile	H4	H4 or HC	Dxe H4 profile	H4 or HC	DX15 or H4
Water Depth (m)	3,000	3,000	3,000	3,000	3,658
Stack Weight	~74 mT w/ connectors	~71 mT w/ connectors and H4	~75mT w/ connector	~80 mT w/ connectors and H4	~40 MT
Footprint	17.25' x 14.6' x 19.17'	16.94' x 16.94' x 17.2'	15' x 11' x 26' (with running tool)	16' x 13.85'	25' x 9'
Diverter Spool Outlets	2 x 3 1/16" gate valves	2 x Outlets w/ 1 x 5-1/8" 15k psi Gate Valves per outlet	3 qty 5-1/8" Bores with 20k psi gate balves per outlet (3 side + 1 center)	2x outlets w/ 2 x 5 1/8" 10k psil Gate valves per outlet	2 x Outlets w/ 2 x 5-1/8" 1 x Outlet w/ 2 x 7-1/6" 15k psi FAI Metal-to Metal Gate Valves per outlet
# Chokes / Flow	One / 130Kbpd / 220 MMCFpd	Two / 130Kbpd / 220 MMCFpd	Two / 130Kbpd / 220 MMCFpd	No chokes - but flowlines can be connected to clamp connector on diverter outlet Flowrate 95 000 bpd (water and oil)	Two / 330,000bpd
Deployment	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Drill Pipe / Wire	Wire
Operation	ROV, hydraulic	ROV, hydraulic	ROV, hydraulic	ROV / Hydraulic	ROV API 17H Class 4 and 5 torque tool capability (ISO 13628-8)
Design Temp degF = (degC x1.8)+32	250 deg F	350 deg F	350 deg F @ 20k PSI	API -20°F to 250°F	0°F to 250 degF base case @ 15k psi. Can go to up to 350 degF with OEM clarification
Manufacturer	WOM	Trendsetter	Trendsetter	Trendsetter	Trendsetter
Transportation Options / Scope	Sea Stored Assembled	Sea Stored Assembled	Sea	Sea Stored Assembled	Air Freight / Sea Freight Stored Assembled Shipped Partially Assembled
API RP 17W Compliant	No	No	No	Yes	Yes
Miscellaneous Comments			Land Transport requires specialist heavy haul transport	Can be dismantled for Air freight, not rated for OSRL flowback connections. Designed for Arctic service	System can be air freighted on 2 x 747-400, 1 747-800F or 1 x AN124 Capping Stack disassembled into 5 parts for rapid response

Glossary of Terms

For purposes of this document, the following terms and definitions apply:

Term	Definition
BOP Stack	Subsea Blow out preventer (BOP) and Lower marine riser package (LMRP) as an assembly.
Capping	The process in which a capping stack is installed onto a flowing well and then used to shut-in the flowing well.
Capping Stack	A subsea device that is installed upon a flowing wellbore to either shut in or regulate flow.
Contractor	Company or other legal entity that provides a service to a client.
Containment	The process in which a capping stack is installed onto a flowing well and then partially closed in such a way that flow is diverted to surface processing facilities. It differs from Capping in that the well is not shut-in.
HAZID	(Hazard Identification) is a qualitative technique for the early identification of potential hazards and threats effecting people, the environment, assets or reputation.
HAZOP	A hazard and operability study (HAZOP) is a structured and systematic examination of a complex planned or existing process or operation in order to identify and evaluate problems that may represent risks to personnel or equipment.
Relief Well	A directional well that is drilled a safe distance from the incident well and designed to intersect the incident well at a certain point and pump fluids into the flowing incident well to stop the flow.
Source Control	The process of stopping an uncontrolled flow to the environment.
Third Party	Independent party that is not the OEM or equipment owner but is one of the following: – A technical classification society (e.g., American Bureau of Shipping [ABS] or Det Norske Veritas [DNV]). – A licensed professional engineering firm that performs verifications.
Verification	Provision of objective evidence that determines the extent to which a procedure, task, equipment item, operating system, or model conforms to its specification

Acronyms

API	American Petroleum Institute
BOP	Blow Out Preventer
BSR	Blind Shear Ram
CFD	Computational Fluid Dynamics
FMECA	Failure Mode, Effects and Criticality Analysis
GIRG	Global Industry Response Group
GOR	Gas Oil Ratio
HCLS	Heave Compensated Landing System
kbopd	Thousand barrels of oil per day
LEL	Lower Explosive Limit
LMRP	Lower Marine Riser package
MEG	Mono-ethylene Glycol
MODU	Mobile Offshore Drilling Unit
OEM	Original Equipment Manufacturer
OIE	Offset Installation Device
ROV	Remotely Operated Vehicle
SPE	Society of Petroleum Engineers
TRL	Technology Readiness Level
UEL	Upper Explosive Limit
VOC	Volatile Organic Compounds
WCD	Worst Case Discharge
WCCD	Worst Case Credible Discharge
WEC	Well Experts Committee

References

Note: In preparing this report, the authors reviewed detailed engineering reports that are not publicly available. If detailed technical information of a given capping stack is required, readers should contact their capping stack provider and request copies of OEM documentation.

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This report was developed to share the design basis of capping stack solutions with industry, regulators, and other stakeholders. It aims to provide confidence that capping stacks can be reliably deployed and function as designed.