Thunderous innovation

BP's field developments in the deep waters of the Gulf of Mexico are setting new benchmarks in almost every aspect of offshore engineering. *Terry Knott* takes a look at the pioneering work done in one particular area – completing the oil and gas wells for the largest of the fields, Thunder Horse

In an industry where technology achievements frequently attract analogies with the space programme, finding new superlatives for oilfield successes can be a little tricky at times. But some achievements stand clear of the pack with or without a catchy superlative label. In this regard, the Thunder Horse development in the Gulf of Mexico is unmistakably accepted as one of the most ambitious offshore field developments ever undertaken.

Located 190km south of New Orleans, the Thunder Horse field is the largest discovery in the region to date. But along with the abundance of reserves, comes a set of challenges of equal if not greater magnitude to recover them.

For the Thunder Horse reservoir lies beneath some 6000m of mud, rock and salt, topped by 1900m of ocean. To reach the hydrocarbons requires some of the longest deviated wells in the world, which when they enter the reservoir are greeted by a combination of formation pressure and temperature rarely encountered in the Gulf of Mexico or anywhere else – over 1200 bar and 135˚C.

In other words, everything about Thunder Horse is at or beyond the limits of the offshore industry's experience. And that means that tried and tested off-the-shelf solutions that have served the industry well over time, are few and far between when it comes to meeting Thunder Horse's inherently difficult operational demands.

Over the past four years since field operator BP and its development partner ExxonMobil embarked on the Thunder Horse project, an army of industry vendors and specialists has been involved in an unprecedented collaborative programme of equipment development, testing and qualification, to come up with a new generation of engineering solutions to handle the field's unique combination of challenges (*Frontiers*, September 2001).

On the seabed where the field's wells are located, new subsea valve trees and >>

The Thunder Horse PDQ platform will be the central hub for the development. It will be located over one of the field's four drilling centres, with wells tied back to the platform. Subsea wells are located at three other drilling centres – one 3.2km to the south, plus two to the north at 5km and 6.8km distances

>> manifolds, and their control systems, have had to be designed and built to withstand the huge pressures, both internal and external. From those subsea wells, steel flowlines taking hydrocarbons several kilometres across the seabed must be insulated against near-freezing sea temperatures to prevent ice-like hydrates forming in the lines – the project has also developed a new low dosage chemical hydrate inhibitor which will be injected into the hydrocarbon stream to help prevent hydrates. And a range of steel catenary risers, longer and stronger than any before – some are up to 600mm in diameter with walls thick enough to make them resemble gun barrels – have been designed to take the gathered well fluids on their long journey to the sea surface and the field's central processing hub. Here the well fluids will be handled onboard the world's largest production semisubmersible, a floating production, drilling and quarters (PDQ) platform with a displacement of 130,000 tonnes (pictured above). The platform is currently being constructed in South Korea, and is scheduled to be transported to Corpus Christi in Texas later this year, and then to its moored location offshore in 2005.

The list of development breakthroughs is formidable even by the standards of large oil industry projects, pushing technical know-how out to new boundaries. In operation, many of these equipment developments will be out of sight beneath the waves. Another set of first-time achievements will be even more invisible – deep down inside Thunder Horse's wells.

The well completions – the complex system of tubing, valves and barriers down inside each well – were a major challenge

Risk reduction

'The wells on Thunder Horse presented us with many new challenges,' says Bill Kirton, BP's wells delivery manager for the project. 'In addition to the very high bottom hole pressures and temperatures, the production rate from individual wells is also high, up to 50,000 barrels per day (bpd) in some cases. This means we needed larger bore tubing inside the wells than is normally used in the Gulf of Mexico, up to 150mm internal diameter, and high strength materials to construct it. On top of this the wells are really deep, stretching to 8200m vertical depth, and drilling the wells has to be carried out from 1900m above the seabed.

'When we started out we acknowledged the uncertainties were many. And sometimes we didn't even know what we didn't know.'

Reducing those uncertainties was aided by forming a strong drilling and completions team comprising hand-picked people from BP and ExxonMobil with experience of high pressure, high temperature (HPHT) developments elsewhere. BP's 'Beyond the Best' process for drilling and completions was employed to strengthen front-end planning, risk assessment and quality assurance activities. Another essential ingredient was the integration of key contractors and vendors into the team, with funding of new technology development where none existed that was capable of meeting the duties required for Thunder Horse. While a close eye was kept on up-front costs – there are more than 25 wells currently envisaged for Thunder Horse – Kirton notes that safety, protection of the environment, and subsequent well performance during operations, took precedence on the project.

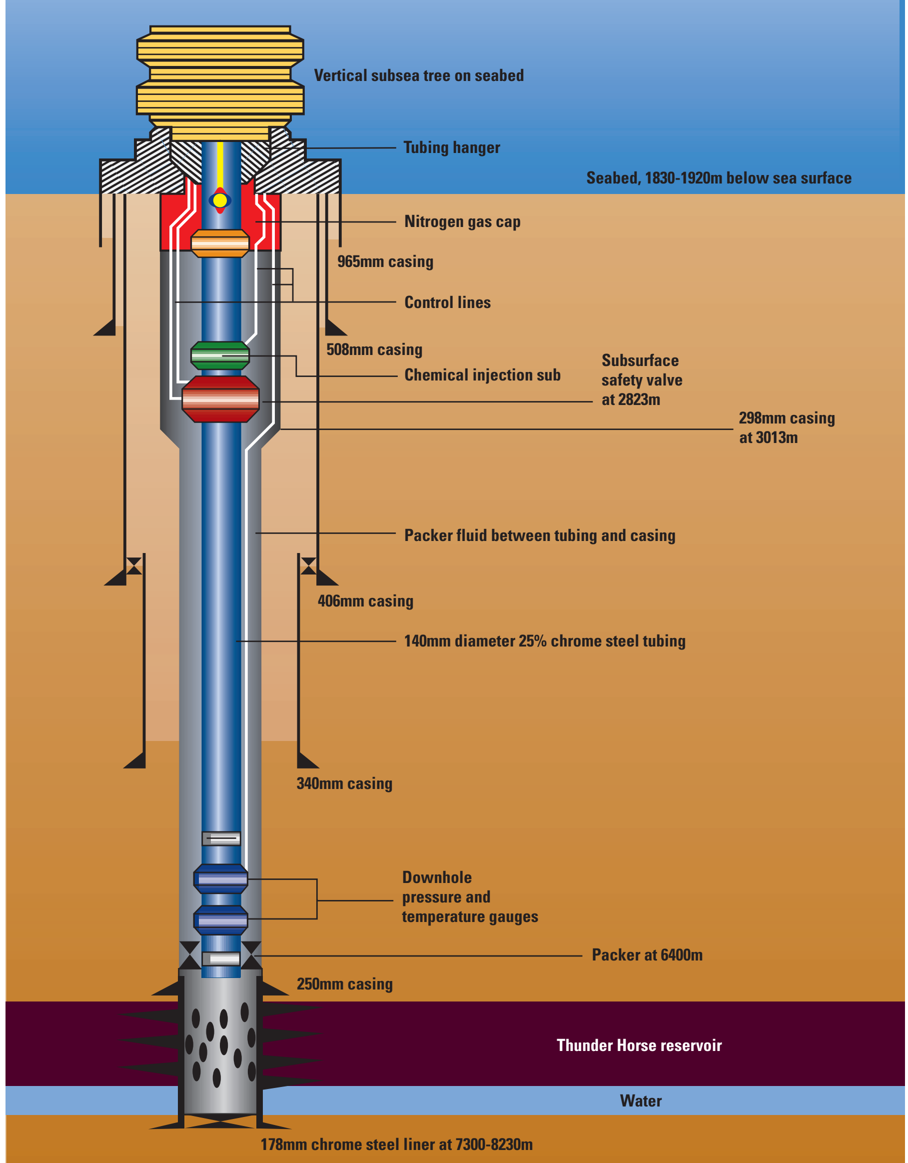
Large and small alike

High on the team's list of new engineering challenges to be addressed were the completions for the wells – the complex system of tubing, valves and barriers installed inside the wells following the drilling operation, which channels hydrocarbons safely from the reservoir producing zone to the wellhead on the seabed. Ensuring the completions were designed correctly, and that they could be installed from the sea surface, was critical, as Eamonn O'Connell, leader of the completions engineering design team, explains.

'Each completion on Thunder Horse costs tens of millions of dollars. It is vital to get each one right first time, because if a well fails, the entire string of completion components must be pulled out of the well for repair – intervention like that can cost as much again, and you lose hydrocarbon production while you do it.

'The tendency in the past has been to focus on the really expensive components in the completions string. But it's often the

Thunder Horse well completion (simplified)



For simplicity, the well in this graphic has been drawn on a simple vertical axis. In practice, wells in the Thunder Horse field are deviated by up to 45˚ from the vertical, to reach out up to 2300m into the reservoir

small widget that can catch you out. We acknowledged these smaller components to be of equal importance for the project and developed a quality assurance programme which would give them equal attention.'

Reflecting the complexity and magnitude of the completions task, an early move in 2002 was to split the activities into two teams – O'Connell's design team would focus solely on designing, developing and testing new components, while an operations delivery team under Steve Schellenberg would turn its attention to the intricate procedures that would be required for the installation of the completions equipment from the state-of-the-art deepwater drillship *Discoverer Enterprise*.

O'Connell notes that having five completions engineers in the design team alone, compared to a more usual one or two, was an indication of the work that had to be done.

'We were doing virtually everything from scratch, and had to question even the most basic assumptions. For example, with wells flowing at 50,000bpd, could the whole completions string vibrate itself to pieces? Answering such questions required an extensive testing and quality assurance programme for the many new components. It is astounding to think that of the 32 major components in a 140mm diameter Thunder Horse completions string, 18 of these are classed as "Serial Number Ones" – that is to say, they are the first of their kind ever made. You might expect one or two Number Ones in a completion. But certainly not eighteen.'

The 18 new design components were just the tip of the iceberg – a further seven were existing designs that had to be modified. And by the time the operations team had developed ways to install and operate the completions strings, a further 89 Serial Number Ones were notched up.

Delivering Number Ones

The new equipment was developed in close conjunction with the coalition of contractors and vendors in the Thunder Horse team, often by asking more than one supplier to come up with competing solutions to solve a given problem. Important to the success of this approach was having 'informed in-house buyers' from BP to monitor developments, challenge decisions, and make selections on which products were best aligned with the project's 'fit-for-function' philosophy.

'While this multiple supplier methodology increases overall workload and creates additional cross-company interfaces, the net result is beneficial,' says Kirton. 'The development programme on Thunder Horse has yielded a range of qualified products, making competitive alternatives available at reasonable cost. This is good for the wider offshore industry, particularly as we move into deeper and deeper waters.'

Funding for design, development and testing was provided for several key items. Among these are the subsurface safety valves (SSSV), one of which sits in each well some 2800m below the seabed. In the event of hydraulic power being lost to control the well, this valve automatically closes to act as a barrier to hydrocarbon flow. To develop and deliver such a valve to handle the high pressure, extreme depth and large tubing sizes on Thunder Horse, took 18 months, with two of the industry's leading suppliers working on the SSSV programme. Advanced electronic downhole gauges for measuring pressure and temperature were also developed anew, as were new packers for sealing off the annular space between the production tubing and well casing outside it – outside tubing diameter is 178mm while the inner casing varies from 250mm to 298mm in diameter.

Another Serial Number One focused on the packer fluids which are used to fill that sealed annular space. The hot oil flowing inside the tubing can cause the packer fluid to expand, rapidly building up pressure in the sealed annulus. This can particularly occur during well startup when packer fluid is very cold, an effect which in extreme circumstances could conceivably collapse the tubing or burst the casing – or vice versa during cooling contractions during shutdown. >>

Installing and connecting hydraulic and electrical control lines for a well has always been a tough and potentially hazardous procedure. The Thunder Horse completions team has improved this operation by developing a new suite of blade-free cutting, bending and connection-making tools

>> Normally, in conventional wells, this pressure is bled off into the flowline from the well, but as the pressures in the Thunder Horse flowlines are so high, this technique is not practical. Instead the completions team developed a method for placing a nitrogen gas cap in the annulus above the packer fluids, which absorbs the effect of the changing packer fluid volume.

'The nitrogen cap acts in a similar way to a car's shock absorber,' adds O'Connell. 'This is the first time this has been done in a deepwater subsea well.' (See diagram on page 11.)

The packer fluid itself is also a Serial Number One in the industry, a nine-month development fulfilling several operational criteria. These include the packer fluid being water-based for added safety, lightweight to meet the well casing design criteria, and low viscosity to enable pumping from and to the surface. In addition, the packer fluid is hydrate-inhibited to prevent freezing, environmentally friendly, and long-term compatible with downhole metallurgy, elastomer seals and the nitrogen gas cap.

The design of the tubing string also presented a challenge. With such long wells with high pressures and high flowrates, it was difficult to design a large bore tubing string that met all of the design requirements. The weight of the completion, which is suspended from the tubing hanger at the top of the well, can reach almost 250 tonnes before it is landed in the well and the packer is set. When the well is flowing, the tubing is subjected to further loads that approach the limits of existing tubing hanger connection ratings.

'Rather than the usual practice of accepting a single standard minimum wall thickness throughout the tubing string,' explains O'Connell, 'we modelled each well to determine precisely what forces the tubing will experience at different points in the well. Then, we worked with the tubing vendor and reviewed wall thickness inspection reports of thousands of joints of similar tubing. We then applied statistical analysis to predict the actual wall thickness of each joint of tubing that we ordered. This enabled us to custom-fit the wall thickness of the tubing to match the force resistance profile of the well, being strongest where it needs to be, giving us an optimised design to reduce overall tubing weight. The thickness only varied by about 2mm, but over an 8000m-long completion, this adds up significantly in terms of weight saved.'

The presence of hydrogen sulphide in the well fluids requires a special steel alloy to be employed for manufacturing the tubing, in order to resist potential corrosion cracking caused by hydrogen embrittlement of the steel. A 25% chrome alloy high-strength steel is being used, with which the industry has only limited experience, requiring a significant testing programme focused on such characteristics as its long-term performance at high pressures and temperatures – steel strength reduces with increasing temperature – and the integrity of joint connections. As the alloy is slightly 'softer' than standard tubular steel, it tends to mark more easily, providing sites for potential corrosion; hence new handling equipment has been developed by the project for installation operations.

Over 100 'Serial Number One' innovations were made during the development of the completions

The tubing hanger was one of several components for which full-scale 'mock-ups' were built, enabling the operations crew to become familiar with the equipment in advance of its installation. For installation, the tubing is made up on the *Discoverer Enterprise* in joints, and lowered down to the well through the drilling riser. At the same time, hydraulic and electrical control lines, connected to downhole tools and sensors in the well, are spooled from large reels and clamped onto the outside of the tubing string, eight lines in all. These lines are encapsulated with a strong thermoplastic cover for protection while sliding down the wellbore. The lines must be cut, the thermoplastic covers stripped, and the lines connected to the tubing hanger at the surface so that connectivity will be maintained with each tool and sensor in the well. Traditionally, the plastic ends have been removed manually using a sharp knife, a tough two-handed operation with inherent safety risks. This practice too was subjected to improvement by the completions team – originating from one BP employee in his garage at home – resulting in the development of a new suite of blade-free cutting, bending and connection-making tools for downhole control lines.

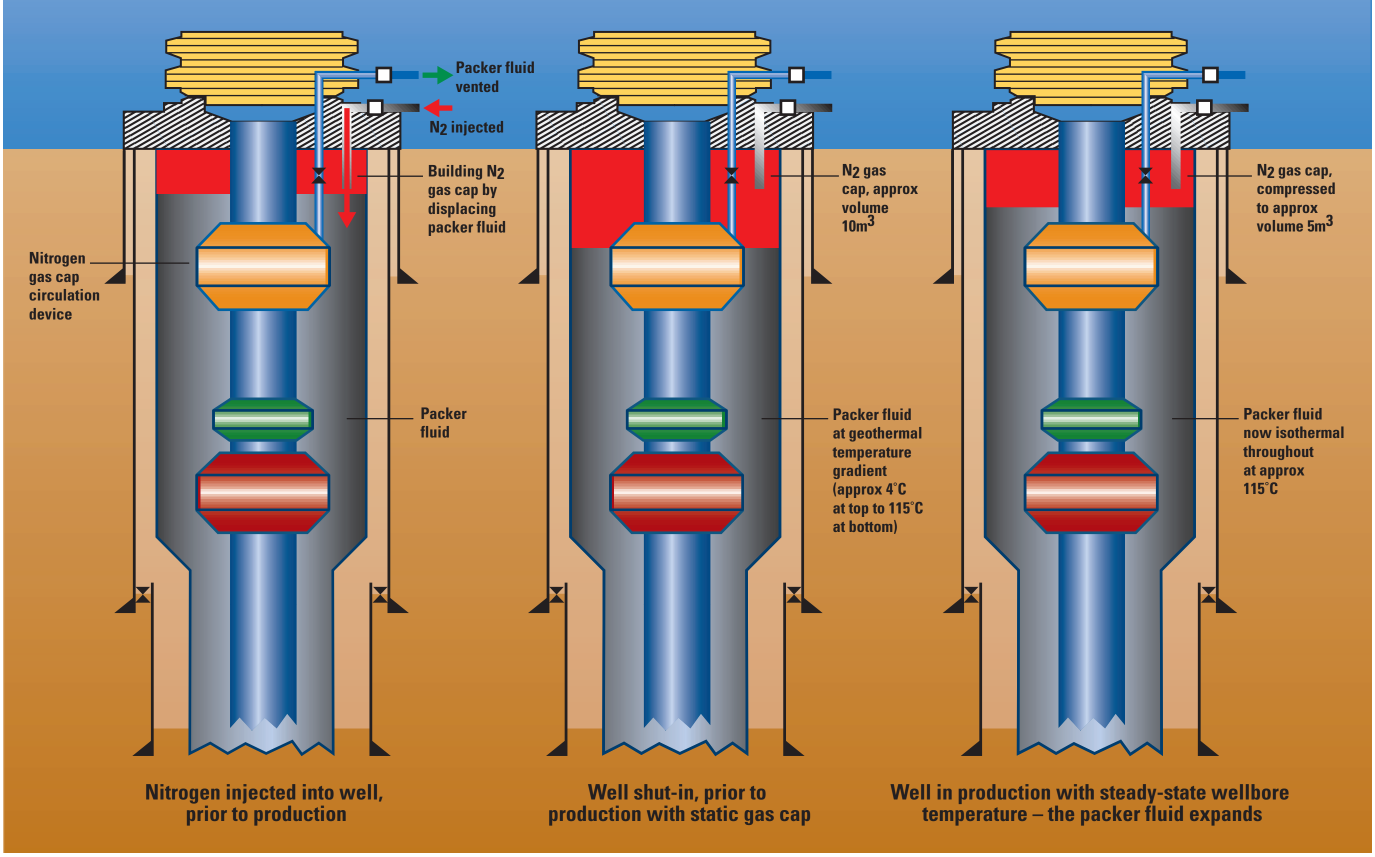
Water and sand

As if the detailed structural analysis of the tubing and its performance during hydrocarbon production was not enough of a challenge, the team also had to take account of the fact that any of Thunder Horse's wells could be switched from hydrocarbon production duty to water injection duty at some stage in the field's life. This would radically change operating pressures and temperatures – typically from 135°C to 4°C. In addition to the capacity of the PDQ platform to handle 250,000bpd of oil, 5.6 million m^3 per day of gas and 140,000bpd of produced water, the platform will also be equipped to deliver 300,000bpd of treated seawater and produced water for injection into the reservoir to maintain pressure. At this rate and with a delivery pressure greater than 550 bar, the injection pumps and associated facilities are the largest in the world.

When the injection water mixes with the water in the reservoir formation, bacterial action will create hydrogen sulphide – hence the chrome alloy steel – but in addition, barium sulphate can be formed, potentially

The nitrogen gas cap – a Thunder Horse 'Serial Number One'

Thermal expansion and contraction of packer fluid in the well's inner annulus causes significant changes in annulus pressure. To accommodate this, the wells contain a nitrogen (N_2) gas cap, which acts like a shock absorber



resulting in severe scaling of well tubing and other equipment. Pre-emptive chemical 'squeezes' can be pumped into the well to prevent scale build-up, for which the project has developed long-acting chemical treatments that will function at high temperatures, containing 'diverting' agents to ensure the chemicals reach all the targeted parts of the reservoir and not only the high permeability zones.

Sand, too, will be produced from the reservoir. Although sand will only be present in small amounts, when travelling at high velocities in the tubing this could cause erosion, particularly where internal diameter changes occur, for example at valve shoulders. Working with the University of Tulsa – acknowledged experts in modelling sand erosion – the project is confident that the completions design will not be adversely affected by sand.

Looking ahead, the well completions have been designed for modification if additional equipment is required at a later stage, including downhole optical fibre sensors for measuring parameters such as temperature and pressure, or 'smart wells' incorporating surface-operated valves to isolate individual zones of the reservoir to minimise water production and maximise hydrocarbon recovery. The three producing zones of the Thunder Horse reservoir formation fortunately contain rock strong enough to be perforated and produced without additional sand control measures (*Frontiers*, August 2003), although a few of the future wells in the northern section of the field may need sand control. Should well intervention be necessary, the project has taken the industry's standard method of using coiled tubing for well intervention to new levels, developing a 50mm diameter coiled tubing system with a yield strength of over 800,000 kilopascals that can operate in wells at distances up to around 10,000m from the surface.

Spreading success

In January this year, the first of Thunder Horse's wells was completed successfully, since which time two more have followed.

'The first well took 51 days to complete from the *Discover Enterprise*, including the time to prepare the well,' says O'Connell. 'We learned a lot and made good use of the twin derricks onboard the drillship to carry out some operations "off-line" in parallel with live operations in the other derrick. For example, we can make up long sections of completion tubing in one derrick while running tubing sections into the well with the other, or have the subsea tree already lowered from the drillship and at the seabed, ready to attach it to the subsea wellhead – operations such as this can save days. By the time we did the third completion, we had the overall time down to 25 days, and reduced the downtime by 75%.'

While Thunder Horse's completions team can rightly be proud of their achievements, their success is also bringing benefits to BP offshore projects around the world, including others in the Gulf of Mexico, such as the deepwater Atlantis field, and in Angola, Azerbaijan and Trinidad. Such has been the effectiveness of the exhaustive quality assurance and control processes on Thunder Horse, that the project's approach to developing new completions has become the standard practice for all BP's completions operations.

Keeping a close eye on even the smallest widgets in Thunder Horse's pioneering completions programme seems to have paid off handsomely for BP's most ambitious deepwater development. ■

Copyright and legal notice

Copyright in all published material including photographs, drawings and images in this magazine remains vested in BP plc and third party contributors to this magazine as appropriate. Accordingly **neither the whole nor any part of this magazine can be reproduced in any form without express prior permission**, either of the entity within BP plc in which copyright resides or the third party contributor as appropriate. Articles, opinions and letters from solicited or unsolicited third party sources appearing in this magazine do not necessarily represent the views of BP plc. Further, while BP plc has taken all reasonable steps to ensure that everything published is accurate it does not accept any responsibility for any errors or resulting loss or damage whatsoever or howsoever caused and readers have the responsibility to thoroughly check these aspects for themselves.

Any enquiries about reproduction of content from this magazine should be directed to the Managing Editor (email: knott@bp.com).