Design criteria, planning critical for successful deepwater well testing in HPHT developments

**By Hercilio P.S. Filho, Petrobras;
Edgar Almanza and Alejandro Salguero, Halliburton**

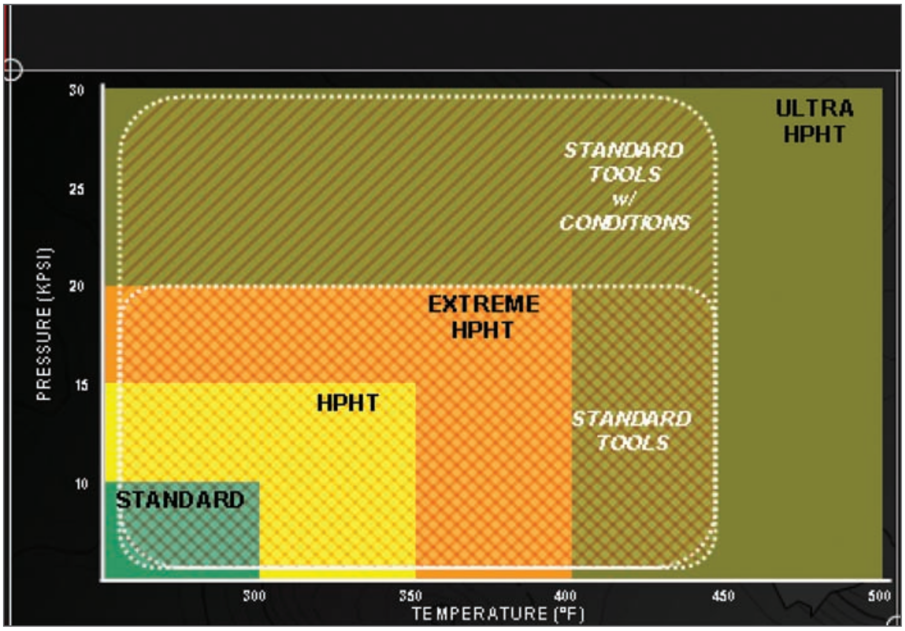


Figure 1: Well classifications based on tool envelope.

CONDITIONS IN DEEPWATER environments have required operators and service companies to resolve many major challenges to well completion. And because these environments are providing some of the biggest opportunities for new oil and gas prospects, it has been well worth the effort to consider these problems and develop new solutions.

Normally, testing is required before any development can be considered, and testing in high-pressure, high-temperature (HPHT) scenarios has been one of the most challenging tasks in the current arena. So have industry efforts to resolve testing problems in deepwater paid off? You bet.

Wells are currently classified based on the environment that will be tested and are divided into four categories (Figure 1). The first category includes routine wells; the second includes HPHT wells; the third includes extreme HPHT wells; and the last is for ultra-deep HPHT wells. This article targets conditions in the second category: These prospects are at least 15,000 ft deep, with bottomhole pressures of approximately 10,000 psi and bottomhole temperatures in excess of 300°F (Tables 1a and 1b).

PROSPECTS, EVALUATIONS

A series of testing operations have been performed in Brazil under Category 2's extreme conditions, and, thanks to careful planning, good results were obtained. The planning included downhole tools, subsea and surface equipment, and the linking of all the variables that could affect the operations and impact the final results of the completion success.

It was important that testing not be considered an isolated operation, nor should it target evaluation of simple variables. All events that could occur during simultaneous operations must be evaluated to determine possible impact on equipment. Also, the evaluations must assess how extreme conditions would impact equipment operation. Thus, mandatory execution of a HAZID/HAZOP analysis by a qualified team of deepwater experts is necessary if a complete assessment of the entire operation is to be targeted. This will allow capitalizing of all technical expertise to make the testing evaluation a success.

EQUIPMENT

To guarantee that targeted results are achieved for an entire operation, several individual evaluations should be performed.

Downhole, subsea and surface equipment evaluation. All specifications and mechanical characteristics of the required equipment must be reviewed to determine operational limits.

Electronic equipment. Electronic equipment that will be part of the evaluation must be assessed to establish compatibility and determine any restrictions due to well conditions during the test. This evaluation is especially important with respect to extreme temperature conditions.

Simulators and evaluation software. Simulators with specialized software allow assessment of the different parameters that could impact equipment performance. The software develops models that must be validated to identify potential changes on the initial specifications, i.e., changes that could affect the performance of the operation. Special considerations are required for the torque and drag models because these allow evaluation of the impact generated by rotation and movements on the DST string.

Other operations. Other critical areas to review are the wireline and slickline operations to assure that they are capable of achieving the test objectives. These operations are critical because they guarantee proper gun positioning and real-time data acquisition for quick reservoir evaluation decisions.

Overall, proper planning is vital during testing operations in deepwater to allow the collection of accurate and representative information and to assure that the evaluation operation will be successful.

PIPE CHARACTERISTICS

Casings and liners. The standard configuration uses heavy piping from 9 ⅝ in. to 10 ¾ in. for the casing and 7 to 7 ⅝ in. for liners.

Testing pipe. Proper tubing must be selected based on the environment that will be tested.

Criteria for selection:

1. The biggest OD required to support heavy strings and good flow areas.

2. Special consideration for the smaller ODs, since they will be in high-collapse-pressure environments.

Table 1a — Short Term Seal Selection Guide O-rings

Information in this chart must be applied within the specific equipment operating envelope and to the approved compounds as listed in the specifications outlined below.

General Information			
ASTM D1418 Designation	**FKM[1]**	**FEPM[2]**	**FFKM**
Trade Name	**Viton®**	**Aflas®**	**Chemraz®**
Specification	600.33001	601.30000	ES-R-15-3
Duration and Temperature Limits			
Min. Temp. °F (°C)	-10 (-23)	100 (38)	40 (4.4)
Max. Temp. °F (°C) for Exposure ≤ 24 hours	500 (260)	500 (260)	450 (232.22)
Max. Temp. °F (°C) for Exposure ≤ 1 to 21 days	400 (204)[4]	400 (204)	450 (232.22)[10]
Pressure and Temperature Limits Without Backups [5,6]			
Max. Pressure at 500°F	NA	NA	5,000psi (34MPa)[12]
Max. Pressure at 400°F	5,000psi (34MPa)[12]	NA	8,000psi (55MPa)[12]
Max. Pressure at 350°F	7,000 psi (48MPa)[12]	NA	10,000psi (69MPa)[12]
Max. Pressure at 275°F	10,000psi (69MPa)[12]	5,000psi (34MPa)[12]	15,000psi (103MPa)[12]
Max. Pressure at 150°F	15,000psi (103MPa)[12]	8,000psi (55MPa)[12]	20,000psi (138MPa)[12]
Pressure and Temperature Limits With 1/4" Thick Backups [5,6]			
Max. Pressure at 500°F	10,000psi (69MPa)	10,000psi (69MPa)	10,000psi (69MPa)
Max. Pressure at 450°F	18,000psi (124MPa)	18,000psi (124MPa)	18,000psi (124MPa)[11]
Max. Pressure at 400°F	20,000psi (138MPa)	20,000psi (138MPa)	20,000psi (138MPa)
Max. Pressure at 350°F	20,000psi (138MPa)	20,000psi (138MPa)	20,000psi (138MPa)
Max. Pressure at 275°F	20,000psi (138MPa)	20,000psi (138MPa)	20,000psi (138MPa)
Max. Pressure at 150°F	20,000psi (138MPa)	20,000psi (138MPa)	20,000psi (138MPa)
Chemical Compatibility			
H_2S	🟨 8	🟩 8	🟩
CO_2	🟩 8	🟩 8	🟩
CH_4 (Methane)	🟩 8	🟩 8	🟩
N_2	🟩 8	🟩 8	🟩
Sweet Crude	🟩	🟩	🟩
Diesel	🟩	🟥	🟩
Aromatic hydrocarbons & Solvents (Xylene & Toluene)	🟩	🟥	🟩
Oil - Based Muds / Fluids	🟦 9	🟦 9	🟩
Ester-based drilling mud	🟨	🟨	🟩
Amine / Oil Inhibitors	🟥	🟩	🟩
Water based inhibitors	🟦	🟩	🟩
Steam	🟦	🟨	🟩
Salt Water	🟩	🟩	🟩
Zn Bromide	🟩	🟩	🟩
Ca Bromide (<14.2 ppg)	🟩	🟩	🟩
Na Bromide (<12.4 ppg)	🟩	🟩	🟩
Formates	🟥	🟩	🟩
High pH fluids (>9)	🟥	🟩	🟩
Alcohols	🟨	🟩	🟩
Methanol	🟦	🟩	🟩
HCl & HF Acid Mixture	🟩	🟩	🟩
Weak Acid (HCL<15%)	🟩	🟩	🟩
Strong Acid (HCL>15%)	🟩	🟩	🟩
Acetic & Formic Acids	🟦	🟩	🟩

🟩 **Recommended**

🟨 **STILL RECOMMENDED Slightly affected, but no significant chemical change**

🟦 **Operational conditions must be considered. Consult material engineer before running**

🟥 **Not Recommended**

1) Use Virgin PEEK backup rings above 400°F (204°C).
2) Use Virgin PEEK backup rings above 350°F (177°C).
4) Field reports have shown successful results for FKM at 410°F (210°C) for 8 days.
5) O-Rings with Virgin PEEK backup rings are rated as follows:
    10,000 psi (68,940 kPa) at 500°F (260°C)
    18,000 psi (124,092 kPa) at 450°F (232°C) - (600.00432)
    20,000 psi (137,880 kPa) ≤ 400°F (204°C)
6) 25% glass Teflon backup rings are rated to 10,000 psi (68,940 kPa) at 400°F (204°C).
8) Explosive decompression is compound dependent and could damage seals or elements. Consult Elastomer Best Practices for ED Resistant compounds.
9) Testing is recommended due to variability of proprietary ingredients of oil based muds
10) Chemraz® o-rings have been tested with virgin PEEK backups (1/4" thick) at 450°F for up to 21 days with a maximum differential pressure in excess of 15,000psi. See report D00269380 - 5" Select Tester Valve Qualification Test
11) See Report D00269382 - 5" Rupture Disk Safety Circulating Valve 450F Qualification Test
12) See Report D00297325 - TTTCP Extrusion Resistance Testing of FKM, Aflas, and Chemraz

Table 1b: General notes and PEEK backup ring requirements and limitations.

The evaluation and selection methods use specialized software that allows assessment and identification of potential risks during the operation, because the identified risks could impact the success of the operation if the test string were to be damaged during evaluation.

ELASTOMERS

Environmental variables such as temperature, pressure and well fluids must be evaluated carefully to properly select elastomers for these challenging conditions. Here are some important factors in well environment that can affect elastomer performance:

Temperature. Maximum temperature determines the selection of O-rings and other elastomers to be used on the various components during the testing evaluation. The minimum temperature and temperature cycling help determine the level of sealability required.

Pressure. Both the hydrostatic and differential pressure across a seal system are critical for proper selection because equipment will be working downhole at very extreme conditions.

Well fluids. Considering the environment normally found in deepwater prospects, the proper control of reservoir pressure requires appropriate drilling fluids. Fluid selection is impacted by cost and compatibility with the elastomer seals used downhole.

Some issues to be considered:

Pressure transmissibility. This is especially important since testing equipment works with applied annulus pressure. Some investigations have demonstrated a difference between the applied surface pressure and the reached bottomhole pressure. The difference between surface and bottom has been established in the range of 500 psi, and this makes it necessary to implement a pressure transmissibility test. It was normally performed in drill-stem testing (DST) operations to properly determine the pressure difference so that the necessary corrections on the applied pressure plan can be made.

Solids precipitation. A proper mud condition is also necessary because solid precipitation can generate a series of problems on the moving parts of the DST tools (Figure 2). This issue makes it necessary to perform additional studies that will allow tools, particularly the circulating and tester valves, to be developed that will work in the particular environ-

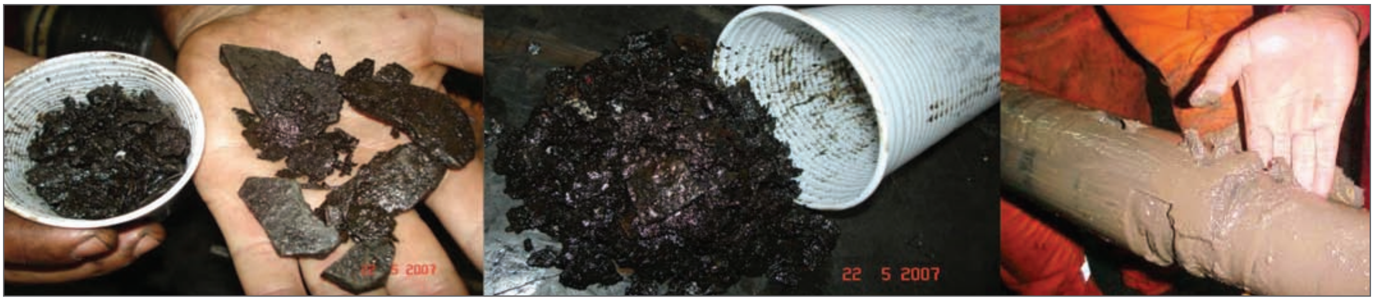


Figure 2: Examples of solids found on the tools used during well testing evaluations.

ment. Research and development projects are ongoing to reduce the negative impact of these conditions on the valves.

Brines. These are alternatives to drilling mud and have been used with very good results. Due to their toxicity, special handling is required to avoid harmful exposure to personnel. With extra care taken to mitigate personnel and environmental risks, brines are actually preferred to mud systems.

AVAILABLE ELASTOMERS

An in-depth discussion is necessary for this topic because these materials are critical to the success of the testing operation. Elastomer needs must be evaluated carefully and selected according to the type of fluid used and the temperature to which they will be subjected since both of these factors strongly affect the integrity of the elastomers. Currently, three types of seals are used:

Aflas (FEPM). Performance of this seal is influenced strongly by temperature. It has good performance at high temperatures but poor performance at temperatures lower than 38°C (100°F). In deepwater, performance is strongly dependent on the duration of exposure and differential pressure across the seal.

The combination of low temperature and high pressure could cause a leak in the tools, especially on the nitrogen chambers, and could affect the progression of the testing operation. Aflas performs well in most fluids but will swell in aromatics and some OBM formulations.

Chemraz (FFKM). This seal material has excellent performance at high and low temperatures and has the broadest well-fluid compatibility of any elastomer. The main concern is that it is expensive and must be manufactured for the specific application. These seals are called for only when bottomhole temperatures are expected to exceed 350ºF.

Viton (FKM). The most commonly used elastomer for testing jobs is FKM, and the most common trade name for FKM is Viton. This material typically has performed very well in environments with temperatures up to 350ºF. It is important to note that while it has been used at 400ºF for a period of a maximum of nine days without any problems, it should not be considered for offshore applications where operations are scheduled to last for long durations and where disconnecting operations are expected.

Viton seals are reasonable in cost and are easy to handle. Seal temperature and fluid compatibility are shown in Table 1.

TESTING EQUIPMENT

Several types of equipment are used for testing operations. Some systems are tubing-conveyed perforating (TCP guns, data acquisition equipment, DST strings, ocean floor equipment and surface equipment.

Tubing-conveyed perforating guns

The most commonly used testing applications require perforation of the well. Underbalance pressure is used because it causes minimal damage to the formation. This is especially critical when prospects with low-permeability formations are to be evaluated. Some considerations must be taken into account when a gun system is selected:

Type of explosive. The explosive could be RDX, HMX, HNS or PYX. Selection must be based on the wellbore temperature and exposure time. Operational limits for the charges are in Figure 3.

Gun-pressure ratings. Use of guns rated to 20,000 psi is necessary, since the gun body must be capable of withstanding the hydrostatic pressure plus the hydraulic firing-head operating pressure.

Hydraulic firing-head pressure calculations. This is a critical parameter since the actuating pressure must not exceed the gun's maximum pressure rating and must have a safe operating margin to avoid collapse of the gun body.

Correlation procedures. To execute this operation, the drill-stem test string must be run without subsea equipment and only with a fluted hanger to perform the initial correlation. Then, the string will be pulled out of the hole and the subsea equipment installed with the proper space-out below, after which the DST string is run again into the hole.

Data acquisition equipment

One the most important factors is the quality of the data acquired. Therefore, the equipment components must be evaluated with extreme care. These components include memory gauges and real-time data acquisition equipment.

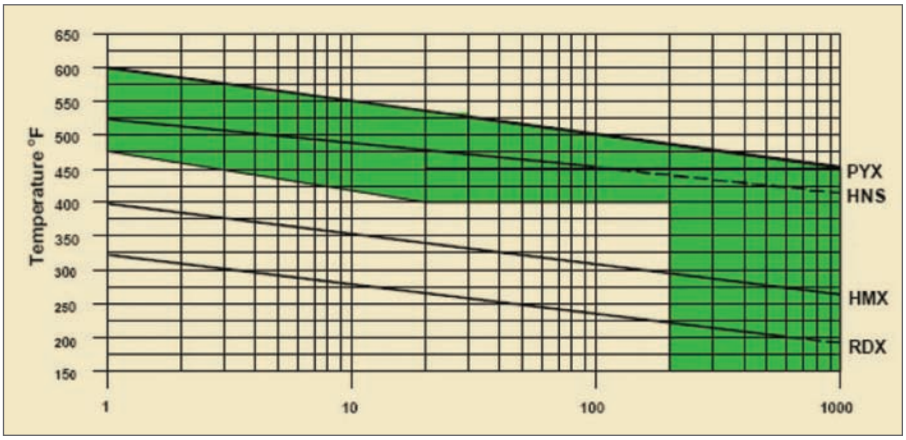


Figure 3: Operational limits for explosives selection.

Selection of memory gauges is based on the critical issues that impact the entire operation – the pressures and temperatures expected downhole.

Pressure. Hydrostatic pressures normally found in this environment make 20,000-psi gauges almost mandatory. Sometimes, the 15,000-psi gauges can be used with the reservoir pressure conditions, but it is highly recommended that 20,000-psi gauges are used in the high hydrostatics and operating pressures typically encountered in deepwater conditions.

Temperature. This is the most critical factor to consider in the selection of electronic equipment for the evaluation. The job normally is developed for two scenarios. First is 350°F to 400°F. Sometimes, high-temperature electronic memory gauges are required if conditions could reach 400ºF. These gauges have some limitations because of the fact that they are required to work in extreme temperatures.

The second scenario is 300°F to 350°F. Gauges with specifications up to 350ºF have been used with very good results.

Real-time data acquisition equipment

Alternatives for real-time data acquisition systems call for the use of wireline under two scenarios: data retrieval during any shut-in period, and data retrieval during a flow using a latch system.

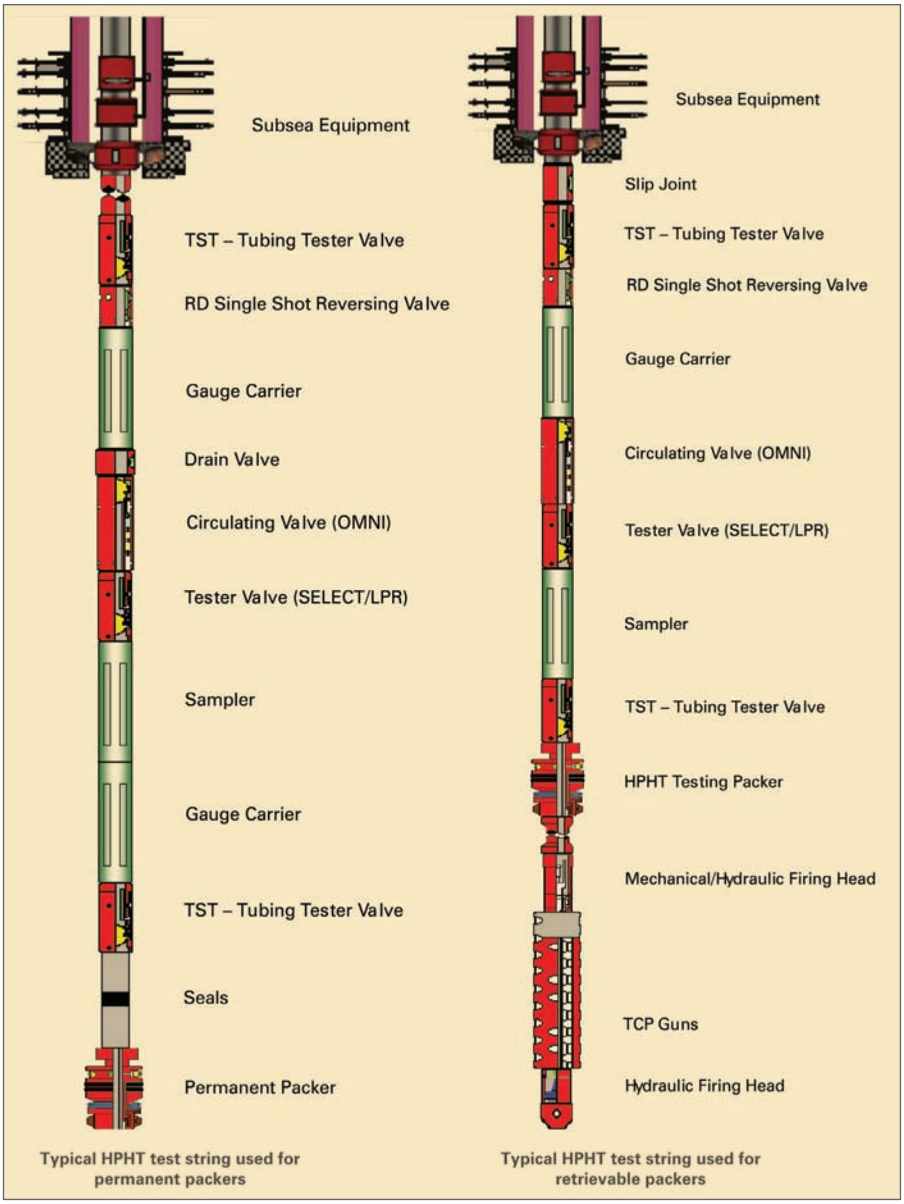
The operation requires the evaluation of two factors that can strongly influence the final results:

Maximum operating temperature. Again, the environment in which the testing will be done must be properly determined. A proper identification of temperatures above or below 300°F is required to select the system since most real-time bottomhole data acquisition systems are rated for 300ºF. Current technologies allow retrieval of data at temperatures of up to 350ºF. This is the current limit, but new technologies are being investigated to increase this temperature.

Operational simulations. These are required to assess the impact that use of long weight-bar strings could have on the job development.

DST String

Use of a 15,000-psi DST string is required because of the challenging conditions. Based on the operation required and the packer to be used for the operation, there are two main configurations for a test string (Figure 4) – retrievable packer and permanent packer



Typical HPHT test string used for permanent packers

Typical HPHT test string used for retrievable packers

Figure 4: Typical DST string configurations – permanent and retrievable packer.

Figure 4 includes examples of the strings used in this environment. These two configurations are the ones normally used for HPHT conditions.

Tool characteristics

Tester valves/multi-cycle circulating valves. These valves are annulus-pressure operated, and their performance can be affected by the temperature found during the execution of certain operations, i.e., circulating, injecting or fracture operations. Normally, they can be used several times over long time periods. New tools more tolerant to different types of debris are under development and should be available in the near future.

Tubing testing tools

Two types of valves can be used. The more commonly used is the flapper valve, but closed-ball-type tool operated (opened) with annulus pressure can also be used. Again, consideration must be given to the environment to be tested and how extreme the conditions will be. In both cases, the valve decisions must be made during job design to avoid problems during the actual testing.

Pressure test. A high-pressure test is normally used because the work usually is performed in deep wells. This testing is linked with the maximum pressure ratings of the tools and equipment that has atmospheric chambers, i.e., memory gauges, samplers, to avoid any overpressuring of the equipment.

Figure 5: The Armada tubing conveyed sampling system was designed for cased-hole environments.

Brines. Toxicity, cost and HSE issues with some of the brines used in this environment could impact the selection of the tool because this equipment will operate as a type of "standing valve." In the case of a flapper valve tool, handling the heave and the back-flow conditions during the operation is a consideration. Sometimes, a closed-valve tool is required.

In this case, the only concern when running a closed system will be the necessity to fill the work string at surface while running in the hole, since this can create some work delays. The tools can be combined, but this can be challenging because of the type of fluids used to test in this environment.

It should be noted that there are some new flapper type valve designs that have made the tool more tolerant to an environment that has high-debris content.

Use of tubing-conveyed perforating (TCP) systems. When valves are used, it is extremely important to perform a pressure test on the entire evaluation string from surface to bottom. The burst, collapse and the tensile rating of the tubing tester valve must be considered as the tool may not have the same capacity as the work string. This is very important since it might become necessary to use excessive pull or jarring to free the string during a fishing operation.

The packer

Two options are available for the operation: a permanent packer and a retrievable mechanical packer. This choice depends on the objective and the type of operation to be performed. When TCP is used, a mechanical packer is the preferred option. In other testing scenarios, the option used most has been the permanent packer. A new 15,000-psi HPHT retrievable packer is now available and is proving to be an excellent choice.

The slip joints

This tool provides flexibility to the string and absorbs length-change effects from the temperature. The best alternative to use for proper design of slip joints is a software program that can determine how to avoid buckling effects. It is important to note that permanent packers do not use slip joints.

New sampling system for cased-hole environments

The Armada sampling system is a state-of-the-art tubing-conveyed fluid-sampling system that was designed for cased-hole environments. It is applicable for testing in normal to heavy/viscous to hostile environments. The full-bore design allows unrestricted passage of wireline tools without affecting or damaging the samplers. It was designed for extended service in HPHT environments and allows capture of at least 80% of its full range of representative monophasic samples in the most extreme environments.

Each of the nine Inconel and inert samplers is rated for 400°F and 20,000-psi service and allows collecting of a 400-cc sample, which is kept monophasic by the exertion of nitrogen pressure.

The system is flexible, allowing the capture of one to nine samples. Several features have been added to improve sample quality and prompt interpretation of the tool performance. For example, the sample piston has a junk chamber for isolating the initial surge of potentially non-representative fluid during sample capture. The sample piston also has a position-location feature, which allows its location to be tracked by non-invasive means. Consequently, within minutes of the recovered sampler being set down on the rig floor, a reasonable understanding of the success of the sampling program can be determined (Figure 5).

Ocean floor equipment

Both 10,000-psi and 15,000-psi equipment are available for HPHT operations. Selection criterion is the maximum differential pressure. Another consideration will be generated from the tubing pressure tests. Equipment operated by electric line is used most often in deepwater operations because of the system's capability for quick response when disconnection is required.

Another important issue is the flowing temperature at the disconnection point since subsea equipment is designed for low ocean-floor temperatures and could be impacted seriously by flowing temperatures greater than the designated operational limit.

Surface equipment

Selection criteria for surface equipment are based on their pressure rating compared with the maximum pressures that could be reached at surface during the different operations.

Coiled-tubing operations

The main criterion to assess is the maximum cut capability of the subsea test tree.

Operational considerations

Different parameters and operations should be considered and evaluated:

- Flowing and static gradient temperature calculations to determine influence on equipment located at the sea bed.

- Reverse/direct circulation operations to establish string-length changes or seal-length design when a permanent packer is used.

- Testing of the string operations. This allows identifying how the pressure test could affect the tubing tensile capacity.

- Operations that could have an empty string. This is to identify potential possibility of collapse, especially in gas wells with poor production or when N_2 is used to reduce the hydrostatic pressure inside the string. Another important factor is that weight on the packer could be increased as a result of an empty or near-empty work string. This results in a generation of forces acting on the entire system that could create damages on the casing, if not properly supported.

Quality control issues

Main requirements are the following:

- DS-1 inspection.

- Pressure testing to guarantee operability of the tools.

- Tools used to apply torque to avoid damages on the equipment.

CONCLUSIONS

Design criteria and planning steps are critical for successful well testing operations in deepwater environments. Following are factors key to evaluation operations:

- Exposure time to high temperatures is critical for electronic equipment, elastomers and explosives.

- Weather conditions can have significant impact on the time needed for testing operations. It can affect the duration of equipment exposure to extreme conditions, especially with temperature.

- Simulations will deliver a clear idea of the events that could happen. This allows assessment of whether proposed equipment will meet job requirements.

Viton is a trademark of the Dupont Company. Chemraz is a registered trademark of the Greene Tweed Company. Aflas is a registered trademark of the Asahi Glass Co. Armada Sampling System is a registered trademark of Halliburton.

This article is based on a presentation at the 2008 Drilling Engineering Association Workshop & Exhibition, 17-18 June, Galveston, Texas.