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Making the Connection for Well Control on Floaters: Evolving Design Rationales for BOP Control Systems

Paul A. Potter

Abstract

In this chapter, a broad technical overview is offered to illustrate the technological advancements that have made the original direct hydraulic system reach those system design features that are shown in figure overleaf, which is a modern general arrangement of the "multiplexing" type of the BOP control system. Behind each discrete advancement, it goes without saying, there was a lot of design work, influenced by the radically different conditions in the subsea marine environment than those that we experience on land. Each step of this enabling technology is reviewed with in-depth reasoning explaining the "whys" and "wherefores" of each particular development. Let us start, as the drilling industry did for the development of BOP designs, at the beginning of the industry's step offshore around 60 years ago. Not least, it should be emphasized that the ways in which the systems' architecture has evolved have, in large part, been "driven" by the statutes laid out by the American Petroleum Institute (API) and later by other class societies that govern design compliance within the industry. The learning objectives of this chapter are to provide factual insights into evolving BOP control system designs as the industry moved from onshore to offshore and subsequently from bottom-supported drilling installations to floating drilling installations. This technology also forms the basis of the underpinning principles of hydraulic/electro and multiplexing subsea control systems that are currently used in the control of all kinds of production trees, subsea production centers, subsea distribution, and pipe line end manifolds (PLEMs). This chapter can be considered as a foundation and introductory overview for the development of control systems used in the subsea environment and those engineering challenges and obstacles that have been successfully surmounted, resulting in the technology basis in use today in the manufacture of subsea control systems.

Keywords: multiplexing, direct hydraulic, volumetric expansion characteristic (VEC) , signal time, sonic speed, closure time limits

1. Introduction

The challenge! How do you make this system?

It can be seen from **Figures 1** and **2** that there are a number of significant differences. Perhaps, the most noticeable difference is that the multiplexing BOP control system depicted, in the previous figure, features dual redundancy hydraulic supplies and command paths (blue/yellow BOP control pods). These are not evident in the direct hydraulic BOP control system shown in **Figure 1** [1–3].

Both command and hydraulic pathways are extended very considerably in the subsea multiplexing version over the direct hydraulic surface BOP control system. Whether it has been considered by the reader at the point of reading the introduction, another very major and significant system design characteristic that is evident is the Class Society rules governing maximum closing times for BOP wellbore functions that represent the underlying design rationale in the development of the control system suited for the use in deep and ultra-deep water locations.
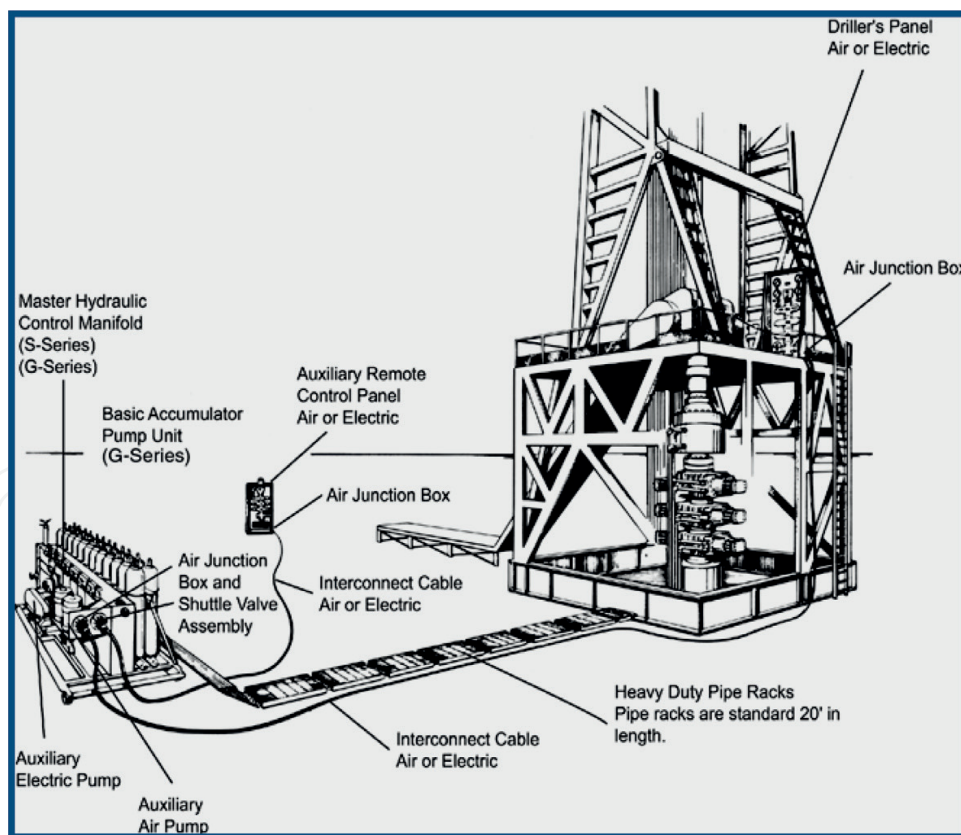

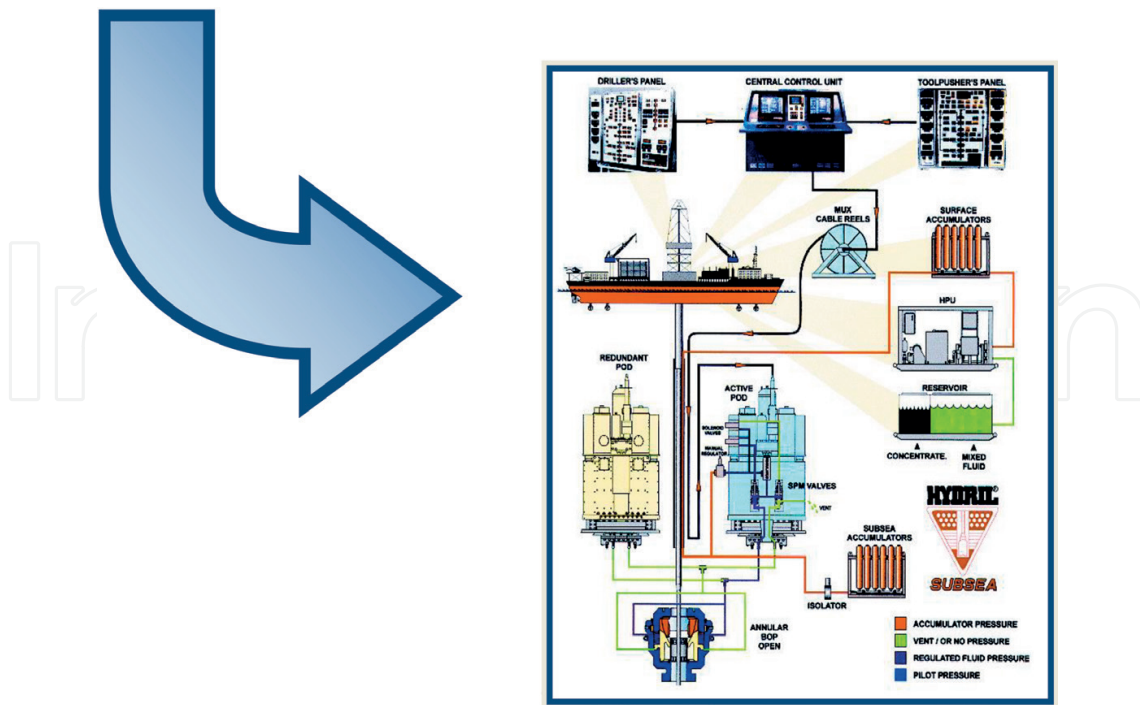**Figure 1.** The fundamental BOP control system for a surface BOP stack.

Figure 2. BOP multiplexing control system.

2. Conceptualizing the initial problems

2.1. Introduction

So, the starting baseline design is a system that is illustrated in **Figure 1**.

Essentially, this system is still in use today on land rigs, jack-ups, and tenders. Certainly, there are a number of design refinements on the basic system but the functionality and practical operability remain.

At this point, it should also be made clear that the core system requirements for the first land-based control systems and those encountered on sixth-/seventh-/eighth-generation ultra-deep water rigs are identical.

The BOP control system's main purpose is:

To exercise efficient and reliable control over the blowout preventer stack in the event of a well influx when the primary well control barrier of the hydrostatic column of drilling fluids in the well has not contained the well influx in the hole. Hence, we can say here that primary well control has been lost.

Put another way, we can state that the blowout preventer is the very last mechanical barrier between the well and us and is known as "secondary well control." All exploratory, appraisal, and development well barriers contain a secondary well control boundary.

2.2. Adaptation of land-based BOP control system for subsea service

In the most simplistic approach, we can now look at the immediate identified obstacles that reared up when the designers were contemplating the reality of making the current land-based system work subsea.

Let's refer once again to **Figure 1** in greater detail.

The normal hydraulic medium used in this closed system is 10 W (10 weight—density reference) mineral-based oil, and there are no environmental "leak" concerns because the system is shore-based or in the case of a bottom-supported drilling installation offshore (jack-up) surface application.

The following two figures further highlight the material requirements in a closed hydraulic control system where each end-user function (blowout preventer and valve hydraulic actuator) requires both a hydraulic supply and return line; this is in contrast to a subsea control system, which is an open hydraulic system (**Figure 2**).

The open hydraulic system, by definition, is one in which the displaced hydraulic fluid from the return/exhaust side of a hydraulic function is not routed via a dedicated return line back the accumulator unit reservoir but allowed to exhaust locally to the environment. In considering the application of BOP control subsea and in the marine environment, an open system must, essentially, employ a hydraulic medium which does not pollute or contaminate the environment in which displaced hydraulic fluid is being released into. Hence, a water-based hydraulic medium is utilized in all subsea BOP control systems (**Figures 3** and **4**).

The fifth figure in this chapter (**Figure 5**) is a simple block diagram of the most simple of a subsea control system maintaining closed hydraulic flow paths, while **Figure 6** shows the hydraulic flow path for one single BOP function, in this instance, a pair of ram type preventers. It should be appreciated that the single function hydraulic flow path depicted in **Figure 6** must be repeated to provide control over all BOP functions. This multiplicity of hydraulic flexible hoses is the basis of the perceived problem.

Let us imagine that we are in the design team that were tasked back in the early 1950s to get this control system working subsea.

Armed with the system architecture described briefly in the previous three pages, a simple approach may have been along these lines.

1. Provide a frame for the surface stack[1].

2. Install the hydraulic power unit on the rig topsides and run rigid pipe for the hydraulic supply and return lines to the moon pool area.

3. Install a hose reel to accommodate a hose bundle.

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[1]In this chapter, we are not considering the choke and kill lines. This becomes an integral topic in the marine drilling riser topics in the appropriate chapter
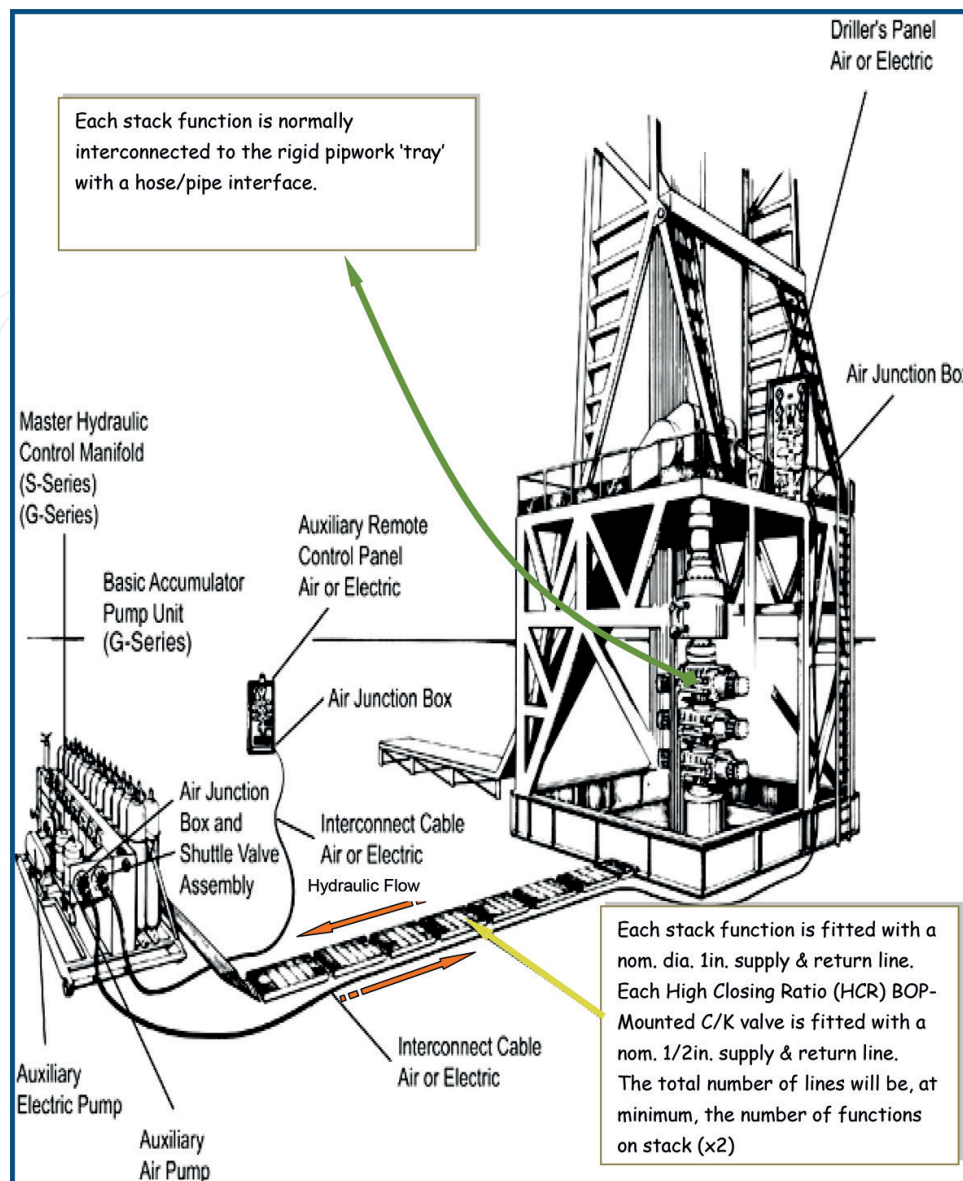
Figure 3. Dimensional details for the land-based BOP control system.

4. Interface the rigid pipework and arrange the hydraulic supply and return lines with flexible hoses to a removable hose stab plate to the hose reel end plate.

5. Spool sufficient hose bundle, containing the required number of supply and return hydraulic hoses, for the maximum operational water depth of the rig (let us say 750 feet).

6. On the BOP stack, connect the appropriately assigned hose (supply and return to each function) to that function.

Figure 7 here inserted as an A3 fold-out schematic is a labeled depiction of a typical surface stack hydraulic power unit (HPU) and its hydraulic manifold. This is for reference in the forthcoming explanations.

Figure 4. Typical surface BOP stack, connected to BOP control system and hydraulic power unit via flexible hoses.

So, assuming that we have suitably stabilized and secured the hose bundle through the water column, is this going to work [3]?

No, of course not! The reasons why not are many and varied and the following list attempts to capture all the impossible shortfalls. These are not listed in the order of importance and relevance necessarily that were facing the first design team as they struggled with all the obvious obstacles.
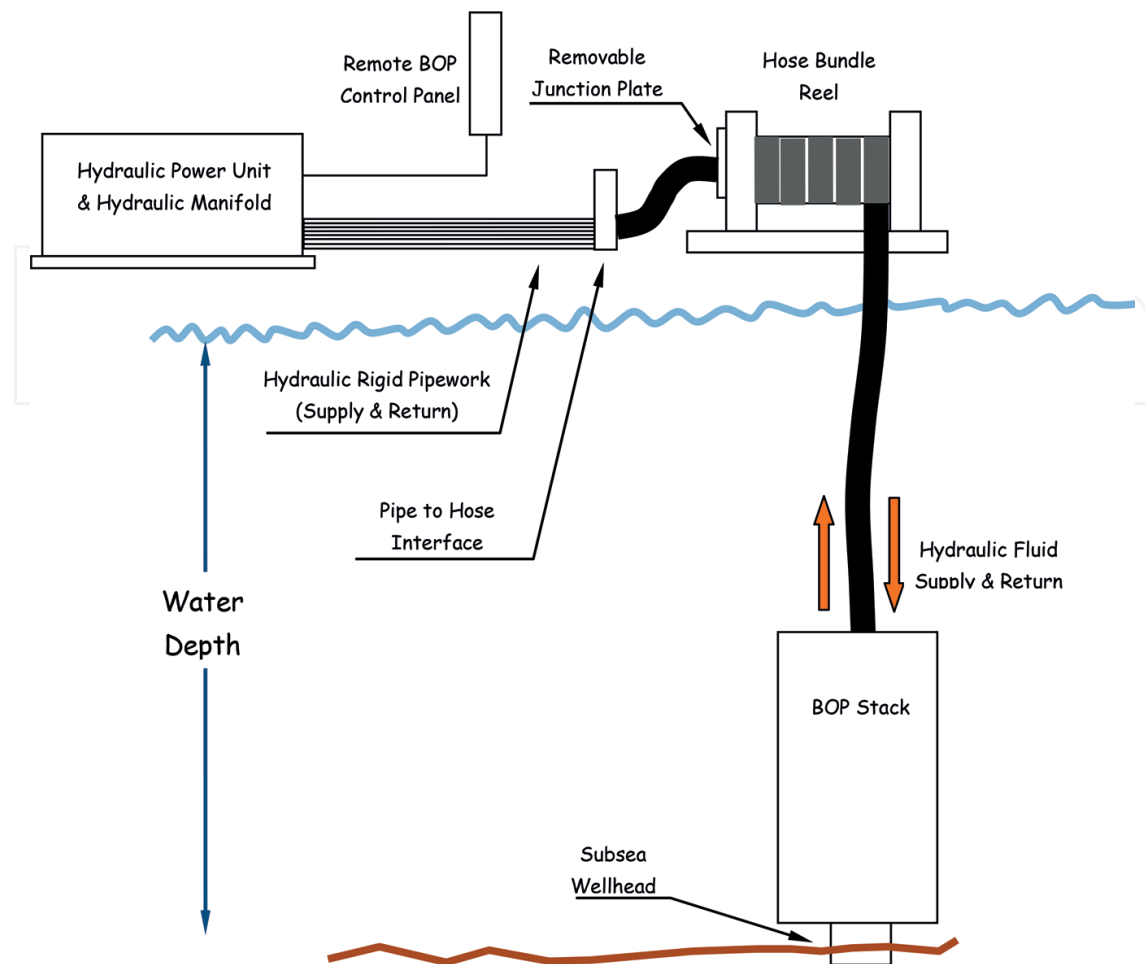
Figure 5. Fundamental but not practical proposed subsea adaptation of the former surface BOP control system.

2.2.1. Hydraulic communication, "surface—subsea" issues

Let us assume that the surface BOP stack has now been submerged for service subsea. Let us use the stack shown in **Figure 4** on page 77. This basic stack shown, using today's nomenclature (API Standard 53) [4] is a Class 4 A1-R3, interpreted this means a total of four preventers, one of which is an annular and the remainder are ram type preventers. The hardware at the base of the stack is a NT2 adapter which nipples up to the riser down on a jack-up. The NT2 adapter is not a hydraulic function on a surface BOP stack and is manually operated by a circular array of mechanical locking dogs [5].

And let us add that the stack has two hydraulically actuated BOP mounted valves (one on the choke line and the other on the kill line) [6, 7].

Therefore to now sum the quantity of supply and return hydraulic hoses required to control the functions of this stack if it were underwater would be:

Annular preventer	2 each 1 in. nominal diameter
Upper pipe rams	2 each 1 in. nominal diameter
Shear blind rams	2 each 1 in. nominal diameter

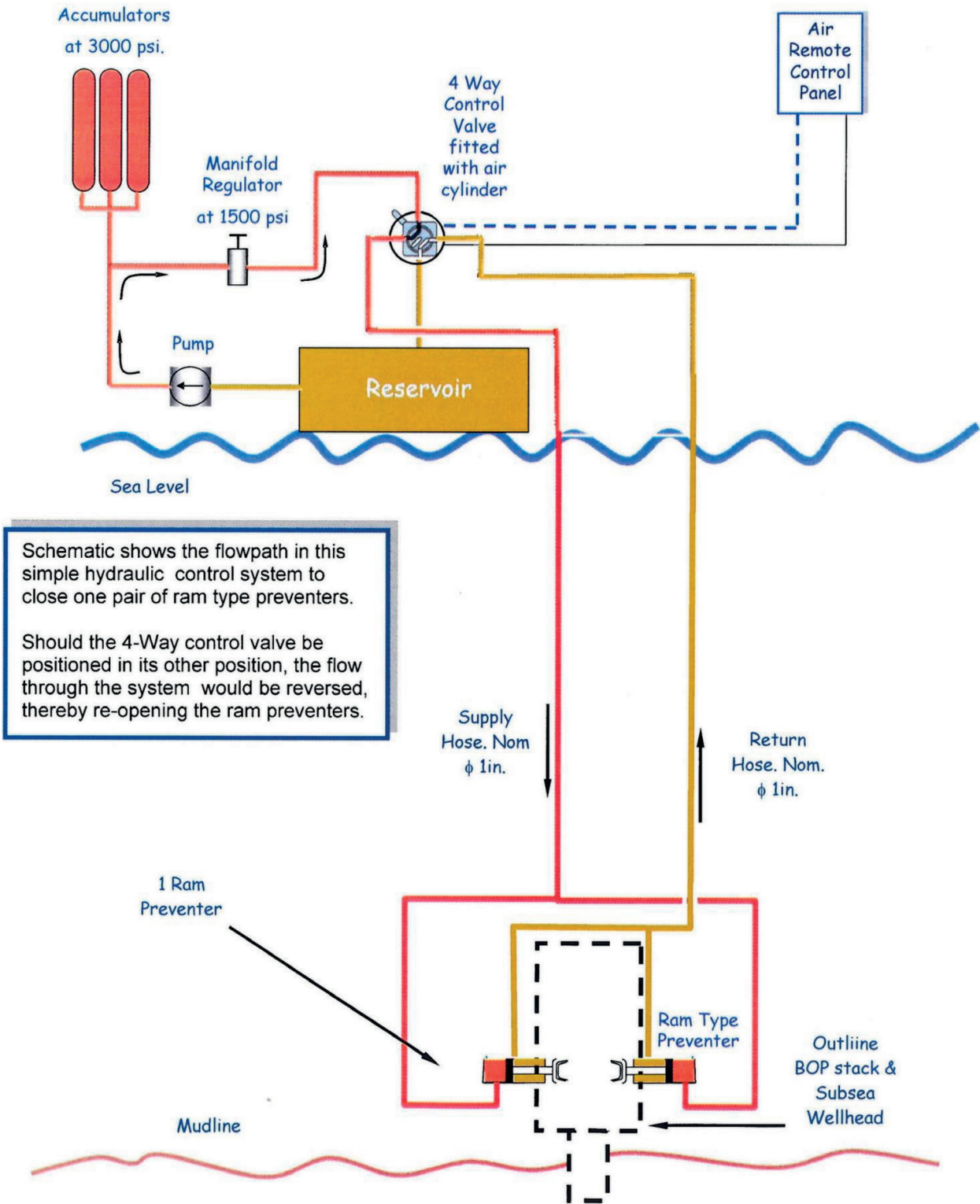| Lower pipe rams | 2 each 1 in. nominal diameter |
| Choke high closing ratio valve (HCR) | 2 each ½ in. nominal diameter |
| Kill HCR | 2 each ½ in. nominal diameter |

Figure 6. Direct hydraulic system with pneumatic control, one function.
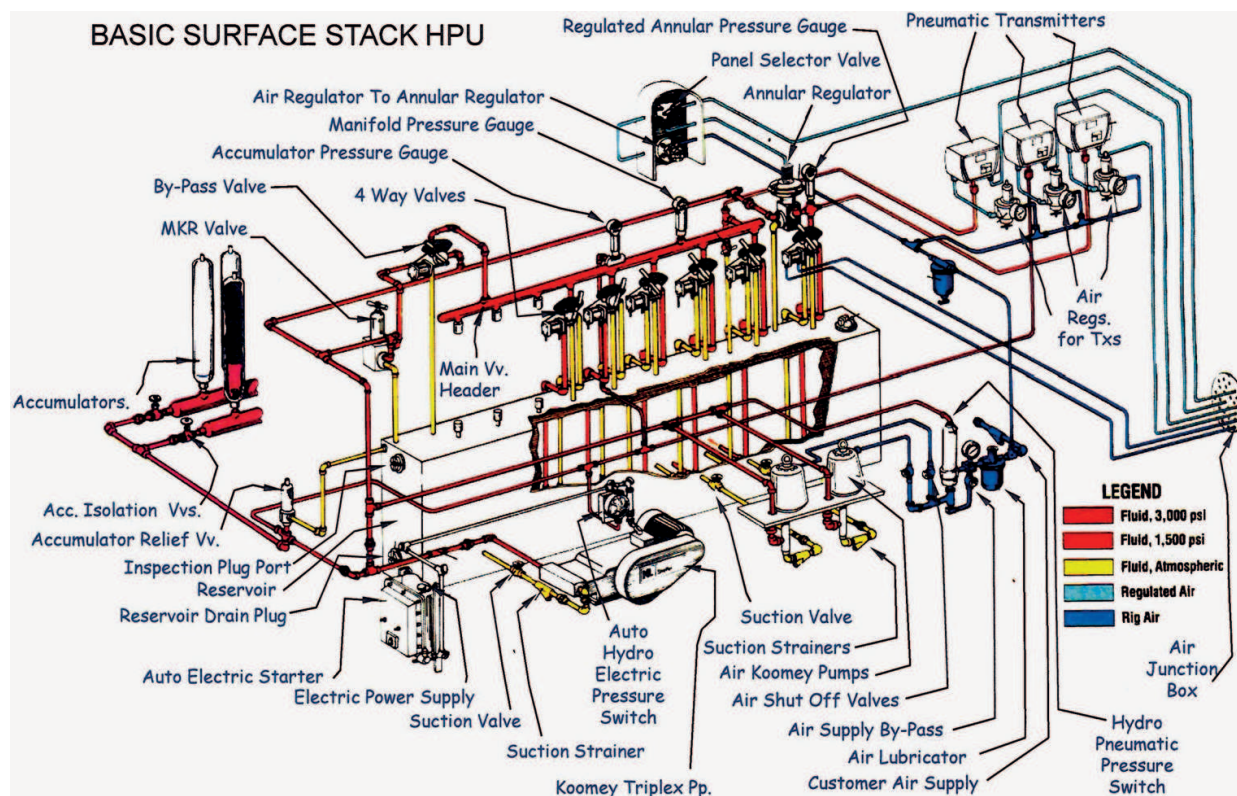
Figure 7. Skid Mounted Surface BOP Control HPU and Control Manifold.

Figure 8 overleaf shows a scaled cross section of a hose bundle that satisfies the requirements to provide the above functions with hydraulic power. We can see, with some spare hoses surplus to requirements, the OD of the entire bundle is only ~6 in.

However, if we consider a BOP stack designed and built for subsea service (not a surface stack submerged!), the story is very different (**Figure 8**).

The subsea blowout preventer stack shown overleaf is an 18¾ in. nominal wellbore diameter, rated at 15000 psi maximum working pressure. This is denoted as "18¾—15 M."

This particular blowout preventer stack is somewhat dated; "third generation" puts its age genre at around 15–20 years (**Figure 9**).

Given that the minimum outside diameter (OD) for the hose bundle is going to be around 7½ in. (with no spare lines in the bundled matrix) and the minimum critical bend radius (MBR) for this bundle, let us give the reel some arbitrary dimensions, as indicated in **Figure 11**.

With these dimensions, the first wrap on this drum would store around 365 feet. Two wraps then would cover the water depth requirement of 750 feet. However, for the "storm loop" hose allowance in the moon pool to accommodate rig heave, another 250 feet would be required. This necessitates three wraps on this reel assembly.

The end plates' diameter would be in the order of 22 feet diameter. The reel assembly, its prime mover, and brake assembly are large scale!
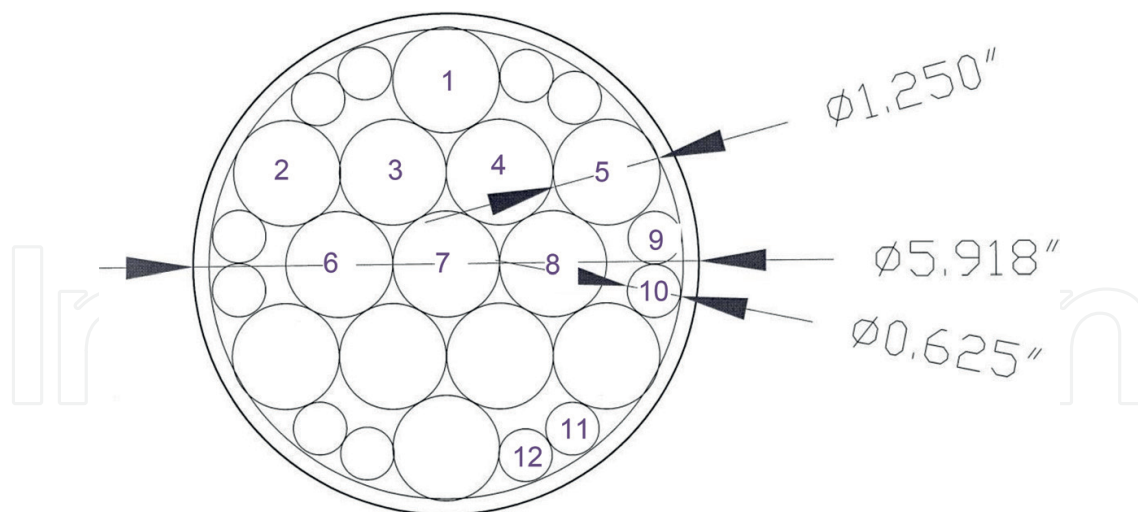
Figure 8. Cross section, hose bundle for minimum outfitted. BOP stack. Hose # 1: annular preventer close; Hose # 2: annular preventer open; Hose # 3: upper pipe ram close; Hose # 4: upper pipe ram open; Hose # 5: shear/blind ram close; Hose # 6: shear/blind ram open; Hose # 7: lower pipe ram close; Hose # 8: lower pipe ram open; Hose # 9: choke HCR close; Hose # 10: choke HCR open; Hose # 11: kill HCR close; Hose # 12: kill HCR open.

Typically, hose reel assemblies are installed at an intermediate elevation above the moon pool weather deck elevation on a mezzanine deck. Two such typical arrangements are shown in **Figures 12** and **13**.

2.2.1.1. Summarizing the impracticalities and identifying the system requirements

It has been shown that using bundled hoses of the required dimensions for the appropriate volumes demanded by the various BOP stack functions is impractical in terms of the physical challenges to build and install such hose reel topsides on a floating drilling installation. However, there are other issues with this concept, which can be summarized in the following list:

- The hydraulic system is closed and therefore the friction losses encountered in the return hoses will effectively slow down the response times, which are clearly detailed and stated in the current specification of API 16D, Edition 4, 2004 [7].

- The system offers zero redundancy and this is considered unacceptable for such a critical control system which must operate reliably and remotely in the "not-unlikely" event that the last mechanical barrier must be put in place immediately (shutting in the well). The prospect of building and installing an identical arrangement to the one illustrated is not in any way a practical solution whatsoever.

- The hydraulic medium is environmentally unfriendly and illegal. The hydraulic medium used in surface BOP stack control systems cannot be used in subsea versions of the system (water-based, as described on page 75).

- The system concept, as shown on previous pages, offers no hydraulic usable volume in storage on the subsea BOP stack, hence the drawdown effect on this system would be formidable and further exacerbate the response time issue for pipe and annular type preventers. Volumetric storage of hydraulic fluid subsea will be discussed in later sections.
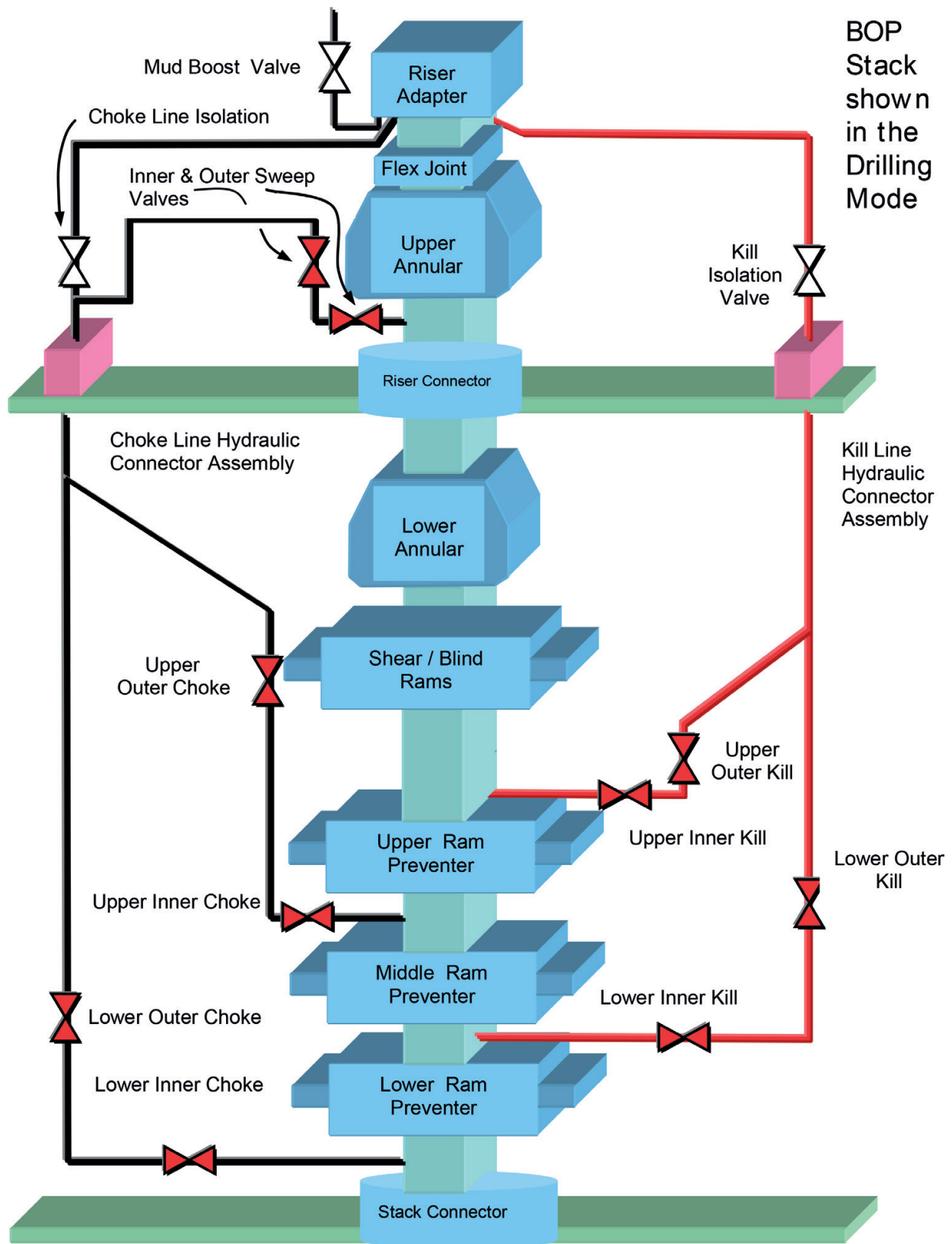
Figure 9. Third-generation BOP stack. Glomar Celtic Sea (**Figure 10**). 18¾ in.—15 M. Hose requirement—Mud boost valve: 2 × ½ in.; upper annular: 2 × 1½ in.; kill isolation valve: 2 × ½ in.; kill line connector: 2 × ½ in.; choke isolation valve: 2/½ in.; riser connector sec. unlock 1 × ½ in.; lower annular: 2 × 1½ in.; S/B rams: 2 × 1 in.; upper pipe rams: 2 × 1 in.; middle pipe rams: 2 × 1 in.; lower pipe rams: 2 × 1 in.; wellhead connector: 2 × ½ in.
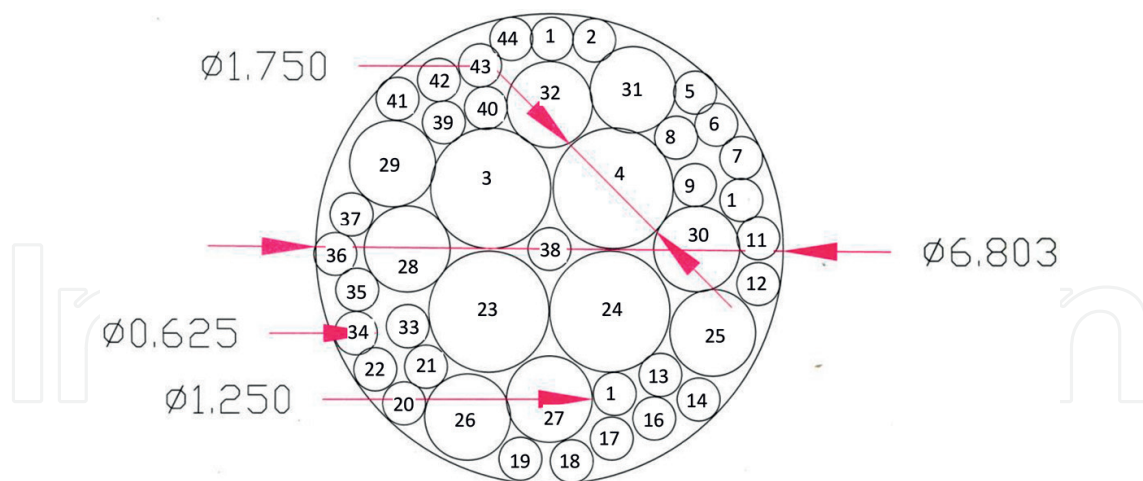
Figure 10. Cross section, hose bundle for third-gen. BOP stack (scaled). Hose # 1: mud boost valve close; Hose # 2: mud boost valve open; Hose # 3: upper annular close; Hose # 4: upper annular open; Hose # 5: kill isolation valve close; Hose # 6: kill isolation valve open; Hose # 7: kill line connector extend; Hose # 8: kill line connector retract; Hose # 9: choke isolation valve: Close; Hose # 10: choke isolation valve open; Hose # 11: choke line connector extend; Hose # 12: choke line connector retract; Hose # 13: inner sweep valve close; Hose # 14: inner sweep valve open; Hose # 15: outer sweep valve close; Hose # 16: outer sweep valve open; Hose # 17: riser connector lock; Hose # 18: riser connector unlock; Hose # 19: riser connector sec. unlock; Hose # 20: upper outer choke close; Hose # 21: upper outer choke open; Hose # 44: lower outer kill close; Hose # 23: lower annular close, Hose # 24: lower annular open; Hose # 25: shear blind rams close; Hose # 26: shear blind rams open; Hose # 27: middle pipe rams close; Hose # 28: middle pipe rams open; Hose # 29: lower pipe rams close; Hose # 30: lower pipe rams open. Estimating size of hose reel required, rig operational water depth: 750 feet.
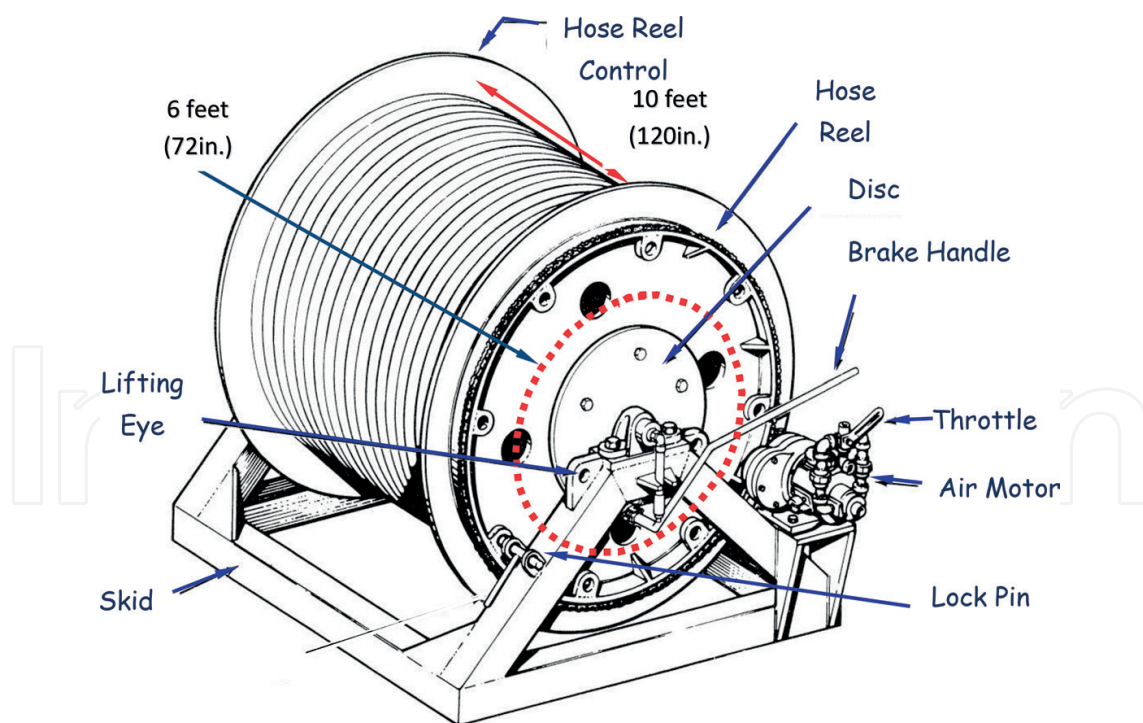

Figure 11. Typical hose reel.

- What has not been discussed are the issues surrounding the realities of topsides and subsea terminations for hydraulic hoses, the minimum multiplicity exampled here is by no means the total number of stack functions now supplied to modern deep and
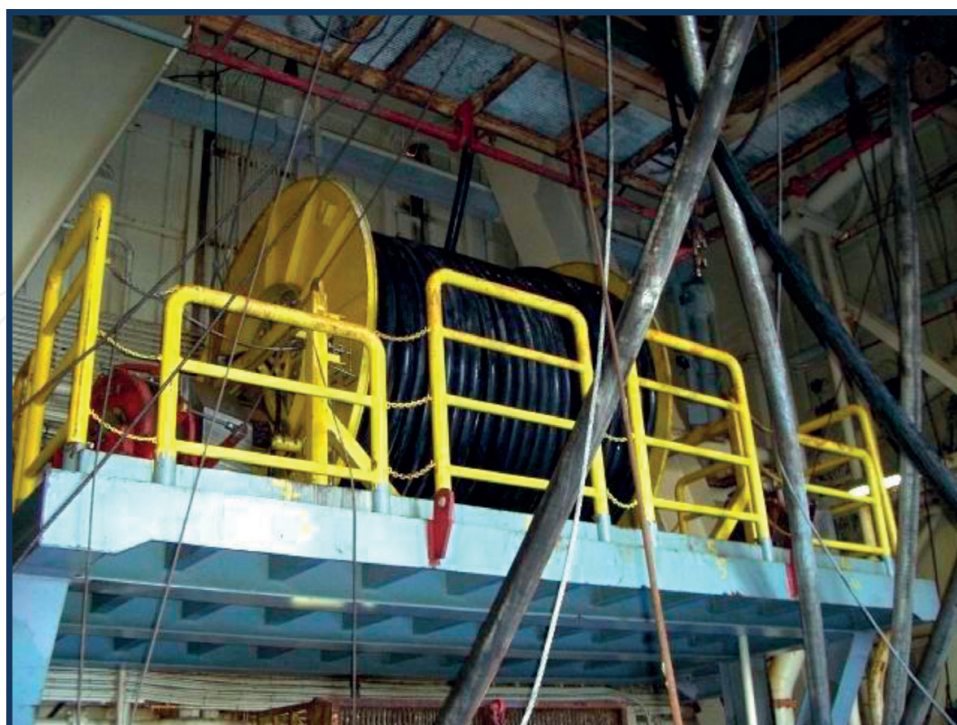
Figure 12. Typical BOP hose reel: mezzanine-deck mounted.
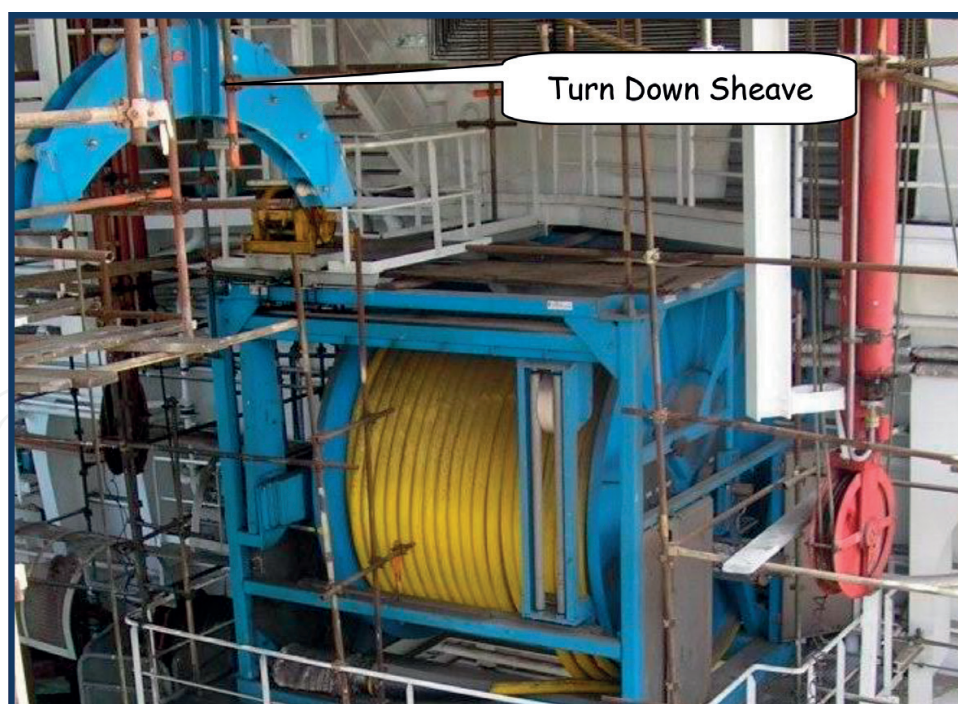

Figure 13. Cameron hose reel installed on the Iran Alborz GVA 6000 semi-submersible drilling installation.

ultra-deep water BOP stacks. The number of functions presented here for this illustrative exercise is 44, and to put that into today's context, modern stacks boast in excess of 110 functions!

- To this point in our design rational discussion on evolving control systems, the requirement for a BOP stack split disconnection has not been introduced. There is a myriad of situations in subsea drilling operations when we need to achieve a disconnection whereby the lower BOP is left latched on the subsea wellhead and the lower marine riser package is retrieved, either to surface or "positioned" in a stand-by location in the water column. The design architecture surrounding this design feature will be discussed in due course.

- In light of the above, we can list the design features that are required for a reliable and fit-for-purpose subsea BOP control system [7]:

  - Provide redundancy

  - Comply with legislation

  - Practical installation

  - Install stored hydraulic fluid

  - Compliance: anti-pollution laws

  - Enhance functional multiplicity

  - Design allowance: disconnect

2.3. Design features, first subsea BOP control system

2.3.1. Introduction

The ingenious design of the first BOP control system, which is now presented as an overview, was developed in the first half of the 1950s when the maximum rated water depth for drilling offshore off floaters was still under 1000 feet (305 m) [8].

The reasons for the water depth limitation are varied and not directly attributed to the restraints of the BOP control system. Some of these were marine, drilling plant topsides' limitations and to a lesser extent, and capabilities of marine drilling riser (the mechanical connection between the subsea BOP stack and the drilling installation).

2.3.2. Concept of the hydraulic pilot-operated control system

The immediate problems facing the pioneering design group:

How do we overcome the excessive dimensions of a simple closed hydraulic system deployed subsea?

How do we diminish the friction losses in the closed hydraulic system where the displaced fluid from the "other" side of the function slows the overall response times of the ram type and annular type preventers?

How do we build in redundancy to a point where the critical control system can satisfy the most stringent of regulators for reliability?

What can be done to minimize the risks of pollution to the marine environment?

Is there some way in which the volume/pressure drawdown effect can be reduced in the direct closed hydraulic system?

How should the topside equipment be arranged for optimum operation and account for rig motions?

What is required to configure the BOP stack to enable a disconnect while leaving the well secured in the coincidental event of a well influx?

Pictorially shown here are the basic principles that were proposed (**Figure 14**).

Pivotal to the success of the prototype design was the use of hydraulic relay valves which are installed in the newly conceived control pod(s) which are activated by a hydraulic pilot signal commanded from the surface. By the use of hydraulic relay valves and agreement that the displaced fluid volume from the "other" side of the function should exhaust directly through the "other side of the function" relay valve directly to the marine environment, it was immediately understood that the prior formidable size of the hose bundles could be greatly reduced, not least caused by using 3/16 in. pilot hoses in the bundle. The main hydraulic supply consequently consisted of one only nominal 1 in. diameter core hose within the bundle (see top right of the previous figure for details).

In order to have an open hydraulic system that exhausted hydraulic fluid directly to the marine environment, the hydraulic medium was changed from lightweight mineral oil to potable water dosed with additives in small percentages of dilution. This new hydraulic medium necessarily influenced careful material selection of both metal and rubber sealing components of the hydraulic valves, regulators, and other subsea control system components. Not only was the marine environment a factor in dispelling the consideration of the use of an oil-based hydraulic medium, but also differential pressure experienced across the thermoplastic wall of flexible hose at increasing hydrostatic pressure from the water column depth. This is discussed in the next sub-section.

100% redundancy was provided by furnishing two identical systems which became color-coded blue and yellow. The system is arranged whereby one to the two identical sides of the system may be used at any given moment but never both. The redundancy satisfied both operators, oil companies, and more importantly, class societies and legislative bodies. Since the early systems, levels of redundancy have been revised, and standard operating procedures adopted formerly have been revised reflecting greater caution and conservatism. This will be discussed in due course.

By the introduction of gas pre-charged hydraulic accumulators, nominally 11 US gallons capacity each, the early problems of system drawdown effects were satisfactorily banished as the 1 in. hydraulic supply in either hose bundle maintained full system working pressure in the stack-mounted accumulator bottles.

This system quickly became field proven and a number of proprietary vendors produced their own systems, however it has to be said that all were based on the principles put forward originally by Paul Koomey and his design team.
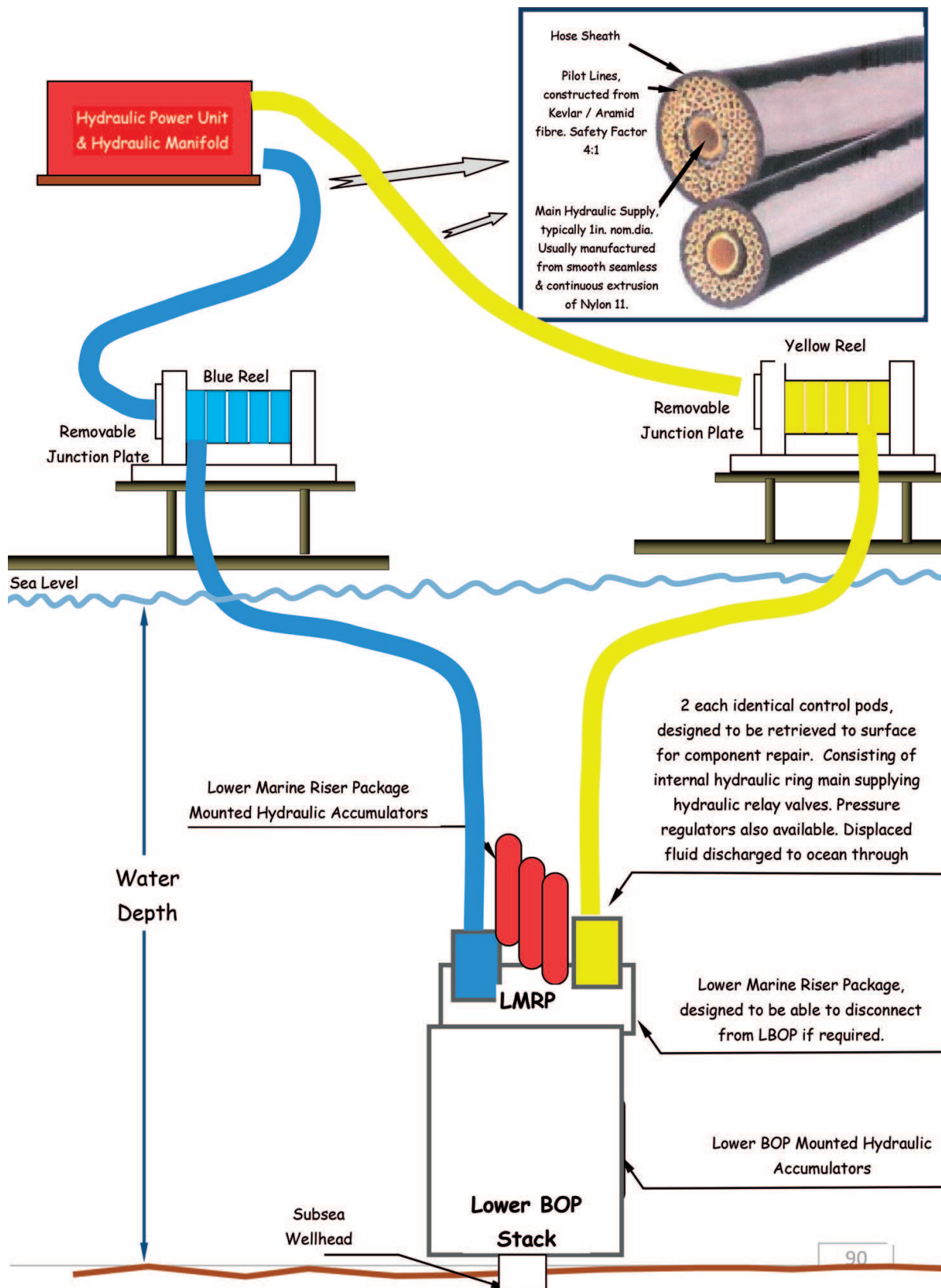
Figure 14. Concept and principles of the open BOP control system.

The remainder of this sub-section concentrates on the general arrangement detail of the system and its operational characteristics and finally limitations identified for this system.

2.3.3. The basic control pod

The hydraulic control system is always equipped with two control pods, designated as the blue or yellow pod. To maintain a fully redundant control system, both pods must be operational at all times.

Formerly, if a control pod becomes inoperable, drilling operations would be normally suspended and the BOP stack controlled with the working pod until repairs are completed and tested. This involved the retrieval to the surface of the defective pod, repair and test on surface before re-deploying subsea to latch back into its dedicated receptacle on the LMRP.

More recently with the advent of deep water drilling, the majority of oil companies will not allow continued drilling operations for the retrieval of one pod to surface for repair. If repairs are to be performed in the midst of a drilling program, drilling operations are suspended, and the well made safe and the entire LMRP retrieved to surface to repair the faulty control pod.

The active and selected control pod is normally alternated between the pods weekly or after a BOP stack test.

Koomey Shaffer introduced a 42 line retrievable pod which featured a double female receptacle design. The separate receptacles enable both the pod to be retrieved or else the entire LMRP (**Figure 15**).

Later, as the drilling contractors began to use BOP stacks with greater number of functions, Shaffer and others introduced a 64 line control pod, which, while featuring a different geometry (cubical rather than cylindrical) operated in the same manner and was intended for retrieval during drilling operations (**Figure 16**).

2.3.4. Control system hoses

2.3.4.1. Introduction

Proprietary manufacturers of subsea hose bundle strive to provide a product which has a low volumetric expansion characteristic (VEC). This ensures that API closing times are not exceeded for ram type and annular type preventers. In the electro-hydraulic control system, the single greatest contributor to lengthening response times is the hydraulic pilot pressure build time and transport time.

2.3.4.2. Pressure characteristics of the control fluid

The fluid parameters that govern the transmission time of a hydraulic signal through a thermoplastic tube are:

- The density of the fluid

- The viscosity of the fluid

- The un-dissolved gas in the fluid
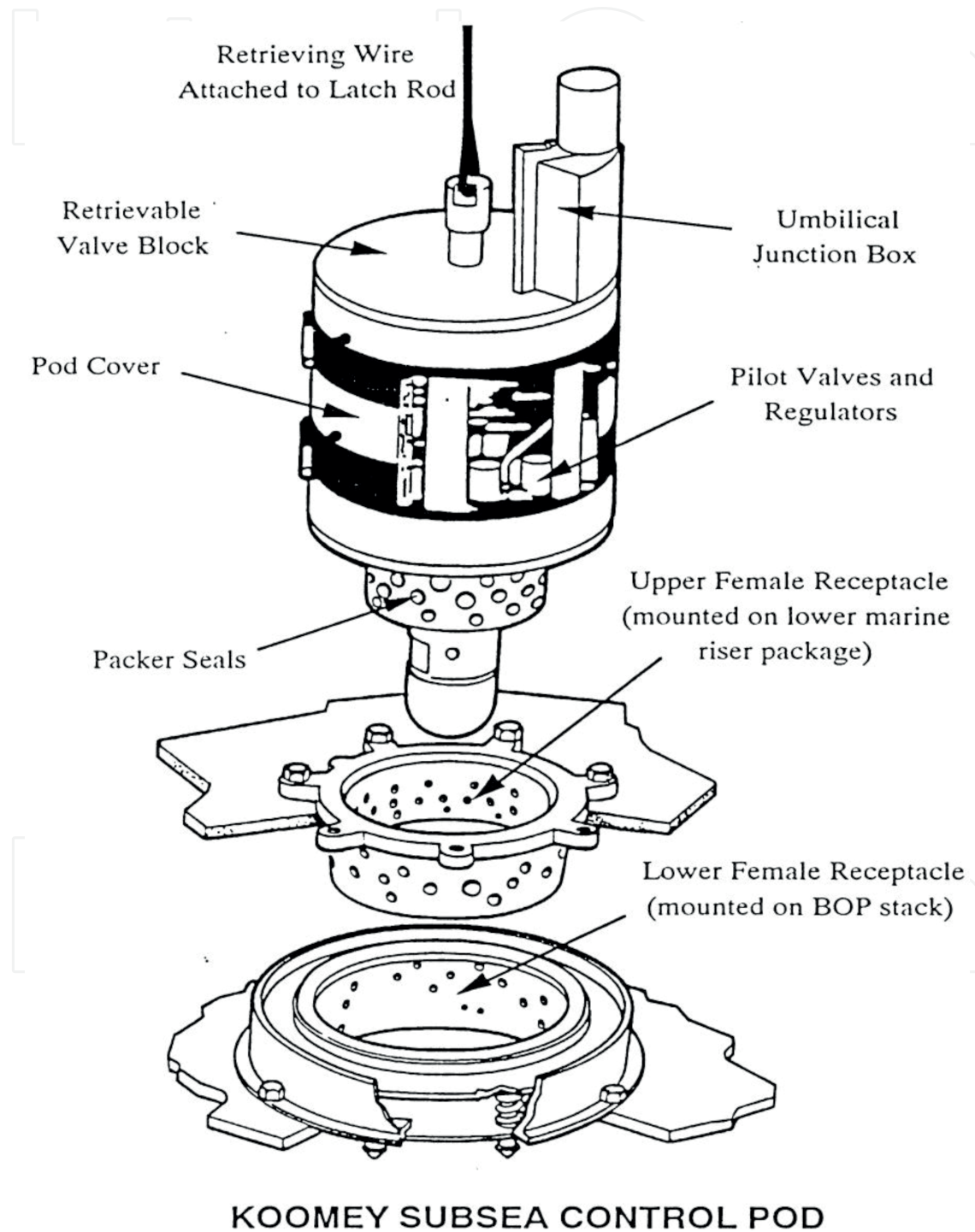
- The bulk modulus of the fluid

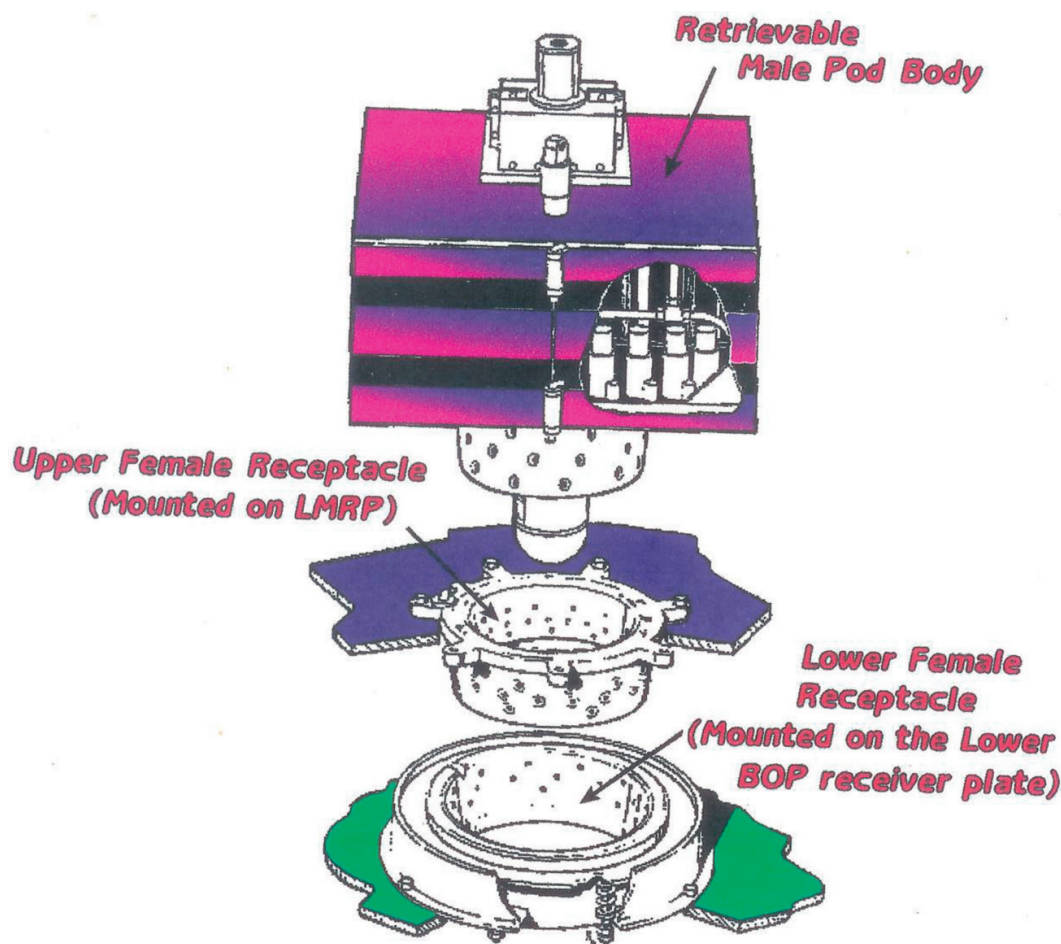**Figure 15.** The 42 line Koomey control pod.

Figure 16. The Koomey Shaffer 64 line retrievable control pod.

The values may change, but this is usually associated with significant changes in the ambient operating temperatures. An extreme example is the difference in control fluid parameters in tropical climates. As opposed to climates in far northerly and southerly latitudes, there will be no monoethyleneglycol (MEG) added to the control fluid medium since the seawater temperature at the mudline is significantly above freezing point. (This is applicable for the relatively shallow water depths in which this type of BOP control system is used, and the previous statement is not true for ultra-deep water: >6000 feet.)

We can say that the density and viscosity of the fluid will remain close at their optimum values in this operational water depth.

2.3.4.3. Factors influencing time response

One of the basic concerns in regard to using thermoplastic hose to transport hydraulic fluids to great depths is differential pressure across the tube wall. At great depths, the external pressure may be sufficient to collapse the hose. The pressure at which collapse takes place is dependent upon the hose construction and the nominal diameter of the hose [4, 7].

The dominant property of differential pressure in this application arises from the differences between seawater and control fluid densities. Wherever in this type of system, there exists a degree of density difference across the hose tube wall, a chance of invoking hose collapse is possible. For instance, at a depth of 5000 feet, a thermoplastic hose containing a typical mineral oil as the hydraulic medium found in surface stack control systems will experience an overburden of around 220 psi, which is quite sufficient to collapse a hose. Pressures as little 30 psi can cause collapse of hoses with nominal diameters in the range of 3/8–½ in.

API specification 17E: specification for subsea production control umbilicals, states for collapse pressure [9]:

"The minimum value of external collapse pressure shall be 150% of the difference in the static head due to hydrostatic pressure at the maximum design depth less the static head at that depth due to the service fluid (hydraulic medium)."

Further unwanted differential pressure will be generated if the hydraulic lines are not 100% fluid filled. If any entrapped air is present in the tube length, the hydrostatic pressure will dominate and tube collapse will occur. This is easily eradicated by thorough purging and venting of all lines in the subsea umbilical hose bundle. The presence of air, however small, also dramatically increases response times due to the compressibility of gases [3].

The differential problem is overcome by choosing a hydraulic medium which has a specific gravity that is close to seawater.

Seawater has a gravity of ~1.03 and water is 1.00. Providing that the hydraulic medium is water-based with additives that only change the specific gravity to a new value remains close to that of the specific gravity of seawater then the possibility of hose collapse is virtually obviated.

2.3.4.3.1. Viscoelasticity

Hoses, being composites with polymeric constituents are found to behave in a time dependent viscoelastic manner when applied load is a hydraulic charge as found within a pilot line hose.

The result of the viscoelasticity manifests itself in a pressure decay after initial pressurization. This is not detrimental for the pilot signals in this application since the hydraulic pilot-operated relay valves subsea "fire" and "vent" at pressures well below the nominal pilot pressure of 3000 psi. **Figure 17** shows the pressure decay versus time. The typical time constraints are well beyond time of the hydraulic relay valves "firing" in this control system.

2.3.4.3.2. Hose geometry changes during pressurization

Extensive laboratory testing has been performed to assess the changes in hose geometry subjected to a step positive change in internal pressure. The changes in geometry were measured using strain gauges, both axially and circumferentially affixed to the outer surface length of the hose under test.
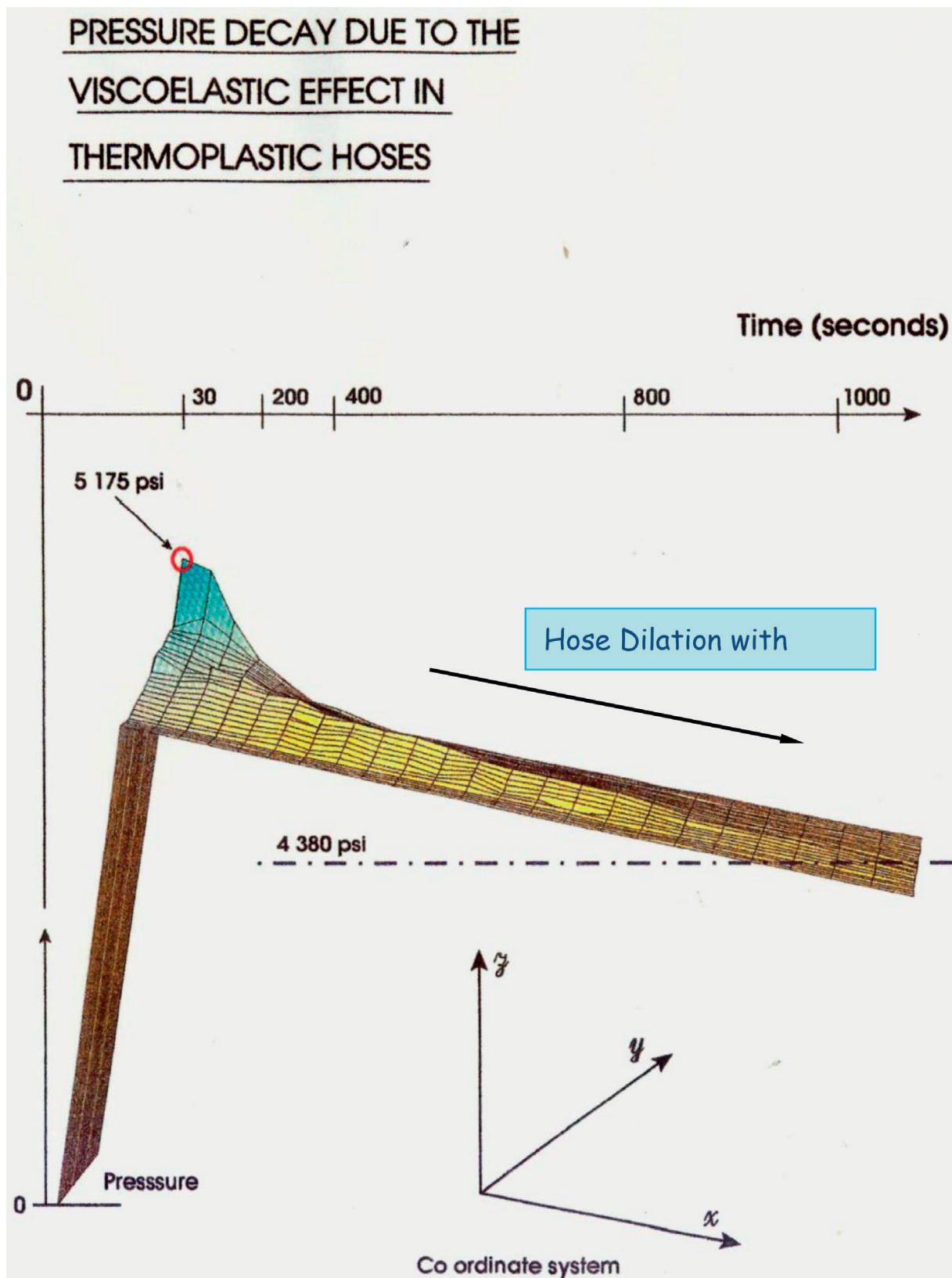
Figure 17. Pressure decay in thermoplastic hoses due to viscoelasticity.

The axial gauges measured any bending strains incurred and the circumferential gauges monitored hoop stresses. It was found that the hose length shortened with pressurization and this is explained by the layers of hose braiding attempting to establish a neutral lay angle during the buildup of pressure. The effect is almost instantaneous and remains constant, and hence the axial strain is not responsible for the viscoelastic effect.

Measured hoop strains correlate to observed pressure responses and shown typical visco-elastic behavior. In tandem with strain measurements, volume measurements have been recorded to estimate the variation in wall thickness. Such measurements have been quantified using two equations which account for the bulk modulus and pressure decay following initial viscoelastic expansion of the hose under test.

Results from these tests showed that both the internal and external diameters of the hose increased with pressurization although the OD significantly less than the ID of the hose.

Overall, this indicates that all hydraulic pilot hoses will "accept" more fluid when a pressure signal is initiated from the source and will duly expand in direct correlation with the VEC of the hose: dependent upon construction and materials. At pressure equilibrium (e.g., 3000 psi), the hydraulic pressure peak will transit the length of the hose at approximately the speed of sound.

2.3.4.3.3. Behavioral phenomena of thermoplastic hose

All hoses that are constructed of material that use a composition of polymers and fibers may be classed as thermoplastic hoses. When subjected to pressure changes internally and exter-nally, they exhibit a viscoelastic time-related response. After an initial pressurization, the pressure decays over a period of time as the hose dilates (see the previous figure) [3].

The extent of the dilation is dependent upon a number of factors such as hose material, con-struction, age, environment, and so on. A similar effect occurs when the hose is depressur-ized, this being a time-related contraction effect.

Against logical intuition, hoses bundled together exhibit greater volumetric expansion (VE) than identical hoses pressurized in isolation. There is a mathematical proof for these phe-nomena but suffice it to say that the reason is simply because there are effects from adjacent bundled hoses which remain pressurized against those vented to zero gauge.

It is known that aging in hoses reduces VE which acts in our favor (in drilling BOP controls) but is considered detrimental in production control systems.

Minimizing the effects of VE promotes faster response times in hydraulically piloted BOP control systems since the pod-mounted relay valves will not "fire" until they have sufficient pressure in the hydraulic pilot signal: normally around 500–700 psi.

The following figures illustrate some of the effects of the volumetric expansion characteristic in thermoplastic hoses (**Figures 18–20**).
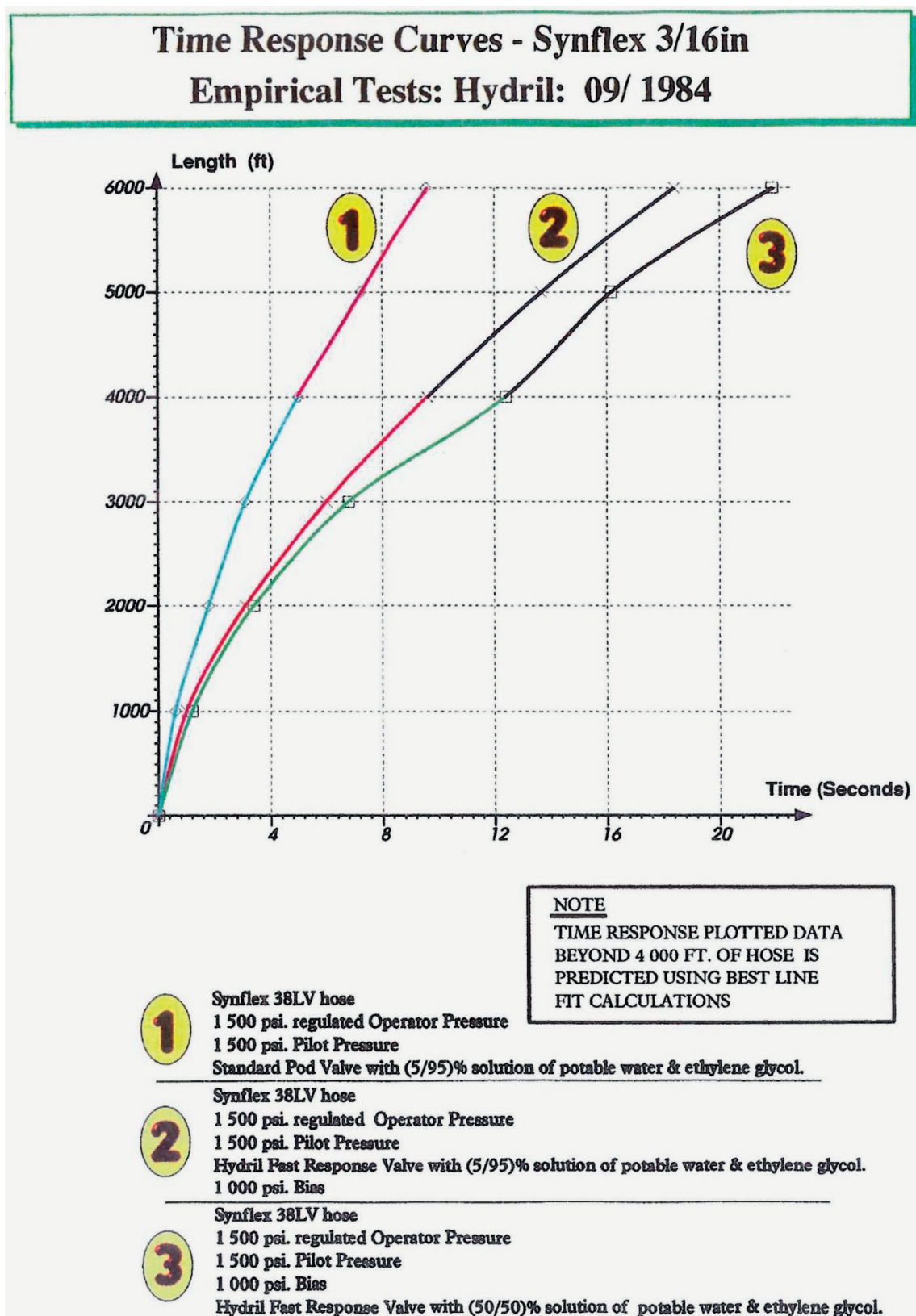
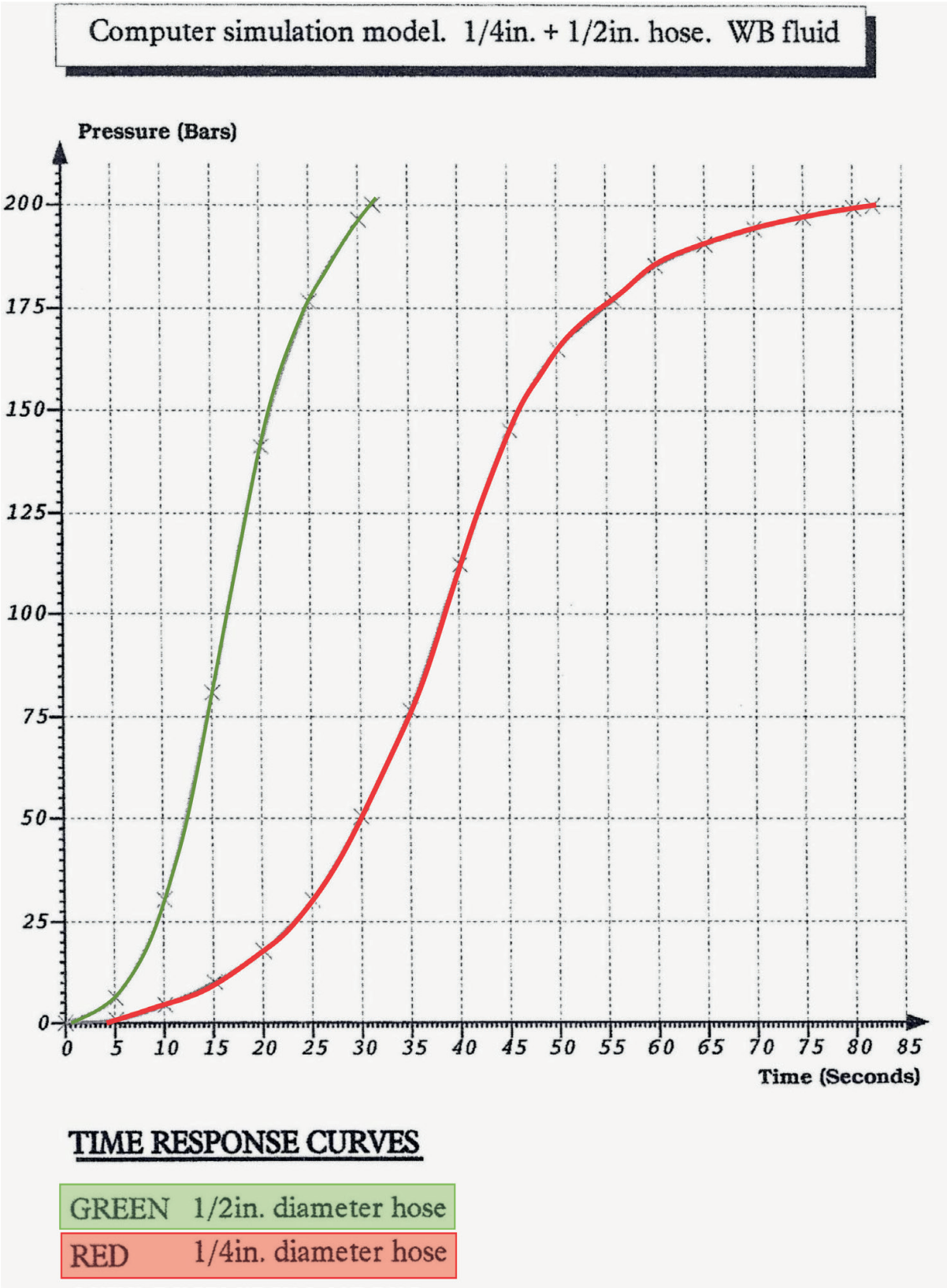**Figure 18.** Time response curves from Hydril® empirical testing.

Figure 19. Typical response times for 1/4 in. and 1/2 in. Diameter thermoplastic hose.

VE Curves for High Pressure Hydraulic Hose

① Synflex 3R 80 3/16in I.D.   SAE 100 R8.
Construction: Inner Nylon Core, 2 layers synthetic fibre reinforcement; Polyurethane cover.

② Kaverner FSSL computer model simulation for 1/4in. thermoplastic hose. (5 000 ft. length)

③ Typical V.E. characteristic for thermoplastic hose. MEC, Whetstone, Liecs. U.K.

④ Synflex 37LV-03 low volumetric expansion hose. 3/16in I.D. SAE J343. W.P. 3 000 psi.
Construction: Inner Nylon Core Tube, 4 layers spirally wrapped fibre bonded to tube. Outer cover:
seamless thermoplastic polyether polyurethane compound, resistant to hydrolysis.
Wall thickness: 0.085in. T.P. 12 000 psi.

⑤ Rogan & Shanley 2004 StR hose. ‹3/16in. I.D. , 0.31in O.D. Min. burst pressure: 34 000 psi.
Construction: Delrin or Nylon 12 core, 2 spiral wound layers of plated high strength wire.
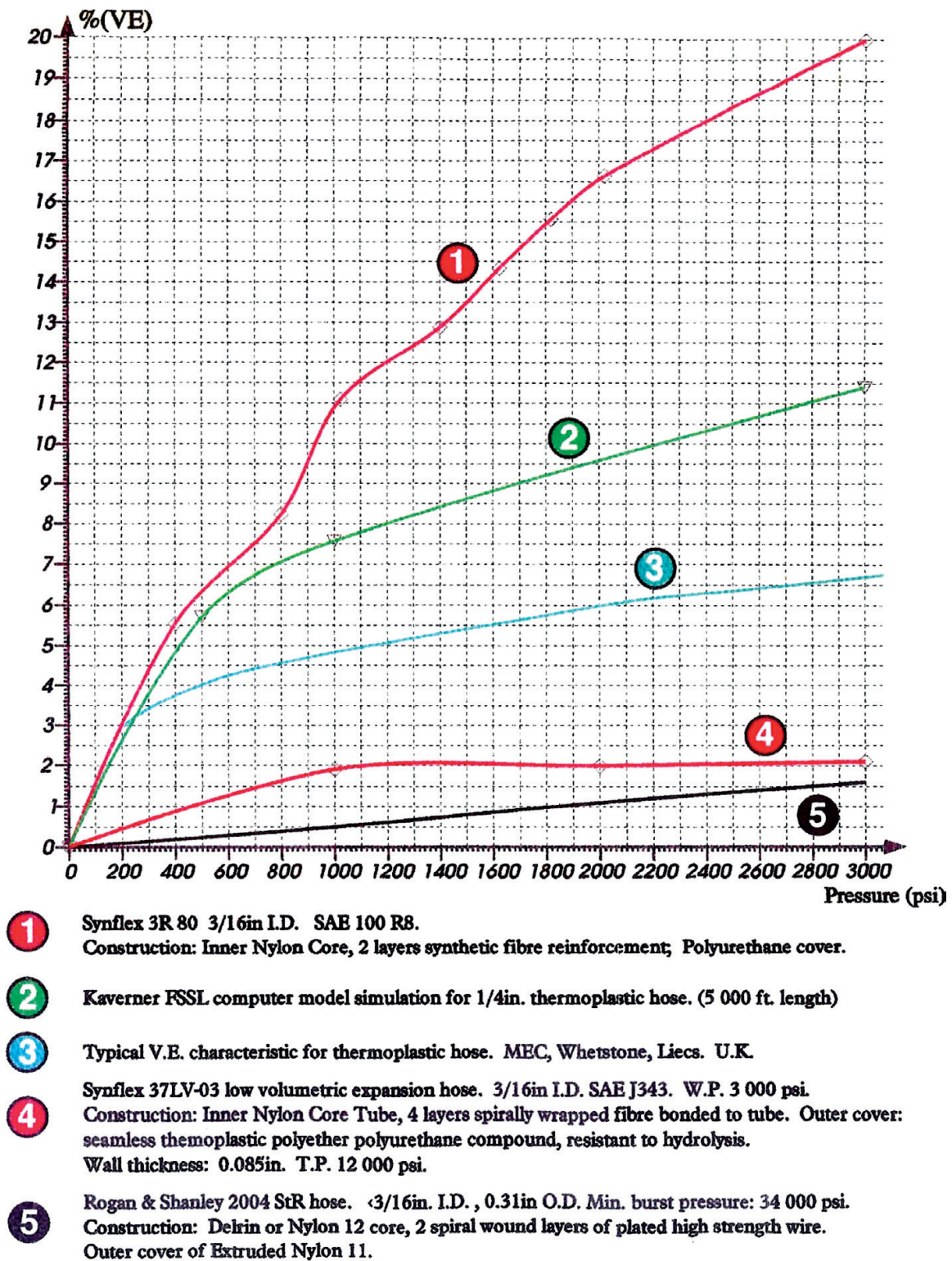Outer cover of Extruded Nylon 11.

Figure 20. VE curves for high pressure thermoplastic hose.

3. Summary

In this chapter, we have explored the evolving design technology that enabled a surface land-based BOP control system to be used reliably in the subsea marine environment. Further, design teams have provided the following system features to the subsea BOP control system:

- 100% inbuilt design redundancy: based on the high level of safety criticality of the subsea BOP control system (the last barrier). Given fundamental design principles of the subsea hydraulic control pod.

- The use of hydraulic devices (such as relay valves and regulators) to satisfy legislative close times on BOP preventers and BOP-mounted valves (Choke and Kill).

- An insight into the development of flexible hydraulic hose to maximize short response times by the limitation of the design VEC of elastomeric hose materials.

- The principles employed to overcome hydraulic drawdown through extended lengths of hydraulic line/hose (accumulator introduction).

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