Trans.I.Mar.E., Vol. 100, pp. 253–262

The installation of flexible flowlines and their protection

J. S. H. Heng, B.Sc., C.Eng., M.I.Prod.E., M.I.E. (Singapore)
Coflexip (U.K.) Ltd.

SYNOPSIS

The use of flexible flowlines as in-field connections between subsea trees, wellheads and production facilities for the transportation of oil, gas and water, has proved their reliability and ability to withstand the severe environment of the North Sea since their introduction in the early 1970s. The design and construction of a flexible flowline is defined by such criteria as product composition, operating conditions, service life, water depths and environmental constraints and to a lesser extent by installation techniques. Guidelines are generally available for the design, construction and commissioning of rigid steel pipes but they are not necessarily applicable to static and dynamic flexible pipes. It was only recently that the Institute of Petroleum published a supplement to the 4th edition of the Pipeline Safety Code (part 6 of the IP Model Code of Safe Practices in the Petroleum Industry), part of which referred to flexible pipelines. This paper reviews the advantages and disadvantages of flexible flowlines and will highlight the design considerations when reviewing the needs for flowline protection. An outline of currently available protection systems, such as trenching, rock/gravel dumping and individual mattressing, is given, and particular attention is paid to the continuous (pipeline) protection system (COPS) developed by Coflexip in conjunction with VSL International.

BACKGROUND

Since 1972, flexible pipes have been extensively used for many different applications. In the latter half of the 1970s and the early 1980s, flexible pipes played an important role in the development of the Argyll and Duncan Fields in the North Sea. The first flexible high-pressure flowline (3000 lb/in^2, 4 inch diameter) was installed in 1979. This was followed by the installation of other flowlines linking new production wells to base manifolds, and the replacement of old and corroding rigid pipelines to operating production wells, and where existing productions were redirected, previously laid flexible flowlines were recovered. To date, thousands of kilometres of flexible flowlines of a wide range of diameters have been laid, some of which are trenched and buried.

To appreciate the increasing confidence placed on flexible flowlines as a means of transporting hydrocarbons, and their use as water injection lines subsea, one must consider the technical and commercial aspects. One of the technical considerations is the susceptibility to internal and external damage, e.g. dropped objects, anchors and trawl boards. Previous papers[1-4] on this subject, along with the various methods of stabilizing a pipeline against waves and current, will be discussed in this paper.

GENERAL DESCRIPTION OF FLEXIBLE FLOWLINES

A flexible flowline is a composite structure made up of several layers of different materials which in its composite form provides pressure containment, radial and axial strength, and external protection.

There are generally two types of flowline construction; non-bonded and bonded. The non-bonded constructions consist of several individual layers wrapped, wound or extruded over in a continuous process. The separation of the layers allows inter-layer movement to take place. These are shown in Figs. 1 and 2. The 'rough bore' structure, illustrated in Fig. 2, is generally used whenever gas is present in the production fluid such as is found in crude oil, whereas the 'smooth bore' (see Fig. 1) is used for a variety of applications including water injection and dead crude export.

J. S. H. Heng joined Coflexip in early 1986 as a Project/Construction Engineer in the Paris office and later moved to the London office with responsibility for the installation of flexible pipeline systems. He is a member of Council of the Institute of Production Engineers.

The bonded construction, developed from technology used in the fabrication of steel-reinforced tyres, is achieved by vulcanizing the fully assembled pipe by a process of heat and pressure. The elastomeric liner must be resistant to sour crude, gas and enhancement chemicals.

Concentrating on the non-bonded type of flexible pipe, the plastic layers are incorporated to provide internal pressure containment and external protection. Depending on the pressure requirements, a number of steel layers will be wound around the structure to achieve resistance to radial, axial and torsional loads. The double steel tension flat wires are cross-wound with a long pitch in the direction of the neutral axis to provide good tensile resistance, and torsion is eliminated by winding the two tension layers in opposite helices. The intermediate spiral steel layers are incorporated into the structure to sustain the radial loads caused by internal pressure.

The rough bore structure has an internal layer of interlocking steel spirals to prevent collapse from external pressure and to eliminate wear of the internal pressure layer.

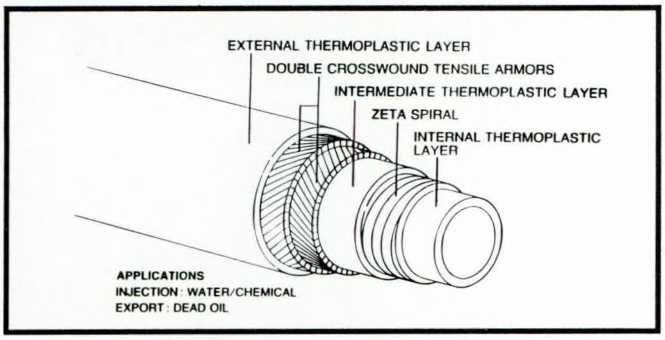

Fig. 1. Typical 'smooth bore' structure

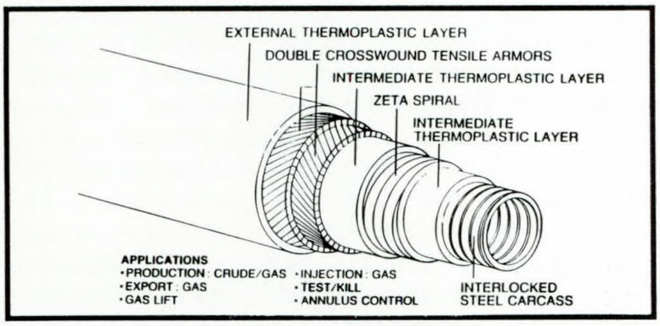

Fig. 2. Typical 'rough bore' structure

ADVANTAGES OF FLEXIBLE FLOWLINES

The principal reason for deciding on the use of flexible pipes is the simplification of the engineering and construction requirements, particularly where:

1. Installations and equipment are designed for a specific service life. Also, where re-routing, relocation or field development are envisaged, the use of flexible flowlines simplifies the recovery and re-routing.
2. The method of installation requires slack to be incorporated in the lines to accommodate potential seabed movements.
3. Subsea structures such as base and production manifold are large and heavy and thus their orientation and alignment may cause problems when using rigid pipelines.

Flexible flowlines can bend freely to a minimum bending radius (MBR) (see Table 1). The construction material may be selected to provide protection against internal and external damage, and thus significantly decreasing the problem of corrosion.

The use of plastic material provides good thermal insulation, the extent of which may be improved by increasing the thickness or by using an extra external insulating layer.

The method of manufacture of flexible flowlines enables long continuous lengths to be made, thus minimizing the

Table 1. Typical minimum bending radius

Internal diameter (inches)	MBR (storage) (m)	MBR (Operation)
4	0.9	1.5 x MBR (storage)
6	1.3	1.5 x MBR (storage)
8	1.7	1.5 x MBR (storage)
10	2.1	1.5 x MBR (storage)

Table 3. Abrasive resistance

Material	Abrasive resistance (10 = Reference value)
Semi-hard steel	10
Steel XC 55P	14
Polyurethane	39
Polyethylene	69
Polyamide	79
Cast iron	169

Table 2. Description of the flexible pipe

Inside diameter (inches)	Design pressure (psi)	Outside diameter (in)	Weight in air empty (kg/m)	Weight in air full of sea water (kg/m)	Maximum continuous length (78.44.50 reel) (m)	Limitations	
						Weight (200 tons)	Volume
1	3000	2.14	5.0	5.5	30910	*	
1	5000	2.30	6.7	7.2	23610	*	
2	3000	3.26	10.7	12.8	13280	*	
2	9000	3.98	26.1	28.2	6020	*	
4	3000	5.71	31.3	29.6	5740	*	
4	7000	6.46	57.5	65.8	2580	*	
6	3000	7.77	41.6	60.3	2820	*	
6	6000	8.95	104.3	123.0	1380	*	
8	3000	10.24	72.4	105.6	1610	*	
8	5000	11.27	144.0	177.2	960	*	
10	2500	12.50	97.3	149.2	1340	*	
10	4500	13.62	195.4	247.3	800 (1)	*	
12	2300	14.72	123.3	198.1	680 (1)		*
12	3800	15.94	249.7	324.5	520 (1)	*	
14	1900	17.31	169.3	271.1	420 (1)		*
14	3600	18.53	316.0	417.8	190 (1)		*
16	1700	19.50	208.9	341.9	200 (1)		*
16	2300	20.72	374.5	507.5	180 (1)		*

Note: Diameter of drum is increased to accommodate the MBR of the flexible pipe.

number of on-site field joints. However, the length that can be produced is limited by the capacity of the storage reel and the current capabilities of the plant, which are shown in Table 2.

The product to be transported often contains grit and sand. The abrasive resistances of the thermoplastic materials used in the manufacture of flexible pipes, compared with typical steel materials, are given in Table 3.

The method of installation is simplified because of its flexibility. The pipes can be wound onto winch-operated reels designed with a radius equal to the minimum laying bending radius. Tension control is provided by the winch on the reel which may be installed on any vessel with a suitable dynamic positioning (DP) system which allows accurate control of the vessel relative to the defined tracks. This is critical when manoeuvring over non-linear tracks and at approaches to target areas where often over-lengths have to be accommodated or allowance made for subsequent tie-in to a subsea structure.

The advantage of flexibility is realized especially when laying in deep water. The wall thicknesses of the inner carcass can be increased to accommodate the increased external pressure, and the axial pulling capacity can be increased to withstand any increase in tensile loads during laying (tensioners may also be used to reduce/prevent overstressing of the stored sections of the flowline on the reels, and to ease spooling). Laying operations in deep waters are essentially the same as those for shallow water and are enhanced by the availability of sophisticated ROVs to minimize/eliminate diver intervention.

Recovery and repairs are straightforward as any damaged flowline can be recovered onto a vessel similar to that used for the installation. The extent of the repair is dependent on the degree of damage, i.e. from application of a new external patch to the replacement of a short section.

Inspection and maintenance are limited to periodic inspection of the cathodic protection system installed on the flexible flowline, inspection of mechanical joints between flowlines and to subsea structures, general survey of the condition of the external layer, and survey of the pipeline route for objects which may affect the integrity of the pipeline system.

DISADVANTAGES OF FLEXIBLE PIPES

Unit cost per metre

The cost of flexible pipes as ex-works hardware is high compared with steel. This is even more significant with short lengths because of the cost of the end terminations, which are made of forged steel with complex internal profiles for the attachment of the various layers of the composite flowline structure. The end fitting is surface-treated to provide internal and external protection against wear and corrosion.

The cost of supply should, however, be evaluated along with the cost of installation, which is significantly less than the cost of installing rigid flowlines.

Handling

Flexible pipes require more care in their handling to avoid damaging the external layer and intermediate structures. Pulling axially should be closely supervised to ensure that the lines are not subjecting the pipes to excessive loads, and reeling onto storage or laying reels should also be monitored to ensure that the pipes are wound torsion-free.

During installation from a lay vessel, the work deck should be clear of sharp points and corners and a steel gutter or rotating wheel should be provided where the pipe goes overboard. The touch down point on the seabed during the laying should be continuously monitored with an ROV to ensure that the flowline is not bent beyond its MBR, and that the laying tension caused by self-weight, water depth and vessel excursion is within that of the laying equipment.

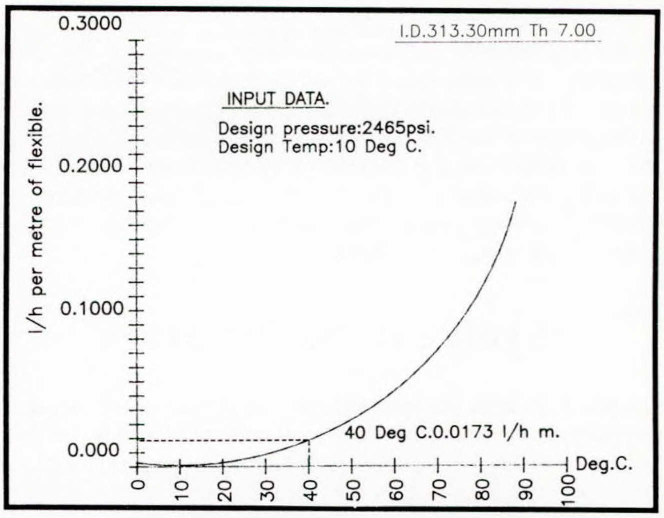

Fig. 3. Methane diffusion through Rilsan sheath

Selection of materials

The selection of materials is crucial especially when the product to be conveyed is at a high temperature, particularly at the wellhead. 'Coflon', a fluorinated polymer used in flexible pipes, was specially designed to cope with high-temperature crudes of up to 130 °C. It is resistant to crude oil and has resistance to stress cracking, wear abrasion and corrosion and is not subject to ageing.

High thermal insulation material 'Cofoam', an extruded semi-rigid PVC foam, is wound around the flexible pipe, the number of layers depending on the degree of thermal insulation required. It is then protected with an external thermoplastic sheath.

Gas diffusion

The process of diffusion of gas through plastics may be described as the condensation and solution of the gas at one surface followed by diffusion in the form of liquid and evaporation to the gaseous state at the other surface. This applies even to rigid steel surfaces but at a much lower rate. Where it is considered necessary to allow the diffused gas to escape, bursting discs can be drilled in the outer sheath. These discs open when the gas pressure between the internal and external sheath exceeds the hydrostatic head, typically 80–150 lb/in^2. Generally, the amount of gas permeating is too small to cause any problems and Fig. 3 shows a plot of the typical diffusion rate of methane against temperature through a polyamide material.

Recent developments have produced a one-way subsea valve designed to be installed on the pipe via a hole drilled through the external sheath behind the end fitting. The valve is held in position by a bolted split-sleeve collar and calibrated to release the diffused gas when the set pressure differential, depending on water depth and operating pressure, is exceeded.

Dimensional limitations

The operational and environmental conditions and the product(s) to be transported dictate the make-up of the material and its weight and physical dimensions. These put a limitation on the length of line that can be carried on a storage/laying reel and thus determine the number of intermediate connections necessary to make up the required length. As mentioned earlier, the consequence of these intermediate connections will be to increase the cost of manufacture.

METHODS OF INSTALLATION

Flexible flowlines are normally installed from a reel vessel, where the lines are stored on vertical reels or turntables on the deck of the vessel. The reels are operated by laying winches mounted on each side of the reel (see Fig. 4) or by a tensioner. The laying vessel is preferably fitted with a DP system with full redundancy, to enable accurate control of the vessel during the installation and to allow laying and abandonment close to platforms, floating production vessels and subsea structures or any other congested seabed areas. Flowlines may be laid on the seabed or be simultaneously laid and trenched to provide additional protection against third party damage.

Fig. 5 shows a typical laying catenary. The top vertical angle at the stern gutter may vary between 30° (for shallow water) and 1° (for deep water), taking into account the excursion of the vessel, the MBR at the touchdown point on the seabed, and the top tension of the flowline on deck (to avoid undue crushing loads on the sections of the line remaining on the reel).

The laying equipment is able to lay the flowline within a corridor of 10 m, depending on water depth. It is also possible to co-ordinate laying of multiple lines simultaneously in such combinations as two or more flowlines, or a bundle of flowlines and umbilicals, restricted only by the vessel's deck space and equipment layout.

During manufacture of the flowline, account is taken of the seabed profile, installation tolerances of wellheads, base manifolds, platform location, and laying methods. The overlength required, deduced from the installation configuration, may vary from 1 to 5%.

Stability of the flowline during the installation is ensured by having it filled with water during laying, which also enables hydrostatic testing to be carried out immediately after laying.

The sequence of operations in the installation of a flexible flowline are as follows.

1. Mobilization of equipment, personnel and vessel
2. The load out of lines
3. On-site pre-installation survey
4. Initiation of lay
5. Laying/trenching/external protection
6. Abandonment of end termination
7. Pigging/gauging/leak test/hydrostatic test
8. The tie-in end terminations
9. Precommissioning

Mobilization

Equipment and material should be laid out on the deck of the vessel according to the installation sequence. Deck reinforcements should also be considered for welding on temporary rigging points and for the location of heavy items. The lay reels should be positioned such that the flowlines may be laid in a logical sequence and items such as heavy stabilization bases (deadman anchors) should be loaded within the reach of the vessel crane. All equipment should be adequately sea fastened and hold-down points should be optimized to minimize deck welding.

Typical DP systems include the following.

1. Artemis – surface orientated, microwave positioning system with a range of about 10 km and an accuracy of 0.5–1.5 m.
2. Syledis – a medium gauge system using a chain of known and fixed locating antennae with a range of 100 km and an accuracy of 5 m.
3. Simrad – a subsea-orientated supershort base acoustic positioning system of one or two hull-mounted hydrophones locating several subsea transponders with a range of about 1 m and an accuracy of 0.5–1% of water depth.
4. Taut-wire system – a dead weight lowered to the seabed by a constant tension winch. Vessel motion is detected by inclinometers. The range of the system is 500 m water depth with an accuracy of about 1% of water depth.

Two independent positioning systems should be on-line during the laying to provide a 100% redundancy. The taut wire is normally kept in station keeping mode in the event of DP failure.

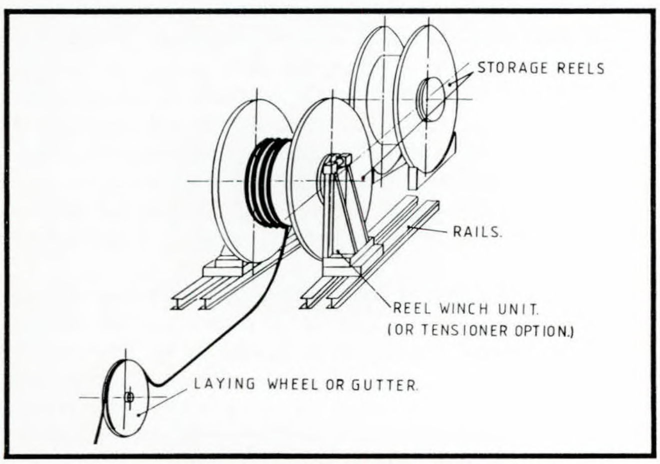

Fig. 4. Mobile laying winch

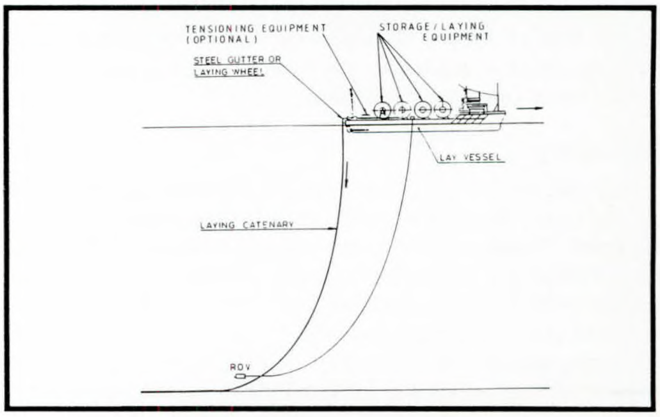

Fig. 5. Reel vessel method

Initiation of lay

The method of starting a lay is dependent on the proposed method of tie-in. For instance, for a riser base manifold subsea structure it may be possible to install pulling cables to the flowline via a pulley system and then pull from the deck of the vessel.

The straightforward method is by positioning the end of the flowline with a deadman anchor at a pre-determined target area (see Fig. 6) with a Simrad beacon or marker buoy attached to aid locating it for subsequent tie-in. An ROV is also used to ensure that the start of the line is correctly positioned in the target area. The deadman anchor should be able to accommodate the horizontal tension in the flowline.

Final abandonment and tie-in

It is imperative that the approach to the target area should be carefully worked out to ensure that there is adequate slack in the line for the final pull in.

The end fitting may be abandoned on the seabed with a similar method used for its initiation. If a tie-in is to be performed immediately, the end termination may be abandoned directly using the abandonment cable from the lay reel with a remote hydraulic disconnector to eliminate any diving work. The laydown area should be sufficiently close to the tie-in point. Typical methods of tie-in are illustrated in Fig. 7.

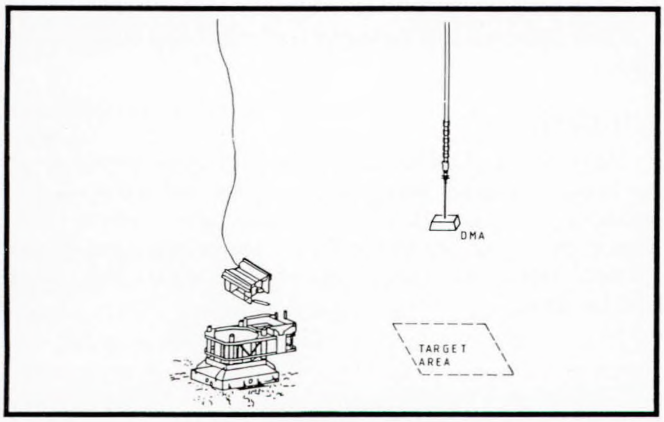

Fig. 6. Initiation of lay

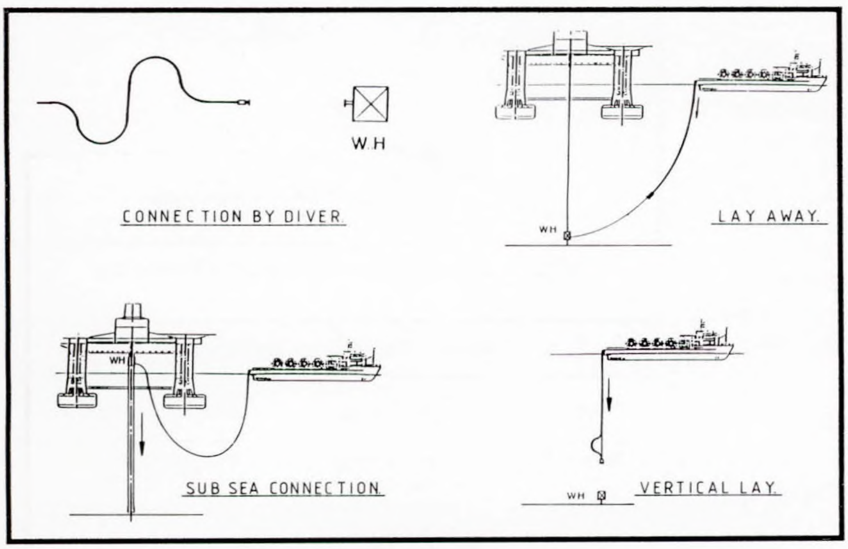

Fig. 7. Methods of tie-in

Connection by divers

The flexible flowline is abandoned on the seabed in an 'S' or 'U' configuration and then pulled by means of a 'come-along' to the connection point, and the connection is made by divers equipped with bolt tightening tools.

Subsea connection

The flexible line is transferred to the completion vessel for connection to the wellhead prior to both being lowered to the seabed.

Lay away method

The flexible pipe termination is fitted with an automatic subsea connector. The assembly is guided to the subsea template/wellhead where it is automatically latched and connected. This method is best suited for first end connection.

Vertical lay method

The flexible pipe, connected with an automatic subsea connector, is lowered to the wellhead without guidelines where it enters into a receptacle and is automatically connected. This method can be used for first end connection only.

THE NEED FOR PROTECTION

The two major concerns in the use of flexible flowlines are their susceptibility to damage as a result of third party incidents, and their stability on the seabed. Because of its intrinsic properties the latter should be addressed differently from the problems associated with the stability of rigid pipes.

Hooking loads

A dragging anchor will either hook on the pipe on first contact or slide along it before passing over. When hooking occurs, the pipe may be pulled along until either the pipe fractures or the breaking strength of the anchor cable is reached. Depending on the size of pipe and type of anchor, the hooking force required to rupture the pipe may warrant external protection.

The risk from fishing activities comes from the trawl board sliding along the flexible pipe and accelerating along the pipe surface at several times the towing speed. This will invariably damage the outer layer(s) of the flexible pipe, exposing the metallic layer to corrosion attack. The other risk of damage is when the pipeline is suspended off the seabed thus allowing trawl boards to be trapped beneath the pipe. The effect is then the same as that from a hooked anchor, although the breaking tension of the trawl warp is much lower. In a series of trials carried out by the Norwegian Deep Water Pipeline Project Committee in 1976, it was observed that hooking never occurred when the trawl door was in an upright position upon contact with the pipe. This behaviour was observed regardless of whether the line was lying on the seabed, suspended, or partially buried.

Impact loads

Impact from vessels, trawl boards and dropped objects are classified as environmental loads and should be taken into consid-

Table 4. Protection methods

Incidents	Protection method	Alternatives
Trawler/fishing	Burial	Public Notice
Earthquake	Slack line	
Chafing	Burial	Stabilization
Strong current	Burial	Stabilization
Anchors	Public notice	External protection (rock/gravel dumping,concrete slabs, mattress)

eration for those parts of the pipeline system where such loads are likely to occur.

The magnitude of the impact force is dependent on the elastic properties of the pipe, water depth and direction of the impact. The pipeline can absorb the energy of a dropped anchor by deflecting in the direction of the force as a result of cylindrical deformation and elastic foundation deformation.

Numerous papers have been presented on the subject of dragging and impact loads on submarine pipelines[1–4].

The type of protection is also affected by such factors as soil condition, current and wave action (see Table 4), and the requirements may vary along a single length of flowline.

STABILITY ON THE SEABED

The stability of the pipeline is one of the primary concerns of the certifying authorities, owners and operators. However, there are no standard methods for verifying the stability of a flexible pipeline on the seabed under design environmental conditions[5–7]. The DNV methods, generally applicable to rigid pipelines, are regarded as rather conservative[5]. A special research programme was initiated by Coflexip and the Institute of French Petroleum (IFP) in 1986 to study the on-bottom behaviour of a flexible pipe, to determine acceptable lateral motion and to develop a calculation method to give reliable prediction of possible motions on the seabed. The results of the research are being evaluated, the initial indication being that a flexible line appears to be more stable than a rigid line under similar design environmental conditions.

It should be noted that a flexible line, because of its composite construction, is heavier than an equivalent strength rigid pipe. Furthermore, its intrinsic flexibility allows considerably more lateral movement without the risk of overstressing, buckling and kinking. Its flexibility also permits the line to follow the contour of the seabed, thus eliminating the danger of free spans occurring. The internal friction between the various layers of the line gives a very high internal damping coefficient and the risk of vortex shedding of a span is very low.

Technically it is feasible to design a flexible flowline structure to account for stability. However, in doing so there is an associated risk of complicating the method of manufacture and increasing the cost of supply. The need to provide an external stabilizing device should therefore be considered.

PROTECTION AND STABILIZATION

Lowering below seabed level by trenching or burial

An open trench provides a limited degree of protection against fishing trawl boards and currents but not against anchors. However, in areas such as the southern North Sea where high currents can be expected, an open trench tends to be filled in with sediment rather rapidly and will thus provide protection against certain anchors. The techniques available for open trenching are ploughing, water jetting and dredging.

The technique applicable is dependent on the soil condition and water depth. Ploughs are generally capable of operating in silt, mud and sandy seabeds and even soft clay bottoms. With the development of lighter vehicles, they can be towed by a DSV instead of lay barges, which improves the speed of trenching. They are capable of simultaneous laying and trenching with a maximum travelling speed of 4.8 km/day.

The technique of water jetting involves disturbing the soil beneath the pipe. The fluidized soil is then drawn into an eductor and thrown out to one side of the pipe. The disadvantage of this method is the difficulty of controlling the depth and profile of the trench, which varies with soil type. The rate of operation, from a lay barge, is about 2.4 km/day.

Dredging, best suited for compact soil, employs a rotating head to break up the soil. The disturbed soil is then removed with a suction pump and dispersed to one side of the line.

By far the most popular method for protection is the simultaneous lay and burial technique which is operable in both hard and soft soil conditions. Machines are now able to provide cover of 0.6–1 m below the seabed. Such depth of cover gives complete protection against all fishing activities, dropped objects and most anchors. The only disadvantage is the high cost involved particularly when employed for a relatively short length of time. A typical marine spread is illustrated in Fig. 8.

Table 5 summarizes the various techniques for different soil conditions.

Self-burial

This is the ideal solution. The rate of burial is dependent on the bottom currents being able to carry and transport the sediment over the flowline. Typical areas where such phenomena occur are in the Dutch Sector and parts of the southern North Sea, which have shallow waters and strong tidal currents.

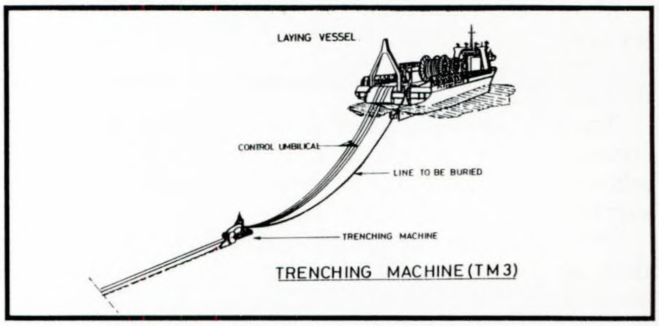

Fig. 8. Simultaneous laying and trenching

Table 5. Protection techniques

Soil type	Soil description	Protection technique
Very soft soil	Very soft clay, fine sand or gravel	Ploughing, jetting
Soft soil	Unconsolidated clay, coarse sand	Trenching, ploughing
Hard soil	Compact limestone, coral reef, soft rocks	Trenching

Reinforcement of pipe structure

Protection of rigid steel pipelines can be effected by the application of a higher-strength concrete coating or by the addition of a protective casing. The former may increase the cost of the concrete by 10–25% and the latter will involve more engineering and construction work.

The thickness of steel layers in a flexible pipe may be increased or extra steel wrap added. This, however, may increase the weight by about 20%.

External protection and stabilization

This technique is applicable to both steel and flexible pipes. It offers good protection against waves and currents and, to a certain extent, depending on the type employed, protection against the impact and dragging actions of anchors and trawl boards. The various methods include rock/gravel dumping, mattress placement for free span correction, cross-over supports, and grouting.

Rock dumping. Rock or gravel dumping is widely used for protection and/or stabilization of subsea pipelines, especially in areas where the soil conditions are unsuitable for trenching.

Two installation techniques are available.

1. Surface dumping where gravel or rocks are dumped from the surface. This method is wasteful and control of placement is difficult.
2. The flexible fall pipe method where the gravel and rocks are guided through a chute to about 5–10 m above the pipe. The end of the fall pipe is connected using an ROV for positioning and survey.

The dumping materials are laid over the pipe with the required cover, which usually varies between 0.5 and 1 m. The grain distribution varies between 2 and 6 inches with a density of about 2.5 t/m^3 and side slopes of 1 to 3. This gives a submerged weight between 1000 and 4500 kg/ m.

Investigations have been carried out in a test tank to assess the risk of damage of the outer coating caused by impact of rocks or gravel simulating the real offshore conditions. The rocks used in the demonstration were 4–17 kg in weight, and where there were indentations on the outer sheath, they were insignificant and did not initiate cracks or tears.

Mattress placement. These are widely used offshore as protection at cross-overs and for short sections of the pipeline over undulatory seabed or where supports are needed to reduce the length of free span.

The mattress may be made up of a blanket of interlocking concrete-filled plastic segments or a reinforced bitumen/sand mix. Both types are prepared onshore prior to load-out on a supply vessel with a lowering crane.

The placement of the interlocking segment mattress can be done using a quick release handling frame, either diver-assisted or by ROV. The placement of grout bags relies heavily on diver intervention.

The interlocking segment-type blanket, because of its flexibility, follows the seabed and pipeline profile very closely. It offers the least possibility of typical anchor ingress following anchor snag, and weaker ropes around the edges are designed to fail to allow the section of the blanket to deflect or dislodge an anchor hook. It can be used in conjunction with rock dumping to enhance the protection of the pipeline.

The bitumen-mix mattress comprises a ballast aggregate bound by bitumen to provide a degree of flexibility and enable the mattress to respond to seabed foundation erosion.

Applications of such mattresses include scour protection, pipeline stabilization, sandwave protection, free-span correction, cross-over padding, and foundation protection.

The typical life span of the mattress is about 35 years. This reduces greatly as loads exceed 15 tons.

Continuous pipeline protection system (COPS)

This is the latest development using grouting as a means of providing continuous protection and stabilization of a pipeline. Unlike the usual grout bags which are 5–10 m long and are laid by divers prior to filling with grout, this method offers a diverless continuous laying operation in water depths of up to 300 m performed by a remotely controlled underwater crawler, the reeled mattress being simultaneously injected with grouting material. The whole operation can be performed from a non-specialist vessel (see Fig. 9).

This method was successfully employed in 1986 in the Gullfacks Field where about 3.0 km of 2 m by 0.2 m grout mattress (in 500 m lengths) were laid over an 8 inch (outside diameter) pipeline and two control umbilicals.

The COPS system (see Fig. 10 and Table 6) consists of the following.

1. A continuous fabric formwork mattress composed of a double polyethylene layer interconnected with spacer straps giving the specified cross-section of the mattress. There is a continuous sealing strip on the uppermost layer.

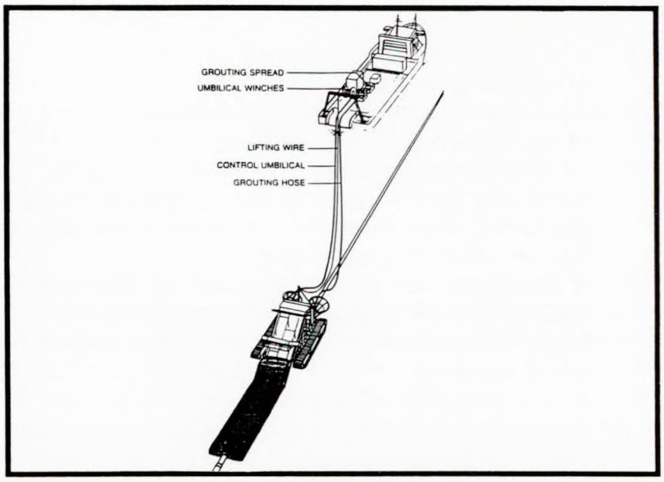

Fig. 9. COPS spread

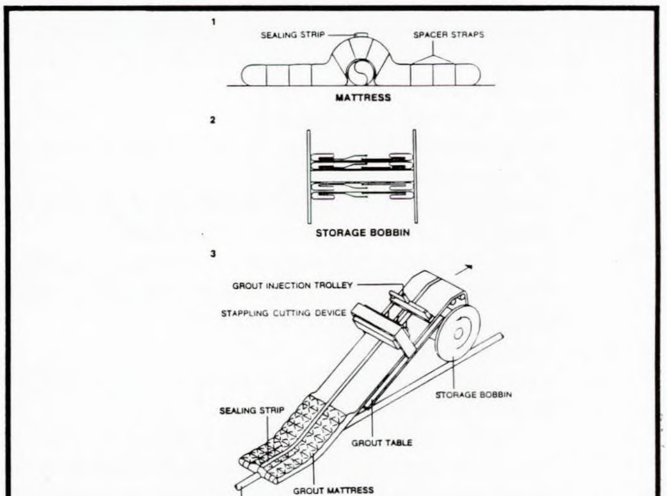

Fig. 10. Placing of mattress

Table 6. Technical data on continuous operating pipeline systems (COPS)

Crawler	
Dimensions	6.5 m x 4.5 m x 4.79 m
Weight in air/in water	9 t/8 t
Hydraulic power pack	15 kW, 60 l/min, 250 bar
Power supply	3 phase, 440 V, 60 Hz
Tracks	Rubber type with grip
Operating speed	Up to 300 m/h
Storage capacity of mattress	Up to 300 m
Grout mixer units	
Dimensions	11.54 m x 2.78 m x 6.8 m
Weight	25 t
Mixing rate	0.16–0.84 m^3/min
Power supply	110 V, 60 Hz
Power	7 kW
Water requirement	320 l/min
Compressed air	4.25 m^3/min, 6 bar
Fuel consumption	23 l/h
Grout pumps	
Dimensions	4.0 m x 2.7 m x 2.67 m
Weight	5.2 t
Pump rate	0.14–0.6 m^3/min
Compressed air requirement	6.5 m^3/min, 7 bar
Fuel consumption	18 l/min

2. A storage drum on which the mattress is reeled either flat or in folded position.
3. An inclined table which supports the mattress during the filling, the lower section of which is articulated.
4. An injection trolley mounted at the top of the table. The function of this is to open the bag by separating the two grip bands, insert the grouting injection nozzle into the bag, and close the sealing strip.
5. A double stapling and cutting device for simultaneous sealing of the end of the grout-filled mattress and the next empty mattress, and cutting the filled mattress after each laying sequence.
6. A self-propelled hydraulically operated crawler designed to carry the above items and the necessary instrumentation for monitoring and control from the support vessel via an electro-hydraulic umbilical. The sensors mounted on the crawler provide data such as location of the crawler on the seabed, position relative to the pipeline, status of the grouting process and control of the as-laid product. Performance characteristics of the system are given later.
7. Surface equipment comprising:
   a. three winches for storage of the two umbilicals and lifting wire;
   b. control room from which the crawler is pilotted and where the grouting process is monitored;
   c. grouting spread consisting of two mixer/pump modules and equipment for controlling the quality of the grout with outputs of up to 32 m^3/h;
   d. cement storage silos;
   e. interchangeable bobbins complete with preformed lengths of mattresses;
   f. a support vessel equipped with a 30 ton A-frame or crane, capable of maintaining position either on DP or on a 4-point mooring, with a free deck space of about 500 m^2.

A typical operation sequence is illustrated in Fig. 11. The crawler is placed over the pipeline either by direct lowering or by crossing the line (the submerged weight of the crawler is only 8 t). The actual track of the vessel is derived from the actual track of the crawler. Movement of the crawler is adjusted according to the movement of the grout level along the track. When the level in the mattress reaches the maximum required level, the crawler is moved forward. Typical grouting speed for a 2 m by 0.2 m mattress is 40 m/h. The distance from the vessel to the crawler during the grouting operation, which is kept constant, is provided to the vessel's bridge via the DP system. On completion of a laying length, the mattress is stapled and cut. The crawler is recovered by the A-frame mounted at the stern of the vessel.

COMPARISON OF PROTECTION INSTALLATION METHODS

The suitability of a protection technique is dependent on factors such as soil conditions, current and wave conditions, location and types of risk to be protected against, and accessibility and proximity to structures. The length of pipeline or section thereof to be protected, depth of water, vessel availability, installation spread required and installation timing affect the cost.

Table 7 shows the typical installation performances of the various continuous protection techniques. In hard soil, the burying technique may progress at 20–50 m/h, and at 50–200 m/h in very soft soil. By far the most widely used technique, burying, can be performed by ploughing, water jetting or dredging, depending on the soil conditions. Rock dumping, an alternative to trenching, especially in very hard soil areas, has been used up to a depth of 150 m. The depth of cover required, the length of pipeline and the need for a sophisticated vessel, dictate the cost of this technique. The cost of the continuous grouting technique is also dependent on the amount of protection required and thus the amount of cement to be injected into the grout bag. The advantages offered by the technique are first the ability to use a non-specialist vessel for the installation and secondly the fact that diver intervention is not required. Depending on the length needed to be covered, COPS can prove to be commercially attractive.

For very short sections of line, mattress placements either of concrete, asphalt or grout should also be evaluated, taking into consideration such factors as saturation diver intervention, suitable weather and sea conditions, intermediate mobilization and demobilization or deployment of supply vessels, daily offshore rates of equipment, and laying rates. With reference to Table 7, there is obviously a commercial break-even point, however hypothetical, between trenching, rock dumping, continuous grouting and mattress placement for relatively short lengths of pipeline. The ultimate choice must always be that which 'ensures protection and integrity of the pipeline'.

FLEXIBLE PIPE GUIDANCE

It was not until recently that the design, installation and commissioning of flexible pipelines was disassociated from the same requirements stipulated for rigid pipelines. As highlighted earlier in the paper, the design criteria for flexible flowline stability on the seabed, as set out in the ref. 7, was questioned. However, it should be noted that since a flexible

Table 7. Installation performance

Item	Pipelaying	Simultaneous laying and burying	Grouting (COPS)	Rock dumping
Mob./demob.	1–3 days	5–10 days	2–5 days	2–3 days
Travel speed	12 knots	12 knots	12 knots	10 knots
Existing capacity	Up to 8 inches, 0–100 m wide. Over 8 inches, 0–500 m wide	Trench depth up to 2.5 m. Trench width up to 0.7 m. Soil 1–4000 t/m².	Bag width up to 3 m Bag height up to 0.4 m Submerged weight up to 1 t/m	Cover 1 m or more Submerged weight up to 4.5 t/m
Installation speed	300–800 m/h	20–200 m/h depending on soil conditions	20–90 m/h depending on grout conditions	50–100 m/h depending on rock conditions
Max. weather conditions	Beaufort 7–8	Beaufort 4–5	Beaufort 5	Beaufort 5

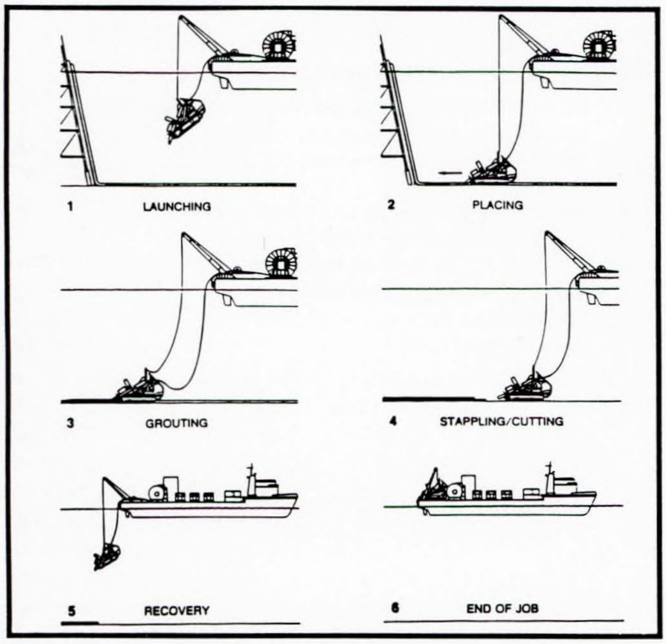

Fig. 11. Operating procedure

pipeline system is generally custom-built, it is difficult to be specific. Recommended practice tends to be presented in general terms to provide guidance, thus allowing for an alternative design approach which may be more applicable for specific cases. A list of current standards is given in the Appendix.

CONCLUSIONS

The use of flexible pipe as flowlines simplifies the installation. In addition, they are more reliable when compared with rigid lines. The need to protect and stabilize a flowline is dependent on the marine environment and third party activities. A summary of the suitability of the various protection techniques is given in Table 8.

As we progress towards exploration and production in deeper waters it is imperative, in putting safety at the forefront, that the industry, the relevant Classification Societies, and the Certifying Authorities should work together to develop realistic standards and guidelines without discouraging development of alternative methods of analysis.

Awareness of the future needs of the offshore industry should be focussed on improving safety and quality, whilst reducing the cost of installation.

Table 8. Flexible pipe stabilization and/or protection

Type of protection	Waves and currents	Trawl dragging	Anchor line dragging	Anchor dropping	Anchor dragging
Pipe reinforcement	Good	Limited	Limited	Limited	None
Gravel dumping	Good	Good	Limited	Good	Limited
Mattress	Very good	Good	Good	Very good	Limited
Burying	Very good	Very good	Very good	Good	Good

ACKNOWLEDGEMENTS

The author wishes to thank colleagues in Coflexip (U.K.) Ltd. for their valued comments and assistance. The author also wishes to thank Hydrofax and SLP for the provision of technical data.

REFERENCES

1. T. Castens, S. P. Kjelden & O. Gjorsvit, 'The Conflict Between Pipelines and Bottom Trawls – Some Results from Laboratory and Field Tests', Presented at the ONS Stavanger (Sept 1978).
2. O. Gjorsvik & S. P. Kjelden, 'Influences of Bottom Travel Gear in Submarine Pipelines', Presented at Offshore Technology Conference, Houston (1975).
3. R. J. Brown, 'Pipelines can be Designed to Resist Impact from Dragging Anchors and Fishing Boards', Presented Offshore Technology Conference, Houston (1972).
4. K. W. Tate, 'Protecting Submarine Cables from Accidental Damage', Presented at Offshore Technology Conference, Houston (1982).
5. Supplement to the 4th edition of the AP Model Code Part 6 – Pipeline Safety Code (Institute of Petroleum).
6. American Petroleum Institute, Recommended Practice 17B (RP17B), draft (Feb. 1987).
7. Det Norske Veritas, Rules for Submarine Pipeline Systems (1981).

APPENDIX

Reference codes and standards

Flowlines: supply and installation

1. Department of Energy, Submarine Pipelines Guidance Notes (October 1984).
2. Institute of Petroleum Model Code of Safe Practice – Petroleum Pipelines, Part 6.
3. ANSI B31.4, American National Standards Institute, 'Liquid Petroleum Transportation Piping Systems' (1982).
4. ANSI B31.8, American National Standards Institute, 'Gas Transmission and Distribution Systems'.
5. ANSI B16.5, American National Standards Institute, 'Steel Pipe Flanges up to and including 24 inch'.
6. ANSI 16.20, American National Standards Institute, 'Ring Joint Gaskets and Grooves for Steel Pipe Flanges'.
7. NACE MR-01-75, National Association of Corrosion Engineers, 'Sulphide Stress Cracking Resistant Metallic Materials for Oil Field Equipment'.
8. NACE RP-04-75, 'Selection of Metallic Material to be used in All Phases of Water Handling for Injection into Oil Bearing Formation'.
9. ASTM D2513, American Society for Testing and Materials, 'Standard Specification for Thermoplastic Gas Pressure Pipe, Tubing and Fittings'.
10. Det Norske Veritas, 'Rules for Design, Construction and Inspection of Submarine Pipelines and Pipeline Risers' (1976).
11. Det Norske Veritas, 'Cathodic Protection Design', RPB401 (March 1986.)
12. BS 4515, 'British Standards Process of Welding of Steel Pipelines on Land and Offshore'.
13. ASTM A194, 'Carbon and Alloy Steel Nuts for Bolts for High Pressure and Temperature Service'.
14. ASTM A193, 'Alloy Steel and Stainless Steel Bolting for Materials for High Temperature Service'.
15. AP 16A API, 'Specification for Wellhead and Christmas Tree Equipment'.

Protection of flowlines

1. Department of Energy, Submarine Pipelines Guidance Notes (Oct. 1984).
2. Institute of Petroleum, 'Model Code of Safe Practice – Petroleum Pipelines', Part 6.
3. SI No 1019, Offshore Installation Operational Safety, Health & Welfare Regulations' (1976).

Other general codes and standards

1. Mineral Workings, Offshore Installations Act (1971).
2. Petroleum and Submarine Act (1975).
3. The Submarine & Petroleum Safety Regulations (SI 1513) (1982).
4. Oil and Gas (Enterprise) Act, Part IV (1982).
5. Continental Shelf Act (1964).
6. Health & Safety at Work Act 1974.
7. Merchant Shipping Act (1979).
8. The Offshore Installations (Construction & Survey) Regulations (SI 289) (1974).

Discussion

R. I. HARPER (Shell Seatex): The paper indicates that flexible flowlines can be retrieved by the laying vessel for repair *in situ*. Can you confirm whether such an operation has in fact been carried out and, if so, where, or is the normal repair of damaged flowlines by replacement?

D. F. D'ABRERA (Brown & Root Vickers Ltd.): How is the joint made between successive lengths of pipe? What quality control is used on the joints? How is the length of pipe supported over the back of the barge while successive reels are being changed over, or while joints are being made and tested?

K. E. J. MILLER (SeaMark Systems Ltd.): What is the cost of the COPS systems compared with trenching? Why was it only used on Gullfaks in 1986 and not on subsequent projects? The paper refers to a 'non-specialized vessel'. Could the author elaborate since the drawings seem to show Flex services 2 or 3 which are both rather specialized vessels? Would a fairly conventional large pipe carrier be acceptable as the mother vessel? What is the minimum vessel specification for the system?

J. DE PREY (UEG): If gas should make its way through the linings of a line, might it not embolize, i.e. expand when the pressure dropped, when this line is lifted for inspection or repair, and thus cause major damage?

It is rumoured that some flexible flowline has been laid in loops. Thus the plough found itself confronted with its own flowline. Have you heard of this happening, and what can be done?

G. T. ASHCOMBE (BP Petroleum Development Ltd.): My first question concerns the limitations of laying larger-diameter lines full of water and the resultant tension required at the lay vessel. We were advised that in extreme cases lines have to be laid full of air.

My question is: If there is a limitation on laying large-diameter lines full of water, would a similar limitation apply in the event of in-service damage requiring the line to be lifted and repaired?

My second question is: The author mentioned in his presentation that lines could be laid in 150 m water depth to a positional accuracy of $\pm$ 10 m. Would simultaneous lay of two or more flowlines enable an improvement on this accuracy? If a greater accuracy were demanded, for example in a congested installation, are there any particular pieces of equipment or procedures which would be required?

Author's reply

In reply to **R. I. Harper:** Repairs *in situ* and replacement of end terminations have been carried out during installation operations in the North Sea and in foreign fields.

The method of repair of damaged lines is dependent on the extent of damage. It may be simply repair of a cut or tear of the outer sheath by means of 'patching', or a major repair in which the damaged section is cut out and new terminations, with or without and intermediate flexible spool piece, are installed. For short lines such as jumpers, it may be commercially viable to recover the complete line and replace with a new length.

In reply to **D. F. D'Abrera:** Each section of the flowline is fitted with end terminations at the manufacturing plant. The end termination, or end fitting, is normally a flange or mechanical clamp (Grayloc or similar) type. The sections are connected together prior to overboarding and lowering to the sea bed. The flowline and connections are then subjected to a pressure test in accordance with applicable codes and standards. This test may be performed with the final termination on the deck of the lay vessel, of after laydown on the sea bed.

A possible alternative method of connection is by butt welding. The terminating spool must have a sufficient length of neck to dissipate the heat generated from the welding process to prevent damage to the flexible line.

On-site connections, sacrificial anode installation, etc., are performed with the vessel on station keeping. It is general safe practice to secure the flowline independently and to have the flowline section on deck tension-free. This is achieved by using appropriately rated Chinese fingers, otherwise known as cable grips, secured to a hold-down on deck.

In reply to **K. E. J. Miller:** It is rather difficult to establish a general scenario for which a realistic cost comparison of the two methods of protecting a flexible line can be made and without jeopardizing the inherent benefits each method can offer for pipeline protection.

One needs to consider such factors as:

- sea bed conditions, marine environment, location, etc.;
- purpose, objectives of providing the protection;
- length of lines to be protected;
- congestion on the sea bed.

Considerations of the above factors will tend to favour the application of the COPS method, whilst for others the trenching method will be more apt.

A lay barge may be used for installing the COPS system. A minimum deck space of about 500 m^2 is required with additional space (below deck, for instance) for the cement silos. The major equipment involved is listed in Table 4 of the paper.

The vessel should have a cranage facility or A-frame of 30 ton capacity for the launching and recovery of the crawler. The vessel should be capable of maintaining position either on DP, or on 4-point mooring. The DP system should consist of at least an acoustic and a surface referencing system.

In reply to **J. De Prey:** To avoid any pressure build-up between the pressure layer and the outer sheath, bursting discs can be fitted onto the outer sheaths of the gas carrying flowlines. The need for these depends on several factors such as operating conditions and composition of the gas, material properties of the flowline, etc., which will give an indication of the permeability of the gas through the sheath material. More recent designs include a pressure relief gas valve integrated into the end fitting or mounted externally on the flexible line.

With regard to flowlines being laid in loops, the author is unable to confirm the rumour that some flexible flowlines, as opposed to umbilicals, have been laid in loops.

In reply to **G. T. Ashcombe:** Laying winches, flowline structure characteristics, vessel stability, marine environment, sea conditions, etc., are some of the factors to consider when laying a flexible flowline. The laying tension can however be controlled by varying the configuration of the flowline catenary.

The consideration to lay a line empty, i.e. full of air, is primarily due to the limiting cranage capacity for loading the packed reel onto the lay vessel.

This accuracy of lay was mentioned as typically ± 10 cm. The accuracy is dependent on the lay control, vessel response, and subsea current condition.

There is no specific benefit in simultaneously laying 2 or more flowlines. The lay control is more critical especially when the lines are of different sizes. Moreover, the lines may have different surface textures, thus resulting in different responses and behaviour to the current.

In congested areas, it is advisable to lay one line after the other. With tight positional control of the laying, using lower vessel speed, touch down point monitoring relative to the prelaid line, an ROV and an acoustic reference system, it is possible to achieve a tighter corridor with an accuracy of 2–5 m relative to the first line.