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REVIEW OF PIPELINE FREEZING OFFSHORE

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REVIEW OF PIPE FREEZING (FREEZE SEALING) OFFSHORE

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1. INTRODUCTION

Pipe freezing (freeze sealing) is a technique which can be used on liquid filled pipes and pipelines to produce a solid, pressure resistant, frozen plug. Such plugs can be used for temporary isolation of a section of pipe or a fitting to allow repair, maintenance or modification, such as changing valves or fittings, extension, blanking of pipework, and pressure testing.

The application of pipe freezing as an isolation procedure offshore should comply with recognised safety procedures, especially in the handling of cryogenic materials. It should also conform to offshore safety procedures. At present, no statutory codes or standards exist for the application of pipe freezing.

This document discusses the factors which should be considered when applying the technique offshore. The basic principles of pipe freezing are described in Appendix I.

1.1 Range of applicability

The technique may be applied to pipes of various sizes, orientations, materials and containing various fluids and is commonly applied to offshore topsides pipework, eg. fire water ring mains, branches and hydrants; service water systems and branches; sections of hydrocarbon pipework; and oil and gas risers. Subsea freezing is less common. Successful completion of a pressure resistant plug requires that the pipe is full of a liquid that may be solidified by freezing, and that any flow is halted or reduced to a very low value. It may not be possible to form a solid pressure resistant plug in all conditions.

Pipes have been successfully frozen over a range of conditions of pipe diameter, fluid temperature and for limited flow rates. Pipes of up to 762 mm (30") diameter have been successfully frozen under favourable conditions and it may be possible to freeze larger pipes. Most freeze isolations are carried out on water filled pipes or pipes back-filled with water to effect a freeze. The freezing times for ice plugs are of the order of an hour for a 152 mm (6") diameter pipe and are approximately proportional to the square of the pipe diameter. Other freeze media (eg. hydrocarbons) can be successfully frozen provided a sufficiently low plug temperature can be achieved; the freeze times for hydrocarbon plugs depend on the origin of the oil but will be considerably in excess of those required to produce an ice plug in the same size pipe. The procedure is concluded by thawing the plug. If no method of accelerating thawing is used, the thawing times are approximately proportional to the pipe diameter and are of the order of a day for ice plugs in a 305 mm (12") diameter pipe.

2. OPERATIONAL REQUIREMENTS

2.1 Planning

Planning should consider all stages of the isolation process. Before undertaking a freeze isolation, adequate preparations should be made including a site survey (eg. to assess access and pipe condition), categorisation of the freeze isolation and a documented work plan. Pre-freeze trials may be required to determine unknown aspects of the freeze.

2.2 Assessment of risk

When a failure would put safety or operational integrity at risk, a formal risk assessment exercise should be carried out. The hazards associated with the failure of the isolation and/or the pipe should be assessed; these include:
(I) momentum of fragments of pipe wall, pressure and temperature of contained liquid, compressed gases within pipe,
(ii) toxic, corrosive or flammable nature of contained liquid, and
(iii) effects of loss of equipment or structural damage caused by pipe failure.

The hazards associated with using cryogens/coolants should be considered (see Appendix II).

2.3 Categorisation of freeze isolation

The freeze isolation should be assessed and classified into a standard category depending on the consequences of failure of the pipe or plug. The categorisation will be used to define the freezing procedures; it should be linked to increasing levels of confidence in plug integrity (see 2.12) and may be the basis for rejecting pipe freezing as a suitable method of achieving an isolation. The following three-level categorisation is consistent with current good practice in the offshore oil industry.

(I) Non-critical: Release of contents poses no serious risk to plant, personnel, environment (hydrocarbon carrying lines excluded on grounds of fire risk); event of pipe/isolation failure does not disable essential emergency services, nor require shutdown of plant (including partial).

(ii) Critical: Release of contents poses immediate but limited loss of hydrocarbon; event of pipe/isolation failure will disable emergency services, and/or result in shutdown (complete or partial) of plant.

(iii) Highly critical: Release of contents means the spillage of a large volume of hydrocarbon with high risk to plant/personnel; event of pipe/isolation failure carries risk to divers, and/or requires long term shutdown to rectify.

2.4 Selection of freeze site

The effects of the pipe geometry, flow in neighbouring branches, and the environmental conditions should be considered in selecting a suitable freeze site. Sufficient space and access to fit the jacket, to locate the cryogen/coolant vessels and to carry out the work on the pipe will be required.

It is inadvisable to freeze at weld sites (other than longitudinal seam welds which are annealed); where significant defects or corrosion are known to exist; and over fittings (eg.

valves), bends, changes of section or where the complex geometry may give rise to undetermined stresses. Visual inspection of the outside surface of the pipe should be performed; depending on the freeze categorisation, an NDT inspection of the freeze site may be required.

2.5 Selection of freezing method

The choice of freezing method depends on the pipe wall material limitations, the severity of the fluid conditions (flow, temperature, pipe diameter) and the freeze categorisation. The highest probability of success is achieved when using liquid nitrogen, however, any reduction in the fracture toughness, taken together with the freeze categorisation, may limit the temperature to which the wall is cooled (see I.5). In selecting the freezing method, the pipe material properties, pipe condition and the applied loading should be considered.

(I) Plain carbon and low alloy steels (BCC materials): These materials undergo a change from ductile to brittle properties at low temperatures which makes them vulnerable to sudden failure on impact loading. The acceptability of a liquid nitrogen freeze on these materials depends on the freeze categorisation, the freeze site itself (eg. the presence of any defects, welds) and the combination of in-situ loads and loading applied during freezing.

(ii) Austenitic stainless steels, copper alloys and aluminium alloys (FCC materials): These materials do not generally undergo a transition to brittle fracture at low temperature. Liquid nitrogen or controlled temperature freezing is generally acceptable. Controlled temperature freezing may be preferred to reduce the stresses resulting from freezing (in particular, the stresses resulting from shock cooling (see I.6.1)).

(iii) Non-metals: Most non-metallic materials are brittle at low temperatures. No freezing method is generally acceptable. Freezing non-metallic pipes incurs a high risk of pipe failure and is not recommended unless this risk is acceptable.

(iv) Lined or coated pipe: Freezing lined or coated pipe involves a risk of damage due to differential contraction. Generally linings and coatings have a greater thermal expansion coefficient than steel, therefore internal linings may become detached and external coatings may split. Unless this is acceptable, freezing is not recommended.

2.6 Personnel

Pipe freezing is normally carried out by specialist contractors. Good communications between all personnel involved in carrying out the freeze and subsequent work on the pipeline is essential to promote co-operation between the normal plant operation, the freezing operation and the intervention works. Training of personnel may be necessary.

2.7 Provision of information

Details relating to the pipeline should be provided to the freezing contractors, including: pipe diameter, pressure (both normal and during freezing), pipe contents, temperature, flow rate and regime, material properties, pipe condition (eg. defects, welds), pipeline layout, presence of flow in adjacent branches, pressure difference required, duration of freeze and the possible/desired location of freeze site.

2.8 Safety equipment
For freezing using liquid nitrogen or carbon dioxide, safety equipment will include oxygen level meters and breathing apparatus (for rescue personnel, located outside the freezing area). Low lying areas (eg. pits) where the oxygen level may drop should be well ventilated. Suitable protective clothing should be worn to avoid contact with cryogens/coolants. The normal site personnel should be notified of any risks; restricted access to the freeze area may be advisable.

2.9 Preparation of freeze site
A site survey should be performed by the freezing contractors prior to the freeze. Attention should be paid to access to the site, ensuring clear entry and exit routes. Where appropriate, the removal of external insulation/corrosion coatings, action to prevent loading on the pipe during the intervention works, cleaning the pipe inner surface and the introduction of the freeze medium should be considered. The degree of protection against loading will depend on the categorisation and whether the pipe is embrittled. If external insulation/corrosion coatings cannot be removed, the effect on freeze time and cryogen/coolant requirements should be considered. Depending on the freeze categorisation, consideration should be given to the provision of a secondary, non-freeze, isolation for use in the event of plug failure. Any flow in the pipe should be minimised and, if possible, stopped; pressure surges during freezing should be prevented. Installation of instrumentation, freezing jacket and additional equipment (eg. safety equipment, additional cooling jackets, pressure relief valves) should be performed where required.

2.10 Cryogen/coolant
Cryogen/coolant supply should be sufficient and maintained throughout freezing and pressure holding stages; breaks in supply will not necessarily jeopardise the success of the process. If the supply system is automated, the effect of a power failure on the cryogen/coolant supply should be considered. Depending on the freeze categorisation, it may be necessary to provide a back-up system capable of maintaining the freeze for the unattended hold time.

Safety margins are required in predicting the coolant/cryogen requirements. Loss of coolant/cryogen due to boil-off during transport, storage, transfer to the jacket and during the freeze should be taken into account. The entire coolant supply should be stored on site for an offshore freeze. The safety requirements during transport, storage and transfer to portable containers (if required) of cryogens/coolants should be considered, including the requirements of other equipment (eg. lifting equipment), and the effect on the freeze process of failure of this equipment. The hoses used to supply cryogen/coolant to the freeze jacket should be rated for the pressure and temperature requirements and attention paid to insulation of the hoses, potential damage to the hoses during use, and the provision of relief valves and isolating valves at the ends of the pipe.

2.11 Freeze monitoring
The freeze should be monitored during plug formation to give early warning of an adverse change in the conditions at the freeze site. To ensure satisfactory progress, the state of the freezing operation should be monitored at intervals not exceeding 10 minutes.

It is advisable to monitor the pipe surface temperature during controlled temperature freezes and during liquid nitrogen freezes where the nitrogen level in the jacket cannot be monitored visually, and also in cases where there is heat input (eg. welding) close to the freeze. For freezes where the consequences of failure are important, two independent temperature measuring systems should be used. Observation of frost collars can provide qualitative information on the progress of the freeze. Additional information on the progress of the freeze can be obtained by measuring the pipe surface heat flux inside the jacket; this may be advisable if the conditions at the freeze site (eg. environmental conditions, pipe geometry, flow in neighbouring branches) are such that there is a risk that a successful freeze may not be possible. The rate of ice growth can be monitored qualitatively by observing changes in the level of heat flux: a decreasing level suggesting freezing and an increasing level suggesting melting. The heat flux level immediately prior to closure can be estimated from simple mathematical analysis[1]. Pressure monitoring and relief should be considered in cases where significant hydrostatic pressure development is possible. These measurements, together with contractor experience, can be used to assess the level of confidence in the likely outcome of the freeze.

2.12 Isolation confirmation

The level of confidence in plug integrity which is required depends on the freeze category. The only positive way to confirm the integrity of the plug is by performing a differential pressure test, during which the plug is subjected to the full line pressure for an agreed period (which depends on the freeze categorisation) by releasing the pressure on one side of the plug making allowance for any pressure transients that may occur. However, this may not always be possible in practice. In the field, confidence in the integrity of the plug is generally assessed by non-quantitative methods based on contractor experience. Depending on the category of the freeze, this may be supplemented by measurements of pipe surface temperature and heat flux.

2.13 Intervention works

Prior to commencing intervention works, it is advisable to continue freezing for a sufficient period following confirmation of plug closure to allow axial plug growth, particularly when a high differential pressure across the plug is required. If appropriate (see 2.9), a secondary, non-freeze, isolation should be deployed. Loading on the frozen pipe should be minimised and impact loading avoided especially if the pipe material is in an embrittled state. Instrumentation should be monitored in order to ensure that the freeze isolation is maintained. Additional cooling jackets may be deployed if the plug is at risk due to hot works (eg. welding).

2.14 Thawing

After the necessary work has been accomplished, the plug should be thawed. This is achieved by halting the coolant supply and removing the freezing equipment. Drained sections of pipe should be refilled and/or pressure balanced before thawing when there is a risk of damage to downstream fittings from a loose plug which may travel at high velocity. Particular care should be used in thawing ice plugs in vertical pipes due to the buoyancy of the plug. Depending on the location of the freeze site, thawing may be accelerated by hosing the outside of the pipe with cold water or by using a warm air (<250°C) blower.

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[1] M J Burton, R J Bowen, and J D Turner; Non-invasive plug detection for cryogenic pipe freezing; pp129-136, Proc Second Conference on Pipework Engineering and Operation; I.Mech.E, 1989.

2.15 Post-freeze reporting

Meetings and/or reports between the relevant personnel may be desirable.

2.16 Documented work plan

The complete plan of work including actual procedures should be specified and agreed upon and should refer to any meetings between all relevant personnel. The freeze operations should be performed according to the documented work plan and should be carried out in accordance with the site procedural and safety requirements eg. issue of work-permits.

3. EXTRA CONSIDERATIONS - SUBSEA FREEZING

Subsea freezing is not common and greater caution and planning will be required. In addition to the requirements of section 2 (for topsides and risers) above, the following should be considered :

(I) Recirculating coolant freezing methods may be most appropriate in this situation.
(ii) Preparations will include input from the diving contractor.
(iii) The vessel or platform from which the freeze is performed should use a dynamic positioning system; the effect of failure of this system (eg. on coolant supply) should be considered.
(iv) The actions required both offshore and onshore to shut down the pipeline in the event of failure of the isolation or of the pipe should be considered.

Freeze site details should be extended to include: sea depth, temperature, currents (on surface and at bed), sea bed relief and condition, pipeline protection (burial, etc). The effect of adverse weather conditions should also be considered.

Preparation should include removal of concrete coatings. Seam welds, if present, should be inspected. The pipe should be supported during the intervention works.

Once the pipe has been cut or separated, a secondary, non-freeze, isolation is required. Between cutting and the deployment of the secondary isolation method, the isolation is entirely dependent on the freeze and therefore cutting should only be performed within a suitable weather window.

APPENDIX I: BASIC PRINCIPLES OF PIPE FREEZING

I.1 Freezing methods

In order to form a solid plug inside a pipe, a short length of pipe, usually between one and four pipe diameters (1D to 4D) long, is cooled. There are several ways of achieving this, the selection of which depends on the prevailing conditions. Methods other than I.1.1 below are often referred to as controlled temperature freezes.

I.1.1 Direct liquid nitrogen freezing: A jacket is attached to the pipe and filled with liquid nitrogen at -196°C. The jacket should be kept full until thawing is required. Using liquid nitrogen produces the lowest practicable pipe wall temperature and hence maximises the likelihood of success under adverse conditions.

I.1.2 Closed circuit, recirculated coolant freezes: The pipe is cooled via a secondary heat transfer fluid maintained at a specified temperature depending on the conditions required. The fluid may either be circulated through a jacket in direct contact with the pipe, or through tubes in good thermal contact with the pipe.

I.1.3 Solid carbon dioxide freezing: Blocks of carbon dioxide are packed in the jacket against the pipe which is cooled during sublimation at -79°C. Heat transfer from the pipe is enhanced if the jacket is filled with a heat transfer fluid.

I.1.4 Liquid carbon dioxide freezing: Liquid carbon dioxide stored at ambient temperature in high pressure cylinders is admitted to the jacket. The expansion causes the production of solid carbon dioxide in contact with the pipe. This method is only viable for small diameter pipes, ie. less than 50 mm (2").

I.2 Factors affecting plug formation

Successful completion of a solid plug depends on a favourable combination of the conditions prevailing at the freeze site. The main factors involved include:

I.2.1 Coolant temperature: The coolant temperature should be below the freezing point of freeze medium. Decreasing the coolant temperature decreases the freeze time and increases the probability of a successful freeze.

I.2.2 Pipe diameter: Larger pipe diameters will extend the freeze time and have an adverse effect on the probability of success.

I.2.3 Freeze medium: Many different fluids are capable of being successfully frozen provided that they are cooled to a low enough temperature. Most freeze isolations however are carried out on water filled pipes. The freezing point of the fluid concerned should be considered when choosing an appropriate freezing method. Hydrocarbon products are particularly difficult to freeze due to the low freezing temperatures necessary and require low temperature coolants.

I.2.4 Additives: When natural convection currents may prejudice successful ice plug formation convection inhibiting additives may be added prior to freezing.

I.2.5 Freeze medium temperature: The closer the freeze medium is to its freezing point, the greater will be the probability of a successful freeze. The maximum superheat temperature that can be tolerated will reduce with increasing pipe size.

I.2.6 Contained fluid flow rate: Any flow through the freezing zone will have an adverse effect on freeze time and may prevent successful completion of the plug. Flow through the freezing zone should be stopped if possible. It should be noted that the combination of pipe flow and a long freezing jacket can lead to "double necking" of the ice plug and the entrapment of a volume of water inside the ice plug. When the trapped water freezes high pressures may be generated which threaten the integrity of the pipe.

I.2.7 Pipe geometry: Freezing at a low point in the pipework will minimise any natural convection effects and encourage plug formation whereas freezing at a high point may adversely affect plug growth. Flow in a branch adjacent to the freeze may also have an adverse effect on the progress and success of a freeze.

I.2.8 Trapped air or gas: Where possible venting should be carried out prior to the freeze to clear any pockets of air or gas.

I.3 Factors affecting plug strength

The maximum pressure a given plug can withstand will depend on a combination of factors, including:

I.3.1 Plug length: Generally a longer plug length will offer a greater pressure holding capability, however caution should be exercised using long jackets when there is any possibility of flow in the pipe, see I.2.6.

I.3.2 Contained fluid: The fluids most likely to be frozen offshore include water-based fluids and hydrocarbon products. The pressure holding characteristics and failure mechanisms of plugs frozen in each are quite different and will vary with conditions.

Since water freezes at a single temperature, once an ice plug has fully formed it will have a pressure holding capability. An ice plug frozen in a clean pipe can normally be expected to withstand a differential pressure of at least 70 bar with a one diameter long jacket and of at least 140 bar with a jacket exceeding two diameters in length.

The temperature at which hydrocarbon crudes and products freeze is much lower than that of water. These fluids gradually solidify as the temperature drops rather than at a single temperature and it is not until the centre of the plug has reached a sufficiently low temperature that it will withstand a significant differential pressure. On pipes of 254 mm (10") diameter and smaller, crude oil plugs can normally be expected to withstand a differential pressure of at least 25 bar with a one diameter long jacket and 50 bar with a jacket exceeding two diameters in length. No data are available for the pressure holding capabilities of hydrocarbon plugs in pipes greater than 254 mm (10") diameter; generally, other factors preclude the use of pipe freezing in these situations.

I.3.3 Pipe inner surface roughness: Generally it is expected that a rough surface will provide a better key for ice and will improve the pressure holding capability. The surface roughness will have little effect on the strength of hydrocarbon plugs since failure is usually by extrusion of the warmest part of the plug, the centre.

I.3.4 Pipe wall contamination: Contamination of the inner pipe wall with hydrocarbon products is likely to cause a severe degradation of the pressure holding capability of an ice plug. Pressures up to 55 bar have been held by ice plugs in oily pipes however, failure pressures may be as low as 14 bar.

I.3.5 Coolant temperature: For ice plugs in clean pipes, plug strength increases with decreasing coolant temperature down to about -10°C. At lower temperatures there is no clear relationship between coolant temperature and plug strength. Hydrocarbon plugs generally increase in strength with decreasing temperature.

I.3.6 Pressure: During the application of pressure to a complete ice plug, minor movement of the plug may occur. The strength of an ice plug in a clean pipe may be significantly increased by repeatedly pressurising to failure provided significant movement of the plug is avoided.

The strength of an ice plug frozen in a pressurised pipe subsequently depressurised on one side may be superior to that of a plug frozen in an unpressurised pipe which is subsequently pressurised on one side.

I.4 Cryogen/coolant requirements: For liquid nitrogen freezes, the minimum quantity of liquid nitrogen needed to form a solid plug varies with plug size, jacket design and local conditions, eg. for cold water with no flow the absolute minimum requirement would be about 30 litres for a 102 mm (4") diameter pipe rising non-linearly to about 5000 litres for a 559 mm (22") diameter pipe. These figures will increase under adverse environmental conditions and abnormal arrangements such as long hoses. Liquid nitrogen consumption during plug holding operations is generally much lower than during formation.

Coolant requirements during controlled temperature freezing are highly dependent on the freezing system used.

I.5 Pipe wall material considerations

The mechanical properties of the pipe material, their dependence on temperature and the condition of the pipe (eg. presence of defects, welds, corrosion) should be identified; these factors are critical in selecting the freezing method and in defining the temperature and pressure loading to which the pipe is subjected during the operation.

I.6 Stresses caused by freezing

During pipe freezing the severe thermal conditions imposed on the pipe cause stresses in the pipe. These stresses are in addition to any residual stresses and in-situ loads, as well as the loads resulting from the intervention work; the combination of these stresses together with the reduced fracture toughness at low temperature and the presence of fabrication defects may threaten the integrity of the pipe.

I.6.1 Temperature gradients: Generally, the maximum stress to which the pipe is subjected during freezing is the shock cooling stress resulting from the through-wall temperature gradient caused by the initial application of the cryogen/coolant. This is a tensile stress in both hoop and axial directions on the outside of the pipe and is proportional to the applied temperature difference. Additional stresses develop in horizontal pipes as a result of temperature gradients in the circumferential direction; these are normally caused by the process of filling the jacket.

I.6.2 Pipe wall/ice interaction: The differential contraction of the pipe wall and freeze medium is another cause of stresses. In the case of the steel/ice combination, the contraction of ice is about 5 times greater than that of steel. For pipes of less than 254 mm (10") diameter the contraction of the ice causes compressive stresses in the pipe wall which are low in magnitude. Some evidence suggests that in pipes greater than 254 mm (10") diameter that tensile stresses may develop in the pipe inside the jacket as the plug grows.

I.6.3 Pressure: Freezing under pressure, using liquid nitrogen, can generate stresses higher than expected from the combination of freezing and internal pressure alone. The application of pressure after freezing is complete is less severe since the ice shields the pipe from the effects of pressure.

I.6.4 Expansion on freezing: As water freezes, it expands. In a confined volume this expansion will cause an increase in hydrostatic pressure. The most extreme example of this occurs when a plug closes off in two places, trapping the water in between. The combination of pipe flow and a long freezing jacket can lead to "double necking" of the ice plug and the entrapment of a volume of water inside the plug (see I.2.6). High pressures may also result if the freeze site is close to a pipe closure, or if two freeze sites are close together; in such cases some method of pressure relief should be provided.

I.6.5 Axial constraint: Cooling the pipe causes it to contract axially and if the pipe is rigidly constrained, tensile axial stresses will result.

APPENDIX II: HAZARDS ASSOCIATED WITH CRYOGENS/COOLANTS

II.1 Health and safety

The safety requirements for the handling of cryogens/coolants should be observed. The hazards are discussed in detail elsewhere[2] and include:

(I) Cold burns (nitrogen, carbon dioxide) from liquid and, to lesser extent, vapour. This can be exacerbated if the surface moisture freezes to the cold surface; the skin will stick to the cold surface and tear on removal. There is also a risk of clothing absorbing cryogens.

(ii) Asphyxiation (nitrogen) due to oxygen depletion. When nitrogen vaporises there is a large change in volume which displaces oxygen. Cold nitrogen gas is heavier than air and therefore gathers in low confined spaces. When subjected to gradual asphyxia due to a gradual decay in the oxygen content, individuals lose the ability and will to help themselves before becoming aware of the danger; sudden asphyxia causes immediate unconsciousness.

(iii) Vapour fog can be caused by water condensing out of the air; this restricts visibility and increases the risk of accidents.

(iv) Local oxygen enrichment is possible on surfaces where the temperature drops below -191 °C, causing a fire risk.

(v) The primary risk from carbon dioxide is due to poisoning. Inhalation of increased levels of carbon dioxide causes discomfort.

(vi) For controlled temperature freezes, the fire risks and toxicity for the particular coolant should be checked.

II.2 Environmental considerations

(I) Generally CFCs and HCFCs are used which are ozone depletors and greenhouse gases. During normal operation very little vapour release is likely, however, care should be taken to avoid spillage and during disposal of the coolant.

(ii) Carbon dioxide is a greenhouse gas.

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[2]Cryogenics Safety Manual (3rd Ed.), Butterworth-Heinemann, 1991