

PIPE FREEZING OPERATIONS OFFSHORE - SOME SAFETY CONSIDERATIONS

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ABSTRACT

Pipe freezing (freeze sealing) is a technique which can be used on liquid filled pipelines to produce a solid, pressure resistant plug which can be used for the temporary isolation of a section of pipe. The safety implications of using this technique offshore are concerned with the risk of plug failure, risk to the integrity of the pipe and the use of cryogenic liquids. These issues are addressed through a discussion of their associated parameters and the principal areas of concern are highlighted. Operational considerations include categorisation of the freeze isolation and risk assessment in addition to the choice of appropriate freezing method. This paper addresses these issues based on experience gained from extensive research into pipe freezing and, whilst no attempt is made to reconcile these to detailed offshore practices, attention is drawn to the main factors that should be considered.

1. INTRODUCTION

Pipe freezing (freeze sealing) is a technique which is often used on liquid filled pipelines to produce a solid, pressure resistant, frozen plug. Frozen plugs can be used in a variety of ways for the temporary isolation of a section of pipe or fitting to allow repair, maintenance or modification. Pipe freezing operations are usually carried out by specialist contractors although most of the research into this technique has been carried out at the University of Southampton. A review of developments in pipe freezing technology is given in Bowen et al (1989) and Burton et al (1990).

Pipes have been successfully frozen over a range of conditions of pipe diameter, fluid temperature and for limited flow rates. Pipe diameters in excess of 813mm (32") have been frozen under favourable conditions; most freeze isolations are carried out on water filled steel pipes. Freezing times are of the order of an hour for a 152mm (6") diameter pipe and increase roughly in proportion to the

square of the pipe diameter when there is no flow in the pipe and the freeze medium is close to its freezing temperature. It is usually necessary for the pipe to be full of liquid and, although small flows can be tolerated, success is far more likely when any flow is stopped or reduced to a very low value.

Many other liquids, including hydrocarbons, can be successfully frozen provided a sufficiently low plug temperature can be achieved, typically below -100°C . The freeze times for hydrocarbon plugs depend on the origin of the oil, but are considerably in excess of those required to produce an ice plug in the same size pipe.

Offshore, the technique is commonly applied to topsides and risers; subsea freezing is less common. Figure 1 shows a 152mm (6") steel riser being frozen using liquid nitrogen. Examples of systems that can be frozen include: fire water ring mains, branches and hydrants; service water systems; sections of hydrocarbon pipework; and oil and gas risers. Typical operations include changing valves or fittings; extension or blanking of pipework; and pressure testing.

Pipe freezing is a potentially hazardous operation however, when it is used by experienced contractors following recognised safe practices it can be a safe, quick and cheap alternative to other isolation procedures. Major international companies now use the technique in their maintenance programmes and their role has been significant in the move towards safer working practices.

This paper presents aspects of the pipe freezing process which should be considered by those concerned with its application offshore. It does not detail offshore safety procedures and practices but does draw attention to factors which should be considered in a safety context. A guidance note covering pipe freezing offshore is currently in preparation by the Health and Safety Executive and comprehensive guidelines in the oil industry both on- and off-shore are documented by Shell (1994).

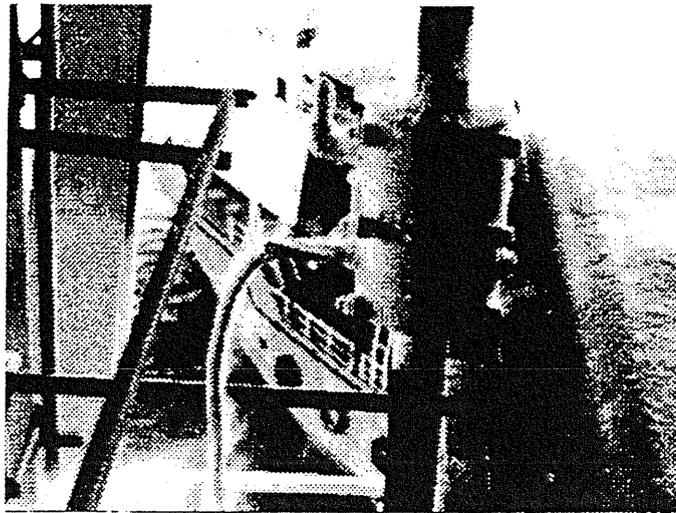


Figure 1: Freezing a 152mm (6") diameter steel riser offshore

2. BASIC PRINCIPLES OF PIPE FREEZING

2.1 Freezing methods

Freezing is usually carried out over a short length of pipe typically between one and four pipe diameters long. There are several ways of achieving this depending on the conditions.

(i) **Direct liquid nitrogen freezing:** A container or jacket is attached to the pipe and filled with liquid nitrogen at -196°C . This is shown in Fig. 2. The container is kept full throughout the plug formation and holding stages until thawing is required. Using liquid nitrogen produces the lowest practicable pipe wall temperature and hence maximises the likelihood of success under adverse conditions.

(ii) **Closed circuit, recirculated coolant freezes:** This method involves cooling the pipe via a secondary heat transfer fluid which is 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.

(iii) **Solid carbon dioxide freezing:** Solid blocks of carbon dioxide are packed in the jacket against the pipe. The pipe is cooled during the sublimation of the carbon dioxide at -79°C . Heat transfer from the pipe is enhanced if the jacket is filled with a heat transfer fluid.

(iv) **Liquid carbon dioxide freezing:** This method uses liquid carbon dioxide. When the liquid is admitted to the jacket the cooling effect during expansion causes the production of solid carbon dioxide in contact with the pipe. This method is only used on small diameter pipes ie less than about 50mm (2").

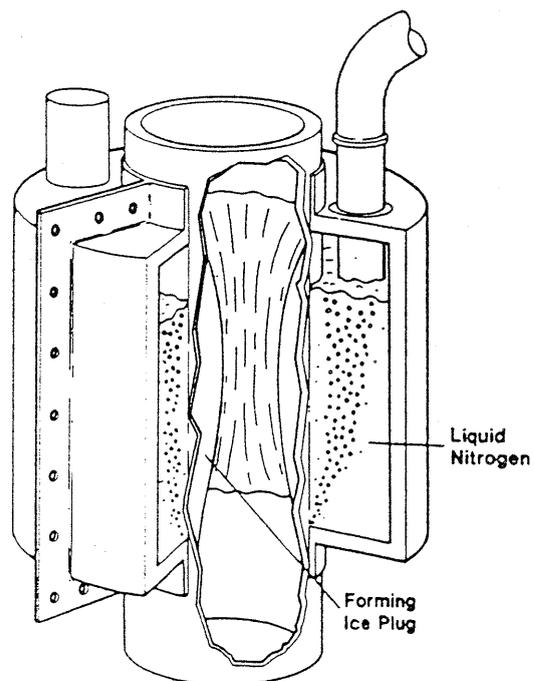


Figure 2 The pipe freezing process

2.2 Plug confirmation

It can be difficult to determine when the ice plug has fully formed and completely sealed the pipe however, this may be established either by a differential pressure test across the plug or by monitoring heat flux measurements at the surface of the pipe. Tavner et al (1996) describe a case study demonstrating the effectiveness of the heat flux technique.

2.3 Plug thawing

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.

3. SAFETY IMPLICATIONS

The three main areas of concern regarding the safety of pipe freezing operations are the possibility of plug or pipe failure and the use of cryogenic liquids. These are discussed in detail below.

3.1 Risk of plug failure

Properly formed and maintained frozen plugs can withstand considerable differential pressures however, certain conditions can lead to the failure of the plug causing spillage of the contained liquid and shut down of the plant either locally or overall. Sudden failure of the plug while the pipe is open and there is stored energy in the system could result in the plug being propelled from the pipe. This would clearly pose a considerable risk both to personnel and equipment.

Although plug failure is rare, it can be caused by a reduction in plug strength or an unplanned overpressurisation. Some of the factors affecting plug strength are given below.

(i) **Plug length:** Generally a longer plug will offer a greater pressure holding capacity. Typically, frozen lengths are in the range one to four pipe diameters. Care should be exercised when using long jackets if there is any likelihood of flow in the pipe due to the possibility of trapping water within the plug and causing an increase in pressure within the plug itself.

(ii) **Contained fluid:** The type of fluid contained in the pipe will affect the strength of the frozen plug. The fluids most likely to be frozen offshore include water-based liquids and hydrocarbon products. The pressure holding characteristics and failure mechanisms of plugs frozen in each are quite different and will vary with conditions. Generally, failure of an ice plug occurs at the ice-pipe interface whereas hydrocarbon plugs extrude at the centre of the pipe.

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.

The temperature at which hydrocarbon crudes and products freeze is much lower than that of water. These fluids solidify

gradually as the temperature drops rather than at a single temperature; it is not until the centre of the plug has reached a sufficiently low temperature that the plug can withstand a significant differential pressure. On pipes of 254mm (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.

(iii) **Pipe inner surface roughness:** The surface condition and roughness will affect the strength of an ice plug. Generally a rougher 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 centre of the plug.

(iv) **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 by preventing the plug from adhering to the pipe. It is likely that other surface contamination, including debris, will also have a deleterious effect on plug strength.

(v) **Coolant temperature:** For ice plugs in clean pipes, plug strength increases with decreasing coolant temperature down to about -10°C, however, at lower temperatures there is no clear relationship between coolant temperature and plug strength. Hydrocarbon plugs generally increase in strength with decreasing temperature, although the behaviour will depend on the type of hydrocarbon.

(vi) **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 which is 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. The former case will require greater caution because stresses due to pressure will exist throughout the freezing zone during the freeze whereas in the latter case they will not. The distinction between these two cases is important and must be properly considered during the pre-freeze assessment.

(vii) **Coolant/Cryogen:** Failure of the coolant supply may lead to the loss of the plug. It is therefore essential to ensure that the supply is maintained while the plug is required to act as a seal and withstand pressure. In the case of long duration liquid nitrogen freezes, care must be taken when changing between liquid nitrogen vessels to make sure that the nitrogen level in the jacket is maintained.

3.2 Risk to the integrity of the Pipe

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 low fracture toughness and the presence of fabrication defects may threaten the integrity of the pipe. Stresses due to intervention work can be minimised when planning the operation, eg. avoiding

shock loading when the pipe is embrittled.

Pipe stresses during freeze isolations are caused by temperature gradients in the pipe wall; differential contraction of the pipe wall and freeze medium; expansion on freezing (water); and by axial contraction if the pipe is constrained. These effects are discussed below.

(i) **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. During liquid nitrogen freezes, stresses up to 300 MPa can be generated during this stage. These stresses can be minimised by cooling the wall slowly and will persist over some considerable time only when the wall material has a poor thermal conductivity, e.g. in non-metallic pipes. 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 and will be more significant in larger pipes where the fill time is longer. The temperature gradient in the axial direction (at the ends of the plug) causes less significant stresses.

(ii) **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 254mm (10") diameter the contraction of the ice causes compressive stresses in the pipe wall which are low in magnitude, typically of the order of 20 MPa. Some evidence (Slater et al, 1992) suggests that in larger pipes (greater than 254mm (10") dia) that tensile stresses may develop in the pipe inside the jacket as the plug grows, although the cause of these stresses is not yet understood.

(iii) **Effects of pressure:** There is evidence (Slater et al, 1992) that freezing under pressure, using liquid nitrogen, generates higher stresses than expected from the combination of freezing and internal pressure alone, although a mechanism to describe this result has not been proposed and further work is needed. The application of pressure after freezing is complete is less severe since in this case the ice shields the pipe from the effects of pressure.

(iv) **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 (greater than 3D) can lead to "double necking" of the ice plug and the entrapment of a volume of water inside the plug. When the trapped water freezes, high pressures can result which may threaten the integrity of the pipe. 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 the pressure should be monitored and some method of pressure relief provided.

(v) **Axial constraint:** Cooling the pipe causes it to contract axially and if the pipe is rigidly constrained, tensile axial stresses will result.

3.3 Safety risks arising from the use of cryogenic liquids

The normal safety requirements for the handling of cryogens/coolants should be observed when using these coolants. The hazards are discussed in detail elsewhere (British Cryogenics Council, 1991) 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.
- (ii) Asphyxiation 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 slow decay in the oxygen content, individuals lose the ability and will to help themselves before becoming aware of the danger.
- (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.

4. OPERATIONAL CONSIDERATIONS

In order to ensure the safe implementation of pipe freezing offshore it is essential to follow a predetermined procedure incorporating all aspects of the freeze isolation process. This will include an assessment (formal in some cases) of the risk and consequences of plug or pipe failure. The freeze isolation should be categorised to determine the most suitable method of freeze isolation.

4.1 Selection of freeze site

Although the general site of the freeze isolation will be determined by the nature of the maintenance e.g. a valve to be changed, there will generally be some scope for choosing the particular position on the pipe at which the freeze will be applied. This choice will be influenced by the local pipe geometry (a horizontal low point being preferable), flow in any neighbouring branches, and the environmental conditions (high ambient temperature may extend the freeze time or prohibit a freeze). 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.

In choosing a site it is inadvisable to freeze over a weld (other than annealed longitudinal seam welds); where defects or corrosion are known to exist; or over fittings (e.g. 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 and, depending on the category of freeze, an NDT inspection of the freeze site may be required.

4.2 Assessment of risk

Freeze isolations offshore are used in a variety of situations, some more critical than others, it is therefore necessary, early in the

planning stage, to assess the freeze isolation with respect to the consequences of plug or pipe failure. When a failure would put safety or operational integrity at risk a formal risk assessment exercise should be carried out. This will provide a measure of the probability and consequences of any failure. The hazards associated with the failure of an isolation, or the pipe, should also be assessed and might include:

- (i) the momentum of fragments of pipe wall, the pressure and temperature of contained liquid, compressed gases within pipe,
- (ii) the toxic, corrosive or flammable nature of the contained liquid, and
- (iii) the effects of loss of equipment or structural damage caused by pipe failure.

4.3 Categorisation of freeze isolation

The objective of this exercise should be to ensure that both the procedures and precautions undertaken are matched by classifying the isolation into a standardised category depending on the consequences of failure. This will aid the choice of isolation method. Some of the factors to be considered will include the potential loss of hydrocarbon and risk of fire, damage to emergency systems and the likelihood of a partial or complete shutdown. A three-level categorisation system is currently being used in some parts of the offshore oil industry, (Shell, 1994).

4.4 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 may be cooled.

In selecting the freezing method, the materials related factors described in the following sections 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 brittle 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 however be preferred to reduce the stresses resulting from freezing. Depending on their composition, duplex steels may require special consideration.

(iii) **Non-metals:** Although freeze isolations are carried out on non-metallic pipe materials many of these materials are brittle at low temperatures and the operation will incur a greater risk of pipe

failure. No freezing method is generally acceptable and each case should be treated individually.

(iv) **Lined pipe:** Freezing lined pipe involves a risk of damaging the lining material. Unless this is acceptable, freezing is not recommended.

4.5 General safety requirements for pipe freezing

A complete plan of work should be specified and agreed upon before the freezing operation is started. This includes all aspects of the isolation process and should include written procedures and meetings between all personnel concerned. An assessment of the risks involved in the entire operation should be performed. The freeze should be carried out in accordance with the site procedural and safety requirements eg. the issue of work-permits, etc. In terms of the safety requirements, other factors which should be considered include the following:

(i) In the preparation of the freeze site, good access with clear entry and exit routes will be necessary.

(ii) The loading on the pipe resulting from intervention work should be considered eg. providing support for the pipe during intervention work. The degree of protection required against impacts will depend on the categorisation of the freeze and whether the pipe is likely to be embrittled.

(iii) Safety margins are required in predicting the coolant/cryogen requirements taking into account loss during transport, storage, transfer to the jacket and during the freeze. The entire coolant supply should be stored on site for an offshore freeze. The safety requirements for the use of the cryogen/coolants should be considered, including the requirements of other equipment eg. lifting equipment and the effect of the failure of this equipment.

(iv) Instrumentation to monitor pipe temperature and/or heat flux should be used especially for freezes where the consequences of failure are important, 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, or if the work on the pipe includes heat input in the form of welding, or similar, close to the freeze. Pressure monitoring and relief should be considered in cases where significant hydrostatic pressure development is possible.

(v) Depending on the freeze categorisation, secondary, non-freeze, isolation methods may be deployed or made available for immediate use in the event of plug failure.

(vi) Attempting to drain a pipe before the plug is completed will cause considerable thawing; it is advisable to assess plug closure by performing a differential pressure test.

(vii) Caution should be exercised during thawing in order to avoid damage to the pipe caused by a loose plug.

4.6 Subsea freezing

Subsea freezing is not common and even greater caution and planning will be required. Preparations will include input from the diving contractor. Recirculating coolant freezing methods may be the most appropriate in this situation. The vessel from which the freeze is performed must use a dynamic positioning system and the effect,

eg. on coolant supply, of any potential failure of this system must be considered.

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

Once the pipe has been cut or separated, a secondary, non-freeze, isolation is required (Department of Energy, 1990). 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 with a suitable weather window.

5. CONCLUSIONS

Experience has shown pipe freezing to be a cost-effective and generally reliable method of local pipeline isolation. Recent research has identified some of the key factors which can influence the safety of a freeze isolation. This has resulted in a set of recommendations covering safety issues during pipe freezing, considering the effects of the failure of the plug and of the pipe and also the safety aspects of handling cryogenics and coolants.

6. ACKNOWLEDGEMENTS

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