RCI AB SWEDEN

STORING GAS IN UNDERGROUND ROCK CHAMBERS

It is not quite 20 years since the technique of transporting and storing natural gas in liquid form was first used in real commercial scale and different parts of the distribution system are therefore still in the process of development. Most progress has been made with condensing methods, sea freight and evaporation, while storage techniques have lagged behind. Granted, there are good designs for tanks intended for above-grade storage. However, it would be preferable if above-ground tanks could be made to withstand higher levels of overpressure in gas (in view for instance of the roll over effect). In most cases too, it is not a satisfactory solution to have above-grade storage of quantities of energy as large as those found at the terminals of the transoceanic trade routes now in existence, which, moreover are rapidly being extended.

One variant of the above-grade tank is “in ground tank” – or the sunken tank -, which offers a greater measure of safety from several standpoints.

The best solution to the problem of storage is to go underground, and particularly when dealing with large quantities of LNG. Let us now try to substantiate this statement.

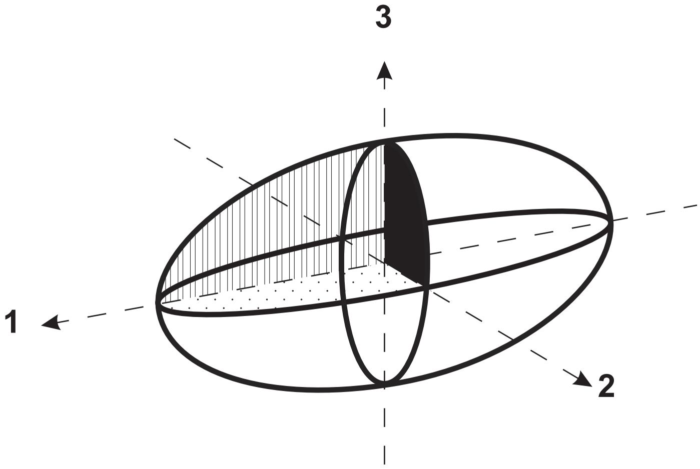
Earlier experiments

Rock caverns without any particular surface finish or seal have been used for the storage of cryogenic liquids for some ten years. Propane has been stored in this way at -42ºC (-43,6º F) and propene at -48ºC (-54,4ºF) without encountering any problems of a fundamental nature. Liquid ammonia is stored in a similar fashion at -33ºC (-27,4ºF) in rough rock caverns, although in such instances, cracks are sealed with plastic grout.

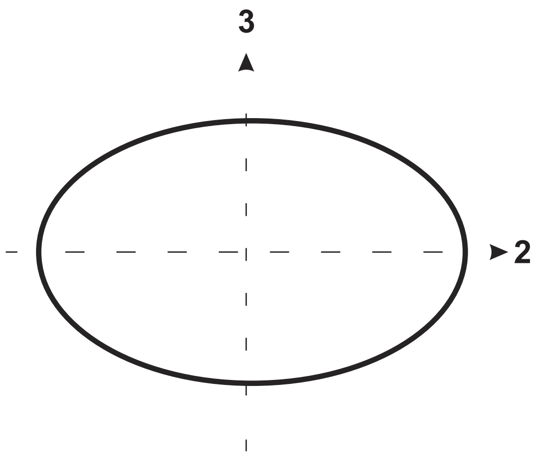
It has thus been established that cryogenic liquids can be stored at temperatures as low as about -50ºC (-58ºF) in rough-hewn, uninsulated rock caverns.

We know, however, that at temperatures in the ranges immediately below -50ºC (-56ºF) certain phenomena occur in the rock itself which render it necessary to give the rock face an interior finish. In brief terms, what happens is that the cold fluid chills the rock face, thus causing the latter to contract. The fine cracks, which are usually filled with water retained by capillary forces, are then sealed in that the water freezes. The cold fluid can easily penetrate the larger, more open cracks, and even cross zones and some tectonic fissures, thus lowering the temperature of the walls. This leads to contraction of the surrounding material, causing the cracks to open even further and thus to allow even more of the liquid to penetrate. This is particularly noticeable with vertical cracks, in that the effect in these is accentuated by the fact that the liquid penetrates at the bas of the cracks and lowers the temperature of the wall while assuming gaseous form, at which point of gas form and more upwards. This has the same effect as a mammoth pump.

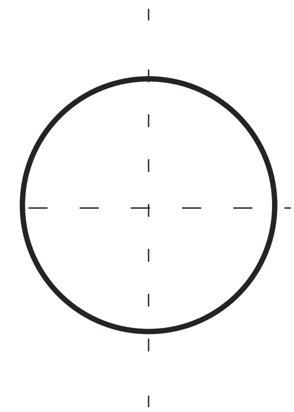
Theoretically, the cracks will widen ad infinitum as long as the tank is filled with a cold fluid. In this way they will then serve as form of a "thermal flange" which absorbs heat even deep in the surrounding rock. In practice, therefore, the point is soon reached at which the entire "flanged surface" of the cracks is so large that the degree of evaporation occurring is too great to make it possible to maintain the pressure in the tank. Given this fact, it is totally unrealistic to try to store cryogenic gases in unlined rock caverns at temperatures below -50ºC.



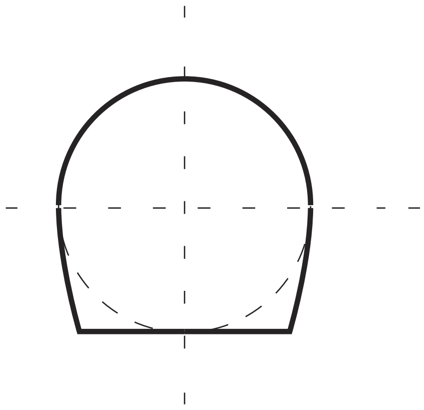
NORMAL STRESS
ELLIPSOID IN ROCK



THE IDEAL CROSS SECTION WITH REGARD TO THE ROCK STRESSES SHOULD BE SHAPED ACCORDING TO THE STRESS ELLIPSOID



THE IDEAL CROSS SECTION CAN USUALLY BE SUBSTITUED BY A CIRCULAR CYLINDRICAL SECTION



FOR CONVENIENCE THE CIRCULAR CROSS SECTION WILL BE MODIFIED WITH A PLANE FLOOR

GENERAL DESIGN OF ROCK CAVERNS FOR STORING OF GAS

Stockholm, Sweden, June, 2015

The problem can be solved either by grouting any cracks appearing with a substance which sets at a temperature slightly above that of the fluid being stored, or by applying a surface seal to the entire rock face. This treatment should preferable be combined with thermal insulation of the rock.

A number of different solutions have been suggested for each of the two systems mentioned, but as far as we know, none of these systems has been developed up to the point at which it would be available for commercial purposes. The method described in this paper is based on sealing and thermal insulation of the rock face. It has been tested on pilot projects over such a long period of time and with such satisfactory results as to be ready for launching on to the market, the commercial name given for this purpose being Cryo Cavern.

The Cryo Cavern Method

As already explained, the storage principle is based on a rock face which has been sealed and thermally insulated. This is done by giving interaction with the rock face and the rock mass behind, assuming that this may be said to be part of the tank structure to a depth of 2 – 4 m. The easiest way to illustrate how this actually works is to explain the method.

Preliminary surveys

The safety requirements for the storage of LNG are extremely strict and thus also the requests for the condition of the rock cavern in question. It is therefore worthwhile to try to establish an optimum location for the rock caverns in view of the stresses found in rock. It is advisable to start by determining the main stresses present in the rock (the stress ellipsoid) and to build the rock caverns with these main stresses as the primary consideration. In addition, cross-sections through the caverns should be such as to make it possible to avoid areas of wall lacking in stresses or having tensile stresses. x) This in practice means that an elliptical or circular cylindrical cross-section should be selected. However, for structural reasons, it is possible to choose a horse-shoe-shaped section with a circular cylindrical roof, without upsetting pressure conditions in the rock.

Blasting techniques

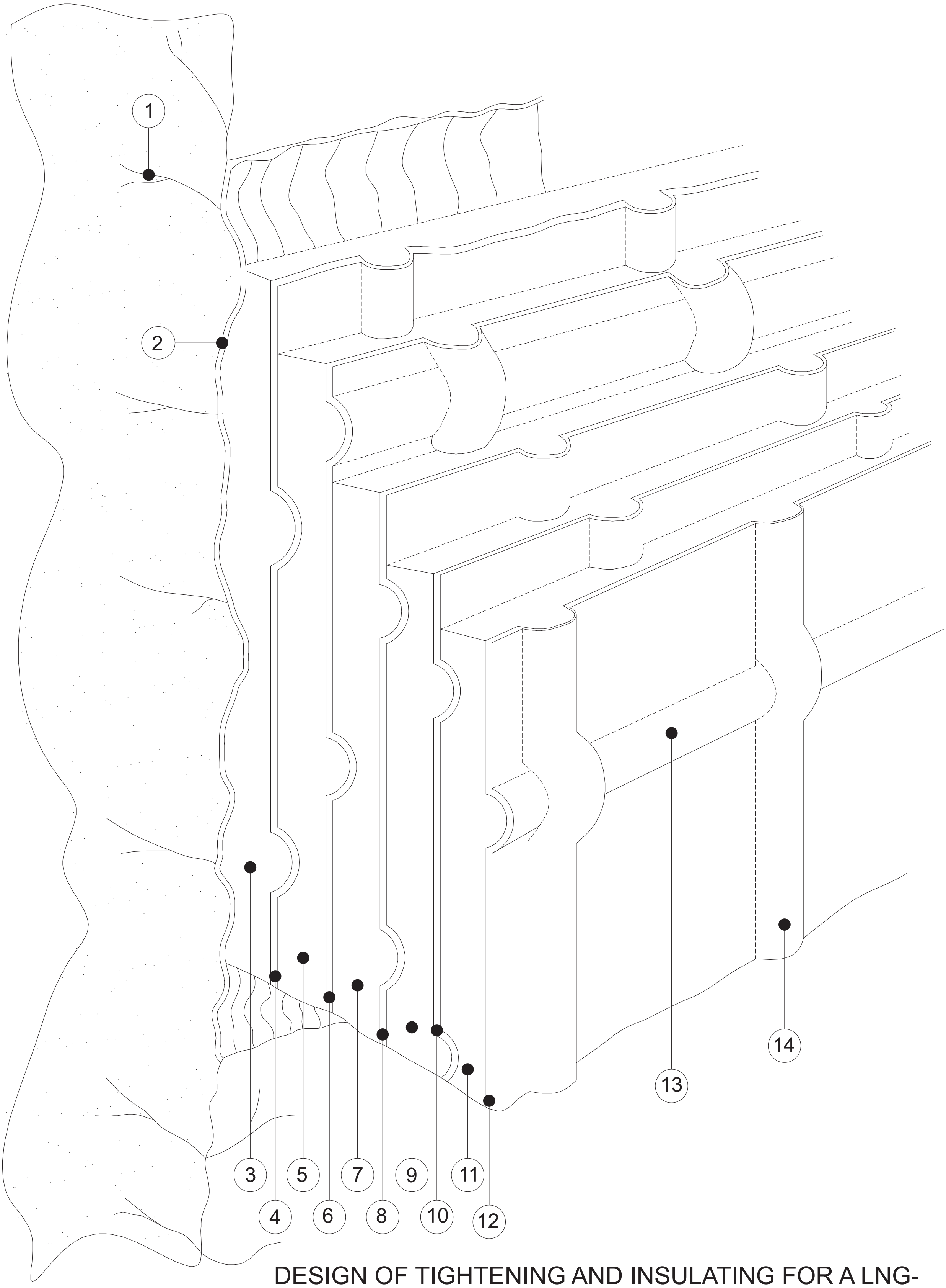
For the sake of safety – to prevent loose rock from detaching itself from the rock face – it is best to avoid causing any new cracks in the rock surface as a result of blasting operations. We also want the smoothest possible rock surfaces as a basis for the plastic finish, the reasons here being both financial and technical. The most advanced blasting techniques available are therefore always used for blasting out rock caverns.

Rock seal

The rock is carefully grouted to avoid moisture from cracks in the rock around the tank from creeping in towards the surface finish and causing this to detach (frost). If the rock is suitable for cement grouting, larger holes and pores are first roughly filled with cement. As cement grouting has no effect on pores and cracks with a width of less than around 0.4 mm, extra grouting operation using epoxy plastic is always necessary, this being known as precision sealing or precision grouting.

x) Note: Henceforth, the terms walls and rock face are used for all surfaces in the rock cavern, and thus even for floor and ceiling.

① CRACKS AND FISSURES IN ROCK TIGHTENED BY MEANS OF CEMENT AND PLASTIC (EPOXY) GROUTING
② GLUE LAYER OF EPOXY RESIN AS BOTTOM LAYER AND SEALANT AGAINST THE ROCK SURFACE
③ FIRST HEAT INSULATING (POLYURETHANE FOAM)
④ FIRST TIGHTENING LAYER (POLYURETHANE ELASTOMER)
⑤ SECOND HEAT INSULATING LAYER
⑥ SECOND TIGHTENING LAYER
⑦ THIRD HEAT INSULATING LAYER
⑧ THIRD TIGHTENING LAYER
⑨ FOURTH HEAT INSULATING LAYER
⑩ FOURTH TIGHTENING LAYER
⑪ FIFTH HEAT INSULATING LAYER
⑫ FIFTH TIGHTENING LAYER
⑬ AND ⑭ ORTHOGONAL SYSTEMS OF RIDGES



DESIGN OF TIGHTENING AND INSULATING FOR A LNG-CAVERN ACCORDING TO THE CRYO CAVERN SYSTEM

Stockholm, Sweden, June, 2015

All grouting operations are if possible performed as pre-grouting and are usually carried out from the inspection tunnels. Cement grouting provides the rock with a rough seal to a depth of some 4 – 6 m from the rock face, while the plastic grouting, which takes place after the cement grouting, precision seals the rock to a depth of at least 2 m or so from the rock face. The plastic mass penetrates the fine cracks fairly slowly and thus does not manage to fill them all before the setting process begins and therefore cannot force all water out. However, with its low surface stresses, the plastic works its way into the mouths of all the cracks and seals them, thus preventing water from entering the cracks from then on.

Rock reinforcement

Thanks to the meticulous design of the caverns and the careful blasting operations, the need for rock reinforcement diminishes considerable as compared to what we know is usually necessary. In addition, the plastic grout will also diminish the need for reinforcement in that the epoxy grout is an excellent glue with a tensile strength of 1.500 N/cm^2 (N = 150 kg/cm^2), which at many point and not least in the cross zones restores the rock to a monolithic entity.

Plastic finishes

The plastic surfacing given the rock consists of 3 different components with which the present techniques are as follows:

1. Glue layer – epoxy seal on rock wall

2. Insulation layer of cellular plastic (urethane cellular plastic)

3. Urethane plastic seal (urethane elastomers).

Glue layer – seal effect

Following completion of grouting and any reinforcement works, the rock surfaces are hosed down with a high-pressure jet and allowed to dry. A 1.5 – 2.0 mm thick layer of epoxy plastic is then sprayed on to the clean rock. The type of epoxy plastic chosen shows excellent adhesion to the rock face, even if the latter is damp, and also constitutes a good example for the subsequent layer of urethane. Furthermore, the epoxy material seals the rock face and prevents all moisture present in micro-cracks in the rock surface from interfering with the setting of the insulation layer to follow.

Thermal insulation

A 5 – 10 cm layer of urethane cellular plastic is then sprayed on to the sealing layer. The surface of this layer is given a ridged configuration, ridges being about 2 cm high as shown. The purpose for these ridges is to help mould the subsequent proofing layer. Urethane cellular plastic is itself a material with excellent insulation properties (= 0.020 W/m ºC), good mechanical strength and good resistance to LNG and most other cryogenic media subjected to storage.

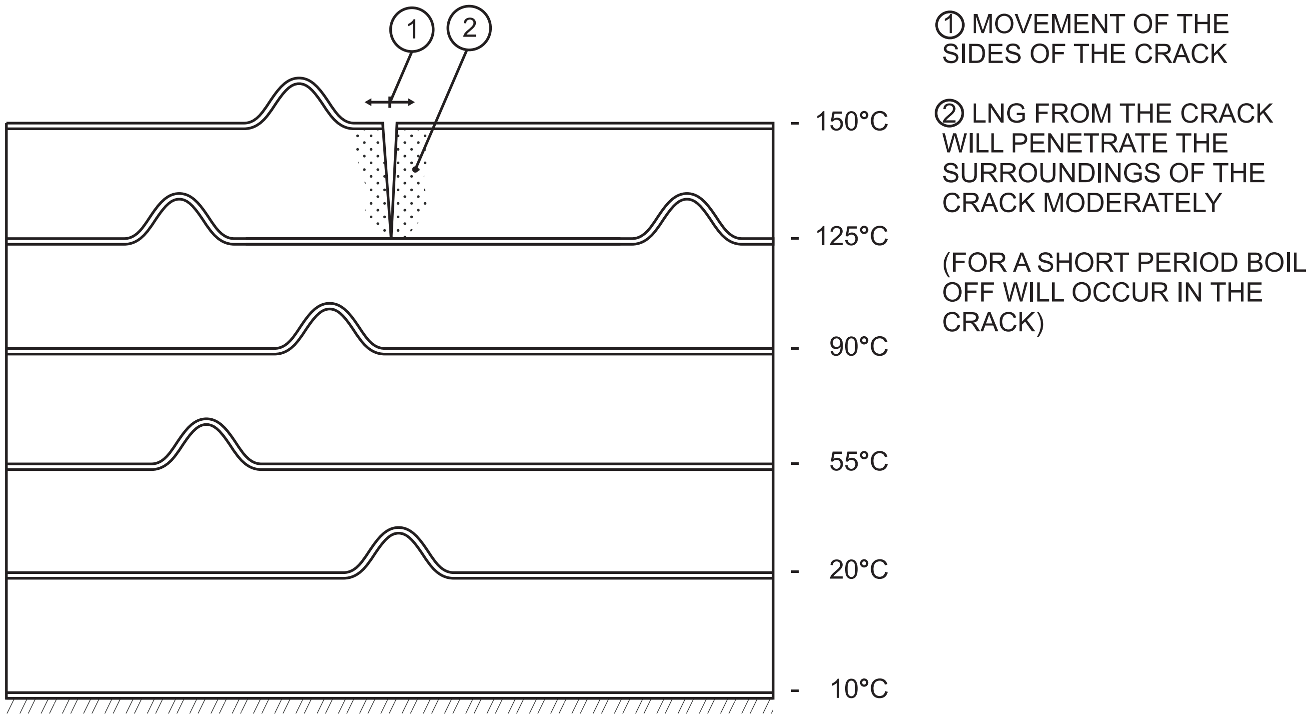
Proofing layer

A 1.5 – 2.0 mm thick layer of urethane elastomers is sprayed on to the wavy surface of the insulating layer. As polyurethane, like most plastics has a relatively high coefficient of linear expansion, around 1.2 % 1 linear contraction occurs in the proofing layer when cooled to an LNG temperature of -160 ºC. This would cause far too great tensile stresses if the surface were smooth. Thanks to the wavy surface acquired by the proofing layer as a result of the ridges in the insulation underneath, tensile stresses in the proofing layer (mainly in the plane zones) and on the surfaces of the ridges will be transformed into bending stresses. The principle here is the same as in the case of tensile and compressive stresses in a pipe when they become bending and stresses at an expansion joint.

<u>Other structural operations</u>

The total thickness of insulation required for storage of LNG is between 300 and 500 mm. This is provided by several layers of insulation each with a thickness of 50 – 100 mm alternating with 1.5 - 2.0 mm layers of proofing, all applied as described earlier, and in a manner ensuring that all proofing layers have a wavy surface. Five 6 – 10 cm thick insulation layers and thus 5 proofing layers are advisable for LNG storage. Several proofing layers offer several fold security against leakage through the surfacing material. If by any chance a crack should form in the outermost layer of proofing (closest to the stored liquid), it may be assumed that the crack will also penetrate the outermost layer of cellular plastic down to the level of the next proofing layer.

If the temperature gradient from the rock to the surface layer is linear, the different layers will have the temperature shown in the diagram at the point when the rock face has a temperature of +10 ºC. The cold fluid will reach proofing layer No. 2 at a temperature of around -125 ºC. The layer has contracted in proportion to this temperature and therefore has a lesser degree of tensile stresses than surface layer No. 1. At the same time, the material has a greater elongation at rapture at this temperature, meaning that the second layer offers a better safety margin than the surface layer. Local strain due to chilling around cracks has been found to distribute itself without causing rapture in all the tests carried out. Fluid penetrating the cellular plastic might possibly be expected to spread sideways in that layer.



THE CONDITIONS IN THE INSULATION IN CASE OF A CRAKE IN THE TOP LAYER

Stockholm, Sweden, June, 2015

It has been observed, however, that this is not the case with any of the cellular plastics used in laboratory experiments and pilot plants. Even if proofing layer No. 2 were to crack, the cold fluid would penetrate down to proofing layer No. 3, which would at that point be subject to stresses corresponding to a temperature of – 90 ºC. The degree of safety is thus increased with each layer as we progress towards the rock.
The structure of the surfacing can, of course, be modified in many different ways. It is, for instance, possible to reinforce one or several layers with organic or inorganic fibres, i.e. in the form of cut fibres, matting or woven material, and the number of proofing layer may be fewer or greater than the number mentioned here. Two layers of insulation and two layers of proofing are sufficient for storage of liquid propane and propene, giving a total insulation of 100 – 150 mm.

Why you should choose the Cryo Cavern Method

The philosophy behind the development of the Cryo Cavern Method may be applied for almost all instances involving the handling and storage of large quantities of energy. This philosophy is based on the assumption that the safest way (and often the only way from the technical standpoint) of handling and storing materials is to go under ground and to use the stabilized foundations, namely the bedrock, which is already there. Storage of LNG using the Cryo Cavern Method involves the construction of rock caverns situated under at least 50 m of rock. Not only does this offer the most stable foundations possible for the tank, it also means that the rock walls and the rock behind are able to withstand high pressure – 30 40 atm or more – from the medium stored in the sealed tank without subsidence or notable deformations occurring.

One consequence of the design is that the surfacing adheres directly to the rock faces at all points and that is anchored to it at all points. Thus, any deformations due to increases in pressure etc. will be the same throughout and no instance of extra load are possible either at isolated points or in the plane of the wall, as is the case, for example, if proofing and insulation is in the form of prefabricated slabs assembled on site and with only sporadic contact with the rock face.

Thanks to the fact that the surfacing is anchored to the rock behind throughout and is in harmony with it, there is no risk of the surfacing collapsing due to, for instance, a vacuum in the tank. Overall anchorage of the surfacing also means that tanks of any size and shape can be proofed and insulated without the need for any changes in method,

Furthermore, with at least 50 m is sufficient to eliminate the risk of tanks being damaged by tremors, except in fairly small areas where there is a direct risk that faults may form.

In that the surfacing adheres to the rock race at all points, there is no room for air to accumulate behind and thus cause risk of explosion if gas were to leak through the proofing materials. The cracks in the rock around tanks are also sealed with epoxy, or alternatively are filled with water; in either case air cannot penetrate from the rock. Moreover, any gas leaks would be noticed immediately in the inspection tunnels outside the tank.

Before being filled with LNG, tanks are cooled with cold nitrogen gas as an inert medium. This eliminates any air which could give rise to fire or explosion between the tank and the ground surface at least 50 m above. There is thus more or less absolute safety from fire and explosions.

Stockholm, Sweden, June, 2015

We have already mentioned that the bedrock easily absorbs considerable quantities of internal overpressure. Cryo Cavern tanks will be designed for a maximum internal overpressure (including pressure from the fluid) of 5–10 atm.

This corresponds to an LNG temperature of -138 ºC (-210 ºF) and -126 ºC (-192 ºF). Given the insulation thicknesses in question, i.e. 30-50 cm, it would take a considerable time for so much heat to find its way from the rock to the stored fluid before pressures and temperatures mentioned were reached. Consequently, all pumps and controls could be out of action for a long time without a critical situation developing in the tank itself. Another consequence is the fact that the Cryo Cavern Method permits high pressures in the tanks, is also that all the risks of roll-over effects, which threaten all above-grade tanks, are totally eliminated.

When storing LNG, it is a good idea to lay all incoming pipelines from, for instance, a certain quay and outgoing pipelines to, for instance, an evaporation plant in tunnels under the ground. This avoids having shafts up to the ground level. Ingoing pipelines, pumps and controls can reach the tank through a vertical shaft from the tunnel housing the pipelines.

If all this is done, the storage facilities will be invisible from above and will thus have no noticeable effect on the surrounding country, while at the same time being impervious to activities in the environment around.

Theoretically speaking, one could actually construct housing or premises for light industry immediately above on LNG store of this type without encountering problems. In practice, however, it is doubtful whether this would be done, in view, for instance, of planning regulations.

The Cryo Cavern Method is eminently safe for the environment and that means, for instance, that the requirements providing for a protective zone around such storage plants can be made much less stringent.

Limitations of the Cryo Cavern Method

Obviously, the presence of good quality rock is an advantage when using the Cryo Cavern Method, in that food quality rock means that the costs of blasting, reinforcement and grouting are low. This, however, is absolutely not a prerequisite for the use of the method.

Today we have reliable methods whereby large rock caverns can be blasted out of fairly poor quality rock with no other complications than higher prices and slightly longer construction times. One such method is the Rib-in-Roc system, which has been developed parallel to the Cryo Cavern Method. There are, however, types of rock which are unsuitable for cavern stores, e.g. unconsolidated rock types containing loose, volcanic tuffs, loose highly porous limestone, porous types of Karst rock, expanding types (containing montmorillonite) and some highly metamorphic types, e.g. some types of mica schist.

An argument which might be used against the method could be that it takes slightly longer time to build underground storage facilities under ground than it takes to build facilities above ground. However, given the time perspectives applying for most gas transport projects, this should seldom prove to be of any practical significance.

Stockholm, Sweden, June, 2015

① LNG-CAVERN

② PIPE SHAFT

③ PIPE TUNNEL

④ PUMPING PIT

⑤ INLET PIPE LNG

⑥ CONCRETE BARRIER

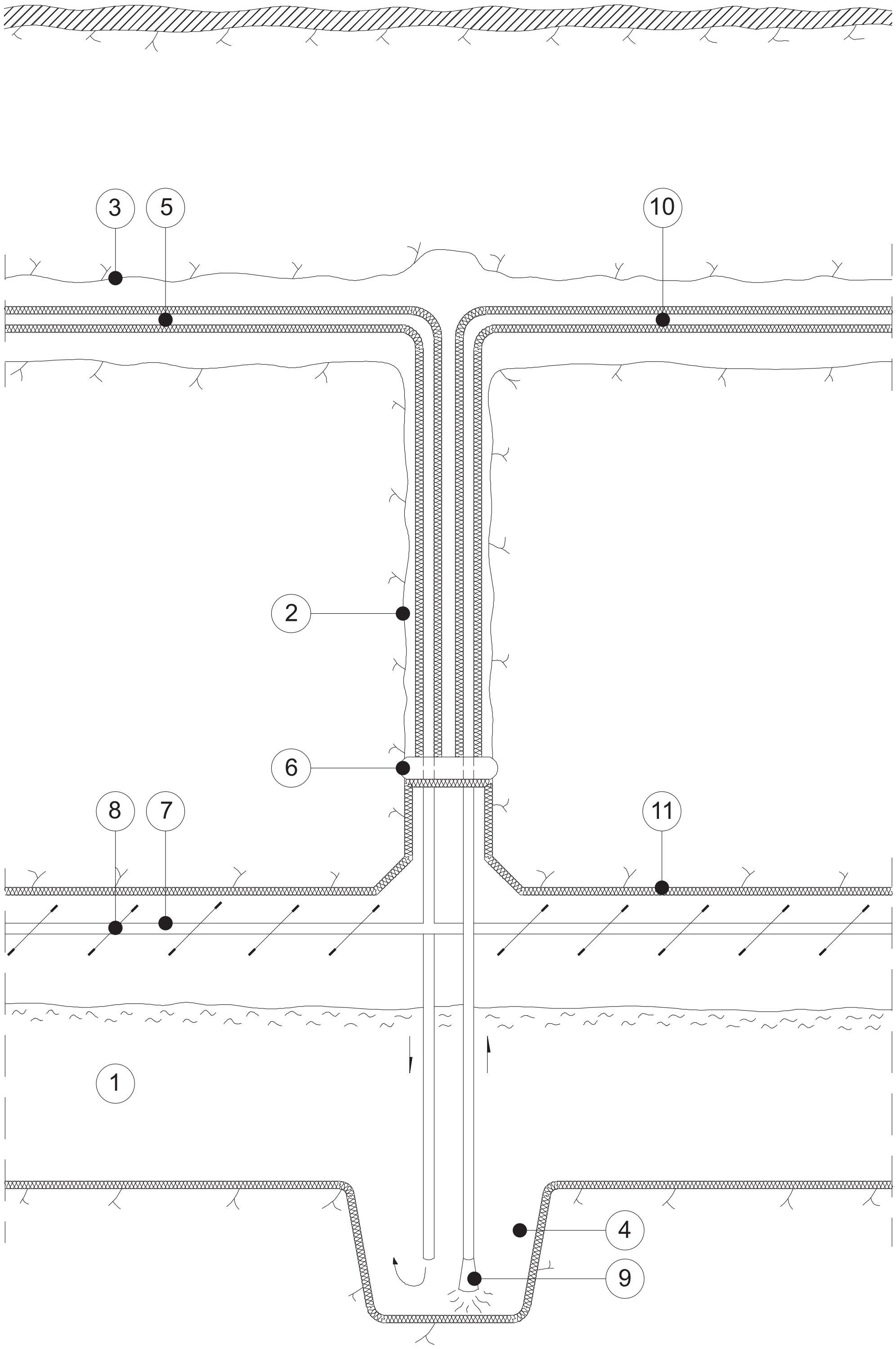
⑦ PIPE AT TOP OF THE CAVERN FOR COOLING OF THE GAS

⑧ SPRAY NOZZLES

⑨ LNG-PUMP

⑩ PIPE TO REGASIFICATION

⑪ INSULATION OF THE CAVERN



GENERAL DESIGN OF EQUIPMENT IN THE PIPE-SHAFT OF A LNG-CAVERN

Stockholm, Sweden, June, 2015

① LNG-CAVERN

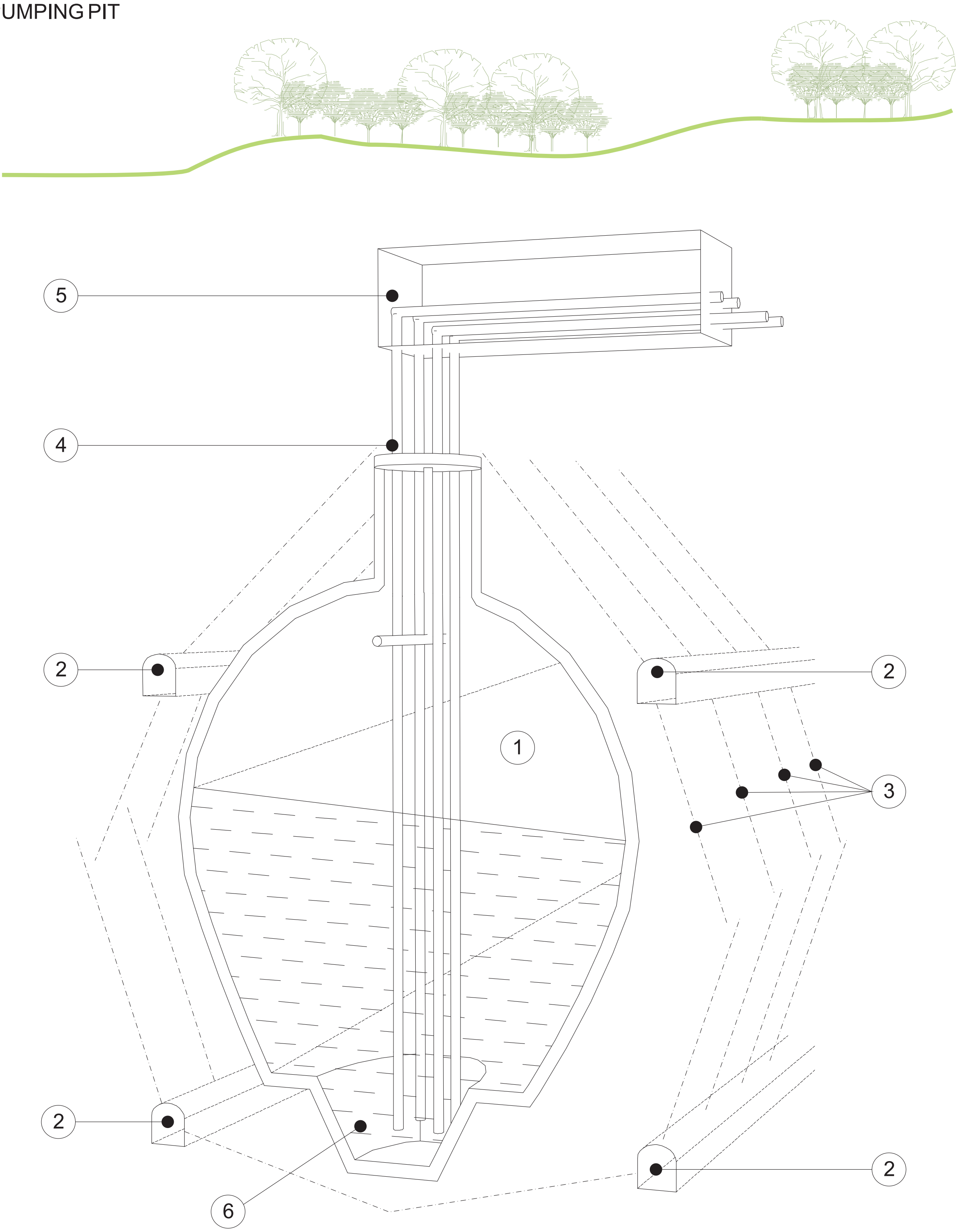
② INSPECTION TUNNELS

③ INSPECTION PIPE CURTAIN

④ PIPE SHAFT

⑤ PIPE TUNNEL

⑥ PUMPING PIT



LNG-CAVERN WITH PRINCIPAL INSTALLATIONS

Stockholm, Sweden, June, 2015

Economic aspects

Construction costs

Given good quality rock, which permits spans of 15 m or more without requiring extensive reinforcement, it may be assumed that the costs of constructing storage tanks in rock will be lower than in the case of above grade or in-ground tanks. Even with poorer quality rock, for which slightly more extensive reinforcement is necessary, (e.g. using Rib-in-Roc method) the construction costs for a Cryo Cavern plant may be competitive when compared to the conventional types. There are in addition several other advantages which have a direct or indirect positive effect on construction costs.

- º Less demand for what is often expensive land for work precincts and safety zones.
- º Storage facilities can be provided closer to consumer centers.
- º Applications for building permits will be dealt with more rapidly by the authorities, in that the system is kind to the environment and discreet, thus meaning less or no inconvenience to the local population or those using the land around.
- º Larger storage plants can be constructed below ground than above, thanks to the fact that the Cryo Cavern Method eliminates the risk of fire or explosions.

Operational costs

The main item on the list of operational costs for tanks is in most cases the re-condensation of the evaporated gas. In the case of above-grade tanks, evaporation is a more or less constant process throughout the life of the tank and is dependent upon the outside temperature.

The ambient temperature, i.e. the temperature of the rock, around most insulated underground tanks is +5 - 15 ºC (+40 – 60 ºF), i.e. approximately the same as the mean annual temperature in the places concerned.

As the rock around the underground tank is cooled, heat leakage from the rock to the tank diminishes and thus the amount of evaporation (after 20 -30 years around 2/3 of the original evaporation rate will remain). The improvement in the operational budget thanks to diminished evaporation is of very great importance in ports from which the gas is shipped and in stores set up to even out seasonal variations where all evaporation represents a direct item of operational cost.

Maintenance costs

All details of the construction of LNG storage plants using the Cryo Cavern Method – i.e. pilot studies, location and design of rock caverns, accurate and careful blasting, grouting methods, application and inspection of proofing and insulation – are designed to ensure the durability of each tank and thus the greatest possible operational safety along with low maintenance costs.

As extra high safety factors are built into the design of the plastic surfacing, the entire plastic covering may appear to be over dimensioned in terms of strength although this at the same time greatly reduces the risk of damage calling for repairs.

The plastic material will also withstand all conceivable permutations of natural gas, and thanks to the low temperature and absolute absence of ozone and ultra-violet rays it does not age.

Stockholm, Sweden, June, 2015

In view of all this, the need for any appreciable maintenance of rock caverns or of the proofing or insulation layers can be discounted. A certain amount of maintenance is, of course, necessary for mechanical and electrical equipment. However, with careful choice of systems and components plus careful assembly even these expenses can be kept at a negligible level compared to the corresponding expenses incurred by an above-grade arrangement.

As no discussion of economic aspects is of real interest without specifications of costs, we would add that price of an underground plant with a storage volume of 200.000 m^3 constructed using the Cryo Cavern Method in good quality rock in Western Europe is estimated to be 275-450 Eur/m^3 for a complete set of facilities, excluding evaporation plants and excluding the cost of land in industrial zones. Plants of the same size, but in poorer quality rock, requiring considerable reinforcement and smaller plants (e.g. with a storage capacity of 50.000 m^3) in good quality rocks are estimated to cost 350-600 Eur/m^3 storage space. It is impossible to say exactly what the operational and maintenance costs will be. However, they will always be lower for underground facilities than for the corresponding above-grade or in-ground facilities.

Development work

Laboratory tests and tests carried out on the pilot plants mentioned earlier have shown that the method is completely reliable. Tests were conducted using liquid nitrogen at temperatures down to -196 ºC and demonstrated that there are now plastics which can withstand such low temperatures with the requisite safety margins. Long-term tests on pilot plant No. 2 using LNG are to start in the autumn of 1977.

There are also plants for the construction of an even larger tank with a capacity of 5 – 10.000 m^3 in the autumn of 1977. Inspections of materials and works are in the hands of Lloyd's Register of Shipping, Industrial Services. The objective, in addition to monitoring the quality of the present plants is also to get the method, materials and design officially certified and approved.

Summary

Increasing attention is being paid to safety and environmental issues throughout the world when discussing decisions concerning construction and location of plants for the handling of energy. As we are being forced to an increasing extent to resort to vast reserves of energy to be found in this planet's natural gas deposits, it is both right and logical for reasons of safety and environmental protection to locate as much storage of LNG as possible below ground. But there are many other reasons for doing so, not least the economic, as the construction, operational and maintenance costs for underground storage are no greater and in many instances lower, than those for above-grade storage facilities. The Cryo Cavern Method presented in this paper is one of the few fully developed systems for underground storage to date – if not the only one – which has been so thoroughly tested and monitored as to represent a practical, safe and economical solution to the storage problem.

Stockholm, Sweden, June, 2015