UNLINED UNDERGROUND ROCK CAVERN STORAGE
FOR PETROLEUM AND LIQUEFIED PETROLEUM GAS

Prepared By

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FOREWORD

The oil industry in India is nearly 100 years old. As such a variety of practices have been in vogue because of collaboration/association with different foreign companies and governments. Standardization in design philosophies and operating and maintenance practices at a national level was hardly in existence. This, coupled with feedback from some serious accidents that occurred in the recent past in India and abroad, emphasized the need for the industry to review the existing state of art in designing, operating, and maintaining oil and gas installations.

With this in view, Oil Industry Safety Directorate (OISD) was established in 1986 staffed from within the industry in formulating and implementing a series of self regulatory measures aimed at removing obsolescence, standardizing and upgrading the existing standards to ensure safer operations. Accordingly, OISD constituted a number of functional committees comprising of experts nominated by the industry to draw up standards and guidelines on various subjects.

The present document on Unlined Underground Rock Cavern Storage for Petroleum & LPG is the new edition of the document prepared by the Functional Committee constituted for developing document. This document is prepared based on the accumulated knowledge and experience of industry members and the various national and international codes and practices. It is hoped that the provision of this document will go a long way to improve the safety and reduce accidents in the Oil and Gas Industry.

This document will be reviewed periodically for improvements based on the new experiences and better understanding. Suggestions may be addressed to:-

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In addition to the above, several other experts from industry contributed in the preparation, review and finalization of this document.
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UNLINED UNDERGROUND ROCK CAVERN STORAGE 
FOR PETROLEUM AND LIQUEFIED PETROLEUM GAS

1.0 INTRODUCTION

A cavern for storage of petroleum & LPG is a large cavity either existing or created underground. The caverns are considered the safest means of storage and beyond certain volumes, caverns are cost effective, compared to surface storages. In view of their inherent advantages, the underground caverns are being used by a number of countries for storage of hydrocarbons viz. crude oil, petroleum products both for commercial and strategic purposes.

Based on the experience from Scandinavian and other countries, underground cavern storage of crude oil, LPG etc. is much safer than the above ground storage such as steel tanks, pressurised spheres/bullets/ refrigerated tanks etc. Some of the major advantages of underground cavern storage are listed below:

- Underground storage is safe from warfare, sabotage, terrorist attacks, earthquakes, storms, etc.
- There is no risk of leakage
- The project is environment friendly
- Caverns require less land area than surface storage facilities
- The natural landscape and scenic beauty of the project area is not affected as the major installations are located underground as compared to above ground storage facilities
- They can be used as buffer/ strategic storage for the country
- For large quantity storage, underground cavern storage is cheaper as compared to above ground storage. Underground storage also needs little maintenance
- The underground storage have long life as compared to surface tanks

1.1 A number of methods exist for storing petroleum/ petroleum products underground and a few have been enumerated below:

1.1.1 Underground Rock Cavern Storage

A cavern is an underground facility consisting of one or more galleries excavated in rock either through a vertical shaft or by an access tunnel. Location and geometry of such facilities are selected based on availability of favourable geological setting and geomechanical properties of the rock. The stored product is prevented from escaping by the principle of hydrogeological containment. The cavern is located at a depth where the water in the surrounding rock creates a counter pressure exceeding that of the stored product, thus preventing its migration outwards.

Underground rock caverns are used for storing petroleum and liquefied petroleum gas (LPG).

1.1.2 Salt Leached Cavern Storage

Rock Salt usually occurs either as extensive bedded salt formations or as saltdomes. In such favourable salt formations, huge artificial underground caverns are created. These caverns are solution mined. Water is injected to the required depth below ground through a bore hole and controlled leaching is carried out by progressive dissolution of the salt formation. The resulting brine is removed and disposed either through surface evaporation or by injecting back into deep sub surface formations.

The caverns are usually cylindrical in shape – several hundred metres in height and several tens of metres in diameter – and may have a volume of several hundred thousand cubic metres.

The cavern shape and volume are determined by deployment of sonar survey. Cavern stability is monitored by periodic sonar surveys of its geometry and continuous surveillance of acoustic emissions (seismic monitoring techniques).
1.1.3 Acquifers and Depleted Fields

A porous and permeable geological formation (the reservoir) can be used to store natural gas provided it fulfills conditions by virtue of the geological setting such as:

a) The reservoir should be overlain by an impermeable stratum (the cover) to prevent any upward migration of the gas.

b) The formation with structural or stratigraphic control should ensure lateral containment, for example in the form of an anticline

c) The formation should be situated, at such depth (between 500 and 2000 m) so that the range of pressures attainable in the reservoir is compatible with that of the transport system.

The formation may be a depleted oil or gas field or an aquifer, which has never held hydrocarbons. For storage, the gas being compressed and injected in gaseous state into the reservoir, it displaces the water and occupies the pores in the rock.

1.1.4 Abandoned Mines

Disused mines can be converted to underground storage as long as these comply with the strict stability and leak-tightness criteria. However, some rehabilitation work may become necessary.

Large quantities of liquid hydrocarbons can be stored at reasonable cost using this method. It can also provide an attractive method for storing natural gas.

1.2 Cavern Containment Principle

The underground storage of liquid and gaseous hydrocarbons in unlined underground rock caverns is based on a principle of hydrogeological containment.

For the cavern to be leak tight (to ensure containment of the stored product), the pressure in the cavern (due to the product stored) at any point of the cavern has to be lower than the pressure of water in the rock mass at the corresponding point. However, for design purpose, in addition to the product vapour pressure, two other factors are also considered i.e., Safety factor and Shape factor when determining the maximum possible pressure in the Cavern.

Shape factor is the additional pressure required depending on the cavern dimension, cavern shape and storage arrangements, etc. Safety factor refers to a designed safety margin. The Cavern Containment Principle is shown in the Figure below.

Figure 1: Cavern Containment Principle

For the purpose of this standard, only unlined underground rock cavern storage for petroleum based on hydrogeological containment principle has been considered.

2.0 SCOPE

This standard lays down the minimum requirements on location, design, layout, operation etc of Unlined Underground Rock Caverns for Storage of Liquid Petroleum and Liquified Petroleum Gas. This standard covers the requirements for various aspects of the mined cavern and includes items like site selection, design criteria, construction methodology, construction safety, operation, inspection, maintenance and emergency plan.
The above ground facilities shall be in line with respective prevailing OISD standards.

3.0 DEFINITIONS

For the purpose of this standard, the following definitions apply:

Casing (for a rock cavern): Pipe or set of pipes that can be screwed or welded together to form a string surrounding the tubing connecting the cavern to the surface.

Cementing: Operation whereby a cement slurry is pumped and circulated down a well, through the casing and then upwards into the annular space between the casing and the open or cased hole.

Containment: Capability of a cavern to prevent migration of stored hydrocarbons.

Exploration: All technical activities connected with the investigation of a geological site.

Inadmissible: which is not permissible as per the prevalent laws/regulations.

Logging: Measurement of any physical parameter versus depth in a well.

Maximum Operating Pressure (MOP) (for a rock cavern): Maximum value of the pressure of any fluid contained in a cavern which can be accepted in normal operation and maintenance.

Modeling: Generating the image of a structure from the information gathered.

Numerical Simulation: Computer simulation of a system.

Permeability: Capacity of a rock to allow fluids to flow through its pores.

Petroleum: means any liquid hydrocarbon or mixture of hydrocarbons and any inflammable mixture (liquid, viscous or solid) containing any liquid hydrocarbon.

Liquified petroleum Gas: A mixture of certain light hydrocarbon predominately C3 & C4, derived from petroleum & natural gas which are gaseous at ambient temperature and pressure, may be condensed to a liquid state at normal ambient temperature by the application of moderate pressure and conforming to IS : 4576 or IS: 14861.

Porosity: Volume of the pore space (voids) within a formation expressed as a percentage of the total volume of the material containing the pores.

Saturation: Percentage of pore space occupied by fluid in the material.

Subsurface Safety Valve: Valve installed in tubing or casing beneath the wellhead for the purpose of stopping the flow of gas in an emergency.

Tubing: Pipe or set of pipes that can be screwed, welded or flanged together to form a string, through which fluids are injected or withdrawn.

4.0 STATUTORY ACTS & REGULATIONS

Construction of cavern, storage of petroleum in cavern and all associated facilities require specific approval from concerned authorities. Various acts and regulations inter alia applicable are as under:

- Environment Protection Act-1986
- Water (Prevention & Control of Pollution ) Act-1974
- Air(Prevention & Control of Pollution ) Act-1981
- Coastal Regulatory Zone( CRZ Act)
- Factory Act- 1948
- Petroleum Act-1934
- Explosives Act-1888
- Indian electricity act
- Manufacture Storage and Import of Hazardous Chemicals Rules-1989
- Hazardous Waste management and Handling Rules-2003
- Municipal corporation/ Town planner / Panchayat as applicable
5.0 GENERAL REQUIREMENT

5.1 Long-term containment of stored products

The storage facility shall be designed to ensure the long-term containment of the stored products.

This presupposes:

- adequate prior knowledge of the geological formation in which the storage is to be developed and of its geological environment;
- acquisition of all relevant information needed for specifying parameter limits for construction and operation;
- demonstration that the storage is capable of ensuring long-term containment of the stored products through its hydraulic and mechanical integrity.
- No other installation or activity shall affect the integrity of the containment & vice versa.

5.2 Environmental & Safety considerations

5.2.1 Underground

The storage facility shall be designed, constructed and operated so as to prevent any inadmissible impact on the environment including ground water table, contamination etc.

This presupposes that the surrounding formations have been identified and their relevant characteristics determined, and that they are adequately protected.

5.2.2 Aboveground

The storage facility shall be designed, constructed and operated so that it shall not cause any inadmissible ground movement at the surface and impact on the environment.

5.2.3 Safety

The storage facility shall be designed, constructed, operated and maintained so as to present no inadmissible risk to the safety of the personnel & property.

Suitable measures shall be taken to reduce the risk and consequences of blow-out and leakages.

5.2.4 Monitoring

In order to verify that the recommendations above are met, monitoring systems and procedures shall be implemented.

6.0 SITE SELECTION

A pre-feasibility study for selection of the site shall be carried out which shall include collection and reviewing of all available geological and hydro-geological data in addition to proximity to transportation infrastructure, dumping areas, population density and environmental concerns. It shall also include availability of land/ Right of way for approaching the storage site and pipeline route.

The detailed feasibility of the selected area shall be carried out once the site has been identified based on pre-feasibility studies. The detailed feasibility studies shall encompass extensive field investigation campaign, followed by analysis of on-site information both laboratory and numerical modeling so as to establish suitability of site. Based on the collected information and results there of, design of the proposed facilities shall be undertaken.

A list of BIS codes for underground civil works including investigations, laboratory & field testing, design & construction etc. is enclosed as Annexure-I. These standards or eqv. International standards / code of practices shall be followed.

Various elements of site selection are as given below:

6.1 Geological Site Characterisation
Site characterization shall include geological, geophysical, geotechnical and hydro-geological investigations & studies, so as to establish the geological and hydro-geological conditions, rock mass characteristics and in-situ stresses of the proposed site.

6.2 Geological Investigations

These shall include review of available reports and maps followed by geological field mapping.

The following minimum geological site characterizations shall be considered:

a) the type & nature of rocks and soils, including the litho stratigraphy.
b) presence and extent of weathering of rocks.
c) structural disposition of the litho types
d) Spacing & Orientation of discontinuities
e) Condition of discontinuities including roughness, separation, weathering and infilling
f) Major & minor faults
g) Intact rock/Rock Mass condition
h) Surface and ground water conditions
i) Quality of ground water.
j) Geological hazards
k) Presence of hazardous gases viz. CH₄, H₂S, SO₂, CO₂ etc.
l) Presence of radioactive minerals

Representative samples shall be collected for the purpose of correlation to mapped formations and for subsequent laboratory analysis which shall include but not limited to, petrography, sonic test, geo-chemical analysis, rock-product compatibility test and radioactivity analysis.

Engineering geological investigation shall be supplemented by geophysical and geotechnical investigations. Information collected during the field campaign shall be represented on engineering geological maps.

6.3 Geotechnical Investigations

Geotechnical investigation includes vertical and inclined core holes located suitably to detect geological profile. The depth of investigation shall extend at least 10m below the anticipated invert of the cavern. Core Recovery, Rock Quality Designation(RQD), discontinuities spacing, joint condition, orientation, dip of strata, cavities, fissures, the occurrence of seams, gouge material etc shall be duly recorded. The engineering geological map shall be prepared with the interpretation of the geotechnical findings. This information shall be used to establish the layout of the rock caverns.

For orientation of the cavern, hydro-fracture stress tests shall be carried out to measure the maximum and minimum horizontal in-situ stresses. The spacing and depth of the measurement shall be kept so as to properly assess the stress profile at and around the cavern depth.

Laboratory tests shall be carried out on intact rock samples as listed in Annexure-II.

6.4 Hydro-Geological Investigations

To establish the permeability profile and seepage water quantity assessment in the caverns, water pressure tests and pumping interference test shall be carried out. Water pressure tests shall be conducted in selected sections of the borehole using either inflatable or mechanical packers. The kind of water pressure test depends on the ground water and rock mass conditions.

The water table fluctuation shall be recorded during investigation campaign. Meteorological statistics such as average rainfall and its impact on water table during pre & post monsoon in the area shall be considered to assess the ground water recharge conditions.

6.5 Geophysical Investigations

After preliminary site selection based on geological and hydro-geological
conditions, detailed geophysical investigations shall be carried out for the selected sites. Geophysical investigations include Seismic refraction, electrical resistivity and geophysical well-logging i.e. sonic, temperature etc. as applicable. The investigation method shall be finalized based on the geological frame work of the site.

6.6 Site Selection Criteria

Based on the data obtained from the investigation campaign and desk top studies, the following criteria shall determine the selection of the site:

6.6.1 Rock Mass

The cavern host rock shall be of low permeability and substantially free of fractures to minimize leakage. The rock shall be competent enough requiring limited artificial support to the cavern.

The rock shall be uniform and shall have little or no jointing, faults and other discontinuities.

6.6.2 Hydro-geological consideration

Availability of sufficient water table to maintain a positive hydrostatic head above the storage cavern shall be ensured.

6.7 Disposal Plan

Identify safe & environment friendly site for temporary storage & final disposal of large volumes of rock to be excavated.

7.0 DESIGN CRITERIA

7.1 Basic Information:

For any storage cavern project, the following information shall be taken as pre-requisite:

- knowledge of geological formation and geological environment
- information about the various parameters pertinent for construction and operation
- type and properties of the product to be stored
- geographical constraints of the area
- environmental consideration and restrictions within the area
- various natural resources / facilities available at the location or the region
- Risk Assessment, Environment Impact Assessment & Hazop studies
- emergency procedures

Design Principles

The facility shall be designed to handle the product stored and to control the entire process from receipt to evacuation of the product from the cavern. The design shall take into consideration the complete range of operating conditions (Pressure, temperature, corrosion, water seepage etc.,) that the facility could encounter. Each individual part of the facility shall conform to the applicable standards.

The design shall only use established methods for analysis and calculations.

The design shall also incorporate emergency procedures.

All design shall be properly documented and shall be based on written procedures and shall be carried out by competent personnel/companies. The design shall comply with the safety and environmental requirements of the location.

The cavern volume shall also include the design volume of hydrocarbon and the vapour phase volume, which shall be at least 3% of the volume of the hydrocarbon. An additional volume equivalent to at least three days seepage water volume shall also be provided.

In addition to the above, the shafts shall also be designed to ensure minimum seepage into the underground works during the entire excavation phase.

All pipelines and fittings shall be adequately protected against corrosion by anti corrosion coatings and / or cathodic protection system.
Provision shall be made to ensure that seepage water, prior to disposal, does not exceed the specified permissible limits as per Water (Prevention & Control of Pollution) Act 1974.

Risk Assessment studies covering the underground and above ground facilities shall be carried out.

7.3 Depth

The cavern shall be located adequately below the groundwater table to ensure that sufficient hydraulic potential is available around the storage to confine the product within the cavern. The conditions created around the cavern shall be such that in spite of the seepage of ground water into the cavern the hydro static head will never get depleted. It may be necessary to enhance the natural hydro-geological flow pattern around the cavern by providing specially designed water curtains.

The cavern shall be located at a depth below the ground water table, corresponding to the maximum operating pressure of the stored product and an additional minimum hydraulic margin (safety margin + shape factor) of 20m of water head. However, for LPG, minimum hydraulic margin shall be kept as 30 m.

7.4 Shape / stability

The shape of the cavern shall be decided on the geological setting in which it is to be located. The geomechanical characteristics and the in-situ stress of the rock mass are the most important inputs for the determining the cavern shape. The shape of the cavern could be subject to change because of the actual rock conditions encountered during excavation.

The layout, cross-sections, pillar widths, intersections shall be designed in a manner that would ensure the stability of the cavern for its entire life.

The designer shall theoretically demonstrate the stability of the cavern through numerical simulations for both static and dynamic cases and address the impact of seismic activity in the design.

7.5 Inter distance

New cavern storage facilities shall not be located less than 50 m from other active, inactive or abandoned storages or excavations. Alternatively, approval shall be taken from the concerned authorities after ensuring structural stability, non-migration of products and establishing the same thru proven modelling/ risk assessment.

Inter distance of all above ground facilities shall conform to applicable OISD standards.

7.6 Operating Parameters

7.6.1 Temperature

For LPG storage, the geothermal temperature of the rock and the temperature gradient shall be considered for determining the depth of the cavern.

7.6.2 Maximum Pressure

The Operating Pressure is a consequence of the following:

- Characteristics of the product to be stored.
- Geothermal temperature of the rock at the depth of the cavern.
- Hydro geological conditions around the cavern.

The range of vapour pressures for products like LPG could vary considerably with the product blend and care shall be exercised in determining the operating pressures as the conditions could vary over a period of time. The possible change in operating philosophy shall also be assessed.

The Maximum Operating Pressure shall be based on the most severe conditions.

For the selected Maximum Operating Pressure, the hydraulic containment
shall be established theoretically by numerical modelling and simulation.

7.6.3 Lines & Fittings

All connections to the cavern shall be defined during the design stage and shall include at least the following:

- Product inlet lines;
- Product outlet lines;
- Instrumentation and monitoring lines and cables;
- Seepage water removal lines;
- Vent line(s).

The location of the pipelines and cables shall be spelt out (Operation shaft, access shaft or boreholes). All casing carrying the pipelines into the cavern shall be tightly embedded in a concrete plug built near the exit of the cavern.

Secondary seal /expandable packers to be provided.

The casings carrying the pipelines shall be protected against corrosion in case of casings installed in the shafts. The material selected for the casings shall withstand the highest pressures that could be encountered during worst case scenarios.

In case of pipelines installed in boreholes, the methodology of avoiding leakages from behind the casings shall be clearly spelt out by the designer.

7.6.4 Instrumentation

Following instruments / fittings shall be provided:

i) Two water level measurement gauges of independent operating mechanism with inter-lock with water pump for starting and stopping. The audio visual alarm of these gauges shall be provided in control panel. Interlock with product pump, in case, water level going beyond max. permissible level, the product pump shall trip.

ii) Two product level measurement gauges with independent operating mechanism with High Level Alarm set at 95 %. The audio visual indication shall be provided on control panel. Further, High High Level alarm shall not be set at more than 97 %, with interlock with incoming LPG pumps. On actuation of High High Level alarm, the pumping in cavern shall stop and all incoming shut down valves shall close.

The capacity of seepage water pump shall be commensurate with maximum seepage rate envisaged in the design. 100 % identical stand by water pump shall also be provided . In case more than one pump is used, 50 % standby pumps shall be provided.

Temperature and pressure gauges representing the entire cavern (as envisaged in design).

Minimum 2 nos. of Safety valves of adequate capacity shall act as impulse to initiate shut down of cavern.

7.6.5 Shut Down Valves

Each emergency shutdown valve shall be capable of activation from the on-site control center as well as from control room, in addition, from field location which shall be easily accessible during emergency.

Each emergency shutdown valve shall be an automatic fail safe device that automatically closes for pre-set conditions.

Each emergency shutdown valve shall be closed and opened at least monthly.

Each emergency shutdown valve system shall be tested at least twice each calendar year at intervals not exceeding six months. The test shall consist of activating the actuation devices, checking the warning system and observing valve closure.

If an emergency shutdown valve system fails to operate as required, the cavern operation shall be immediately suspended.

8.0 CONSTRUCTION
The construction plan shall be defined at the design stage and shall include the following:

- Method of access (whether shaft or inclined access)
- Method of ensuring rock remains saturated with water during construction.
- Method of excavation (drill & blast, road runners etc)
- Type of rock support, structural reinforcement and grouting works required;
- Method of isolating the cavern (location of concrete plugs)

Water curtain bore holes shall be charged at least 20 Metres ahead of the main cavern excavation face.

The excavation method shall be designed to handle/ accommodate the following:

- Access of men and material into the cavern during construction
- Movement of all equipment required for the underground works
- Removal of muck

In case of the depth of access shaft (vertical) exceeds 40 m, a properly guided hoisting mechanism with safety contrivance shall be provided.

The construction activities shall comply with best engineering practices and also OISD-GDN-192 as applicable.

9.0 MONITORING PLAN

Cavern monitoring can be classified as follows:

i. Hydro Geological Monitoring
ii. Seismic Monitoring
iii. Operation Monitoring

9.1 Hydro Geological Monitoring

Hydro geological monitoring shall be carried out during pre-construction, construction and operation of rock caverns to ensure that there is no impact on the hydraulic safety of the caverns at any point of time. Equipments for monitoring during construction shall include piezometers, pressure cells, underground pressure gauge holes, flow meters, and equipment for monitoring seepage water. However, piezometers and pressure cells shall also form part of the permanent monitoring system to be used during operations of the storage facility. Additionally, temperature monitoring shall be carried out during commissioning.

The hydro-geological boundary shall be defined in advance to monitor the ground water table. The land use in hydro geological boundary shall not adversely affect the cavern containment principle.

A buffer zone of at least 200 m shall be considered. No heavy blasting shall be allowed in buffer zone which can develop any fissures and cracks which propagates to the storage area.

Hydro geological monitoring of the rock caverns during construction shall include the following:

- water levels in piezometers, monitoring wells and shafts
- hydraulic potentials by pressure readings from pressure cells
- pressure on underground pressure gauge holes
- the flow rate of water injected and pressure in individual water curtain bore holes
- seepage for individual sections of the underground works
- chemical and bacteriological analysis of water samples from piezometers, water curtain and seepage water.
- rainfall, tide levels, etc.

9.1.1 Piezometers

Piezometers shall consist of boreholes drilled from surface and equipped for water level measurements and sampling. The piezometers shall have either single or double completion equipment. All piezometers shall be equipped with galvanized tube slotted at the level of the piezometric window. Inside diameter of borehole shall be at least 50mm.

9.1.2 Pressure Cells
Pressure cells shall be installed in especially drilled holes in order to measure the pore pressure around the cavern. Pressure cells boreholes can be vertical or inclined. The range of pressure measurement shall be suited to the depth below water level.

Underground pressure gauge holes shall be drilled from the access tunnel, water curtain tunnel and the main storage galleries. These should be either vertical or inclined. The equipment for the pressure gauge hole shall include mechanical packer, isolation valve, main valve and a pressure gauge.

9.1.3 Analysis of Water Samples

Analysis of water samples shall consist of physical analysis, chemical analysis, bacteriological analysis and dissolved gas analysis in line with prevalent regulations.

9.1.4 Other Requirements

All water pumped out from the underground works shall be measured on a daily basis.

9.2 Seismic Monitoring

As part of operational requirements permanent seismic monitoring system shall be put in place to record all the disturbance in the ground round the clock and for the long term stability of the facility. The ground disturbances could be due to various reasons, viz., movements due to proximity to faulted zones, structural discontinuities, weak zones developed during blasting, movements due to displacement of rock bolts, etc. All these movements may lead to major hazards and require continuous monitoring.

Seismic monitoring system includes planting of geophones, installation of seismographs, preamplifiers, filters, analog and digital recorders compatible to computers and acquisition/processing software. The software shall be equipped with a built-in alarm system that is always on the job and shall alert personnel to changes in pressure/stress, within the cavern and to prevent the loss of product.

The entire monitoring shall be through a network of transducers and each location of transducer shall give the magnitude and direction of disturbance, so that the movements in different directions can be computed. The transducers shall be cemented into the borehole and shall be installed from the water curtain gallery through the instrumentation well.

The system shall be designed to detect and record seismic events equivalent to a rock fall of 0.5m³ from the top of any gallery to an accuracy of location better than half the diameter of the main storage gallery.

9.3 Operation Monitoring

The operating pressure of cavern shall be measured continuously at the shaft and within the cavern. the pressure differential between the shaft pressure and the pressure in the cavern shall be calculated

The MOP shall not be exceeded.

Wellhead pressure, product level, water level, and operating status of each cavern shall be monitored.

9.3.1 Inventory

Product injected into or withdrawn from the storage facility shall be metered. The measurements shall be counterchecked by means of the product level measurement in the cavern.

The operator of the storage facility shall investigate any variation in inventory and the reasons for the variations. In case of variations of stock due to migration of the stored hydrocarbon / seepage, the operator shall undertake a study to review the integrity of the storage system.
10.0 TESTING AND COMMISSIONING

10.1 General
- Testing and commissioning shall be based on written procedures and performed by skilled personnel.
- Casings shall be pressure tested before commissioning.
- Safety devices shall be functionally tested prior to operation.

10.2 Air pressure test
- After construction, the cavern shall be filled with compressed air to a test pressure at least equal to the MOP to demonstrate gas tightness. The test pressure shall not jeopardize the ability of the groundwater level to maintain the hydraulic containment.
- The rate of depressurization shall be such that it should not jeopardize the hydraulic containment principle.
- During air test, all piezometers around the cavern facilities shall be monitored and any abnormal fluctuation shall be analysed.
- When several caverns are involved, each cavern shall be pressurized in turn, the other caverns being kept at atmospheric pressure.
- A test report shall be generated.
- All relevant data concerning the tests (such as test records or quality assurance documentation) should be made available before acceptance.

10.3 First hydrocarbon filling
- The first product filling shall take place only after successful completion of the air pressure test.
- Purging with inert gas before first filling
- During the first product filling, the part of the caverns where the product is in the vapour phase shall not lead to any explosive mixture with air.

Typical testing and commissioning procedure for LPG caverns is attached as Annexure – III.

11.0 OPERATION AND MAINTENANCE

11.1 Operating principles
- The Operating manual shall be prepared based on approved operating instructions, safety procedures, best practices and experiences of operating similar facilities. The manual shall cover start-up, normal operations, emergency conditions, shutdown and maintenance operations.
- The management should employ operating staff of suitable ability and experience. The management shall ensure that they are trained to carry out their duties in a safe manner.
- Safety training shall be given and updated as necessary.
- Safety audits shall be conducted on a regular basis.

11.2 Maintenance

11.2.1 Maintenance procedures
The operator of the storage facility shall:
- Possess approved maintenance procedures, including procedures for cavern maintenance;
- Maintain the gas storage facilities in compliance with such procedures;
- Keep records necessary to administer such procedures;
- Update such procedures as experience dictates and as changes in operating conditions require.
- Execute routine inspection and maintenance schedule for surface
and subsurface safety equipment shall be prepared

- Periodically check all safety devices to ensure reliability of functioning properly.
- Carry out periodic instrumentation calibration checks shall be carried out, at a frequency depending upon the required accuracy. Special attention should be paid to gas detectors, legal metrology equipment and cavern level instruments, which can be used to cross-check each other.

12.0   EMERGENCY PROCEDURES

The operator of the storage facility shall:

- Possess established emergency procedures, including procedures for the safe operation or the shut-down of the storage facility or parts thereof, in the event of a failure or other emergency, and safety procedures for personnel at emergency site;
- Possess documented emergency procedures to deal with product releases, including mitigation of the release, notification and protection of operating personnel, notification and protection of the public, and communications with community and regulatory bodies;
- Test the procedures for operating personnel at frequencies determined by such factors as the condition of the system and the population density;
- Document the test results and recommendations;
- Possess a programme in place to demonstrate that personnel are familiar with the emergency procedures.

13.0   INTEGRITY MANAGEMENT

13.1 A comprehensive manual containing program & practices shall be developed for existing cavern to manage cavern integrity taking into consideration various consequence due to operations / failures.

13.2 The integrity management program framework shall take into consideration continual / periodic assessment & an evaluation process as to its effectiveness of the current health of the cavern & associated facilities to prevent any failure in future.

13.3 To maintain safe operating conditions in case of an adverse condition detected, cavern should be shut down until the required repairs are completed and clearance for operation is given.

13.4 Corrosion monitoring shall be periodically carried out. In case, the values are beyond acceptable limits as given in design, necessary corrective action be taken.

13.5 The integrity assessment during the lifetime shall consist of an initial (base line) & continual assessment.

14.0   CAVERN CLOSURE AND ABANDONMENT

A rock cavern which has been inactive for three (3) years or longer shall be considered to have been abandoned and shall be plugged unless otherwise authorized by environmental authority. Plan for plugging the cavern shall be prepared for submission to appropriate authority.
LIST OF LABORATORY TESTS

The laboratory tests on intact rock samples shall include, but not limited to the following:

1. **Index Tests**
   - Specific Gravity
   - Bulk Density (Wet/Dry)
   - Water Absorption
   - Water Content
   - Porosity
   - Slake Durability
   - Swelling Index
   - Hardness & Abrasivity

2. **Strength Tests**
   - Point Load Test
   - Unconfined Compressive Strength
   - Tri-axial Compression Test
   - Tensile Strength

3. **Compressibility Tests**
   - Elastic Modulus and Poisson's Ratio
   - Uniaxial Compression
   - Dynamic Modulus

4. **Petrography-Thin Section Study and Rock Composition**
5. **Chemical Tests**
6. **Geochemical Analysis**
7. **Water Quality**
8. **Permeability**
9. **Joint Roughness Coefficients-Kn and Ks**
10. **Sonic Velocity**
# Annexure - II

## BIS Codes

(Underground Structures in Rock-for reference)

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**Design & Construction**

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1. GENERAL

Before commissioning the storage facility, the gas-tightness of the storage galleries must be tested with compressed air according to a procedure developed for underground rock caverns to meet the same requirements as aboveground pressure storage vessels.

The test consists of recording pressure changes over time which must coincide (to within the experimental error) with the pressures calculated for a non-leaking cavern. Pressure changes must be caused solely by air temperature variations in the cavern, air dissolved into the seepage water and, if applicable, water level changes in the pit.

The test is performed before filling the cavern with LPG for the first time.

2. DESCRIPTION

The test consists of injecting compressed air. In the case of two caverns, injection of compressed air into the second cavern can be done, totally or partially, from the first compressed cavern.

Once the test pressure is reached in the cavern temperatures are allowed to stabilise. This waiting period is minimized by using water coolers to bring the injected air as close as possible to the initial cavern temperature. The test can start after a period of stabilisation. The cavern is considered to be stable when no temperature recorded by any cavern transducer is changing by more than 0.1°C per day. This activity typically requires four (4) days.

The cavern test pressure is set with reference to:

a. hydrogeological parameters:
   - hydraulic potential at the cavern roof
   - shape factor
   - hydraulic safety margin

b. operating conditions:
   - maximum working pressure
   - safety valve settings

3. ACCEPTANCE TEST PROCEDURE

3.1 Instrumentation

Pressures and temperatures are recorded every hour during the test.

The specific test instrumentation required is as follows:

1. Three-wire platinum Resistance Temperature Detectors (RTD), resistance 100 ohms at 0 °C, tolerance 1/3 of IEC Standard 751 class B, i.e. +0.1 °C at 0 °C (installed according to attachment).
2. Pressure Standard with digital display for measuring pressure at top of vent, repeatability 50 Pa at test pressure, with calibration certificate.
3. Digital barometer with an accuracy on measured values of 20 Pa, with calibration certificate.
4. Real time acquisition and recording system (Programmable Logic Controller).
5. Microcomputer for test control, data storage and data reduction.
6. One instrument measuring temperature in test shed, accuracy ± 0.1 °C.
7. One RTD in the vent line at wellhead to measure the air temperature during compression, accuracy ± 1°C.
8. Dial pressure gage, scale 1.5 MPa, accuracy 5 kPa, at wellhead.

The temperature transducers are installed after final cleaning of the galleries, just before closure of the access works.

Each instrument cable is brought out to the surface in a single length without splices or junction boxes, through dedicated casing provided in the operation shaft. The 3 wires of each RTD (item 1) shall have the same impedance, lower than 10 ohms. Each RTD cable is shielded and the 3 wires of each cable are twisted.

A shed sited as near as possible to the shaft is used as the control centre for the test. The shed will have a solid floor and the temperature inside will be controlled around 20°C. Stability of the shed against vibrations must be ensured and circulation of heavy vehicles around the shed shall be restricted.

The instrument cables are connected to the acquisition and recording system in the shed. All the cables shall be clearly labeled.

For cavern pressure measurements, temporary piping is installed from the equilibrium casing to the control centre.

3.2 Test Procedure

The steps in the pressure test are:

- prepare the cavern(s) and fill access tunnel with water
- pressurize the cavern(s) with air
- allow temperatures to stabilize
- run the test

3.2.1 Preparation of Cavern(s)

When all construction works in the cavern(s) are finished (including final plugs), a designed volume of water is injected in each cavern and then pumped out in order to:

- Fill the geometric traps to get an accurate value of water seepage flowrate during the acceptance tests;
- Check water level measurement equipment,
- Check that the water seepage pumps work properly,
- Check that the product pumps work properly.

Alternatively, the pumping of the water seepage can be stopped during a sufficient period of time in order to have 3000 m3 of water in the cavern.

Before starting the cavern compression, some information is required:

- The geothermal temperature inside the cavern (from the RTDs)
- The water seepage flowrate,
- The cavern volume vs depth curve (from the galleries photoprofiles), including the sump and the pit.

3.2.2 Access tunnel / Access shaft water filling

After the storage cavern(s) cavern(s) is (are) closed, all the access (operation shaft, access shaft, access tunnel) begin to be filled with bacteria free fresh water before the compression of the cavern(s). The water shall be injected at a flowrate sufficient to assure that the rise in level is not less than 10 m/day (i.e. 75 m along the access tunnel). When the water reaches a level of 25 m above the crown of the cavern, the compression of this cavern can begin, provided hydrogeological parameters are satisfactory.
During the simultaneous access tunnel / access shaft water filling and cavern compression, the height of water above the crown of the cavern will be set at 102 % of cavern pressure + 25 m.

3.2.3 Cavern Compression

Air is supplied by a bank of compressors, for 24 hours continuously until the cavern pressure test.

The compressed air is injected through the vent line, and the number of compressors shall be adapted to produce a pressure increase in the cavern around 1 kg/ cm² per day. A backup compressor is mandatory.

This compression rate may be reduced in the event of abnormal evolution of the pore pressure in the rockmass, and/or the piezometric behaviour.

Air is supplied from a bank of compressors. Wellhead air temperature is kept close to the geothermal temperature with variation no more than 2 °C, using temporary air cooling system.

The cooling system may be required to start or stop several compressors at different times, in order to meet the above requirements and to minimize the stabilization time.

During this stage, the following readings are taken every hour:

- cavern pressure, from the pressure standard
- atmospheric pressure, on digital barometer,
- compressed air inlet temperature,
- temperatures from cavern RTD's,
- test room temperature,
- volume of water pumped out of the cavern using the meter at the wellhead, and at the same time, water level in the pit, pressure cells (with an automatic system, the readings of the pressure cells are taken every hour).

The control of the air inlet temperature shall be performed by a thermometer just after the air cooling system, and by an RTD on the vent line just before the wellhead.

Once daily, piezometer levels and water levels in access works (shaft and/or tunnel) are recorded. (The frequency of the piezometer level records can be adjusted during the compression phase).

For cavern pressure measurement, the connection shall be made to the pressure measurement (equilibrium) line of the cavern, not to the vent line.

During the test, it is necessary to have the following information :

- status of the seepage water pump(s) : in function or not in function (signal ON/OFF)
- level switch E+H information (signal ON/OFF),

3.2.4 Stabilization Stage

The temperature stabilization stage lasts about four days, and is considered complete when no transducer records a temperature change in excess of 0.1 °C per day and per RTD.

The following are recorded every hour:

- cavern pressure, from pressure standard
- atmospheric pressure, from digital barometer
- cavern temperatures from RTDs,
• test room temperature,
• water volume pumped out of the cavern and water level in the pit.

Daily readings are taken from the piezometers and water level in the access works (shaft and/or tunnel). The frequency of the piezometric readings can be adjusted during this phase. Readings are taken hourly from the pressure cells in case of automatic system.

In case of transient phenomena in relation with the hydrogeology, it will be necessary to increase the duration of the stabilization phase.

If cavern pressure measured at shaft head goes below the test pressure, it will be necessary to restart compression and to repeat the stabilization stage.

3.2.5 Testing time

The test is run continuously for not less than 100 hours. Its duration is long enough to detect any pressure drop in excess of 5 mm of Water Column in the cavern.

The following parameters are recorded hourly at constant water level in the sump:

1. Cavern pressure, atmospheric pressure, cavern temperatures (RTDs), test room temperature, test shed temperature to correct cavern temperature recordings if required sump water level (nominally the level at which the seepage water pump stops) volume of water pumped out of the cavern.
2. All piezometer levels and water level in access works are recorded daily, the pressure cells are recorded twice a day. The frequency of these readings can be adjusted on the site.

4. PRELIMINARY OPERATIONS BEFORE START UP

At the end of the gas-tightness test, the cavern(s) contains pressurized air.

It is necessary, before the first LPG filling in the cavern(s), to inert the cavern(s) to avoid creation of an explosive mixture.

As soon as the calculations from test measurements have proved the gas-tightness of the cavern, preliminary operations before start-up can commence.

The procedure is as follows:

• fill the cavern with water to a level to be defined according to actual cavern geometry given by profile scanning
• inject nitrogen in the remaining air space with simultaneous removal of water
• fill with water up to the same level to flush out the air-nitrogen mixture.

After this procedure is successfully completed, the cavern will be ready to receive liquid propane or butane (with simultaneous withdrawal of water).

4.1 Water Filling

4.1.1 Water Quality

During the water filling operation, the cavern can be filled either with water from the natural environment (river, lake, sea ...) or with fresh water from a specific network (city water, fire system). For example, a mixture of seawater with fresh water can be used.

With natural environment source, the injected water must satisfy the following criteria:

• quantity of suspended material < 20 mg/1. This figure corresponds to maximum suspended material fixed by the LPG and seepage water pumps supplier (to be confirmed at Detail Design
stage);

- maximum bacteria content:
  - total aerobic bacteria  < 1000 bacteria per ml
  - total anaerobic bacteria  < 1000 bacteria per ml
  - sulphur reducing bacteria      = 0  "  "
  - slime forming bacteria            = 0  "  "

In case of water with silt content greater than 20 mg/l, a filtering system is required. In case of water containing bacteria, a sodium hypochlorite treatment is required.

4.2 Procedure

4.2.1 Single cavern

The water is injected into the cavern through a metering system (accuracy < 1 %) via the filling line. The water flowrate does not exceed 1000 m³/h.

The upper water level in the storage is defined according to the cavern crown geometry. Ultimately a small volume of air remains under the crown. This small volume, called free air volume shall be determined by a specific operation just before the end of the water filling:

A known volume of water (installation and supply of a flowmeter, accuracy 0.1 %) is injected in the cavern for about two hours at a rate not exceeding 50 m³.

The pressure inside the cavern is the test pressure at the beginning of the water filling. This pressure is lowered to the minimum operating pressure at a pressure drop around 1 kg/cm² per day.

The air is evacuated through the vent line (the air flow is controlled by a valve fitted on the vent line) down to minimum operating pressure at a maximum rate of 1 kg/cm² per day. Silencer to be used to bring down noise below permissible levels.

4.2.2 Two Caverns

Identical procedure but optimisation is possible.

During injection of water in cavern A, the air removed can be injected in cavern B until the test pressure is reached in cavern B.

During this phase, cavern B acceptance test can be completed. If the test and calculation show that cavern B is gas-tight, depressurization can commence at the rate mentioned above.

Cavern B can be filled with water coming from cavern A, during the dewatering and first LPG filling of cavern A.

4.3.3 Measurements and controls

The water filling provides an opportunity to cross-check the volume/level calibration curve drawn from the profiles scanning.

During the water filling phase, the following measurements will be performed every two hours:

- the volume of water entering the cavern using the meter on the water filling pipe
- the water temperature near the filling point at wellhead,
- the temperature in the cavern using the temperature probes installed in the cavern,
- the water level in the cavern with equipment used for measuring the LPG level during operation,
• the cavern pressure with pressure standard,
• the atmospheric pressure with digital barometer.

At the end of this phase, the exact free air volume of the cavern, corresponding to the upper water level in relation with the cavern crown geometry, is performed according to a specific operation.

All piezometer levels, pressure cell readings and water level in access works are recorded daily.

4.4 Injection of Nitrogen

Before the initial filling with LPG, the volume of air remaining in the cavern will be inerted by injecting gaseous nitrogen at ambient temperature.

4.4.1 Procedure

Nitrogen or other inert gases like CO2 is injected through the vent line, with simultaneous removal of water at a maximum rate permitted by the water pumping and such the maximum pressure variation in the cavern is lower than 1 kg per day.

The quantity of nitrogen to be injected shall be 1.5 times the free volume of air in the cavern, in order to reduce oxygen content to 8%.

The required equipment for the nitrogen injection shall be:

• vaporiser, to transform the liquid nitrogen into gaseous nitrogen,
• flowmeter and thermometer, to follow the quantity and the temperature of the injected nitrogen.

4.4.2 Measurements and Controls

Record every two hours:

• cavern pressure shown on pressure standard
• atmospheric pressure on the digital barometer
• water level in the cavern,
• water volume evacuated during the procedure
• injected nitrogen volume,

and once a day all piezometer levels and water level in access works, and twice a day for the pressure cells.

4.5 Removal of the air-nitrogen mixture

4.5.1 Procedure

After inerting, the cavern will contain a large quantity of gas. To avoid mixing this gas with LPG, which could induce difficulties during possible recompression, the gas mixture is vented through the vent line, controlling the pressure variation to a rate lower than 1 kg per day. The cavern is filled with water to the upper water level according to the cavern crown geometry.

Before discharging the air-nitrogen mixture through the vent line to the atmosphere, a stabilization period is necessary to allow the air-nitrogen mixture to mix (usually around one day).

4.5.2 Measurements and controls

Record every two hours:
• cavern pressure on pressure standard
• atmospheric pressure on digital barometer
• injected water volume shown on water meter
• water level
• oxygen content of gaseous mixture,

and once a day all piezometer levels, pressure cell readings and water level in access works.

5 FIRST FILLING WITH LIQUID LPG

5.1 Procedure

The procedure for the first filling with liquid LPG will be as follows:

• injection of liquid LPG via the vent line,
• removal of water at the flowrate of LPG pumps.

At the beginning, the cavern pressure is low. LPG will first vaporize until the vapour pressure in the cavern (assumed at water temperature) is reached. Then LPG will stay in a thermodynamic two-phase equilibrium, the condensation rate is related LPG and water flowrates.

Injection of product will be done in two steps.

5.1.1 First step

Liquid or gaseous LPG will be injected slowly (from trucks, coastal tanker, etc.) into the cavern to gradually increase its partial pressure to its vapour pressure.

Operating pressure shall not exceed the maximum operating pressure of the caverns by controlling the filling parameters.

5.1.2 Second step

When the change of the pressure rate becomes small, there is liquid LPG in the cavern and the product will be injected according to the maximum dewatering flowrate. Water and/or product rates will be controlled in order not to exceed the maximum operating pressure.

If it appears that LPG delivery is not possible at a sufficient flow, it will be necessary to adjust the water flow according to LPG flow, in order to maintain the cavern pressures above atmospheric pressure.

Before starting these operations, all safety equipment, detection and monitoring instruments shall be ready to use.

Operational safety procedures shall be applied at this stage.

5.2 Measurements and Controls

The following parameters will be monitored every two hours:

• cavern pressure on pressure standard
• mass of LPG injected in the cavern,
• water volume pumped out from the cavern,
• LPG and water levels in cavern(s) (water level being also given by plotted curve from water filling).

The water evacuated from the cavern with the LPG pump(s) is sent to the sea, via a drainage system (water pond) equipped with gas detector to detect the first traces of LPG in the discharged water.
Before the water has reached normal operation levels, and before traces of LPG are detected in water (more than 25 ppm), the LPG pump(s) will be replaced by the seepage water pump(s) and the water shall be sent to the stripper prior to being discharged.

The storage will be operational when the water level reaches the normal operation level.

During these operations, a control valve and a flow totaliser are necessary on the dewatering line.

6 TEMPORARY WORKS

All temporary works and equipment required for performing the test shall be checked & certified by authorized person before initiating the cavern acceptance test.

These drawings shall include:

- the temporary connection for air pressurization of the cavern
- the temporary works for air depressurization of the cavern,
- the temporary lines for water injection in the cavern including the metering unit,
- In case of two caverns, the temporary works for cavern B water filling from cavern A including metering unit),
- the temporary connections for nitrogen injection,
- the temporary connections for first LPG filling through the vent line.