Natural Gas Salt Cavity Storage – Guidance to Inspectors on Borehole and Cavern Design, Cavern Leaching and Operation of the Borehole and Cavern

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To	ED Wells Inspectors and other ED inspectors conducting inspections of underground salt cavity gas storage sites and the assessment of Pre-Construction and Pre-Operational parts of COMAH Safety Reports for such sites

Content

1 Purpose

To give guidance to wells inspectors, and others, involved in the assessment of COMAH Pre-Construction and Pre-Operation parts of Safety Reports and the inspection of borehole sites for the development of salt cavities and underground salt cavity gas storage sites. It relates to borehole and cavern design, cavern leaching and subsequent operation of the caverns and boreholes.

The information provided in this semi-permanent circular (SPC) is based on current API and European/British Standards on the design and operation of solution-mined gas storage cavities. It also draws on current oil and gas well construction standards recognised by HSE in Great Britain and on the UK Continental Shelf.

2 Background

An increasing number of applications to develop underground gas storage facilities have been submitted by various operators in the UK. The salt cavities, wellheads, interconnecting pipe work and the import and export processing facility are considered as one establishment under COMAH legislation. HSE's Energy Division (ED) Well Engineering and Operations Inspectors have become involved in the assessment of Pre-construction and Pre-operation parts of Safety Reports, assessing the design and construction of the boreholes and cavities and associated risk assessment. Where requested, wells inspectors will also be involved in subsequent site inspections of drilling, leaching and operation of natural gas storage cavern facilities.

3 Legislation

3.1 Relevant regulations

The Borehole Sites and Operations Regulations 1995: These regulations are considered to apply to salt cavern wells as, during the salt solution mining operation, minerals are being extracted through the borehole. The regulations require the preparation of a health and safety document. It must demonstrate that the risks to employees and the borehole site have been determined and assessed and that adequate measures will be taken to safeguard their health and safety. It must also demonstrate that the design, use and maintenance of the workplace and of the equipment are safe. Where appropriate the document must include plans to provide employees with adequate escape or rescue in the event of danger, the prevention of fire and explosions including blowouts, a fire protection plan and, where necessary, a plan for the detection and control of toxic gases, such as H_2S.

The Control of Major Accident Hazards Regulations 2015 : These regulations require the operator of an upper-tier site to produce a safety report. Its key requirement is to demonstrate the operator has taken all measures necessary to prevent major accidents and to limit the consequences to people and the environment of any that do occur. The report provides a comprehensive description of the establishment, its surroundings, the associated hazards and risks and the control measures in place. The operator is required to submit parts of the safety report at a point before those 'front end' or conceptual design decisions are finalised which will affect safety and the environment, and which will be difficult and costly to reverse as the Pre-Construction part of the Safety Report'.

Within a reasonable period prior to the start of operation of the establishment the remaining part of the safety report must be developed. This Pre-Operation part of the Safety Report should build upon, and update, the earlier report and describe how any previously outstanding safety and environmental issues have been resolved.

3.2 Good practice

The Offshore Installations and Wells (Design and Construction, etc.) Regulations 1996 do not currently apply to Natural Gas Salt Cavity Storage activities. Nonetheless, most of the requirements of the regulations represent good practice which should, in any case, be followed where appropriate. Regulation 18 (Arrangements for Examination), requires that before the design of a well is commenced or adopted the well operator must put in place arrangements in writing for examination by independent and competent persons. The examination must demonstrate that the pressure boundary of the well is controlled throughout the well's life cycle and that the pressure containment equipment that forms part of the well is suitable for this purpose. Although compliance with the regulations is not currently enforceable, in discussions with operators of natural gas salt cavity installations, HSE has had success in persuading operators to adopt this principle as good industry practice,

4 Geotechnical assessment

4.1 Geological assessment

Salt formations are either bedded sedimentary formations or intrusive salt formations (domes and ridges). Bedded formations often underlie large basins, with relatively thin salt beds (< 300m thick) often separated by beds of porous or impervious layers of other sediments. Salt dome formations have intruded from roots in deeply buried salt beds, and tend to be plugs of large diameter and with great depth. To date, natural gas salt cavity storage in the UK has been within bedded salt formations.

A geological assessment must be undertaken to obtain sufficient geological knowledge about the site to determine the geological suitability of the site. Available geological and geophysical data should be gathered from old borehole logs and cores, previous seismic work and regional geological data available.

Additional geological or geophysical surveys may have to be carried out if the existing data is not sufficient. Exploration drilling should be carried out to determine the quality of the salt and the distribution of impurities. Salt cores should be taken to enable laboratory tests to be undertaken to determine salt composition, mechanical strength and its solution characteristics. Well logging should be carried out to determine salt composition of uncored parts of the salt and to evaluate the quality of the overlying formation. Information on the thickness and strength of the overburden formations is particularly important in the development of bedded caverns. These layers are part of the structural support for the cavern.

A summary of the data should be included in the Pre-construction part of the Safety Report' which can be used to define the most favourable zones for locating cavities, taking into account thickness of the saline layer, distribution of insoluble, faults and other structural anomalies in the salt and surrounding formations.

4.2 Geomechanical testing

Proper design of a salt cavern requires knowledge of the *in-situ* stress state and the mechanical properties of the salt. These properties should be evaluated on the basis of laboratory tests on borehole samples and / or in-situ tests in the well.

The tests form the basis for the determination of the material parameters used for the selection of a rheological model which shows the rheology of the salt being studied. The main mechanical disturbances that need to be represented or quantified are:

- The change in volume loss by creep in the salt formation (convergence).
- The distribution of cavity wall and floor deformation.
- The distribution of surrounding stress induced by the cavity in the surrounding rock.

A summary of the data should be included in the Pre-construction part of the Safety Report which can be used to determine cavern geometry (shape, height, diameter, roof guard), positioning (well pattern, depths, pillars, distances to cap and bed rocks), the distance to neighbouring activities, and maximum and minimum operating pressures.

5 Borehole design parameters

A summary of the design data should be included in the Pre-construction part of the Safety Report under the COMAH Regulations.

5.1 Conductor

A borehole conductor should be set to case off shallow, often unconsolidated formations, to allow returns of drilling fluids to surface and to provide a foundation for blowout prevention and wellhead equipment.

Conductors may be driven as well as drilled and cemented in place. The choice of conductor connection should be suitable for the method of conductor installation to be followed.

5.2 Casings

The casing programme should be configured to accommodate all identified subsurface hazards and to minimise risks either from cross-flow between formations or the uncontrolled release of wellbore fluids to surface, throughout the life of the well.

Casing shoe depths must be selected not only to protect the sensitive areas of strata from contamination by well fluids but also prevent the ingress of strata fluids into the well. In particular, any fresh water aquifers must be protected from risk of contamination. The production casing (last cemented casing string) must be set as required within the top of the salt strata at a depth sufficient to allow for the roof of the cavern to be set deep enough to allow:

- The formation fracture gradient to be sufficient to exceed the maximum cavern operating pressures, and
- provide sufficient salt thickness between the cavern roof and the cap-rock to ensure adequate roof support of the overburden.

The material specification of the casing should be suitable for the anticipated well bore fluids to which it may be exposed. The casing diameters must be selected to meet the leaching, gas production and gas storage requirements.

Casings should be designed to withstand the worst conditions of burst, normal collapse, tensile and triaxial loading anticipated in the well. All casing installed in the well should have adequate properties to contain the maximum loads to which it may be exposed during the lifetime of the well. There should be adequate allowance for deterioration in service from whatever cause, including wear, corrosion and erosion.

All surface, intermediate and production casings should be pressure tested to an appropriate value for the well being constructed and subsequent cavern operating parameters. Normally this should be carried out prior to drilling out the shoe track. The casing seat and cement of the production casing should also be pressure tested after drilling out and exposing at least 3m (10ft) of salt below the shoe. The test pressure to be based on the maximum cavern operating pressure related to the casing shoe.

5.3 Cement

All conductor and surface casing should normally be cemented back to the surface. Intermediate and production casings should, where appropriate, be cemented back inside the previous casing shoe.

The density of cement must be suitable for the proposed operation in question. The formations should be capable of withstanding the hydrostatic head of the cement column. Cement slurry density and spacer fluid should be sufficient to prevent any influx of well fluids.

Cement evaluation logs for verification of cement bonding should be run on intermediate and production casings and across any vulnerable aquifers

5.4 Production wellheads

In gas storage operations the term wellhead refers to the totality of the wellhead and associated valve arrangements for control of the flows into and out of the cavity under normal and emergency operating conditions**.**

All wellhead equipment should be manufactured, inspected and tested to the appropriate ISO or API specifications, ISO 10423:2009 (API spec 6A) specification for Wellhead and Christmas Tree equipment. It should be designed for the maximum operating pressure of the cavity.

Salt cavities must have a master isolation valve. This valve must isolate the wellhead from the cavity in the event of an emergency or for maintenance.

On the major intakes and offtakes the wellhead should have a manual and / or an actuated valve. The wellhead has to be equipped with devices to shut down the well in case of unallowable operation or emergency. The safety devices must close automatically in the event of:

- Line break e.g. extra low pressure.
- Failure of the wellhead panel.
- Site emergency shutdown system actuated either remotely or at the cavity.

A system for hydrate inhibition may be provided at the wellhead to inhibit and control hydrate formation.

5.5 Production completions

All wells must include a dedicated gas tight completion string of casing or tubing and should incorporate at least two barriers to flow between the cavern and surface, normally the tubing hanger and packer. Suitable fully welded completion tubing is considered to be acceptable

The completion should include the facility to plug the completion deep, close to the cavern, and at the wellhead. Additional landing nipples may be required at strategic points in the well.

All completions should incorporate a subsurface safety valve at an appropriate depth below surface to minimise the inventory of gas which could be released in the event of wellhead failure. The valve should be appropriate to the functional requirements of the well and in accordance with API spec 14A Specification for Subsurface Safety Valve Equipment.

Production casing/ tubing should be designed for worst case burst, collapse, tensile and tri-axial loading and should be manufactured, inspected and tested to the appropriate specification, API spec 5CT Specification for Casing and Tubing

Packers should be manufactured, inspected and tested to the appropriate ISO specification ISO 14310:2008 (API spec 11D1) Specification for Packers and Bridge Plugs.

The production completion must enable the brine to be removed from the cavity and permit the safe injection and withdrawal of gas into and from the cavity. The design must allow a brine eductor string to be run. The eductor string is connected gastight to the wellhead and usually contains landing nipples so located as to be able to isolate the string from gas cavity pressure, if necessary.

5.6 Deviated drilling

In instances where the boreholes are drilled from a single drilling pad using deviated drilling techniques for correct cavern spacing then the tri-axial stresses in the casings and production tubing should be considered and comply with company standards. Calliper logs of the production casing and production tubing should be run for a base line survey.

5.7 Annulus monitoring

Valve and gauge assemblies must be available to accurately monitor the Production Tubing / Production Casing annulus. Other annuli should be monitored where required. Company policies must be in place for maximum allowable annuli pressures and procedures be in place to manage the annulus pressures.

6 Cavern design parameters

Proper analysis of the design of a cavern site involves the following:

- Assessment of the in-situ lateral stresses.
- The range of operating pressures in the cavern.

- The structural properties of the salt over the full height of the caverns.
- In bedded formations, the properties of the overburden rock layer in the stress field.

Increasing the density of caverns in a formation will increase the differential stress in the salt formation which results from the difference between the in-situ pressure of the overburden on the salt formation and the operating pressure within the caverns. If a cavern site is not properly designed, salt creep can lead to both capacity loss and surface subsidence, which can cause excessive stresses on tubing strings in the immediate area.

Generally, the required separation distance between wellheads divided by the average diameter of the caverns (P/D) will increase with increasing depth in order to maintain adequate salt strength and cavern operating pressures. Where solution mining is taking place in a cavern adjacent to another, the salt pillar between them must remain adequate to prevent the flowing of fluids from the higher to the lower pressure cavern.

Cavities must be designed for long-term stability under the permitted operating conditions. The principal stability parameters that need to be defined within the cavity design are:

- The cavity geometry i.e. cavity shape, height of cavity, cavity diameter and roof guard.
- The location of the cavity i.e. the well pattern, the depth of the cavities, pillars (P/D ratios), distances to cap-rock and bedrock, distances to major faulting etc.
- The planned maximum operating pressure in relation to the overburden pressure
- The minimum operating pressure.

The cavern design should demonstrate the mechanical stability of caverns under permitted operating conditions. It should also consider cavity behaviour under emergency conditions; the possibility of subsidence should also be considered.

A summary of the design process and parameters should be included in the Pre-construction part of the Safety Report'.

7 Cavern solution mining/leaching

Solution mining or leaching is the process by which a void or cavity is created in an underground salt formation for storage purposes. This cavity is created by the dissolution of salt when fresh water or unsaturated brine is injected into the formation under controlled conditions. An outline of the planned procedure and equipment specification should be included in the Pre-construction part of the Safety Report.

The injection of fresh water/ brine and removal of produced brine are accomplished through two pipe strings, which are suspended concentrically below the production casing string. Water is injected into the developing cavity through the wash string. Brine is removed through the solution mining string. The setting depths and position of these strings relative to each other and to the cemented production casing shoe are based on the desired shape and geometry of the storage cavern and on the solution method employed.

An essential part of the solution mining operation is the placement and maintenance of a blanketing material in the annular space between the production casing and the suspended wash and solution-mining strings. The blanketing material prevents the removal of the salt-cement seal around the permanently cemented casing strings, limits the upward growth of the cavern and helps to control the shape of the cavern. The blanketing material must be insoluble in salt, immiscible with water and brine, and its density less than that of water.

The development of the cavity is controlled by the following factors:

- Water injection rate, which determines the rate of cavern growth.
- Blanketing material and water interface level, which protects the cemented production casing shoe, establishes the upper limit of cavern growth, and can exert an influence on horizontal cavern growth.
- Water injection and brine removal points, whose locations in the well and relative to each other and the blanket-water interface determine the cavern shape along with the method of circulation involved.

Solution mining techniques vary from direct circulation or reverse circulation methods to more complex methods requiring multiple manipulations of string positions. Generally the direct circulation method when combined with string and blanket interface positioning results in a teardrop or pear-shaped cavern, whilst reverse circulation creates greater relative growth at the top of the cavern, resulting in an inverted pear or mushroom shape.

The precipitation of insoluble material onto the cavern floor as a consequence of salt dissolution will reduce planned cavern capacity and inhibit lower cavern growth. Control of the insolubles is achieved by removing the insolubles with the effluent brine; it is also achieved by allowing the insolubles to settle in a sump created below the maximum working depth of the cavern.

Cavern development should be checked periodically by sonar calliper or other suitable methods to verify that the size, shape and direction of growth of the storage cavern are in accordance with solution mining programme objectives.

7.1 Solution mining/leaching wellheads

The solution mining wellhead must be designed to allow leaching water and brine to pass into and out of the cavity via the centre string and middle annulus. Blanketing fluid passes down the annulus between the last cemented casing and the outer solution mining string.

The solution mining wellhead must be designed to allow a workover or drilling rig to be assembled over it and still allow access for dismantling and re-building it with the rig in-situ.

Leaching wellheads should be designed to the maximum pressure of the solution mining operation. All wellhead equipment should be manufactured, inspected and tested to the appropriate ISO or API specifications, ISO 10423:2009 (API spec 6A) specification for Wellhead and Christmas Tree equipment.

7.2 Solution mining/leaching completions

The solution mining completion enables the cavity to be leached in a controlled manner. Casing or tubing used in leaching strings should be designed for the combined effects of axial loading and bending stresses and fabricated, manufactured and tested to the appropriate specification, API spec 5CT Specification for Casing and Tubing.

7.3 Dewatering and snubbing operations

For dewatering operations on initial gas fill of the solution mined cavity, due consideration should be taken for the early break-through of hydrocarbons to the dewatering string due to tubing leakage. Facilities should be available at surface to monitor for early break through and to shut down and isolate the dewatering process.

If the dewatering string is removed after initial gassing up of the cavern then Hydraulic Snubbing operations will be required.

8 Cavern operating parameters and procedures

Operators of natural gas storage salt cavern facilities must be aware of various hydraulic factors that can affect safe and efficient operations. The safe hydraulic operating limits should have been established during the design process. If the cavern is converted from another service such as brine production, safe hydraulic operating parameters will need to be re-established prior to using the cavern for natural gas storage.

The planned operating parameters and an outline of the required procedures for safe cavern operation should be included in the Pre-construction part of the Safety Report.

In addition, the Pre-operation part of the Safety Report should be used to build upon all the issues discussed in the Pre–construction Safety Report and confirm the cavern operating parameters and procedures as discussed below.

8.1 Pressure

8.1.1 Casing seat pressure

Operators should be aware of the various factors such a gas injection and withdrawal flow rates, fluid densities, casing and tubing configuration, cavern roof depth, and system back pressure which can affect the pressure at the casing seat. The cavern must not be operated such that the pressure at the casing seat exceeds the fracture pressure of the formation at that depth.

It is imperative that the production casing shoe is set at the depth in the salt in accordance with the planned programme to ensure the planned operating pressure at the cavern shoe can be safely applied. If because of operational problems the shoe cannot be set at the correct depth, this can impair safe operation of the cavern. If the required mechanical integrity test at the casing shoe is unable to prove the shoe integrity, cavern conversion to natural gas storage may have to be abandoned.

8.1.2 Maximum allowable operating pressure

Maximum allowable operating pressure is the pressure at the wellhead of a storage cavern that has been calculated to be safe with respect to a) fracture pressure, b) wellhead equipment and casing design, and c) adjacent cavern spacing. An alarm or safety shut-down device should be installed to prevent over-pressuring of the cavern.

8.1.3 Minimum allowable operating pressure

Minimum allowable operating pressure is the pressure at the wellhead of a storage cavern that has been calculated to prevent cavern closure due to a) plastic flow, b) the prevention of formation subsidence, or c) the prevention of overstressing of the vertical walls due to adjacent cavern pressure.

8.1.4 Rate of pressure change

It is considered possible that rapid depressurisation may cause roof collapse or side-wall ‘slabbing’. A maximum pressure release rate should be determined for the salt formation being used and the release rate should be closely controlled.

8.2 Maximum gas injection rate

Maximum injection flow rate is a function of the casing/ tubing design, cavern roof depth, fluid injected, and maximum allowable casing seat pressure for the cavern.

8.3 Cavity testing and miscellaneous surveys

After drilling has been completed, the cement and formation around the last cement casing shoe should be leak tested. Caverns should be tested before they are placed in operation to verify pressure integrity and the capability of the cavern to store natural gas within the design limitations.

8.3.1 Cavern mechanical integrity testing

A full hydrostatic pressure test using brine provides verification of the pressure integrity of the cavern. It is generally used to test a new cavern well before dissolution is started and before any hydrocarbon is injected. The test requires the collection of precise pressure data and can be of several days’ duration depending upon cavern size, stability of the cavern and the fluid in the cavern.

A nitrogen/brine interface observation style of test is a method for testing the integrity of a cavern’s wellhead, casing, tubing and the cemented annulus between the production casing and the formation (at the casing shoe area). An interface observation test is typically conducted prior to the initial storage of hydrocarbon, and normally requires the assumption that the cavern itself has integrity.

The integrity of new caverns should be determined prior to the initial storage of hydrocarbons. A retest should be conducted whenever operational or other data indicates a condition which could adversely affect cavern integrity.

The acceptance criteria for mechanical integrity testing, depends upon the type of test to be undertaken. Typical criteria for acceptance for a nitrogen/brine interface test, dependent on a Calculated Leak Rate (CLR) compared to a Minimum Detectable Leak Rate (MDLR) are:

In conjunction with the fact that the CLR must be less than the MDLR:

1. Below 50 litres/day, the well passes the mechanical integrity test (MIT)

2. Below 150 litres/day, but above 50 litres/day, additional investigation is required before (and if) the well is deemed to have passed the MIT
3. Above 150 litres/day, the well does not pass the MIT.

8.3.2 Sonar cavity testing

Sonar calliper logs are utilised to determine the size, shape and directional growth (if any) of a cavern. Sonar logs are run during solution mining of a cavern and at the start of cavern life. Periodic sonar surveys should subsequently be run to provide an indication of cavern growth over time compared to design and operating criteria. Particular attention should be paid to the location and configuration of the cavern top and bottom, to reveal any upward dissolution or roof falls. In addition, lateral dissolution of the cavern sides should be monitored to detect any degradation of the integrity of adjacent caverns.

8.3.3 Geophysical logs

Periodic logging of the cavern may be undertaken to determine the position and thickness of the salt roof. Logs can be run to locate the cavern floor, bottom of the tubing strings, natural gas/ brine interfaces, bottom of production casing and to determine washouts below the production casing shoe.

8.3.4 Subsidence surveys

Annual surveys at approximately the same time of the year will provide the most accurate data for detecting or measuring subsidence. Control surveys should be tied into a bench mark e.g. Ordnance Survey bench mark. Periodic surveys over the life of the cavern will determine if subsidence is occurring.

8.3.5 Cavity monitoring and maintenance

The operating pressure of each cavern must be measured continuously at the wellhead or down hole. Wellhead pressures, temperature, stock and operating status of each cavity must be monitored.

To check for gas leakage to the annulus, the annuli pressures must be measured, and any build-up of pressure in the annulus safely vented.

A routine inspection and maintenance schedule for surface and subsurface safety equipment must be prepared and followed. If a well repair is carried out, datum logs for the wall thickness of the production casing string and the quality of the cementation should be run.

9 Technical standards

1. British Standard: BS EN 1918-3:2016 Gas Infrastructure. Underground Gas Storage. Functional recommendations for storage in solution-mined salt cavities.
2. American Petroleum Institute Recommended Practice 1114, 2nd Edition January 2013, Design of solution-mined underground storage facilities.
3. American Petroleum Institute Recommended Practice 1115, 1st Edition September 1994, Operation of solution-mined underground storage facilities.
4. HSE Research Report RR605 - An appraisal of underground gas storage technologies and incidents, for the development of risk assessment methodology
5. HSE Research Report RR606 - Scoping calculations for releases from potential UK Underground Gas Storage facilities

10 Further information

Further information can be obtained from: TBA. Additional guidance on borehole integrity can be found in *Well Life Cycle Integrity Guidelines*, Issue 3, March 2016, published by Oil & Gas UK.