




BowTie Analysis for the hazard “Storage of H₂ in a Salt Cavern”

In this Annex A.2 the BowTies are detailed for the measures that can be taken to reduce risks and mitigate consequences, including monitoring

Categories of measures:

- Prevention measure (green colour) 
 - Design (including material selection, operational management)
 - Testing
- Monitoring measure (yellow colour) 
 - Monitoring
 - Logging
- Recovery measure (orange colour) 

T1: Leakage of H₂ in the subsurface

Detailed BowTies include:

T1-W: Top Event 1, Well

T1-O: Top Event 1, Overburden

T1-C: Top Event 1, Cavern

T1-X: Top Event 1, XConsequences

Detailed BowTie – Subsurface Leakage Well Threats – T1-W

Annex A.2 to TNO report 2021 R10526 "Identification and quantification of risks of subsurface hydrogen storage in salt caverns"

H₂ embrittlement of well materials

Use austenitic steels with appropriate hardness

Avoid damaging the oxide layer that prevents/delays embrittlement

Keep P, T within safe operating limits to avoid large thermo-mechanical stresses

P, T monitoring

Internal corrosion of steel components exposed to brine, H₂S, and MIC

Use of corrosion-resistant steel

Apply anti-corrosion measures

Protection of casing with tubing and packer

Lab experiments to assess the risk of H₂S formation

H₂S formation - add microbial growth- and reaction-inhibiting additives

Lab experiments to assess the risks of MIC-corrosion

Periodic caliper log and/or downhole camera inspection

Monitor gas and brine composition periodically

Connections not H₂ tight

Use welded connections

Test welds before running down casing

Minimize vertical strain on casing

Keep P, T within safe operating limits to avoid large thermo-mechanical stresses

Perform an MIT (N₂ & H₂ in pilot)

P, T monitoring

Mechanical failure of the casing (fatigue)

Use existing design standards from UGS

Keep P, T within safe operating limits to avoid large thermo-mechanical stresses

P, T monitoring (P in annulus)

Poor quality and/or bonding of the cement

Use flexible cements (flexstone, pozo)

Test cements exposed to hydrogen under operational P, T and env. conditions

Stimulate natural sealing behavior of halite

Perform an MIT (N₂ & H₂ for pilot)

Cement bond logging

Cement degradation

Use flexible cements (flexstone, pozo)

Test cements exposed to hydrogen under operational P, T and env. conditions

Stimulate natural sealing behavior of halite

Keep P, T within safe operating limits to avoid large T-M stresses

P, T monitoring

Monitor downhole chemical conditions

Integrity failure of last-cemented casing shoe

Use flexible cements (flexstone, pozo)

Leach cavern neck below LCCS

Stimulate natural sealing behavior of halite

Keep P, T within safe operating limits to avoid large thermo-mechanical stresses

Perform an MIT (pre-operation)

P, T monitoring

Packer integrity failure

Use H₂-resistant packer materials (steel, elastomer)

Increase weight below packer to improve effectiveness of packer antislip clamps at install

Avoid slip at top of packer below the elastomer

Keep P, T within safe operating limits to avoid large thermo-mechanical stresses

P, T monitoring (P in annulus)

Degrading durability of materials due to scaling

Implement measures to avoid scaling on tubing walls and SSSV

Periodic removal of scaling

Monitor injection and withdrawal performance

Periodic caliper log and/or downhole camera inspection

Hazard

Storage of H₂ in a salt cavern

Top event

Leakage of H₂ in subsurface

Detailed BowTie – Subsurface Leakage Overburden Threats – T1-O

Hazard

Storage of H₂
in a salt
cavern

Top event

Leakage of H₂
in subsurface

External corrosion of the
casing (including
conductor, anchor
casing)

Upfront site characterization (e.g.
identify microbiological activity – risk
of MIC; fluid flow and compositional
characteristics)

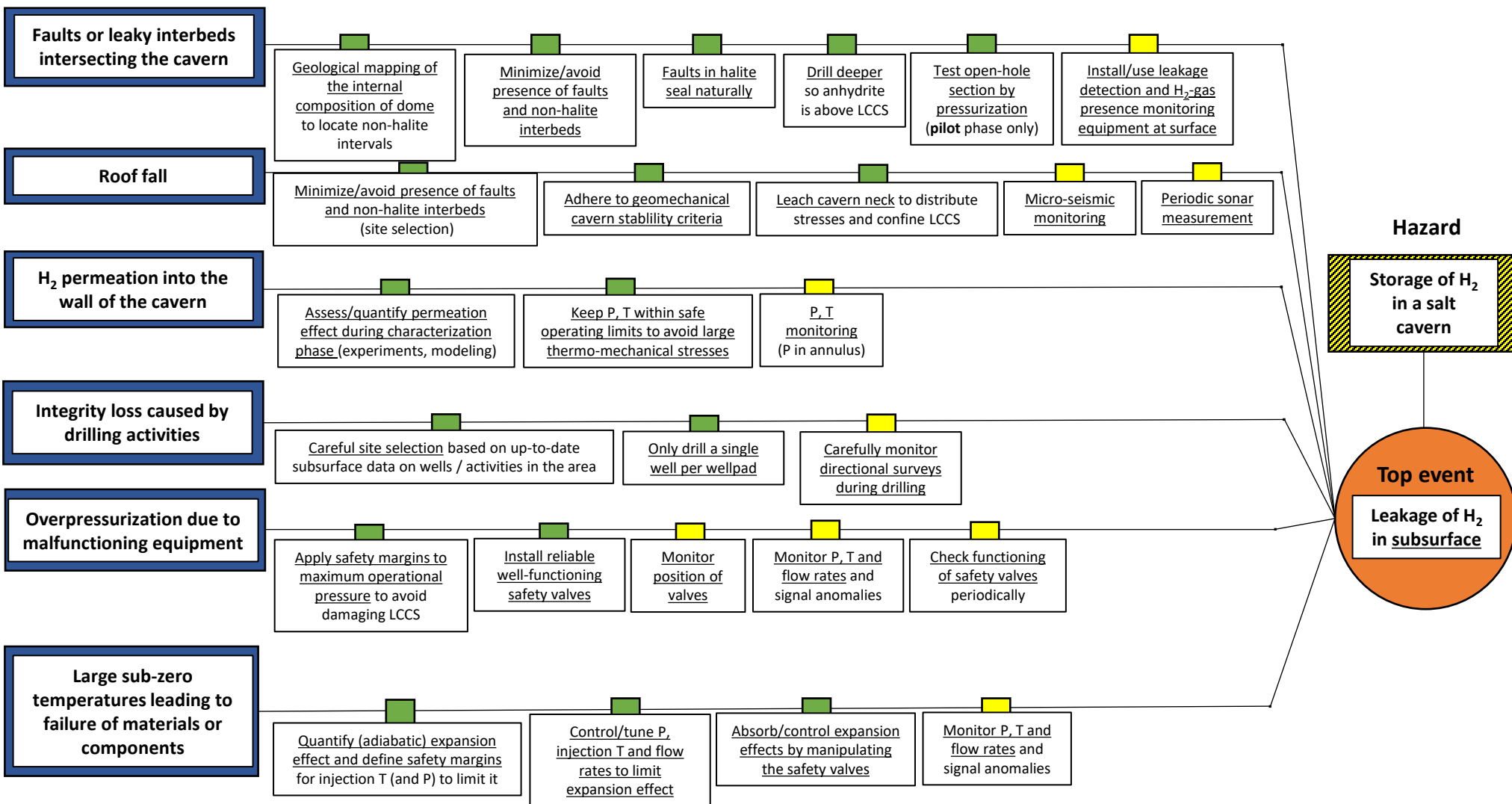
Use (verified/tested) corrosion-
resistant steel (material selection
based on expected P, T & env.
conditions, incl. risk of MIC)

Implement multiple
barriers to leakage
(conductor, anchor and
production casing)

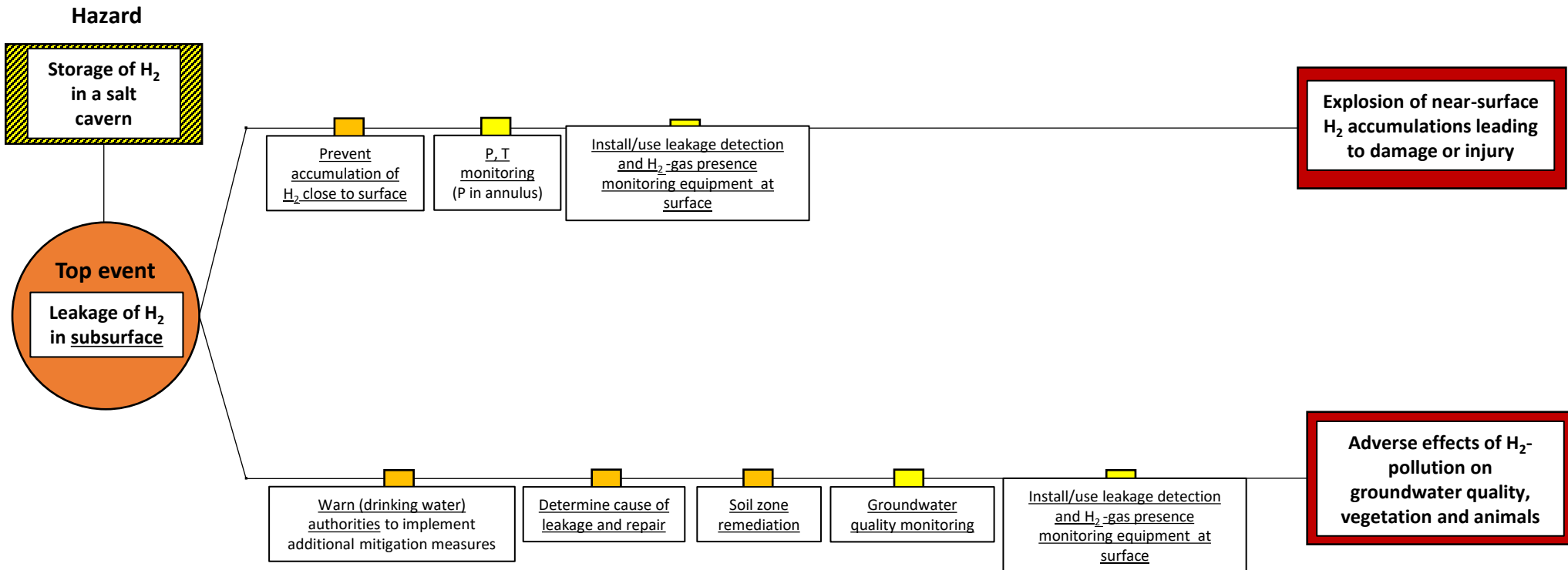
P, T
monitoring
(P in annulus)

Install/use leakage
detection and H₂-gas
presence monitoring
equipment at surface

Detailed BowTie – Subsurface Leakage Cavern Threats – T1-C



Detailed BowTie – Subsurface Leakage Consequences – T1-X



T2: Leakage of H₂ at the surface

Detailed BowTies include:

T2-W: Top Event 2, Well

T2-X: Top Event 2, XConsequences

Detailed BowTie – Surface Leakage Well Threats – T2-W

Catastrophic x-mas tree damage due to collision

Enforce a no-drive zone around wellhead with reinforced concrete blocks

Completely submerge wellhead cellar and close it off

Install a functioning SSSV, tested after installation under operational storage pressures

Periodically check SSSV

Catastrophic x-mas tree damage due to vandalism/terrorism

Security fence around wellpad

Completely submerge wellhead cellar and close it off

Install a functioning SSSV, tested after installation under operational storage pressures

Periodically check SSSV

Security surveillance

Video surveillance

Failing wellhead flange or hose connection

Use austenitic steels with appropriate hardness

Use H₂-tested wellhead, components and materials

Install a functioning SSSV, tested after installation under operational storage pressures

Install/use leakage detection and gas presence monitoring equipment at surface

Periodically check SSSV

Improperly closed wellhead valve

Use a pressure control system on tube trailer (pilot)

Enable remote control of valves

Install a functioning SSSV, tested after installation under operational storage pressures

Repeated performance tests of valves

Monitor position of valves

P, T (and flow) monitoring

Periodically check SSSV

Integrity failure during workover under pressure

Use H₂-tested well intervention equipment, tools and materials

Use H₂-compliant intervention techniques

Perform well intervention with qualified and competent staff

Perform detailed and dedicated risk assessment

Test debrining procedure during pilot

H₂ dissolved in brine coming to surface during debrining

Quantify/measure volume of H₂ that will dissolve into brine at operational conditions

Install separator to de-hydrogenate the brine

Migration of H₂ via overburden to surface

Characterize overburden to assess migration pathways and risk

Install/use leakage detection and H₂-gas presence monitoring equipment at surface

Hazard

Storage of H₂ in a salt cavern

Top event

Leakage of H₂ at the surface

Detailed BowTie – Surface Leakage Consequences – T1-X

Hazard

Storage of H₂ in a salt cavern

Top event

Leakage of H₂ at the surface

Minimize volume and flow rate during release

Minimize presence of humans & animals in vicinity of site

Execute emergency response plan (evacuation etc)

Warn local stakeholders and authorities

Determine cause of leakage and repair

Install/use leakage detection and H₂-gas presence monitoring equipment at surface

Adverse effects to humans and animals due to air pollution with H₂

Minimize presence of humans & animals in vicinity of site

Use proper Personal Protective Equipment

Execute emergency response plan (evacuation etc)

Warn local stakeholders and authorities

Determine cause of leakage and repair (difficult due to noise)

Extreme noise levels leading to hearing damage

Prevent accumulation of a high-concentration H₂ cloud

Stimulate immediate ignition on release to prevent explosion

Execute emergency response plan (evacuation etc)

Install/use leakage detection and H₂-gas presence monitoring equipment at surface

Shockwave from explosion causing structural damage, injury or death

Execute fire prevention plan

Execute emergency response plan (evacuation etc)

Warn local stakeholders and authorities

Determine cause of leakage and repair

Install/use leakage detection and H₂-gas presence monitoring equipment at surface

Heat radiating from flash fire or jet flame causing structural damage, injury or death

Perform a QRA (quantify physical effects, assess failure frequencies)

Reconsider ATEX zonation (debrining risk)

Minimize presence of humans & animals in vicinity of site

Warn local stakeholders and authorities

Execute emergency response plan (evacuation etc)

Record incidents and follow-up with additional measures

Injury or death – occurs in combination with other consequences (fire, explosion)