

EON LIVE

Situation Room

The flight simulator for industrial plants.

120 real situations. Real physics. Real consequences.



The scenario library for EON Live · research + design review · July 2026



A library of situations. Press play.

TITLES

Every scenario is a title — one story, one poster, one card. A mission library — the way pilots pick simulator scenarios.

GENRES

Titles are grouped on 7 genre shelves — from lockout mistakes to blackouts — plus a flagship row.

LEVELS

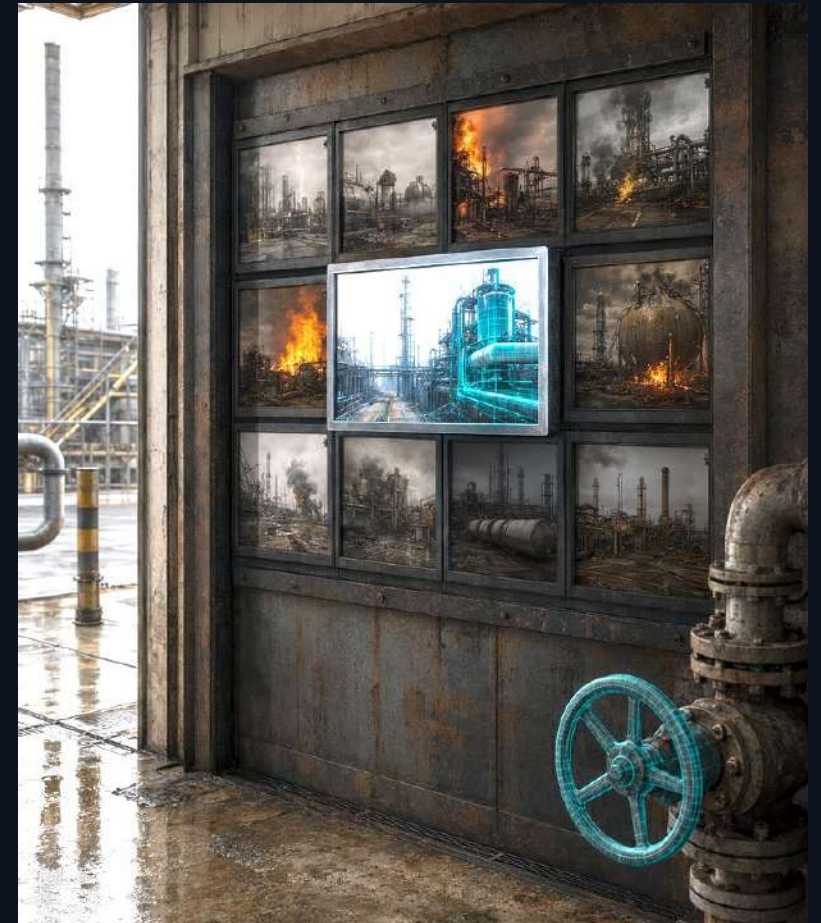
Difficulty lives INSIDE each title: Beginner → Operator → Expert. Same story, harder dials.

MATCH

Universal reads your rig and auto-marks which titles fit it — no manual setup.

▶ RUN

One press dresses the live-physics console. The situation starts happening to YOUR plant.



3 levels per title · **fit badges** · greyed = doesn't fit

One simulator underneath. The library is how people meet it.

Every title is grounded in a real disaster.

THE SOURCE MATERIAL IS HISTORY

Piper Alpha, North Sea — 1988

167 killed. A standby pump restarted into a defeated boundary. It is title #5 on the Rotating Equipment shelf.

BP Texas City — 2005

15 killed, ~180 injured. Overfill and relief-system overwhelm — a full genre covers this pattern.

Buncefield, UK — 2005

Tank overfill → vapour cloud. Widely described as the UK's largest peacetime explosion.

DuPont La Porte — 2014

4 workers killed by a toxic release into an occupied area — the LOTO shelf's trapped-liquid pattern.

Every card teaches

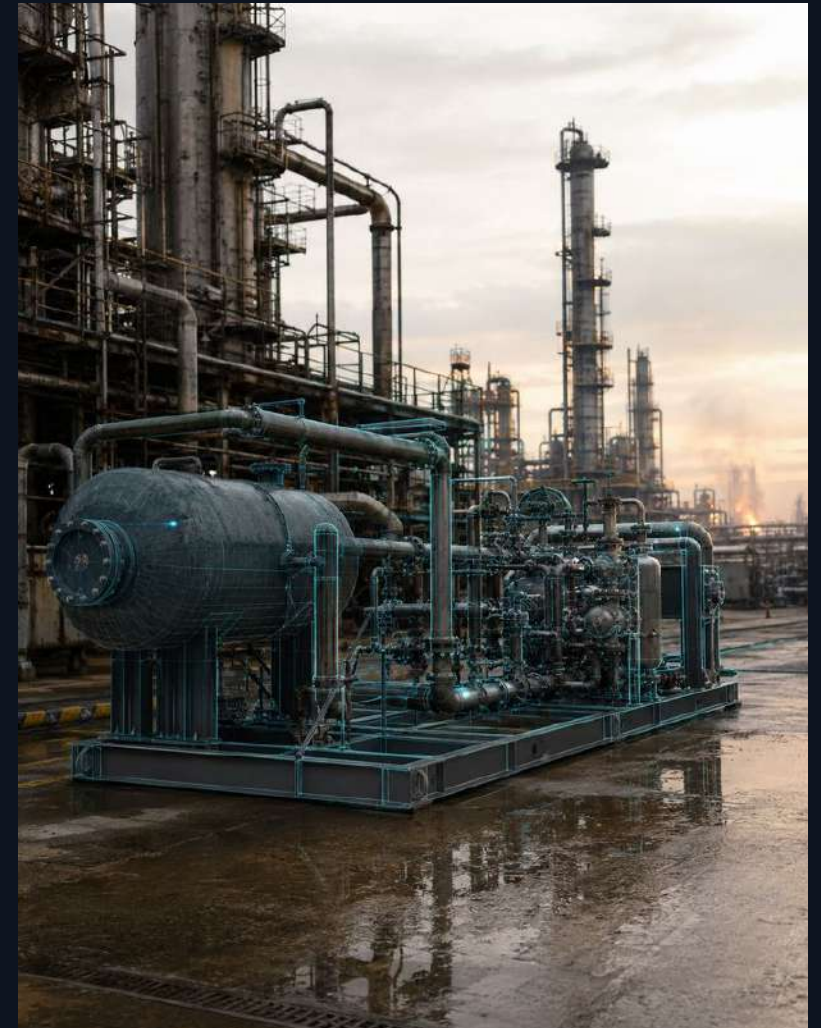
WHAT happens · WHY it matters · HOW the physics works — plus THE FACTS: verified statistics with sources and confidence flags.

One simulator, infinite variations

120 titles × 3 levels × your own rig. The same physics engine plays every story — content scales without new code.

This is what buyers pay for

Not a generic VR demo — a curated catalog of the exact situations that killed people, runnable on the customer's own facility.



7 genres + the flagship set = 120 titles

01

Safety, Isolation & Stored Energy (LOTO)

15 titles

02

Start-up, Shutdown & Transients

15 titles

03

Overpressure, Relief & Flare

15 titles

04

Rotating Equipment

15 titles

05

Process Upsets & Abnormal Operations

15 titles

06

Loss of Containment — Leaks, Fire & Dispersion

15 titles

07

Utilities & Support Systems

15 titles

08

Flagship Set — the 15 marquee scenarios

15 titles



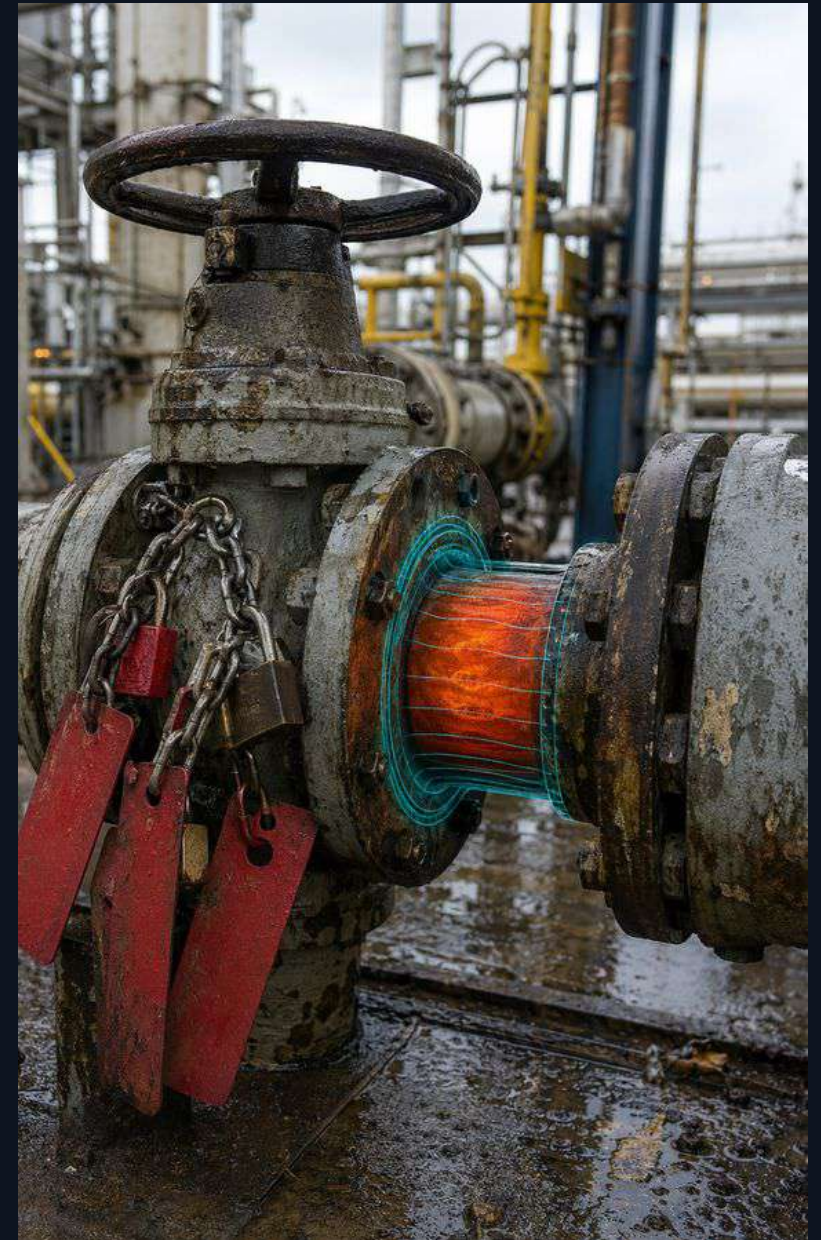
105 genre titles + 15 flagships = 120 · every title researched and cited · every title gets a poster, a card, and three levels

Safety, Isolation & Stored Energy (LOTO)

Visual motif: Padlocks, danger tags and lock-out chains on valves; a half-unbolted flange; the trapped energy glowing hot *INSIDE* the teal wireframe — danger you can't see with the naked eye, made visible by the twin.

- 01 Line Breaking on an Inadequately Isolated / Un-drained Line
- 02 Blocked-In Equipment Isolated From Its Relief Device
- 03 Toxic Trapped Liquid in a Vent / Drain Header
- 04 Energy Isolation Missed on a Pump — Toxic Auto-Start Equipment
- 05 Pyrophoric Iron Sulfide Ignition on Opening Sour
- 06 Double-Block-and-Bleed Failure (Passing Block / Plugged Bleed)
- 07 Blind / Spade Insertion on a Not-Fully-Depressured Line
- 08 Stored Electrical Energy / Arc Flash on De-energization

- 09 Unexpected Startup — Stored Mechanical / Rotating Energy
- 10 Trapped Hydraulic / Accumulator Stored Energy
- 11 Stored Thermal Energy — Steam / Hot-Condensate Line Break
- 12 Auto-Refrigeration & Brittle Fracture on a Light-Ends Drain
- 13 Isolating the Wrong Equipment / Battery-Limit Verification
- 14 Inert Purge-Gas Backflow / Migration Into an Occupied Area
- 15 Confined-Space Entry Prep — Drain / Purge / Gas-Test Sequence



Start-up, Shutdown & Transients

Visual motif: Dawn light on the horizon; frost, ice and steam — the plant waking up or going down. Thermal contrast made visible: frost-white cold steel against warm process glow, condensation, warming pipes.

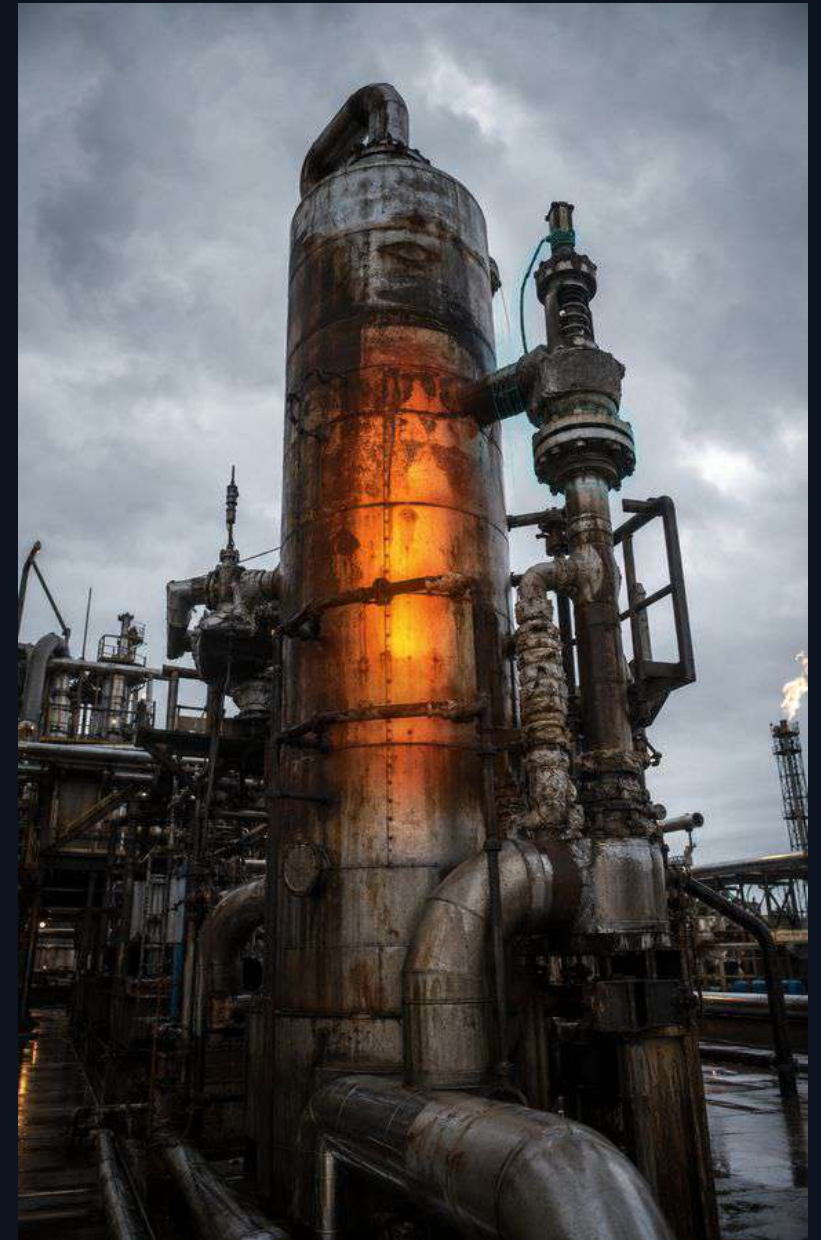
- | | |
|---|--|
| 01 Cold-Restart Brittle Fracture (Thermal Shock) | 09 Pyrophoric Iron-Sulfide Self-Ignition on Opening |
| 02 Differential Thermal Growth & Piping Strain (Warm-Up / Cool-Down) | 10 Fired-Heater Light-Off Firebox Explosion |
| 03 Rapid Depressurization Auto-Refrigeration Embrittlement | 11 Restart With a Safeguard Removed / Trapped Pressure |
| 04 Isolated-Exchanger Heat-Up Overpressure on Return to Service | 12 Idled-Unit Hydrocarbon Backflow During Shutdown Prep |
| 05 First-Fill Water Hammer / Trapped-Air Surge | 13 Gas Blow-By / Loss of Level to LP Equipment |
| 06 LNG/LPG Rollover Overpressure on Filling | 14 Utility Loss During a Transient |
| 07 Settle-Out Pressure After Compressor Trip | 15 Commissioning Line-Up Error After Turnaround |
| 08 Insufficient Purge — Flammable Envelope Crossed at Start-Up | |



Overpressure, Relief & Flare

Visual motif: *The straining vessel — heatmap-skinned steel bulging with pressure; the PSV as a character (lifting, plumed, frozen, or valved-out); the flare-stack plume on the horizon; pressure made visible as internal glow.*

- 01 Blocked Outlet: Pressure to the PSV
- 02 Control Valve Fails Open → Gas Blowby into the Low-Pressure System
- 03 Overfill-Induced Overpressure & Relief-System Overwhelm
- 04 Heat-Exchanger Tube Rupture (High-Pressure → Low-Pressure Interface)
- 05 PSV Fails to Lift (Plugged / Frozen / Stuck)
- 06 PSV Isolated From the Equipment It Protects
- 07 Thermal (Hydraulic) Relief of Blocked-In Liquid
- 08 External Fire Case & Emergency Depressuring to Flare
- 09 PSV Chatter From Excessive Inlet Pressure Loss
- 10 Relief-Header Backpressure Defeats a Conventional PSV
- 11 Runaway Reaction Overwhelms the Relief System
- 12 Flare / Blowdown System Overload & Atmospheric Release
- 13 Check-Valve Failure: Reverse-Flow Overpressure
- 14 Low-Pressure Tank Overpressure: Blocked Pressure Vent
- 15 Vacuum & Overtemperature Relief Failure



Rotating Equipment

Visual motif: *The pump or compressor as the hero machine — heat shimmer off the casing, a glowing bearing or seal, vibration rendered as motion-blur ghosting on the teal wireframe; couplings, shafts, lube-oil skids.*

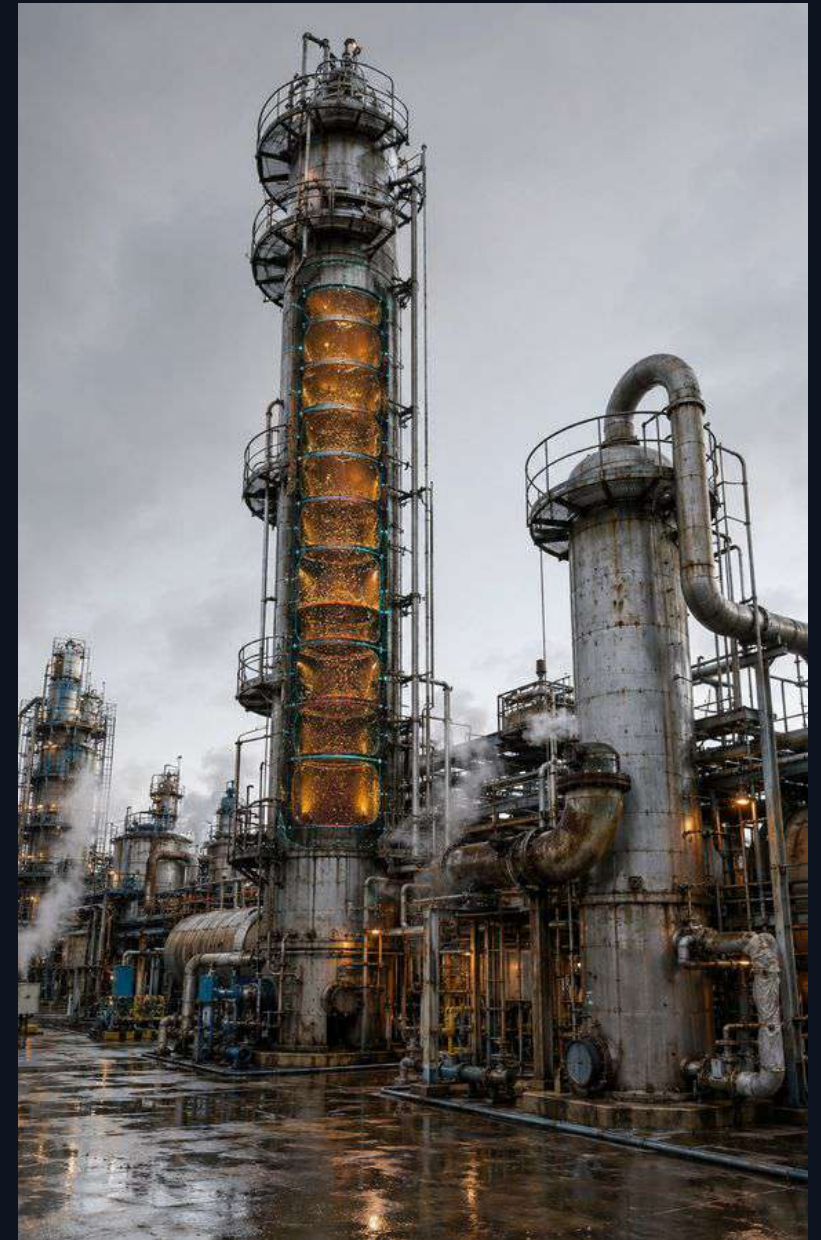
- | | |
|---|--|
| 01 Pump Dry-Running / Loss of Suction | 09 Coupling Failure / Shaft Misalignment |
| 02 Pump Minimum-Flow Violation (Low-Flow Recirculation) | 10 Motor Driver Overload / Locked-Rotor / Rapid Restart |
| 03 Mechanical Seal Failure & Loss of Seal Flush | 11 Centrifugal Compressor High Discharge-Temperature Thermal Trip |
| 04 Seal Blowout → Loss of Containment / Pump Fire | 12 Compressor Suction-Scrubber Liquid Carryover |
| 05 Standby Pump Restart Into a Defeated Boundary (Piper Alpha pattern) | 13 Reciprocating Compressor Liquid Hydraulic Lock (Slug) |
| 06 Bearing Failure & High Vibration | 14 Reciprocating Compressor Valve Failure / Interstage Overpressure |
| 07 Loss of Lube-Oil Pressure (Forced-Lube Train) | 15 Steam Turbine Overspeed / Trip |
| 08 Reverse Rotation / Backspin on Trip | |



Process Upsets & Abnormal Operations

Visual motif: Boiling gauges and foam — process chemistry misbehaving: foaming columns, surging separators, fouled exchangers, hydrate-plugged lines; level and interface chaos rendered as churning glow inside the twin wireframe.

- | | |
|---|---|
| 01 Gas Blowby (Loss of Liquid Seal in a Separator) | 09 Heat-Exchanger Fouling (Loss of Cooling / Duty Drift) |
| 02 Three-Phase Separator Interface Upset (Oil/Water) | 10 Gas Hydrate Formation & Plug in a Gas Line |
| 03 Pipeline Slugging / Separator Slug Overload | 11 Wax / Paraffin Deposition & Line Restriction |
| 04 Fired-Heater Low-Flow Tube Overheat & Rupture | 12 Winterization Freeze-Up (Instrument & Deadleg Freezing) |
| 05 Loss of Reflux (Column Pressure/Temperature Excursion) | 13 Runaway Reaction: Loss of Agitation / Mixing |
| 06 Distillation Column Flooding (Hydraulic Overload) | 14 Runaway Reaction: Mischarge / Wrong Sequence |
| 07 Amine / Glycol Contactor Foaming & Carryover | 15 Loss of Cooling-Water / Utility Failure Cascade |
| 08 Feed Composition Swing (Wet/Light Slug to a Hot Vessel) | |



Loss of Containment — Leaks, Fire & Dispersion

Visual motif: *The gas cloud and the distant fire — an amber-orange vapor cloud drifting low and heavy through the unit; jet-fire lances; pool-fire glow in a bund; the release as a living, spreading thing; escape and detection.*

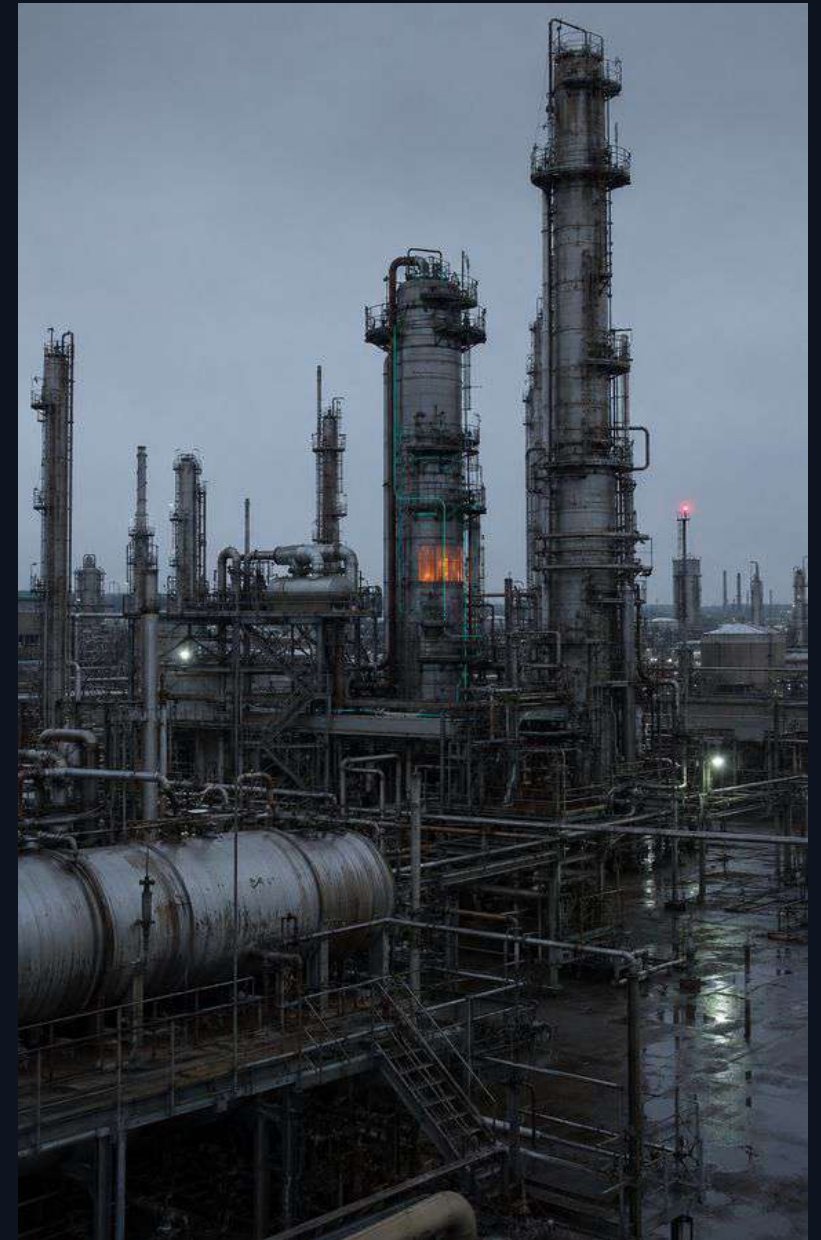
- | | |
|---|--|
| 01 Flange / Gasket Weep — Detect & Isolate Early | 09 Domino Escalation to Adjacent Equipment |
| 02 Corroded Pipe Rupture — Sudden Large Release | 10 Toxic H ₂ S Release — Sour Service |
| 03 Pump Mechanical Seal Failure — Flammable Release | 11 Toxic / Corrosive Cloud — HF or Acid Gas |
| 04 Flammable Gas-Cloud Dispersion → Vapour-Cloud Explosion (VCE) | 12 Emergency Isolation & ESD Activation |
| 05 Ignition-Source Control in a Hazardous Area | 13 Fire-&-Gas Detection and Muster / Egress |
| 06 High-Pressure Gas Jet Fire | 14 Blowout / Loss of Well Control → Gas on Deck |
| 07 Pool Fire in a Bund / Dike | 15 Spill to Secondary Containment / Bund Management |
| 08 BLEVE of an LPG Vessel | |



Utilities & Support Systems

Visual motif: *The dead control room, the dark plant — power and utility failure as darkness and silence: a blacked-out unit under moonlight, dead screens, valves slamming to fail-safe, one emergency light; the twin overlay as the only thing still glowing.*

- 01 Total Instrument-Air Failure (Plant-Wide Fail-Safe Cascade)
- 02 Local Control-Valve Air Failure (Fail-Open vs Fail-Closed Surprise)
- 03 Cooling-Water Loss (Overpressure / Overheat Cascade)
- 04 Loss of Refrigeration / Chilling on a Volatile or Reactive Inventory
- 05 Loss of Heating Medium / Hot-Oil Circulation → Cold Embrittlement
- 06 Total Electrical Power Failure / Blackout
- 07 Partial Power Loss (Single Bus / Single Driver Trip)
- 08 Loss of Backup Power (UPS / DC / Emergency Generator)
- 09 Steam-System Loss (Turbine Drives + Stripping + Tracing)
- 10 Fuel-Gas Upset (Fired-Heater Flameout / Burner Instability)
- 11 Nitrogen / Inerting (Blanket) Loss — Air Ingress
- 12 Loss of Lube Oil (Bearing / Rotor Trip)
- 13 Loss of Seal Oil / Dry-Gas Seal Supply — Compressor
- 14 Flare / Relief Header Unavailable (Overfill or Blockage)
- 15 Utility-Failure Cascade into Unit Trip (the meta-scenario)



The Mission Library — browse by genre

Genre rows

One shelf per genre + a flagship row.

Horizontal scroll

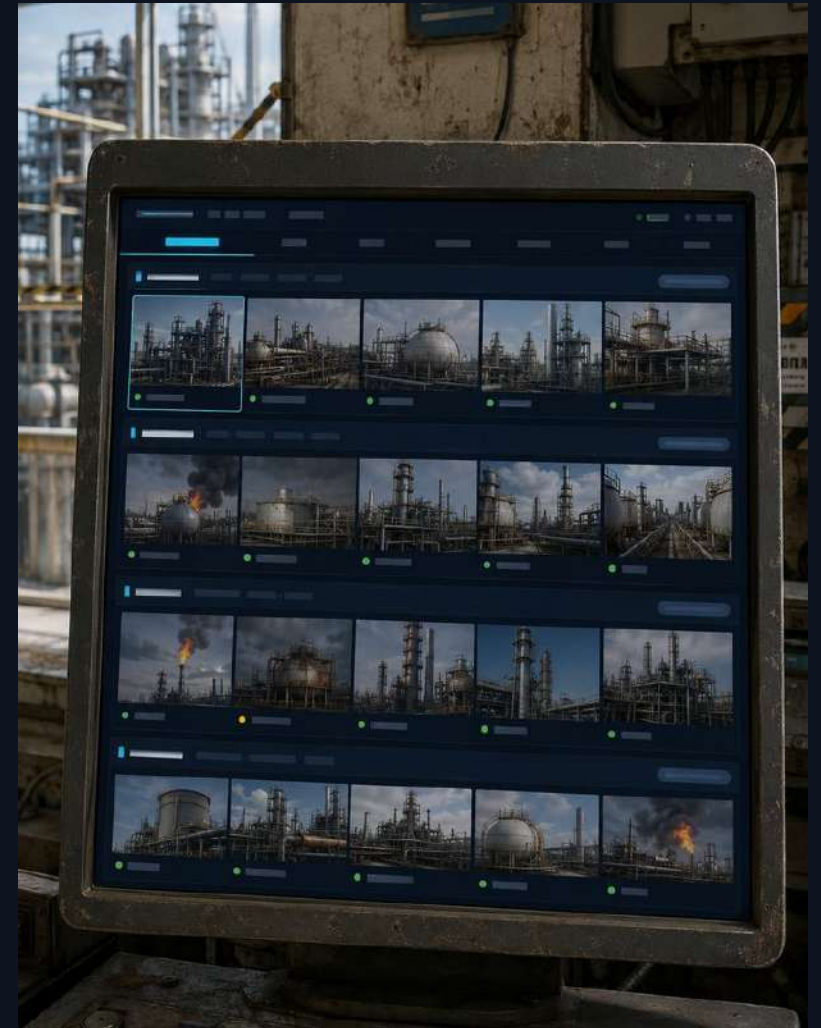
Each shelf scrolls sideways through its 15 posters.

Fit badges

Every tile shows whether it fits the loaded rig.

Greyed = doesn't fit

Non-fitting titles stay visible, greyed, with the reason on hover — never a silent grey-out.



No text is baked into posters — titles, severity and fit badges are live UI overlays.

One card tells the whole story

WHAT / WHY / HOW

Plain-language blocks: what happens, why it matters, the physics in play.

Difficulty selector

Beginner / Operator / Expert — with each level's dial summary shown.

THE FACTS — cited

Verified statistics with sources and confidence flags (verified / secondary / unverified).

▶ Run

Dresses the live Operate console. If the title doesn't fit your rig, Run is disabled and the why-not is shown instead.

Read more

mission-briefing style longer story + the named real incidents (CSB cases, dates, links).



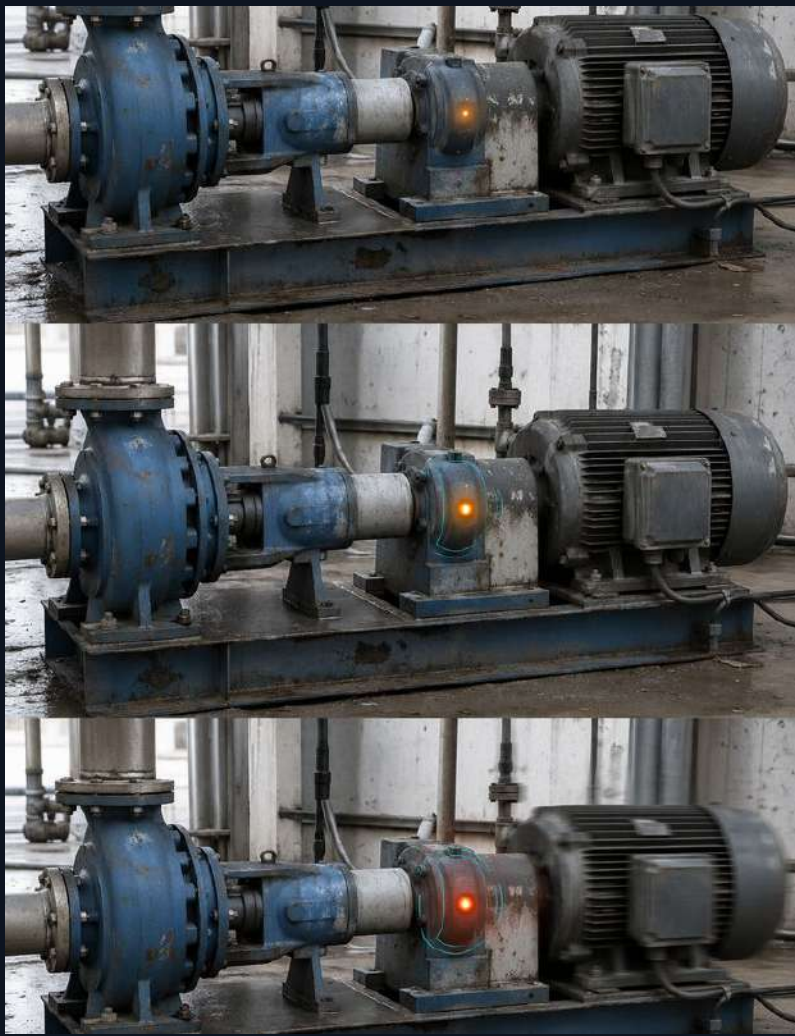
One title, three levels — difficulty is dials, not new content

All three levels run the SAME scenario card, trigger pattern and rubric — only the dials move.

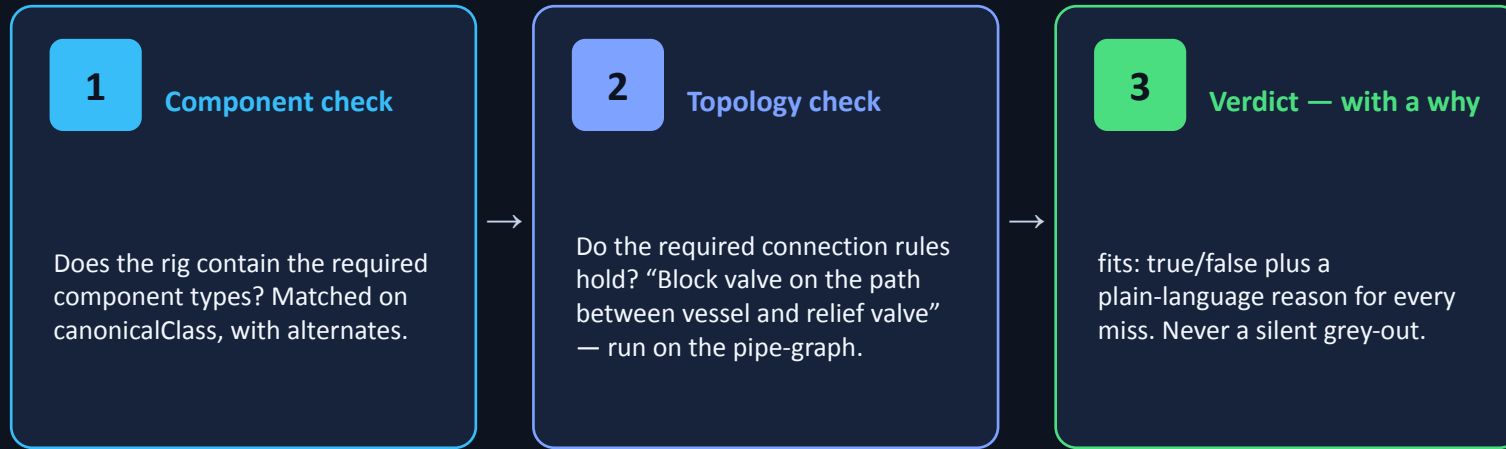
	BEGINNER	OPERATOR	EXPERT
Guidance / hints	on	off	off
Fault structure	single clean fault	single fault, subtle onset	cascade — fault triggers fault
Sensor honesty	all honest	honest	≥1 lying or dead sensor
Time & margins	generous	realistic	tight

Career Path: a guided ramp — start with easy titles on Beginner; each pass unlocks the next level and heavier genres.

v2: dynamic difficulty — the engine adjusting dials mid-run. Not in v1.



Universal reads your rig, then curates the library



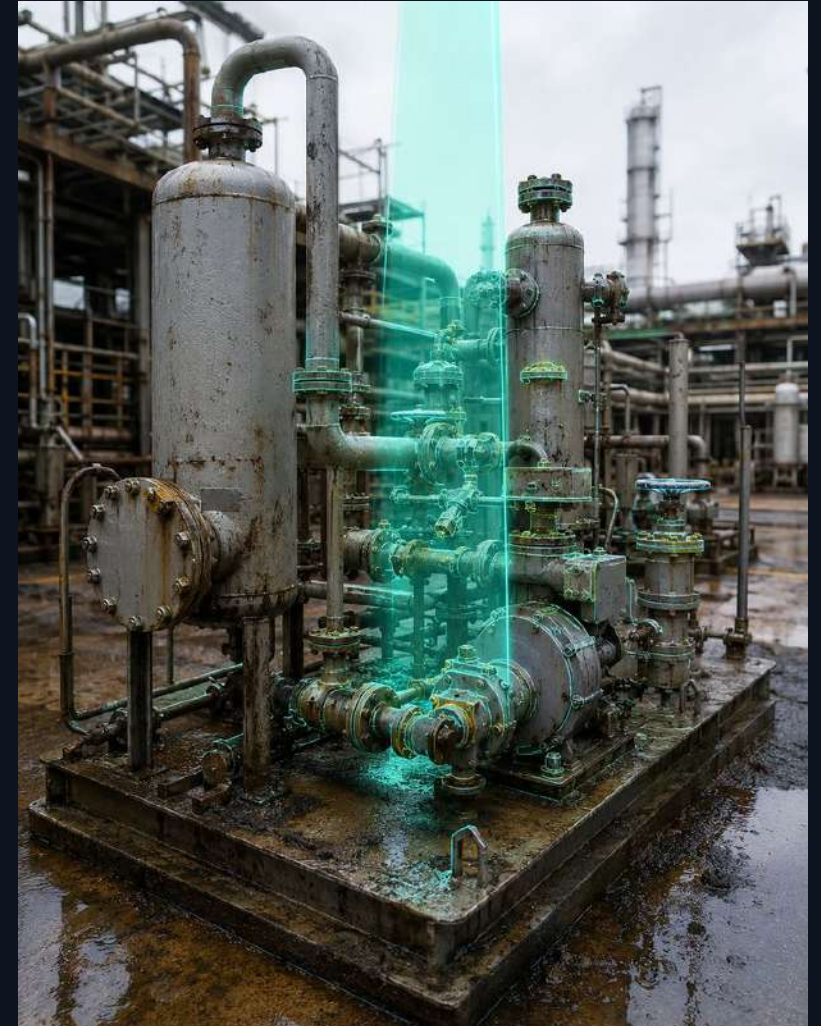
“14 of 120 scenarios fit this rig” — the gallery header, per loaded facility
(example count)

WHEN A TITLE DOESN'T FIT, IT SAYS WHY

“needs a storage tank ✗”

“has a pump ✓ but no auto-start logic ✗”

Strengtheners don't gate fit — they raise a match-quality score used to order titles within shelves.



One studio, one film — 120 posters from one kit

THE STYLE BIBLE, IN BRIEF

Night refinery — dark cinematic industrial night; honest real-world hardware — nothing sci-fi.

Teal twin glow — key equipment wears a glowing teal wireframe twin — cool, precise knowledge.

Hazard hot — the danger is amber/red and IS the subject — one beat before disaster, never aftermath.

Severity = grade — critical: red-amber dominant · high: amber · medium: blue-teal watchful.

Atmosphere — wet reflective ground, volumetric haze; people small, glow-outlined, unharmed.

NO text in images — titles and badges are live UI overlays — baked-in text gets rejected.

Naming: poster_[genre#]_[scenario#]_[slug].png
e.g. poster_03_05_psv-fails-to-lift.png — every file joins mechanically to its index row.

poster_01_02_blocked-in-from-relief.png · the master prompt, filled

Cinematic wide shot, dark industrial oil & gas facility at night, photorealistic CGI film still.

SUBJECT: a horizontal heat exchanger with a chained-shut block valve standing between it and its small relief valve, steam heat shimmering beneath. The equipment is overlaid with a glowing teal (#2DD4BF, #38BDF8) wireframe digital-twin hologram — thin luminous edge-lines and node points tracing its 3D geometry.

HAZARD: the exchanger shell skinned in a blue-to-red heatmap glow, swelling red at the center, its relief pipe dark and cold — pressure with nowhere to go. Rendered hot in amber (#F59E0B) and red-orange (#EF5B45), the visual focus of the frame.

CAMERA: low-angle along the exchanger toward the isolated relief valve.

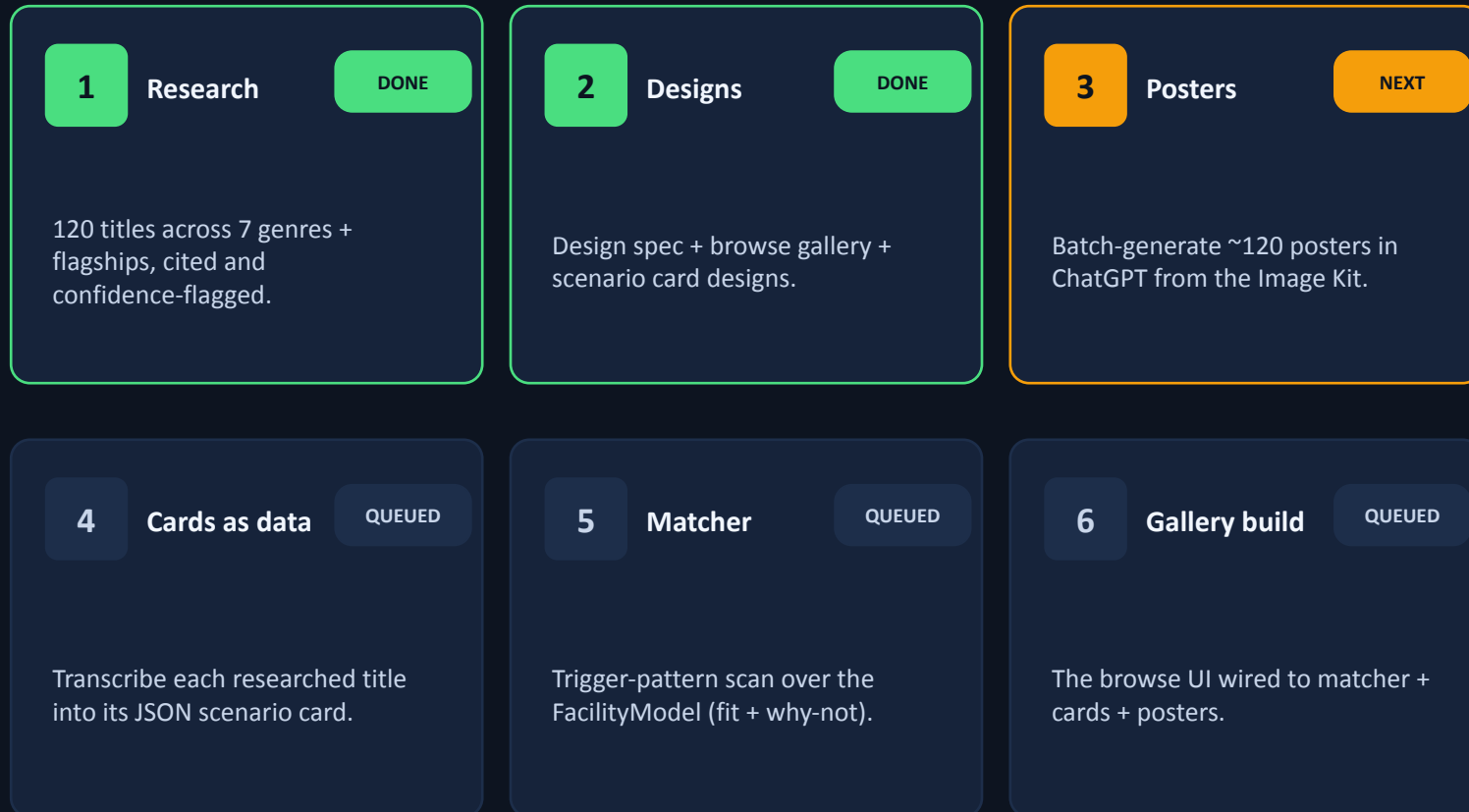
GRADE: critical — red-amber dominant, hot hazard glow dominates, teal twin-lines hold the edges.

Wet reflective concrete ground mirroring the glow, volumetric light through night haze and steam. ABSOLUTELY NO text, words, numbers, logos or signage. No gore or injury. Aspect 3:2 landscape, 1216x832.

Posters are generated in Chat GPT from this kit — same template every time, only four slots change.



Where we are, what comes next



The engine is not waiting on any of this: the live-physics core (C1–C3) is already built and adversarially verified.



The plant, running. The situations, real.

EON Live — Situation Room (working title) · 120 titles · 7 genres · 3 levels · your rig



Which situations need which hardware?

76 63%

⚙️ EQUIPMENT-BOUND

The matcher must FIND the parts — vessel + relief valve, separator + dump valve, heater, column. Offered only where the equipment exists.

29 24%

🏭 GENERIC

Built only from ubiquitous parts — pump, pipe, flange, valve, drain, gauge. Fits nearly every process facility from day one.

15 13%

📋 PROCEDURAL

The hazard is the procedure, the air, the person. Always available on any facility — runs on staged, pre-set consequences.

The Beast today: ~50 of 120 fit (estimate) — richer facilities light up more of the library.



FLAGSHIP · 15 SCENARIOS

Flagship — The Marquee Set

Visual motif — No single motif — each flagship borrows its home genre's look at marquee scale, graded by its own severity.

one card per situation follows — poster prompt in each card's notes

CRITICAL

WHAT · WHY · HOW

A worker prepares to open a pipe or vessel for maintenance. Electrical power is locked out, but pressure or trapped fluid is still bottled up behind a closed valve. Cracking the flange releases that stored energy suddenly. OSHA 29 CFR 1910.147 requires that after isolation, all potentially hazardous stored or residual energy be relieved, restrained, and rendered safe (OSHA 1910.147); LOTO is perennially an OSHA Top-10 most-cited standard, showing how routinely energy control is done wrong.

1 Isolate all energy sources (not just electrical). · 2 Bleed/vent the trapped section to zero pressure. · 3 Verify at a gauge or telltale that pressure actually reads ~0. · 4 Drain residual liquid.

HOW OFTEN · CONSEQUENCES

How often The National Safety Council reported 48 deaths tied to hazardous-energy-control failures in 2023 (NSC via LegalClarity LOTO statistics); OSHA estimates the LOTO standard prevents ~120 fatalities and ~50,000 injuries per year (OSHA modeling estimate, not a measured count); LOTO ranked #4 on OSHA's Top-10 cited standards in FY2025 with 2,177 citations (OSHA Top-10 via LegalClarity).

Consequences Sudden blowdown at the flange — struck-by, chemical burn, engulfment; hazardous-energy injuries are typically catastrophic (amputations, crush, severe burns) with ~24 lost workdays on average (OSHA LOTO fact sheet via US Made Supply).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (OSHA enforcement pattern rather than one anchor incident); the source file anchors it to the perennial Top-10 citation record.

48 hazardous-energy-control deaths in 2023 (NSC). (via LegalClarity)

[confidence-flagged stats](#) · [full cited list in slide notes](#)

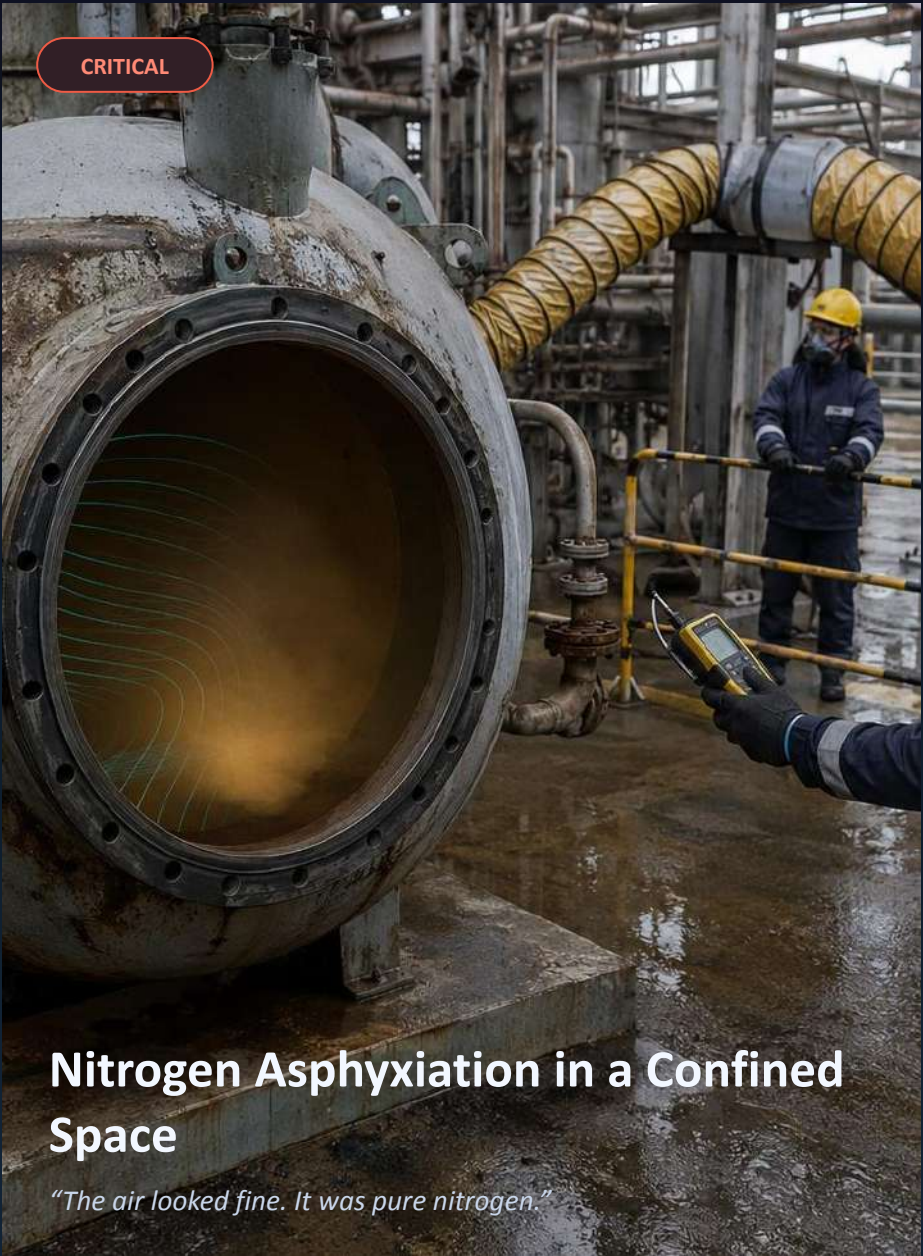
READ MORE

Full narrative, incident history and sources — in the Situation Room.

[expand ▼](#)

Stored-Pressure Release During Maintenance (LOTO)

"He locked the switch, opened the flange, and the line that was "empty" wasn't."



CRITICAL

Nitrogen Asphyxiation in a Confined Space

“The air looked fine. It was pure nitrogen.”

WHAT · WHY · HOW

A vessel is purged with nitrogen to keep oxygen out. A worker enters or reaches in without confirming breathable air and is overcome in seconds; a would-be rescuer rushes in and is overcome too. CSB identified 85 nitrogen incidents in the U.S. (1992–2002) causing 80 deaths (CSB Nitrogen Asphyxiation Bulletin 2003); nitrogen is odorless and colorless — an oxygen-deficient atmosphere gives no warning and is detectable only with an instrument.

- 1 Verify O₂ with a calibrated meter before any entry or reach-in.
- 2 Enter only under permit, with ventilation and an attendant.
- 3 Use supplied air where the atmosphere cannot be verified safe.
- 4 If someone collapses, call trained rescue — never attempt an impulsive self-rescue.

HOW OFTEN · CONSEQUENCES

How often CSB: 85 nitrogen incidents / 80 deaths over 1992–2002 (~8 deaths/yr) (CSB Bulletin 2003); more broadly, BLS counted 1,030 confined-space occupational deaths 2011–2018 (~129/yr, range 88–166) (BLS fact sheet).

Consequences Collapse within one or two breaths below ~10% O₂; frequent multiple fatalities because rescuers follow — ~60% of confined-space fatalities are would-be rescuers (NIOSH-derived figure via safety-industry compilations); contractors were 60%+ of CSB's nitrogen fatalities (CSB Bulletin).

THE FACTS — CITED STATS

✓ VERIFIED

Valero Delaware City refinery, 2005 (CSB case study) — contract worker asphyxiated reaching into a nitrogen-purged reactor; his foreman died attempting...

80 deaths from nitrogen asphyxiation in the U.S., 1992–2002 (85 incidents). (CSB)

confidence-flagged stats · full cited list in slide notes

READ MORE

Full narrative, incident history and sources — in the Situation Room.

expand ▾

CRITICAL

WHAT · WHY · HOW

Welding, cutting, or grinding is done on or near a tank that still holds flammable residue or vapor. The sparks ignite the vapor space and the tank or piping ruptures. CSB's Hot Work Safety Bulletin (2010) identified 60+ fatalities since 1990 from hot-work fires/explosions on or near tanks, and mandates hazard assessment plus atmosphere monitoring with a calibrated combustible-gas detector before and during work (CSB Hot Work Bulletin).

- 1 Consider alternatives to hot work first.
- 2 Do a hazard assessment; isolate/clean the tank and connected lines.
- 3 Gas-test with a calibrated detector — verify well below LEL.
- 4 Monitor continuously during the work, not just at the start.

HOW OFTEN · CONSEQUENCES

How often CSB counts 60+ hot-work fatalities since 1990 (~1.7/yr in its incident set) (CSB Hot Work Bulletin 2010); U.S. fire departments responded to an average 4,630 structure fires involving hot work per year (2013–2017) (NFPA via BHHHC Safety Center).

Consequences Tank/piping rupture and deflagration; multiple-fatality events are typical of the class — 3 killed at PCA Tomahawk alone (CSB).

THE FACTS — CITED STATS

✓ VERIFIED

Packaging Corp. of America, Tomahawk WI, 29 July 2008 — welding above an 80-ft tank ignited hydrogen from decomposing fiber waste; 3 workers killed (CSB).

60+ hot-work fatalities since 1990 in CSB's dataset. (CSB Hot Work Bulletin 2010)

source: CSB · confidence-flagged stats · full cited list in slide notes

READ MORE

Full narrative, incident history and sources — in the Situation Room.

expand ▾

Hot Work Ignition of Trapped Flammable Vapor

"One spark, one tank, and the vapor nobody tested for."

CRITICAL



Distillation Column Overfill on Start-Up

“The gauge said the tower was low. It was already flooding.”

WHAT · WHY · HOW

During start-up a distillation tower is filled while the drain path stays closed and the level reading misleads. The tower overfills and pushes liquid into downstream equipment not designed to take it. BP Texas City (23 March 2005): the raffinate splitter was overfilled and overheated during startup; liquid overflowed to a blowdown drum/stack, the vapor cloud ignited — 15 dead, 170+ injured. CSB cited a bottoms valve left closed for hours and misleading level indication (CSB investigation).

- 1 Treat startup level indications as suspect — cross-check independent indications (flows in vs out...
- 2 Confirm the bottoms draw-off path is open before and during filling.
- 3 Restore outflow at the first sign of level divergence.
- 4 Hold level in band; never let the tower fill blind toward the overhead.

HOW OFTEN · CONSEQUENCES

How often CCPS: process safety incidents occur ~5× more often during startup than normal operations, and ~50% of process safety events occur in the <10% of time spent in transient operations (CCPS via Chemical Processing "Tame Your Transient Operations", LNS Research). Column-overfill-specific rates: not quantified in public sources.

Consequences Liquid carryover to blowdown/flare, vapor cloud formation, and explosion — Texas City killed 15 and injured 170+, the worst U.S. refinery accident since 1989 (CSB).

THE FACTS — CITED STATS

✓ VERIFIED

BP Texas City refinery, 23 March 2005 (CSB) — 15 dead, 170+ injured.
Startup incidents ≈ 5× more frequent than normal operation (CCPS). (Chemical Processing/CCPS)
confidence-flagged stats · full cited list in slide notes

READ MORE

Full narrative, incident history and sources — in the Situation Room.

expand ▾

HIGH

WHAT · WHY · HOW

After maintenance, an exchanger or reactor is brought back online. Pressure and temperature are ramped, and a weakened, under-verified component fails suddenly, releasing hot hydrocarbon that ignites. Tesoro Anacortes (2 April 2010): during a post-maintenance restart a shell-and-tube exchanger catastrophically ruptured from High-Temperature Hydrogen Attack; hot hydrogen and naphtha auto-ignited, killing 7. ...

1 Check the component's inspection/condition status before restart. · 2 Ramp pressure and temperature in stages, within specified rate limits. · 3 Watch for abnormal readings during the ramp; hold points are mandatory. · 4 Escalate rather than force when condition data is ambiguous.

HOW OFTEN · CONSEQUENCES

How often The 2016 edition of API RP 941 records 13 new HTHA failures below the carbon-steel Nelson curve (all non-PWHT carbon steel) — enough to force a new design curve (NACE CORROSION 2016 paper on API RP 941 data); more broadly, ~50% of process safety events occur during transient operations (CCPS/LNS). Absolute restart-failure rates: not quantified in public sources.

Consequences Catastrophic rupture and auto-ignition of hot hydrogen/naphtha — 7 dead at Tesoro Anacortes, the deadliest U.S. refinery event since Texas City (CSB).

THE FACTS — CITED STATS

✓ VERIFIED

Tesoro Anacortes refinery, 2 April 2010 (CSB) — HTHA exchanger rupture, 7 dead.

Tesoro Anacortes 2010: 7 killed in an HTHA rupture during post-maintenance restart. (CSB)

confidence-flagged stats · full cited list in slide notes

READ MORE

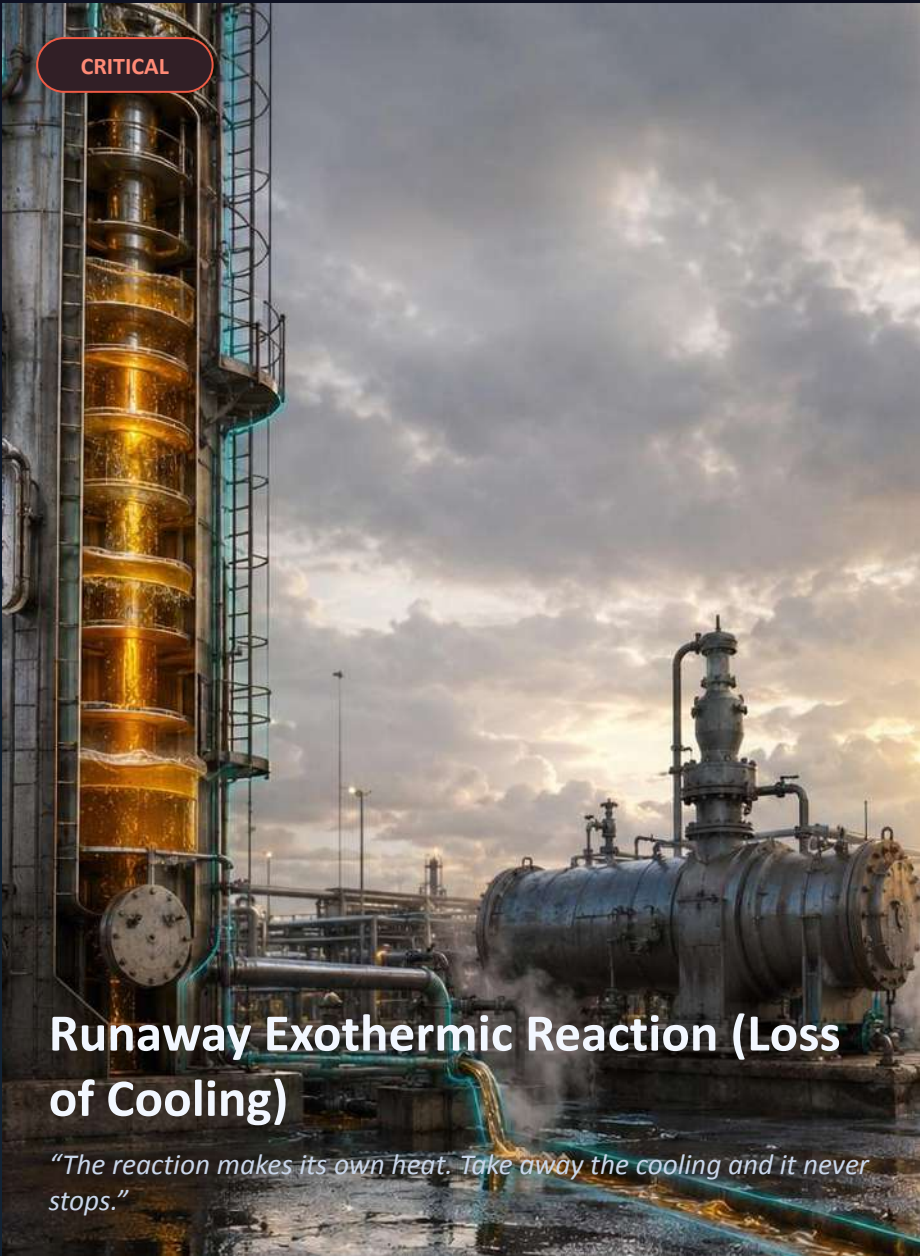
Full narrative, incident history and sources — in the Situation Room.

expand ▼

Heat-Exchanger / Reactor Cold Restart Transient

"Bring it back up too hard, and steel that looked fine lets go."

CRITICAL



Runaway Exothermic Reaction (Loss of Cooling)

“The reaction makes its own heat. Take away the cooling and it never stops.”

WHAT · WHY · HOW

An exothermic reaction needs constant cooling to stay controlled. When cooling is lost, temperature climbs, which speeds the reaction, which makes more heat — a runaway that spikes pressure until the vessel bursts. T2 Laboratories (19 December 2007): loss of reactor cooling during MCMT production caused a thermal runaway; the ~2,500-gal reactor burst with a blast likened to ~1,400 lb TNT, killing 4 and injuring 32. ...

- 1 Detect rising temperature against falling cooling duty early.
- 2 Restore cooling immediately (standby pump/coolant path).
- 3 If cooling can't be restored, add quench/inhibitor to kill the reaction.
- 4 Initiate emergency depressuring before the runaway threshold.

HOW OFTEN · CONSEQUENCES

How often 167 serious reactive-chemical incidents occurred in the U.S. 1980–2001, ~35% caused by thermal runaway (~3/yr) (CSB reactive hazards data via Texas A&M MKOPSC thesis); China logged 271 thermal-runaway incidents 1984–2019 (J. Loss Prevention, ScienceDirect); ~24–25% of European/French chemical accidents involve reaction runaway (ScienceDirect review).

Consequences Reactor burst and explosion — T2's blast (≈1,400 lb TNT equivalent) killed 4, injured 32, and destroyed the facility (CSB).

THE FACTS — CITED STATS

✓ VERIFIED

T2 Laboratories, Jacksonville FL, 19 December 2007 (CSB) — 4 dead, 32 injured.
U.S. 1980–2001: 167 reactive incidents, 35% thermal runaway. (CSB data via MKOPSC)
confidence-flagged stats · full cited list in slide notes

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HIGH

WHAT · WHY · HOW

A separator or knock-out drum keeps liquid out of gas going to a compressor or flare. Its level control fails, liquid backs up and carries over, and the downstream machine gets slugged with liquid it can't handle. Carryover events feed the industry's API RP 754 process-safety-event metrics (Tier 1/2 loss-of-containment classes) (API RP 754 fact sheet); liquid into a centrifugal compressor is essentially incompressible into the rotor — surge and mechanical damage follow (rotating-equipment sources).

1 Detect the rising level despite the failed loop (cross-check gauge vs transmitter vs flows). · **2** Take manual control of the dump valve or switch to standby control. · **3** Reduce inlet feed to buy time. · **4** Prevent liquid reaching the gas outlet; verify downstream machines are protected.

HOW OFTEN · CONSEQUENCES

How often Class-level composite — no single-incident statistic; LOPA practice assigns a BPCS level-loop failure $\sim 1 \times 10^{-1}$ per year per loop as the initiating-event frequency (HAZOP360/CCPS LOPA guidance, iFluids LOPA example: level controller $\approx 1 \times 10^{-7}$ /yr).

Consequences Compressor surge/mechanical damage, fired-heater flame instability, or liquid slugs into the flare — API 754-reportable loss-of-containment pathways (API RP 754; see card_00_13 for surge mechanics).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (composite of a common upset class; no single named CSB case).

Carryover/upset events are tracked industry-wide as API RP 754 Tier 1/2 process safety events. (API RP 754 fact sheet)

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Level-Control Failure & Liquid Carryover

"The drum was supposed to catch the liquid. It sent it downstream instead."



GENERIC

FLAGSHIP

TRAIN / OPERATE / FIELD

HIGH



Blocked-In Liquid Thermal Expansion Overpressure

“Trap cold liquid in a pipe, let the sun hit it, and something has to give.”

WHAT · WHY · HOW

A liquid-full pipe or exchanger is valved shut at both ends. As it warms, the liquid tries to expand with nowhere to go; pressure shoots up until it lifts a relief valve or ruptures the weakest fitting. API 521 explicitly names hydraulic (thermal) expansion of blocked-in liquid as a standard overpressure case to design against (API 521 via AText overview); because liquids are nearly incompressible, only a small temperature rise is needed, and a tiny 3/4"x1" thermal relief valve suffices to protect it.

- 1 Recognize the blocked-in liquid-full condition after an operation (isolation both ends).
- 2 Identify the heat source warming it (sun, tracing, adjacent process).
- 3 Establish a relief/expansion path — crack a vent or confirm the thermal relief valve is in service.
- 4 Institutionalize: never leave liquid-full sections blocked without thermal relief.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (a design-basis overpressure case under API 521 rather than a tracked event class).

Consequences Rupture of the weakest fitting — flange leak, gasket blowout, or pipe failure — releasing process liquid; the steep P-vs-T rise gives little warning (API 521 thermal-expansion case; PSV-sizing guidance).

THE FACTS — CITED STATS

✓ VERIFIED

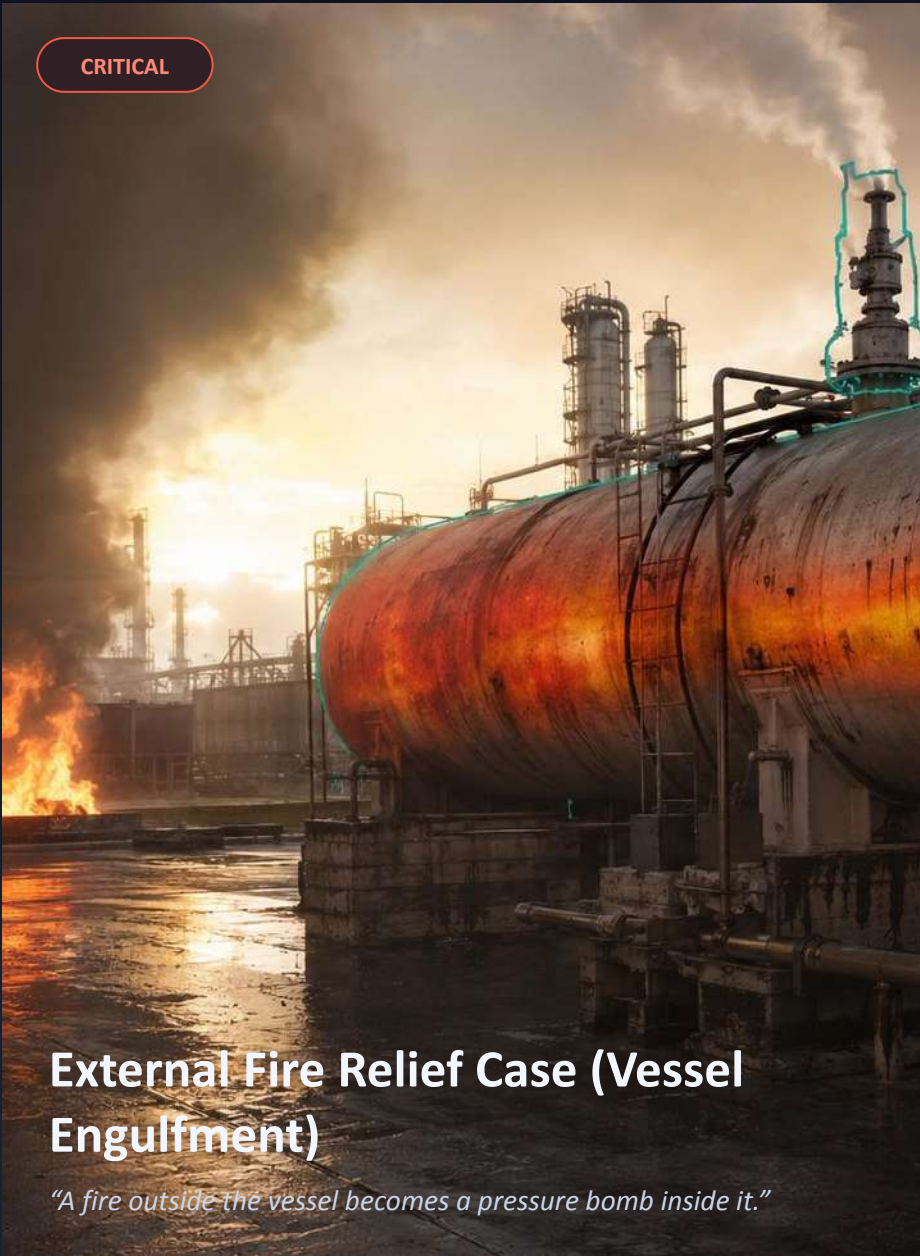
Class-level (API 521 design case; no single named anchor).
API 521 names hydraulic (thermal) expansion as a standard overpressure contingency. (API 521 via AText)
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CRITICAL



External Fire Relief Case (Vessel Engulfment)

“A fire outside the vessel becomes a pressure bomb inside it.”

WHAT · WHY · HOW

A fire near a pressure vessel heats it from outside, boiling the liquid inside and building pressure. The relief device must open and vent fast enough to keep the vessel from bursting while it's being cooked. API 521 defines the fire case — external pool-fire heat input to a vessel — as a primary sizing basis for relief and depressuring systems across refining and petrochemicals (API 521 via ATex); applying API 520 sizing without API 521 scenario analysis is a recognized serious error (Inspenet API...

- 1 Confirm the relief/depressuring system is active and the path is clear.
- 2 Initiate emergency depressuring (blowdown) if available.
- 3 Apply cooling water to the engulfed vessel.
- 4 Make the escalation/evacuation call correctly as the pressure trend dictates.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (fire-engulfment relief is a universal design-basis case under API 521 rather than a published event rate).

Consequences Uncontrolled fire-driven overpressure can escalate to BLEVE / vessel rupture with blast and fireball (general process-safety knowledge; represent as a state change, not a resolved blast).

THE FACTS — CITED STATS

Class-level (API 521 design case; no single named anchor in the source research).
API 521's fire case governs relief/depressuring sizing industry-wide. (API 521 via ATex)
confidence-flagged stats · full cited list in slide notes

✓ VERIFIED

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HIGH



Blocked Outlet Overpressure to Relief

“Close the wrong valve with the pumps still running and pressure has nowhere to go.”

WHAT · WHY · HOW

An outlet valve is shut by mistake or control failure while feed keeps coming. Pressure climbs with no way out, and the relief valve becomes the only thing between normal operation and a rupture. API 521 lists "blocked outlet" among the primary overpressure causes a relief system must be designed for (API 521 via ATex); relief is the last line of defense — if the path is undersized, isolated, or plugged, overpressure proceeds to rupture (API 520/521 via Inspenet).

- 1 Diagnose the blocked outlet from the pressure trend and flow mismatch.
- 2 Find and clear the block (or open the correct bypass).
- 3 Cut or reduce feed while the block is being cleared.
- 4 Verify relief availability throughout — ideally keep the system off the relief valve entirely.

HOW OFTEN · CONSEQUENCES

How often LOPA practice treats inadvertent valve closure / BPCS control failure at $\sim 1 \times 10^{-1}$ per year per loop as the initiating event for blocked-outlet cases (HAZOP360/CCPS LOPA initiating-event guidance). Blocked-outlet event rates specifically: not quantified in public sources.

Consequences Overpressure to relief lift; if relief is unavailable or undersized, vessel/pipe rupture and loss of containment (API 520/521 design rationale).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (API 521 design case; no single named anchor).
API 521 names blocked outlet among primary overpressure causes (with fire, control failure, tube rupture). (API 521 via ATex)
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HIGH

Pump Dead-Head (Closed Discharge)

“A running pump with a shut discharge cooks itself from the inside.”

WHAT · WHY · HOW

A centrifugal pump runs with its discharge valve closed. The same liquid churns inside, heats from friction, and can flash to vapor — destroying seals and bearings and in the worst case over-pressuring or bursting the casing. Dead-heading heats trapped liquid until it flashes, cutting cooling to seals/bearings — seal failure, cracked bushings, and possible casing rupture/explosion follow (StreamPumps; Hayes Pump); the standard safeguard is a minimum-flow bypass or automatic recirculation valve.

- 1 Recognize dead-head: motor running, flow zero, discharge pressure at shut-off head.
- 2 Watch casing/fluid temperature rise as confirmation.
- 3 Open a flow path — discharge valve or min-flow bypass.
- 4 If no path can be opened promptly, stop the pump before seal/casing damage.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (dead-heading events are not tracked as a public statistic).

Consequences Seal failure and leakage, bearing damage, vapor-bound rotor, and in extreme cases casing overpressure/rupture with release of hot fluid (StreamPumps; Hayes Pump).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (no single named anchor).

At zero flow, nearly all shaft power becomes heat in the trapped liquid — rapid temperature rise. (pump-engineering sources)

source: no single named anchor · confidence-flagged stats · full cited list in slide notes

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MED

WHAT · WHY · HOW

When suction pressure drops too low — hot liquid, clogged strainer, low tank level, throttled suction — vapor bubbles form at the impeller and implode, hammering the metal, causing vibration, and wrecking seals and bearings. Cavitation occurs when suction pressure falls below the liquid's vapor pressure; the imploding bubbles erode/pit the impeller and casing and damage seals/bearings (IPE Pumps; Michael Smith Engineers). The design rule is NPSH-available > NPSH-required.

1 Recognize the onset — gravel-rattle noise, vibration, erratic flow/pressure. · 2 Identify which NPSH term collapsed (level, temperature, strainer, suction valve). · 3 Restore margin: raise level, open/clean suction, cool the fluid, or slow the pump. · 4 Verify smooth operation and inspect for damage if it ran cavitating.

HOW OFTEN · CONSEQUENCES

How often No per-year rate published; industry compilations attribute nearly 60% of premature pump failures to improper suction conditions — the cavitation precursor (Alfa Pumps cavitation overview, secondary compilation).

Consequences Impeller pitting/erosion, seal and bearing failure, performance loss, and eventual pump wreck if run in cavitation (IPE Pumps; Rotech).

THE FACTS — CITED STATS

Class-level (no single named anchor).

~60% of premature pump failures linked to improper suction conditions. (Alfa Pumps, secondary)

source: no single named anchor · confidence-flagged stats · full cited list in slide notes

SECONDARY

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Pump Cavitation / Low NPSH

"It sounds like the pump is chewing gravel — that's the impeller eating itself."

HIGH



Centrifugal Compressor Surge

“Push a compressor past its limit and the gas slams backward through it.”

WHAT · WHY · HOW

When flow through a centrifugal compressor drops too low for its pressure ratio, flow suddenly reverses and slams back and forth. Surging shakes the machine, hammers the thrust bearing, and can wreck seals and impeller in seconds. Surge causes rapidly alternating axial thrust that overloads the thrust bearing, pressure pulsations that damage seals, and can drive catastrophic impeller failure; axial machines can be damaged after only a few surge cycles (Petrotech; PGJ). The safeguard is a fast-acting anti-surge control system.

- 1 Track the operating point against the surge line as demand or head changes.
- 2 Open the anti-surge/recycle valve at the controller's line — or manually if the controller fails.
- 3 Alternatively restore forward flow or reduce speed/head.
- 4 Confirm the point is safely right of the surge line before returning to auto.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (surge events per machine-year are not published; industry practice treats every approach to the surge line as an anti-surge-system demand).

Consequences Thrust-bearing overload, seal destruction, impeller failure within a few cycles — a wrecked machine and a unit outage (Petrotech; PGJ).

THE FACTS — CITED STATS

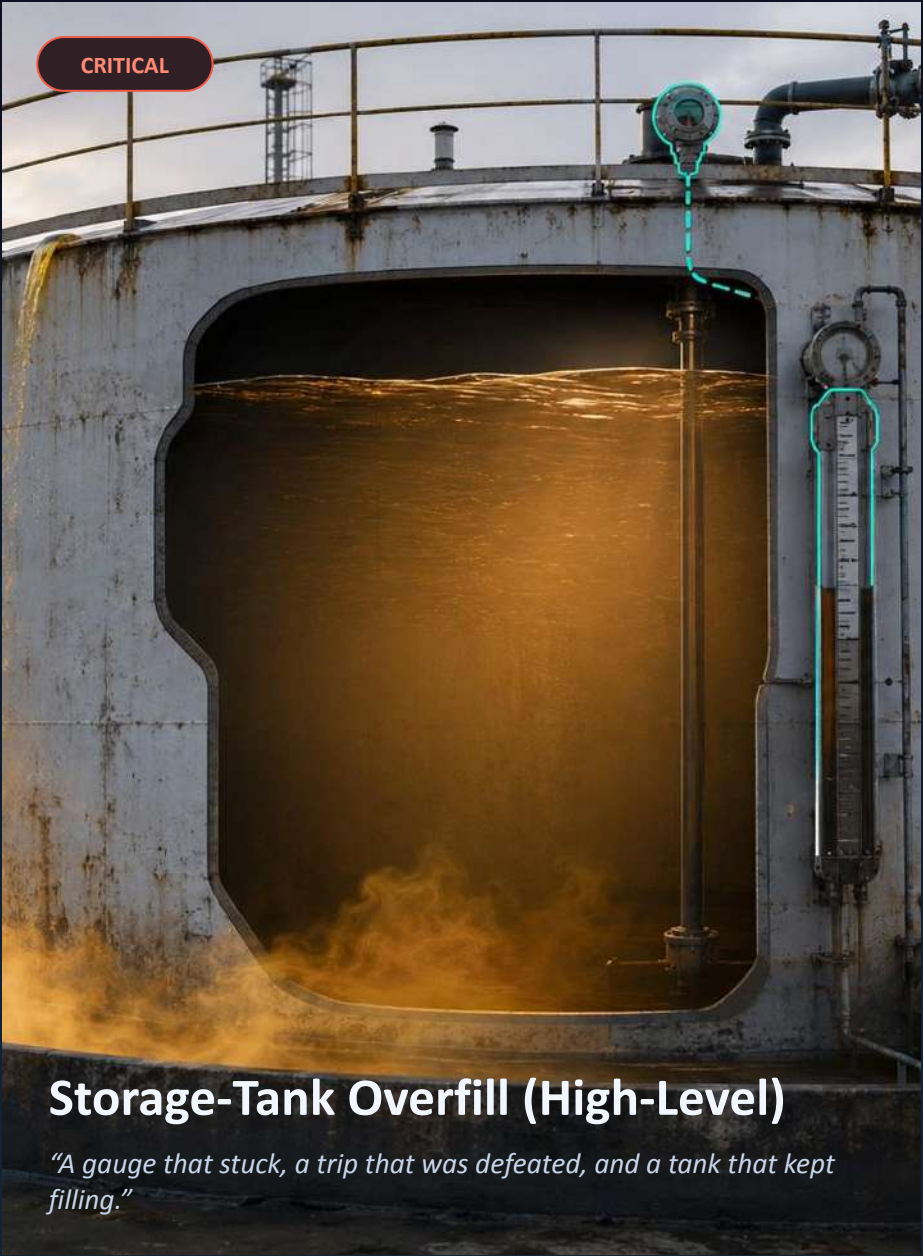
✓ VERIFIED

Class-level (no single named anchor).
Axial compressors can be damaged after only a few surge cycles. (Petrotech/PGJ)
source: no single named anchor · confidence-flagged stats · full cited list in slide notes

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WHAT · WHY · HOW

A tank is being filled while its level gauge stops updating and the independent high-level cutoff isn't working. The tank overflows, a large flammable vapor cloud forms at ground level, and finds ignition. Buncefield (11 December 2005): tank 912 overfilled ~300 tonnes of gasoline; the gauge had stuck (a known intermittent fault) and the independent high-level switch was inoperable because a required padlock was never fitted. ...

- 1 Confirm the high-level trip is functional BEFORE starting the transfer.
- 2 Cross-check level by independent means during filling (volume balance, timing, manual gauging).
- 3 Treat a non-moving gauge during an active fill as failed, not fine.
- 4 Stop the transfer at the first unresolvable discrepancy.

HOW OFTEN · CONSEQUENCES

How often Insurance-industry data: overfills occur about once per 3,300 tank fillings — the statistic behind API 2350's overfill-prevention requirements (Emerson, The Complete Guide to API 2350).

Consequences Overflow, ground-level vapor cloud (~360 m diameter at Buncefield before igniting ~22 minutes after first CCTV sighting), explosion and multi-tank fire; Buncefield injured 43 and destroyed the terminal (Buncefield MIIB).

THE FACTS — CITED STATS

✓ VERIFIED

Buncefield oil storage depot, Hemel Hempstead, UK, 11 December 2005 (MIIB).
~1 overfill per 3,300 fillings (insurance data underpinning API 2350). (Emerson/API 2350 guide)
source: MIIB · confidence-flagged stats · full cited list in slide notes

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HIGH



Atmospheric Tank Vacuum Collapse

"You can crush a giant steel tank with almost no vacuum at all."

WHAT · WHY · HOW

Atmospheric tanks are strong against slight internal pressure but very weak against vacuum. Pump out liquid too fast, cool a steam-filled tank quickly, or lose the nitrogen blanket, and outside air pressure buckles the tank like a soda can. Atmospheric and low-pressure tanks are structurally weak against underpressure — even a small differential buckles them (AIChE CEP 2019 — Protect Tanks from Overpressure and Vacuum; ChemEngZone); API 2000 sets the venting requirements against both over- and under-pressure.

1 Recognize the in-breathing demand (fast pump-out, steam-out cooldown, blanket loss). · **2** Verify the vacuum vent / blanketing make-up is functioning. · **3** Slow the withdrawal rate to within venting capacity. · **4** If vacuum keeps developing, stop outflow and open a make-up path (vent/manway) before the collapse threshold.

HOW OFTEN · CONSEQUENCES

How often No absolute rates published — qualitatively, tanks fail under vacuum far more often than under overpressure (de Nevers, "Vacuum Collapse of Vented Tanks," Process Safety Progress 1996); dramatic tank failures feature in about a quarter of CCPS Beacon case histories (Chemical Processing). Frequency: not quantified in public sources.

Consequences Structural buckling and collapse of the tank, loss of contents and containment, and a destroyed asset — often within minutes of the venting imbalance (AIChE CEP 2019; ChemEngZone case histories).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (rich case-history literature — e.g., steam-out collapse cases in AIChE CEP/CCPS Beacon — but no single canonical anchor).

Vacuum failures of tanks are more frequent than overpressure failures. (de Nevers 1996, Process Safety Progress)

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GENRE 01 · 15 SCENARIOS

Safety, Isolation & Stored Energy (LOTO)

Visual motif — Padlocks, tags and lock-out chains; a half-unbolted flange; trapped energy glowing hot inside the teal wireframe.

one card per situation follows — poster prompt in each card's notes

CRITICAL



Line Breaking on an Un-drained Line

“They'd been trying to pull that pipe for two weeks. It was still full of naphtha.”

WHAT · WHY · HOW

A crew has to remove a leaky pipe attached to a big hot tower that is still running. They think the pipe is empty, but it is still full of flammable liquid. If they open it, the liquid pours onto the hot tower and catches fire. This exact mistake killed 4 workers at the Tosco Avon refinery in 1999.

- 1 Confirm every isolation valve on the line is shut (and blinded where required) against a written isolation...
- 2 Run the drain and prove the line goes to zero — and stays at zero.
- 3 Check the telltale/bleed independently; do not trust valve position alone.
- 4 Refuse the cut while any live or unverified path into the line remains.

HOW OFTEN · CONSEQUENCES

How often No public rate specific to line-breaking releases. Family-level: OSHA estimates compliance with the LOTO standard (29 CFR 1910.147) prevents ~120 fatalities and ~50,000 injuries per year (OSHA Fact Sheet FS-3529); LOTO was the #4 most-cited OSHA standard in FY2025 (secondary sources report the citation count between 2,177 and 2,562).

Consequences Tosco Avon (Martinez CA, 1999): naphtha released from a line never drained or isolated during 13 days of attempts ignited on the hot fractionator — 4 workers killed, 1 seriously injured; 3 of the dead were contractors (CSB final report).

THE FACTS — CITED STATS

✓ VERIFIED

Tosco Avon refinery naphtha fire — Martinez CA, 23 February 1999 — 4 dead, 1 seriously injured (CSB).
4 killed, 1 seriously injured replacing piping on a running crude fractionator (CSB, Tosco Avon, 1999)
source: CSB · confidence-flagged stats · full cited list in slide notes

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CRITICAL



Blocked-In Equipment Isolated From Its Relief Device

“Someone shut the valves between the vessel and its safety valve. Then the heat came on.”

WHAT · WHY · HOW

A spare heat exchanger is parked full of liquid propane with all its valves shut — including, by mistake, the valves between it and its safety relief valve. Then someone turns the heat back on. With the safety valve cut off, the trapped liquid expands with nowhere to go and the vessel bursts. At Williams Geismar in 2013 this killed 2 workers and injured 167.

- 1 Before admitting any heat, walk the relief path and confirm every block valve in it is open...
- 2 Treat a valved-out relief device as an immediate stop-work condition.
- 3 If the vessel is blocked in and liquid-full, relieve or remove the inventory first.
- 4 Only admit heat once the relief path is verified in service.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for this specific failure class (relief path valved out + heat admitted). Family-level: LOTO/isolation errors are the #4 most-cited OSHA standard in FY2025.

Consequences Williams Olefins (Geismar LA, 2013): the off-line reboiler over-pressured and catastrophically ruptured (BLEVE) and burned — 2 workers killed, 167 injured, mostly contractors (CSB case study).

THE FACTS — CITED STATS

✓ VERIFIED

Williams Olefins plant explosion — Geismar LA, 13 June 2013 — 2 dead, 167 injured (CSB).
2 killed, 167 injured in the Geismar reboiler BLEVE (CSB, 2013)
source: CSB · confidence-flagged stats · full cited list in slide notes

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CRITICAL



Toxic Trapped Liquid in a Vent / Drain Header

“They opened the drain valves expecting water. It was liquid methyl mercaptan.”

WHAT · WHY · HOW

Workers inside a building open drain valves on a pipe header to fix a pressure alarm, thinking the trapped liquid is just water. It's actually a poisonous chemical that turns to gas the moment it gets out. In a closed room the gas builds up fast and there's no time to escape. At DuPont La Porte in 2014, four workers died this way.

- 1 Before opening any drain, positively identify what is actually trapped in the header (records, prior work... · 2 Confirm where the released material will go — never into an occupied or enclosed space. · 3 Verify building ventilation and toxic-gas detection are working. · 4 Stage the right PPE before cracking the first valve.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for this specific class (toxic trapped liquid released from a drain header indoors). Adjacent class: BLS counted 126 fatal single-episode inhalations of a harmful substance in confined spaces, 2011–2018 (BLS CFI fact sheet).

Consequences DuPont La Porte (TX, 2014): ~24,000 lb of methyl mercaptan released inside a manufacturing building; 4 workers died (three operators and a shift supervisor) from asphyxia/toxic exposure (CSB report 2015-01-I-TX).

THE FACTS — CITED STATS

✓ VERIFIED

DuPont La Porte methyl mercaptan release — La Porte TX, 15 November 2014 — 4 dead (CSB).
~24,000 lb methyl mercaptan released indoors; 4 dead (CSB, 2014 incident, report 2019)
source: CSB · confidence-flagged stats · full cited list in slide notes

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CRITICAL

WHAT · WHY · HOW

A worker walks into a pump house to check a broken pump. Nobody locked the pump out, so its automatic controls are still live — and it starts by itself while he's standing next to it, releasing poison gas (H₂S). H₂S can knock you out in seconds, and the next person who comes looking becomes the second victim. At Aghorn in 2019 both a worker and his wife died this way.

1 Apply and verify LOTO before touching the pump — including defeating the auto-start logic. · 2 Confirm zero energy (try-start / verify the pump cannot activate). · 3 Wear and confirm a working personal H₂S monitor; check building gas detection and ventilation. · 4 If someone goes down, do NOT rush in — rescue only with monitoring and supplied air.

HOW OFTEN · CONSEQUENCES

How often H₂S killed 46 US workers 2011–2017 and 106 workers 2001–2017 (BLS data, ~6–8/yr); H₂S is among the leading causes of workplace gas-inhalation deaths (OSHA H₂S overview). Rate specific to auto-start-during-troubleshooting events: not quantified in public sources.

Consequences Aghorn Operating (Odessa TX, 2019): operator overcome and killed by H₂S when the un-locked-out pump auto-started; his spouse, entering later through unlocked gates, also killed — 2 fatalities (CSB).

THE FACTS — CITED STATS

✓ VERIFIED

Aghorn Operating waterflood station H₂S release — Odessa TX, 26 October 2019 — 2 dead (CSB).

2 killed at Aghorn waterflood station (CSB, 2019)

source: CSB · confidence-flagged stats · full cited list in slide notes

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Energy Isolation Missed on a Pump — Toxic Auto-Start

“He went in to check the pump. It wasn't locked out, and it started on its own.”

CRITICAL

WHAT · WHY · HOW

A tank or pipe that carried sour (rotten-egg gas) fluid is opened up for cleaning. The black crust inside is a special kind of rust that catches fire all by itself when air touches it and it dries out. The glowing crust can ignite any leftover fuel vapor and start a flash fire right at the open manway — a classic turnaround fire with people standing at the opening.

- 1 Treat all sour-service equipment as pyrophoric by default.
- 2 Keep the internal scale wet (or keep the equipment inerted) until it is passivated or removed.
- 3 Control the rate of opening and air ingress.
- 4 Gas-test before and continuously during opening; confirm no flammable atmosphere.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an incident rate. Qualitatively, peer-reviewed literature identifies pyrophoric FeS as a leading cause of turnaround fires in crude columns and sulfur/crude/asphalt tanks (J. Loss Prev. Process Ind. review, 2023).

Consequences Class-level: self-heating FeS ignites residual hydrocarbon vapor → flash fire at the opening. A searched "2010 West Virginia, 1 death / 6 injuries" refinery case could not be tied to a primary investigation — treat casualty figures as illustrative only; the mechanism itself is well established.

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (no verified named-fatality anchor; mechanism verified to peer-reviewed literature).

FeS scale on sour-service steel oxidizes exothermically in air and can spontaneously ignite (peer-reviewed review, J. Loss Prev. ... confidence-flagged stats · full cited list in slide notes

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Pyrophoric Iron Sulfide Ignition on Opening Sour Equipment

"The scale inside was cold and black — until air hit it and it started to glow."

HIGH



Double-Block-and-Bleed Failure (Passing Block / Plugged Bleed)

"Two valves shut, bleed cracked, no flow. It looked isolated. One valve was passing."

WHAT · WHY · HOW

To make a pipe safe, workers shut two valves in a row and open a small vent between them. The vent reading zero is the proof the big valves are holding. Here one big valve is leaking through — or the vent itself is plugged — so the "safe" pipe is actually still live. A worker opens a joint trusting a false zero and takes the release straight on. The bleed is the only honest witness, and in this scenario it's been silenced.

1 Set both blocks, open the bleed, and vent the cavity to zero. · 2 Watch the bleed over time — isolation is proven only if it HOLDS zero. · 3 On any rising reading, stop and re-check; suspect a passing block. · 4 Never accept valve position alone as proof of isolation.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for DBB-specific failures. Family-level: LOTO/energy-isolation was the #4 most-cited OSHA standard in FY2025.

Consequences Class-level: opening onto a passing boundary releases live process fluid at the break point — the core line-break trap (AIChE Process Safety Beacon on DBB). No single named-fatality anchor in the source.

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (AIChE Process Safety Beacon teaching case; no named fatality in source).

DBB works only when the bleed proves the blocks are holding; venting the cavity to zero gives verifiable assurance (AIChE Process... confidence-flagged stats · full cited list in slide notes)

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HIGH

WHAT · WHY · HOW

The safest way to isolate a pipe is to bolt a solid steel plate (a blind) into a joint. But to put the plate in, you have to open the joint first — and if the pipe wasn't really emptied, whatever is trapped comes out at your hands. The insertion itself is the exposure: a passing valve or a skipped bleed means the "controlled" flange break is actually a live line break.

- 1 Depressure and drain the spool between the last valve and the flange.
- 2 Prove zero AT the flange (bleed/telltale/gas check) immediately before loosening bolts.
- 3 Crack the flange in a controlled way (loosen far-side bolts first, stand clear — never fully unbolt an...)
- 4 Install the blind and verify it's rated and seated.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for blind-insertion releases specifically. Family-level: LOTO/energy-isolation was the #4 most-cited OSHA standard in FY2025.

Consequences Class-level: cracking a still-charged spool releases trapped pressure/liquid directly onto the crew at the flange; escalation depends on the fluid (flammable/toxic/hot).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (standards-anchored; no named fatality in source).

IOGP Energy Isolation Life-Saving Rule requires confirming zero energy and testing for residual/stored energy — including a gas check...

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Blind / Spade Insertion on a Not-Fully-Depressured Line

"Positive isolation means a steel plate in the flange. You still have to open the flange to fit it."

CRITICAL

WHAT · WHY · HOW

Electrical gear is switched off and everyone assumes it's dead. But "off" isn't proven until you test it — capacitors, drives, or a hidden second feed can still be holding lethal energy. Touching "dead" gear that's actually live can trigger an arc flash — an electrical explosion hot enough to kill or cause life-changing burns instantly.

1 Identify and isolate ALL energy sources (including possible back-feeds). · **2** Discharge/bleed stored energy (capacitors, VFD DC buses) and wait the required time. · **3** Lock and tag every isolation point. · **4** Test for absence of voltage with a proven meter — live-dead-live.

HOW OFTEN · CONSEQUENCES

How often Industry estimates: ~30,000 arc-flash incidents per year in the US, ~7,000 burn injuries, ~2,000 hospitalizations, ~400 fatalities per year (widely cited industry figures — Eaton/ESFI-compiled estimates, secondary). OSHA/BLS ground truth: 1,201 OSHA-recorded electrical-cause workplace fatalities 2011–2021 (~109/yr, all electrical causes).

Consequences Class-level: arc flash burns, blast injuries, and fatalities on gear that was "switched off" but never tested dead; OSHA and NFPA 70E both treat untested parts as energized because this failure mode kills (OSHA 4472 / NFPA 70E).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (standards-anchored: OSHA 1910.333 / NFPA 70E; no single named incident in source).

OSHA 29 CFR 1910.333: circuits must be locked out AND verified de-energized by a qualified person with proper instruments; untested...

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Stored Electrical Energy / Arc Flash on De-energization

"The breaker was off. Nobody tested it. It wasn't the only feed."

CRITICAL

WHAT · WHY · HOW

A machine is being repaired under lockout. At shift change, one lock gets removed too early — or a second worker never put their own lock on — and the machine suddenly starts with hands inside it. Unexpected startup is the exact reason the LOTO rule exists: machines that restart during maintenance crush, entangle, and kill. One removed lock re-exposes everyone.

1 Every authorized worker applies their OWN personal lock — no sharing, no covering. · **2** Isolate every energy source, including rotating inertia, springs, gravity, and actuators (restrain stored... · **3** Verify zero energy with a try-start before hands go in. · **4** Maintain locks continuously across shift change with a formal handover.

HOW OFTEN · CONSEQUENCES

How often OSHA estimates LOTO compliance prevents ~120 fatalities and ~50,000 injuries per year — i.e., hazardous-energy incidents at that scale are what the standard suppresses (OSHA FS-3529). LOTO was the #4 most-cited OSHA standard in FY2025 (secondary sources report 2,177–2,562 citations). ~3 million US workers service equipment under LOTO exposure (OSHA).

Consequences Class-level: unexpected energization during service causes fatal crushing/entanglement/amputation; injured hazardous-energy workers lose an average of 24 workdays recuperating (OSHA FS-3529).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (standards-anchored: OSHA 1910.147; group-LOTO/shift-change gap pattern).

1910.147 exists specifically to prevent "unexpected energization or start up... or release of stored energy" during service (OSHA... confidence-flagged stats · full cited list in slide notes

READ MORE

Full narrative, incident history and sources — in the Situation Room.

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Unexpected Startup — Stored Mechanical / Rotating Energy

"Two crews, one machine, one lock pulled at shift change — and it spun up."

HIGH

WHAT · WHY · HOW

A hydraulic machine is shut down, but a pressure bottle in the circuit (the accumulator) still holds fluid at very high pressure. Opening a fitting releases a cutting jet of oil — or makes the machine's arm move on its own. High-pressure fluid injection and unexpected actuator motion main; "pump off" tells you nothing about what the accumulator is still holding.

1 Isolate the hydraulic power source. · 2 Bleed the accumulator AND all trapped lines to zero. · 3 Verify zero at a gauge you trust (confirm the gauge actually sees the circuit). · 4 Restrain the actuator against motion before opening any fitting.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for accumulator-specific releases. Family-level: 1910.147 requires stored/residual energy to be relieved and verified — the requirement exists because this class recurs (OSHA 1910.147).

Consequences Class-level: high-pressure oil jet (injection injury) and/or unexpected actuator/valve stroke with workers in the path.

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (standards-anchored; maps to valve actuators, BOP/HPUs, hydraulic tooling).

1910.147 requires stored or residual energy to be relieved/restrained and verified before work (OSHA, current)

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Trapped Hydraulic / Accumulator Stored Energy

"The pump was off. The accumulator was still holding 3,000 psi."

HIGH

WHAT · WHY · HOW

A steam pipe has been "off" for hours, so the crew assumes it's cold and empty. It actually still holds boiling-hot water under pressure. Opening it makes the water flash into a cloud of steam. Flashing condensate scalds anyone at the break, and trapped water slugs can slam through the line as steam/water hammer — hard enough to break piping.

- 1 Verify the line has actually cooled (not just that the steam valve is shut).
- 2 Drain the condensate; verify the trap/drain is actually working.
- 3 Verify zero pressure at a telltale before breaking.
- 4 Stand clear of the flash/hammer path when cracking the joint.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for steam-line break scalds as a class. The stored-thermal-energy requirement in 1910.147 (relieve and verify residual thermal/pressure energy) is the standards-level marker that the class recurs.

Consequences Class-level: scald/steam-burn injuries at the break point; water/steam hammer can rupture piping and fittings (established engineering knowledge, not a single-incident citation).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (mechanism-grounded, no named incident in source).

1910.147 requires residual thermal and pressure energy relieved and verified before service work — a "switched-off" steam line is not...

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Stored Thermal Energy — Steam / Hot-Condensate Line Break

"The steam was off for hours. The line was still full of scalding condensate under pressure."



HIGH

Auto-Refrigeration & Brittle Fracture on a Light-Ends Drain

“He cracked the LPG drain a hair. It flashed, frosted over, and the steel went brittle in his hands.”

WHAT · WHY · HOW

A worker opens a small drain on a pipe carrying liquid propane-type fluid. As the liquid escapes it boils instantly and gets extremely cold — cold enough to make ordinary steel brittle like glass, while also making a cloud of flammable gas. A "small" bleed can snap the frozen fitting and turn into a big uncontrolled flammable release — two failure modes from one careless valve crack.

- 1 Bleed slowly, routed to a safe location.
- 2 Watch for frosting — it is the visible sign of auto-refrigeration.
- 3 Control the rate so metal temperature stays above its low-temp limit.
- 4 Eliminate ignition sources and run gas monitoring around the bleed.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an incident rate. Mechanism-grounded: auto-refrigeration/brittle-fracture underlies API relief and low-temperature design guidance (engineering principle, not a single named incident).

Consequences Class-level: brittle fracture of carbon-steel fittings escalates a small bleed to a large flammable loss of containment; flashing jet is ignitable.

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (mechanism-grounded, no named incident in source).
Flashing a liquefied light hydrocarbon absorbs heat and can carry carbon steel below its ductile-to-brittle transition → brittle...
confidence-flagged stats · full cited list in slide notes

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HIGH

WHAT · WHY · HOW

In a plant full of twin machines, the crew locks out the wrong one — the identical pump next to the one on the permit. The machine they actually open was never isolated at all. A perfect lockout on the wrong equipment protects nobody. The paperwork says "safe" while the work item is fully live.

- 1 Positively match the equipment tag/ID to the permit AT the point of isolation. · 2 Trace the isolation boundary and confirm it actually bounds the permitted item. · 3 Perform the zero-energy test ON the work item itself, not its neighbor.
- 4 Stop on any tag/ID mismatch or ambiguity.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for wrong-item isolations specifically. Standards-level marker: IOGP made "verify isolation is effective for the CORRECT equipment" an explicit Life-Saving Rule element because the error class recurs.

Consequences Class-level: worker breaks into fully live equipment while holding a valid-looking permit and locks; consequence profile = whatever the live fluid/energy delivers.

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (standards-anchored; parallel-train / look-alike pattern).

IOGP Energy Isolation LSR explicitly requires verifying the isolation is effective for the correct piece of equipment or pipeline — ...
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Isolating the Wrong Equipment / Battery-Limit Verification

"They locked out Pump B. The permit was written for Pump A."

CRITICAL

WHAT · WHY · HOW

To make a tank safe to work on, it's filled with nitrogen — a gas you can't see or smell that pushes the air out. But the nitrogen sneaks through connected pipes into a pit next door where people are working, and quietly replaces their air. Inert gas gives zero warning — one breath of pure nitrogen can drop you. It kills workers AND the rescuers who rush in after them, often far from the tank being purged.

1 Before purging, map every path the inert gas can take (shared headers, cross-ties, low-point drains). · 2 Route/vent the purge to a safe location. · 3 Monitor O₂ in adjacent and LOW spaces — not just in the vessel. · 4 Keep monitoring during the whole purge; ventilate any space that trends down.

HOW OFTEN · CONSEQUENCES

How often CSB documented 80 nitrogen-asphyxiation deaths in 85 incidents, 1992–2002 (~8 deaths/yr), repeatedly involving inert migration into unexpected spaces (CSB Nitrogen Asphyxiation Safety Bulletin, 2003).

Consequences Asphyxiation of workers in adjacent/low spaces plus would-be rescuers; the CSB bulletin's core finding is that the hazard zone extends beyond the purged equipment (CSB, 2003).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level anchor: CSB Nitrogen Asphyxiation Safety Bulletin (2003) — 80 deaths, 1992–2002.

80 deaths from nitrogen asphyxiation, 1992–2002 (CSB Safety Bulletin, 2003)

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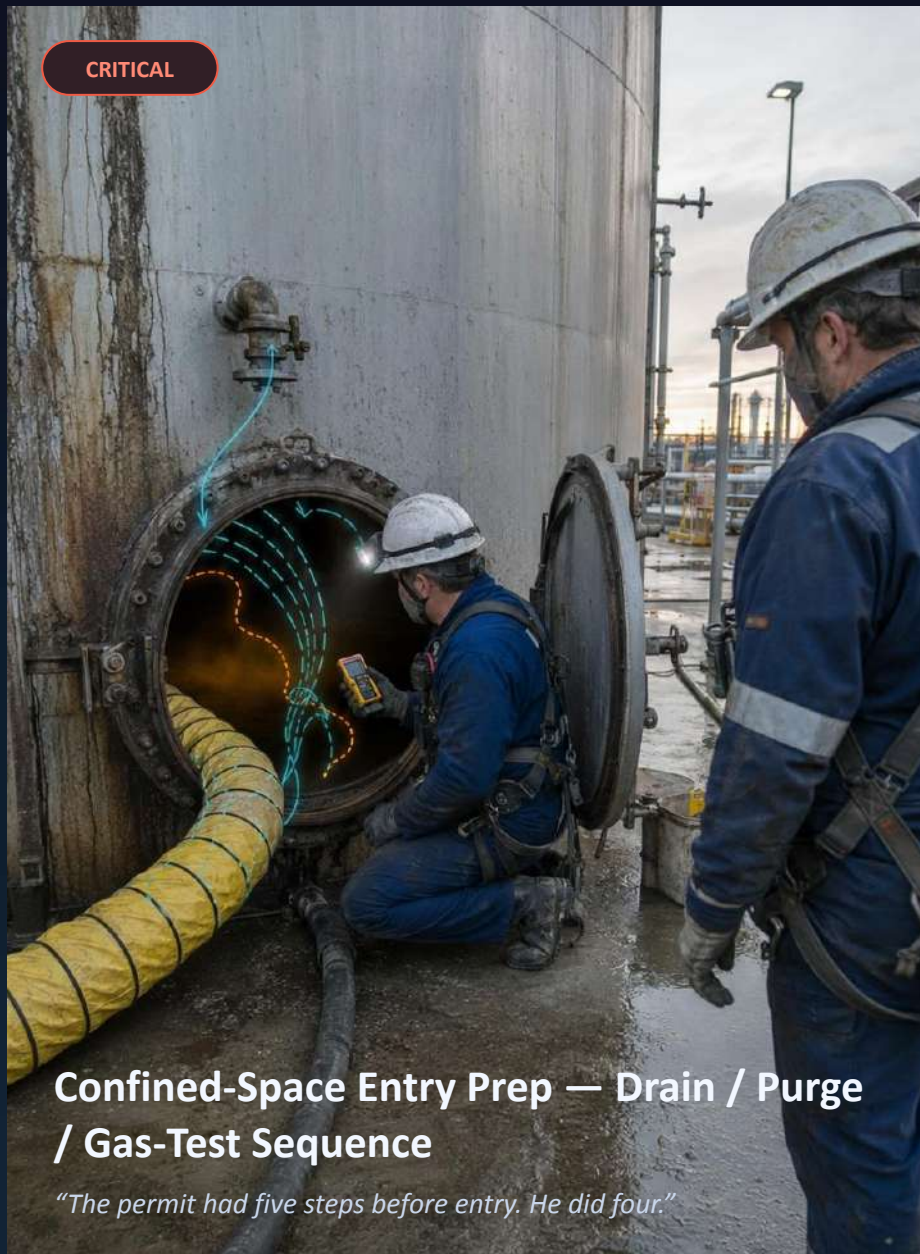
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Inert Purge-Gas Backflow / Migration Into an Occupied Area

"The nitrogen made the vessel safe — and quietly filled the pit next door."

CRITICAL



Confined-Space Entry Prep — Drain / Purge / Gas-Test Sequence

"The permit had five steps before entry. He did four."

WHAT · WHY · HOW

Before anyone climbs inside a tank, five things must happen in order: empty it, flush out the fumes, blow in fresh air, test the air with a meter, and keep testing. Skip or shuffle one step and the air inside can still be deadly even though the tank "looks" ready. Confined spaces kill quietly — bad air has no color and often no smell — and they kill rescuers too. This is one of the most consistently fatal situations in industry.

1 Drain the contents completely. · 2 Purge/displace hydrocarbons (inert), THEN ventilate to breathable air — in that order. · 3 Gas-test O_2 (~19.5–23.5%), flammables (below LEL), and toxics with a calibrated multi-gas meter. · 4 Monitor continuously during entry; one reading is never enough.

HOW OFTEN · CONSEQUENCES

How often 1,030 US workers died in confined-space incidents 2011–2018 (~129/yr; annual range 88–166) (BLS CFI fact sheet); 126 of those were single-episode harmful-substance inhalations, most commonly H_2S (38), CO (23), methane (10) (BLS).

Consequences Valero Delaware City (2005): a contractor and his would-be rescuer died in a nitrogen-purged reactor — entry deaths come from un-verified atmospheres and impulsive rescue, not absent paperwork (CSB).

THE FACTS — CITED STATS

✓ VERIFIED

Valero Delaware City refinery — 5 November 2005 — 2 dead (worker + rescuer) in a nitrogen-purged reactor (CSB).

1,030 confined-space occupational deaths, 2011–2018 (BLS CFI, 2020)

source: CSB · confidence-flagged stats · full cited list in slide notes

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GENRE 02 · 15 SCENARIOS

Start-up, Shutdown & Transients

Visual motif — Dawn light, frost, ice and steam — the plant waking up or going down; thermal contrast made visible.

one card per situation follows — poster prompt in each card's notes

CRITICAL

WHAT · WHY · HOW

During an upset, a heat exchanger loses its warming stream and its steel chills far below the safe metal temperature. Restarting the hot pump slams hot fluid into cold-embrittled metal and cracks the vessel open. This exact sequence killed 2 workers at Esso Longford (1998) and cut natural-gas supply to the state of Victoria for about two weeks; the Royal Commission found not even the plant manager understood cold-metal embrittlement — a training gap, which is what this card trains out.

1 On loss of any warming stream, immediately start tracking metal temperature against the vessel's MDMT... · **2** Before any restart, verify actual metal temperature — do not infer it from process temperature alone. · **3** If metal is below or near MDMT, re-warm gradually (low-rate warm stream, tracing, or diverted flow) instead... · **4** Limit the ΔT of any reintroduced stream to the procedure's thermal-shock margin.

HOW OFTEN · CONSEQUENCES

How often Mechanism-specific frequency: not quantified in public sources. Class context: ~50% of refining process-safety incidents occur during start-ups/shut-downs/infrequent operations (2010 refining study, via CSB Safety Digest), and CCPS puts start-up incident frequency at ~5× normal operation (secondary).

Consequences Esso Longford 1998: brittle fracture of exchanger GP905, vapour release, explosion and fire — 2 dead, 8 injured, Victoria's gas supply cut ~2 weeks (Longford Royal Commission).

THE FACTS — CITED STATS

✓ VERIFIED

Esso Longford gas plant, Victoria, Australia, 25 September 1998 (Longford Royal Commission) — named anchor.

Exchanger GP905 chilled to about $-48\text{ }^{\circ}\text{C}$ after lean-oil flow was lost; restart introduced oil at roughly $230\text{ }^{\circ}\text{C}$ into the embrittled...
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Cold-Restart Brittle Fracture (Thermal Shock)

"The metal went cold enough to shatter, and the hot restart oil finished the job."

HIGH**WHAT · WHY · HOW**

As a line heats up on start-up (or cools on shutdown), the steel expands or contracts by inches over a long run. If a fixed anchor, jammed expansion loop, failed spring hanger, or mis-installed bellows fights that growth, the strain concentrates at a flange and it leaks or fails. Constrained thermal growth is one of the most common start-up leak and joint-failure mechanisms in hot piping systems — it is why expansion loops, bellows, and spring hangers exist, and warm-up/cool-down is exactly when growth is fastest and least uniform.

1 Before warming, walk the line: confirm expansion joints, bellows, and spring/constant-load hangers are free... · **2** Ramp temperature within the procedure's rate limit — no fast warm-ups to "catch up" the schedule. · **3** Watch for asymmetric growth (one line hot, its neighbour cold) at shared supports and anchors. · **4** Monitor flanges and fittings near anchors for early weep/strain indications during the ramp.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for this failure mode specifically; it is treated as a standard design case in ASME B31.3 piping flexibility practice (that the case is standard). Class context: falls in the transient bucket holding ~50% of refining process-safety incidents (2010 study via CSB digest).

Consequences Class-level: flange leaks, bellows/expansion-joint failures, damaged supports, and hydrocarbon releases during warm-up/cool-down; consequence severity tracks the fluid (hot hydrocarbon leak → fire risk). (Engineering-class statement per ASME B31.3 flexibility rationale.)

THE FACTS — CITED STATS

Class-level — a very common start-up leak/failure mode grounded in ASME B31.3 piping-flexibility practice; no single named CSB case.

Steel grows on the order of ~1 mm per metre per ~85 °C of temperature rise — a long hot run moves inches. ...

[confidence-flagged stats](#) · [full cited list in slide notes](#)

SECONDARY**READ MORE**

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Differential Thermal Growth & Piping Strain (Warm-Up / Cool-Down)

"Hot steel grows. Pin both ends and something has to bend, leak, or snap."

HIGH

WHAT · WHY · HOW

When a pressurized gas system is blown down quickly, the escaping gas chills sharply (Joule-Thomson cooling) and drags the metal down with it. If carbon steel drops below its brittle limit while still stressed, the depressuring meant to make the system safe can crack it. API 521 makes low-temperature effects of depressuring an explicit design and operating case; a wrong blowdown rate turns a routine shutdown step into a brittle-fracture and loss-of-containment risk.

1 Identify the metallurgy of the blowdown path — is the boundary rated for deep cold? · 2 Depressure at the staged/controlled rate in the procedure, not full-open. · 3 Track metal temperature against MDMT during the transient, not just gas pressure. · 4 If metal approaches the brittle limit, pause or slow the blowdown and let the metal recover.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an incident rate; auto-refrigeration below MDMT is a recognized API 521 depressuring design case (that the case is standard practice). Class context: transient-operations bucket holds ~50% of refining process-safety incidents (2010 study via CSB digest).

Consequences Class-level: brittle fracture of carbon-steel boundaries during blowdown → sudden loss of containment of flammable gas while personnel are executing the shutdown; this is why blowdown lines carry cold-service metallurgy and rate limits (API 521 rationale).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level — recognized API 521 low-temperature depressuring case; no single named investigation anchor.

API 521 requires evaluating low-temperature effects of depressuring: rapid blowdown causes Joule-Thomson auto-refrigeration that can...

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Rapid Depressurization Auto-Refrigeration Embrittlement

“Blow it down too fast and the pipe freezes itself brittle.”

CRITICAL

WHAT · WHY · HOW

A liquid-full exchanger that has been off-line is warmed for return to service while still isolated from its pressure-relief valve. The trapped liquid expands, pressure rockets with nowhere to go, and the shell ruptures. This is the Williams Geismar (2013) BLEVE: 2 dead, 167 injured, because a reboiler could be heated while valved off from its relief device — a classic return-to-service trap that a single verification step prevents.

- 1 Before applying any heat, confirm the vessel's relief path is open and in service (block valves... · 2 Check whether the equipment is liquid-full and isolated between valves. · 3 Apply heat only with a verified expansion/relief route available. · 4 If an isolated relief is discovered mid-heat-up, remove the heat source first, then restore the relief path.

HOW OFTEN · CONSEQUENCES

How often Scenario-specific frequency: not quantified in public sources. Class context: ~50% of refining process-safety incidents occur during start-up/shutdown/infrequent operations (2010 study via CSB digest); CSB found the enabling PSM deficiencies at Geismar had persisted 12 years, indicating the latent condition is long-lived, not rare.

Consequences Williams Olefins, Geismar 2013: reboiler shell catastrophically ruptured in a BLEVE — 2 workers killed, 167 injured, over 30,000 lb of hydrocarbons released (CSB).

THE FACTS — CITED STATS

✓ VERIFIED

Williams Olefins, Geismar, Louisiana, 13 June 2013 (CSB) — named anchor.

Heat was introduced to a reboiler off-line and isolated from its pressure-relief device; the confined propane mixture over-pressured...

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Isolated Exchanger Heat-Up Overpressure on Return to Service

"They warmed up a vessel that was still sealed off from its relief valve."

HIGH**WHAT · WHY · HOW**

A new or drained line is filled during commissioning. Filled too fast, or onto an air pocket trapped at an unvented high point, the moving liquid column compresses the gas and hammers to a stop — a pressure spike that cracks fittings, damages supports, or unseats valves. Hydraulic transients generate pressures far above steady operating pressure — measured condensation-induced hammer events have peaked at up to 37× operating pressure — and first-fill is when the system has never seen liquid, so trapped pockets are most likely.

- 1 Walk the line before filling: identify high points, dead-legs, and their vents. · 2 Open high-point vents and fill at the procedure's controlled (slow) rate. · 3 Vent air progressively as the column advances; never fill against a closed pocket. · 4 Watch pressure for surge signatures (spikes on column arrest) and slow further if seen.

HOW OFTEN · CONSEQUENCES

How often Related quantified data: condensation-induced water hammer occurs on average every 4–5 years per nuclear power plant per a published study of CIWH events (study figure, adjacent mechanism — steam-system hammer, not first-fill specifically; ScienceDirect). ...

Consequences Class-level: fractured pipes/fittings with near-explosive effect, escaping process fluid or live steam, propelled fragments; a DOE-documented condensate-hammer event caused a fatality (OSTI for the steam-system class; OSTI record).

THE FACTS — CITED STATS

Class-level — well-understood commissioning hazard; steam-system hammer fatality documented at a DOE facility (OSTI) as the nearest named analogue.

Hydraulic-transient (Joukowsky) surge scales with density, wave speed, and velocity change, amplified by trapped-gas compression.

...

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SECONDARY**READ MORE**

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First-Fill Water Hammer / Trapped-Air Surge

“Fill an empty line too fast and the liquid slams into a wall of trapped air.”



LNG/LPG Rollover Overpressure on Filling

“Two layers of cold liquid quietly built energy, then flipped and boiled the tank.”



EQUIPMENT-BOUND

START-UP / SHUTDOWN

TRAIN / OPERATE / FIELD

WHAT · WHY · HOW

A cryogenic tank is filled with product of a slightly different density than the heel inside. The layers stratify and silently exchange heat for hours, then suddenly overturn ("roll over"), flashing the stored heat to vapour and spiking tank pressure far above normal. At La Spezia (1971) a stratified tank rolled over ~36 hours after filling, exceeded its design pressure, and vented roughly 186 tonnes of gas; rollover remains the reason LNG fill direction, density monitoring, and circulation protocols exist.

1 Before transfer, compare incoming cargo density/temperature against the heel. · 2 Choose fill point to promote mixing: top-fill denser cargo, bottom-fill lighter cargo. · 3 Monitor layer densities and temperatures during and after fill for stratification signatures. · 4 If stratification forms, circulate/mix (pump-around) or adjust the fill before layers approach density...

HOW OFTEN · CONSEQUENCES

How often Quantified: 24 rollovers reported to GIIGNL over roughly 60 years, while an industry survey identified 41 incidents at 22 plants in 1970–1982 alone — meaning rollover is rare per tank-year but persistently recurring and likely under-reported. / (GIIGNL "Rollover in LNG Storage Tanks", 2nd ed. public report)

Consequences La Spezia 1971: sudden overpressure exceeded the ~50 mbar design pressure of a ~50,000 m³ tank; safety valves lifted and roughly 186 tonnes of natural gas vented to atmosphere over ~16 hours (MDPI review). No fatalities, but a tank-integrity near-miss and a major release.

THE FACTS — CITED STATS

✓ VERIFIED

La Spezia LNG terminal, Italy, August 1971 — named anchor.
Bottom-filling denser LNG onto a lighter heel led to rollover ~36 hours later. (MDPI Processes review, sea-man.org guidance)
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Settle-Out Pressure After Compressor Trip

"The compressor stopped, and the high and low sides met in the middle — above what the low side can take."

WHAT · WHY · HOW

When a running compressor trips, its high-pressure discharge and low-pressure suction equalize to a single "settle-out" pressure in between. If that pressure exceeds the rating of anything on the low side, the trip itself creates an overpressure. Settle-out is a standard API 521 design and operating case; compressor trips are among the most common transients, and a mishandled settle-out either over-pressures the low side or sets up a dangerous restart.

- 1 On trip, anticipate settle-out: know (or look up) the expected equalized pressure for the connected volumes.
- 2 Confirm low-side equipment ratings and relief protection against the settle-out value.
- 3 Watch the discharge check valve — leakage raises the low side above prediction.
- 4 Blow down / hold per procedure to bring pressure to a safe restart state.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an incident rate; settle-out is a standard API 521 relief-analysis case and compressor trips are described as among the most common transient events (engineering-class statement). Class context: transient bucket holds ~50% of refining process-safety incidents (2010 study via CSB digest).

Consequences Class-level: low-side equipment over-pressured toward relief or rupture on the trip, or a restart attempted against a bad pressure state; consequence scales with gas inventory and low-side rating margin (API 521 rationale).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level — standard engineering concept (API 521); no single named investigation anchor.
Settle-out pressure — the equalized pressure of connected suction+discharge volumes after a trip — is a recognized API 521...
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CRITICAL

WHAT · WHY · HOW

Before start-up, a system must be purged so fuel and air never coexist in the flammable range. If the purge is cut short — too few volumes exchanged or a dead-leg skipped — a flammable mixture remains inside, and start-up supplies the ignition. Keeping systems out of the flammable envelope during air↔hydrocarbon transitions is a core start-up/shutdown control; when hydrocarbon meets an ignition source instead, the result is Skikda-scale — 27 dead and three LNG trains destroyed.

- 1 Follow the purge procedure's target: required purge volumes AND verified end-point composition (O_2 or HC...
- 2 Sample at representative points, explicitly including dead-legs and low-flow branches.
- 3 Confirm no leak path is reintroducing hydrocarbon during the purge.
- 4 Keep ignition sources (fireboxes, non-rated equipment) segregated until composition is verified.

HOW OFTEN · CONSEQUENCES

How often Scenario-specific frequency: not quantified in public sources; incomplete purging is a repeatedly-cited transient-operations failure in CSB's start-up/shutdown digest (qualitative). Class context: ~50% of refining process-safety incidents occur during start-up/shutdown/infrequent ops (2010 study via CSB digest).

Consequences Skikda LNG, Algeria 2004: hydrocarbon ingested by a boiler firebox ignited, breached the boiler, and set off a vapour-cloud explosion — 27 killed, ~74 injured, three of six LNG trains destroyed (OGJ).

THE FACTS — CITED STATS

✓ VERIFIED

Skikda LNG complex, Algeria, 19 January 2004 — named anchor (extreme case of fuel meeting a firebox).

Skikda, 19 January 2004: cold-box hydrocarbon leak reached a running boiler's firebox; 27 dead, ~74 injured, 3 trains destroyed. ...

source: extreme case of fuel meeting a firebox · confidence-flagged stats · full cited list in slide notes

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Insufficient Purge — Flammable Envelope Crossed at Start-Up

"They swept the line — just not long enough — and started up with a flammable mix inside."

HIGH

WHAT · WHY · HOW

In sour (H_2S) service, rust converts to iron sulfide inside equipment. It sits harmless while sealed, but when the equipment is opened at shutdown and air reaches dry deposits, the sulfide oxidizes fast, glows red-hot, and ignites any flammable vapour still present. Pyrophoric iron sulfide is one of the most common substances found in refinery columns and vessels, and most pyrophoric fires happen exactly at the shutdown/opening step this card trains — the control is entirely procedural (neutralize, wet, inert, gas-test).

1 Before opening sour-service equipment, chemically neutralize/passivate deposits or plan for continuous... · 2 Keep deposits wetted (or under inert atmosphere) through the entire opening sequence. · 3 Gas-free and gas-test: confirm flammable vapour is below limits before air exposure. · 4 Admit air only when deposits are wet/neutralized and flammables are cleared.

HOW OFTEN · CONSEQUENCES

How often Qualitative frequency, cited: most pyrophoric fires occur during shutdowns when equipment is opened (WorkSafeBC hazard alert); industry hazard guidance states most refineries experience iron-sulfide spontaneous ignition on the ground or inside equipment at one time or another (AFPM HAZID sheet). A per-turnaround numeric rate is not quantified in public sources.

Consequences Class-level, cited examples: fires in crude columns during turnarounds, explosions in sulfur/crude/asphalt storage tanks, and vessel over-pressurizations attributed to pyrophoric ignition are widely reported (AFPM/industry literature); a 2010 West Virginia refinery pyrophoric-related explosion killed 1 and seriously...

THE FACTS — CITED STATS

✓ VERIFIED

Class-level — recurrent refinery shutdown hazard (WorkSafeBC/AFPM guidance); no single canonical CSB anchor.

Pyrophoric iron sulfide forms from iron oxide + H_2S in low-oxygen conditions and is "one of the most common substances found in..."

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Pyrophoric Iron-Sulfide Self-Ignition on Opening

"The deposits inside had been waiting for air. Opening the manway gave it to them."

CRITICAL



Fired-Heater Light-Off Firebox Explosion

"He lit the burner into a firebox that still held unburned fuel."

WHAT · WHY · HOW

Before lighting a fired heater, furnace, or boiler, the firebox must be purged to sweep out leaked fuel. Light off without a proper purge — or keep feeding fuel to a burner that failed to light — and the accumulated fuel-air mixture explodes on the ignition attempt. Firebox explosions on light-off are the canonical burner-management failure; NFPA 86 and API burner-management standards exist almost entirely to force the purge-verify-light sequence this card trains.

1 Complete the measured pre-ignition purge (duration/volumes per NFPA 86 / BMS permissives) before any... · **2** Verify fuel valves are tight (no leak-by loading the box during the purge). · **3** Light each burner per sequence and confirm flame on each before proceeding. · **4** On any failure-to-light, isolate fuel immediately.

HOW OFTEN · CONSEQUENCES

How often Scenario-specific frequency: not quantified in public sources; published root-cause reports on furnace explosions repeatedly come back to inadequate pre-purge, bypassed BMS interlocks, and undetected flame failure (industry-literature pattern, e.g. ...)

Consequences Class-level: firebox explosions kill and injure operators at the heater and destroy the fired equipment; the extreme fuel-reaches-firebox case is Skikda 2004 (27 dead — see card_02_08). Majority of serious boiler-related accidents involve fatalities per National Board commentary.

THE FACTS — CITED STATS

✓ VERIFIED

Class-level — burner-management failure mode (NFPA 86/API 556 rationale); Skikda 2004 as the extreme named analogue.

NFPA 86 requires a pre-ignition air purge whose duration/volume is established by measurement before light-off. (ANSI blog on NFPA 86)

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CRITICAL



Restart With a Safeguard Removed / Trapped Pressure

"They restarted the pump the day shift had taken apart — and its relief valve was gone."

WHAT · WHY · HOW

Equipment goes down for maintenance and a safeguard — a relief valve, spool, or instrument — is removed and the opening blinded. A later crew, unaware because the permit/hand-over failed, restarts and pressurizes it, and product escapes from the incomplete boundary. This is the Piper Alpha sequence: a standby pump restarted with its relief valve removed killed 167 people. Permit-to-work and isolation integrity are the whole game — verify the boundary is complete before re-energizing.

- 1 Before restart, check permit-to-work status for ALL work on the equipment — including other crews' permits. · 2 Physically walk the isolation: confirm every removed safeguard (PSV, spool, blind, instrument) is restored. · 3 Verify the pressure boundary is complete (blinds out where they must be out, flanges made up to spec). · 4 Confirm relief protection is reinstalled and in service.

HOW OFTEN · CONSEQUENCES

How often Quantified, class-level: roughly 30% of reported chemical-industry incidents are maintenance-related, and permit-to-work systems are implicated in over 20% of those maintenance incidents (IChemE paper, Gould); UK HSE studies found failure to implement effective permit-to-work systems was the most significant cause of maintenance-related accidents in the UK chemical industry (HSE, via Wikipedia...

Consequences Piper Alpha 1988: condensate leak from the blind-flange assembly ignited and escalated to platform-destroying explosions and fires — 167 of 226 on board killed (Cullen Inquiry).

THE FACTS — CITED STATS

✓ VERIFIED

Piper Alpha, North Sea, 6 July 1988 (Cullen Inquiry) — named anchor.
A standby condensate pump's PSV was removed and the opening blind-flanged; a later shift, unaware due to permit-to-work failure...

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WHAT · WHY · HOW

A unit is idled ("safe-parked") rather than fully shut down while maintenance isolation is prepared. A pressure change lets hydrocarbon flow backwards through the process into equipment full of ignition sources — at Torrance, an electrostatic precipitator — and it explodes. Idle states are true transients — neither running nor safely shut down — and are frequently un-proceduralized; CSB cited exactly that gap (no safe operating limits for the idled state, reliance on unverifiable safeguards) at ExxonMobil Torrance.

- 1 Treat the idled/safe-park state as a defined operating mode with written limits, not a limbo.
- 2 Map credible reverse-flow paths (shared headers, check valves) before changing any line-up.
- 3 Maintain a verified positive isolation or safe pressure differential toward ignition zones.
- 4 Monitor ΔP across the idle boundary continuously during isolation work.

HOW OFTEN · CONSEQUENCES

How often Scenario-specific frequency: not quantified in public sources; CSB flagged un-proceduralized idle states as a recurring gap (qualitative, Torrance report). Class context: ~50% of refining process-safety incidents occur during start-up/shutdown/infrequent operations (2010 study via CSB digest).

Consequences ExxonMobil Torrance 2015: explosion in the FCC electrostatic precipitator injured 2 workers and threw catalyst dust up to a mile into the surrounding community; the unit was out for months with regional gasoline-price impacts (CSB for the event/injuries).

THE FACTS — CITED STATS

✓ VERIFIED

ExxonMobil Torrance refinery, California, 18 February 2015 (CSB) — named anchor.
A pressure deviation in the idled "safe-park" FCC let hydrocarbons backflow through the process and ignite in the ESP. ...
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HIGH

WHAT · WHY · HOW

A high-pressure separator's liquid level normally seals its liquid outlet. During start-up, if the level is lost — drained low, dump valve stuck open, or bad level reading — high-pressure gas "blows by" through the liquid line into downstream low-pressure equipment that cannot take it. Gas blow-by is a named overpressure scenario in API RP 14C, and start-up is the highest-risk moment because levels are being established for the first time and level controls are being commissioned.

1 Establish and verify the liquid seal (level above the outlet) before lining up downstream. · 2 Confirm level trips and high/low sensors are in service — not bypassed for start-up. · 3 Watch level and downstream LP pressure together; a falling level with rising LP pressure is blow-by starting. · 4 Re-establish the seal (close dump, restore level) or isolate/trip before LP pressure approaches rating.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an incident rate; it is a named API RP 14C design scenario, and engineering literature states most LP-separator overpressure accidents involve relief inadequately sized for the blow-by case (textbook-class claim, surface-facility relief text).

Consequences Class-level: downstream LP vessel driven to relief or rupture by HP gas breakthrough; consequence scales with the HP/LP rating gap and relief adequacy (API RP 14C rationale).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level — named API RP 14C overpressure case; no single canonical investigation anchor.

Gas blow-by (loss of level at an HP/LP interface) is a named overpressure scenario in API RP 14C, guarded by level sensors and...
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Gas Blow-By / Loss of Level to LP Equipment

"The separator ran dry on start-up and shot high-pressure gas straight into the low-pressure vessel."

HIGH

WHAT · WHY · HOW

Start-ups lean hard on utilities — instrument air, power, cooling water, steam. Lose one mid-transient and many control valves snap to fail-safe positions at once, rotating equipment stops, and the operator faces a cascade of simultaneous trips instead of one clean problem. Utility loss is a recognized common-cause upset that can defeat multiple safeguards simultaneously; mid-transient is the worst time because the plant is already off steady state and the operator is already loaded with non-routine tasks.

1 Recognize the common cause: many simultaneous valve/equipment state changes = suspect a utility, not ten... · **2** Confirm which utility failed and what every dependent element's fail-safe position is. · **3** Drive the unit to its defined safe state per procedure rather than fighting individual loops. · **4** Manage relief/flare loads deliberately (depressure, isolate, prioritize).

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as a mid-transient incident rate; utility failure is an explicit relief-design case under API 521 (that it is a standard case). Class context: transients hold ~50% of refining process-safety incidents (2010 study via CSB digest).

Consequences Class-level: multiple simultaneous trips, relief/flare loading, and loss of cascade control; a mismanaged cascade escalates to overpressure or release (API 521 utility-failure rationale).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level — utility failure is a design case (API 521); no single named incident anchor.

Loss of instrument air / power / cooling water / steam is a recognized common-cause overpressure case; relief and depressuring systems...

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Utility Loss During a Transient

"The start-up was going fine until the instrument air quit."

CRITICAL

WHAT · WHY · HOW

After a turnaround, a unit restarts with dozens of valves, blinds, and instruments that were moved during the work. If the line-up is wrong — a blind left in, a valve mis-lined, an instrument not returned to service — the first start-up flow dead-heads, over-pressures, or releases. Post-turnaround restart is the archetypal infrequent operation: it concentrates non-routine steps, which is precisely why ~half of process-safety incidents land in the start-up/shutdown/infrequent-ops bucket and why PSSR verification exists.

1 Reconcile the blind/spade list and valve line-up sheet against the field — walk it, don't desk-check it. · **2** Complete the pre-start-up safety review (PSSR): confirm installed controls are calibrated, tested, and... · **3** Resolve every list-vs-field discrepancy before introducing feed — a mismatch is a stop. · **4** Introduce first flow slowly, watching for dead-head pressure or mis-routed flow signatures.

HOW OFTEN · CONSEQUENCES

How often Quantified at the bucket this scenario defines: a 2010 study of the refining industry (led by ExxonMobil) found ~50% of process-safety incidents occur during start-ups, shut-downs, and other infrequent events — the post-turnaround restart is the archetype of that bucket (widely-cited study figure, surfaced via CSB Safety Digest and press coverage, e.g. ...)

Consequences Class-level: dead-heads, overpressure against a closed point, and start-up releases from a single missed blind or mis-lined valve; CSB's digest documents start-up/shutdown incidents from 2001, 2002 and 2008 with a combined 5 fatalities and 3 injuries (CSB digest coverage).

THE FACTS — CITED STATS

SECONDARY

Class-level — anchored to the start-up statistic and PSSR practice (CSB digest / OSHA PSM) rather than one named incident.

~50% of refining process-safety incidents occur during start-ups/shut-downs/infrequent operations (2010 study, via CSB Safety Digest). ...

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Commissioning Line-Up Error After Turnaround

"Fresh from turnaround, one blind left in and one valve lined up wrong."

GENRE 03 · 15 SCENARIOS

Overpressure, Relief & Flare

Visual motif — A straining, heatmap-skinned vessel; the PSV as a character; the flare plume on the horizon.

one card per situation follows — poster prompt in each card's notes

HIGH

WHAT · WHY · HOW

An outlet valve closes — by mistake, control failure, or a downstream plug — while feed keeps coming. With no way out, pressure climbs until the relief valve lifts or, if relief is unavailable, the weakest part fails. API 521 names "closed outlets on vessels" among the primary overpressure causes a relief system must be designed for; the PSV is the last line of defense, and if it is undersized, isolated, or plugged, overpressure proceeds to rupture. (API 521 scenarios, API 520 device selection)

1 A downstream isolation/control valve closes (operator error, control failure, or downstream plug) while feed... · 2 With zero outflow, vessel pressure climbs steadily toward the PSV set pressure. · 3 The PSV lifts and holds the system at set-plus-overpressure — or, if the relief path is compromised, pressure... · 4 Trainee must find and clear the block (or cut feed) and verify the relief path is truly available, ideally...

HOW OFTEN · CONSEQUENCES

How often CCPS LOPA guidance assigns a generic initiating-event frequency of ~0.1/year per loop for control-valve failure and BPCS control-loop failure — the classic drivers of a blocked outlet (iFluids LOPA IEF guide, HAZOP360). Frequency of blocked-outlet events specifically reaching rupture: not quantified in public sources.

Consequences Vessel exceeds MAWP and ruptures if relief is unavailable; loss of containment, blast, and fire potential — relief sizing per API 520/521 exists precisely because this progression is credible. (API 520)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level API 521 design case.

API 521 lists blocked outlet among the primary overpressure causes, alongside fire, control-valve failure, and tube rupture. (source) confidence-flagged stats · full cited list in slide notes

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Blocked Outlet — Pressure to the PSV

"Close the one valve that mattered, keep feeding, and the relief valve is all that's left."

CRITICAL

WHAT · WHY · HOW

A high-pressure separator's level control valve fails wide open (or the level transmitter lies), the liquid seal drains out, and HP gas blows by into the next vessel downstream — rated for much lower pressure. That vessel's PSV becomes the only thing between it and rupture. Gas blowby past an emptied separator is the classic way a low-pressure vessel gets over-pressured; API 521 §4.4.8.3 gives specific gas-breakthrough guidance, and most LP-separator overpressure accidents trace to PSVs not sized for the blowby case. (EnggCyclopedia, Becht — separator blow-through)

1 The level control valve fails open or a level transmitter reads falsely high. · 2 Liquid drains until the seal at the vessel bottom is lost. · 3 HP gas flows freely through the open valve into the downstream LP vessel; its pressure climbs fast. · 4 The LP vessel's PSV lifts — and only saves the vessel if it was sized for blowby.

HOW OFTEN · CONSEQUENCES

How often CCPS LOPA generic initiating-event frequency for a control-valve/BPCS-loop failure (the blowby initiator) is ~0.1/year per loop (iFluids LOPA IEF guide, HAZOP360). Frequency of blowby events that actually over-pressure the LP vessel: not quantified in public sources.

Consequences Rupture of the downstream low-pressure vessel with loss of containment; "most accidents involving overpressuring of low-pressure separators are a result of relief valves not being adequately sized to handle the gas-blowby condition." (process relief requirements)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level mechanism grounded in API 521 §4.4.8.3.

Most LP-separator overpressure accidents trace to PSVs not sized for gas blowby; downstream vessels should carry a PSH and a...
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Control Valve Fails Open — Gas Blowby into the LP System

"The separator drained dry, and the high pressure gas walked straight into a vessel built for a fraction of it."

CRITICAL

WHAT · WHY · HOW

A tower is overfilled until its relief valves lift — but the relief goes to an old atmospheric blowdown drum that itself overfills and geysers hot flammable liquid out the top at ground level, forming a vapor cloud that finds ignition. This is the BP Texas City 2005 mechanism — 15 killed, ~180 injured — and the reason CSB called on the industry to eliminate atmospheric blowdown drums in favor of properly designed flares. (CSB investigation digest.pdf), CSB recommendation)

- 1 During start-up fill, draw-off is closed/throttled and the level indication saturates or misleads.
- 2 Fill outpaces draw; the vessel floods and pressure reaches relief set.
- 3 The PSVs lift and pass rated flow into a finite-capacity receiving drum.
- 4 The receiver's own level climbs to overflow — hot flammable liquid discharges at ground level and forms a...

HOW OFTEN · CONSEQUENCES

How often Marsh Ltd. (2011, US data) found atmospheric storage tank overfill occurs about once in every 3,300 filling operations (cited in API 2350 training material). secondary citation; overfill-to-relief-overwhelm progression frequency not separately quantified in public sources.

Consequences BP Texas City: vapor cloud ignition killed 15 and injured ~180; the event also drove industry-wide replacement of atmospheric blowdown drums. (CSB digest.pdf))

THE FACTS — CITED STATS

✓ VERIFIED

BP Texas City refinery, 23 March 2005 (CSB) — overfill drove relief into an atmospheric blowdown drum that overflowed; 15 dead, ~180 injured.

BP Texas City, 23 March 2005: raffinate splitter overfilled/overheated; relief valves opened into a blowdown drum that overflowed — 15...

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Overfill-Induced Overpressure & Relief-System Overwhelm

"The relief valves did open. They just dumped into a drum that had nowhere left to put it."

CRITICAL

WHAT · WHY · HOW

In a shell-and-tube exchanger with a high-pressure side and a much lower-rated side, a tube ruptures and HP fluid blasts into the LP shell. Pressure on the weak side spikes almost instantly, and the LP relief valve must swallow the surge or the shell fails. API 521 defines the tube-rupture case: if the HP side can over-pressure the LP side, LP overpressure protection must consider a full tube rupture; the 10/13 rule decides when the case is credible. (CheCalc tube rupture, API 521 scenarios)

1 A tube fails (corrosion, erosion, vibration fatigue) between the HP and LP sides. · 2 HP fluid flows through the break as a critical-flow orifice into the LP shell, flashing as it goes. · 3 LP pressure and level climb rapidly; the transient can momentarily exceed even test pressure despite a relief... · 4 The LP-side PSV lifts and must pass the make-up rate.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — the tube-rupture modeling literature notes it is "often difficult to find statistics on the frequency of tube ruptures" because failure databases record them under other names; UK offshore Hydrocarbon Release Database data shows most offshore tube ruptures occur in gas compression systems, without a published per-exchanger rate (BMC Chemical...)

Consequences LP shell overpressure and rupture with loss of containment; the rupture transient can momentarily exceed even the corrected hydrotest pressure despite relief. transient magnitude model-dependent (CheCalc)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level API 521 design case.

10/13 rule: a tube-rupture PSV may be unnecessary only if the LP side's corrected hydrotest pressure ($\approx 1.3 \times \text{MAWP}$) equals or exceeds...

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Heat-Exchanger Tube Rupture (HP→LP Interface)

"One tube splits, and the high-pressure side empties into a shell that was never built to hold it."

CRITICAL

WHAT · WHY · HOW

An overpressure event begins, but the relief valve can't open — inlet plugged with polymer/solids/hydrate, internals gummed or corroded stuck, or a frozen tailpipe. Pressure blows past the set point because the only escape route is sealed. Relief only protects if the device can actually open and pass rated flow; API 520/521 govern the selection, inlet/outlet design, and service conditions (fouling, plugging, freezing, wrong isolation) that defeat a device. (API 520, API 521 principles)

1 Any overpressure driver starts (block, blowby, fire). · 2 Pressure reaches PSV set point — and nothing happens: the device is plugged, seized, or frozen. · 3 Pressure keeps climbing past set toward MAWP and beyond, following the pure no-outflow build. · 4 Trainee must spot that pressure exceeded set with no relief flow/noise, then act upstream — cut the driver...

HOW OFTEN · CONSEQUENCES

How often Statistical analyses of three independent proof-test data sets predict an initial fail-to-open probability of ~1–1.6% for new spring-operated PRVs installed without pre-service testing (exida analysis of PRV proof test data); Bukowski et al., from >4,800 new ASME Section VIII valve proof tests, estimated fail-to-open in 0.31–2.0% of a stainless-steel subpopulation, with seat-disc adhesions forming...

Consequences A routine upset converts into a vessel rupture: with the relief coefficient near zero, pressure runs to MAWP and beyond with loss of containment. (mechanism per API 520/521)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level mechanism flagged (fouling/plugging grounded in API 520/521 practice).

~1–1.6% of new spring-operated PRVs are predicted to be installed already in the fail-to-open state (three independent data sets).

...

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PSV Fails to Lift (Plugged / Frozen / Stuck)

"Pressure climbed to the set point, and the valve that was supposed to save the vessel never moved."

CRITICAL

WHAT · WHY · HOW

Equipment shares a relief valve with a neighbor through a manual isolation valve. Someone closes that valve for maintenance on the neighbor — leaving the equipment with no relief path. Heat or feed is applied anyway, and pressure builds against a wall with no escape until rupture. Williams Olefins Geismar (2013) is CSB's textbook case: a propane reboiler blocked in and isolated from the column's relief valve ruptured when heated — 2 killed, 100+ injured; CSB found 12 years of PSM deficiencies left it unprotected. (CSB case study, CSB news release)

1 A neighbor unit goes into maintenance; the manual isolation valve to the shared PSV is closed. · 2 The protected item is later heated or fed while still valved off from relief. · 3 A pressure driver (thermal expansion, feed, blowby) builds unchecked — there is no relief node connected. · 4 Pressure runs to rupture unless someone re-opens the relief path first.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — the mechanism is a configuration/administrative-control failure documented through CSB investigation rather than rate databases (CSB Geismar case study).

Consequences Geismar: catastrophic reboiler rupture, explosion and fire — 2 killed, 100+ injured (reports cite ~114; cite CSB's own number when finalizing). (CSB)

THE FACTS — CITED STATS

✓ VERIFIED

Williams Olefins, Geismar LA, 13 June 2013 (CSB) — isolated reboiler ruptured on thermal expansion; 2 dead, 100+ injured.

Williams Geismar, 13 June 2013: reboiler isolated from its only relief path by manual valves installed years earlier; hot quench water...

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PSV Isolated From the Equipment It Protects

"They valved the reboiler off from its only relief valve, then poured heat into it."

HIGH

Thermal (Hydraulic) Relief of Blocked-In Liquid

“Trap cold liquid between two closed valves, add a little heat, and something has to give.”

WHAT · WHY · HOW

A liquid-full line, exchanger, or vessel is valved shut at both ends. As it warms — sun, heat tracing, a warm process stream — the liquid expands with nowhere to go, and pressure shoots up very fast until a small thermal relief valve lifts or the weakest fitting bursts. API 521 names hydraulic (thermal) expansion of blocked-in liquid as a standard overpressure case requiring relief; the absence of thermal relief is exactly what ruptured the Geismar reboiler. (API 521 principles, CSB Geismar)

1 A section is blocked in full of cool liquid after an operation or during maintenance. · **2** Ambient or process heat warms the trapped liquid; it tries to expand. · **3** Because liquid barely compresses, pressure rises steeply with temperature ($dP \approx (\beta/\kappa) \cdot dT$). · **4** A small thermal PSV caps it — or, with none (or one valved off), the weakest fitting or shell ruptures.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — hydraulic-expansion events are a standard API 521 design case documented by mechanism and incident (Geismar) rather than published rate data (API 521 scenario guide).

Consequences Fitting or shell rupture and loss of containment; at Geismar the mechanism ruptured a propane reboiler catastrophically — 2 dead, 100+ injured. (CSB)

THE FACTS — CITED STATS

✓ VERIFIED

Williams Geismar (2013) is CSB's textbook example of "no thermal relief" — liquid propane blocked into a shell with relief valved off, then heated. (CSB)

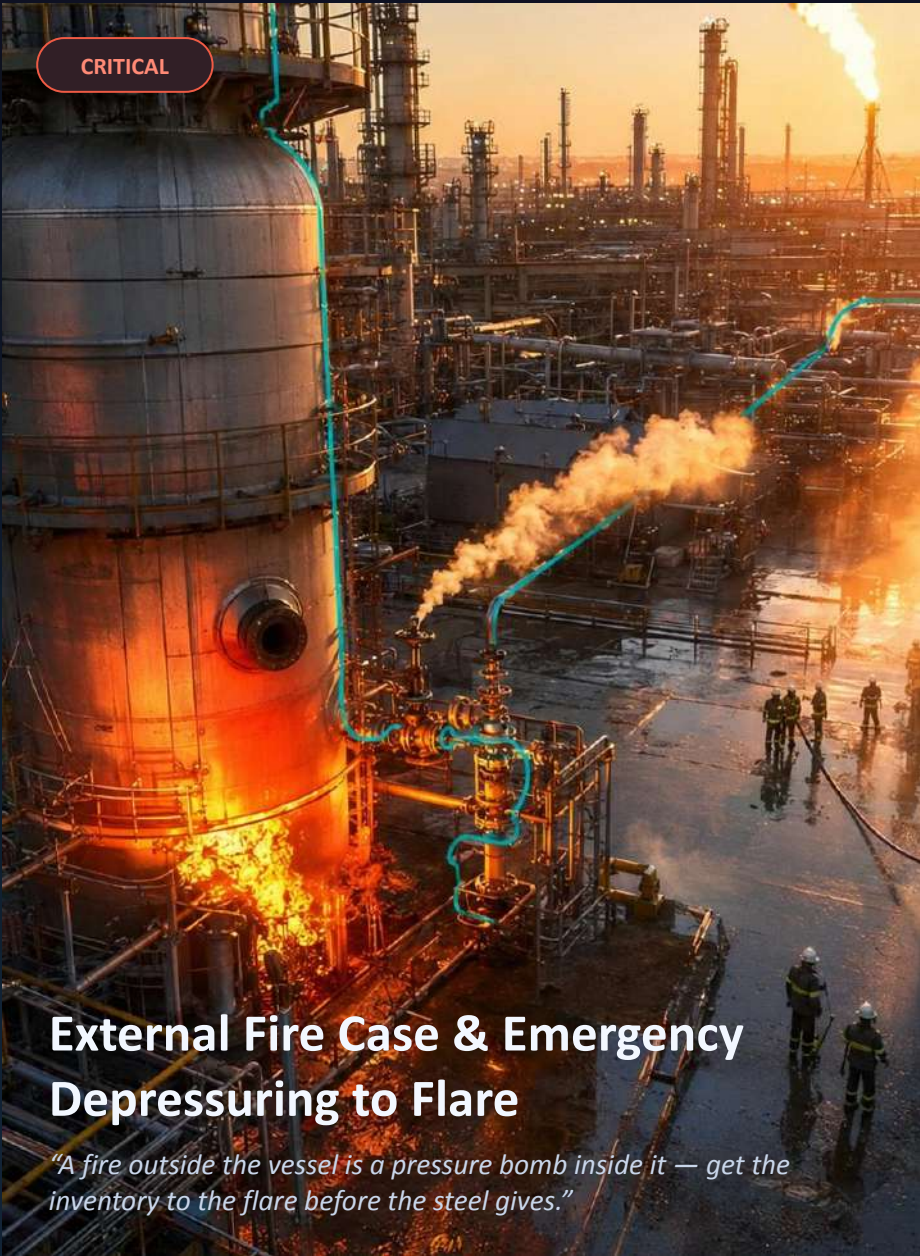
API 521 lists hydraulic (thermal) expansion of blocked-in liquid as a standard overpressure case requiring relief. (ATex/API 521)

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WHAT · WHY · HOW

A fire near a pressure vessel boils the liquid inside and builds pressure while weakening the hot metal. The relief valve vents the boil-off, but the real save is emergency depressuring — dumping contents to the flare fast enough that the wall survives. API 521 defines the external-fire case as a primary sizing basis for relief and depressuring systems; the industry rule is to reduce vessel pressure to ~50% of design (or 100 psig, whichever is lower) within about 15 minutes via blowdown to flare. (API 521 principles, API 521 6th-ed. ...

- 1 An external pool fire begins engulfing the vessel; fire heat flux raises contents temperature and vapor...
- 2 Pressure climbs; the PSV lifts and caps the peak while the fire also weakens the hot wall.
- 3 Trainee confirms relief is active and initiates emergency depressuring/blowdown to flare.
- 4 Blowdown produces an exponential pressure decay toward the 50%-of-design / ~15-minute target; cooling water...

HOW OFTEN · CONSEQUENCES

How often Industrial Fire World database analysis (Jan 2000–Jul 2013, US) indicates a refinery can expect an external fire roughly once every 10 years; chemical plants handling flammables roughly once every 500 years (Bluefield Process Safety analysis). database-derived estimate; per-vessel fire-exposure frequency not separately quantified.

Consequences Without depressuring, the heated wall weakens while pressure rises, ending in vessel rupture/BLEVE with blast, fireball, and escalation across the unit. (mechanism per API 521)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level API 521 fire-case design basis.
Depressuring rule: ~50% of design pressure (or 6.9 barg/100 psig, whichever lower) within ~15 minutes — based on a ~1-inch...
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HIGH



PSV Chatter From Excessive Inlet Pressure Loss

“The relief valve finally opened — and then hammered itself to pieces at a hundred cycles a second.”

WHAT · WHY · HOW

When a relief valve lifts, the rushing flow drops pressure in its own inlet line. If that line is too long, too small, or partly closed, pressure at the valve falls below reseal, so it slams shut — then rebuilds and reopens, over and over. ... API 520 Part II's "3% rule" limits non-recoverable inlet-piping pressure loss to 3% of set pressure; violating it is the single most common cause of valve chatter. (Process Engineering Associates)

- 1 Pressure rises toward set on a PSV fed by a long/small/partly-obstructed inlet line.
- 2 The valve lifts; relief flow drives an inlet-line loss $\propto \text{flow}^2$, dropping valve-inlet pressure below reseal.
- 3 The valve slams shut; inlet pressure rebuilds; it reopens — cycling on the order of 10–100 Hz.
- 4 Effective relief capacity collapses while the valve batters its own disc and seat.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — industry reviews report 3%-rule violations as "one of the most common issues" uncovered when auditing existing PSV installations against RAGAGEP, but no published percentage of installations or chatter-event rate was found (Process Engineering Associates, ioMosaic primer).

Consequences The valve wrecks its disc/seat and delivers a fraction of rated capacity, so the protected vessel can keep rising toward rupture while the PSV "operates." (ioMosaic)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level API 520 relief-performance case.
API 520 Part II 3% rule: inlet non-recoverable loss $\leq 3\%$ of set pressure; violation is the single most common cause of chatter. ...
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HIGH

Relief-Header Backpressure Defeats a Conventional PSV

"Every valve on the header opened at once, and the backpressure held this one shut."

WHAT · WHY · HOW

Many relief valves share one flare header. When several lift together in a common upset, header pressure builds — and on a conventional PSV that backpressure pushes back on the disc, raising its effective opening pressure, cutting its flow, or holding it shut, so its vessel isn't really protected. A conventional PSV's set pressure and capacity are sensitive to backpressure — beyond roughly 10% of set pressure, lift/capacity degrade — which is why balanced-bellows or pilot-operated valves are specified for high-backpressure headers; superimposed + built-up backpressure limits are governed by...

1 A common-mode upset (power/cooling failure) lifts several PSVs into the shared flare header at once. · 2 Header pressure builds as a function of total relief flow and header resistance. · 3 Built-up backpressure enters the conventional valve's disc force balance: effective opening pressure rises... · 4 The protected vessel keeps rising even though the valve is nominally "open."

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — simultaneous relief on a shared header is a standard flare-header design load, but no incident-rate data or named-event frequency is published for the backpressure-defeat mechanism (source flags it as class-level design knowledge).

Consequences The protected vessel can exceed its intended pressure limit during a plant-wide event even with its relief valve open, progressing toward rupture while attention is on the wider upset. (mechanism per API 520 Pt II)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level flare-header design case.

Beyond ~10% of set pressure, a conventional valve's lift/capacity degrade with backpressure — the trigger for specifying...
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CRITICAL

WHAT · WHY · HOW

A vessel holds a reactive mixture. A skipped step, wrong concentration, or lost cooling starts a runaway decomposition making heat and gas faster and faster. Even a correctly working relief valve can't vent fast enough for a full runaway, and the vessel bursts. Bayer CropScience (2008) proved it: a runaway decomposition overwhelmed the relief system and burst a 4,500-gallon residue treater — 2 killed, 8 injured; DIERS/API two-phase methods exist precisely because a valve sized for a normal upset can be hopelessly undersized for a runaway. ...

1 A trigger occurs — bad charge, defeated interlock, or lost cooling — in a reactor/treater with self-heating... · 2 An Arrhenius-style feedback begins: heat and gas generation grow with temperature, which grows with heat. · 3 Pressure accelerates; the PSV lifts but generation exceeds relief capacity. · 4 Past the tipping point, generation wins and the vessel ruptures.

HOW OFTEN · CONSEQUENCES

How often CSB documented 167 serious reactive incidents in the US between January 1980 and June 2001 (~8/year serious) causing 108 deaths; 35% were runaway reactions and 70% occurred in chemical manufacturing (CSB reactive hazards data release).

Consequences Bayer CropScience: vessel rupture and explosion — 2 killed, 8 injured; reactive incidents in the CSB study produced fires/explosions in 42% of cases and toxic emissions in 37%. (CSB, CSB 167-incident data)

THE FACTS — CITED STATS

✓ VERIFIED

Bayer CropScience, Institute WV, 28 August 2008 (CSB) — runaway decomposition burst a residue treater during methomyl-unit restart; 2 dead, 8 injured.

Bayer CropScience, Institute WV, 28 August 2008: overridden interlock let residue into the treater early; runaway overwhelmed relief...

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Runaway Reaction Overwhelms the Relief System

"The relief valve opened wide — and the reaction still out-ran it."

HIGH



Flare / Blowdown System Overload & Atmospheric Release

“Everything relieved at once, the flare couldn't take it, and the overflow went to the ground.”

WHAT · WHY · HOW

All plant relief eventually goes to one flare through a shared header and knock-out drum. In a big common upset that system can be overloaded: the KO drum fills with liquid, the flare can't burn it all (or the flame goes out), and hydrocarbons escape at ground level or as unburned vapor. After BP Texas City, CSB urged the industry to replace atmospheric blowdown drums with properly engineered flares, because an under-designed relief-disposal system turns a relief event into a ground-level flammable release. (CSB recommendation)

- 1 A common-mode event (power/cooling loss) lifts many relief devices into the shared flare header at once.
- 2 Aggregate relief flow exceeds disposal capacity; the KO drum's liquid level climbs.
- 3 Liquid carries over to the flare tip, and/or flare load exceeds capacity or the pilot fails.
- 4 Hydrocarbons escape unburned or at ground level instead of being safely destroyed.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — flare overload is treated as a design-load case under API 521 (header sizing, KO-drum capacity, smokeless capacity) rather than a mechanism with published event-rate data (API 521 principles).

Consequences Ground-level flammable release or unburned vapor cloud — the Texas City pattern CSB's recommendation targets; radiation/dispersion magnitudes are facility- and weather-specific. / (CSB)

THE FACTS — CITED STATS

✓ VERIFIED

BP Texas City (2005) is the anchoring disposal-system failure (blowdown drum overflow); the general flare-overload case itself carries no single named...
CSB formally recommended eliminating atmospheric blowdown drums of the Texas City type in favor of properly designed flares. (CSB)

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HIGH

WHAT · WHY · HOW

A check valve should let flow go only one way. When it fails (stuck open, worn, installed backward), high-pressure fluid flows in reverse — over-pressuring upstream low-pressure equipment or spinning a stopped pump backward. API 521 treats loss of a normally-closed backflow barrier as a credible overpressure contingency when a higher-pressure source can communicate backward into lower-rated equipment; it is the same family as gas blowby and tube rupture — an HP source reaching LP equipment through a failed barrier. ...

1 Normal forward flow holds the check valve open; the valve wears, sticks, or was installed wrong. · **2** The driving direction reverses — a pump trips or an HP header pressurizes. · **3** The check valve fails to seat; HP fluid flows backward per the pressure difference and open Cv. · **4** Upstream LP pressure rises toward its PSV/MAWP, and/or an idle pump spins in reverse.

HOW OFTEN · CONSEQUENCES

How often CCPS LOPA data treats a single check valve as having a generic probability of failure on demand of 0.1 (risk-reduction factor of just 10), with initiating-event frequencies of 0.1/yr for single and 0.01/yr for dual check valves in high-demand service; API 521 (2014) allows no credit at all for a single check valve (JCL Risk / Modi, "Check Valves as Safeguards," 2017). generic/class-level values.

Consequences Overpressure of upstream low-pressure equipment to rupture, and mechanical damage from reverse rotation of idle pumps/compressors. class-level relief-engineering practice (source file)

THE FACTS — CITED STATS

SECONDARY

No single named incident cited in source; class-level mechanism flagged (standard rotating-equipment and relief-engineering practice).

CCPS generic PFD for a single check valve as a protective layer: 0.1 — i.e., expect it to fail to stop backflow 1 demand in 10. ...

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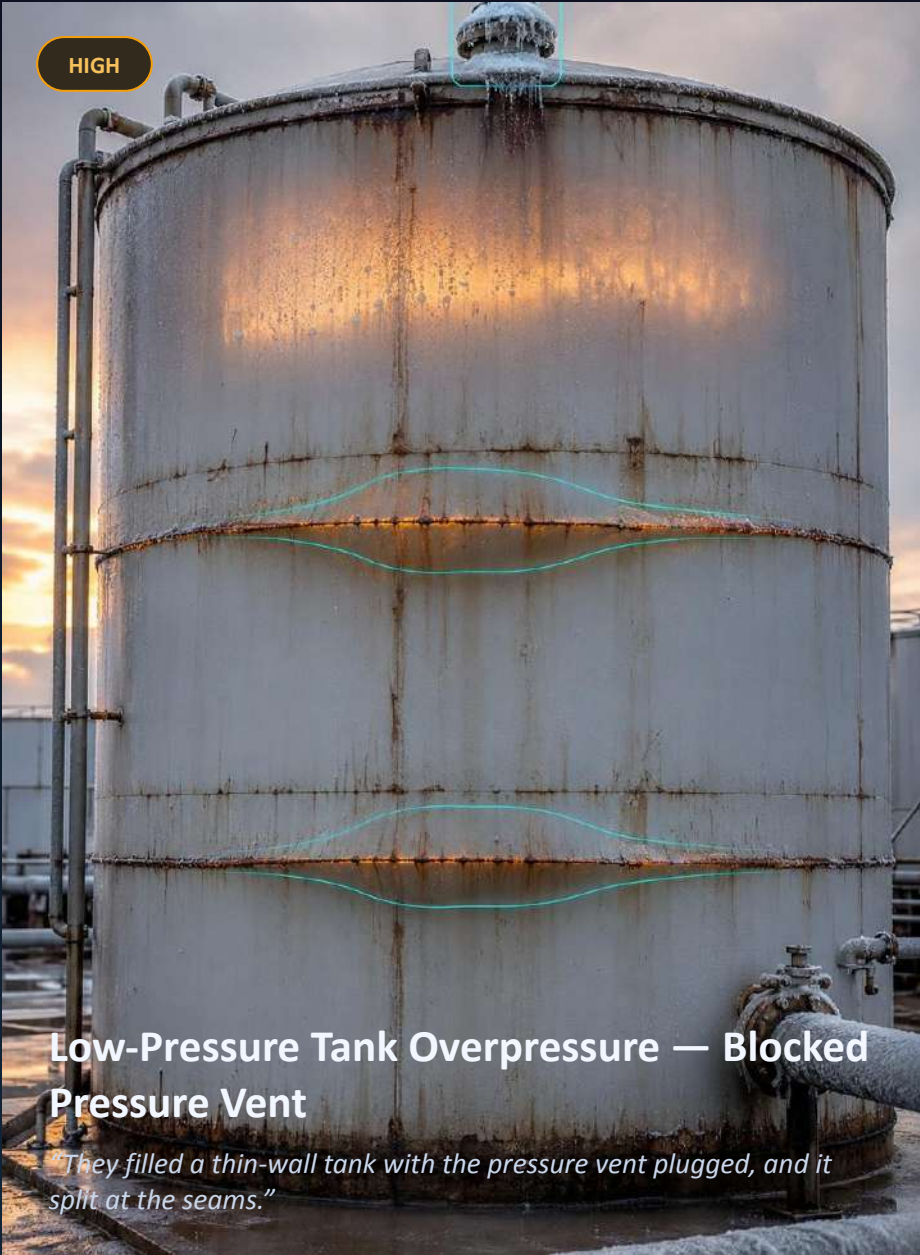
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Check-Valve Failure — Reverse-Flow Overpressure

"The one-way valve wasn't, and the high-pressure side came back the way it left."



WHAT · WHY · HOW

Atmospheric and low-pressure tanks breathe through a small pressure/vacuum vent. Pump liquid in (or heat the vapor space) and displaced vapor must leave through that vent. ... API Standard 2000 sets the venting requirements protecting tanks against both overpressure and vacuum, covering normal in/out-breathing (filling, emptying, thermal) and emergency (fire) venting; a blocked pressure vent during filling can exceed a tank's tiny rating in minutes. (API 2000 overview)

1 A transfer into (or heating of) the tank begins. · 2 The pressure vent is blocked, frozen, or undersized; displaced vapor cannot escape. · 3 Tank pressure climbs past its very low rating (often ounces to a few psi). · 4 The roof lifts or the seams split — deformation happens quickly at these thin-wall margins.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — API 2000 defines the venting design basis but no published rate of blocked-vent overpressure events was found; incident reports (e.g., a fatty-acids-plant tank roof thrown 25 m by pressure overload) document the mechanism, not its frequency (API 2000 overview, Piping Technology System).

Consequences Roof lift, seam split, and loss of containment of the tank contents; documented cases include a 5-ton, 8-m tank roof propelled 25 m by pressure overload. single-case illustration (Piping Technology System)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level API 2000 out-breathing case.

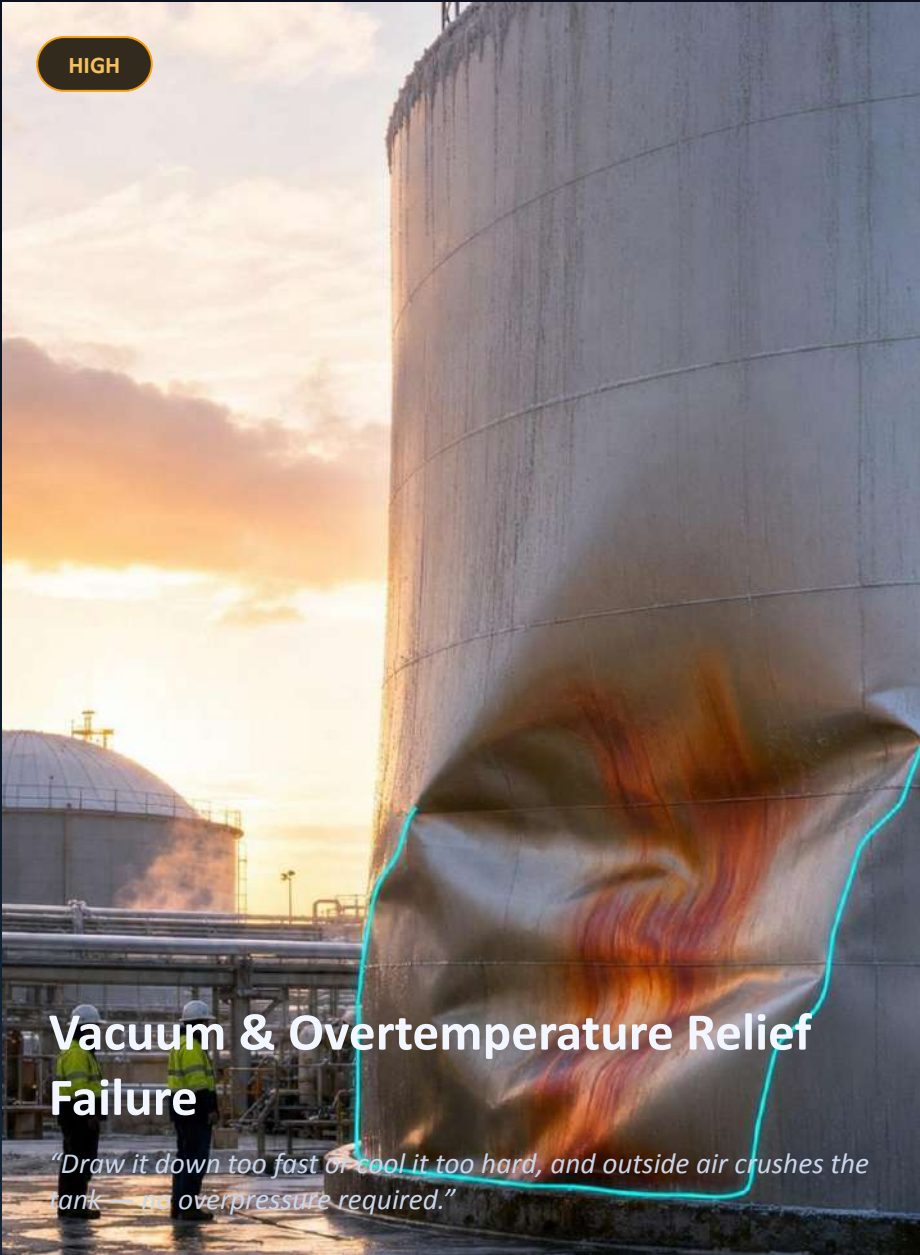
API 2000 covers both normal in/out-breathing (filling, emptying, thermal) and emergency fire venting for atmospheric/low-pressure...

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WHAT · WHY · HOW

Pump liquid out fast, or let hot vapor cool and shrink after steam-out, or lose a nitrogen blanket, and internal pressure drops below atmospheric. A tank strong against a little internal pressure can be crushed like a soda can by a tiny vacuum. ... Atmospheric/low-pressure tanks are structurally weak against underpressure — even a small vacuum can buckle them; API 2000 governs the in-breathing (vacuum) side just as it does overpressure, and API 521 covers overtemperature/thermal-relief contingencies. (AIChE CEP 2019, API 2000 overview)

- 1 The tank is being emptied fast, freshly steamed out, or running on a hot stream.
- 2 Withdrawal or vapor contraction/condensation outpaces make-up air/gas through the vacuum vent (vent plugged...
- 3 Internal pressure falls below the tank's tiny vacuum rating and the shell buckles inward — or, in the mirror...
- 4 Trainee must slow the outflow, restore make-up gas/venting (or relief), or open a manway before the tank...

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — vacuum-collapse events are documented as a recognized hazard class (AIChE CEP; ScienceDirect literature on protecting tanks against vacuum collapse) without published event-rate data (AIChE CEP 2019, ScienceDirect).

Consequences Structural buckling/collapse of the tank shell with loss of containment — or seam failure on the overtemperature side; collapse can occur at vacuum levels far below 1 atm because the shell is not designed for external pressure. (AIChE CEP)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident cited in source; class-level API 2000/521 in-breathing and overtemperature case. Even a small vacuum can buckle an atmospheric/low-pressure tank not designed for underpressure. (AIChE CEP 2019)
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GENRE 04 · 15 SCENARIOS

Rotating Equipment

Visual motif — The pump or compressor as hero machine — glowing bearings and seals, vibration ghosting the wireframe.

one card per situation follows — poster prompt in each card's notes



Pump Dry-Running / Loss of Suction

“A pump with nothing to pump still spins — and cooks its own seal and bearings.”

EQUIPMENT-BOUND

ROTATING EQUIPMENT

TRAIN / OPERATE

WHAT · WHY · HOW

A centrifugal pump keeps running after its suction source empties or is cut off (drained tank, closed suction valve, plugged strainer, gas break-in). With no liquid inside to cool and lubricate the seal and internals, temperatures climb fast and the seal and bearings can seize. The pumped liquid IS the seal's coolant and lubricant; lose it and the machine destroys itself in minutes while looking "on" from the control room. It is one of the fastest self-inflicted pump kills an operator can catch or cause.

1 Suction source is lost — tank drains, suction valve closes, strainer plugs, or gas breaks into the line. · 2 Flow collapses toward zero with no liquid inventory in the casing; motor amps sag. · 3 Nearly all shaft power turns into heat inside a near-empty casing; seal-face and casing temperature climb... · 4 Residual liquid vaporizes; the seal faces run dry and overheat.

HOW OFTEN · CONSEQUENCES

How often Around 30% of pump failures are traced back to dry running per vendor/industry blogs (secondary, unaudited — Iwaki America, National Pumps & Boilers). Irreversible damage can begin within ~20–30 seconds of running dry (same sources). No audited event-rate (events/pump-year) found in public sources.

Consequences Seal destruction and possible leak path to atmosphere, bearing seizure, wrecked pump internals; on hydrocarbon service a failed seal is a loss-of-containment path (API 682 seal literature — Seal FAQs).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level composite — no single named public incident used; the mechanism is standard API 682 / pump-reliability literature.

Lack of lubrication is the primary cause of mechanical-seal failure (Seal FAQs / API 682 literature).

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MED-HIGH



Pump Minimum-Flow Violation (Low-Flow Recirculation)

“A pump throttled down too far tears itself apart from the inside — while still moving liquid.”

WHAT · WHY · HOW

A centrifugal pump runs well below its minimum continuous stable flow (discharge throttled hard, or the min-flow bypass lost). Internal recirculation at the impeller drives vibration, hydraulic thrust, erosion and a steady temperature rise that punishes seal, bearings and shaft. It is the slow-burn cousin of dead-head: nothing is "off", nothing is "closed", yet the machine is accumulating damage every minute it runs below minimum. Operators routinely throttle pumps without knowing where MCSF sits.

- 1 Discharge is throttled far down, or the minimum-flow bypass/ARV closes or plugs. · 2 Flow falls below MCSF while remaining non-zero. · 3 Suction/discharge recirculation sets in — vibration and radial hydraulic thrust rise. · 4 Most input power turns to heat in a small flow; temperature climbs steadily.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (no audited rate of below-MCSF operating events found). Prevalence context: pump MTBF in US refineries runs roughly 3–10 years (Bloch reliability data secondary compilation — ReliaMag), with low-flow operation a recognized contributor in the reliability literature (Pumps & Systems).

Consequences Seal and bearing damage, excessive wear, possible shaft failure from recirculation, vibration and radial thrust (Pumps & Systems, Dynapro).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level composite — chronic-degradation scenario, no single named public incident.
Operating below MCSF causes suction/discharge recirculation, increased vibration and radial hydraulic thrust (Pumps & Systems).
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HIGH

WHAT · WHY · HOW

A pump's mechanical seal depends on a thin liquid film between precision faces, kept cool and clean by an API 682 flush plan (Plan 11 recirculation, Plan 52/53 barrier fluid). ... Seals are the single dominant pump-reliability problem, and the flush plan is the seal's life-support. Recognizing a dying seal-support system before blowout is a core operator skill.

1 The seal-support system degrades: flush orifice plugs, seal pot runs low, or barrier pressure collapses. · 2 Seal-face cooling/lubrication is lost; face temperature rises. · 3 Small leakage (weep) begins at the seal. · 4 Left alone, faces overheat and fail; leakage grows toward gross release.

HOW OFTEN · CONSEQUENCES

How often Mechanical-seal failures account for roughly ~70% of centrifugal-pump maintenance / pumps removed from service (widely cited secondary industry figure — Power Zone, Seal FAQs). ...

Consequences Seal distress then leakage of process fluid to atmosphere or flare/drain; on volatile service the precursor to a blowout/fire (see card_04_04) (API 682 literature — Wikipedia/API 682).

THE FACTS — CITED STATS

Class-level composite — grounded in API 682 practice and reliability datasets rather than a single named case.

~70% of pump repairs are seal-related (secondary — Power Zone); ESA dataset: 60.4% of 3,500 failures (ReliaMag).

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SECONDARY

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Mechanical Seal Failure & Loss of Seal Flush

"The flush stops, the faces run dry, and the seal that holds the product in lets go."



CRITICAL

WHAT · WHY · HOW

A mechanical seal on a pump handling hot and/or volatile hydrocarbon fails suddenly and releases product to atmosphere. Because the fluid is above its auto-ignition temperature or forms a flammable cloud, the leak becomes a fire or vapor-cloud hazard right at the pump. This is where a pump-reliability problem becomes a process-safety event: the most common pump failure (the seal) sitting on the most dangerous service (hot/light hydrocarbon) is a direct loss-of-containment and ignition path.

1 Seal on hot/volatile hydrocarbon service fails suddenly (often preceded by lost flush/barrier). · **2** Process fluid releases at the seal; a flammable cloud grows around the pump. · **3** Fluid above auto-ignition temperature ignites without a spark, or the cloud finds an ignition source. · **4** Running pump keeps feeding inventory to the leak/fire until isolated.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources for ignited seal-release events specifically. Context: the underlying initiator (seal failure) is the dominant pump failure mode — ~70% of pump repairs / 60.4% of an ESA 3,500-failure dataset (see card_04_03 sources) — but the fraction escalating to fire is not published.

Consequences Loss of containment, pump fire or vapor-cloud ignition, escalation to unit damage and personnel exposure; API 682 dual seals, barrier fluids and quench plans exist specifically to contain such releases (API 682 overview, Power Zone flush plans).

THE FACTS — CITED STATS

SECONDARY

Class-level composite — a common release path in refining/upstream practice, deliberately not tied to a single named CSB case in the source research.

Seal failure is the leading pump maintenance event (~70% / 60.4% ESA — see card_04_03).

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Seal Blowout → Loss of Containment / Pump Fire

“A seal on hot, light hydrocarbon fails wide open — now you have a leak looking for a spark.”

CRITICAL

WHAT · WHY · HOW

A duty/standby pump pair shares a header; the standby is under maintenance with part of its pressure boundary opened (relief valve removed, blind only hand-tight). ... This is the Piper Alpha pattern: the deadliest offshore disaster in history began as a rotating-equipment return-to-service decision made without knowing the machine's true isolation state. Permit discipline is the entire lesson.

1 Standby pump enters maintenance; a PSV is removed and the flange blinded only hand-tight; permit status is... · 2 The duty pump trips; production pressure mounts to restore flow. · 3 Operators, unaware the standby is not intact, move to start it. · 4 Discharge head is applied to a segment open to atmosphere; inventory releases through the incomplete boundary.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an event rate. This is a named-incident pattern (Piper Alpha, 1988) whose root causes — permit-to-work and isolation-handover failure — remain standard audit findings, but no public dataset counts "standby restarts into defeated boundaries" per year.

Consequences Piper Alpha's first explosion, escalation and platform loss killed 167 people (The Chemical Engineer, IChemE summary); generically: release of pressurized flammable inventory at a point believed isolated.

THE FACTS — CITED STATS

✓ VERIFIED

Piper Alpha, North Sea, 6 July 1988 — standby condensate injection Pump A restarted toward service with its PSV removed; Cullen Inquiry.

Piper Alpha, 6 July 1988: 167 fatalities (Cullen Inquiry via The Chemical Engineer).

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Standby Pump Restart Into a Defeated Boundary (Piper Alpha pattern)

"They restarted the standby pump nobody knew was open to atmosphere."

HIGH

WHAT · WHY · HOW

A bearing on a pump, compressor or turbine begins to fail (contamination, fatigue, lost lubrication, misalignment). Vibration and bearing temperature rise steadily; if the trend is ignored or the protection bypassed, the bearing collapses and the machine can wreck itself in seconds. Vibration is the number-one early warning on rotating machinery — the entire API 670 machinery-protection layer exists because bearings announce their death well in advance. Riding a failing bearing converts a planned swap into a train wreck.

1 A bearing starts degrading (contamination, fatigue, lubrication loss, misalignment). · 2 Vibration amplitude and bearing-metal temperature trend upward. · 3 Alarm thresholds fire; the trend continues toward trip levels. · 4 Operator either reduces load, swaps to spare, or takes an orderly shutdown — or bypasses/ignores the trip.

HOW OFTEN · CONSEQUENCES

How often Bearings are the leading electric-motor failure component: ~44% of failures in the IEEE Motor Reliability Working Group survey (1,141 motors) and ~41% in the EPRI survey (6,312 motors) (published survey data — CBM Connect review of the IEEE/EPRI studies, ResearchGate summary). Note: reported percentages shift 10–15% with how "failure" is defined.

Consequences Bearing collapse → rotor drop → seal/impeller/casing contact and potential wreck of the whole train; secondary loss-of-containment risk on process machines (API 670 protection rationale — Meggitt).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level composite — evidenced by the IEEE/EPRI failure surveys and API 670 practice rather than a single named case.

IEEE survey: bearing-related failures ~44% of motor failures (1,141 motors) (CBM Connect).

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Bearing Failure & High Vibration

"The machine tells you it's dying in vibration long before it flies apart — if you listen."

CRITICAL

WHAT · WHY · HOW

A large compressor or turbine rides on oil-film journal bearings fed by a forced lube-oil console. ... There is no slower failure mode hiding inside this one — journal bearings die in seconds without oil. The protective sequence (auto-start standby, accumulator bridge, low-oil trip) is the whole game, and defeating the trip to "keep it running" is the classic fatal move.

- 1 Main lube-oil pump trips or oil header pressure sags. · 2 Header pressure decays at a rate set by accumulator size vs. standby-pump start time. · 3 Standby pump should auto-start; the accumulator must hold pressure through the ~1-second transfer window. · 4 If pressure isn't restored, the low-oil-pressure trip must shut the train down.

HOW OFTEN · CONSEQUENCES

How often Loss of lube oil is identified as the highest-frequency severe-event category in steam-turbine insurance loss experience (overspeed is the highest-severity) (qualitative ranking from insurers' review — IMIA WGP 42-05, Maintenance and Overhaul of Steam Turbines). ...

Consequences Catastrophic bearing failure within a few seconds — journal-bearing babbitt destroyed, rotor sinks and loses clearance; potential full train wreck (Turbomachinery Magazine).

THE FACTS — CITED STATS

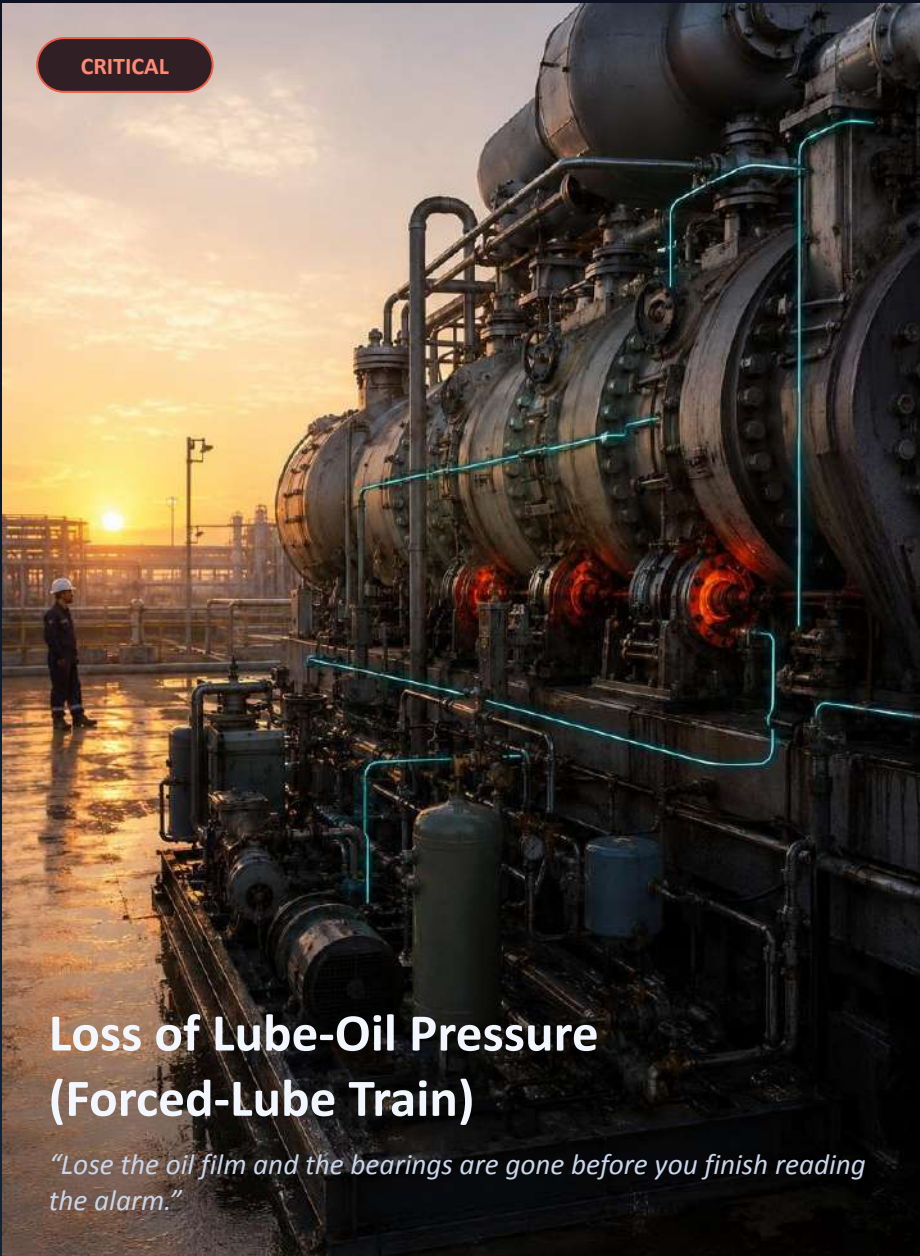
✓ VERIFIED

Class-level composite — grounded in API 614 changeover practice and insurers' loss experience rather than one named case. Cutting off oil flow to turbomachinery can destroy journal bearings in a few seconds (Turbomachinery Magazine).
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Loss of Lube-Oil Pressure (Forced-Lube Train)

"Lose the oil film and the bearings are gone before you finish reading the alarm."

HIGH

WHAT · WHY · HOW

In a duty/standby pair on a common discharge header, the idle pump is held back by a check valve. If that valve leaks, header pressure drives liquid backward through the idle pump, spinning it in reverse. ... The hazard is invisible from the start button: a pump that looks stopped is actually rotating backward. It turns the most routine action in the plant — starting the spare — into a shaft-snapping event.

- 1 The idle pump's discharge check valve leaks or fails.
- 2 Static header ΔP drives reverse flow through the idle pump.
- 3 The pump backspins — often silently, with no control-room indication unless shaft speed/direction is...
- 4 A start is requested (pump swap); starting torque is applied against reverse rotation.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an absolute event rate. Relative datum: a poorly maintained single check valve has been estimated at ~455× the catastrophic-event frequency of a well-designed dual tight-shutoff check-valve arrangement with an integrity program (PHA-methodology estimate, secondary — JCL Risk, "Check Valves as Safeguards").

Consequences Seal and bearing failure from reverse running; threaded impeller can unscrew and destroy the pump; starting against backspin stresses shaft, coupling and motor to failure (Crane Engineering, Fluid Handling).

THE FACTS — CITED STATS

Class-level composite — standard pump-engineering literature; no single named public incident used.

A leaking/failed discharge check valve lets reverse flow drive the idle pump backward (Crane Engineering).

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✓ VERIFIED

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Reverse Rotation / Backspin on Trip

"The idle pump is quietly spinning backward — start it now and the shaft snaps."

MED-HIGH

Coupling Failure / Shaft Misalignment

"A few thousandths of an inch out of line quietly eats the bearings and seal."

WHAT · WHY · HOW

Driver and driven machine are coupled shaft-to-shaft. Misalignment (thermal growth, soft foot, worn coupling) or a degrading coupling raises vibration and cyclic loads that shorten bearing and seal life — and a badly degraded coupling can fail outright, releasing or unbalancing the train. Misalignment is one of the most common chronic root causes in all of rotating machinery — it silently loads exactly the components (bearings, seals) whose failures dominate downtime. Catching it early is cheap; ignoring it compounds.

1 Misalignment develops — thermal growth on warm-up, soft foot, settling baseplate, or coupling wear. · **2** Vibration rises with a characteristic misalignment signature (often at 2× running speed). · **3** Cyclic loads accelerate bearing and seal wear on both machines. · **4** Left uncorrected, secondary damage accumulates or the coupling fails outright.

HOW OFTEN · CONSEQUENCES

How often Widely cited industry estimates put shaft misalignment behind roughly 30–50% of rotating-machinery failures, with some sources claiming up to 50–70% of machine vibration problems (secondary/vendor training figures; ranges vary widely by source and definition — Dovient alignment fundamentals, Dynamox, Fluke). No audited primary dataset found — treat all these percentages as estimates.

Consequences Premature bearing and seal failure, elevated vibration, and possible outright coupling failure releasing/unbalancing the train (API 670 machinery-protection practice — Meggitt).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level composite — chronic degradation scenario, not a single named incident.

Misalignment is one of the most common chronic causes of rotating-machine vibration and premature bearing/seal failure (Meggitt / API...

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MED-HIGH

WHAT · WHY · HOW

An electric motor driving a pump or compressor is overloaded (mechanical bind, over-dense/viscous fluid, jammed rotor) or started too many times in quick succession. ... Motors have hard thermal limits — starts per hour and locked-rotor I^2t — that no amount of production urgency changes. Hammering the start button is one of the most common ways operators convert a mechanical problem into a burned motor.

1 An abnormal load appears: mechanical bind, dense/viscous fluid, or a locked rotor — or a trip prompts... · 2 Motor current spikes (locked rotor = very high current at zero speed). · 3 Winding temperature climbs on an I^2t trajectory toward the insulation limit. · 4 Thermal-overload/anti-restart protection trips (or is defeated).

HOW OFTEN · CONSEQUENCES

How often Stator/winding failures — the damage mode this scenario drives — account for roughly 20–30% of motor failures in the IEEE/EPRI reliability surveys (EPRI ~36–37% stator-related in some breakdowns) / (survey data; category definitions vary — CBM Connect on the IEEE/EPRI studies, ResearchGate summary). Frequency of overload/rapid-restart events themselves: not quantified in public sources.

Consequences Winding insulation damage or burnout, motor and coupling failure from starting against abnormal conditions (Crane Engineering); lost driver = lost train availability.

THE FACTS — CITED STATS

✓ VERIFIED

Class-level composite — grounded in motor-protection practice, not a single named incident.

Stator winding failures ~20–30% of motor failures per IEEE/EPRI surveys / (CBM Connect).

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Motor Driver Overload / Locked-Rotor / Rapid Restart

“Slam the start button one time too many and the motor cooks itself.”

HIGH

WHAT · WHY · HOW

A centrifugal compressor's discharge temperature climbs toward its limit — from prolonged anti-surge recycle operation, a fouled or bypassed cooler, high suction temperature, or low flow. ... It is the trap hiding inside surge protection: the recycle loop that saves the machine from surge slowly cooks it instead. Operators must recognize that "safe on recycle" is a countdown, not a parking spot.

1 Cooling is lost (cooler fouled/bypassed/fan off), or the machine is left on heavy anti-surge recycle / low... · 2 Hot compressed gas recirculates; suction and discharge temperatures ratchet upward. · 3 Discharge temperature trends toward the seal/material limit; alarms fire. · 4 Operator diagnoses the cause — cooling loss vs. ...

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (no published rate of high-discharge-temperature trips found). The mechanism — prolonged recycle raising temperatures until a thermal trip — is recognized compressor-operations practice (consistent with anti-surge/thermal design; source file 04, Scenario 11).

Consequences Dry-gas seal damage, lube-oil degradation, internals/rotor damage, and a unit-tripping thermal shutdown (API 617 scope — Rotating.Equipment).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level composite — standards-grounded (API 617/670); no single named public incident used.

API 617 governs centrifugal/axial compressors; discharge-temperature limits protect seals, materials and rotor integrity (API 617... confidence-flagged stats · full cited list in slide notes

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Centrifugal Compressor High Discharge-Temperature Thermal Trip

"Recycle it too hard or foul it up, and the discharge gets hot enough to hurt the seals and the steel."

HIGH

WHAT · WHY · HOW

A centrifugal compressor is protected by a suction scrubber/knock-out drum that removes entrained liquid from the gas. ... The scrubber is the last line of defense between liquid and a machine built to compress only gas. A single failed level loop converts a routine upset into rotor damage.

1 Scrubber level control fails high — stuck dump valve or failed level transmitter. · **2** Liquid inflow exceeds dump rate; level rises toward the gas outlet. · **3** Past the carryover threshold, liquid entrains into the suction gas. · **4** Liquid enters the running compressor — mechanical damage, surge risk, trip.

HOW OFTEN · CONSEQUENCES

How often The first-stage suction scrubber is reported as the highest-frequency failure location for gas compressors (vendor/industry qualitative claim — JCI Group); on the Gryphon Alpha FPSO, recurring liquid carryover caused a history of compressor piston-rod failures, each a ~6-day outage (operator case study — OEUK / Maersk Oil). No industry-wide events/compressor-year rate found in public sources.

Consequences Rotor/seal/internals damage (liquid is effectively incompressible in the rotating element), erosion and mechanical damage, extended outages (rotating-equipment practice; MySep white paper on carryover troubleshooting); tracked as process-safety upset events under API RP 754 (API RP 754 fact sheet).

THE FACTS — CITED STATS

✓ VERIFIED

Gryphon Alpha FPSO (North Sea) — recurring liquid carryover into gas compressors caused piston-rod failures and six-day outages (OEUK case study).

Liquid carryover into a centrifugal compressor causes mechanical damage to rotor/seals — the reason KO drums and high-level trips...

source: OEUK case study · confidence-flagged stats · full cited list in slide notes

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Compressor Suction-Scrubber Liquid Carryover

"The scrubber that keeps liquid out of the compressor just filled up and sent it in."

CRITICAL

WHAT · WHY · HOW

A reciprocating compressor squeezes gas in a cylinder with a piston. ... This is the most unforgiving failure in the genre: zero warning time once the slug reaches the cylinder. The entire defense is upstream — level detection, draining, and refusing to start until the suction is verified dry.

1 Liquid accumulates in the suction bottle/scrubber — level control fails, upstream carryover, or condensate... · 2 Liquid threatens to enter the cylinder, or a start is attempted with liquid present. · 3 A liquid fraction enters the swept volume; the piston stroke meets an incompressible slug. · 4 Cylinder pressure spikes near-vertically — hydraulic lock.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an industry-wide event rate. Documented recurrence exists at single facilities — e.g., Gryphon Alpha FPSO's history of carryover-driven piston-rod failures (OEUK) — and API 618's ~99%-removal separator requirement exists precisely because ingestion events are credible (SwRI on API 618).

Consequences Catastrophic single-stroke destruction of valves, piston rod or crosshead due to hydrolock; liquid slugging also damages compressor valves short of full lock (Forge Reliability).

THE FACTS — CITED STATS

✓ VERIFIED

Gryphon Alpha FPSO — liquid carryover into gas compressors identified as the cause of repeated piston-rod failures (OEUK case study); otherwise...

Liquid in a recip cylinder creates high risk of catastrophic hydrolock failure due to incompressibility in the clearance volume (Forge...

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Reciprocating Compressor Liquid Hydraulic Lock (Slug)

"A slug of liquid in a cylinder can't be squeezed — so something has to break, instantly."

HIGH

WHAT · WHY · HOW

A recip cylinder depends on suction and discharge valves timing correctly. A valve that sticks open, leaks or breaks causes recompression/backflow, overheating the cylinder and packing and pushing abnormal pressure and temperature into the interstage systems — up to overpressuring the next stage. Valves are the number-one failure item on reciprocating compressors, and a missed valve failure cascades: heat, packing damage, interstage overpressure. Localizing it from stage trends is the bread-and-butter recip-operator skill.

1 A suction or discharge valve on one cylinder fails — sticks open, leaks or breaks (often a valve spring). · **2** Gas recompresses/backflows in the affected cylinder; that stage's discharge temperature climbs. · **3** Interstage pressures drift abnormal; the next stage sees rising suction pressure. · **4** Trainee localizes the failing valve from stage temperature, interstage pressure and P-V signature.

HOW OFTEN · CONSEQUENCES

How often Broken/failed valves are the leading cause of unscheduled reciprocating-compressor shutdowns at ~36%, ahead of pressure packings (~18%) and piston rings (~7%), per a 2009 PROGNOST Systems failure-mode survey / (vendor survey, widely cited — DigitalRefining); valve failure is likewise called the leading recip maintenance item in reliability practice (Forge Reliability).

Consequences Cylinder/packing overheating, interstage overpressure toward relief, rod/packing secondary damage, unscheduled shutdown — with unscheduled recip downtime cited up to ~\$100k/day production loss (industry estimate — DigitalRefining).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level composite — evidenced by the PROGNOST failure-mode survey and API 618 monitoring practice rather than a single named case.

Valve failures ≈36% of unscheduled recip shutdowns; packings ≈18%; rings ≈7% / (PROGNOST 2009 survey — DigitalRefining).

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Reciprocating Compressor Valve Failure / Interstage Overpressure

"One broken compressor valve overheats the cylinder and shoves pressure into the next stage."

CRITICAL



Steam Turbine Overspeed / Trip

"Take the load off a turbine with a stuck governor and it races until the rotor bursts — unless the overspeed trip fires."

WHAT · WHY · HOW

A steam turbine driving a pump or compressor suddenly loses its load (driven machine trips or coupling fails) while steam keeps flowing. ... Overspeed is the highest-severity event a turbine can produce — a burst rotor throws fragments like missiles. The layered protection (governor, then independent trip) is the textbook example of defense-in-depth, and defeating it is the textbook fatal shortcut.

1 Load is suddenly lost — the driven machine trips or the coupling fails — while steam is still admitted. · **2** Drive torque wildly exceeds load torque; the rotor accelerates fast ($d\omega/dt = \text{net torque} / \text{inertia}$). · **3** The governor should cut steam; in this scenario it sticks or lags. · **4** Speed passes rated toward the overspeed setpoint (~110% of maximum continuous speed).

HOW OFTEN · CONSEQUENCES

How often Overspeed events are the highest-SEVERITY steam-turbine loss category in insurers' experience (loss of lube oil is the highest-frequency) (qualitative ranking — IMIA WGP 42-05). ...

Consequences Destructive overspeed can be reached within several seconds of load loss; failure of all protection layers risks catastrophic rotor burst and missile generation / (EPRI, IMIA WGP 42-05).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level composite — overspeed identified as the highest-severity loss category in the IMIA steam-turbine loss review (IMIA WGP 42-05); no single named...

API 612 requires overspeed protection on special-purpose steam turbines; the trip is commonly set ~110% of rated speed, tested to $\pm 1\%$...

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GENRE 05 · 15 SCENARIOS

Process Upsets & Abnormal Operations

Visual motif — Boiling gauges and foam — chemistry misbehaving; level and interface chaos churning inside the twin.

one card per situation follows — poster prompt in each card's notes

CRITICAL

WHAT · WHY · HOW

A high-pressure separator keeps a pool of liquid at the bottom; that liquid seal stops the high-pressure gas from escaping down the liquid outlet. If the level drops to zero, gas "blows by" straight into the downstream low-pressure vessel. Blowby gas flow can be orders of magnitude higher than the liquid line's design flow, so a downstream vessel rated far lower can be grossly overpressured — a rupture-class event, which is why API 521 treats it as a formal relief-sizing case.

1 Level control fails — dump valve sticks open or feed is lost — and separator level drives down. · 2 Level reaches the liquid-outlet elevation; the liquid seal is lost. · 3 High-pressure gas flows choked through the liquid line into the low-pressure vessel. · 4 Downstream pressure surges far faster than its relief can breathe.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources. API 521 treats HP→LP gas breakthrough on loss of level as a standard credible overpressure scenario that relief systems must be sized for — evidence of recognized recurrence, but no public event-rate statistics exist. (scenario status per API 521; rate itself unpublished)

Consequences Gross overpressure of the downstream low-pressure vessel, potential rupture and loss of containment; relief systems must be sized for the blowby case because gas flow can exceed normal liquid design flow by orders of magnitude. (EnggCyclopedia, Becht — separator blow-through)

THE FACTS — CITED STATS

✓ VERIFIED

No single named public incident in source; class-level scenario grounded in API 521 breakthrough-overpressure practice and hydroprocessing relief...

Blowby gas flow can be orders of magnitude higher than normal liquid design flow into the LP system. (EnggCyclopedia; Becht)

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Gas Blowby — Loss of Liquid Seal in a Separator

"The drum ran dry, and the high-pressure gas took the liquid's exit straight into equipment built for a fraction of the pressure."

HIGH

WHAT · WHY · HOW

A three-phase separator must hold two levels: total liquid and the hidden oil/water interface. If interface control drifts, water rides out with the oil or oil sinks out with the water — while total level looks perfectly normal. Losing the interface ships off-spec crude (BS&W) downstream and sends oil to the water-treatment system — a product-quality, environmental-compliance, and fire-hazard triple hit that the obvious instrument never shows.

1 Interface control drifts — failed interface transmitter, emulsion/rag-layer buildup, or a feed water-cut... · 2 The oil/water interface climbs (or sinks) while total level stays in band. · 3 Water crosses the oil-outlet elevation (carryover) or oil crosses the water outlet (carry-under). · 4 Water fouls downstream units / oil contaminates the produced-water system.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources. Interface upsets are described in separation-engineering literature as a leading cause of off-spec crude (BS&W) and oil-in-water excursions, but no public event-rate data exists. (class-level practice; SPE/JPT — Savvy Separator)

Consequences Water carryover to the oil outlet (off-spec product, downstream fouling) or oil carry-under to the water outlet (environmental excursion, fire hazard in water treatment), plus loading of downstream systems. (SPE/JPT)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident; class-level composite grounded in SPE/JPT separation-engineering practice.

Three-phase separators require interface level control distinct from total-level control. (SPE/JPT)

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Three-Phase Separator Interface Upset (Oil/Water)

"The gauge held the total level steady while the water quietly climbed under the oil — and left with the crude."

HIGH

WHAT · WHY · HOW

In long pipelines and risers, liquid collects in low spots and gets pushed out as a large "slug" all at once. When it hits the inlet separator, level shoots up and pressure swings; if control can't keep up, the separator carries over, trips, or demands relief. Severe slugging routinely swamps inlet facilities with intermittent liquid volumes far beyond steady-state design, and an unmanaged slug cascades into the carryover/compressor-damage and relief paths.

1 Liquid accumulates in a riser base or terrain low spot during steady two-phase flow. · 2 A slug is released (riser unloading, pigging, rate change) and arrives at the separator as a large inflow... · 3 Level rises fast and pressure swings; level and pressure control saturate. · 4 If unabsorbed: liquid carries over to compressor/flare, high-level trip fires, or relief lifts.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an incident rate. Slugging is a continuous, design-basis phenomenon in long multiphase lines and risers (slug catchers exist because of it) rather than a counted "event"; no public statistics on separator slug-overload upsets exist. (class-level multiphase-flow practice)

Consequences Rapid level swings, pressure surges, control instability, liquid carryover to compressors/flare, high-level trips, and relief demand. (established facilities practice); carryover mechanics per master library liquid-carryover scenario.

THE FACTS — CITED STATS

SECONDARY

No single named incident; class-level composite grounded in multiphase-flow and facilities-design practice.

Terrain/riser slugging delivers intermittent large liquid volumes causing level swings, surges, and trips — a core slug-catcher design...

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Pipeline Slugging / Separator Slug Overload

"The line had been quiet for an hour, then a wall of liquid arrived all at once."

CRITICAL

WHAT · WHY · HOW

A fired heater passes process fluid through tubes sitting in open flame; the flowing fluid is what keeps the tube metal cool. If flow through a pass drops while burners keep firing, tube-metal temperature climbs past its limit until the tube ruptures and the hot hydrocarbon ignites. This is exactly what burned an operator over 80% of his body and did ~\$350M damage at Marathon Martinez (2023) — a misaligned manual valve diverted flow around a firing heater. Low-flow detection and firing cuts are the difference between a trend and a tube rupture.

1 A valve misalignment (or pump loss) diverts or starves process flow through a heater pass while burners keep... · 2 Optionally, blocked burner air degrades combustion, adding afterburning/convection-section heat. · 3 With heat input fixed and flow falling, tube-metal temperature climbs toward the metal's strength limit. · 4 The tube ruptures; released hot hydrocarbon ignites in or at the firebox.

HOW OFTEN · CONSEQUENCES

How often In a published historical survey of 142 fired-equipment combustion-chamber accidents, tube rupture was the most frequent cause — 58 of 142 cases (~41%). (ScienceDirect — Fired equipment combustion chamber accidents: a historical survey). Absolute per-plant-year rates: not quantified in public sources.

Consequences Tube rupture, firebox fire/explosion; at Marathon Martinez: one operator with third-degree burns over ~80% of his body and ~\$350M property damage. (CSB final report, Inspectioneering)

THE FACTS — CITED STATS

✓ VERIFIED

Marathon Martinez Renewables, Martinez CA, 19 Nov 2023 — CSB final report issued March 2025.

Marathon Martinez (19 Nov 2023): 1 operator seriously burned (~80% third-degree), ~\$350M property damage. ...

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Fired-Heater Low-Flow Tube Overheat & Rupture

“Most of the flow bypassed the furnace while the burners kept firing — so the tube cooked until it split.”

HIGH

WHAT · WHY · HOW

A distillation column depends on cool reflux liquid pouring back down from the top. If reflux is lost — pump trip, condenser cooling loss, or a closed valve — the column stops separating: overhead temperature and pressure climb, product goes off-spec, and pressure trends toward relief. With the reboiler still adding vapor and nothing condensing/returning it, the column becomes a pressure vessel filling with vapor; API 521 treats reflux/cooling failure as a credible overpressure scenario for relief sizing.

1 Reflux is lost: reflux pump trips, overhead condenser loses cooling, or a reflux valve closes. · 2 Reboiler keeps generating vapor that is no longer condensed and returned. · 3 Column pressure and overhead temperature climb together; separation collapses. · 4 Heavy material rides up into the overhead product (off-spec).

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as a standalone rate. API 521 lists reflux/cooling failure among the standard credible overpressure scenarios every relief design must consider — recognized recurrence without published event-rate statistics. (scenario status per API 521; rate unpublished)

Consequences Off-spec overhead product, column pressure/temperature excursion toward relief; same upset family as the BP Texas City (2005) tower overfill covered in the master library. (Cheresources — distillation control; API 521 cooling-failure cases)

THE FACTS — CITED STATS

✓ VERIFIED

Class-level scenario; nearest named relative is BP Texas City (2005) in the master library (tower overfill family). /

Loss of reflux with reboil continuing drives overhead temperature and column pressure up; recovery = cut reboiler duty/feed and...
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Loss of Reflux — Column Pressure/Temperature Excursion

"The reflux stopped, the tower stopped separating, and pressure and temperature walked off together."

HIGH

WHAT · WHY · HOW

A column's trays handle only so much vapor and liquid traffic. Push loading past the flood point and rising vapor stops liquid from draining: liquid stacks up, differential pressure spikes, and the tower "pukes" liquid out the top toward the flare. The tell-tale dP signal lags the hydraulic reality by minutes, and the wrong corrective move (more reflux) accelerates the flood — recognition and the right first action are everything.

1 Vapor or liquid traffic rises past the flood limit (reboiler duty pushed up, feed/reflux increased, or... · 2 Rising vapor hinders downcomer drainage; liquid begins stacking on trays. · 3 Column differential pressure climbs sharply — but only after the tower is already in trouble. · 4 Operators who add reflux to chase purity worsen the flood.

HOW OFTEN · CONSEQUENCES

How often Kister's published malfunction surveys compile ~900 distillation-tower malfunction case histories over ~50 years (reported cases only; the rate of new malfunctions was not declining), with hydraulic/flooding events among the recurring categories. (Kister — What Caused Tower Malfunctions in the Last 50 Years?, Trans IChemE/ScienceDirect). ...

Consequences dP spike, loss of separation and product quality, liquid carryover into the overhead/flare header, unit trip. (Emerson — flooding dP diagnostics, EPCLand — flooding guide)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident; grounded in Kister's tower-malfunction survey corpus and Emerson dP-diagnostics literature. /

A sudden rise in column dP is the classic flooding indicator; adding reflux worsens it until the tower carries liquid to flare. ...

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Distillation Column Flooding (Hydraulic Overload)

"Push too much vapor up against too much liquid coming down, and the trays drown."

HIGH

WHAT · WHY · HOW

In gas treating, solvent (amine or glycol) flows down a contactor while gas rises through it. Contaminants — condensed hydrocarbons, corrosion products, surfactants — make the solvent foam: dP spikes, treating fails, and solvent carries over with the gas into downstream KO drums and compressors. Foaming collapses treating (off-spec/acid gas slipping through), loses expensive solvent, and puts liquid into compressors — tying directly into the rotating-equipment damage path; the first-response playbook (antifoam + cut gas rate) is specific and learnable.

1 A contaminant slug enters — hydrocarbon condensation upstream, surfactant ingress, or solvent degradation... · 2 Solvent surface behavior changes and foam fills the contactor's void space. · 3 Column dP spikes, level reads erratic/lost, treated gas drifts off-spec. · 4 Foam/solvent carries over with the gas into downstream KO drums and compressors.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources. Industry literature (OGJ, Gas Processing & LNG case-study series) treats foaming as among the most common amine-unit operating problems — recurring enough to sustain a troubleshooting literature — but publishes no event-rate statistics. (class-level; OGJ)

Consequences Loss of treating (off-spec gas), high tower dP, solvent loss and carryover to downstream KO drums/compressors — up to temporary plant shutdown. (OGJ, Norton Engineering)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident; grounded in published amine-foaming troubleshooting case-study literature (OGJ, Gas Processing & LNG).

Most common causes: condensed liquid hydrocarbons, contaminant/surfactant ingress, solvent degradation products. (OGJ; Norton)

source: OGJ, Gas Processing & LNG · confidence-flagged stats · full cited list in slide notes

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Amine / Glycol Contactor Foaming & Carryover

"Something in the gas turned the solvent to foam, and the foam went everywhere the gas went."

HIGH



Feed Composition Swing — Wet/Light Slug to a Hot Vessel

“A slug of water reached the hot oil, and a cupful of liquid became a roomful of vapor.”

WHAT · WHY · HOW

Units are tuned for a certain feed. When a slug of water or unusually light material reaches hot equipment, it flashes to vapor almost instantly — water in hot oil expands enormously (boilover effect), light ends spike pressure — and the operator is fighting a feed they didn't order. Water-into-hot-oil is the classic boilover/froth-over mechanism behind vessel and tank overpressure events; flashing drives pressure toward relief and light-end breakthrough can overpressure or over-chill downstream equipment.

1 Feed composition swings — a water slug or light-ends surge enters the unit unannounced. · **2** The slug reaches a hot vessel/column/desalter and flashes to vapor near-instantly. · **3** Pressure and level surge; local temperature dips as vaporization steals heat. · **4** Continued feeding sustains the vapor-generation pulse toward relief or boilover/overpressure.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources. Feed/water-cut swings are recognized upset triggers for hot separators, columns, and desalters, and API 521 carries abnormal-feed cases as credible scenarios, but no public event-rate data exists. (class-level; API 521 abnormal-feed basis)

Consequences Violent flash/boilover, vessel overpressure toward relief or rupture, froth-over/slop-over releases; light-end breakthrough can overpressure or over-cool downstream equipment. / (established process-safety principle; API 521 abnormal-feed/utility scenarios, master library relief scenarios)

THE FACTS — CITED STATS

No single named CSB incident cited in source; class-level composite from process-safety and firefighting practice.

Water contacting hot oil flashes with very large volume expansion — the boilover/slop-over mechanism. ...

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SECONDARY

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MED



Heat-Exchanger Fouling — Loss of Cooling / Duty Drift

“Nothing failed suddenly — the cooler just quietly stopped cooling.”

WHAT · WHY · HOW

Heat exchangers gradually foul: scale, coke, wax, or corrosion products coat the tubes and choke heat transfer. Coolers cool less, reboilers boil less, condensers condense less — downstream temperatures creep the wrong way and safety margin silently erodes. Fouling is the archetypal slow-onset upset that sets up sharper failures elsewhere (loss of cooling → temperature excursion; higher dP → flow shortfall), and it carries an enormous, well-documented industry cost.

1 Deposits accumulate on tube surfaces; overall heat-transfer coefficient (U) falls and dP rises. · 2 Exchanger duty drifts down; outlet temperature moves off target. · 3 Operators compensate (more firing, more cooling demand) and margin quietly shrinks. · 4 Uncaught, a downstream temperature/quality/safety limit is breached — or the fouled service enables a sharper...

HOW OFTEN · CONSEQUENCES

How often Chronic and effectively universal rather than episodic: crude-preheat-train fouling alone costs the US refining sector an estimated ~US\$1.2B/yr (Heat Transfer Engineering 2024 estimate); total US fouling-related costs are estimated at \$4.2–10B/yr. (fouling literature review). Per-exchanger fouling-upset rates: not separately quantified in public sources.

Consequences Lost duty and capacity, rising dP and energy cost (~\$20k/day lost production possible for a 100 kbbl/d refinery), downstream temperature/quality limit breaches, and in fired service higher tube-metal temperatures toward rupture. (PetroSolutions, IGS coking case study)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident; class-level chronic degradation grounded in heat-transfer/operations literature and cost studies.

Fouling cuts U and usable area, reducing duty and raising dP; tube-side coking both restricts flow and insulates the wall. ...

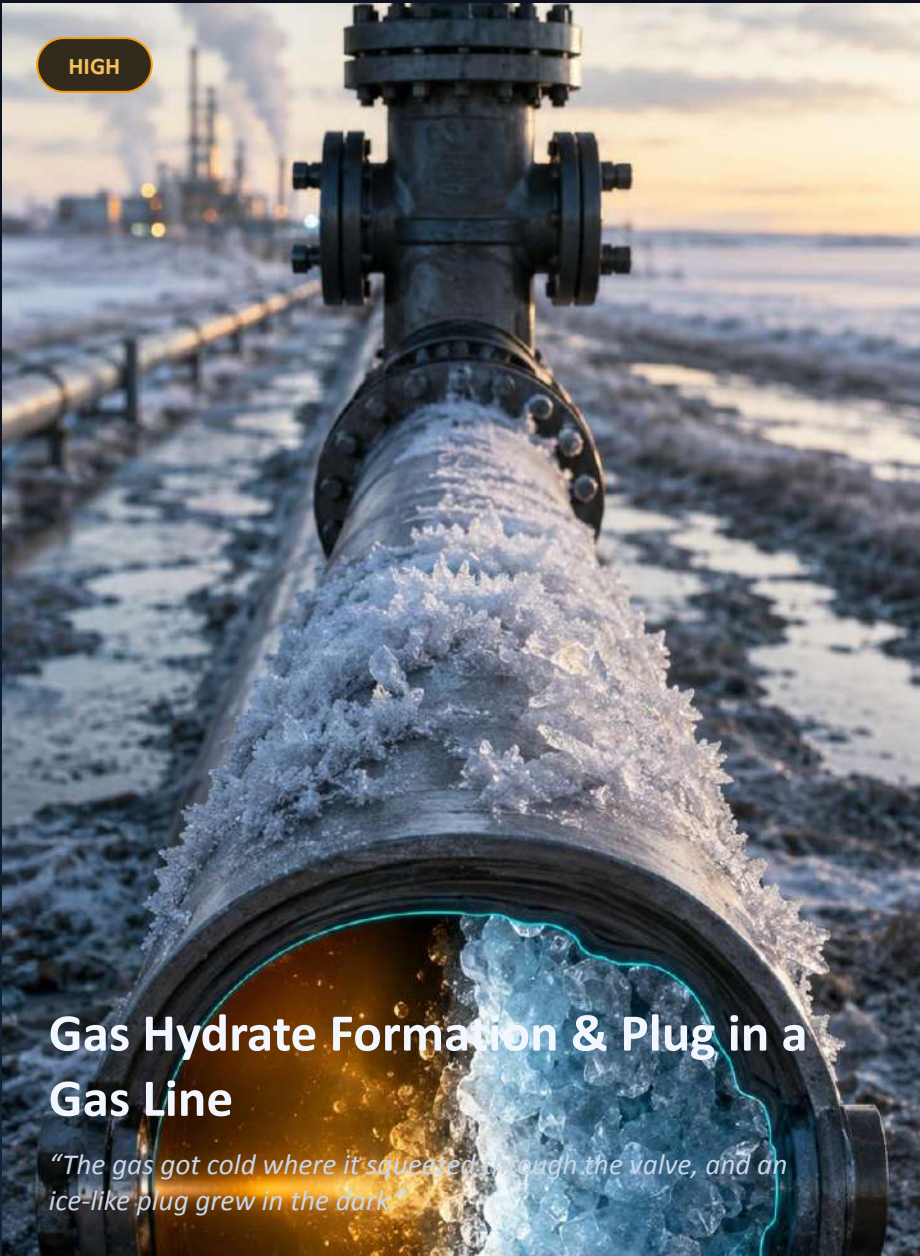
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HIGH



Gas Hydrate Formation & Plug in a Gas Line

"The gas got cold where it squeezed through the valve, and an ice-like plug grew in the dark."

WHAT · WHY · HOW

When wet natural gas expands through a valve or choke it cools sharply (Joule-Thomson effect). With water present at pressure and low temperature, gas and water form hydrates — an ice-like solid that plugs the line. Removing a plug wrong turns it into a projectile or bursts the pipe. Hydrates are the oil-and-gas industry's dominant offshore flow-assurance hazard, and the removal step has killed people — dislodged plugs travel like bullets and confined heating ruptures pipe.

- 1 Conditions drift into the hydrate envelope: high dP across a let-down point, water present, low temperature... · 2 JT cooling drops gas temperature below the hydrate-formation boundary. · 3 Hydrate accumulates at/downstream of the restriction; upstream dP climbs, flow falls, then stops. · 4 Improper removal — one-sided depressuring or heating a confined plug — launches the plug or ruptures the...

HOW OFTEN · CONSEQUENCES

How often A 1999 Welling & Associates survey of 110 energy companies ranked flow assurance the top offshore technical problem, with hydrates the largest problem in the Gulf of Mexico "by an order of magnitude" over other production concerns. (Offshore Magazine; Sloan, *Natural Gas Hydrates in Flow Assurance*). Per-line plug counts/rates: not quantified in public sources.

Consequences Blocked flow and hidden trapped pressures; on removal, hydrate projectiles that rupture piping and kill, or confined-heating pressure bursts — hydrate-plug removal has its own safety literature. (SPE — hydrate plug removal, MDPI — JT-expansion hydrate formation)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident in source; hazard class documented in SPE hydrate-plug-removal safety literature.
Large pressure drops across valves/regulators cool gas below hydrate-formation temperature, forming ice-like plugs. ...
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MED

WHAT · WHY · HOW

Waxy crude and condensate carry paraffins that stay dissolved while warm but drop out as solid wax once the fluid cools below its cloud point. The wax layer narrows the bore, raises the pressure needed to push flow, and can eventually plug the line. Wax is a core flow-assurance hazard alongside hydrates — and clearing it wrong (stuck pig, gelled cold restart) can overpressure the line, so early trend recognition is the safe play.

1 Line fluid cools below its cloud point — cold ambient, subsea, low throughput, or a shutdown cold-soak. · 2 Paraffins precipitate onto the cool pipe wall; effective bore shrinks. · 3 ΔP rises at constant rate (or flow falls at constant pressure); deposition compounds. · 4 Uncorrected: the line plugs, or a gelled restart / stuck pig overpressures the pipe.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources. Wax deposition is a chronic, design-basis flow-assurance concern for lines operating near/below cloud point (routinely managed by pigging programs and insulation), but no public plug/incident-rate statistics exist. (class-level flow-assurance practice)

Consequences Rising pumping pressure and lost capacity, line plugging (especially subsea/cold-ambient and post-shutdown gelled restarts), and overpressure risk from stuck pigs or gel-yield restarts. (established flow-assurance/production-operations practice)

THE FACTS — CITED STATS

SECONDARY

No single named incident; class-level composite grounded in flow-assurance practice.

Wax deposition narrows the bore, raises dP and pumping requirements, and can plug lines — core flow-assurance hazard alongside...

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Wax / Paraffin Deposition & Line Restriction

“As the crude cooled, the wax fell out of it and slowly closed the pipe.”

HIGH

WHAT · WHY · HOW

In hard freezes, water trapped in deadlegs, drains, and instrument impulse lines freezes. Frozen impulse lines lock transmitters at a false steady value — operators act on a lie — and ice expansion cracks fittings that leak product when they thaw. Acting on a frozen reading means fighting the wrong process; the 2021 Gulf-Coast deep freeze showed how a single cold snap multiplies upsets across an entire region's plants at once.

1 Heat trace fails or ambient plunges below design; a water-bearing impulse line or deadleg drops below... · 2 The line freezes; the connected transmitter locks at a stale value while the real process moves. · 3 Operators act (or fail to act) on the frozen reading. · 4 Ice expansion cracks fittings/small-bore piping; on thaw, hydrocarbon leaks from the ruptures.

HOW OFTEN · CONSEQUENCES

How often Regional freeze events produce measurable upset spikes: during Winter Storm Uri (Feb 11–18, 2021), Texas facilities logged 174 emissions events vs 37–46 in typical weeks (~4x), with ~200 facilities in 54 counties reporting ~3.5 million lb of excess pollution. (Texas Tribune/TCEQ). Per-plant freeze-up rates outside such events: not quantified in public sources.

Consequences False/frozen readings masking real conditions (wrong operator action), burst fittings and small-bore piping releasing hydrocarbon on thaw, and region-wide upset cascades in severe freezes. (established winterization practice; Uri figures per Texas Tribune/TCEQ)

THE FACTS — CITED STATS

SECONDARY

Class-level scenario; the Feb 2021 Gulf-Coast deep freeze (Winter Storm Uri) is the illustrative regional event (in source; Uri emissions-event counts via...

Frozen sensing lines freeze the reading, masking real conditions; ice expansion ruptures fittings, releasing hydrocarbon on thaw. ...
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Winterization Freeze-Up — Instrument & Deadleg Freezing

"The transmitter read steady all night — because the water in its sensing line had frozen solid."

CRITICAL

WHAT · WHY · HOW

Many reactions are kept safe by constant stirring: it spreads reactants and moves heat to the cooling surfaces. ... This is the Morton International (1998) mechanism — a runaway that outran the kettle's heat removal and tripped a secondary decomposition, injuring 9. Distinct from the master library's loss-of-cooling runaway (T2 Labs): here the driver is mixing, not the jacket.

1 Agitation is lost — motor trip, coupling failure, or mixing that was never adequate after a batch-size change. · 2 Reactants stratify and accumulate unreacted; heat transfer to the jacket degrades. · 3 Accumulated material reacts at once; heat generation outruns removal and temperature/pressure accelerate. · 4 Temperature crosses the secondary-decomposition threshold — a second, faster runaway.

HOW OFTEN · CONSEQUENCES

How often CSB's reactive-hazard study documented 167 serious reactive incidents in the US from Jan 1980–Jun 2001 (~8/yr), causing 108 deaths; 35% of reactive incidents in chemical manufacturing were runaway reactions. (CSB reactive hazard report, CSB 167-incident data release). Loss-of-agitation-specific rates: not separately quantified.

Consequences Runaway temperature/pressure, secondary decomposition, vessel overpressure and flammable release with ignition; at Morton: 9 employees injured (2 seriously). (CSB Morton report, case page)

THE FACTS — CITED STATS

✓ VERIFIED

Morton International, Paterson NJ, 8 April 1998 — CSB investigation.

Morton (8 Apr 1998): runaway in a ~2,000-gal kettle making Automate Yellow 96; reaction exceeded heat-removal capability, high... confidence-flagged stats · full cited list in slide notes

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Runaway Reaction — Loss of Agitation / Mixing

"The stirrer stopped, the reactants layered and pooled, and then all of it reacted at once."

CRITICAL

WHAT · WHY · HOW

Batch reactions assume a recipe: right quantities, right order, right dilution before the reactive step. Front-load too much reactant, skip the moderating solvent, or bypass the sequence interlock, and the batch generates heat far faster than designed — running away and bursting the vessel. Two CSB-investigated disasters turn on exactly this: Synthron (2006, 1 dead, 14 injured — a 12% batch increase front-loaded into one step raised peak heat output $\geq 2.3\times$) and Bayer CropScience (2008, 2 dead — a bypassed dilution interlock let concentrated methomyl run away).

1 A recipe/sequence error is introduced: oversized or front-loaded charge, skipped dilution solvent, or a... · 2 The charged batch's peak heat-generation potential now exceeds the cooling system's design basis. · 3 The reactive step begins; heat generation outruns removal from the start. · 4 Temperature and pressure run away faster than operators or relief can manage.

HOW OFTEN · CONSEQUENCES

How often CSB's reactive-hazard study: 167 serious US reactive incidents Jan 1980–Jun 2001 (~8/yr), 108 deaths; 35% of chemical-manufacturing reactive incidents were runaways, with ~60% involving inadequate hazard identification/evaluation — the management gap behind mischarge events. (CSB reactive hazard report, CSB data release). Mischarge-specific rates: not separately quantified.

Consequences Runaway, vapor-cloud explosion/vessel burst, fatalities: Synthron — 1 killed, 14 injured; Bayer CropScience — 2 killed, 8 injured, residue treater ruptured. (CSB Synthron case study, CSB Bayer CropScience)

THE FACTS — CITED STATS

✓ VERIFIED

Synthron LLC, Morganton NC, 31 Jan 2006; Bayer CropScience, Institute WV, 28 Aug 2008 — both CSB investigations.

Synthron (31 Jan 2006): batch size +12%, all extra monomer front-loaded; CSB lab testing showed $\geq 2.3\times$ maximum heat output →... confidence-flagged stats · full cited list in slide notes

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Full narrative, incident history and sources — in the Situation Room.

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Runaway Reaction — Mischarge / Wrong Sequence

“The right chemicals in the wrong amount, or the wrong order, loaded the reactor like a spring.”

HIGH

WHAT · WHY · HOW

Whole units share a few utilities — cooling water, power, instrument air, steam. Lose one and the failure fans out everywhere at once: every cooler and condenser stops rejecting heat together, or every control valve snaps to its fail position together. API 521 treats utility failures as credible, often plant-wide overpressure scenarios precisely because one root cause defeats multiple safeguarding services simultaneously — a coordinated, multi-front upset that overwhelms one-gauge-at-a-time operating.

1 A shared utility is lost: cooling-water pump trip, instrument-air compressor failure, or a power dip. · **2** Every dependent service degrades at once — condensers stop condensing, coolers stop cooling, valves drive to... · **3** Temperatures and pressures rise across the unit simultaneously; multiple alarms flood in. · **4** Operators who chase individual symptoms fall behind; unaddressed services head for relief/trip.

HOW OFTEN · CONSEQUENCES

How often Utility-driven cascades are frequent enough to be a mandatory design case: API 521 requires cooling-water, power, and instrument-air failure to be evaluated as credible plant-wide overpressure scenarios; the Feb 2021 Texas freeze/power crisis showed the cascade at regional scale — 174 emissions events in one week vs 37–46 baseline (~4x) as utilities and weather failed together. ...

Consequences Simultaneous temperature/pressure excursions across the unit, multiple services driven to relief or trip, and degraded compressor/pump seal & lube cooling — several of this genre's upsets landing at once under one root cause. / (API 521 principles; fan-out description class-level)

THE FACTS — CITED STATS

✓ VERIFIED

No single named incident in source; class-level scenario grounded in API 521 utility-failure design cases (Winter Storm Uri 2021 as regional...

API 521 treats cooling-water, power, and instrument-air failure as credible, often plant-wide overpressure scenarios for relief design.

confidence-flagged stats · full cited list in slide notes

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Loss of Cooling-Water / Utility Failure Cascade

"One utility went down, and every cooler, condenser, and compressor on it started to run hot at the same moment."

GENRE 06 · 15 SCENARIOS

Loss of Containment — Leaks, Fire & Dispersion

Visual motif — The gas cloud and the distant fire — a release as a living, spreading thing across the unit.

one card per situation follows — poster prompt in each card's notes

HIGH

Flange / Gasket Weep — Detect & Isolate Early

"It started as a drip you could have wiped with a rag. Nobody isolated it."

WHAT · WHY · HOW

A flanged or gasketed joint on a pressurised hydrocarbon line starts to weep from a bad gasket, under-torqued bolt, thermal cycling, or vibration. Small at first, it grows into a vapour source next to live equipment if nobody blocks it in. Flanges, gaskets, and small-bore connections are consistently among the most common LOPC sources; minor releases are the leading indicators of major ones (this is exactly why API RP 754 tracks LOPC tiers). Every disaster in this genre started as a containment breach that wasn't stopped early.

1 Detect the rising leak early — gas-detector uptick, visual weep, cautious use of senses. · **2** Identify the exact leaking segment and its isolation boundary. · **3** Block in the segment (close isolation valves both sides). · **4** Depressure/vent the trapped inventory to a safe path.

HOW OFTEN · CONSEQUENCES

How often Common — the highest-frequency event family in the genre. IOGP member companies reported 193 Tier 1 and 622 Tier 2 process safety events (essentially LOPC) in 2021 alone — Tier 1 rate 0.12 per million work hours across ~1,655 million work hours (IOGP Safety performance indicators — process safety events, 2021 data, data.iogp.org). ...

Consequences Ignored, a weep grows into a flammable cloud beside live equipment — the common origin of the rupture/fire/VCE scenarios that follow (API RP 754 LOPC-tier logic; source doc Scenarios 2–9). Caught early it is a block-in and a gasket change.

THE FACTS — CITED STATS

✓ VERIFIED

No single flagship incident — this is the class-level origin event of Scenarios 2–9 (e.g., Piper Alpha began with a leaking flanged connection).

193 Tier 1 + 622 Tier 2 LOPC events reported to IOGP for 2021; Tier 1 rate 0.12 / Tier 2 rate 0.38 per million work hours (IOGP PSE... confidence-flagged stats · full cited list in slide notes)

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CRITICAL

Corroded Pipe Rupture — Sudden Large Release

"The wall had been thinning for years. It let go all at once."

WHAT · WHY · HOW

A pipe carrying hot hydrocarbon has been quietly thinning from corrosion and ruptures without warning, dumping a large flammable volume — often above auto-ignition temperature — into the open. A vapour cloud forms in seconds with workers inside it. Chevron Richmond 2012 proved the wall thinning was inspectable and predictable — the failure was a mechanical-integrity/inspection gap, not bad luck. Trainees must learn both halves: act on marginal condition flags before failure, and respond correctly when the pipe lets go anyway.

1 (Field/what-if) Act on the marginal/overdue thickness flag — take the line out of service before failure. · **2** On rupture: get people out of the line of fire immediately. · **3** Activate ESD / remote isolation to cut the source feed. · **4** Confirm blowdown/depressuring of the ruptured segment.

HOW OFTEN · CONSEQUENCES

How often Piping LOPC is a steady global occurrence: IOGP members reported 193 Tier 1 LOPC events in 2021 (rate 0.12 per million work hours) (IOGP PSE 2021 data), and US EPA RMP facilities reported 3,236 chemical accidents 2004–2019 — an average of ~202 per year (EPA NCEE working paper 2023-01). ...

Consequences Chevron Richmond 2012: 19 workers narrowly escaped the cloud; ~15,000 nearby residents sought medical evaluation after the fire (CSB). PES Philadelphia 2019: corroded elbow rupture → vapour cloud → explosions, vessel fragments thrown across a river (CSB).

THE FACTS — CITED STATS

Chevron Richmond refinery, 6 August 2012 (CSB); secondary: PES Philadelphia, 21 June 2019 (CSB).

Richmond: 8-inch #4 sidecut line ruptured from sulfidation corrosion of low-silicon carbon steel (CSB...

source: CSB · confidence-flagged stats · full cited list in slide notes

✓ VERIFIED

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CRITICAL

WHAT · WHY · HOW

A running pump on flammable service loses its mechanical seal — wear, dry-running, or a seal-plan/flange failure — and sprays product as a fine, easily-ignited mist right at the pump, surrounded by hot surfaces and motors. Rotating-equipment seals and their flanges are a leading LOPC source, and a maintenance error on exactly this equipment class (hand-tight blind flange on a condensate pump) initiated Piper Alpha, the deadliest offshore disaster in history.

1 Detect the seal release (gas detector rise, visible spray/mist). · 2 Trip and isolate the pump (stop, close suction/discharge). · 3 Block in and depressure the loop to remove the inventory path. · 4 Clear/control ignition sources around the atomised mist.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources at card level. ...

Consequences Piper Alpha's initiating condensate leak from pump maintenance work ignited and started the chain that killed 167 (Cullen Inquiry / HSE). Atomised mist lowers effective ignition energy, so seal sprays ignite more easily than pooled liquid (source doc physics).

THE FACTS — CITED STATS

✓ VERIFIED

Piper Alpha, North Sea, 6 July 1988 — 167 dead; reshaped global offshore safety (Safety Case regime) (Cullen Inquiry / HSE).

Piper Alpha, 6 July 1988: PSV removed, blind flange left hand-tight; restart leak ignited; 167 dead (HSE — Cullen Inquiry).

source: Cullen Inquiry / HSE · confidence-flagged stats · full cited list in slide notes

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Pump Mechanical Seal Failure — Flammable Release

“The seal that kept the product inside the pump gave way — and it was pumping something that burns.”



CRITICAL

Flammable Gas-Cloud Dispersion → Vapour-Cloud Explosion

“The fuel didn't stay where it spilled. It rolled out, found a spark, and the whole area went up.”

WHAT · WHY · HOW

A release of volatile liquid or gas forms a heavier-than-air cloud that spreads low between equipment until it finds an ignition source. Congestion and confinement accelerate the flame, turning ignition into an explosion rather than a fire. Buncefield and Flixborough are the defining cases: a drifting cloud plus one spark produced two of the largest industrial explosions in European history. The trainable skill — interpreting the gas-detection map and isolating before the clock runs out — is exactly what was missing in both.

- 1 Read the spreading gas-detection pattern across fixed detectors.
- 2 Isolate the source feeding the cloud (ESD/block-in).
- 3 De-energise and clear ignition sources within the cloud footprint.
- 4 Initiate area muster/evacuation away from the cloud path.

HOW OFTEN · CONSEQUENCES

How often VCEs are the dominant catastrophic-loss mechanism: Marsh's "100 Largest Losses in the Hydrocarbon Industry" finds vapour cloud explosions account for the greatest frequency of losses in the energy sector since 1974 (Marsh 100 Largest Losses reports, marsh.com). ...

Consequences Buncefield 2005: ~250–300 tonnes of petrol overfilled → ~360 m cloud → one of Europe's largest peacetime explosions, ~43 injured (Buncefield MIIB report). Flixborough 1974: ~40 tonnes cyclohexane → VCE killed 28 and destroyed the plant (HSE case study).

THE FACTS — CITED STATS

✓ VERIFIED

Buncefield, UK, 11 December 2005 (HSE/MIIB); Flixborough, UK, 1 June 1974 (Court of Inquiry).

Buncefield: cloud ignited ~22 minutes after vapour first seen — the isolation window is real and short (MIIB).

source: Court of Inquiry · confidence-flagged stats · full cited list in slide notes

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Full narrative, incident history and sources — in the Situation Room.

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HIGH

WHAT · WHY · HOW

In a classified (Zone) area where a flammable atmosphere may be present, an ignition source is about to be introduced — hot work without a valid gas test, a non-rated tool or radio, a hot surface, or static from a fast transfer. This trains the ignition half of the fire triangle. Area classification (IEC 60079 / API RP 500/505 / ATEX) exists precisely to keep ignition sources out of places where flammable atmospheres can occur, and hot work is one of the most frequently fatal industrial activities — CSB counted 60+ hot-work fatalities since 1990.

1 Gas-test the atmosphere with a calibrated detector before any energy is introduced. · **2** Verify the permit and that equipment is rated for the zone (or remove the source). · **3** Maintain continuous LEL monitoring during the task. · **4** Stop work immediately if LEL rises; re-verify before resuming.

HOW OFTEN · CONSEQUENCES

How often US fire departments responded to an average of 3,396 structure fires involving hot work per year (2017–2021), causing an average 19 civilian deaths, 120 injuries, and \$292M property damage per year (NFPA, "Structure Fires Started by Hot Work"); CSB documented 60+ hot-work fatalities at US facilities since 1990 (CSB Hot Work Safety Bulletin, 2010).

Consequences Introducing one un-rated spark into a flammable atmosphere converts a leak into the VCE/fire scenarios of this genre; CSB's bulletin exists because monitoring failures kept killing welders and fire watches (CSB 2010).

THE FACTS — CITED STATS

✓ VERIFIED

No single flagship incident — CSB's 2010 Hot Work Safety Bulletin aggregates the fatality record that defines this scenario (CSB).

60+ hot-work fatalities since 1990; combustible-gas monitoring required before and during hot work (CSB Hot Work Safety Bulletin).

source: CSB · confidence-flagged stats · full cited list in slide notes

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Ignition-Source Control in a Hazardous Area

"There was gas in the air and a spark waiting to happen — one of them had to go."



WHAT · WHY · HOW

A high-pressure gas leak ignites at the source into a jet fire — a long, roaring, intensely radiant flame driven by escaping pressure. It stabs in one direction, and whatever it impinges on (vessel, riser, steel) heats toward failure in minutes. Piper Alpha's death toll came from sustained high-pressure gas-riser fires — fed because connected platforms kept pumping gas to the burning platform. ...

- 1 Remotely isolate the leaking segment (ESD/SDV) — do not approach.
- 2 Initiate emergency depressuring/blowdown to starve the flame.
- 3 Confirm neighbouring inventories are being isolated and cooled.
- 4 Escalate and evacuate per emergency plan.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an ignited-jet-fire annual rate. ...

Consequences Piper Alpha: riser jet fires destroyed the platform; 167 dead (HSE/Cullen). Jet-fire flame impingement can fail an adjacent vessel or pipe in minutes — far faster than radiant heating from a distant pool fire (API 521 depressuring principles).

THE FACTS — CITED STATS

✓ VERIFIED

Piper Alpha, 6 July 1988 — gas-riser jet fires central to the 167 deaths (Cullen Inquiry / HSE).

Piper Alpha escalated because connected platforms kept feeding gas to the fire (HSE/Cullen).

source: Cullen Inquiry / HSE · confidence-flagged stats · full cited list in slide notes

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High-Pressure Gas Jet Fire

"The leak lit into a blowtorch you could hear over everything — and it was pointed at the next vessel."

CRITICAL



Pool Fire in a Bund / Dike

“The spill was contained in the bund. Then it caught, and the bund became a fire pit.”

WHAT · WHY · HOW

A liquid hydrocarbon spill collects in its bund — containment working as designed — then ignites. The bund now holds a sustained, broad, radiant pool fire that threatens the tank it surrounds and every neighbour in radiant range. Buncefield's fuel burned as large pool/tank fires for days, and the firewater-plus-fuel mixture then defeated the containment itself. Pool-fire radiant heat to adjacent equipment is a primary relief/depressuring design case (API 521 external fire).

1 Isolate/stop the source feeding the pool. · 2 Apply cooling water to exposed neighbouring vessels/tanks. · 3 Apply foam to the burning pool (correct extinguishing medium). · 4 Manage bund drainage — contain without spreading burning liquid.

HOW OFTEN · CONSEQUENCES

How often Media-reported large storage-tank fires run 15–20 per year worldwide (1990s–2000s data), and 480 tank fire incidents were recorded globally 1951–2003, lightning the leading cause (Persson & Lönnermark, SP Report 2004:14, "Tank fire incidents 1951–2003"); a later study analysed 595 tank-farm fires worldwide (Process Safety and Environmental Protection, 2023, ScienceDirect).

Consequences Buncefield: pool/tank fires burned for days; firewater + fuel overwhelmed the bund and contaminated groundwater (MIIB). Radiant heat can escalate to neighbouring tanks — ~4.5% of low-flashpoint tank fires involved 12+ tanks (595-fire study, PSEP 2023).

THE FACTS — CITED STATS

Buncefield, 11 December 2005 — post-VCE pool/tank fires and containment failure (MIIB report).
15–20 reported tank fires/year worldwide (SP Report 2004:14).

source: MIIB report · confidence-flagged stats · full cited list in slide notes

✓ VERIFIED

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CRITICAL



BLEVE of an LPG Vessel

"The fire outside cooked the tank until the whole thing flashed into a fireball."

WHAT · WHY · HOW

A pressurised liquefied-gas vessel (LPG/NGL) is engulfed or impinged by fire. The liquid boils, pressure climbs, and the unwetted vapour-space steel weakens until the vessel tears open — the superheated liquid flashes instantly into a blast plus a huge fireball: a BLEVE. Feyzin 1966 put "BLEVE" into industry vocabulary by killing 18 (mostly firefighters cooling the wrong things); Pemex San Juanico 1984 chained successive BLEVEs into one of the worst industrial disasters in history. A BLEVE fireball's lethal radius extends far beyond the plant fence.

1 Apply cooling water to the fire-exposed vessel — especially the vapour space. · **2** Initiate emergency depressuring to lower stored energy. · **3** Track pressure and wall-temperature trend against the escalation clock. · **4** Order withdrawal to safe distance BEFORE the BLEVE threshold — the decisive call.

HOW OFTEN · CONSEQUENCES

How often Rare but recurrent: literature surveys count 74 BLEVEs worldwide 1926–1986 causing 1,427 fatalities (Abbasi & Abbasi BLEVE overview, ResearchGate), and 77 BLEVE accidents 1941–1990 with ~900 deaths and >9,000 injuries (BLEVE bibliometric review, J. Loss Prev. Process Ind./ScienceDirect 2023 — counts vary between surveys; treat as order-of-magnitude).

Consequences Feyzin 1966: sphere BLEVE'd after ~90 minutes of fire exposure; 18 dead, ~80 injured (well-cited history; primary = French inquiry). Pemex San Juanico 1984: chained LPG-sphere/bullet BLEVEs; commonly cited ~500–600 dead, thousands injured (estimate range — never cite as precise).

THE FACTS — CITED STATS

Feyzin refinery, France, 4 January 1966 (figures well-cited but secondary); PEMEX San Juan Ixhuatepec, Mexico City, 19 November 1984 (death toll = ...)

74 BLEVEs 1926–1986, 1,427 fatalities (Abbasi overview).

source: death toll = estimate range · confidence-flagged stats · full cited list in slide notes

SECONDARY

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CRITICAL

WHAT · WHY · HOW

An established fire or blast heats or breaches a neighbouring inventory, releasing more fuel and starting the next fire — a domino chain. Disaster scale is set not by the first release but by how many neighbours it takes down. Piper Alpha's 167 deaths were driven by escalation (riser failures kept feeding the fire), and San Juanico was a chain of successive BLEVEs. The EU Seveso Directive formally requires operators to assess domino risk — this card trains the move that breaks the chain.

1 Identify which neighbouring inventories are threatened and their time-to-failure order. · 2 Remotely isolate the most-threatened inventories first. · 3 Depressure/blow down those inventories to cut stored energy. · 4 Apply cooling water to exposed equipment.

HOW OFTEN · CONSEQUENCES

How often Darbra et al. analysed 225 domino-effect accidents in process/storage plants and hazmat transport, 1961–2007 (~5 recorded per year on average over the period); most frequent causes were external events (31%) and mechanical failure (29%); storage areas (35%) and process plants (28%) were the most common settings; 89% involved flammables, LPG most frequent (Darbra, Palacios & Casal, J. ...)

Consequences Piper Alpha: escalation, not the first leak, drove the 167 deaths (HSE/Cullen). San Juanico: successive BLEVEs across the terminal (death-toll estimates vary — see BLEVE card).

THE FACTS — CITED STATS

Piper Alpha 1988 (escalation via risers) (HSE/Cullen); PEMEX San Juanico 1984 (BLEVE chain).

225 domino accidents recorded 1961–2007 (Darbra et al. 2010).

source: BLEVE chain · confidence-flagged stats · full cited list in slide notes

✓ VERIFIED

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Domino Escalation to Adjacent Equipment

"One fire didn't stay one fire — it opened up the tank next door, and that's what killed everyone."

CRITICAL

WHAT · WHY · HOW

A leak on a sour (H₂S-bearing) system releases hydrogen sulphide — heavier than air, invisible, lethal at low concentrations, and it paralyses your sense of smell exactly when it becomes dangerous. A drifting toxic plume threatens everyone downwind, including would-be rescuers. At Aghorn (Odessa, 2019) an H₂S release killed the operator — and then his wife, who came looking for him. H₂S deceives the nose: the rotten-egg warning disappears just as the real hazard begins, so instrument trust and upwind escape are the whole lesson.

- 1 React to the H₂S alarm instantly — don escape breathing apparatus.
- 2 Move cross-wind or upwind, never downwind.
- 3 Raise the alarm; muster and take headcount.
- 4 Isolate the source remotely if possible.

HOW OFTEN · CONSEQUENCES

How often US BLS Census of Fatal Occupational Injuries data attribute 46 worker deaths to hydrogen sulfide in 2011–2017 and 60 deaths in 2001–2010 — roughly six per year, making H₂S one of the leading causes of workplace gas-inhalation death in the US (BLS CFOI figures as summarized in OSHA-linked and safety-industry compilations; e.g. [osha.gov/hydrogen-sulfide](https://www.osha.gov/hydrogen-sulfide), [blacklinesafety.com](https://www.blacklinesafety.com)).

Consequences Aghorn 2019: operator and his wife both killed by one release; CSB cited gaps in H₂S detection, safety systems, emergency response (CSB). Physiology: IDLH 100 ppm; olfactory fatigue ~100–150 ppm; ~500–700 ppm causes rapid collapse and death (OSHA).

THE FACTS — CITED STATS

✓ VERIFIED

Aghorn Operating Waterflood Station, Odessa TX, 26 October 2019 — operator and spouse killed (CSB).

IDLH = 100 ppm; smell fails at ~100–150 ppm; 500–700 ppm = rapid collapse (OSHA, [osha.gov/hydrogen-sulfide/hazards](https://www.osha.gov/hydrogen-sulfide/hazards)).

source: CSB · confidence-flagged stats · full cited list in slide notes

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Toxic H₂S Release — Sour Service

“You smell rotten eggs for a second, then you smell nothing — because it’s already shutting your body down.”

CRITICAL

WHAT · WHY · HOW

A release from a unit handling a toxic, corrosive chemical — classically hydrofluoric acid (HF) in an alkylation unit, or acid gas/chlorine — forms a dense, low-lying cloud that is acutely harmful to workers and potentially the public downwind. At PES Philadelphia 2019 a corroded elbow released HF-bearing fluid; CSB credited the unit's water-mitigation and rapid-deinventory systems with preventing a far worse offsite toxic release. ...

1 Detect the release on area toxic monitors. · 2 Activate water-spray/curtain mitigation to knock down the cloud. · 3 Initiate rapid acid de-inventory to the safe dump drum. · 4 Isolate the leaking source.

HOW OFTEN · CONSEQUENCES

How often Close to 50 US refineries use hydrogen fluoride and have reported 200+ HF-related accidents to EPA over ~25 years (~8 per year) (NRDC compilation of EPA data, [nrdc.org](https://www.nrdc.org) — advocacy source, figures traceable to EPA filings); more broadly, EPA RMP facilities reported 3,236 chemical accidents 2004–2019, ~202 per year (EPA NCEE working paper 2023-01).

Consequences PES 2019: >5,000 lb of HF released; a 38,000-lb vessel fragment thrown across the Schuylkill River; ~\$750M property damage; mitigation systems prevented a worse offsite toxic outcome (CSB; damage figure via EPA/press accounts).

THE FACTS — CITED STATS

✓ VERIFIED

PES Philadelphia refinery, 21 June 2019 — corroded elbow, HF alkylation unit (CSB).

Thousands of pounds of HF involved at PES; water mitigation + rapid de-inventory credited by CSB (CSB — PES investigation).

source: CSB · confidence-flagged stats · full cited list in slide notes

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Toxic / Corrosive Cloud — HF or Acid Gas

"It wasn't just flammable — it was a chemical that burns lungs and skin, drifting toward the fence line."

CRITICAL

WHAT · WHY · HOW

A release is developing and the single most consequential action is to isolate the source: close the right ESD valves to cut feed, then blow down the trapped inventory to flare before ignition or escalation. Pure decision-training on the isolation boundary and sequence. Piper Alpha escalated partly because isolation was inadequate and connected platforms kept feeding hydrocarbons; the Cullen reforms centred on emergency isolation and the Safety Case regime. Time-to-safe-pressure versus the escalation clock is exactly a lumped-parameter race.

1 Select the correct isolation boundary for the leaking segment. · 2 Activate ESD promptly from board or field. · 3 Verify the valves actually closed (fail-safe confirmation). · 4 Initiate blowdown/depressuring to flare.

HOW OFTEN · CONSEQUENCES

How often Demand frequency = LOPC frequency: every reportable release is a demand on emergency isolation. ...

Consequences Piper Alpha: inadequate isolation + continued feed from connected platforms turned a leak into 167 deaths (HSE/Cullen). Correct, fast ESD + blowdown is the difference between a logged event and a disaster (API 521 depressuring practice).

THE FACTS — CITED STATS

✓ VERIFIED

Piper Alpha, 1988 — the defining isolation failure (Cullen Inquiry / HSE).

Cullen Inquiry reforms centred on emergency isolation, temporary-refuge integrity, Safety Case regime (HSE).

source: Cullen Inquiry / HSE · confidence-flagged stats · full cited list in slide notes

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Emergency Isolation & ESD Activation

"A leak stays a leak or becomes a disaster depending on how fast — and how right — you hit the shutdown."



CRITICAL



Fire-&Gas Detection and Muster / Egress

“The fire was survivable. Being in the wrong place, waiting for the wrong plan, was not.”

WHAT · WHY · HOW

A fire/gas event is underway and the F&G system alarms. People must muster at the right assembly point and escape by routes that are still safe — some are cut off by fire, smoke, or gas. Teams reading the F&G picture and making the muster/egress call, including re-routing. Most of Piper Alpha's 167 dead were in the accommodation module awaiting an evacuation that never came, overcome by smoke and gas; the survivors largely made their own way to the sea against standing instructions. Muster and egress decisions — not the fire itself — decided who lived.

- 1 Interpret the F&G panel — which detectors alarmed, where.
- 2 Select a safe muster point and a viable egress route (not the compromised primary).
- 3 Direct personnel and perform headcount.
- 4 Monitor whether the refuge itself is threatened.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources — muster/egress demand rates are not centrally published. ...

Consequences Piper Alpha: a majority of the 167 dead were in the accommodation awaiting rescue, overcome by smoke and gas (HSE/Cullen). Cullen reforms drove temporary-refuge, evacuation, and escape requirements (HSE).

THE FACTS — CITED STATS

Piper Alpha, 1988 — the muster/egress catastrophe of record (Cullen Inquiry / HSE).
Majority of Piper Alpha fatalities were in the accommodation module (Cullen Inquiry / HSE).

source: Cullen Inquiry / HSE · confidence-flagged stats · full cited list in slide notes

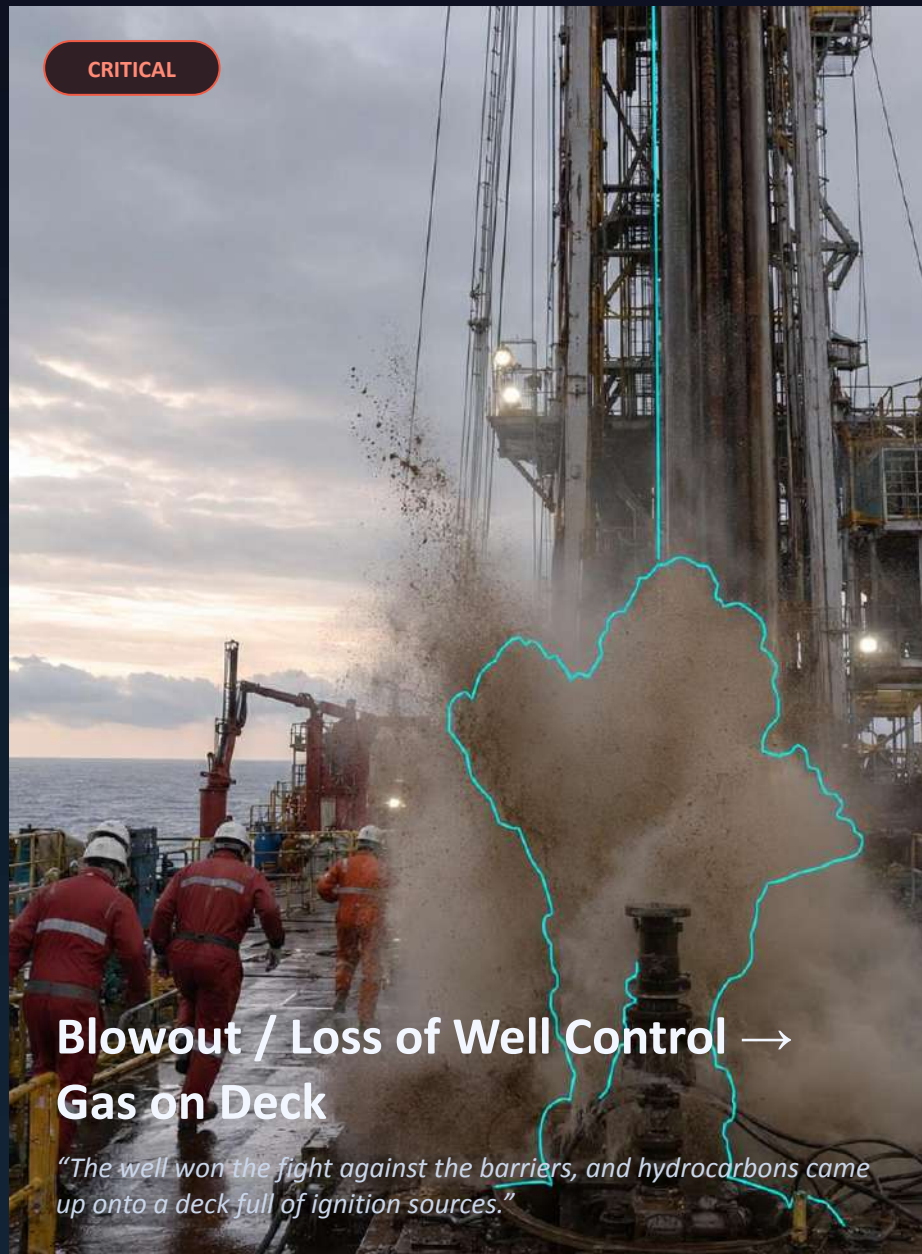
✓ VERIFIED

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CRITICAL



Blowout / Loss of Well Control → Gas on Deck

"The well won the fight against the barriers, and hydrocarbons came up onto a deck full of ignition sources."

WHAT · WHY · HOW

During drilling, formation pressure overcomes the well-control barriers — an uncontrolled kick becomes a blowout. Hydrocarbons flow up the well to the rig, and gas spreads across a deck full of engines, electrics, and people. Detection of the kick and correct shut-in is the decisive window. Deepwater Horizon 2010: loss of well control sent hydrocarbons up the riser to the rig, gas found ignition sources, 11 workers died and the rig sank — CSB found failures in barrier management, kick detection, and the BOP. Kick detection is the trainable skill that closes this door.

1 Detect the kick early — pit gain, flow-out vs flow-in delta, pressure changes. · **2** Execute the correct shut-in procedure (close the BOP). · **3** Divert gas safely overboard/away from ignition sources. · **4** Begin the well-control sequence to circulate out the influx.

HOW OFTEN · CONSEQUENCES

How often IOGP Report 434-2 (v3.0, 2019, from the SINTEF database, GoM/UKCS/Norway 1980–2005) gives blowout frequencies of $\sim 1.9 \times 10^{-3}$ per well drilled for deepwater HPHT wells and $\sim 3.1 \times 10^{-4}$ per well for "normal" deepwater wells (IOGP 434-2, Risk Assessment Data Directory — Blowout Frequencies); the SINTEF Offshore Blowout Database records 573 offshore blowouts/well releases worldwide since 1955 (SINTEF).

Consequences Deepwater Horizon: 11 killed, 17 injured, rig sank, largest US offshore oil spill (CSB — Macondo investigation).

THE FACTS — CITED STATS

Deepwater Horizon / Macondo, Gulf of Mexico, 20 April 2010 (CSB).

Blowout frequency $\sim 1.9 \times 10^{-3}$ per HPHT deepwater well; $\sim 3.1 \times 10^{-4}$ per normal deepwater well (IOGP 434-2).

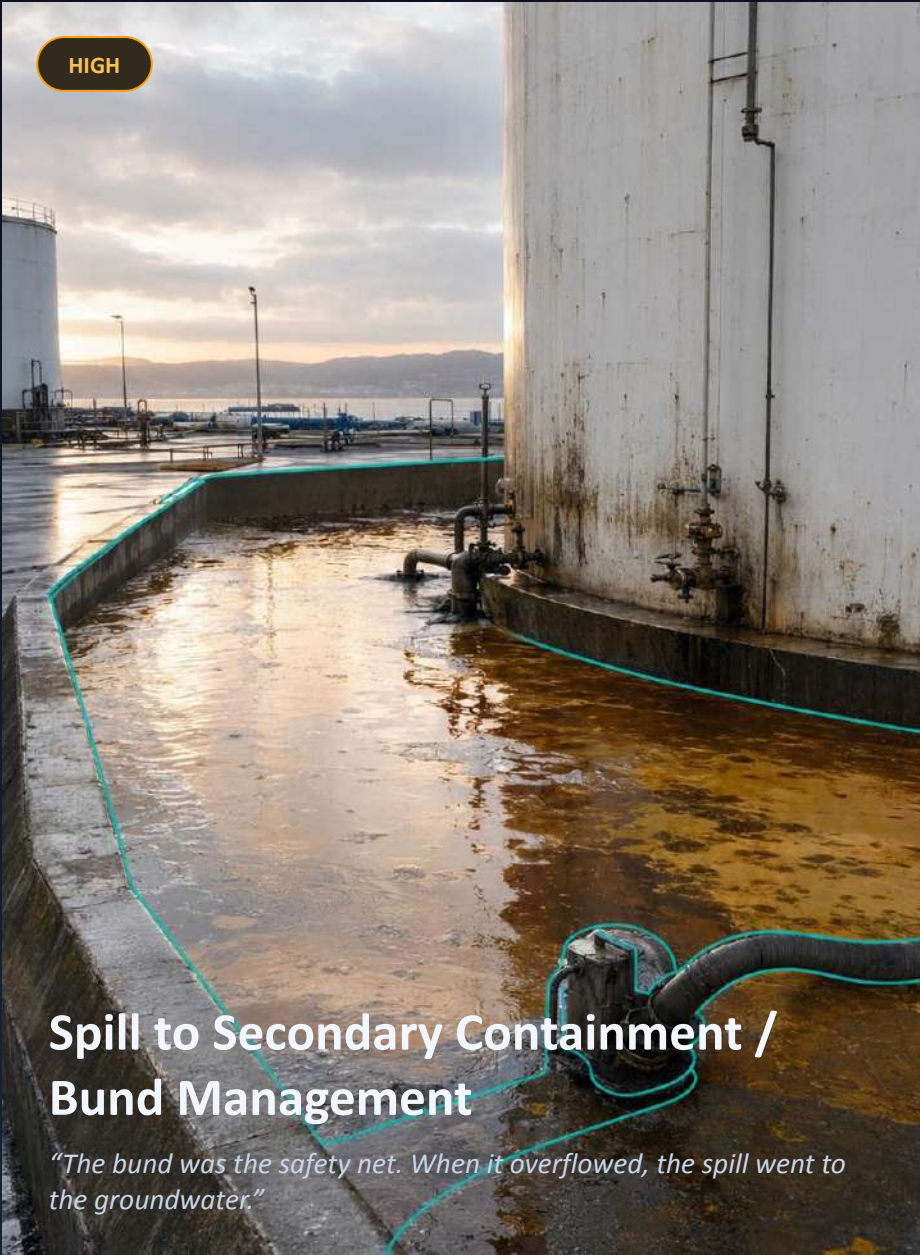
source: CSB · confidence-flagged stats · full cited list in slide notes

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WHAT · WHY · HOW

A liquid spill (or firewater carrying product) collects in the bund/dike/interceptor. The trainee manages bund level and drain valves so contained liquid doesn't overflow, doesn't reach a live/clean drain, and is routed to safe recovery — while keeping the door open for fire response. Buncefield's second disaster was environmental: fuel plus firefighting water overwhelmed the bund and tertiary containment and contaminated soil and groundwater, driving new UK guidance on containment and firewater management. Bund drain valves are normally kept closed for exactly this reason.

1 Stop/isolate the source feeding the spill. · 2 Verify drain valves are lined up to contain or safe-recover — never to a clean drain or watercourse. · 3 Track bund level against capacity. · 4 Balance firewater addition against remaining bund capacity to prevent overflow.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as an annual bund-failure rate. Related research: scale-model experiments show a 110%-capacity bund is overtopped in almost every catastrophic tank-failure case, even with slow (~30 s) release (Atherton et al., "Bund overtopping — the consequence of catastrophic tank failure", J. Loss Prev. ...

Consequences Buncefield: containment defeated by fuel + firewater; soil and groundwater contaminated; classified a Major Accident to the Environment (MIIB report; post-Buncefield HSE/EA guidance).

THE FACTS — CITED STATS

✓ VERIFIED

Buncefield, 2005 — the environmental containment failure of record (MIIB report).
110% bund capacity is the normal design basis — sufficient for continuous release, not catastrophic failure (HSE secondary-containment...
source: MIIB report · confidence-flagged stats · full cited list in slide notes

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GENRE 07 · 15 SCENARIOS

Utilities & Support Systems

Visual motif — The dead control room and the dark plant — the twin overlay as the only thing still glowing.

one card per situation follows — poster prompt in each card's notes

CRITICAL

WHAT · WHY · HOW

The plant's compressed instrument-air supply fails, so every air-operated control valve snaps to its spring-defined "fail" position at the same moment — some slam shut, some fly open. The coordinated jolt trips or upsets the whole unit at once. API Standard 521 names loss of instrument air as a standard overpressure contingency relief systems must be designed against; CCPS teaches that a plant air loss drives all control valves to their predetermined fail action simultaneously, and the hazard is the combined system state, not any single...

1 Recognise a global loss-of-air signature (many loops moving together), not a single bad loop. · 2 Verify the safety-critical valves actually reached their designed fail states (fuel isolated, cooling... · 3 Confirm the relief path is available and protected. · 4 Drive an orderly shutdown of the unit rather than chasing individual alarms.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources as a plant-level rate. ...

Consequences Simultaneous valve movement produces plant-wide pressure/flow/level transients — fuel cuts, blocked outlets, lost cooling — that can escalate to overpressure and loss of containment if a valve failed the "wrong" way for the current mode (CCPS/AIChE Beacon June 2020; CCPS China 2014 fail-position paper).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (no single named anchor); CCPS Beacon June 2020 documents the mechanism; kin to Texaco Milford Haven 1994's utility-disturbance cascade.

API 521 explicitly lists loss of instrument air among named utility-failure overpressure contingencies. (API 521 7th ed. overview)

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Total Instrument-Air Failure — Plant-Wide Fail-Safe Cascade

"The air went away, and every valve in the plant moved at once."

HIGH

WHAT · WHY · HOW

A single air-operated control valve loses its air or signal and goes to its spring fail position — but that position turns out to be wrong for the current operating mode, dumping feed forward or blocking an outlet with the pump still running. CCPS documents a real incident where different fail positions under loss-of-signal vs loss-of-air over-pressurised very large vessels during shutdown, with loss of containment near an occupied building; guidance stresses identifying the correct fail position for every safety-critical valve, and...

- 1 Predict where the valve went on loss of air (know its fail action for the current mode).
- 2 Catch the resulting transient early (pressure, level, or flow diverging).
- 3 Take manual action — block/bypass the valve, cut the pump, or open a relief path.
- 4 Verify the system is rebalanced and the relief path stayed clear.

HOW OFTEN · CONSEQUENCES

How often LOPA practice treats a BPCS instrument-loop/control failure as $\sim 1 \times 10^{-1}$ per year per loop (dangerous failure rate $\geq 1 \times 10^{-5}$ /hr for non-IEC-61511 BPCS) (HAZOP360 LOPA initiating-event guidance, iFluids LOPA blog cites level controller failure $\approx 1 \times 10^{-1}$ /yr).

Consequences Over-pressurisation of vessels, blocked-outlet transients, runaway feed-forward flow, and loss of containment near occupied areas (CCPS China 2014 incident paper).

THE FACTS — CITED STATS

✓ VERIFIED

CCPS China 2014 conference paper — vessel over-pressurisation and loss of containment from mismatched control-valve fail positions (facility not publicly...

A real CCPS-documented incident: asymmetric fail-safe positions (loss-of-signal vs loss-of-air) over-pressurised very large vessels...

source: facility not publicly named · confidence-flagged stats · full cited list in slide notes

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Local Control-Valve Air Failure — Fail-Open vs Fail-Closed Surprise

"Everyone thought the valve would close. On loss of air, it opened."

CRITICAL

WHAT · WHY · HOW

The cooling-water supply to condensers, exchangers, or a reactor jacket is lost while heat keeps arriving. Vapour stops condensing, temperatures climb, and pressure rises toward the relief set. API 521 lists loss of cooling water as a named utility-failure overpressure contingency — when the condenser loses cooling while the reboiler keeps boiling, the relieving rate is essentially the whole incoming vapour rate; the same mechanism drove the T2 Laboratories runaway (2007, 4 dead) (API 521...

1 Detect the cooling loss early (rising condenser outlet temperature, climbing pressure). · **2** Cut the heat input — reduce reboiler duty, feed, or firing. · **3** Verify the relief path is clear and adequate if pressure keeps rising. · **4** Restore cooling (standby pump, alternate header) and rebalance before returning to rate.

HOW OFTEN · CONSEQUENCES

How often CCPS-style LOPA guidance assigns loss of cooling water an initiating-event frequency of $\sim 1 \times 10^{-1}$ per year — about once every 10 years per system (HAZOP360 LOPA initiating-event guidance citing CCPS tables).

Consequences Pressure spikes to relief lift or vessel failure; on reactors, cooling loss escalates to thermal runaway — T2 Laboratories' reactor burst with a blast likened to $\sim 1,400$ lb TNT, killing 4 (CSB T2 Laboratories report).

THE FACTS — CITED STATS

✓ VERIFIED

T2 Laboratories, Jacksonville FL, 19 December 2007 (CSB) — cooling loss as the trigger of a fatal runaway (cross-anchor; the loss-of-cooling case itself...

API 521: with condensation stopped, relieving rate $\approx$ incoming vapour rate — a governing relief-sizing case. (API 521 overview)
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Cooling-Water Loss — Overpressure / Overheat Cascade

"Take away the cold side, and the heat has nowhere left to go."

CRITICAL

WHAT · WHY · HOW

A stored liquid that must be kept cold loses its refrigeration. The liquid warms, vapour pressure rises, and a reactive material can begin self-heating — while the mitigation utilities (flare, scrubber) may themselves be unavailable. Bhopal (1984), the worst chemical disaster in history, turned on exactly this: the MIC refrigeration had been shut down, the high-temperature alarm disconnected, the flare out of action ~3 months, and the scrubber in standby — so a runaway had no functioning safeguard (Wikipedia — Bhopal disaster...

1 Detect the warming trend early (inventory temperature and vapour pressure). · 2 Restore refrigeration, or reduce inventory / add quench if it cannot be restored. · 3 Verify mitigation utilities (relief, scrubber, flare) are actually available — never assume. · 4 Keep temperature below the runaway/relief threshold; escalate before crossing it.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (no published rate for refrigeration-loss events on hazardous inventories).

Consequences Rising vapour pressure to relief or containment failure; for reactive inventories, self-heating runaway and toxic release — at Bhopal, thousands died when the MIC tank ran away with all safeguards down (National Academies; Wikipedia — Bhopal disaster).

THE FACTS — CITED STATS

✓ VERIFIED

Bhopal, India, 2–3 December 1984 — Union Carbide MIC release; worst chemical disaster in history.

Bhopal MIC refrigeration was shut down (freon removed by mid-1984); tank high-temperature alarm disconnected. ...

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Loss of Refrigeration on a Volatile or Reactive Inventory

"A tank that must stay cold, a refrigeration unit switched off to save money, and a flare that was already dead."



Loss of Heating Medium — Cold Embrittlement on Restart

“The warm oil stopped flowing, the steel went cold, and when they warmed it back up it shattered.”

WHAT · WHY · HOW

A warm-circulation utility (lean oil, hot oil, glycol) is lost when its pump trips, and the metal it warmed chills far below its safe design temperature. Reintroducing hot fluid onto the cold, embrittled steel cracks it and releases hydrocarbon. At Esso Longford (1998) a lean-oil pump trip chilled exchanger GP905; restarting hot lean oil at ~230 °C onto the cold shell fractured it — 2 killed, 8 injured, Victoria's gas supply cut for weeks. ...

- 1 Recognise the loss of warm circulation and track metal temperature, not just process values. · 2 Identify metal that has gone below its low-temperature design limit. · 3 Do NOT dump hot fluid onto embrittled steel — isolate or hold. · 4 Rewarm slowly within specified temperature-ramp limits before restoring full flow.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (no published rate for heating-medium-loss / brittle-fracture events).

Consequences Brittle fracture of vessels or exchangers on rewarm, gas release, and fire — Longford killed 2, injured 8, and cut state gas supply for ~2 weeks (Wikipedia — 1998 Esso Longford fire; IChemE).

THE FACTS — CITED STATS

✓ VERIFIED

Esso Longford gas plant, Victoria, Australia, 25 September 1998 (Longford Royal Commission).
GP905 exchanger fractured when ~230 °C lean oil was reintroduced onto a cold, embrittled shell. ...

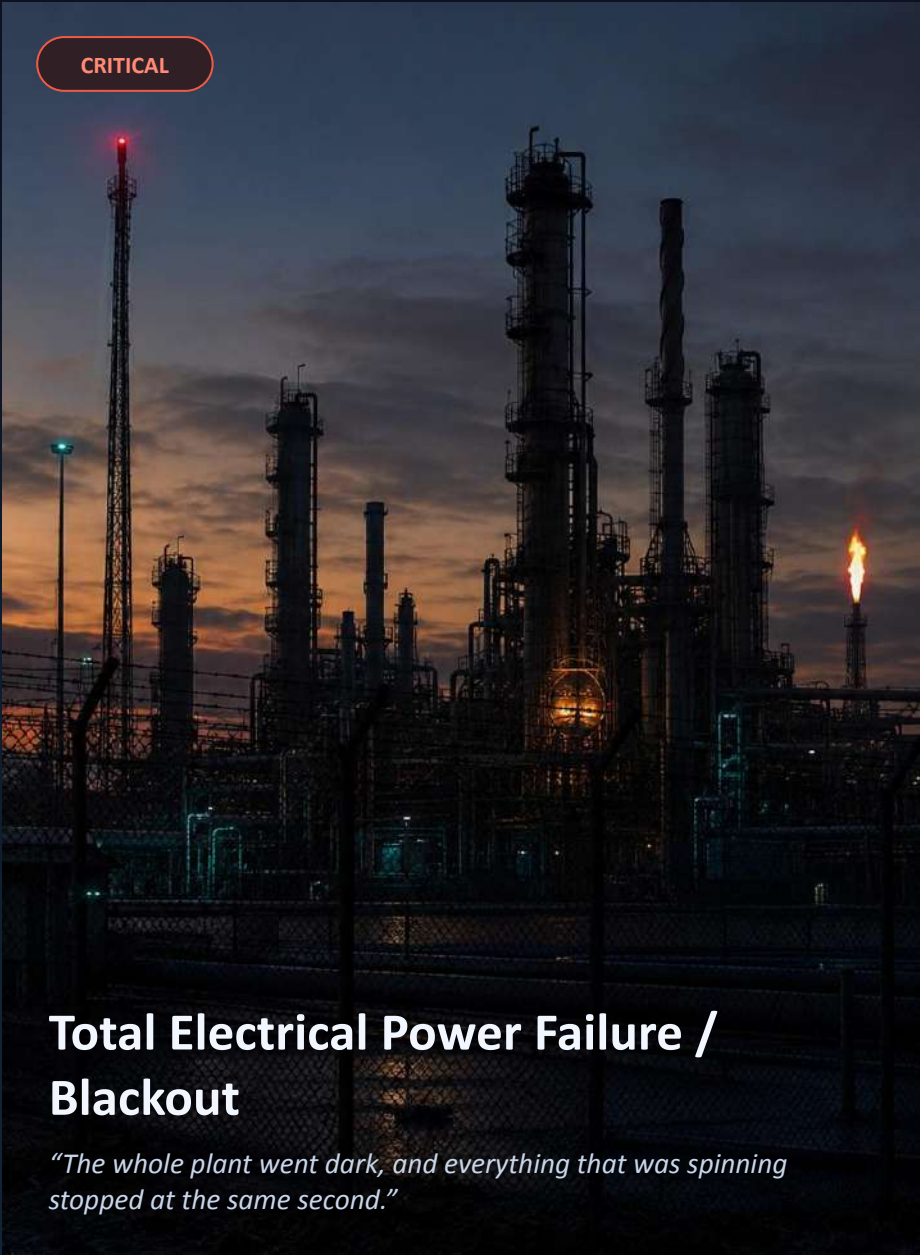
source: Longford Royal Commission · confidence-flagged stats · full cited list in slide notes

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CRITICAL



Total Electrical Power Failure / Blackout

“The whole plant went dark, and everything that was spinning stopped at the same second.”

WHAT · WHY · HOW

Site electrical power is lost. Every motor-driven pump, fan, and compressor trips together; instrument air and cooling water stop; and the plant sheds its inventory to the flare at once. Backup generators and flare capacity are all that stand between a controlled trip and a release. API 521 names loss of electric power as a headline utility-failure contingency — a general power failure trips pumps, fans, and compressors simultaneously, and relief/flare must be sized for the coincident load (API 521 overview). ...

1 Recognise a total power loss (everything down at once), not a cluster of individual failures. · 2 Confirm backup power picked up the critical loads (instruments, ESD, emergency lighting). · 3 Manage the coincident flare load and protect the flare KO drum. · 4 Isolate feeds and bring the unit to a safe shut state in priority order.

HOW OFTEN · CONSEQUENCES

How often The average U.S. electricity customer experienced ~1.4 interruptions and 5.6 hours of power interruption in 2022 (grid-wide proxy; industrial sites with dual feeds see fewer) (U.S. EIA). During Winter Storm Uri (Feb 2021), power loss forced emergency shutdowns and flaring across ~200 Texas facilities (Grist).

Consequences Mass flaring and excess emissions (~3.5 million lb excess air pollutants across ~200 facilities in Uri, including benzene, SO₂, CO, H₂S) (Grist); overloaded relief paths risk KO-drum overfill and loss of containment (API 521; HSE Milford Haven).

THE FACTS — CITED STATS

✓ VERIFIED

Texas Winter Storm Uri, February 2021 — blackout-driven mass shutdown and flaring across the Gulf Coast petrochemical belt.

API 521: general power failure trips pumps, fans, and compressors simultaneously — a governing relief-sizing case. (API 521 overview)

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HIGH

WHAT · WHY · HOW

One electrical bus or one critical driver is lost — say the cooling-water pumps' bus or a single reflux pump — while the rest of the unit keeps running and keeps feeding heat or flow into the section that lost it. API 521 treats partial power failure as its own contingency distinct from total power loss, because the coincident running equipment defines the relieving case (API 521 overview). ...

1 Spot the specific loss — which bus/driver tripped — rather than assuming general trouble. · 2 Start the standby driver (verify auto-start actually worked). · 3 Cut the matching heat/feed on the surviving side to rebalance. · 4 Watch the affected section's pressure/temperature/level back into band before restoring rate.

HOW OFTEN · CONSEQUENCES

How often Not quantified separately in public sources as a partial-loss rate; grid-wide, U.S. customers averaged ~1.4 interruptions in 2022 (proxy that includes partial/feeder events) (U.S. EIA).

Consequences Slow pressure/temperature/level divergence to relief lift or equipment trip — lost cooling with heat continuing, or lost reflux with feed continuing — recognised in API 521 as a distinct relieving case (API 521 overview).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (no single named anchor); the mechanism is embedded in API 521's contingency taxonomy.

API 521 treats partial power failure (single feeder/bus or single motor) as its own overpressure contingency. (API 521 overview)

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Partial Power Loss — Single Bus / Single Driver Trip

"Half the plant lost power. The other half kept pushing into it."

HIGH

WHAT · WHY · HOW

The UPS/DC backup power that keeps the control system, safety shutdown system, and critical instruments alive is lost during a power outage. Operators lose their eyes and their automatic shutdown at exactly the moment they most need them. Backup power exists to keep instrumentation, the BPCS, and the ESD energised through a power failure so the plant can reach a safe state; losing it removes the final protective layer, and the fail-safe assumptions behind every other utility scenario stop holding (IEC 61511 SIS design principle; API...

1 Recognise that instruments and ESD are no longer trustworthy (frozen/blank indications). · 2 Fall back to manual field actions and hard-wired trips. · 3 Preserve and verify the critical isolations by hand. · 4 Safe the unit without relying on the dead automation; re-establish monitoring as power returns.

HOW OFTEN · CONSEQUENCES

How often Emergency diesel generator fail-to-start probability ranges from 0.0013 (well-maintained, 99.87% start reliability) through 0.0066 (average) to 0.0165 (poorly maintained) per demand (NREL data via Bluefield Process Safety); U.S. NRC tracks EDG fail-to-start/fail-to-run performance at nuclear plants 1998–2022 (INL/OSTI Enhanced Component Performance Study).

Consequences Blind operation — frozen indications, control loops at default, ESD that may not execute — while the physical process keeps evolving; failed safe-shutdown assumptions can convert any concurrent upset into loss of containment (API 521 / IEC 61511 principle).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level / design-principle scenario (per source file); no single named public anchor.

Well-maintained standby generators: fail-to-start $\approx$ 0.13% per demand; poorly maintained $\approx$ 1.65%. (NREL via Bluefield Process Safety)

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Loss of Backup Power (UPS / DC / Emergency Generator)

“The main power was already down. Then the batteries that ran the controls died too.”



WHAT · WHY · HOW

The steam header collapses (boiler trip, header break). Steam-turbine-driven pumps stop, strippers and reboilers lose their heat medium, and steam tracing fails so cold-sensitive lines congeal — one utility loss showing up as three different failures at once. API 521 includes loss of steam among utility-failure overpressure contingencies — steam drives critical pumps and provides reboiler/stripping heat, so its loss trips flow and shifts heat balance simultaneously (API 521 overview). ...

- 1 Trace the multiple simultaneous symptoms to one common cause: the steam header.
- 2 Protect the critical steam-driven service (swap to electric spare if available).
- 3 Manage the heat-balance and level shift from lost reboiler/stripping duty.
- 4 Guard cold-sensitive traced lines against freezing/congealing before damage.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (no published rate for steam-header loss events).

Consequences Coincident flow loss, composition/level shift, and line freeze; overpressure where turbine-driven relief-critical services stop — recognised as an API 521 relieving contingency (API 521 overview).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (no single named anchor in the source research).

API 521 lists loss of steam among named utility-failure overpressure contingencies. (API 521 overview)

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HIGH

WHAT · WHY · HOW

The fuel-gas supply to a fired heater swings — a pressure sag starves the burners to flameout, or a spike over-fires them. If fuel isn't cut and the box purged after flameout, unburned fuel accumulates in a hot furnace and a relight risks a firebox explosion. API 521 treats fuel-supply failure as a utility contingency; fired equipment is doubly sensitive because fuel loss removes heat input AND creates an unburned-fuel accumulation hazard (API 521 overview). ...

1 Detect the fuel-gas upset (header pressure sag or spike) and the flameout. · 2 Cut fuel immediately on flameout — confirm the BMS tripped the safety shutoff valves. · 3 Purge the firebox completely; verify purge before any relight attempt. · 4 Relight only after a verified purge; on over-fire, reduce firing and protect tubes.

HOW OFTEN · CONSEQUENCES

How often A historical survey of fired-equipment combustion-chamber accidents catalogued 142 industrial cases, with accident frequency rising 1970–2005 then declining as safety standards spread; tube rupture was the most frequent cause (58/142) and fire the most frequent outcome (71% of tube-rupture cases) (Fired equipment combustion chamber accidents: a historical survey, Journal of Loss Prevention). ...

Consequences Furnace/firebox explosion on relight into an unpurged box; tube overheat and rupture on over-fire, with fire the dominant outcome (fired-equipment historical survey; NFPA 85/86 rationale).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (fired-equipment accident survey); no single named anchor in the source research.

142 fired-equipment combustion-chamber accidents catalogued in the historical survey; frequency declined after 2005 as standards took...

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Fuel-Gas Upset — Fired Heater Flameout / Burner Instability

"The fuel pressure sagged, the burners blew out, and gas kept pouring into a hot firebox."

HIGH

WHAT · WHY · HOW

A tank kept under nitrogen blanket loses its inert supply. As internal pressure falls, air is drawn in through vents — putting oxygen into a flammable vapour space — or, if make-up can't keep up, pulling the tank toward vacuum collapse. Blanketing keeps a flammable vapour space below the oxygen needed to burn (inerting principle; CSB Nitrogen Bulletin 2003); it also protects atmospheric tanks against in-breathing collapse — API 2000 names loss of nitrogen blanketing as an in-breathing case that can buckle a tank (API 2000...

- 1 Detect the blanket loss (falling blanket pressure, rising O₂%).
- 2 Restore N₂ supply or switch to the backup regulator.
- 3 Slow or stop the draw-off so in-breathing demand drops.
- 4 Keep O₂% and internal pressure out of their danger bands; verify before resuming.

HOW OFTEN · CONSEQUENCES

How often Frequency: not quantified in public sources (no published rate for blanketing-loss events).

Consequences Flammable headspace atmosphere awaiting an ignition source, or vacuum buckling of the tank — both recognised design cases under inerting practice and API 2000 (CSB Nitrogen Bulletin 2003; API 2000 overview).

THE FACTS — CITED STATS

✓ VERIFIED

Class-level (no single named anchor); mechanism anchored in API 2000 design cases.

Nitrogen blanketing holds the vapour space below the oxygen level needed to burn. (CSB Nitrogen Asphyxiation Bulletin 2003, cross-ref)

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Nitrogen Blanket Loss — Air Ingress or Vacuum Pull-Down

"The nitrogen blanket failed, and air crept into a space that must never see oxygen."

HIGH

WHAT · WHY · HOW

A large rotating machine loses its lube-oil supply — main oil pump trips and the standby fails to start. Without the oil film, bearings run metal-to-metal, temperatures spike within seconds, and the machine can seize or wreck its rotor. Lube-oil systems for major machinery (API 614 / API 617) are designed with main + standby pumps and a low-oil-pressure trip precisely because loss of lubrication leads to rapid bearing failure (standard-level citation); the auto-trip exists to stop the machine before catastrophic mechanical failure...

1 Detect falling oil pressure fast (before the bearing-temperature spike). · 2 Start the standby oil pump / restore supply; verify pressure recovers. · 3 If oil cannot be restored, trip the machine promptly — do not ride it down. · 4 Confirm coast-down lubrication (rundown tank/head) protects the bearings.

HOW OFTEN · CONSEQUENCES

How often No per-year event rate published, but lubrication problems dominate bearing failures: SKF attributes 36% of premature bearing failures to lubrication (other analyses run 40–80%), and bearing damage accounts for ~45–55% of rotating-machinery failures (SKF via Reliamag bearing-failure statistics, Machinery Lubrication).

Consequences Bearing over-temperature within seconds, seizure, rotor/casing wreck, and — on hydrocarbon machines — potential loss of containment from the resulting mechanical failure (machinery-protection principle; API 614/617 design rationale).

THE FACTS — CITED STATS

Class-level (no single named anchor in the source research).

Lubrication issues ≈ 36% of premature bearing failures (SKF split: lubrication 36%, fatigue 34%, mounting 16%, contamination 14%).

...

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SECONDARY

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Loss of Lube Oil — Bearing / Rotor Trip

"The oil pressure dropped, and a machine the size of a bus started to seize."

HIGH

WHAT · WHY · HOW

A centrifugal compressor's shaft seals lose their support utility — seal oil held above process pressure, or dry-gas-seal buffer gas. The seal can no longer hold back process gas at the shaft, so flammable or toxic gas leaks out unless the machine is tripped and depressured. Compressor seal systems (API 614 seal oil; API 617/692 dry-gas seals) maintain a controlled pressure margin over process to keep gas from escaping past the shaft (standard-level citation); seal-support loss on flammable/toxic service is treated as a trip condition because the alternative is an...

1 Recognise the collapsing seal margin (support pressure minus process pressure). · **2** Restore seal-oil / seal-gas supply if possible. · **3** If not, trip the compressor and depressure it before a release develops. · **4** Route any leakage to vent/flare and confirm gas detection is clear.

HOW OFTEN · CONSEQUENCES

How often No per-year rate published, but seal problems are the single biggest cause of unplanned centrifugal-compressor downtime — ~48% of compressor failures trace to seals, and ~80% of dry-gas-seal failures are contamination-driven (Cowseal dry-gas-seal failure analysis, Gas Processing & LNG DGS reliability article).

Consequences Uncontrolled shaft-seal release of flammable/toxic gas — a fire/toxic hazard — or a forced trip and outage; dry-gas-seal replacement outages are among the costliest compressor downtime events (Cowseal; Turbomachinery Magazine DGS failure modes).

THE FACTS — CITED STATS

Class-level (no single named anchor in the source research).

~48% of centrifugal compressor failures trace directly to seal problems. (Cowseal secondary compilation)

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SECONDARY

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Loss of Seal Oil / Dry-Gas Seal Supply — Compressor

"The seal support failed, and the gas that was sealed in started finding its way out along the shaft."

CRITICAL

WHAT · WHY · HOW

During an upset, streams relieve to the flare header, but the knock-out drum overfills because its liquid pump-out is lost or an outlet valve is wrongly closed. Liquid carries into the flare line and the relief path — the last line of defence — is compromised exactly when it's needed. At Texaco Milford Haven (1994), a storm-driven upset left flammable liquid pumping continuously into the FCCU flare KO drum while its outlet was effectively closed (a valve believed open was shut); the drum overfilled, ~20 tonnes released from the outlet line and exploded, injuring 26 (UK HSE case...

1 Watch the flare KO drum level as a first-class parameter during any upset. · 2 Verify the drum's outlet path is genuinely open (don't trust a single indication). · 3 Restore pump-out or open the correct outlet; cut the inbound liquid source. · 4 Keep the flare path clear — reduce relieving load if carryover approaches.

HOW OFTEN · CONSEQUENCES

How often Texas industry reported 4,067 emissions events (breakdowns/upsets, heavily flaring-related) from 275 companies in 2017 alone, and a study logged ~3,900 refinery upset events in Texas over 44 months — flare-system demands are routine; KO-drum overfill specifically is not quantified in public sources (Environment Texas "Major Malfunction" / Grist excess-emissions reporting; ResearchGate — ...

Consequences Liquid carryover defeats the relief system itself; at Milford Haven ~20 t of hydrocarbon released and exploded, injuring 26 and devastating the FCCU (no fatalities only because it was a Sunday) (HSE; IChemE).

THE FACTS — CITED STATS

✓ VERIFIED

Texaco refinery, Milford Haven, UK, 24 July 1994 (UK HSE investigation).

Milford Haven 1994: KO-drum outlet valve believed open was shut; ~20 t release; 26 injured. (UK HSE case study)

source: UK HSE investigation · confidence-flagged stats · full cited list in slide notes

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Flare / Relief Header Unavailable — KO Drum Overfill

"Everything was dumping to the flare, but the drum that protects it was quietly filling with liquid."

CRITICAL

WHAT · WHY · HOW

A single utility loss propagates: lose power → the air compressor and cooling pumps stop → control valves fail to position and the heat sink disappears → pressure and temperature climb → everything relieves to the flare at once → the relief path is stressed. Managing the domino order is the skill. CCPS frames the cascade explicitly — power failure stops the cooling-water pump and instrument-air compressor, failing all control valves to their predetermined action at once (CCPS/AIChE Beacon June 2020); Milford Haven 1994 and Longford 1998 are, at root, utility-disturbance cascades that...

1 Identify the root utility, not the symptoms (one cause, many coincident effects). · **2** Anticipate the next dominoes from the dependency chain (air, cooling, drivers, valves). · **3** Act in priority order: secure fuel/heat input, protect cooling and relief, manage the flare. · **4** Drive a coordinated safe shutdown; verify the relief path stays intact throughout.

HOW OFTEN · CONSEQUENCES

How often Cascade-scale events are documented but not rate-quantified; as context, Winter Storm Uri's blackout cascaded ~200 Texas facilities into emergency shutdown and flaring in one week (Grist), and Texas plants reported 4,067 upset/emissions events in 2017 (Environment Texas / EIP). Per-site cascade frequency: not quantified in public sources.

Consequences Coincident relief loads that can overwhelm the flare system, loss of containment, and multi-week outages — Milford Haven (26 injured, FCCU destroyed) and Longford (2 dead, state gas supply cut) both began as utility disturbances (HSE; Longford Royal Commission via Wikipedia/ICHEME).

THE FACTS — CITED STATS

✓ VERIFIED

Texaco Milford Haven 1994 and Esso Longford 1998 — both root-caused as utility-disturbance cascades (HSE; Longford Royal Commission).

CCPS: one power failure = simultaneous loss of cooling water, instrument air, and all control-valve positions. ...

source: HSE; Longford Royal Commission · confidence-flagged stats · full cited list in slide notes

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Utility-Failure Cascade into Unit Trip (The Meta-Scenario)

"One utility went down, and like dominoes it took the rest of the plant with it."

The plant, running. The situations, real.

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