DRAFT — 21 OF 21 MODES PENDING DISPOSITION

DFMEA · Cryogenic supercritical hydrogen storage tank · drafted with Opus 5.5

Crewed reusable orbiter cryogenic hydrogen tank (design review draft)

DFMEA HUMAN-RATED

· 10/30/2026 · component level · occurrence per mission · phases: build and acceptance, installation in the orbiter, ground servicing at the pad (fill, standby), launch and ascent, on-orbit operations, entry and landing, post-landing safing and offload (assumed), turnaround between flights, reuse

One hydrogen tank of the orbiter's fuel cell reactant storage system: inner pressure vessel, outer shell, supports, vapor-cooled shield, insulation, annulus vacuum and its vac-ion pump, the heater probe (two elements), quantity probe, fluid temperature sensor, heater assembly temperature sensor, two tank pressure sensors (one feeds the heater controller), fill and vent quick disconnects and their caps, and this tank's relief valve and relief port. Out of scope (interfaces only): filter, check valves, valve modules and manifold, manifold relief valve, heater controller and power circuits, oxygen tanks, fuel cells, lines, ground equipment

21	6	4	0	21	0	9	12	0	0
MODES	CRITICAL	PROVISIONAL: NO DATA	ACCEPTED	PENDING	REJECTED	RPN 200 OR MORE (ANY DATA)	100–199	50–99	<50

TOP RISKS — RANKED BY SEVERITY, THEN RPN, THEN ACTION PRIORITY

#	FAILURE MODE	S	O	D	RPN	AP
1	CRITICAL Inner pressure vessel ruptures (structural loss of containment), releasing the stored supercritical hydrogen into the annulus and midfuselage	9	4*	10	360	High
2	CRITICAL Fill or vent quick disconnect fails to stay sealed for flight: hydrogen leaks externally past the QD poppet seat and its flight cap into the midfuselage	9	5*	8	360	High
3	CRITICAL Loss of inner-vessel restraint: one or more tension straps or their end fittings fracture or pull out, so the inner vessel is no longer held in position under ascent, entry or landing loads	9	4*	8	288	High
4	CRITICAL Heater-controller tank pressure sensor reports an in-range but falsely HIGH pressure (out-of-spec high indication) to the heater controller	9	5*	5	225	High
5	CRITICAL Tank relief valve fails to open (relief function lost on demand) when tank pressure exceeds the 310 psia relief setting	9	5*	5	225	High

ANALYSIS INPUTS

COMPONENT Cryogenic supercritical hydrogen storage tank

DESCRIPTION Double-walled sphere with a vacuum annulus storing about 92 lb of supercritical hydrogen for the fuel cells. Flights carry two to five tank sets (one hydrogen and one oxygen tank each) in the midfuselage under the payload bay liner. Built only from the tank's design description; anything not stated is (assumed).

PRESSURE heaters on automatically at 200 to 206 psia and off at 220 to 226 psia (tanks 1 and 2), on at 217 to 223 and off at 237 to 243 psia (tanks 3 and 4); in paired auto mode a high-pressure signal from either tank turns off both tanks' heaters; supply to the manifold 200 to 243 psia; tank relief valve relieves at 310 psia; ground fill supply 300 to 320 psia; caution and warning below 153 or above 293.8 psia; pressure display 0 to 400 psia; design, proof and burst pressures not stated

TEMPERATURE hydrogen stored supercritical from about -420 °F; the tank sits in the midfuselage under the payload bay liner; hydrogen is warmed to at least 40 °F downstream before the fuel cells

WORKING FLUID / MEDIUM hydrogen, single phase (supercritical)

CYCLES / DUTY one fill per launch attempt (up to 45 min; filling stops 2 min 35 s before launch); missions of several days to about two weeks (assumed); heaters cycle on pressure; tanks 1 and 2 supply ascent and entry, tanks 3 and 4 on orbit; tanks certified for 100 missions with turnaround between flights

VIBRATION / LOADS launch and ascent vibration and acoustics, on-orbit thermal cycling, entry and landing loads, ground handling (levels not stated)

OTHER ENVIRONMENT ground equipment powers the vac-ion pump during servicing. Verification: certified for 100 missions; test matrix not stated

MATERIALS Inner pressure vessel: aluminum 2219, 41.51 in diameter (wall not stated); Outer shell: aluminum 2219, 45.5 in diameter; Supports: twelve low-conductive supports, filament-wound epoxy S-glass straps loaded in tension (assumed for this tank); Shield and insulation: vapor-cooled radiant shield between vessel and shell; silverized Kapton multilayer insulation with nylon net spacers (assumed for this tank); Vac-ion pump: on the annulus; also works as the vacuum gauge; Heater probe: one probe with two elements (A and B); element and sheath materials not stated; Quantity probe: capacitance type; materials not stated; Sensors: two tank pressure sensors, fluid temperature sensor, heater assembly temperature sensor; types not stated; Fill and vent quick disconnects and caps; relief valve and relief port: materials not stated; Dry weight: 216 lb

INTERFACES Supply line through a relief valve and 12-micron filter package to valve modules (a check valve per tank line, manifold valves) and the manifold feeding three fuel cells; Heater controller on cold plates in the midbody: automatic on and off from the heater controller pressure sensor; paired-tank auto mode; crew heater switches auto, on, off; Heater power from orbiter buses through the controller (voltage not stated); Instrumentation: quantity, pressures, fluid and heater assembly temperatures to displays, meters, caution and warning, and telemetry; Ground equipment: fill (300 to 320 psia) and vent through the quick disconnects; vac-ion pump power during servicing; Paired oxygen tank in the same tank set; one tank set can supply all three fuel cells

MISSION CONTEXT Crewed orbiter. Three fuel cells supply the orbiter's electrical power in flight; each tank set's hydrogen and oxygen feed them. Losing this tank's hydrogen loses its tank set. A hydrogen leak or tank rupture in the midfuselage can damage the orbiter and endanger the crew.

MODEL Opus 5.5 (claude-opus-5-5)

AUTHORSHIP — EVERY FIELD CARRIES WHO WROTE ITS CURRENT TEXT

◇ AI draft ◆ AI self-corrected (Pass 7) ✓ Engineer accepted ✎ Engineer edited ✍ Engineer written · STALE an input, finding or evidence it rests on changed (§5.3)

WORKSHEET SUMMARY — RANKED BY CRITICALITY

FAILURE MODE	S	O	D	RPN	AP	DISPOSITION
Store about 92 lb of supercritical hydrogen (21.39 cubic ft) from fill to the end of the mission						
CRITICAL Inner pressure vessel ruptures (structural loss of containment), releasing the stored supercritical hydrogen into the annulus and midfuselage	9	4*	10	360	High	pending
Limit heat leak with the vacuum annulus, the vapor-cooled shield and multilayer insulation						
PROVISIONAL: NO DATA Degraded radiant insulation performance with vacuum intact: MLI and/or vapor-cooled shield pass more heat than design, giving a partial, persistent increase in heat leak	5	5*	8	200	Medium	pending
Hold supply pressure with the heaters as hydrogen is drawn off						
Heater probe delivers no or insufficient heat on demand, so tank pressure decays below the commanded supply band as hydrogen is drawn off	7	5*	5	175	High	pending
Heaters fail to switch off at the upper setpoint, so continued heating drives tank pressure above the commanded band toward relief	7	5*	5	175	High	pending
Tank pressure overshoots, undershoots or oscillates outside the commanded band during heater cycling (degraded pressure regulation)	4	6*	5	120	Medium	pending
Measure quantity, pressure (two sensors), fluid temperature and heater assembly temperature						
CRITICAL Heater-controller tank pressure sensor reports an in-range but falsely HIGH pressure (out-of-spec high indication) to the heater controller	9	5*	5	225	High	pending
Heater-controller tank pressure sensor reports an in-range but falsely LOW pressure (or reads zero), so heaters are not commanded off	7	5*	5	175	High	pending
Capacitance quantity probe indicates hydrogen quantity out of spec (plausible in-range over-reading) through the mission	7	5*	5	175	High	pending
Supply hydrogen to the manifold and three fuel cells						
PROVISIONAL: NO DATA Supply flow to the manifold is restricted or blocked (partial supply) by solid contaminants carried out of the tank.	7	5*	8	280	High	pending
Relieve tank overpressure through the relief valve and relief port						
CRITICAL Tank relief valve fails to open (relief function lost on demand) when tank pressure exceeds the 310 psia relief setting	9	5*	5	225	High	pending
CRITICAL Partial relief: valve lifts but relief valve or relief port flow capacity is insufficient, so tank pressure overshoots well above 310 psia	9	4*	5	180	High	pending
Unintended relief: valve cracks below setting or fails to reseat, venting hydrogen continuously through the relief port	7	5*	5	175	High	pending
Accept ground fill and vent through quick disconnects, sealed by caps for flight						
CRITICAL Fill or vent quick disconnect fails to stay sealed for flight: hydrogen leaks externally past the QD poppet seat and its flight cap into the midfuselage	9	5*	8	360	High	pending
Fill quick disconnect fails to pass, or restricts, fill flow during pad servicing, leaving the tank short of its 92 lb load when filling stops	5	5*	6	150	Medium	pending
Vent quick disconnect fails to pass vent flow during fill, standby or post-landing offload, so tank pressure rises toward the relief setpoint and the tank cannot be vented or detanked through the ground path	5	5*	6	150	Medium	pending
Keep the annulus evacuated with the vac-ion pump, which also reads the vacuum						
PROVISIONAL: NO DATA Annulus vacuum degrades beyond what the vac-ion pump can hold, so the annulus loses its insulating vacuum (partial or total).	8	5*	5	200	High	pending
Erroneous annulus vacuum indication from the vac-ion pump: a plausible in-range reading that is falsely good or falsely bad.	5	5*	7	175	Medium	pending
The vac-ion pump stops pumping or loses pumping capacity, so the annulus is no longer actively evacuated.	5	5*	6	150	Medium	pending
Support the inner pressure vessel within the outer shell through ground handling, launch, ascent, entry and landing loads while minimizing conducted heat (twelve tension straps, assumed)						
CRITICAL Loss of inner-vessel restraint: one or more tension straps or their end fittings fracture or pull out, so the inner vessel is no longer held in position under ascent, entry or landing loads	9	4*	8	288	High	pending

FAILURE MODE	S	O	D	RPN	AP	DISPOSITION
PROVISIONAL: NO DATA Degraded support stiffness: progressive loss of strap preload over reuse leaves straps slack, so the inner vessel moves excessively in the annulus under vibration and handling loads	6	5*	10	300	Medium	pending
Support path conducts heat out of spec: excess conducted heat leak into the inner vessel through the straps, or through vessel/shield-to-shell contact the suspension fails to prevent	7	5*	5	175	High	pending

FAILURE-MODE DETAIL

Control tags read (kind or method · coverage · observes: what is actually seen · status). A control with no status tag is **assumed** — planned and verified controls say so; verified is only earned by a closed verification activity. Occurrence is scored per mission unless a mode states its own unit; the controls a D score credits are marked in its detection list.

Store about 92 lb of supercritical hydrogen (21.39 cubic ft) from fill to the end of the mission

Inner pressure vessel ruptures (structural loss of containment), releasing the stored supercritical hydrogen into the annulus and midfuselage ◇

RPN 360 · AP High · CRITICAL · Pending

WHY HERE ◇The welded aluminum 2219 inner sphere (41.51 in diameter, wall not stated) holds hydrogen at about -420 °F. Its pressure cycles between the heater on/off setpoints, up to 243 psia, with relief at 310 psia. Each turnaround it also cycles between ambient and cryogenic temperature, and it is certified for 100 missions. Pressure plus cryogenic thermal cycling over that reuse life is the fatigue spectrum acting on its weld and penetration flaws. A rupture would dump about 92 lb of hydrogen inside the closed midfuselage under the payload bay liner, beside the paired oxygen tank. Design, proof and burst pressures are not stated, so the structural margin is unknown to this draft.

LOCAL EFFECT ◇Inner vessel wall fractures and hydrogen floods the vacuum annulus. The 2219 outer shell (45.5 in) is not stated to be rated for internal pressure, so it is assumed to overpressurize and fail.

NEXT-LEVEL EFFECT ◇Hydrogen and fragments are released into the midfuselage. The paired oxygen tank, other tank sets, supply lines and structure are damaged. This tank set is lost and other sets may be lost.

END EFFECT ◇**Fire or overpressure in the midfuselage damages the orbiter, leading to loss of vehicle and crew. The crew is aboard from pad standby through ascent, on orbit and entry.**

CAUSES / MECHANISMS

- **Fatigue crack growth from undetected porosity or lack-of-fusion flaws in the inner-vessel girth or penetration-boss welds. Drivers are heater-driven pressure cycling between setpoints, fill-to-flight pressurization, and ambient-to-cryogenic thermal cycles accumulated over up to 100 missions until a flaw reaches critical size. The welding process is assumed.** ◇ — Reuse to 100 missions with a cryogenic thermal cycle and pressure cycle every flight is a classic safe-life/fracture-control driver for welded 2219 pressure vessels. Weld flaws are the likely initiation sites. (fatigue)
- **Overpressure beyond vessel capability from two coincident failures. First, heating continues past the upper setpoint (heater controller fails on, or the crew switch is left ON), or the ground fill supply exceeds 310 psia (its range is 300 to 320 psia). Second, this tank's relief valve fails to crack at 310 psia because frozen contaminant or particulate is in the relief port or seat.** ◇ — The relief valve is the only in-scope overpressure protection. The ground fill supply range brackets the relief setpoint, and the heaters are the pressurant source. The heater controller itself is out of scope and is an interface only. (overload fracture buckling)

MANUFACTURING CHAIN ◇Fusion welding of Al 2219 inner-vessel hemisphere girth and penetration-boss welds (process assumed) → porosity, lack of fusion, crack-like flaws → reduced net section and stress intensification at flaw tips → flaws grow under pressure and cryogenic thermal cycles over reuse to critical size, then fracture unstably · one row covers the flaw population distributed along all girth and boss welds, screened by acceptance NDE

PREVENTION CONTROLS

- Aluminum 2219 for inner vessel and shell. Assumption: this alloy was chosen for weldability and toughness retention at cryogenic temperature. Engineer to confirm temper and weld filler. (material selection) ◇
- Fracture-control / safe-life analysis of the inner vessel for the 100-mission pressure and thermal-cycle spectrum, with an acceptance proof test. Neither the test matrix nor the design/proof/burst pressures are stated. (qualification) ◇
- Relief valve at 310 psia. Heaters switch off automatically at the upper setpoint, and in paired auto mode a high-pressure signal from either tank turns off both tanks' heaters. (design feature) ◇

DETECTION CONTROLS

- Radiography of all inner-vessel girth and penetration welds at build (radiography · every unit · observes: Porosity, lack-of-fusion or crack-like indication in the weld exceeding the acceptance limit) credited for D ◇
- Acceptance proof pressure test of the inner vessel (proof test · every unit · observes: Leak, permanent deformation or failure at proof pressure) credited for D ◇
- Annulus vacuum monitored through the vac-ion pump, which is powered by ground equipment during servicing (telemetry monitor · every unit · observes: Rise in vac-ion pump current (annulus pressure), indicating hydrogen entering through a through-wall crack before break) credited for D ◇
- Tank pressure telemetry with caution and warning above 293.8 psia; the crew can switch heaters off (no automatic response) (telemetry monitor · every unit · observes: Tank pressure exceeding 293.8 psia and rising toward the 310 psia relief) ◇

SCORING

S9 ◇ *Loss of vehicle, no public risk; or loss of crew (crewed vehicle)* — End effect is a midfuselage rupture with loss of vehicle and crew while the crew is aboard. The mission context states that tank rupture in the midfuselage can endanger the crew. No credit is taken for controls. The engineer should evaluate S10 for rupture during ascent if debris can reach public-exposure zones.

O4 ◇ *engineering judgment, no data* LOW CONFIDENCE — No test or flight history is provided, and qualified fatigue life versus the required 100 missions is not stated. The 100-mission certification is a requirement, not history. The score uses the design-FMEA no-data floor. Assumption — engineer to calibrate from analogous program data and the fracture-control analysis.

D10 ◆ *No detection — first sign is the consequence* — Build radiography and proof screen the initial weld-flaw population across the full article, but only once at build. Crack growth occurs during reuse after those checks, and no periodic in-service NDE is stated. The ground vac-ion annulus reading catches growth only if the crack goes through-wall and leaks before it breaks, which is not established. Pressure telemetry detects only the overpressure cause, not fatigue growth. For the dominant fatigue cause, detection rests on between-flight ground indications at best. [Pass 7: No in-service inspection exists, as periodic NDE is only the recommended_action. Build radiography and proof are one-time checks. The annulus reading relies on leak-before-break, which is not established. Fracture onsets in flight, so the first sign is the consequence.]

RECOMMENDED ACTION ◇Obtain the design/proof/burst pressures and a 2219 weld fracture-mechanics (safe-life or leak-before-break) analysis for the 100-mission pressure and cryo-thermal spectrum, then set a turnaround NDE or annulus-vacuum trend requirement accordingly.

Limit heat leak with the vacuum annulus, the vapor-cooled shield and multilayer insulation

Degraded radiant insulation performance with vacuum intact: MLI and/or vapor-cooled shield pass more heat than design, giving a partial, persistent increase in heat leak ◇

RPN 200 | AP Medium | PROVISIONAL: NO DATA | Pending

WHY HERE ◇With the annulus evacuated, this tank's heat leak is set by radiation through the silverized Kapton MLI and by the vapor-cooled shield intercepting heat. The MLI performs only if its nylon-net-spaced layers stay uncompressed and its low-emissivity silver coating stays clean. The shield performs only if outflowing hydrogen actually cools it. Launch vibroacoustics, hand layup around a 41.51 in sphere with strap and penetration pass-throughs, turnaround exposure, and low-draw periods each degrade one of these specific properties.

LOCAL EFFECT ◇Radiant and layer-contact conduction through the blanket rises, or the shield runs warm. Heat flux to the hydrogen increases moderately while annulus pressure reads nominal.

NEXT-LEVEL EFFECT ◇Pressure rises faster at low draw and heater on-time falls. If heat leak exceeds what the minimum fuel cell draw removes, pressure climbs toward the high C&W of 293.8 psia and the relief at 310 psia. That escalation to venting and tank-set loss is captured under the loss-of-vacuum row's end effect. On the pad, standby pressure rise between fill completion and launch is faster than planned.

END EFFECT ◇**Ground: excessive standby pressure rise forces a hold or scrub. Flight: the crew manages pressure by raising fuel cell load or using this tank preferentially; the mission proceeds with reduced hydrogen margin.**

CAUSES / MECHANISMS

- **MLI layer compaction, slump or shifting under launch/ascent vibroacoustics. Nylon net spacing collapses, raising layer-to-layer contact conduction, and blanket edges open gaps.** ◇ — A loose-layered blanket on a sphere is vulnerable to vibration-driven settling; levels are not stated in the input. (environment vibration shock emi)
- **MLI installation defects at layup and closeout: over-compressed seams, gaps around strap and penetration pass-throughs, torn silverized Kapton, shield-to-blanket contact.** ◇ — Hand layup around twelve strap pass-throughs and multiple penetrations creates many local radiation leak paths. (assembly installation error)
- **Vapor-cooled shield receives insufficient cooling. Shield cooling depends on outflowing hydrogen, which is low during low-draw on-orbit periods and pad standby. Contaminant blockage of the shield cooling path is also possible (shield flow routing assumed).** ◇ — Shield effectiveness is tied to draw rate, which varies with fuel cell load and with which tanks are in use (tanks 1 and 2 for ascent/entry, 3 and 4 on orbit). (fluid dynamic)
- **Tarnish or corrosion of the silver coating on the Kapton from moisture or sulfur-bearing contaminants admitted during build or any annulus breach and re-pump, raising emittance.** ◇ — Silver is susceptible to tarnish; low emittance is the property the MLI depends on. (material degradation)

MANUFACTURING CHAIN ◇Hand layup and closeout of silverized Kapton/nylon-net MLI and installation of the vapor-cooled shield around the 41.51 in inner vessel (assumed process) → compressed seams, gaps at strap and penetration pass-throughs, torn or contaminated film, shield-to-blanket contact → higher effective blanket conductivity and local radiation leak paths → increased heat flux to the hydrogen and faster pressure rise at low draw · defect population: distributed seams and pass-through gaps across the whole blanket, treated as one population

PREVENTION CONTROLS

- Controlled MLI layup procedure with layer count, density and seam/pass-through closeout requirements; cleanroom handling of silverized film (assumed) (procedure or training) ◇
- Vapor-cooled shield designed to be cooled by the hydrogen outflow (stated design feature) (design feature) ◇

DETECTION CONTROLS

- Heat-leak acceptance test: locked-up pressure-rise rate or boil-off measurement at build and at pad standby versus a baseline (assumed standard practice) (functional test · every unit · observes: pressure-rise rate with heaters off above baseline for the measured fluid quantity) credited for D ◇
- In-flight trend of tank pressure, fluid temperature and heater on-time versus hydrogen draw via telemetry (telemetry monitor · every unit · observes: reduced heater duty or pressure rise above prediction at a given draw) ◇

SCORING

S5 ◇ *Test or launch scrub; significant turnaround impact* — Worst credible direct end effect is excessive pad standby pressure rise forcing a hold or scrub (S5). In flight the effect is a recoverable workaround (S4). Escalation to relief venting and tank-set loss needs heat leak to grow beyond minimum draw capacity and is captured in the loss-of-vacuum row, so it is not imported.

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — No test or flight history was provided; assumption, engineer to calibrate from analogous program data. Reasoning: hand-laid MLI on a reused tank is exposed to ascent vibroacoustics every mission across 100 missions. Shield cooling is inherently reduced at low draw, so partial degradation is judged more likely than the design floor of O4.

D8 ◆ *Operational anomaly evident only via downstream effects* — Installation defects (cause 1) are present before flight and show as an elevated locked-up pressure-rise rate in the routine heat-leak/standby check. The sealed annulus cannot be inspected directly, so the integrated thermal response is the only practical method. Vibration-induced compaction onsets in flight after that check and is visible only as a subtle heater-duty/pressure trend, which would rate D8 if it were the justifying cause. Engineer to confirm a heat-leak acceptance limit exists. [Pass 7: The only credited control is a ground check whose acceptance limit is still a recommended_action. Vibration compaction onsets in flight, and the draft rates the in-flight trend signature D8.]

RECOMMENDED ACTION ◇Define a per-flow heat-leak acceptance metric (locked-up pressure-rise rate) and an in-flight heater-duty-versus-draw trend limit; confirm shield cooling at minimum draw.

Hold supply pressure with the heaters as hydrogen is drawn off

Heater probe delivers no or insufficient heat on demand, so tank pressure decays below the commanded supply band as hydrogen is drawn off ◇

RPN 175 | AP High | Pending

WHY HERE ◇The hydrogen is stored single-phase supercritical, so there is no ullage boil-off to restore pressure. Drawing hydrogen off lowers pressure unless the heater probe adds heat. Both heater elements (A and B) sit in one probe and are switched by one controller pressure sensor. A probe-level or sensor-level fault can therefore remove all pressurization for this tank, and pressure can fall below the heater-on setpoints and toward the low caution-and-warning limit of 153 psia.

LOCAL EFFECT ◇Heaters stay off or under-deliver heat. Tank pressure falls below the heater-on setpoint (200-206 psia for tanks 1-2, 217-223 psia for tanks 3-4) and keeps falling as fuel cells draw hydrogen.

NEXT-LEVEL EFFECT ◇Supply pressure from this tank to the manifold drops below its band. A low-pressure caution and warning trips below 153 psia. This tank can no longer deliver its hydrogen, and its tank set is lost to the fuel cells.

END EFFECT ◇**Loss of this tank set's hydrogen. The fuel cells continue on the remaining tank sets with reduced reactant margin, which likely forces mission shortening or early return (mission-critical degradation).**

CAUSES / MECHANISMS

- **Open circuit in heater element A and/or B at the element-to-lead or probe lead-through junction. The assumed driver is fatigue from repeated cryogenic chill-down to about -420 °F and warm-up each fill and offload over the 100-mission life, combined with launch vibration. A shared probe lead-through or connector fault removes both elements at once.** ◇ — Thermal cycling between cryogenic and ambient temperatures every flight, plus ascent vibration, loads the element junctions inside the single probe. Element and sheath materials are not stated, so this mechanism is assumed. (fatigue)
- **The heater-controller pressure sensor reads falsely high but still in range (zero/span drift or cold-induced offset). The controller sees pressure above the heater-on setpoint and never commands the heaters on.** ◇ — Only one of the two tank pressure sensors feeds the heater controller. A plausible in-range high reading defeats the automatic on logic without any obvious fault indication. (sensor instrumentation)
- **In paired auto mode, a false high-pressure signal from the paired tank's controller sensor turns off both tanks' heaters. This tank's heaters are inhibited even though its own pressure is low.** ◇ — The input states that in paired auto mode a high-pressure signal from either tank turns off both tanks' heaters. This is a cross-tank common-cause path. (sensor instrumentation)
- **Heater element insulation breaks down and shorts to the sheath or ground. Circuit protection then trips and removes power from the element.** ◇ — Insulation sees cryogenic contraction cycling and handling. Element insulation materials are not stated (assumed). (electrical open short drift)

PREVENTION CONTROLS

- Two independent heater elements (A and B) in the probe, so the loss of one element leaves heating capability. (redundancy) ◇
- Crew heater switches (auto/on/off) allow manual ON to bypass a false-high controller sensor or paired-mode inhibit. (design feature) ◇
- Heater probe qualified for cryogenic thermal cycling and vibration across the certified 100-mission life (test matrix not stated). (qualification) ◇

DETECTION CONTROLS

- Tank pressure telemetry with a low-pressure caution and warning below 153 psia. (telemetry monitor · every unit · observes: Tank pressure falling below the heater-on setpoint without recovery, then a low-pressure C&W below 153 psia.) credited for D ◇
- Cross-check between the second (non-controller) tank pressure sensor and the controller sensor on displays and telemetry. (telemetry monitor · every unit · observes: The two tank pressure readings disagree, with the controller sensor reading high relative to the independent sensor.) credited for D ◇
- Heater assembly temperature telemetry while heaters are commanded on. (telemetry monitor · every unit · observes: No heater assembly temperature rise when pressure is below the on setpoint.) credited for D ◇
- Heater element resistance and insulation-resistance functional check during turnaround and servicing (standard practice, assumed). (functional test · every unit · observes: Element resistance out of tolerance (open) or low insulation resistance to sheath.) ◇

SCORING

S7 ◇ *Mission-critical degradation; payload to off-nominal orbit needing mitigation* — The end effect is loss of this tank set's hydrogen. The orbiter continues on the remaining tank sets (one set can supply all three fuel cells) with reduced reactant margin, likely forcing mission shortening. This is mission-critical degradation needing mitigation, not loss of vehicle or crew. If a flight carries only two tank sets, the engineer should reassess whether the mission is lost (S8).

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — Several independent causes contribute: element/junction fatigue from cryogenic cycling over a 100-mission life, in-range drift of the controller sensor, paired-mode false-high inhibit, and insulation breakdown. No test or flight history is provided. Scored above the O4 floor because several causes apply and element and sensor types are unknown. note 1

D5 ◇ *Detected in flight via telemetry, no automated response* — Onset can occur in flight, after any ground check, so the turnaround functional test cannot earn better than D5. Pressure telemetry with the 153 psia C&W, the independent second pressure sensor and heater assembly temperature reveal the decay or the sensor disagreement in flight. The response is crew or ground action (manual heater ON, tank reconfiguration), not automated safing. All controls are assumed.

RECOMMENDED ACTION ◇Obtain heater probe element/lead-through design and thermal-cycle qualification data, and confirm the paired-auto-mode inhibit logic and crew manual-override procedure, to calibrate O and verify the pressure-sensor cross-check detection.

Heaters fail to switch off at the upper setpoint, so continued heating drives tank pressure above the commanded band toward relief ◇

RPN 175 AP High Pending

WHY HERE ◇In single-phase supercritical hydrogen, heat added by the probe converts directly into pressure rise, because there is no liquid-vapor interface to buffer it. Heater shutoff depends on the single controller pressure sensor reaching the off setpoint (220-226 or 237-243 psia). If shutoff fails, pressure climbs past the 293.8 psia high caution and warning until the tank relief valve vents hydrogen at 310 psia.

LOCAL EFFECT ◇Heater elements remain energized above the off setpoint, and tank pressure rises continuously.

NEXT-LEVEL EFFECT ◇A high-pressure caution and warning trips above 293.8 psia. If heating is not stopped, the tank relief valve cracks at 310 psia and repeatedly vents hydrogen, depleting this tank. Rupture would require the relief function to also fail; that case is captured under the relief-function rows.

END EFFECT ◇**Loss of this tank's hydrogen through relief venting, and so loss of its tank set. The mission continues on the remaining sets with reduced margin, likely shortening it.**

CAUSES / MECHANISMS

- **The heater-controller pressure sensor reads falsely low but still in range (drift, scaling error or cold-induced offset). The controller never sees the off setpoint and keeps the heaters on.** ◇ — Only one tank pressure sensor feeds the controller, and an in-range low reading looks valid to the automatic logic. (sensor instrumentation)
- **The crew heater switch is left in ON (manual) after a workaround or checklist step. This bypasses automatic pressure shutoff.** ◇ — The input states that crew heater switches offer auto/on/off positions. ON removes the automatic off at the upper setpoint. (operational error)
- **The heater controller output switching element fails closed, so heater power from the orbiter bus stays applied regardless of commanded state. The controller is an interface item outside this boundary.** ◇ — Heater power reaches the probe from orbiter buses through the controller. A failed-closed output keeps the elements energized. (electrical open short drift)

PREVENTION CONTROLS

- Tank relief valve set at 310 psia, above the heater off setpoints and below the burst pressure. Design, proof and burst pressures are not stated; margin to burst is unverified. (design feature)
- Crew procedure to return heater switches to AUTO, and to switch heaters OFF on a high-pressure caution and warning. (procedure or training)
- Calibration of the controller pressure sensor at cryogenic conditions during acceptance and turnaround (standard practice, assumed). (process control)

DETECTION CONTROLS

- Tank pressure telemetry with a high-pressure caution and warning above 293.8 psia. (telemetry monitor · every unit · observes: Tank pressure rising through the heater off setpoint without leveling, then a high-pressure C&W above 293.8 psia.) credited for D
- Cross-check between the independent second tank pressure sensor and the controller sensor. (telemetry monitor · every unit · observes: The controller sensor reads low relative to the independent sensor while the heaters remain on.) credited for D
- Heater assembly temperature telemetry. (telemetry monitor · every unit · observes: Sustained elevated heater assembly temperature with pressure above the off setpoint.) credited for D

SCORING

S7 *Mission-critical degradation; payload to off-nominal orbit needing mitigation* — The direct end effect, with the relief valve functioning, is venting depletion of this tank and loss of its tank set. The mission continues on the remaining sets with reduced margin: mission-critical degradation. Escalation to rupture in the midfuselage needs a second, independent failure (relief valve), so it is not imported here; it is captured under the relief-function mode.

O5 *engineering judgment, no data* **LOW CONFIDENCE** — Causes include in-range low drift of the single controller sensor, a manual-mode switch error and a failed-closed controller output. No test or flight history is provided. Scored above the O4 floor because a single-sensor control path and a human-procedure path both exist. note 1

D5 *Detected in flight via telemetry, no automated response* — Onset is in flight. Tank pressure telemetry with the 293.8 psia high C&W, the independent second pressure sensor and heater assembly temperature reveal continued heating before or at relief. Response relies on the crew or ground switching heaters off; no automated response for this tank is stated. The paired-mode cutoff relies on the faulty sensor's own reading. All controls are assumed.

RECOMMENDED ACTION Evaluate an automatic heater cutoff driven by the independent second pressure sensor or heater assembly temperature, and confirm relief valve set point margin to stated proof and burst pressures.

Tank pressure overshoots, undershoots or oscillates outside the commanded band during heater cycling (degraded pressure regulation)

RPN 120 | AP Medium | Pending

WHY HERE On orbit, supercritical hydrogen heated by a single local probe gets little buoyant convection in microgravity. Heat stays near the probe while the bulk fluid and the pressure sensor lag. Later mixing (maneuvers, outflow changes) produces pressure spikes or collapses relative to the on/off setpoints. Effectively single-phase hydrogen with a localized heater makes the bang-bang pressure control susceptible to this.

LOCAL EFFECT Heater on/off cycling no longer tracks bulk pressure. Pressure overshoots the off setpoint or collapses below the on setpoint after mixing, and the heater assembly temperature runs high during prolonged on-periods.

NEXT-LEVEL EFFECT Supply pressure to the manifold excursions outside the 200-243 psia band. Nuisance high or low caution and warning are possible (above 293.8 or below 153 psia), along with uneven draw between paired tanks.

END EFFECT **Recoverable in-mission anomaly. The crew or ground manage pressure with manual heater switching or tank reconfiguration, and the mission proceeds with a workaround.**

CAUSES / MECHANISMS

- **Thermal stratification of supercritical hydrogen around the heater probe in microgravity. Without buoyant convection, heat is not distributed to the bulk, so sensed pressure lags heater input; vehicle maneuvers or outflow changes then mix the warm layer and cause abrupt pressure rise or collapse. The effect is assumed to worsen at low quantity and low density late in the mission.** — The on-orbit phase plus single-phase hydrogen and one localized heater probe. No destratification device is stated in the input (assumed absent). (fluid dynamic)
- **Scale or zero error in the controller pressure sensor shifts the effective on/off band so it no longer matches the commanded setpoints, without driving the reading out of range.** — The controller acts on one sensor's reading. Cryogenic exposure and reuse over 100 missions can shift calibration (assumed). (sensor instrumentation)

PREVENTION CONTROLS

- Heater on/off setpoint deadband plus crew auto/on/off switches, allowing ground- or crew-managed heater cycling when stratification is suspected. (design feature)
- Flight procedure for tank management at low quantity, such as switching active tanks and limiting continuous heater-on duration (assumed). (procedure or training)

DETECTION CONTROLS

- Tank pressure and heater assembly temperature telemetry trended by ground and displayed to the crew. (telemetry monitor · every unit · observes: Pressure overshoot past the off setpoint or sudden pressure drop after maneuvers, with high heater assembly temperature during long on-periods.) credited for D
- Fluid temperature and quantity probe telemetry compared with pressure. (telemetry monitor · every unit · observes: Fluid temperature and density inconsistent with tank pressure, indicating stratification.) credited for D

SCORING

S4 *Recoverable in-mission anomaly; mission proceeds with workaround* — The direct end effect is pressure excursions and nuisance C&W, managed by manual heater or tank reconfiguration while the mission proceeds. If an undershoot or overshoot persists unmanaged, it becomes the separate no-heat or fail-to-stop rows. It is not a single-step escalation, so their severity is not imported here.

O6 *engineering judgment, no data* **LOW CONFIDENCE** — Stratification is inherent to localized heating of supercritical cryogen in microgravity, and it recurs in every on-orbit heater cycle at low quantity. No test or flight history is provided, so this is set above the floor on physical reasoning alone. note 1

D5 *Detected in flight via telemetry, no automated response* — Onset is in flight. Pressure, heater assembly temperature, fluid temperature and quantity telemetry show the overshoot or collapse signature, but the response is manual (crew or ground). No automated response is stated, and all controls are assumed.

RECOMMENDED ACTION Obtain on-orbit pressure and heater-cycle data from analogous supercritical tanks, and define a low-quantity tank-management and heater duty-limit procedure to bound stratification excursions.

Measure quantity, pressure (two sensors), fluid temperature and heater assembly temperature

Heater-controller tank pressure sensor reports an in-range but falsely HIGH pressure (out-of-spec high indication) to the heater controller

RPN 225 | AP High | CRITICAL | Pending

WHY HERE ◇In paired auto mode a high-pressure signal from either tank turns off BOTH tanks' heaters. A falsely high but in-range reading from this tank's controller sensor therefore inhibits pressurization of its own tank and its paired tank. The reading still looks plausible, so validity checks do not reject it. This single-sensor-to-two-tank coupling exists only because of this tank's paired heater logic and its dedicated controller sensor.

LOCAL EFFECT ◇The controller sees pressure at or above the heater-off setpoint and keeps the heaters off. True tank pressure decays as hydrogen is drawn off.

NEXT-LEVEL EFFECT ◇Heaters on both tanks of the pair stay inhibited. Supply pressure from both hydrogen tanks falls below the 200 psia lower supply band. The fuel cells must draw from other tank sets unless the crew switches heaters to manual on.

END EFFECT ◇**The paired hydrogen tanks are lost as usable reactant sources. Fuel cells keep running on the remaining tank sets, so the mission continues with reduced reactant redundancy (loss of redundancy on a critical function).**

CAUSES / MECHANISMS

- **Zero or span drift high in the pressure transducer from repeated cryogenic thermal cycling at each fill over the reuse life. Transducer type and mounting temperature are not stated (assumed).** ◇ — Each launch attempt chills the tank to about -420 °F and the tank is reused for up to 100 missions. Accumulated thermal-cycle shift of the sensing element is a known drift mechanism for strain-gauge transducers (assumed type). (sensor instrumentation)
- **Intermittent connector or harness fault (shorted or open signal or excitation) that drives the reading toward full scale. The fail direction depends on transducer and controller design, which are not stated.** ◇ — The harness sees launch vibration, entry and landing loads, and turnaround handling in the midfuselage. Fretting or pin back-out can cause an intermittent full-scale indication. (electrical open short drift)
- **EMI or switching transient coupled onto the sensor signal line from heater power switching or orbiter bus transients, producing a spurious high trip in the controller (assumed harness routing).** ◇ — Heater power comes from orbiter buses through the same controller that reads this sensor. A transient at heater cycling can momentarily exceed the off setpoint if the line is not filtered. (environment vibration shock emi)

PREVENTION CONTROLS

- Pressure transducer qualified for cryogenic thermal cycling over the 100-mission certified life (assumed) (qualification) ◇
- Crew heater switch override (auto/on/off) allows manual heater control independent of the controller pressure sensor (design feature) ◇
- Shielded, filtered sensor signal lines separated from heater power wiring (assumed standard practice) (design feature) ◇

DETECTION CONTROLS

- Caution and warning on low tank pressure below 153 psia (telemetry monitor · every unit · observes: True tank pressure on the independent sensor falls below 153 psia on both paired tanks while the heaters remain off) credited for D ◇
- Telemetry comparison of this tank's two pressure sensors, plus heater state (telemetry monitor · every unit · observes: Controller sensor reads at or above the heater-off band while the second sensor reads lower and falling; heaters off on both tanks of the pair) credited for D ◇
- Pre-flight pressure sensor calibration and functional check against a ground reference during turnaround (functional test · every unit · observes: Zero or span offset versus reference gauge at ambient and fill pressure) ◇

SCORING

S9 ◆ *Loss of vehicle, no public risk; or loss of crew (crewed vehicle)* — End effect: loss of the paired hydrogen tanks as usable sources while other tank sets keep the fuel cells powered. This is loss of redundancy on a critical function with no direct crew hazard. Ascent and entry are worst-case because tanks 1 and 2 supply then. The engineer should raise to S7 or S8 if the flight's tank-set count leaves no margin without this pair. [Pass 7: A paired-mode false-high inhibits both paired tanks' heaters. On a stated two-tank-set flight those are all the hydrogen tanks, so all three fuel cells are starved: loss of power with the crew aboard. Manual heater override is a response and is not credited in severity.]

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — No test or flight history provided. The transducer is reused over a 100-mission life with a cryogenic chilldown each fill, and paired logic lets any high excursion act on two tanks. Scored one row above the design floor. Assumption; engineer to calibrate from analogous program sensor-drift data.

D5 ◇ *Detected in flight via telemetry, no automated response* — Onset can occur in flight, so ground calibration (control 2) earns no credit for in-flight drift or intermittency. The independent second pressure sensor and the low-pressure caution and warning (controls 0 and 1) reveal the true decaying pressure in telemetry. The response is manual crew heater switching; no automated reversion is stated.

RECOMMENDED ACTION ◇Confirm transducer fail direction. Evaluate adding a cross-check against the second pressure sensor before a single high signal inhibits both paired tanks' heaters.

Heater-controller tank pressure sensor reports an in-range but falsely LOW pressure (or reads zero), so heaters are not commanded off

RPN 175 | AP High | Pending

WHY HERE ◇The heaters turn off only when this tank's controller sensor reaches the 220 to 226 or 237 to 243 psia off band. A falsely low reading keeps the heaters on, and true pressure climbs toward the 310 psia relief setting. At about -420 °F, any air or moisture admitted at the fill or vent quick disconnects freezes solid, so a frozen plug can isolate the sensing port at a stale low pressure. This mechanism depends on this tank's cryogenic hydrogen service and ground-fill interface.

LOCAL EFFECT ◇Heaters remain energized past the off setpoint, and tank pressure and heater assembly temperature rise.

NEXT-LEVEL EFFECT ◇Tank pressure exceeds the 293.8 psia caution and warning limit and reaches the 310 psia relief setting. The relief valve vents hydrogen through the relief port; port discharge location is not stated (assumed overboard). If the relief valve also failed, the tank would see overpressure, but that is a separate relief-function row requiring a second failure.

END EFFECT ◇**This tank's hydrogen is lost through relief venting, which loses its tank set. Remaining tank sets keep the fuel cells powered, with reduced reactant redundancy.**

CAUSES / MECHANISMS

- **Frozen contaminant (air or moisture admitted at the fill or vent quick disconnect during ground servicing) plugs the pressure sensing port or line at hydrogen temperature. This isolates the sensor at a lower pressure.** ◇ — Ground fill and vent pass through quick disconnects each launch attempt. Everything except helium freezes at about -420 °F, so any ingress becomes a solid plug in small sensing passages. (contamination fod)
- **Open circuit in the signal line (connector pin back-out or broken wire from vibration or handling), read by the controller as low or zero pressure. Fail direction is not stated (assumed).** ◇ — The harness sees launch vibration and acoustics, entry and landing loads, and turnaround handling. An open signal commonly reads at the bottom of range. (electrical open short drift)
- **Transducer zero or span drift low from cryogenic thermal cycling over the reuse life (transducer type not stated).** ◇ — One cryogenic chilldown per fill, repeated up to the 100-mission certified life, accumulates zero shift in the sensing element. (sensor instrumentation)

PREVENTION CONTROLS

- Quick disconnect caps for flight and purge procedures at fill and vent connections to exclude air and moisture (assumed) (cleanliness or handling)
- Tank relief valve set at 310 psia limits overpressure if heaters stay on (design feature)
- Crew heater switch to off overrides automatic control (design feature)

DETECTION CONTROLS

- Caution and warning on tank pressure above 293.8 psia, from the second (non-controller) pressure sensor; routing assumed (telemetry monitor · every unit · observes: Second sensor pressure exceeds 293.8 psia while the controller sensor reads within or below the heater band) credited for D
- Heater assembly temperature telemetry (telemetry monitor · every unit · observes: Heater assembly temperature rising continuously with heaters never cycling off) credited for D
- Pre-flight pressure sensor calibration and functional check during turnaround (functional test · every unit · observes: Offset versus ground reference; sluggish or no response to pressurization indicates a blocked port)

SCORING

S7 *Mission-critical degradation; payload to off-nominal orbit needing mitigation* — Direct end effect is relief venting of this tank's hydrogen and loss of its tank set, with other sets still feeding the fuel cells: loss of redundancy on a critical function. Escalation to overpressure needs an independent relief valve failure (separate row), so catastrophic severity is not imported. If the relief port discharges into the midfuselage rather than overboard, re-score to S9 because the crew would be exposed. [Pass 7: The stated end effect, relief venting and loss of the tank set, is scored S7 in every other row including Heaters fail to switch off at the upper setp... (same physics). S6 understates it.]

O5 *engineering judgment, no data* LOW CONFIDENCE — No test or flight history provided. A fill through ground quick disconnects every launch attempt plus 100-mission reuse with cryogenic cycling gives several credible paths to a low reading. Scored one row above the design floor. Assumption; engineer to calibrate from analogous program data.

D5 *Detected in flight via telemetry, no automated response* — A frozen plug or open can occur after the pre-flight check, so control 2 earns no in-flight credit. The independent second pressure sensor's high caution and warning and the heater assembly temperature telemetry (controls 0 and 1) show the rising true pressure. Crew response is manual, with no automated safing stated. If caution and warning is driven by the same faulty sensor, D rises to 8.

RECOMMENDED ACTION Confirm which sensor drives the 293.8 psia caution and warning, the controller sensor's open-circuit fail direction, and the relief port discharge location.

Capacitance quantity probe indicates hydrogen quantity out of spec (plausible in-range over-reading) through the mission

RPN 175 AP High Pending

WHY HERE The quantity probe is capacitance type and senses the dielectric of single-phase supercritical hydrogen. Hydrogen's dielectric constant is close to that of vacuum, so the useful capacitance change is small (general physics; no source claim cited). Stray or lead capacitance shifts and local density non-uniformity therefore produce a proportionally large error. This would not hold for a denser, higher-permittivity reactant or a different gauging principle.

LOCAL EFFECT Indicated quantity exceeds the true hydrogen remaining in this tank.

NEXT-LEVEL EFFECT Reactant budgeting for the 92 lb load overstates remaining hydrogen, and tank depletion arrives earlier than planned. The pressure can no longer be held by the heaters near depletion.

END EFFECT **Unplanned hydrogen shortfall forces mitigation such as early mission termination or curtailed operations to protect entry reactant reserves (mission-critical degradation).**

CAUSES / MECHANISMS

- **Drift in lead, connector or stray capacitance (cable flexing at handling, moisture at the connector, cryogenic contraction of the electrode mounting) shifts the zero, which is a large fraction of the small hydrogen signal.** — The low dielectric contrast of hydrogen makes the probe sensitive to small stray-capacitance changes, and the tank is chilled and handled every flow across 100 missions. (sensor instrumentation)
- **Thermal and density stratification of supercritical hydrogen around the probe during heater cycling in low gravity, so the probe senses local rather than mean density.** — Heaters cycle on pressure while there is no buoyant mixing on orbit, so fluid near the heater probe and quantity probe can differ in density from the bulk. (fluid dynamic)
- **Electrode gap change from launch vibration loading or differential contraction between the probe and the aluminum 2219 inner vessel mounting.** — The probe spans the 41.51 in vessel at about -420 °F, and a small gap change alters cell capacitance directly. (thermal contraction expansion)

PREVENTION CONTROLS

- Probe calibration on hydrogen density across the operating pressure and temperature range at acceptance (assumed) (qualification)
- Reactant budgeting margin held in mission planning for gauging uncertainty (assumed) (margin or derating)

DETECTION CONTROLS

- Ground cross-check of probe quantity against density computed from tank pressure and fluid temperature via the hydrogen equation of state (telemetry monitor · every unit · observes: Divergence between probe-indicated mass and pressure-temperature-derived mass) credited for D
- Reactant consumption reconciliation from integrated fuel cell current versus indicated quantity drop (telemetry monitor · every unit · observes: Indicated quantity decreasing slower than consumption computed from fuel cell current) credited for D
- Load reconciliation at fill: indicated quantity versus ground-delivered quantity (functional test · every unit · observes: Indicated load differs from expected full load)

SCORING

S7 *Mission-critical degradation; payload to off-nominal orbit needing mitigation* — End effect is a reactant shortfall requiring mitigation (early termination or curtailed operations), not direct loss of vehicle or crew, since entry tanks 1 and 2 and other tank sets remain. The engineer should raise to S8 for extended-duration flights where the shortfall ends the mission objectives.

O5 *engineering judgment, no data* LOW CONFIDENCE — No test or flight history provided. Low dielectric contrast plus low-gravity stratification make offsets credible on every flight. Scored above the design floor. Assumption; engineer to calibrate from analogous program gauging data.

D5 *Detected in flight via telemetry, no automated response* — Error can develop in flight with stratification or drift, so the fill reconciliation (control 2) cannot cover onset after loading. The pressure and fluid temperature sensors on this tank give an independent density estimate, and fuel cell current gives consumption (controls 0 and 1). Both are seen in telemetry with ground analysis; no automated response exists.

RECOMMENDED ACTION Define a documented pressure-temperature density cross-check with a flight-rule disagreement tolerance, and characterize probe error versus fill level and stratification.

Supply hydrogen to the manifold and three fuel cells

Supply flow to the manifold is restricted or blocked (partial supply) by solid contaminants carried out of the tank. ◇

RPN 280 · AP High · PROVISIONAL: NO DATA · Pending

WHY HERE ◇At about -420 °F, water, nitrogen, oxygen and CO2 are all solid. Any air or moisture admitted through the fill and vent quick disconnects during per-launch-attempt servicing becomes particulate in the hydrogen. That particulate can migrate to the tank outlet and the 12-micron filter package on the supply line. A warm-gas tank would carry these as gases and not suffer this restriction.

LOCAL EFFECT ◇Frozen and particulate contaminants collect at the tank outlet and the 12-micron filter package, raising pressure drop on this tank's supply line.

NEXT-LEVEL EFFECT ◇Hydrogen delivery from this tank falls below fuel cell demand, and inlet pressure to the fuel cells it feeds drops. The crew must isolate the line and feed from other tank sets through the manifold.

END EFFECT ◇**Loss of usable supply from this tank and its tank set, so the mission is shortened. Separately, solidified oxygen carried into hydrogen is a potential reactivity hazard; the engineer should evaluate it as its own row.**

CAUSES / MECHANISMS

- **Air or moisture enters through the fill or vent quick disconnects during ground-equipment connect/disconnect or cap removal, when purge is inadequate.** ◇ — The quick disconnects are broken and re-sealed every launch attempt. The fill pressure is 300 to 320 psia, and caps seal the quick disconnects for flight. (contamination fod)
- **Ground-supply hydrogen carries impurities (nitrogen, oxygen, moisture) above specification and loads them into the tank.** ◇ — Every fill passes ground-equipment hydrogen directly into the inner vessel. (contamination fod)
- **Manufacturing debris (weld spatter, chips) is retained in the 2219 inner vessel, or particles shed from internal probes. Launch and ascent vibration liberates them.** ◇ — The inner vessel holds heater and quantity probes of unstated materials and sees launch vibration and acoustics. (manufacturing defect)

PREVENTION CONTROLS

- Ground hydrogen purity specification and sampling before fill (process control) ◇
- Quick-disconnect purge, cap handling and connect procedures (procedure or training) ◇
- Precision cleaning of the inner vessel and probes at build (cleanliness or handling) ◇

DETECTION CONTROLS

- Quantity and tank pressure telemetry, compared across tank sets (telemetry monitor · every unit · observes: This tank's quantity falling more slowly than demand while pressure holds in band) credited for D ◇
- Ground hydrogen sample analysis before fill (functional test · sample · observes: Impurity concentration above limit) ◇
- Visual inspection of quick-disconnect and cap seals before connect (visual · every unit · observes: Seal damage or debris at the quick-disconnect face) ◇

SCORING

S7 ◇ *Mission-critical degradation; payload to off-nominal orbit needing mitigation* — End effect is loss of this tank set's supply. The other sets carry all three fuel cells, but the mission is shortened. The oxygen-in-hydrogen reactivity hazard is not scored here and should be its own row.

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — No test history provided; assumption, engineer to calibrate from analogous program data. Quick disconnects are broken every launch attempt, and any admitted air freezes, so the score is set one row above the design floor.

D8 ◇ *Operational anomaly evident only via downstream effects* — No pressure-drop or flow measurement exists inside this tank boundary. A restriction shows up only as a downstream effect: this tank depleting more slowly than demand, or fuel cell inlet pressure falling. Ground sampling cannot catch ingress at the quick disconnects after sampling.

RECOMMENDED ACTION ◇Define ground hydrogen purity and quick-disconnect purge acceptance limits, add supply-line filter pressure-drop or flow trending, and assess the hazard of solidified oxygen in hydrogen.

Relieve tank overpressure through the relief valve and relief port

Tank relief valve fails to open (relief function lost on demand) when tank pressure exceeds the 310 psia relief setting ◇

RPN 225 · AP High · CRITICAL · Pending

WHY HERE ◇This tank's relief valve sits in the supply line wetted by hydrogen at about -420 °F. At that temperature any air, nitrogen or moisture admitted at the fill and vent quick disconnects during ground servicing freezes solid. The input lists the relief valve ahead of the 12-micron filter package, which is our reading of the line order and an assumption, so solids can reach the poppet and guide. The relief valve is the only overpressure barrier inside this tank's boundary. Heater cut-off logic, which could latch the heaters on, sits in the out-of-scope controller. The failure is latent until a demand occurs.

LOCAL EFFECT ◇Poppet stays seated or lifts only above the 310 psia setting while tank pressure keeps rising.

NEXT-LEVEL EFFECT ◇If a demand condition coincides (heater latched on through the controller, outflow blocked downstream, or heat leak raised by loss of annulus vacuum), pressure climbs through the 293.8 psia caution limit and past 310 psia. The only remaining barriers are the paired-auto high-pressure heater cut-off and crew heater-off action.

END EFFECT ◇**Overpressure rupture of the 2219 aluminum inner vessel in the midfuselage under the payload bay liner. This destroys the orbiter structure and adjacent tank sets, causing loss of vehicle and crew.**

CAUSES / MECHANISMS

- **Frozen air, nitrogen or water ice from incomplete purge of the fill and vent quick disconnects or ground lines carries into the relief valve poppet and guide and locks it at -420 °F** ◇ — Hydrogen at this temperature solidifies every other servicing contaminant except helium. The ground fill path through the quick disconnects is the ingress route each launch attempt. (contamination fod)
- **Poppet-to-guide clearance closes from differential thermal contraction between poppet, guide and body materials (not stated) at hydrogen temperature, binding the poppet** ◇ — Valve materials are not stated. Mismatched contraction from ambient to about -420 °F is a known binding mechanism for cryogenic poppet valves. (thermal contraction expansion)
- **Galling or cold-welding of poppet guide surfaces after repeated lifts during ground fill (fill supply 300–320 psia straddles the 310 psia setting) across up to 100 missions** ◇ — The fill supply pressure overlaps the relief setting, so the valve may cycle at each fill. Clean hydrogen gives little lubrication. (wear galling fretting)
- **Crack pressure set high or setpoint shim and spring mis-assembled during turnaround rework or replacement** ◇ — Reuse over 100 missions with turnaround implies valve removal and rework opportunities. (assembly installation error)

PREVENTION CONTROLS

- Helium purge and evacuation of fill and vent quick disconnects and ground lines before hydrogen flow; cap the quick disconnects after servicing (cleanliness or handling)
- Poppet, guide and body materials and clearances selected for matched contraction and anti-galling at hydrogen temperature (material selection)
- Relief valve setpoint verification and torque/assembly procedure on any rework (procedure or training)

DETECTION CONTROLS

- Tank pressure telemetry with caution and warning above 293.8 psia, displayed to crew (telemetry monitor · every unit · observes: Tank pressure exceeding 293.8 psia and continuing to rise through 310 psia without a relief plateau) credited for D
- Relief valve crack and reseat functional test each turnaround (functional test · every unit · observes: Crack pressure outside the 310 psia setting tolerance or no lift)

SCORING

S9 *Loss of vehicle, no public risk; or loss of crew (crewed vehicle)* — End effect is inner-vessel rupture in the crewed midfuselage, i.e. loss of vehicle and crew exposed to it. S10 is not assigned because the input states no public-exposure debris case. The engineer should check the ascent-phase debris footprint before confirming.

O5 *engineering judgment, no data* LOW CONFIDENCE — Engineering judgment. The cause is driven by contaminant freezing and fill-cycle lifting, and each launch attempt presents a new fill with quick-disconnect contamination opportunity. No test history or valve data is provided. This is an assumption; the engineer should calibrate from analogous program data.

D5 *Detected in flight via telemetry, no automated response* — Ice from the current fill can form after any ground check, so the turnaround functional test cannot claim better than ground detection. In flight, pressure telemetry with the 293.8 psia caution alarm shows the failure (pressure passing 310 psia with no plateau). Crew heater-off is a manual response, and no automated relief backup within this item is credited. All controls are assumed.

RECOMMENDED ACTION Obtain relief valve qualification and acceptance records, confirm valve position relative to the 12-micron filter, and add a pre-fill helium purge-verification step with a post-fill relief crack check.

Partial relief: valve lifts but relief valve or relief port flow capacity is insufficient, so tank pressure overshoots well above 310 psia

RPN 180 AP High CRITICAL Pending

WHY HERE The relief port discharges hydrogen at about -420 °F. During pad fill and standby, ambient humidity can freeze at a chilled port exit, and the input's 300–320 psia fill supply can lift the 310 psia valve during servicing. Relief capacity must also cover a heater element latched on together with the much higher heat leak that follows loss of annulus vacuum. Design, proof and burst pressures are not stated, so the margin between overshoot and rupture cannot be established from the input.

LOCAL EFFECT Relief flow through the valve and port falls below the pressure-rise rate. Tank pressure keeps rising after crack.

NEXT-LEVEL EFFECT Sustained pressure above the 293.8 psia caution limit and above 310 psia. Recovery depends on crew or paired-auto heater cut-off and increased draw-off.

END EFFECT **If the overshoot reaches inner-vessel burst (burst pressure not stated), the vessel ruptures in the midfuselage with loss of vehicle and crew.**

CAUSES / MECHANISMS

- **Atmospheric moisture freezing at the relief port exit chilled by cold hydrogen discharge during pad fill and standby, partially blocking the port** — The fill supply overlaps the relief setting, so the port can flow cold hydrogen on the pad where humid air is present. (contamination fod)
- **Relief port protective cover or plug left installed after servicing or turnaround** — Reuse and repeated ground servicing create closeout-error opportunities. A port cover is assumed, not stated. (assembly installation error)
- **Relief valve and port sized for nominal heat leak but not for heater element on at full power combined with degraded annulus vacuum and higher heat leak** — The input states no relief sizing case. Vacuum loss and heater failed-on are credible simultaneous inputs to this tank's pressure rise. (fluid dynamic)

PREVENTION CONTROLS

- Relief sizing analysis covering heater failed-on with loss of annulus vacuum (margin or derating)
- Closeout checklist verifying relief port cover removed and port clear before flight (procedure or training)

DETECTION CONTROLS

- Tank pressure telemetry with caution and warning above 293.8 psia (telemetry monitor · every unit · observes: Pressure rising above 310 psia with only a reduced rate after crack instead of a plateau) credited for D
- Closeout visual of relief port before flight (visual · every unit · observes: Cover installed, ice or debris in port)

SCORING

S9 *Loss of vehicle, no public risk; or loss of crew (crewed vehicle)* — Burst and proof pressures are not stated, so overshoot cannot be credited as staying below burst. Overpressure above relief is single-step physics toward rupture in the crewed midfuselage. The engineer may lower this only if a relief capacity analysis shows peak pressure below proof.

O4 *no data (floor)* LOW CONFIDENCE — No data. This is the design FMEA floor, applied because nothing in the input supports either a lower or higher number. Engineer to calibrate.

D5 *Detected in flight via telemetry, no automated response* — Port icing can form after the closeout visual, so the visual check cannot claim more. In-flight pressure telemetry shows the overshoot past 310 psia, but the response is crew action with no automated relief backup. Controls are assumed.

RECOMMENDED ACTION Request the relief sizing analysis (heater failed-on plus vacuum loss) and the vessel proof/burst pressures to bound overshoot margin.

Unintended relief: valve cracks below setting or fails to reseat, venting hydrogen continuously through the relief port

RPN 175 AP High Pending

WHY HERE The ground fill supply (300–320 psia) straddles this valve's 310 psia setting, so the valve can lift at each fill. It must then reseat at about -420 °F, where seat materials (not stated; a soft polymer seat is assumed) contract and stiffen. Particulate in the cold hydrogen ahead of the 12-micron filter reaches the seat. Repeated over up to 100 missions, this makes seat leakage specific to this valve's duty.

LOCAL EFFECT Hydrogen flows overboard through the relief port with the valve partly open or leaking at the seat.

NEXT-LEVEL EFFECT Tank pressure decays and heater duty rises. Quantity depletes faster than fuel-cell draw, and this tank set's hydrogen is lost early. Remaining tank sets can still supply all three fuel cells.

END EFFECT **Reduced reactant margin forcing early mission termination. This assumes the relief port discharges overboard; if it discharges inside the midfuselage, hydrogen accumulation endangers the crew and severity must be raised to S9.**

CAUSES / MECHANISMS

- **Particulate from ground fill or quick disconnects embedded in the seat during a fill-time lift, holding the valve off-seat** ◇ — The fill supply above the setting lifts the valve while servicing flow carries debris. (contamination fod)
- **Cold-flow and permanent imprint of the seat after repeated thermal cycles and lifts over reuse, losing seal contact at hydrogen temperature** ◇ — 100-mission certification with a fill per launch attempt accumulates seat loading cycles. (creep relaxation coldflow)
- **Spring relaxation lowering crack pressure toward the 243 psia top of the supply band** ◇ — The margin between the operating band and the 310 psia setting is the only buffer. Qualified spring life is not stated. (creep relaxation coldflow)
- **Chatter during fill-time lifts near 310 psia wearing seat and poppet** ◇ — Fill supply hovering at the setting promotes unstable lift. (wear galling fretting)

PREVENTION CONTROLS

- Fill procedure holding servicing pressure below relief crack to avoid lifting during fill (procedure or training) ◇
- Seat material and spring qualified for cryogenic cycling over the certified mission life (qualification) ◇

DETECTION CONTROLS

- Quantity and pressure telemetry compared against fuel-cell consumption (telemetry monitor · every unit · observes: Quantity loss exceeding fuel-cell draw, pressure decay, increased heater on-time) credited for D ◇
- Relief valve seat leak test at operating pressure each turnaround (leak test · every unit · observes: Seat leakage above acceptance limit) ◇

SCORING

S7 ◇ *Mission-critical degradation; payload to off-nominal orbit needing mitigation* — Loss of one tank set's hydrogen degrades the mission and forces early termination. Other sets keep the fuel cells supplied, so this is not loss of crew, provided overboard discharge is confirmed. If the relief port vents inside the midfuselage, this becomes S9.

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — Engineering judgment. The fill-time lift opportunity exists every launch attempt because the fill supply straddles the setting, and seat or spring degradation accumulates with reuse. No qualified life or test history is provided; engineer to calibrate.

D5 ◇ *Detected in flight via telemetry, no automated response* — A seat can be held off by debris at the current fill, after the turnaround leak test. In flight, quantity-versus-consumption telemetry reveals the leak, but crew must respond manually. Controls are assumed.

RECOMMENDED ACTION ◇Confirm relief port discharge routing (overboard vs. midfuselage) and fill pressure limit relative to the 310 psia crack setting.

Accept ground fill and vent through quick disconnects, sealed by caps for flight

Fill or vent quick disconnect fails to stay sealed for flight: hydrogen leaks externally past the QD poppet seat and its flight cap into the midfuselage ◇

RPN 360 · AP High · CRITICAL · Pending

WHY HERE ◇The fill and vent QDs are opened by ground equipment on every launch attempt at about -420 °F hydrogen. For flight they must reseal against tank pressure up to the 310 psia relief setpoint inside the closed midfuselage under the payload bay liner. The mission context states that a hydrogen leak there can damage the orbiter and endanger the crew. A leak that would be benign on an open stand, or with an inert fluid, is a crew hazard on this tank. QD and cap seal materials are not stated, so the specific seal behavior is an assumption.

LOCAL EFFECT ◇Hydrogen escapes past the QD poppet seat and the cap seal (or an absent or loose cap) at the tank's fill or vent port.

NEXT-LEVEL EFFECT ◇Hydrogen accumulates in the midfuselage under the payload bay liner. Heaters cycle to hold pressure, which masks small leaks while depleting this tank faster than fuel cell demand. A large leak loses this tank's hydrogen and with it the tank set.

END EFFECT ◇**Flammable hydrogen accumulates in the crew-occupied vehicle's midfuselage. Ignition causes orbiter damage and possible loss of crew and vehicle. In a less severe, non-igniting case, the tank set is lost and the mission ends early.**

CAUSES / MECHANISMS

- **Frozen air or moisture, or particulate from the ground coupling, lodges on the poppet seat at disconnect and holds the poppet off its seat. This occurs if the QD cavity is not purged before chill-in or disconnect.** ◇ — At -420 °F, air and water entering the QD cavity freeze solid. The QD is connected and disconnected on every fill. (contamination fod)
- **Differential contraction between the QD body and the poppet seat or cap seal at cryogenic chill reduces seal squeeze. Seal material is not stated; a polymeric seal is assumed.** ◇ — The seal sees ambient-to-cryogenic thermal cycling on each fill and warm-up across the turnaround and reuse life. (thermal contraction expansion)
- **The flight cap is omitted, cross-threaded or under-torqued, or the cap seal is missing or damaged at closeout. This removes the second barrier.** ◇ — Caps are removed and reinstalled on every servicing flow by ground crews. (assembly installation error)
- **Launch and ascent vibration and acoustics back off an under-preloaded cap or chatter a marginally seated poppet.** ◇ — The QDs fly through ascent vibroacoustics. Levels are not stated. (environment vibration shock emi)
- **Wear or scoring of the poppet seat and seal from repeated ground-coupling connect and disconnect cycles accumulates over the 100-mission certified life.** ◇ — Every launch attempt adds a connect and disconnect cycle, including scrubs. The tank is reused. (wear galling fretting)

PREVENTION CONTROLS

- Dual barrier: the QD poppet is backed by a sealed flight cap on both the fill and vent ports. (design feature) ◇
- Helium or inert purge of the QD cavity before ground-coupling connect and after disconnect, with protective covers to exclude moisture and FOD. (cleanliness or handling) ◇
- Witnessed cap installation with specified torque and seal inspection or replacement at each closeout. (procedure or training) ◇

DETECTION CONTROLS

- In-flight monitoring of tank quantity and pressure via telemetry and caution and warning (low limit 153 psia); quantity depletion compared against fuel cell consumption. (telemetry monitor · every unit · observes: Quantity decreasing faster than predicted fuel cell draw; increased heater duty; pressure decay toward the 153 psia caution limit for large leaks) credited for D ◇
- Leak check of each QD and installed cap after ground-coupling disconnect at closeout. (leak test · every unit · observes: Hydrogen or helium detected at the cap or QD interface above the allowable leak rate) ◇

SCORING

S9 ◇ *Loss of vehicle, no public risk; or loss of crew (crewed vehicle)* — The crew is aboard and exposed in flight. The mission context states that a hydrogen leak in the midfuselage can endanger the crew, so the worst credible end effect is loss of crew. No credit is taken for controls. Ignition requires an ignition source, so the engineer should confirm with midfuselage purge and ventilation analysis whether S8 (tank-set loss, early mission end) is the bounded case.

O5 ◇ *engineering judgment, no data* **LOW CONFIDENCE** — Several independent causes act on this mode. The seal is opened and reclosed by ground equipment on every launch attempt, at cryogenic temperature, with human cap closeout, and it accumulates wear over the 100-mission reuse life. The dual barrier reduces the chance of a through-leak. No test history or seal data was provided; this is an assumption, and the engineer should calibrate it from analogous cryogenic QD program data.

D8 ◆ *Operational anomaly evident only via downstream effects* — Leak onset can occur after closeout (ascent vibration, thermal contraction on orbit), so the ground leak check cannot claim D5 or better. Credit goes to in-flight quantity and pressure telemetry, which shows a significant leak as excess depletion with no automated response. Small leaks may stay below quantity-probe resolution and be masked by heater cycling, so D may be worse. Midfuselage hydrogen detection is not stated in the input. [Pass 7: Leak rates sufficient for flammable midfuselage accumulation can fall below quantity/pressure telemetry resolution, as the justification admits. No hydrogen detection is stated in the input, so the hazard is seen only via downstream effects.]

RECOMMENDED ACTION ◇Obtain QD poppet and cap seal materials, cryogenic leak-rate qualification and seal-life data for the 100-mission reuse life. Confirm whether midfuselage hydrogen detection or purge exists to bound accumulation, and add a post-disconnect cap leak check at closeout.

Fill quick disconnect fails to pass, or restricts, fill flow during pad servicing, leaving the tank short of its 92 lb load when filling stops ◇

RPN 150 | AP Medium | Pending

WHY HERE ◇Fill uses a ground-coupled QD at a 300 to 320 psia supply into a tank at about -420 °F. Filling is time-boxed (up to 45 min) and must stop 2 min 35 s before launch. A poppet held shut, a mis-engaged coupling or a frozen-contaminant blockage at the cryogenic QD directly prevents reaching the stated load in that window. Without a time-boxed cryogenic fill through a QD, this mode would not exist.

LOCAL EFFECT ◇Little or no hydrogen flow passes through the fill QD into the inner vessel.

NEXT-LEVEL EFFECT ◇The tank does not reach about 92 lb before fill termination, so this tank set's reactant margin for the mission is short.

END EFFECT ◇**Launch scrub or hold to troubleshoot or re-service the fill interface, with significant turnaround impact.**

CAUSES / MECHANISMS

- **Ground-coupling half mis-engaged or not fully actuated, so the flight-half poppet is not depressed open.** ◇ — The coupling is mated manually or remotely at each fill. (assembly installation error)
- **Air or moisture trapped in the QD cavity freezes on chill-in, blocking the poppet or flow passage.** ◇ — Atmospheric constituents freeze at the -420 °F hydrogen temperature if the QD cavity is not purged. (contamination fod)
- **Poppet stem binds in its guide from galling or debris after repeated cycles over reuse.** ◇ — The QD is cycled every launch attempt across the 100-mission life. Materials are not stated. (wear galling fretting)

PREVENTION CONTROLS

- Pre-chill purge of the fill QD cavity with inert gas before hydrogen flow. (cleanliness or handling) ◇
- Coupling engagement verification step (indicator or witnessed latch) in the servicing procedure. (procedure or training) ◇

DETECTION CONTROLS

- Monitoring of tank quantity and pressure rise against fill-line supply pressure during loading. (in process parameter monitor · every unit · observes: Quantity not rising, or rising slower than the fill profile, while supply pressure is held at 300 to 320 psia) credited for D ◇
- Functional connect-and-flow check of the fill QD with ground equipment during turnaround. (functional test · every unit · observes: Low or no flow through the mated QD at check pressure) credited for D ◇

SCORING

S5 ◇ *Test or launch scrub; significant turnaround impact* — The failure manifests during pad servicing before launch. The worst credible end effect is a launch scrub with turnaround impact, because filling must complete before the 2 min 35 s cutoff. A launch with an undetected underfill depends on a quantity-probe failure, which belongs to the measurement function's row.

O5 ◇ *engineering judgment, no data* **LOW CONFIDENCE** — The QD is mated and chilled on every launch attempt, so purge, engagement and stem-wear causes all have a per-mission opportunity. No servicing history was provided; this is an assumption, and the engineer should calibrate it from pad servicing records.

D6 ◇ *Detected during normal ground-processing acceptance test* — Onset is during ground servicing, before launch, so a ground check is valid for this mode. The tank's own quantity and pressure readings during loading show the absence of fill directly and at full scale. The turnaround flow check catches stem bind before the pad. There is no automatic response.

RECOMMENDED ACTION ◇Define fill-rate acceptance limits and a coupling-engagement verification in the servicing procedure, and obtain QD stem-bind and purge-effectiveness data from servicing history.

Vent quick disconnect fails to pass vent flow during fill, standby or post-landing offload, so tank pressure rises toward the relief setpoint and the tank cannot be vented or detanked through the ground path ◇

RPN 150 | AP Medium | Pending

WHY HERE ◇The ground fill supply of 300 to 320 psia overlaps this tank's 310 psia relief setpoint. During fill, the vent QD is therefore the path that keeps the tank below relief. If it blocks, the fill supply alone can drive the tank onto its relief valve. The same QD is the path for offload after landing (assumed). A tank whose fill supply sat well below its relief setting would not have this interaction.

LOCAL EFFECT ◇Vent flow through the vent QD is blocked or restricted.

NEXT-LEVEL EFFECT ◇Tank pressure climbs during fill or standby above the 293.8 psia caution limit toward the 310 psia relief. The tank relief valve lifts and vents hydrogen through the relief port, or fill is halted. Post-landing offload cannot proceed through the ground vent path. Escalation to overpressure rupture requires an additional relief valve failure and is captured under the relief function.

END EFFECT ◇**Fill terminated and launch scrubbed, with significant turnaround impact. Post-landing safing is delayed.**

CAUSES / MECHANISMS

- **Air or moisture frozen in the vent QD cavity or passage at cryogenic temperature blocks flow.** ◇ — Vent gas leaving the tank is at hydrogen temperature, cold enough to freeze any air or water present. (contamination fod)
- **Vent ground-coupling half not fully engaged, so the vent poppet stays closed.** ◇ — Mating of the vent coupling is a manual step at each servicing. (assembly installation error)
- **Vent poppet stem galls or binds after repeated cycles over reuse.** ◇ — The QD is cycled every launch attempt across the 100-mission life. Materials are not stated. (wear galling fretting)

PREVENTION CONTROLS

- Inert purge of the vent QD and line before chill-in. (cleanliness or handling) ◇
- Tank relief valve set at 310 psia limits pressure if the vent path blocks. This is a separate in-scope function and is credited only as a mitigation, not for detection. (design feature) ◇

DETECTION CONTROLS

- Tank pressure monitoring during fill and standby via telemetry and the 293.8 psia high caution limit. (telemetry monitor · every unit · observes: Tank pressure rising above the expected fill profile toward 293.8 psia with low vent flow) credited for D ◇
- Vent-line flow or pressure at the ground equipment during servicing. (in process parameter monitor · every unit · observes: No or low vent flow while tank pressure rises) credited for D ◇

SCORING

S5 ◇ *Test or launch scrub; significant turnaround impact* — The direct end effect occurs on the ground: fill is stopped and launch is scrubbed. The relief valve venting is a consequence of the blockage, not a separate failure. Rupture requires a second, independent relief valve failure (a distinct row under the relief function), so terminal severity is not imported. No credit is taken for controls.

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — Purge, engagement and stem-bind causes recur at every fill and offload over the 100-mission reuse life. No servicing or test history was provided; this is an assumption, and the engineer should calibrate it from pad data.

D6 ◇ *Detected during normal ground-processing acceptance test* — Onset occurs during ground servicing, offload or standby while the tank is monitored. Tank pressure telemetry and ground vent-flow data directly show the pressure rise caused by the blocked path. Detection relies on operator response, with no automatic action credited.

RECOMMENDED ACTION ◇Confirm ground-equipment fill regulation keeps tank pressure below the 310 psia relief setpoint with a blocked vent, and add an automatic fill-stop on high tank pressure during servicing.

Keep the annulus evacuated with the vac-ion pump, which also reads the vacuum

Annulus vacuum degrades beyond what the vac-ion pump can hold, so the annulus loses its insulating vacuum (partial or total). ◇ RPN 200 AP High PROVISIONAL: NO DATA Pending

WHY HERE ◇The inner vessel holds hydrogen at about -420 °F inside a 2219 aluminum outer shell at ambient midfuselage temperature. At that temperature difference, any gas in the annulus, especially hydrogen leaking from the inner vessel, conducts heat across the gap. That gas also defeats the silverized Kapton MLI and the vapor-cooled shield, which only work in a hard vacuum. The single vac-ion pump has finite capacity against this gas load. The mode would not apply to a warm, single-wall or foam-insulated tank.

LOCAL EFFECT ◇Annulus pressure rises. Gas conduction and loss of MLI effectiveness raise the heat leak into the supercritical hydrogen.

NEXT-LEVEL EFFECT ◇Tank pressure climbs faster than heater control expects. Heaters stay off and pressure rises toward the 310 psia relief setting. High-pressure caution and warning triggers above 293.8 psia, and the relief valve vents hydrogen. Usable quantity is lost faster than the mission plan assumes. If hydrogen leaking into a sealed annulus has no annulus relief path (not stated, assumed unknown), the outer shell can overpressurize. That is a distinct hydrogen-release/rupture mode under the storage function and is not imported here.

END EFFECT ◇**This tank's usable hydrogen is lost early on orbit, which loses its tank set. The mission is shortened or forced to minimum duration on the remaining tank sets (mission-critical degradation, crew not directly exposed).**

CAUSES / MECHANISMS

- **Hydrogen leaks from the inner vessel into the annulus through porosity or a microfissure in a 2219 weld seam. The leak path opens or grows under cryogenic contraction at each fill.** ◇ — Hydrogen at fill pressure (300-320 psia ground supply) on a cryogenically contracted welded aluminum vessel can drive gas through a defect too small to see in a warm leak check. Hydrogen is also a high-conductivity gas once in the annulus. (manufacturing defect)
- **Air or moisture enters through the outer shell seams or penetration seals (pump, sensor and line feedthroughs) during ground processing and turnaround. It is cryopumped onto the cold inner wall and released on warm-up.** ◇ — Over the 100-mission certified life, the penetrations see repeated thermal cycling between cryogenic fill and ambient turnaround. (seal leakage)
- **The silverized Kapton MLI and nylon net spacers outgas absorbed water and residual volatiles, adding gas load beyond pump capacity. This is worst after incomplete bake-out or after exposure to atmosphere during annulus rework.** ◇ — Polyimide and nylon absorb moisture. The MLI blanket has large surface area inside a sealed annulus with only one pump. (contamination fod)
- **A fatigue crack forms at an outer shell penetration or strap attachment, driven by launch/ascent vibration and acoustics plus thermal cycling, and opens an external leak into the annulus.** ◇ — Vibration levels are not stated (assumption). Repeated flights and fills accumulate cycles at stress-concentrating penetrations through the thin outer shell. (fatigue)

MANUFACTURING CHAIN ◇Fusion welding of 2219 inner vessel and outer shell seams (process assumed) → through-thickness porosity or microfissure leak path → leak conductance into the annulus that can open under cryogenic contraction → annulus pressure rises beyond vac-ion pump capacity, gas conduction heat leak to the hydrogen · distributed porosity along all girth/penetration weld seams of both shells, one row covers the population

PREVENTION CONTROLS

- Bake out the annulus and MLI under vacuum before final pinch-off and after any annulus rework. (process control) ◇
- Ground equipment powers the vac-ion pump during servicing so the annulus is pumped through fill and standby. (design feature) ◇
- Apply weld process control and volumetric weld inspection to the 2219 inner vessel and outer shell seams at build. (process control) ◇

DETECTION CONTROLS

- Helium mass-spectrometer leak test of the inner vessel and outer shell at acceptance. (leak test · every unit · observes: helium leak rate into annulus above allowable) ◇
- Read vac-ion pump current (annulus vacuum) during ground servicing, standby and turnaround. (functional test · every unit · observes: pump current rising above the annulus vacuum limit) credited for D ◇
- In-flight telemetry of tank pressure, fluid temperature and quantity, with high-pressure caution and warning above 293.8 psia. (telemetry monitor · every unit · observes: faster pressure rise with heaters off, loss of heater cycling, early approach to 310 psia relief) credited for D ◇

SCORING

S8 ◆ *Loss of mission (payload not delivered), controlled vehicle disposal* — The direct end effect is loss of this tank's usable hydrogen through excess heat leak and relief venting. That loses one tank set and degrades or shortens the mission. Remaining tank sets can feed the fuel cells, so this is not loss of vehicle. Outer-shell overpressure from an internal hydrogen leak is a separate, multi-step escalation and is not imported. Engineer to confirm the relief-port discharge location and whether a minimum two-tank-set flight would make this S8. [Pass 7: Reconciled with merged (removed mode) (S8). The input states two-tank-set flights occur. Early on-orbit loss of one set credibly ends the mission objectives with a crew-safe return, which is S8.]

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — No test history provided. note 1 Rated above the O4 floor because four independent gas sources (weld leak, penetration leak, MLI outgassing, fatigue crack) feed one pump. The tank is also reused across a 100-mission certified life with repeated cryogenic fills and atmosphere exposure in turnaround.

D5 ◇ *Detected in flight via telemetry, no automated response* — Onset can occur in flight, for example a weld leak opening at cryogenic temperature. So the ground pump-current check and the acceptance leak test cannot claim D5 or better for in-flight onset. In-flight tank pressure telemetry and the 293.8 psia caution and warning reveal the heat-leak signature (pressure climbing with heaters off). There is no automated response beyond the passive relief valve, which is not a detection control. The ground pump reading covers pre-launch onset.

RECOMMENDED ACTION ◇Confirm the relief-port discharge location and annulus overpressure protection. Define an in-flight heat-leak trend limit (pressure-rise rate with heaters off) as a crew/ground call for tank-set management.

Erroneous annulus vacuum indication from the vac-ion pump: a plausible in-range reading that is falsely good or falsely bad. ◇

RPN 175 | AP Medium | Pending

WHY HERE ◇On this tank, the vac-ion pump is both the pumping element and the only vacuum gauge, and annulus pressure is inferred from pump current. Any current not produced by gas ionization corrupts the reading. Examples are leakage or field-emission current, or zero current when high voltage is lost. A gas species different from the calibration gas (hydrogen-rich here) also corrupts it. A separately gauged annulus would not have this common-element failure.

LOCAL EFFECT ◇Indicated annulus vacuum does not match actual annulus pressure.

NEXT-LEVEL EFFECT ◇A wrong go/no-go call on annulus condition at servicing or turnaround. A false-bad reading triggers troubleshooting or detank. A false-good reading lets the tank be loaded with a degraded annulus, which requires an actual vacuum loss to matter (escalation to the vacuum-degradation row, not imported).

END EFFECT ◇**An unnecessary scrub, detank or turnaround delay to troubleshoot a healthy annulus (false-bad). Or loss of the ground screen against a degraded annulus (false-good).**

CAUSES / MECHANISMS

- **Leakage or field-emission current across contaminated insulators, or from cathode flakes in the anode cell. The pump reports this as gas current, so the reading is falsely high.** ◇ — Hydrogen-loaded cathode flaking and feedthrough contamination accumulate over reuse, adding non-gas current to the gauge signal. (sensor instrumentation)
- **The HV supply or lead opens, giving near-zero pump current. Without a separate HV readback, this reads as excellent vacuum, so the reading is falsely good.** ◇ — Pump power comes through ground equipment during servicing. A zero-current reading is indistinguishable from hard vacuum unless HV presence is checked. (electrical open short drift)
- **The current-to-pressure scale is calibrated for a different gas than the hydrogen-dominated annulus gas, biasing the indicated pressure (assumed calibration basis).** ◇ — Ion-pump current per unit pressure is gas-species dependent. The annulus gas here is dominated by hydrogen from the inner vessel. Gauge calibration gas is not stated (assumption). (sensor instrumentation)

PREVENTION CONTROLS

- Provide a pump HV voltage readback separate from current, so loss of HV cannot read as good vacuum. (design feature) ◇
- Calibrate the pump current-to-pressure scale for hydrogen-dominated annulus gas. (process control) ◇

DETECTION CONTROLS

- During standby, cross-check the indicated vacuum against tank thermal performance: pressure-rise rate with heaters off versus nominal heat leak. (telemetry monitor · every unit · observes: good indicated vacuum but above-nominal pressure-rise rate (false-good), or bad indicated vacuum with nominal rise rate (false-bad)) credited for D ◇
- Pump functional check at turnaround: HV on/off current response and comparison with an independent temporary gauge on the annulus port. (functional test · every unit · observes: current does not respond to HV switching, or disagrees with the reference gauge) credited for D ◇

SCORING

S5 ◇ *Test or launch scrub; significant turnaround impact* — The worst direct end effect of the indication fault alone is an unnecessary scrub, detank or turnaround troubleshooting of a healthy annulus. A false-good reading is consequential only if an independent actual vacuum loss also occurs. That is covered by its own row and not imported.

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — No test history provided. note 1 Three independent indication-error paths exist on a single combined pump/gauge that is reused with accumulated hydrogen loading. Calibration basis is unknown.

D7 ◇ *Detected during ground processing only with effort* — The gauge itself cannot reveal its own false-good reading. Catching a lost-HV zero-current reading needs a deliberate effort: either the thermal-performance cross-check (pressure-rise rate during standby lockup) or a turnaround HV on/off check against a reference gauge. Both are ground-processing checks requiring effort, not routine acceptance.

RECOMMENDED ACTION ◇Add HV-presence readback to the vac-ion pump ground monitor, and confirm the gauge calibration gas for hydrogen-dominated annulus conditions.

The vac-ion pump stops pumping or loses pumping capacity, so the annulus is no longer actively evacuated. ◇

RPN 150 | AP Medium | Pending

WHY HERE ◇This tank relies on a single sputter-ion (vac-ion) pump, powered by ground equipment during servicing, to remove the annulus gas load. The dominant gas in this annulus is hydrogen, which permeates or leaks from the inner vessel. Hydrogen is taken up into the pump's cathode material, where it accumulates and can cause flaking and shorting. A pump on a non-hydrogen dewar, or a sealed getter-only annulus, would not share this loading path.

LOCAL EFFECT ◇Pumping stops or degrades, and the annulus gas load from outgassing and leakage accumulates.

NEXT-LEVEL EFFECT ◇The cold inner wall cryopumps some gas while hydrogen is loaded (assumed), masking the loss in flight. Annulus pressure rises at ambient during turnaround and standby, and vacuum is out of limits at the next servicing. If undetected, this progresses to the vacuum-degradation mode above (multi-step, dwell time required; not imported).

END EFFECT ◇**Annulus vacuum is out of limits at servicing or turnaround, forcing a scrub, or pump replacement and annulus re-pump before the tank can be loaded (significant turnaround impact).**

CAUSES / MECHANISMS

- **Loss of high voltage to the pump: an open or short in the ground power path, cable, connector or HV feedthrough, or loss of ground-equipment power during servicing.** ◇ — The pump depends on externally supplied power during servicing. The interface is connected and disconnected each fill campaign. (electrical open short drift)
- **Hydrogen loads the pump cathodes over repeated fills and the 100-mission life. The cathode material expands, embrittles and flakes, shorting the anode-cathode gap or reducing pumping speed.** ◇ — The annulus gas load on this tank is hydrogen-rich, and the pump is reused across turnarounds without stated element replacement (assumed). (material degradation)
- **The HV feedthrough insulator or its braze joint cracks under launch vibration and the thermal cycling of each cryogenic fill, causing arcing or an open circuit.** ◇ — The pump rides on the annulus through launch/ascent vibration and landing loads (levels not stated) on every flight. (environment vibration shock emi)

PREVENTION CONTROLS

- Size the pump for the hydrogen gas load with cathode life margin over the reuse interval. (margin or derating) ◇
- Qualify the HV feedthrough and connector for launch vibration and cryogenic thermal cycling. (qualification) ◇
- Check pump health and replace or regenerate the pump element on condition at turnaround. (procedure or training) ◇

DETECTION CONTROLS

- Read pump current and voltage at every servicing and turnaround. (functional test · every unit · observes: zero current with HV applied, or current at supply limit (short)) credited for D ◇
- Trend annulus vacuum and pump current across turnarounds. (spc · every unit · observes: upward drift in base current across flights) ◇

SCORING

S5 ◇ *Test or launch scrub; significant turnaround impact* — The direct end effect is an out-of-limit annulus discovered at ground servicing or turnaround, forcing a scrub or pump replacement and re-pump: significant turnaround impact. Degraded thermal performance in flight requires dwell time plus actual vacuum loss, which is a separate row. Not escalated.

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — No test history provided. note 1 Hydrogen cathode loading is life-limited, but no qualified pump life is stated, so no life ratio can be argued. Rated above the floor because of repeated power connect/disconnect at servicing and accumulated hydrogen loading over reuse.

D6 ◇ *Detected during normal ground-processing acceptance test* — The pump current and voltage read at each servicing directly shows an open (zero current) or a cathode short (current at limit). This is a normal ground servicing check, and the consequence lands on the ground, at the next servicing. The pump is assumed unpowered in flight, so there is no in-flight onset to miss.

RECOMMENDED ACTION ◇Confirm whether the pump is powered in flight, and define a pump-element replacement interval tied to accumulated hydrogen exposure over the 100-mission certification.

Support the inner pressure vessel within the outer shell through ground handling, launch, ascent, entry and landing loads while minimizing conducted heat (twelve tension straps, assumed) AI-suggested

Loss of inner-vessel restraint: one or more tension straps or their end fittings fracture or pull out, so the inner vessel is no longer held in position under ascent, entry or landing loads ◇

RPN 288 AP High CRITICAL Pending

WHY HERE ◇The twelve filament-wound S-glass/epoxy straps (assumed) span from the 2219 inner vessel holding supercritical hydrogen from about -420 °F to the warmer 2219 outer shell. Each strap is therefore loaded in tension while its cold end and composite-to-metal fitting are thermally cycled on every fill, including every launch attempt, across a 100-mission certification. The suspended mass is the inner vessel plus about 92 lb of hydrogen under launch, ascent, entry and landing loads. This sentence would be false for a foam-supported, single-wall or non-cryogenic tank.

LOCAL EFFECT ◇Strap or end-fitting separation removes restraint along that strap's line of action, and load redistributes to the remaining straps. If several straps fail, the inner vessel and vapor-cooled shield displace within the annulus.

NEXT-LEVEL EFFECT ◇A displaced vessel overloads the plumbing penetrations that cross the annulus (supply, fill, vent and relief lines) and can contact the outer shell. The likely result is a line or penetration crack releasing hydrogen into the annulus and then the midfuselage under the payload bay liner, plus an abrupt thermal short. Escalation from gross displacement to line overload is treated as single-step physics under ascent or landing load (assumption; engineer to confirm with line flexibility analysis).

END EFFECT ◇**Hydrogen release into the midfuselage during ascent, entry or landing with fire or explosion hazard. Orbiter damage and loss of crew are credible (crew exposed).**

CAUSES / MECHANISMS

- **Cryogenic thermal-cycle microcracking of the epoxy matrix at the strap cold end, plus differential contraction between the composite strap and its metal end fitting / 2219 vessel boss. Damage accumulates over one fill per launch attempt (scrubs add cycles) and 100-mission reuse until the wrap zone or bond fails.** ◇ — Each fill drives the strap cold end to near hydrogen temperature while the warm end stays at shell temperature. Matrix toughness at cryogenic temperature and CTE mismatch at the fitting govern crack growth. (thermal contraction expansion)
- **Filament-winding defects in the straps (voids from undegassed resin, dry spots, fiber misalignment or wrinkling where fibers wrap the end bushings, cure gradient) reduce tensile strength below design allowable.** ◇ — The wrap zone around end bushings is where winding tension and fiber path control are hardest. It carries peak tension and cannot be inspected once sealed inside the vacuum annulus. (manufacturing defect)
- **Combined ascent random vibration/acoustic loads, or entry/landing loads, exceed remaining strap capacity because an adjacent strap is slack or broken (load redistribution) or because a dynamic amplification of the suspended vessel was not enveloped.** ◇ — Load levels are not stated in the input. Tension-only straps cannot carry compression, so a slack strap shifts its share to neighbours under reversing dynamic loads. (overload fracture buckling)
- **Assembly error at build: end-fitting pin or retainer not fully engaged, strap twisted or misaligned, or strap tension set out of tolerance, causing bending or overload at the fitting.** ◇ — The straps are installed and tensioned before the outer shell closes and the annulus is evacuated. Errors are locked in and invisible afterward. (assembly installation error)

MANUFACTURING CHAIN ◇Filament winding and cure of S-glass/epoxy straps around end bushings → Voids, dry spots, fiber misalignment/wrinkling in the bushing wrap zone, cure gradient → Reduced tensile strength and accelerated matrix microcracking under cryogenic cycling → Wrap-zone fracture or fitting pull-out under combined ascent/landing load, leading to vessel displacement · Defect population: distributed winding voids and wrap-zone misalignment across all twelve straps of a build lot, treated as one population, not one row per defect

PREVENTION CONTROLS

- S-glass/epoxy strap material chosen for low conductivity and cryogenic toughness, with strength margin on the combined handling/ascent/landing envelope (margin value not stated). (material selection) ◇
- Strap and end-fitting qualification under cryogenic cycling to a count covering 100 missions plus scrub fills (input states 100-mission certification; test matrix not stated). (qualification) ◇
- Controlled filament-winding process (resin degassing, winding tension, fiber path at bushings, cure profile) for strap fabrication. (process control) ◇
- Torque/engagement and strap-tension setting procedure with witnessed verification before shell closure. (procedure or training) ◇

DETECTION CONTROLS

- In-flight and ground telemetry of tank pressure, heater cycling and vac-ion pump annulus vacuum. Shows only downstream effects of displacement (thermal short, line leak into annulus). (telemetry monitor · every unit · observes: Abrupt rise in heater-off pressure rise rate, or rise in annulus pressure on the vac-ion pump reading) credited for D ◇
- Proof load test of each strap/end-fitting assembly before tank assembly (standard practice for composite tension supports). (proof test · every unit · observes: Strap fracture, fitting slip or permanent elongation at proof load) ◇
- Acceptance heat-leak (boiloff) test of the assembled tank at build. (functional test · every unit · observes: Heat leak above acceptance limit indicating mis-installed or contacting support) ◇

SCORING

S9 ◇ *Loss of vehicle, no public risk; or loss of crew (crewed vehicle)* — End effect is hydrogen release in the midfuselage with crew exposed. The input states a hydrogen leak or tank rupture there can damage the orbiter and endanger the crew, so loss of crew is credible: S9. Engineer to consider S10 if debris could reach a public-exposure zone during entry over land.

O4 ◇ *no data (floor)* LOW CONFIDENCE — No test or flight history provided. 100-mission certification is a requirement, not results data. The score sits at the design-FMEA floor because twelve redundant straps are assumed to be designed with margin. Cryogenic cycling on every fill including scrubs, plus multi-mission reuse, argue against any lower value. Assumption: engineer to calibrate from strap qualification and fleet data.

D8 ◇ *Operational anomaly evident only via downstream effects* — The build-time proof test (index 1) catches gross winding defects but not fatigue damage that initiates during reuse. That later onset (cause 0) is the governing case. Once the tank is sealed, nothing observes strap integrity directly. Only telemetry of pressure-rise rate and annulus vacuum (index 0) reveals the downstream thermal short or line leak, and by then displacement has occurred.

RECOMMENDED ACTION ◇Obtain strap cryo-cycled tensile/fatigue qualification data covering 100 missions plus scrub fills, and confirm by analysis that the suspension and penetrating lines tolerate one failed strap under ascent and landing loads.

Degraded support stiffness: progressive loss of strap preload over reuse leaves straps slack, so the inner vessel moves excessively in the annulus under vibration and handling loads ◇

RPN 300 · AP Medium · PROVISIONAL: NO DATA · Pending

WHY HERE ◇Tension-only S-glass/epoxy straps (assumed) hold the inner vessel by preload. That preload must survive sustained tension, one cryogenic contraction/re-warm cycle per fill and 100 missions of turnaround. Epoxy creep and fitting wear reduce it, and once a strap goes slack it carries nothing under load reversal. A compression-capable or bonded support, or a single-use tank, would not exhibit this cumulative reuse behaviour.

LOCAL EFFECT ◇Slack straps let the inner vessel and shield move and rattle under launch vibration and acoustics and under landing and handling loads, and dynamic amplification rises.

NEXT-LEVEL EFFECT ◇Remaining straps and the penetrating lines see higher cyclic loads, and the MLI/shield may chafe. Escalation to strap fracture or line fatigue is captured in the loss-of-restraint mode and needs further dwell/cycles.

END EFFECT ◇**Loss of structural margin and of strap-load redundancy in the vessel support. The mission continues with no margin until refurbishment.**

CAUSES / MECHANISMS

- **Creep and stress relaxation of the epoxy matrix and cold-flow at strap-to-bushing bearing surfaces under sustained preload, accumulated over turnaround dwell and 100-mission life.** ◇ — Polymer-matrix tension members relax under sustained load, mostly at the warm end and during long ground dwell between flights. (creep relaxation coldflow)
- **Fretting wear at strap end pins/bushings from ascent vibration and from the relative sliding each fill's cryogenic contraction and re-warm causes.** ◇ — Each fill and each flight's vibration produces small relative motion at fittings in vacuum, where no lubricant film is available (assumed). (wear galling fretting)
- **Back-out of strap tension adjusters or retainer nuts under launch vibration and landing shock.** ◇ — Preload is assumed to be set by adjustable end hardware, which can lose torque under random vibration if locking features are inadequate. (environment vibration shock emi)

PREVENTION CONTROLS

- Locking features (safety wire/locking inserts) on strap tension adjusters and retainers. (design feature) ◇
- Creep/relaxation and fretting qualification of strap assemblies covering 100-mission life including ground dwell (certification stated; test matrix not stated). (qualification) ◇

DETECTION CONTROLS

- Acceptance proof and preload verification of straps at build only; does not observe in-service relaxation. (proof test · every unit · observes: Strap tension below setting at build) ◇
- Pressure/heater telemetry: shows only a resulting thermal short if motion causes contact; slack itself is not observable. (telemetry monitor · every unit · observes: Step change in heater-off pressure rise rate) ◇

SCORING

S6 ◇ *Loss of redundancy on a critical function (mission continues, no margin)* — Direct end effect is loss of support margin and strap-load redundancy while the mission continues: S6. The terminal loss-of-restraint effect (S9) is not imported, because escalation needs further cycles or additional failures and is scored in its own row.

O5 ◇ *engineering judgment, no data* LOW CONFIDENCE — Life-limited mechanism (creep/fretting), but no qualified life or test history is stated, so a life-margin ratio cannot be formed. Scored above the floor by engineering judgment because exposure accumulates every flight across 100-mission reuse. Assumption: engineer to replace with qualified life ÷ required life once qualification data are supplied.

D10 ◇ *No detection — first sign is the consequence* — Creep relaxation (cause 0) develops during reuse inside the sealed vacuum annulus. The build proof test cannot see later relaxation, and no turnaround check of strap preload or suspension stiffness is stated. Telemetry sees only a later thermal short and does not reliably show slack. No control is credited, and the first sign is the consequence.

RECOMMENDED ACTION ◇Define a non-invasive turnaround check of suspension health (e.g., modal/tap-test signature against build baseline) and obtain creep/fretting qualification data to set a life margin against 100 missions.

Support path conducts heat out of spec: excess conducted heat leak into the inner vessel through the straps, or through vessel/shield-to-shell contact the suspension fails to prevent ◇

RPN 175 · AP High · Pending

WHY HERE ◇This tank keeps hydrogen supercritical from about -420 °F with a vacuum annulus, a vapor-cooled shield and silverized Kapton MLI (assumed). Once radiation and gas conduction are suppressed, the twelve low-conductivity straps and the vessel-to-shell clearance they maintain become the controlling solid-conduction path. Extra heat goes directly into tank pressure, which the heater controller can only add to, never remove. The sentence would be false for an uninsulated or non-cryogenic tank, or one with active cooling.

LOCAL EFFECT ◇Heat leak into the hydrogen rises above design.

NEXT-LEVEL EFFECT ◇Tank pressure rises faster than drawoff can relieve and the heaters stay off. In paired auto mode, this tank's high pressure also turns off the paired tank's heaters. Pressure may exceed the 293.8 psia caution limit and reach the 310 psia relief setting, venting hydrogen through the relief port. On the pad it raises standby boiloff after fill stops.

END EFFECT ◇**Usable hydrogen in this tank is lost early, and with it the tank set. On flights carrying few tank sets this forces mission shortening (mission-critical degradation). Crew safe, provided relief venting exits overboard (assumed).**

CAUSES / MECHANISMS

- **Ascent vibration and acoustics displace or compress the vapor-cooled shield or MLI (nylon net spacers crushed, blanket slumps), creating solid contact between shield and vessel or shell across the annulus.** ◇ — The suspension sets annulus clearance. Vibration-driven relative motion of the shield and blankets can close it, and that onset happens in flight. (environment vibration shock emi)
- **Strap lengths or tensions mis-set at assembly leave the inner vessel off-centre. When the vessel contracts on cryogenic fill it shifts until the vessel or shield touches the outer shell.** ◇ — The inner vessel contracts relative to the warm shell on every fill, so a clearance adequate at ambient can close at cryogenic temperature. (assembly installation error)
- **Strap or end-fitting thermal conductance above design: a resin-rich or wrong-fiber strap, a missing thermal standoff/isolator at the fitting, or a strap substituted with a higher-conductivity part.** ◇ — The strap conductance budget assumes S-glass/epoxy geometry. Any material or geometry deviation raises solid conduction directly. (manufacturing defect)

PREVENTION CONTROLS

- Design clearance between vessel, vapor-cooled shield and shell sized for cold contraction and dynamic deflection, with standoffs to keep MLI from bridging the gap (values not stated). (design feature) ◇
- Strap length/tension setting and vessel centring procedure verified before shell closure. (procedure or training) ◇
- Material certification and traceability of strap fiber/resin and fitting isolators. (process control) ◇

DETECTION CONTROLS

- Telemetry of tank pressure and heater duty during ground standby and in flight. A rising heater-off pressure rise rate shows elevated heat leak (crew/ground monitoring; C&W at 293.8 psia). (telemetry monitor · every unit · observes: Heater-off pressure rise rate above flight baseline; heaters not cycling; pressure approaching 293.8 psia C&W) credited for D ◇
- Acceptance heat-leak (boiloff) test at build and pad standby pressure trend after fill. (functional test · every unit · observes: Boiloff or pressure rise rate above acceptance limit) ◇

SCORING

S7 ◇ *Mission-critical degradation; payload to off-nominal orbit needing mitigation* — End effect is early loss of this tank set's hydrogen, with likely mission shortening on minimum-tank-set flights: mission-critical degradation, S7. On flights with spare tank sets this reduces to S6 loss of margin. If the relief port does not vent overboard, the end effect and S must be re-evaluated (engineer to confirm).

O5 ◇ *engineering judgment, no data* **LOW CONFIDENCE** — No test or flight history provided. Engineering judgment places this above the floor: clearance closure needs only shield/MLI motion or modest centring error combined with cold contraction, both exercised every flight. Assumption: engineer to calibrate from heat-leak acceptance data and flight pressure-trend history.

D5 ◇ *Detected in flight via telemetry, no automated response* — Vibration-induced contact (cause 0) begins in flight, after any ground check. Pressure telemetry (index 0) directly shows the heat-leak symptom as a higher heater-off pressure rise rate. Response is crew/ground action, with no automated safing of the support-path fault, so D5. The acceptance test (index 1) catches only build-time causes.

RECOMMENDED ACTION ◇Establish a per-tank heater-off pressure-rise-rate baseline from acceptance and prior flights, with alert limits in ground and flight monitoring, to flag support-path thermal shorts early.

NOTES REFERENCED ABOVE — EACH PRINTED ONCE

1 This is an assumption; the engineer should calibrate it from analogous program data.

AI SELF-CORRECTIONS (PASS 7)

Inner pressure vessel ruptures (structural loss of containment), releasing the stored supercritical hydrogen into the annulus and midfuselage

- **D:** 9 → 10
- **D justification:** ...rests on between-flight ground indications at best. ADDED [Pass 7: No in-service inspection exists, as periodic NDE is only the recommended_action. Build radiography and proof are one-time checks. The annulus reading relies on leak-before-break, which is not established. Fracture onsets in flight, so the first sign is the consequence.]

Degraded radiant insulation performance with vacuum intact: MLI and/or vapor-cooled shield pass more heat than design, giving a partial, persistent increase in heat leak

- **D:** 6 → 8
- **D justification:** ...Engineer to confirm a heat-leak acceptance limit exists. ADDED [Pass 7: The only credited control is a ground check whose acceptance limit is still a recommended_action. Vibration compaction onsets in flight, and the draft rates the in-flight trend signature D8.]

Heater-controller tank pressure sensor reports an in-range but falsely HIGH pressure (out-of-spec high indication) to the heater controller

- **S:** 6 → 9
- **S justification:** ...flight's tank-set count leaves no margin without this pair. ADDED [Pass 7: A paired-mode false-high inhibits both paired tanks' heaters. On a stated two-tank-set flight those are all the hydrogen tanks, so all three fuel cells are starved: loss of power with the crew aboard. Manual heater override is a response and is not credited in severity.]

Heater-controller tank pressure sensor reports an in-range but falsely LOW pressure (or reads zero), so heaters are not commanded off

- **S:** 6 → 7
- **S justification:** ...re-score to S9 because the crew would be exposed. ADDED [Pass 7: The stated end effect, relief venting and loss of the tank set, is scored S7 in every other row including Heaters fail to switch off at the upper setp... (same physics). S6 understates it.]

Fill or vent quick disconnect fails to stay sealed for flight: hydrogen leaks externally past the QD poppet seat and its flight cap into the midfuselage

- **D:** 5 → 8
- **D justification:** ...Midfuselage hydrogen detection is not stated in the input. ADDED [Pass 7: Leak rates sufficient for flammable midfuselage accumulation can fall below quantity/pressure telemetry resolution, as the justification admits. No hydrogen detection is stated in the input, so the hazard is seen only via downstream effects.]

Annulus vacuum degrades beyond what the vac-ion pump can hold, so the annulus loses its insulating vacuum (partial or total).

- **S:** 7 → 8
- **S justification:** ...whether a minimum two-tank-set flight would make this S8. ADDED [Pass 7: Reconciled with merged (removed mode) (S8). The input states two-tank-set flights occur. Early on-orbit loss of one set credibly ends the mission objectives with a crew-safe return, which is S8.]

ENGINEER EDITS

None yet — every field still reads as the AI's final version.

OPEN ITEMS — 48

Assumed control credited for detection (34) — each reads: ... — needs a closed verification activity.

- D10 on "Inner pressure vessel ruptures (structural loss of containme..." credits assumed control "Radiography of all inner-vessel girth and penetration welds at build"
- D10 on "Inner pressure vessel ruptures (structural loss of containme..." credits assumed control "Acceptance proof pressure test of the inner vessel"
- D10 on "Inner pressure vessel ruptures (structural loss of containme..." credits assumed control "Annulus vacuum monitored through the vac-ion pump, which is powered by ground equipment during servicing"
- D8 on "Degraded radiant insulation performance with vacuum intact: ..." credits assumed control "Heat-leak acceptance test: locked-up pressure-rise rate or boil-off measurement at build and at pad standby versus a baseline (assumed standard practice)"
- D5 on "Heater probe delivers no or insufficient heat on demand, so ..." credits assumed control "Tank pressure telemetry with a low-pressure caution and warning below 153 psia."
- D5 on "Heater probe delivers no or insufficient heat on demand, so ..." credits assumed control "Cross-check between the second (non-controller) tank pressure sensor and the controller sensor on displays and telemetry."
- D5 on "Heater probe delivers no or insufficient heat on demand, so ..." credits assumed control "Heater assembly temperature telemetry while heaters are commanded on."
- D5 on "Heaters fail to switch off at the upper setpoint, so continu..." credits assumed control "Tank pressure telemetry with a high-pressure caution and warning above 293.8 psia."
- D5 on "Heaters fail to switch off at the upper setpoint, so continu..." credits assumed control "Cross-check between the independent second tank pressure sensor and the controller sensor."
- D5 on "Heaters fail to switch off at the upper setpoint, so continu..." credits assumed control "Heater assembly temperature telemetry."
- D5 on "Tank pressure overshoots, undershoots or oscillates outside ..." credits assumed control "Tank pressure and heater assembly temperature telemetry trended by ground and displayed to the crew."
- D5 on "Tank pressure overshoots, undershoots or oscillates outside ..." credits assumed control "Fluid temperature and quantity probe telemetry compared with pressure."
- D5 on "Heater-controller tank pressure sensor reports an in-range b..." credits assumed control "Caution and warning on low tank pressure below 153 psia"
- D5 on "Heater-controller tank pressure sensor reports an in-range b..." credits assumed control "Telemetry comparison of this tank's two pressure sensors, plus heater state"
- D5 on "Heater-controller tank pressure sensor reports an in-range b..." credits assumed control "Caution and warning on tank pressure above 293.8 psia, from the second (non-controller) pressure sensor; routing assumed"
- D5 on "Heater-controller tank pressure sensor reports an in-range b..." credits assumed control "Heater assembly temperature telemetry"
- D5 on "Capacitance quantity probe indicates hydrogen quantity out o..." credits assumed control "Ground cross-check of probe quantity against density computed from tank pressure and fluid temperature via the hydrogen equation of state"
- D5 on "Capacitance quantity probe indicates hydrogen quantity out o..." credits assumed control "Reactant consumption reconciliation from integrated fuel cell current versus indicated quantity drop"
- D8 on "Supply flow to the manifold is restricted or blocked (partia..." credits assumed control "Quantity and tank pressure telemetry, compared across tank sets"
- D5 on "Tank relief valve fails to open (relief function lost on dem..." credits assumed control "Tank pressure telemetry with caution and warning above 293.8 psia, displayed to crew"
- D5 on "Partial relief: valve lifts but relief valve or relief port ..." credits assumed control "Tank pressure telemetry with caution and warning above 293.8 psia"
- D5 on "Unintended relief: valve cracks below setting or fails to re..." credits assumed control "Quantity and pressure telemetry compared against fuel-cell consumption"
- D8 on "Fill or vent quick disconnect fails to stay sealed for fligh..." credits assumed control "In-flight monitoring of tank quantity and pressure via telemetry and caution and warning (low limit 153 psia); quantity depletion compared against fuel cell consumption."
- D6 on "Fill quick disconnect fails to pass, or restricts, fill flow..." credits assumed control "Monitoring of tank quantity and pressure rise against fill-line supply pressure during loading."
- D6 on "Fill quick disconnect fails to pass, or restricts, fill flow..." credits assumed control "Functional connect-and-flow check of the fill QD with ground equipment during turnaround."
- D6 on "Vent quick disconnect fails to pass vent flow during fill, s..." credits assumed control "Tank pressure monitoring during fill and standby via telemetry and the 293.8 psia high caution limit."
- D6 on "Vent quick disconnect fails to pass vent flow during fill, s..." credits assumed control "Vent-line flow or pressure at the ground equipment during servicing."
- D5 on "Annulus vacuum degrades beyond what the vac-ion pump can hol..." credits assumed control "Read vac-ion pump current (annulus vacuum) during ground servicing, standby and turnaround."
- D5 on "Annulus vacuum degrades beyond what the vac-ion pump can hol..." credits assumed control "In-flight telemetry of tank pressure, fluid temperature and quantity, with high-pressure caution and warning above 293.8 psia."
- D6 on "The vac-ion pump stops pumping or loses pumping capacity, so..." credits assumed control "Read pump current and voltage at every servicing and turnaround."

- D7 on "Erroneous annulus vacuum indication from the vac-ion pump: a..." credits assumed control "During standby, cross-check the indicated vacuum against tank thermal performance: pressure-rise rate with heaters off versus nominal heat leak."
- D7 on "Erroneous annulus vacuum indication from the vac-ion pump: a..." credits assumed control "Pump functional check at turnaround: HV on/off current response and comparison with an independent temporary gauge on the annulus port."
- D8 on "Loss of inner-vessel restraint: one or more tension straps o..." credits assumed control "In-flight and ground telemetry of tank pressure, heater cycling and vac-ion pump annulus vacuum. Shows only downstream effects of displacement (thermal short, line leak into annulus)."
- D5 on "Support path conducts heat out of spec: excess conducted hea..." credits assumed control "Telemetry of tank pressure and heater duty during ground standby and in flight. A rising heater-off pressure rise rate shows elevated heat leak (crew/ground monitoring; C&W at 293.8 psia)."

Critical / AP-High mode undecided (14) — each reads: No decision yet on ...

- critical mode "Inner pressure vessel ruptures (structural loss of containme...".
- AP-High mode "Heater probe delivers no or insufficient heat on demand, so ...".
- AP-High mode "Heaters fail to switch off at the upper setpoint, so continu...".
- critical mode "Heater-controller tank pressure sensor reports an in-range b...".
- AP-High mode "Heater-controller tank pressure sensor reports an in-range b...".
- AP-High mode "Capacitance quantity probe indicates hydrogen quantity out o...".
- AP-High mode (provisional: no data) "Supply flow to the manifold is restricted or blocked (partia...".
- critical mode "Tank relief valve fails to open (relief function lost on dem...".
- critical mode "Partial relief: valve lifts but relief valve or relief port ...".
- AP-High mode "Unintended relief: valve cracks below setting or fails to re...".
- critical mode "Fill or vent quick disconnect fails to stay sealed for fligh...".
- AP-High mode (provisional: no data) "Annulus vacuum degrades beyond what the vac-ion pump can hol...".
- critical mode "Loss of inner-vessel restraint: one or more tension straps o...".
- AP-High mode "Support path conducts heat out of spec: excess conducted hea...".

APPENDIX — AI SELF-REVIEW (PASS 7)

15 modes rest only on the item identity for some claims: no specific input was named for failure mode, why this applies here. Name the input each claim depends on, or accept the item identity as its basis.

Alias scan added 656 dependencies across 21 mode(s) that the draft did not declare: "fill" → mission phase "ground servicing at the pad (fill" ×66; "heater" → material "Heater probe: one probe with two element..." ×59; "flight" → mission phase "on-orbit operations" ×56; "servicing" → function "Accept ground fill and vent through quic..." ×29; "telemetry" → function "Measure quantity, pressure (two sensors)..." ×27; "cryogenic" → temperature "hydrogen stored supercritical from about..." ×25; "reuse" → mission phase "reuse" ×22; "relief valve" → material "Fill and vent quick disconnects and caps..." ×22.

Duplicate physical mode. External hydrogen leakage past the fill/vent QD poppets and flight caps appears under both the containment function ((removed mode)) and the fill/vent function (Fill or vent quick disconnect fails to stay...). Merged into Fill or vent quick disconnect fails to stay... , because the QD poppet and cap seal is the function this leak directly defeats. The relief-valve seat leakage in (removed mode) is the same physical mode as Unintended relief: valve cracks below settin... . (removed mode) assumed the seat leak discharges into the midfuselage, while Unintended relief: valve cracks below settin... assumed it goes overboard. That inconsistency must be resolved; see the relief-port note.

Duplicate physical mode: loss or degradation of annulus vacuum appears three times. It is under the heat-leak function ((removed mode)), as the inner-vessel-to-annulus leak under containment ((removed mode)), and under the vacuum function (Annulus vacuum degrades beyond what the vac-...). All three share the same weld-flaw population, cause set and relief-venting end effect. Merged into Annulus vacuum degrades beyond what the vac-... , since keeping the annulus evacuated is the function directly defeated. (removed mode)'s mode is a cause of vacuum loss, not external leakage, so it does not defeat the containment function as worded. Severity is reconciled upward to S8 (see score edit).

Duplicate physical modes across the supply and pressure-maintenance functions. 'Supply pressure decays below 200 psia, heaters fail to restore' ((removed mode)) is the same mode as Heater probe delivers no or insufficient hea... . 'Supply pressure rises above 243 psia' ((removed mode)) is the same mode as Heaters fail to switch off at the upper setp... . The causes match too: heater open, controller sensor drift, paired-mode inhibit, switch left ON. Merged into the pressure-maintenance rows, because holding the band is that function's intent. (removed mode)'s stratification cause belongs to Tank pressure overshoots, undershoots or osc... . (removed mode)'s annulus-vacuum causes belong to Annulus vacuum degrades beyond what the vac-... .

Duplicate physical mode: a solid conduction bridge or contact across the annulus appears under both the heat-leak function ((removed mode)) and the support function (Support path conducts heat out of spec: exce...). The two rows were scored O4 and O5. Merged into Support path conducts heat out of spec: exce... , because the support function explicitly includes minimizing conducted heat and owns the strap/centring causes. O5 is retained: it is the more conservative no-data value, and the O4 relied on an unsupported 'low-load design' claim.

Consequence underestimated (Heater-controller tank pressure sensor repor...). In paired auto mode, a false-high from this sensor turns off BOTH paired tanks' heaters. The input states flights carry two to five tank sets, so on a two-set flight the paired tanks 1 and 2 are the only hydrogen tanks. The end effect then is all hydrogen supply decaying and starvation of all three fuel cells, which means loss of electrical power with the crew aboard (S9). 'Fuel cells keep running on the remaining tank sets' does not hold on a two-set flight. Manual heater ON is a crew response and a detection credit, not a severity reducer. Raised to S9. The engineer should confirm the paired-mode pairing on minimum-set flights. Heater probe delivers no or insufficient hea... cause 2 (paired false-high) carries the same two-tank consequence but is scored at the single-tank S7. Reassess it or move that cause to Heater-controller tank pressure sensor repor... . Once S9, Heater-controller tank pressure sensor repor... must be pinned critical.

Consequence underestimated (Heater-controller tank pressure sensor repor...). Its end effect is relief venting and loss of this tank set. Every other row scores that same end effect S7 (e.g. Heaters fail to switch off at the upper setp... , same physics), but this row uses S6 'loss of redundancy'. Raised to S7 for consistency with its own stated end effect.

Cross-row severity policy needed. 'Loss of one tank set's hydrogen' is scored S7 in most rows and S8 in the merged vacuum row. The input states two-tank-set flights occur. On such a flight, early on-orbit loss of one set is credibly a crew-safe loss of mission (S8), not just shortening (S7). The engineer should set one policy for this end effect and apply it to all affected rows. Severity was not mass-raised here because each row's stated end effect reads as mission-shortening (S7).

Open question that governs severity: the relief port discharge location (overboard vs inside the midfuselage) is not stated in the input. Several rows are S6/S7 only on the assumption of overboard discharge and say they would be S9 otherwise. The dropped (removed mode) assumed the opposite. This is the single highest-leverage fact for the engineer to confirm.

Detection over-credited (Inner pressure vessel ruptures (structural l...). D9 'post-flight inspection only' presumes an in-service inspection exists, and none does. Radiography and proof are one-time build checks. The justification itself says the vac-ion annulus reading works only if leak-before-break holds, and that is not established. Periodic NDE is the recommended action, not a current control. Final fatigue fracture onsets in flight. Raised to D10.

Detection over-credited (Degraded radiant insulation performance with...). The only credited control is a ground heat-leak check, but vibration-induced MLI compaction onsets in flight after that check. The draft's own reasoning rates the in-flight trend at D8. The heat-leak acceptance limit the ground check would need is the recommended action ('define a per-flow heat-leak acceptance metric'), not an existing control. Raised to D8.

Detection coverage at the defect scale (Fill or vent quick disconnect fails to stay...). The S9 hazard is flammable hydrogen accumulating in the midfuselage, and leak rates large enough for that can be far below what quantity/pressure telemetry resolves. The justification admits small leaks may be masked by heater cycling. No midfuselage hydrogen detection is stated in the input. The control credited in the dropped (removed mode) was explicitly 'not stated in input'. Raised to D8 (detected only via downstream effects). The engineer should consider D10 for small leaks.

Vague detection method. The two-pressure-sensor 'cross-check' credited in these rows has no defined disagreement limit or alarm. Sibling rows recommend adding one, which implies it does not exist today. The D5 credit should rest on the 153/293.8 psia C&W alone, so the engineer should confirm those cover onset before relief or starvation. Similarly, Support path conducts heat out of spec: exce... credits a 'rising heater-off pressure-rise rate', but its recommended action is to establish that baseline. Until then, only the 293.8 psia C&W supports D5.

Detection coverage (Tank relief valve fails to open (relief func... , Partial relief: valve lifts but relief valve...). The 293.8 psia C&W detects the overpressure demand, not the latent stuck or undersized relief path. The failure itself becomes visible only when pressure passes 310 psia without a plateau. Burst pressure is not stated, so whether the crew has time to respond is not established. The D5 justifications should address this. In Tank relief valve fails to open (relief func... the sentence about the turnaround test 'claiming better than ground detection' is muddled and should be rewritten.

Provenance: D5 in Heater-controller tank pressure sensor repor... depends on the 293.8 psia C&W being driven by the second (non-controller) pressure sensor. The input does not state which sensor drives C&W, and the row itself labels this 'routing assumed'. The engineer should confirm. If the C&W comes from the faulty controller sensor, D becomes 8 per the row's own note.

Provenance: Tank relief valve fails to open (relief func... places the tank relief valve upstream of the 12-micron filter, based on the interface fact 'supply line through a relief valve and 12-micron filter package'. That valve may be a line relief valve rather than this tank's 310 psia valve, and the tank valve's location is not stated. The contamination-path argument therefore rests on an assumption that should be listed in input dependencies.

Provenance: 'the dominant gas in this annulus is hydrogen' (The vac-ion pump stops pumping or loses pump...) and the 'hydrogen-dominated annulus' calibration-gas cause (Erroneous annulus vacuum indication from the...) are not stated in the input. Both presume an inner-vessel leak or permeation that is itself a failure mode. Mark these as assumptions.

COTS, hedged. The vac-ion pump is a catalog sputter-ion pump, and its internal mechanisms (cathode flaking, field-emission current, gas-species calibration) are normally characterized by the vendor. No vendor qualification is provided, so this is not over-analysis on the evidence available. If vendor life data cover hydrogen loading over the 100-mission use, the engineer may collapse these rows to pump-level loss-of-pumping and false-indication modes.

Sensor gap in the measurement function. No mode covers the fluid temperature sensor, the heater assembly temperature sensor, or the second (non-controller) pressure sensor. Several rows credit those sensors for detection, so their failures would silently remove that credit. Quantity-probe under-reading and loss of signal are also not considered. Gap noted only; no modes invented.

Gap: annulus and outer-shell overpressure. Several rows defer 'outer-shell overpressure from an internal hydrogen leak' to 'the rupture row', but Inner pressure vessel ruptures (structural l... covers inner-vessel rupture only. No annulus relief device is stated in the input. No row covers pressurization of the 2219 outer shell by hydrogen leaking into the annulus. Gap noted; engineer to confirm whether an annulus burst disc exists.

Gap: the 2219 outer shell (45.5 in vacuum jacket) appears only as a leak path. Its structural integrity under external atmospheric pressure with an evacuated annulus, plus handling, landing and strap-attachment loads, is not examined. Gap noted, hedged, as the wall thickness is not stated.

Gap flagged by Supply flow to the manifold is restricted or... itself: solid oxygen or air carried into hydrogen through the QDs is a reactivity hazard, but it is not scored anywhere. A related open question: the heater assembly temperature sensor exists, yet no row examines heater or probe over-temperature at low fluid density late in the mission. Gaps noted only.

failure mode mixes in cause or effect. Supply flow to the manifold is restricted or... names its cause ('by solid contaminants') and places the restriction partly at the 12-micron filter, which is out of scope. Suggested correction: 'supply flow restricted or blocked at the tank outlet'. Inner pressure vessel ruptures (structural l... appends the effect ('releasing ... into the annulus and midfuselage'). Release to the midfuselage also needs the outer shell to fail, so the mode should read as inner-vessel structural rupture only.

Occurrence reasoning is internally inconsistent (Tank pressure overshoots, undershoots or osc...). The justification says stratification 'recurs in every on-orbit heater cycle at low quantity'. That describes a per-mission frequency near the top of the scale, not O6. Either the out-of-band excursion is rarer than the stratification itself, or O is under-scored. Engineer to reconcile. Not edited.

RPN ranking hides criticality. S9 Partial relief: valve lifts but relief valve... (RPN 180) and the now-S9 Heater-controller tank pressure sensor repor... rank below S6 Degraded support stiffness: progressive loss... (300) and S7 Supply flow to the manifold is restricted or... (280). The engine pins S≥9 as critical. Confirm Heater-controller tank pressure sensor repor... is pinned after the severity raise, and do not prioritize by RPN.

Same QD poppet/cap external leak. Kept under the fill/vent function, whose sealed-for-flight intent it directly defeats. Scores were identical (S9/O5/D5). Carry over the cap close-out time-pressure cause (filling stops 2 min 35 s before launch) and the assumed midfuselage gas-detection control, flagged 'not in input', for the engineer to confirm. The relief-seat leakage portion belongs to Unintended relief: valve cracks below settin... , and its discharge-location assumption must be resolved there.

Loss of annulus vacuum is one physical mode. The inner-vessel leak into the annulus is one of its causes. Kept under the vacuum-maintenance function. Severity reconciled up to the dropped row's S8 (crew-safe loss of mission on a two-tank-set flight). O5 retained over (removed mode)'s O4 because the merged row carries four gas sources. Carry over (removed mode)'s recommended relief-capacity check for the loss-of-vacuum heat flux and (removed mode)'s penetration thermal-cycle qualification request.

Pressure decay below the band from no or insufficient heater heat is the same mode. Kept under the pressure-maintenance function. Scores were identical (S7/O5/D5). The zero-g stratification cause moves to Tank pressure overshoots, undershoots or osc... . Carry over the two-sensor disagreement alarm recommendation.

Pressure above the band toward relief is the same mode, with the same sensor-low and switch-left-ON causes. Kept under the pressure-maintenance function. Scores were identical (S7/O5/D5). The annulus-leak and outgassing heat-input causes belong to Annulus vacuum degrades beyond what the vac-... .

A conductive bridge or contact across the annulus is the same mode. Kept under the support function, which explicitly includes minimizing conducted heat. O5 kept over O4, because the O4 rested on an unsupported 'low-load design' claim. Carry over the FOD-in-annulus cause and the post-ascent pressure-rise-rate comparison recommendation. Strap fracture leading to contact overlaps Loss of inner-vessel restraint: one or more... and stays there.

APPENDIX — SCORING RUBRIC (ANCHORS REFERENCED ABOVE BY CODE)

#	SEVERITY	OCCURRENCE	DETECTION
10	Loss of vehicle, uncontained debris reaching public-exposure zone	>1 in 2 (will occur most missions / hot fires)	No detection — first sign is the consequence
9	Loss of vehicle, no public risk; or loss of crew (crewed vehicle)	~1 in 10	Post-flight inspection only
8	Loss of mission (payload not delivered), controlled vehicle disposal	~1 in 50	Operational anomaly evident only via downstream effects
7	Mission-critical degradation; payload to off-nominal orbit needing mitigation	~1 in 200	Detected during ground processing only with effort
6	Loss of redundancy on a critical function (mission continues, no margin)	~1 in 1,000	Detected during normal ground-processing acceptance test

#	SEVERITY	OCCURRENCE	DETECTION
5	Test or launch scrub; significant turnaround impact	~1 in 5,000	Detected in flight via telemetry, no automated response
4	Recoverable in-mission anomaly; mission proceeds with workaround	~1 in 20,000	Detected in flight, automated abort possible but not implemented
3	Nuisance affecting ground ops; ≤24h delay	~1 in 100,000	Detected in flight, automated abort/safing implemented
2	Annoyance; data quality affected; no schedule impact	~1 in 1,000,000	Detected during normal pre-flight checkout, response automatic
1	No discernible effect	No plausible cause identified ("incredible")	Detected and prevented by design (cannot occur)

Generated by Faultline — AI proposes, engineer disposes. Every AI-drafted field remains a draft until dispositioned by the responsible engineer. This document is a DRAFT: modes are still pending disposition.