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ENGINEERING **RESEARCH REPORT · Engineering research report**

Vacuum-Gripping Capacity, Leakage Compensation, and Subsystem Engineering Release for Cartons and Porous Workpieces

Study of Suction Load Capacity, Continuous Leakage, Dynamic Safety, and Fault-Release Criteria for Cartons and Porous Surfaces

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Calculation model · Test matrix · Engineering release criterion

Report structure

> Judgment rules This report uses explicit input and a unified calculation chain, and the formal judgment can only be passed or failed; failure of any hard threshold means no release.

00 Executive Summary

Cartons, corrugated board, bags and porous composite materials are not ideally airtight workpiece. The gas pumped out by the vacuum source comes from the pipeline volume, cup seal gap and material pores at the same time; when the air intake volume approaches the effective suction flow rate of the vacuum source under working vacuum, the system will build up slowly, pressure will fluctuate, and may even never reach the suction permission threshold. Therefore, the static calculation of selection based on the "pressure difference multiplied by the area" of the smooth steel plate will miss the leakage flow, establishing time, friction, eccentricity, dynamic acceleration and local failure.

GB/T 41098—2021, Cranes—Safety—Load Lifting Attachments, is currently in force and is identical to ISO 17096:2015 [1][2]. Both apply only to non-fixed load-lifting attachments for cranes, hoists, and hand-controlled load-manipulating devices. ISO 17096 expressly excludes hazards from pneumatic components, so it cannot be extended directly into a complete safety basis for a robot end effector or pneumatic circuit. GB/T 32293—2015 is currently in force and is used only to select a leak-test method for hardware leakage Q_H in vacuum equipment; it does not establish standards conformity for carton porosity flow Q_P or process inflow at the cup lip Q_E [3]. ISO 4414:2010 applies to design, isolation, residual energy, and maintenance of pneumatic systems on machinery, but excludes factory air-supply systems, gas cylinders, and air receivers [4].

This report establishes engineering release of the vacuum gripping subsystem. Complete-machine risk assessment, validation of safety-related control functions, robot-integration compliance, and air-receiver compliance are prerequisite gates. If any prerequisite lacks a formal record, passing every vacuum-subsystem test in this report does not permit complete-machine safety release. The load safety factor 2.5, flow reserve factor 1.5, establishment-time limit 2.0 s, and four-zone fault tolerance are the common engineering baselines used throughout this report.

unified research baseline

Project	Lock value for this report	pass conditions
Failure to maintain minimum pressure differential	Δp_min,LB = 45 kPa	Adopt a measurement lower bound; each healthy partition will not fall below this value during the fail-to-support transition
Normal lifting allowable pressure difference	Δp_pick,LB = 50 kPa	20 consecutive 100 Hz sampling points in each area are all ≥50 kPa, and the peak-to-peak value of the window is ≤2 kPa
Load safety factor	S_L = 2.5	Capacity/design requirements ≥ 1.00 for all path attitudes, accelerations and eccentricities
Leak flow reserve coefficient	K_Q = 1.5	Fixed item coefficients for Q_S,LB/Q_L,UB

Project	Lock value for this report	pass conditions
Conservative Flow Criterion	$Q_{S,LB}/Q_{L,UB} \geq 1.50$	The source flow rate is lower bound, the leakage amount is upper bound, and the standard state is completely consistent.
Vacuum establishment time limit	$t_{pick} \leq 2.0$ s	200 ms from suction cup contact to all partitions reaching 50 kPa lower bound and stabilizing
Zoning principle	4 mutually isolated partitions	Any partition still meets the load and moment criteria after complete failure
standby build	$t_1-t_0 \leq 0.10$ s	t_0 is the loss of main energy supply, t_1 is the lower bound of the air supply pressure at the inlet of the four zones generator ≥0.40 MPa
Fault confirmation	$t_2-t_0 \leq 0.50$ s	t_2 confirms and issues the placement command for the control system
Controlled placement	$t_3-t_2 \leq 4.00$ s	t_3 is the load completes the support transfer; $t_{res} \geq 0.50+2\times4.00=8.50$ s
Sample acceptance rules	Each boundary element, FAT and SAT are independently zero-failure	If any one of them fails, the entire item will fail. After rectification, the entire item will be re-executed from the first time.

Core conclusion

- The vacuum gripping capacity must be calculated jointly by "pressure difference - effective area - load direction - friction - moment"; the rated suction power or the suction cup quantity alone cannot constitute release evidence.
- For a porous workpiece, measure the leakage-flow upper bound in the actual contact condition and verify it against the vacuum-source flow lower bound at a 45 kPa pressure differential and minimum supply gauge pressure of 0.40 MPa. If $Q_{S,LB}/Q_{L,UB}<1.50$, the condition fails.
- Suction permission shall come from a pressure switch or sensor in every zone. Lifting is permitted only when the pressure lower bound in every zone remains at least 50 kPa continuously for 200 ms and peak-to-peak variation is no greater than 2 kPa. A fixed delay alone shall not be used to declare suction established; doing so fails the criterion. SMC's official selection information likewise requires pressure-signal confirmation of established suction rather than reliance on a timer alone [5].
- Single zone faults must not be masked by the "average pressure" of the large central cavity. Each zone must have independent pressure taking, current limiting or non-return isolation and identifiable alarms.

- For a high-leakage carton, an air receiver without validation of its discharge model and performance at minimum supply pressure shall not be treated as loss-of-air protection. Recalculate the backup vacuum source or compressed-air reserve using adiabatic discharge, the flow lower bound at minimum supply pressure, and the air-consumption upper bound, and verify it by a physical fault-injection test that shuts off the main energy supply.
- For configurations that do not have leakage records, dynamic envelopes, single-zone failure records, and controlled placement records, the conclusion can only be "No release" and must not be replaced by an experience signature.

01 Research objects, system scope and symbols

This report covers corrugated cartons, unlaminated paperboard, porous bag materials, and similar workpieces gripped from the top or another designated suction surface. The carrier may be a Pneumatic Industrial Manipulator, robot, or purpose-built handling machine. The system boundary begins at contact between suction cups and the workpiece and covers vacuum generation, distribution, monitoring, motion, fault isolation, and safe set-down. Apply GB/T 41098—2021/ISO 17096:2015 only when the equipment is a non-fixed load-lifting attachment as those standards define it. A robot end effector requires separate robot-system integration and control-safety validation.

The R1 prerequisite gate comprises carton structural design, air-receiver compliance, complete-machine risk assessment, control-system safety-integrity validation, and selection for explosive atmospheres. Enter subsystem engineering release only after the record number for each of the five items is recorded in R1. If any record is missing, R1 fails immediately.

symbol	meaning	unit
Δp_LB	The lower bound of measurement of the difference between atmospheric pressure and absolute pressure of suction cup cavity	Pa or kPa
A_eff,LB,i	The lower bound of the effective area of the i-th suction cup under the locked compression amount and after deducting the uncertainty	m^2
C_i	Normal capacity of the i-th suction cup, C_i=Δp_min,LB A_eff,LB,i	N
Q_S,LB	The lower bound of the suction flow rate of the vacuum source at the specified pressure difference and the minimum air supply pressure	NL/min
Q_L,UB	Upper bound on leakage flow within sample, attitude, compression, and contamination boundaries	NL/min

symbol	meaning	unit
μ_{LB}	The lower bound of the friction coefficient of the contact pair under the boundaries of contamination and life, after deducting uncertainty	—
N_i、T_i	Normal tensile force carried by suction cup i and the two-dimensional tangential-force vector in the suction plane	N
m_{UB}、g	Workpiece mass upper bound and gravitational acceleration; this report uses $g=9.81\ m/s^2$	kg、m/s^2
$a_{n,UB}$、$a_{t,UB}$	Upper bounds of normal and tangential acceleration during normal motion, fault braking, and controlled set-down	m/s^2
S_L、K_Q	Load safety factor, flow reserve coefficient	—
$V_{Z,UB}$	The upper bound of the equivalent volume that needs to be evacuated in a single partition	L
p_N、T_N	Reference state; fixed in this report at 101.325 kPa and 293.15 K	kPa、K
U_x	Extended measurement uncertainty of quantity x, k=2	Same as x

Effective area shall be derived from suction-cup geometry, the locked compression range of 5–9 mm, and measurement uncertainty; the outer-contour area shall not be used directly as effective area. This report requires $U_A/A\le2\%$ and uses $A_{eff,LB}=A_{eff,meas}-U_A$ in calculations. Schmalz's official technical information expresses theoretical holding force as $F=\Delta pA$ and notes that porous, rough workpieces reduce the achievable vacuum [6][7]. Supplier-catalog holding force is used for preliminary selection; subsystem engineering release consistently uses the pressure-differential lower bound, effective-area lower bound, and this report's safety factor.

02 Breathability, edge sealing and leakage mechanism

The system air intake consists of three parts: material pore flow Q_P, seal leakage Q_E caused by the cup lip and surface microchannels, and joint, valve and pipeline leakage Q_H.

$$Q_L = Q_P + Q_E + Q_H$$

Corrugated-surface fibers, creases, print coatings, adhesive seams, sealing tape, and local warpage alter flow resistance; suction-cup compression, cup-lip hardness, and suction-cup placement alter the edge seal. Piab's official technical information on corrugated board states that board porosity and cup sealing cause cycle-to-cycle leakage variation and uses $F = AP$ to explain the load-capacity rationale for low vacuum and large area [8]. That information supports the leakage mechanism and selection method.

The original research by Tiwari and Persson demonstrated through experiments on different roughness substrates and suction cup that leakage caused by interface roughness, suction cup volume and stiffness will jointly affect the detachment time [9]. The original study by Gabriel et al. incorporated surface roughness, suction cup diameter and quantity into the leakage and energy consumption model [10]. The two studies jointly support an engineering conclusion: leakage must be characterized under real contact pairs and real compression conditions, and cannot be assigned a fixed coefficient just by the name of the material.

Leak testing shall distinguish hardware leakage from process leakage through the workpiece. First seal every suction cup against an impermeable standard plate and measure Q_H at a 45 kPa pressure differential; then install the actual workpiece and measure Q_L. The fixed hardware gate is $Q_{H,UB}/Q_{S,LB} \le 0.05$. If exceeded, stop and repair the system; increasing source capacity shall not mask a failed fitting or valve. Actual-workpiece measurement uses the ten numerical boundary cells in Chapter 08; labels such as worst, similar, or typical do not replace a numerical cell.

02.1 Fixed test method for leakage boundaries

The same sequence is performed for each test: suction cup contacts at a normal speed of 0.10 m/s, the compression amount is locked to 5 mm, 7 mm or 9 mm according to the boundary unit, the single-zone vacuum source is turned on, and the pressure and standard flow rate are recorded from 0 to 12 s. The stability window is fixed at 10.0~12.0 s; the lower limit of each pressure within the window must be ≥50 kPa, and the peak value of the pressure indication must be ≤2 kPa. The leakage indication value takes the largest 100 ms sliding average within the window, and then adds U_Q to obtain $Q_{L,UB}$. suction cup does not reach the 50 kPa lower limit within 2.0 s after contact and stabilizes for 200 ms. This cycle directly determines R4 failure, and the original data is still retained.

The contamination boundary is fixed at 23±2 °C and 50±10% relative humidity. Prepare and sieve material from the same carton batch into 75–150 μm paper dust and apply 0.50 g/m² uniformly to the suction surface. Cartons above that areal density or containing liquid water, oil, or adhesive contamination are outside this release boundary. The service-life boundary is reached when a suction cup has completed 100000 rated compression cycles or its sealing lip has worn 0.50 mm relative to a new cup, whichever occurs first. Friction, effective-area, leakage, and dynamic tests shall cover both new cups and cups at this service-life boundary.

The cycle fails immediately and the suction-cup placement point is added to the prohibited-zone map if the paper surface tears, the cup lip crosses an opening in the carton lid, the lid pulls up, or the minimum distance from the sealing lip to a crease, indentation, or tape step with height difference/depth ≥0.50 mm is <10 mm. The prohibited-zone map uses tooling coordinates, with boundary coordinates specified to 1 mm.

Workpieces may share leakage data only when material grade, flute type, number of layers, coating, print coverage, tape configuration, permitted suction-cup placement, and upper mass limit are all identical. Any difference requires a separate dataset. This converts a visual judgment that cartons look similar into an auditable boundary and prevents low-leakage samples from masking a high-leakage batch.

03 Suction Load Capacity, Friction, and Dynamic-Load Model

The lower bound of the normal capacity of the i-th suction cup and the total system capacity are:

$$C_i = \Delta p_{min,LB} A_{eff,LB,i}$$
$$F_{N,cap,LB} = \Sigma C_i$$

Let the suction surface rotate through θ from horizontal and calculate the normal and tangential design demands using the following equations. Use measured upper bounds for mass, acceleration, and eccentricity. The acceleration envelope shall include per-axis peaks during normal production, braking after a single-zone fault, motion to a safe position, and controlled set-down; average speed is not a substitute.

$$F_{N,d} = S_L m_{UB} \max_t |g \cos\theta + a_{n,UB}(t)| \quad F_{T,d} = S_L m_{UB} \max_t \sqrt{(g \sin\theta + a_{x,UB}(t))^2 + a_{y,UB}(t)^2}$$

Fast screening conditions: $F_{N,cap,LB} \geq F_{N,d}$ $\mu_{LB} F_{N,cap,LB} \geq F_{T,d}$

For the friction-coefficient test, use three carton batches with 10 independent specimens per batch. At pressure differentials of 45 kPa and 50 kPa, measure the tangential force at the onset of continuous 2 mm slip. Complete 30 trials for every combination of pressure differential, new/end-of-life cup, and clean/0.50 g/m² paper-dust state. Calculate $\mu_{meas}=F_{slip}/(\Delta p A_{eff,meas})$, take the minimum of all results, and subtract U_μ to obtain μ_{LB}; U_μ shall be ≤0.02. The baseline condition uses $\mu_{LB}=0.35$. Schmalz design information requires suction tests on porous workpieces and lists safety factors of at least 2 for horizontal workpieces and at least 2.5 for rotated workpieces [6]; this report uses 2.5 for every load direction.

After passing the rapid screening, the combined load and three-dimensional eccentricity must still be checked. The origin of the coordinates is fixed at the center of gravity of workpiece, r_i is the vector from the center of gravity to the action point of the i-th cup, n is the unit normal direction of the suction surface, T_i is the two-dimensional vector in the surface, $f_i=N_i n+T_i$; $M_{external}$ only contains independent external force couples that are not expressed with the resultant force of the center of gravity. For each 10 ms path sampling moment, a set of suction cup forces that meet the following conditions must be obtained:

$$N_i \geq 0$$
$$N_i/C_i + ||T_i||/(\mu_{LB} C_i) \leq 1$$

$$\Sigma f_i + f_{external} = 0$$
$$\Sigma(r_i \times f_i) + M_{external} = 0$$

The linear interaction envelope prohibits simultaneous use of full normal capacity and full friction capacity at the same suction cup. The condition passes only if a force distribution exists that satisfies all equilibrium equations and the interaction envelope. Include the three-dimensional suction-cup coordinates, three-dimensional center-of-gravity coordinates, moment arm through the workpiece thickness, and peak fault-braking loads in the external moment. Separate material-bearing criteria address local crushing of paperboard, liner delamination, and carton-lid cracking; passing vacuum capacity does not automatically establish carton structural acceptance.

03.1 Local pressure bearing and deformation threshold of cartons

Use $\Delta p_{min,LB}$ as the average compressive stress over the suction-cup area, while recognizing stress concentration in the narrow cup-lip annulus. Perform static holding and dynamic cycling on the target carton and inspect the suction surface after acceptance testing. The hard acceptance conditions are: the lid does not pull open; the liner does not separate from the corrugated medium; and no through-damage occurs. At 60 s after unloading, the measurement upper bound of permanent indentation in the suction zone relative to the unloaded reference plane shall be ≤2.00 mm. Any structural damage makes R9 fail even if vacuum pressure, load, and cycle time all pass.

Run the material-bearing test for 10 min at each lower-bound pressure differential, 45 kPa and 50 kPa. For the dynamic test, run 120 cycles for each of the six dynamic-path cells in Chapter 08. More suction cups increase total load-bearing area but do not automatically reduce local stress beneath an individual cup; the placement and compression of every cup shall satisfy the gates above.

04 Leakage flow balance and vacuum establishment time

The vacuum source selection uses the lower flow rate limit of the actual pipeline, valve, filter and generator combination at the lowest gas supply gauge pressure of 0.40 MPa and 45 kPa pressure difference, and does not use the two isolated catalog values of "maximum suction flow" or "final vacuum level". Source and leakage must be uniformly converted to p_N=101.325 kPa, T_N=293.15 K. The hard criteria for single partition are:

$$Q_{S,LB} = Q_{S,meas} - U_{QS} Q_{L,UB} = Q_{L,meas} + U_{QL} Q_{S,LB}(45\ \text{kPa},\ 0.40\ \text{MPa gas supply}) / Q_{L,UB} \geq 1.50$$

Use the maximum $Q_{L,meas}$ indication in the complete test matrix, not the average, and do not discard a sample merely because suction succeeded despite high leakage. Include the combined expanded uncertainties from the flow meter, supplier curve, and piping conversion in U_Q; this report requires $U_Q/Q \leq 2\%$. SMC's official information describes how to back-calculate leakage using the actual generator, suction cups, workpiece, and vacuum gauge, and explains that leakage through rough or porous workpieces can prevent the required vacuum from being reached [5]. GB/T 32293—2015 is used only to select the hardware Q_H leak-test method; Q_P, Q_E, and total process flow Q_L use the workpiece process tests in this report. Records shall state pressure, temperature, range, sampling rate, and reference state.

In the pressure difference range from 0 to 50 kPa, the lower bound of the standard flow rate of the vacuum source after deducting leakage is Q_net,LB. The conservative time for a single zone to be pumped from atmospheric pressure p_0 to target absolute pressure p_1 is:

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Q_net,LB = min[Q_S,LB(p) - Q_L,UB(p)]
t_ev = V_Z,UB (p_0 - p_1) / (p_N Q_net,LB)
t_pick = t_ev + t_stable + t_aux
```

Convert Q to L/s and set target p_1=p_0−50 kPa. If Q_net,LB≤0, the condition fails immediately. Set t_stable=0.20 s and fix the combined upper bound for valve response, sensor response, PLC scan, and permissive output at t_aux=0.10 s. The total time from contact until every zone reaches a 50 kPa pressure lower bound, 20 consecutive samples pass, and window peak-to-peak variation is ≤2 kPa shall be ≤2.0 s. Inhibit lifting and horizontal acceleration if any zone times out, any sample falls below threshold, no new analog sample arrives within 30 ms, or discrete and analog signals conflict for more than 50 ms.

05 Zoning, non-return, current limiting and leakage compensation architecture

The four partitions are configured with vacuum generating branches, pressure detection, isolation components and diagnostic numbers respectively. Each zone suction cup geometrically spans both sides of the center of gravity of workpiece; the actual three-dimensional coordinates after losing any zone must be balanced by the combined load in Chapter 03, and shall not be replaced by "the quantity of suction cup is sufficient" or two-dimensional appearance judgment. Chapter 06 Lock the x-z plane and set all y inputs to zero. Central main pressure is for diagnostic purposes only and is not a substitute for zoning permits.

architectural elements	Force function	Nonconforming Condition
Independent partition pressure taking	Identify local air leaks, air suction and cup detachment	Only measure main pipe pressure
Check or vacuum throttling	Blocking faulty areas brings down healthy areas	Open circuit in any zone will cause the lower pressure limit of any healthy zone to be less than 45 kPa
Vacuum source flow reserve	Maintain threshold below leakage upper bound	Q_S,LB/Q_L,UB < 1.50
pressure permission logic	The lower limit of pressure in each zone is ≥50 kPa, continuous for 200 ms, and the peak-to-peak value is ≤2 kPa	Only use timer or single total signal
Backup energy supply	t_1−t_0≤0.10 s and maintained until t_3	Adiabatic holding time <8.50 s or Q_S,LB/Q_L,UB <1.50 at 0.40 MPa

architectural elements	Force function	Nonconforming Condition
controlled exhaust	The double supports are released after confirming for 500 ms, speed ≤ 0.01 m/s, and position error ≤ 5 mm.	If any of the conditions are not met, exhaust can still occur

SMC's vacuum energy-saving valve data shows that air leakage not covered by suction cup can be restricted, thereby maintaining the vacuum of the remaining circuits [5]; Piab's foam tooling data also uses check valve technology for materials with different porosity [11]. These elements are not automatically safe: stuck valves, contamination, reverse leakage and response times must be fed into fault injection.

Apply leakage compensation in this priority order: increase effective suction area; improve suction-cup placement and sealing; shorten and enlarge the main line; distribute the vacuum sources; then increase source flow. Do not substitute unlimited extraction flow for zone isolation, because a large local opening can still consume all available flow and mask a cup that is losing contact.

06 Calculation and unique determination of benchmark operating conditions

The fixed calculation conditions in this chapter are as follows: handling object always keeps the suction surface horizontal, $\theta=0$; the calculation plane is x-z, lock $a_{y,UB}=0$, $e_{y,UB}=0$, $M_x=0$, $M_z=0$. Taking the geometric center of the suction cup array as the temporary calculation origin, the suction cup projection is $x=\pm0.25$ m, $y=0$, and the center of gravity coordinates are $(0.060, 0, -0.160)$ m; when entering the vector equations in Chapter 03, r_i is converted according to "suction cup coordinates minus the center of gravity coordinates". When the y-direction acceleration, eccentricity or moment is not zero, enter all three-dimensional coordinates and perform vector balance.

Input amount	Locked value including uncertainty
Carton quality upper bound m_{UB}	18.0 kg
suction cup quantity and partition	8, 4 zones, 2 in each zone
Lower bound of single cup effective area $A_{eff,LB}$	0.0060 m²
suction cup two-dimensional projection coordinates	Relative to the center of the array, $x=\pm0.25$ m, $y=0$; one cup on each side of the positive and negative sides of each area
Fault-maintained pressure difference lower bound $\Delta p_{min,LB}$	45 kPa

Input amount	Locked value including uncertainty
Lower bound of allowable pressure difference for normal lifting Δp_pick,LB	50 kPa
Friction coefficient lower bound μ_LB	0.35
Normal and fault upward acceleration upper bound a_z,UB	1.50 m/s²
Normal and fault level acceleration upper bound a_x,UB	2.00 m/s²
Y-direction acceleration and eccentricity	a_y,UB = 0； e_y,UB = 0
Center of gravity horizontal offset upper bound e_x,UB	0.060 m
Upper bound h_UB of center-of-gravity height above the suction plane	0.160 m
External roll and yaw moment	M_x = 0； M_z = 0
Specify support level	S1＝(1.00, 0, −0.20) m; the upper limit of fault path length is 1.20 m
Upper bound of equivalent pumping volume in single zone V_Z,UB	1.80 L
Single zone leakage maximum indication value and U_QL	55.0、1.1 NL/min； Q_L,UB = 56.1 NL/min
Minimum indication value of source flow in single area and U_QS	90.0、1.8 NL/min； Q_S,LB = 88.2 NL/min
Applicability conditions for source flow	Full range of 0~50 kPa, air supply gauge pressure 0.40 MPa, filter life limit
Stable and auxiliary time	t_stable = 0.20 s； t_aux = 0.10 s
Upper bounds for air-receiver volume, supply pressure, and initial temperature	The lower limit of the effective volume is 25.0 L; the lower limit of the initial gauge pressure is 0.70 MPa, and the upper limit of the lowest available gauge pressure is 0.40 MPa; T_1,UB=298.15 K
Maximum four-zone air-consumption indication and U_Qair	300、6 NL/min； Q_air,UB = 306 NL/min

06.1 Normal state bearer

The lower bound of the total area is 8×0.0060＝0.0480 m², and the capacity of a single cup C_i ＝45000×0.0060＝270 N:

$F_{N,cap,LB} = 45000 \times 0.0480 = 2160$ N; $F_{N,d} = 2.5 \times 18 \times (9.81 + 1.50) = 508.95$ N; normal capacity ratio = 2160 / 508.95 = 4.24 > 1.00: pass. $F_{T,cap} = 0.35 \times 2160 = 756$ N; $F_{T,d} = 2.5 \times 18 \times 2.00 = 90$ N; tangential capacity ratio = 756 / 90 = 8.40 > 1.00: pass.

Taking the center of the suction cup array as the center of gravity, the pitching moment formed by horizontal acceleration and center of gravity offset is:

$M_d = F_{N,d}\, e_x + F_{T,d}\, h = 508.95 \times 0.060 + 90 \times 0.160 = 44.94$ N·m Normal force difference on both sides $\Delta F = M_d / 0.25 = 179.76$ N High load side demand = (508.95 + 179.76) / 2 = 344.36 N low load side demand = (508.95 - 179.76) / 2 = 164.60 N capacity per side = 4 × 45000 × 0.0060 = 1080 N passed on both sides

Evenly distributed according to four cups/side, N_H=344.36/4=86.09 N per cup on the high-load side, N_L=164.60/4=41.15 N per cup on the low-load side, and the tangential force of the eight cups is T=90/8=11.25 N. The linear combination envelope is:

$\eta_H = 86.09/270 + 11.25/(0.35\times270) = 0.44$ $\eta_L = 41.15/270 + 11.25/(0.35\times270) = 0.27$ $\max(\eta_H,\eta_L) = 0.44 \le 1.00$, the combined load passes

06.2 Flow and establishment time

The upper leakage bound is 56.1 NL/min and the source flow lower bound is 88.2 NL/min:

Source/leakage ratio = $Q_{S,LB} / Q_{L,UB}$ = 88.2 / 56.1 = 1.572 ≥ 1.50: pass. Demand-capacity ratio = $Q_{S,LB}$ / (1.5 $Q_{L,UB}$) = 88.2 / 84.15 = 1.048 ≥ 1.00: pass. $Q_{net,LB}$ = 88.2 - 56.1 = 32.1 NL/min = 0.535 L/s; p_1 = 101.325 - 50 = 51.325 kPa; t_{ev} = 1.80 × (101.325 - 51.325) / (101.325 × 0.535) = 1.66 s; t_{pick} = 1.66 + 0.20 + 0.10 = 1.96 s ≤ 2.00 s: pass.

"Source/leak ratio" and "demand capacity ratio" are two different indicators, the former has a threshold of 1.50, and the latter has a threshold of 1.00. The four zones must reach the lower limit of 50 kPa and stabilize for 200 ms respectively; if any zone exceeds 2.00 s, R4 will not pass.

06.3 Complete failure of single zone

After any zone is isolated, there are 6 suction cup remaining, with an area of 0.0360 m²; since each zone has one cup on the positive and negative sides of x, there will still be 3 cups on each side after any zone fails.

$F_{N,1fail}$ = 45000 × 0.0360 = 1620 N; normal capacity ratio = 1620 / 508.95 = 3.18: pass. $F_{T,1fail}$ = 0.35 × 1620 = 567 N; tangential capacity ratio = 567 / 90 = 6.30: pass. Remaining capacity on one side = 3 × 45000 × 0.0060 = 810 N; 810 > 344.36 N and 810 > 164.60 N: moment distribution passes.

After any zone fails, there will be three cups left on each of the high load side and the low load side. Take each cup T=90/6=15 N:

$N_{H,1fail}$ = 344.36/3 = 114.79 N; $N_{L,1fail}$ = 164.60/3 = 54.87 N; $\eta_{H,1fail}$ = 114.79/270 + 15/(0.35×270) = 0.584; $\eta_{L,1fail}$ = 54.87/270 + 15/(0.35×270) = 0.362; max($\eta_{H,1fail}$,$\eta_{L,1fail}$) = 0.584 ≤ 1.00: pass.

Therefore, within the validated 18 kg upper mass limit, horizontal suction surface, fixed normal/fault acceleration bounds, and two-dimensional eccentricity envelope, both rapid screening and combined-load verification pass in the normal state and with complete failure of any one zone.

06.4 Main energy supply loss and controlled placement

The base working condition adopts the compressed air reserve with an effective volume lower limit of 25.0 L, a lower starting gauge pressure of 0.70 MPa, and an upper limit of the lowest available gauge pressure of 0.40 MPa; p_N=0.101325 MPa, absolute pressure P_1=0.801325 MPa, P_2=0.501325 MPa. An adiabatic rigid tank deflation model with air γ = 1.4 is used, the standard temperature is $T_N = 293.15$ K, the upper bound of the initial temperature in the tank is $T_{1,UB} = 298.15$ K; the upper bound of the air consumption in the four zones is 306 NL/min = 5.10 NL/s. When the minimum air supply gauge pressure is 0.40 MPa, each zone $Q_{S,LB}$ = 88.2 NL/min, and has passed the 1.50 flow gate.

$m_2/m_1 = (P_2/P_1)^{(1/\gamma)} = (0.501325/0.801325)^{(1/1.4)} = 0.7153$; $V_{N,use} = 25 \times (0.801325/0.101325) \times (293.15/298.15) \times (1 - 0.7153) = 55.34$ NL; $t_{res} = 55.34 / 5.10 = 10.85$ s; $t_{required} = (t_2-t_0)_{max} + 2(t_3-t_2)_{max} = 0.50 + 2 \times 4.00 = 8.50$ s; $10.85 > 8.50$ s: pass.

Sole calculation conclusion: this configuration passes R2, R3, the establishment-time calculation, single-zone-failure calculation, and backup-duration calculation and may proceed to FAT/SAT under Chapters 08 and 09. Engineering release of the vacuum gripping subsystem is achieved only when every FAT and SAT boundary cell and fault injection has zero failures and all complete-machine prerequisite-gate records are present.

07 Single-Zone Failure, Total Loss of Air, and Controlled Set-Down Logic

Run permission logic must not mix alarms and safety actions in a delay chain. The state machine uses the following hard logic:

Lift_Enable =Workpiece_Present∧ Zone_A_OK ∧ Zone_B_OK ∧ Zone_C_OK ∧ Zone_D_OK∧ Δp_{LB} per zone ≥ 50 kPa continuous 200 ms∧ 200 ms window peak-to-peak value ≤ 2 kPa∧ Motion_Envelope_OKSingle_Zone_Fault →Prohibit continued production path∧ $|a_{z,UB}| \le 1.50$ m/s²∧ $\sqrt{a_{x,UB}^2+a_{y,UB}^2} \le 2.00$ m/s²∧ Overturning prohibited∧ Execute registered support position S1 placement Main_Supply_Loss → Standby establishment $t_1-t_0 \le 0.10$ s∧ Fault confirmation $t_2-t_0 \le 0.50$ s∧ Maintain all healthy partitions ∧ Support transfer $t_3-t_2 \le 4.00$ s

The four timestamps use the same 1 ms time base. t_0 is the earlier of the first instant when the main-supply inlet-pressure lower bound falls below 0.55 MPa gauge or the main-valve-open signal is lost. t_1 is the first instant when the inlet supply-pressure lower bound at all four zone generators reaches 0.40 MPa gauge. t_2 is when the controller sets the energy-supply fault and issues the set-down command. t_3 is the first instant when both independent support sensors are ON and the support-force lower bound has reached 0.95m_UBg continuously for 500 ms. The 4.00 s interval begins at t_2; the total upper limit from loss of main energy to transfer onto support is 4.50 s.

In this working condition, the registered support position S1 = (1.00,0,−0.20) m, the position tolerance is ±5 mm, the upper limit of the path length from any point of the motion envelope to S1 is 1.20 m; the lower limit of the support force is 0.95×18×9.81=167.75 N. The R1 input table must register the support position coordinates, path upper limit and support force gate; unregistered positions do not constitute safe support positions.

Do not actively vent after any failure occurs. The release permission must simultaneously meet: the end position enters S1±5 mm; the movement speed is ≤0.01 m/s for 500 ms continuously; the two independent support sensors are continuously set for 500 ms; the lower limit of the support force is ≥0.95m_UBg; the manual release command is maintained for 500 ms. Exhaust is allowed only after all five items are met. Pressure recovery is not allowed to continue running automatically. It must complete t_3. Check workpiece and manually reset it to establish a new cycle.

Verify the backup energy supply by shutting off main energy under the combined conditions of initial gauge pressure 0.70 MPa, leakage upper bound, air-consumption upper bound, filter service-life boundary, and 1.20 m fault path. From t_0 through t_3, controlled set-down fails if any healthy-zone pressure lower bound is <45 kPa, any fault-acceleration upper bound is exceeded, any t_1/t_2/t_3 time gate is exceeded, or a person supports the workpiece manually.

08 Test matrix, measurement chain and recording requirements

Run the complete matrix separately at FAT and SAT for every carton specification; FAT data cannot be credited against SAT. The coordinate origin is the carton's design suction center. Fix permitted suction-cup placement offset at ±20 mm in both x and y and compression at 5–9 mm. Use independent cartons for every boundary cell: three incoming batches × 10 cartons/batch × 5 cycles/carton = 150 cycles. Save four zone curves per cycle, giving 600 zone curves per cell.

unit	Suction-Cup Placement Point / State	Amount of compression	Contamination and Service Life	Samples per stage
E1	(0,0) mm, center area not printed	7 mm	Clean new parts	150 cycles/600 curves
E2	(+20,0) mm	7 mm	Clean new parts	150 cycles/600 curves
E3	(−20,0) mm	7 mm	Clean new parts	150 cycles/600 curves
E4	(0,+20) mm	7 mm	Clean new parts	150 cycles/600 curves
E5	(0,−20) mm	7 mm	Clean new parts	150 cycles/600 curves
E6	100% printing coverage area, sealing lip is 10 mm away from the tape edge	7 mm	Clean new parts	150 cycles/600 curves
E7	(0,0) mm	5 mm	Clean new parts	150 cycles/600 curves
E8	(0,0) mm	9 mm	Clean new parts	150 cycles/600 curves
E9	(0,0) mm	7 mm	0.50 g/m² paper powder, new	150 cycles/600 curves
E10	(0,0) mm	7 mm	0.50 g/m² paper powder, 100000 cycles or 0.50 mm wear parts	150 cycles/600 curves

For each carton specification at each stage, complete 1500 leakage/establishment cycles and 6000 zone curves; FAT and SAT together total 3000 cycles and 12000 zone curves. If carton material, flute type, number of layers, coating, tape, or upper mass limit changes, treat it as a new specification and repeat the full quantities.

Dynamic handling sets six path units: D1 is 18 kg, $a_{z,UB} = +1.50$ m/s² and $a_{x,UB} = 0$; D2 is 18 kg, $a_{x,UB} = +2.00$ m/s² and $a_{z,UB} = 0$; D3 is 18 kg, $a_{x,UB} = -2.00$ m/s² and $a_{z,UB}=0$; D4 applies $a_{z,UB}=+1.50$ m/s², $a_{x,UB}=+2.00$ m/s² at the same time; D5 applies $a_{z,UB}=+1.50$ m/s², $a_{x,UB}=-2.00$ m/s² at the same time; D6 falls to S1 along the 1.20 m upper boundary path after a single zone fault. All six units use E10 contamination and life status, three batches per unit × 10 boxes × 4 cycles = 120 cycles. Each stage of the dynamic test is 720 cycles, and the total of FAT and SAT is 1440 cycles.

At each stage, independently complete: effective area: 8 cups × 3 compression levels × 2 life states × 10 trials = 480 trials; coefficient of friction: 2 pressure differentials × 2 life states × 2 contamination states × 30 trials = 240 trials; and, with generator supply gauge pressure at 0.40

MPa and filter pressure drop at 5 kPa, 4 zones × 10 curves from 0 to 50 kPa = 40 curves. These counts may not be credited against E1 to E10 or D1 to D6.

Measurement items	Instrumentation and Sampling	Must be recorded	Judgment
Zone pressure	Independent absolute pressure or differential pressure sensor for each zone, ≥100 Hz, U_p/p≤2%	Δp_meas、U_p、Δp_LB	Δp_LB≥50 kPa before lifting; Δp_LB≥45 kPa in healthy area during fault
Leakage and Source Flow	Standard flow meter ≥100 Hz, U_Q/Q≤2%	Q_meas, U_Q, standard status	Q_S,LB/Q_L,UB≥1.50
mass and coordinates	Calibration scale U_m≤0.10 kg; three-dimensional measurement U_r≤1.0 mm	m_meas, U_m, suction cup/center of gravity/support position coordinates	m_UB=m_meas+U_m; take the absolute value of eccentricity and moment arm plus U_r
dynamic load	Independent three-axis accelerometer ≥200 Hz, U_a≤0.05 m/s²	Indication value of each axis, U_a, fault braking peak value	a_UB = max
Displacement/slip	≥100 fps visual measurement, U_s≤0.20 mm	Start point, peak point, end point and scale	s_UB = s_meas+U_s≤2.00 mm
Supporting force	Calibrate force measuring element, U_F/F≤2%	F_support,meas, U_F and double support signals	F_support,LB＝F_meas−U_F≥0.95m_UBg and maintain for 500 ms
Volume, gas storage pressure and temperature	Volume U_V/V≤2%; pressure U_P≤0.005 MPa; temperature U_T≤1 K	Partition/tank volume, P_1, P_2, T_1 and each U value	Use the upper bound for evacuated volume; use the lower bounds for air-receiver volume and P_1, and the upper bounds for P_2 and T_1.
Effective area	Calibration image or size measurement, U_A/A≤2%	Compression, seal inner boundary and area	Calculation only uses A_eff,LB=A_meas−U_A
Friction coefficient	Calibration force gauge, U_μ≤0.02	Slip starting point force, pressure difference, area, state	Calculation only uses μ_LB=min(μ_meas)−U_μ
Backup energy supply	Pressure, flow and 1 ms event time base	t_0, t_1, t_2, t_3, lowest partition pressure	≤0.10 s, ≤0.50 s, ≤4.00 s and healthy area Δp_LB≥45 kPa

Pressure permission always uses a lower bound. When $U_p/p=2\%$, the lower bound of 50 kPa corresponds to an indication value of at least 51.02 kPa, and the lower bound of 45 kPa corresponds to an indication value of at least 45.92 kPa. The sampling clock difference must be ≤10 ms. When the pressure switch only has a switching value, the recordable analog pressure must be added; there is no original curve, only a success/failure bit, and R10 does not pass.

The release window is fixed at $0 \le \Delta p_{UB} \le 5$ kPa and lasts for 500 ms. If the simulated pressure change is less than 0.50 kPa within 300 ms after the valve operates, or there is no new sample for 30 consecutive ms, it is judged as signal stagnation; if the switching value and analog value conflict for more than 50 ms, it is judged as a diagnostic fault.

Raw data shall not consist only of images. Each curve shall retain timestamp, zone number, sample number, batch number, suction-cup placement-point number, pressure, flow, acceleration, valve state, and permissive state, with units in field names or metadata. Archive data-processing scripts and parameters together, and make every calculated output traceable back to its raw row. Exclude data only for a clearly demonstrated instrument failure, retaining the exclusion reason, failure evidence, and retest record together. Deleting a high-leakage or slow-establishment cycle as an outlier makes R10 fail immediately.

09 FMEA driven fault injection matrix

This chapter converts the failure modes identified by FMEA into repeatable fault injections without deleting faults with low occurrence rates. Each injection uses an 18 kg mass upper bound, E10 contamination/lifetime status, and a 1.20 m fault path; FAT and SAT perform full table quantities separately. The non-energy supply fault uses t_F to represent the physical injection time, and the fault confirmation gate is $t_2 - t_F \le 0.50$ s; the main power supply fault continues to use Chapter 07 t_0~t_3.

failure mode	Injection method	times per stage	Control actions that must occur	pass standard
Single suction cup not covered	Set 6.0 mm calibration opening per cup	8 cups × 10 = 80	Alarm in the corresponding area and execute S1 placement	Healthy area $\Delta p_{LB} \ge 45$ kPa, $t_2 - t_F \le 0.50$ s, $t_3 - t_2 \le 4.00$ s
Single zone pipeline disconnection	The quick-disconnect connectors in each zone are completely disconnected	4 areas × 10 = 40	Isolate the fault area and implement S1 placement	All 40 trials meet the time, pressure, acceleration, and slip gates
Check valve stuck	The bypass check valve in each zone forms a fully open passage	4 areas × 10 = 40	The health area independently diagnoses and implements S1 placement	If Δp_{LB} in any healthy area is less than 45 kPa, the entire project fails.

failure mode	Injection method	times per stage	Control actions that must occur	pass standard
Pressure sensor card height	Inject full-scale high level into each channel: 5 trials before lifting and 5 during motion	4 channels × 10 = 40	Permission is prohibited before lifting; perform S1 placement during movement	No error Lift_Enable is generated, and gates t_2 and t_3 are satisfied during motion.
Pressure sensor stuck low	Inject 0 kPa signal into each channel; 5 times before lifting and 5 times during exercise	4 channels × 10 = 40	Lock before lifting; perform S1 positioning during movement	Bypass operation is prohibited; healthy-zone pressure remains within the acceptance limit
Main compressed air cut off	Close the main valve 1.20 m away from the S1 path	10	Execute S1 placement after t_1 and t_2	t_1−t_0≤0.10 s, t_2−t_0≤0.50 s, t_3−t_2≤4.00 s
Standby Reserve Low Pressure	The initial gauge pressure is fixed at 0.39 MPa	10	Lock before starting	10/10 Lift_Enable must not be generated
Partial collapse of carton	The suction area is prefabricated with a depression of 30 mm in diameter and 5.0 mm in depth.	10	Perform S1 placement after pressure failure	No tearing, no drop, and s_UB≤2.00 mm
Software timer advance	Fixed delay to 0.50 s	10	Pressure interlock continues to prevent movement	There is no improvement in any area where Δp_LB＜50 kPa
Exhaust valve malfunction	Inject exhaust output request at midpoint of path	10	Five Release License Blocking Requests	t_3 front exhaust valve must not be powered on

A total of 290 fault injections are performed in each stage, and FAT and SAT total 580 times. Fault injection must use anti-fall receiving devices and clear the danger zone. Any unexpected movement, pressure lower limit crossing, time limit exceeding, acceleration upper limit exceeding limit, slip upper limit exceeding limit, exhaust malfunction or manual support of workpiece will be counted as a failure; after failure, no additional attempts are allowed. After the rectification is completed, the failure mode will be re-executed from the first time in this stage.

10 FAT, SAT, and Engineering Release Criteria for the Vacuum Gripping Subsystem

Subsystem engineering release comprises four gates: prerequisites, design data, factory acceptance testing (FAT), and site acceptance testing (SAT). Engineering release of the vacuum gripping subsystem requires all four gates to pass. Passing calculations cannot replace physical acceptance testing; FAT data cannot be credited against SAT; and supplier samples cannot replace the target carton.

No.	Release Gate	Clear passing standards
R1	Prerequisite Gate and Input Freeze	Complete-machine risk assessment passes; validated PL/SIL for Lift_Enable, fault detection, exhaust inhibition, and controlled set-down is ≥ the risk-assessment requirement; robot integration, air-receiver compliance, and environmental compliance pass; and mass/center of gravity/three-dimensional coordinates/acceleration/safe position/A_eff,LB/μ_LB/Q_L,UB/Q_S,LB and all U values are version-controlled
R2	Static/dynamic hosting	The fast capacity ratio is ≥1.00 when normal and any zone fails, and there is a three-dimensional equilibrium solution with η_i≤1.00 at all 10 ms moments.
R3	Flow reserve	Each zone Q_S,LB(45 kPa, 0.40 MPa gas supply)/Q_L,UB≥1.50
R4	Setup time	The 150/150 cycle and 600/600 partition curves of each unit of E1~E10 all reach the 50 kPa lower limit within 2.0 s and stabilize for 200 ms.
R5	Dynamic handling	D1～D6 120/120 cycles per unit; zero drop, s_UB≤2.00 mm, the upper limit of acceleration does not exceed the calculation envelope
R6	Single zone failure	The four zones were disconnected 10 times each, and the check valve was stuck 10 times each; the healthy zone Δp_LB≥45 kPa, all dropped to S1 on time
R7	Main energy supply loss	10/10 times meet t_1−t_0≤0.10 s, t_2−t_0≤0.50 s, t_3−t_2≤4.00 s, t_0~t_3 healthy zone Δp_LB≥45 kPa
R8	fault injection	Chapter 09 290/290 times per stage with zero error permission, zero false exhaust, zero time/pressure/acceleration/slip line crossing

No.	Release Gate	Clear passing standards
R9	carton structure	No cover is opened, surface layer is peeled off or perforated; upper limit of permanent depression ≤ 2.00 mm after unloading for 60 seconds
R10	record integrity	The original pressure/flow/acceleration/displacement curve, t_0~t_3 log, instrument U value, configuration and conclusion are traceable

FAT and SAT use the same thresholds and independently complete the full required quantities. If the vacuum generator, suction-cup model/hardness, pipe diameter, filter, valve, control program, carton material, coating, tape, mass, center of gravity, or path acceleration changes on site, the existing release boundary expires immediately and R1–R10 shall be repeated in full. Conditional release is not permitted: if any item is not met, the vacuum gripping subsystem fails engineering release.

11 Engineering control and maintenance requirements

1. Suction cups and placement points: the sealing lip shall not cross a carton-lid opening, damage, or a crease, indentation, or tape step with height difference/depth ≥0.50 mm. Its minimum distance from those boundaries shall be ≥10 mm. Mechanical guidance limits compression to 5–9 mm.
2. Filtration and drainage: Each zone is equipped with a pressure difference monitoring filter. When the upper limit of the filter pressure difference reaches 5 kPa or the use reaches 500 h, whichever comes first, lock and replace it; perform the Q_H pre-shift test again after replacement.
3. Zone inspection: Use an airtight standard plate to perform hardware leakage self-inspection at a pressure difference of 45 kPa before the start of each shift; any zone with Q_H,UB/Q_S,LB > 0.05 will be out of service for maintenance.
4. Sensor diagnostics: before suction, 0≤Δp_UB≤5 kPa continuously for 500 ms. Set a fault if the change is <0.50 kPa within 300 ms after valve actuation, no new sample arrives for 30 ms, or the discrete and analog signals conflict for >50 ms.
5. Pressure threshold protection: Δp_LB per zone must be ≥50 kPa during normal movement. If a 100 Hz sampling point Δp_LB <45 kPa appears in any healthy zone, the controller sets a fault in the next scan cycle, and the t_2 time gate must still be ≤0.50 s.
6. Change management: suction cup, sealing materials, valves, hose lengths, vacuum sources, program parameters and carton materials are all included in version management. No substitution is allowed without recalculation and corresponding re-inspection.
7. Personnel protection and energy isolation: before maintenance, shut off and lock out the supply and release residual pneumatic energy. Permit entry only after the support-force

lower bound reaches 0.95m_UBg continuously for 500 ms. ISO 4414:2010 applies to design, installation, operation, and maintenance of pneumatic systems on machinery; it excludes compressors, factory air distribution, gas cylinders, and air receivers [4]. Air-receiver compliance records are part of the R1 prerequisite gate.

12 Research conclusions

Vacuum handling of cartons and porous workpieces is not solely a suction-force problem; it is a system problem combining load capacity, leakage, dynamics, zoning, and response to loss of air. This report fixes engineering release of the vacuum gripping subsystem to six non-substitutable criteria:

1. Using $\Delta p_{min,LB}$, $A_{eff,LB}$, μ_{LB} and 2.5 times dynamic load to check the normal and single-zone fault status, the fast capacity ratio is ≥ 1.00, and there is a three-dimensional equilibrium solution with a combination coefficient $\eta_i \leq 1.00$ at every 10 ms moment.
2. Each zone meets $Q_{S,LB}/Q_{L,UB} \geq 1.50$ at a pressure difference of 45 kPa and a minimum air supply gauge pressure of 0.40 MPa.
3. Every zone reaches a 50 kPa lower bound within 2.0 s; 20 consecutive samples pass and window peak-to-peak variation is ≤2 kPa; the permissive comes from per-zone pressure signals.
4. When any zone completely fails, the lower bound of the pressure in the healthy zone remains ≥45 kPa, the upper bound of the fault acceleration does not exceed the envelope, and the system falls to the registered support level.
5. $t_1-t_0 \leq 0.10$ s, $t_2-t_0 \leq 0.50$ s, $t_3-t_2 \leq 4.00$ s; the adiabatic model with backup energy supply based on $\gamma=1.4$ and 298.15 K initial temperature upper limit satisfies $t_{res} \geq 8.50$ s.
6. FAT and SAT independently complete, for each specification, ten boundary cells, six dynamic cells, and 290 fault injections, all with zero failures and complete R1 prerequisite-gate records.

Chapter 06 gives a single calculation-pass conclusion for the 18 kg carton baseline: normal and tangential rapid capacity ratios are 4.24 and 8.40, respectively, with a maximum interaction coefficient of 0.44; after one-zone failure, the rapid capacity ratios are 3.18 and 6.30, with a maximum interaction coefficient of 0.584; $Q_{S,LB}$=88.2 NL/min and $Q_{L,UB}$=56.1 NL/min; source/leakage ratio is 1.572 and demand-capacity ratio is 1.048; establishment-permissive time is 1.96 s; and adiabatic backup-energy duration is 10.85 s, greater than 8.50 s. This calculation result proceeds to the specified FAT/SAT verification process.

The vacuum gripping subsystem passes only after R1–R10 each has independent zero-failure FAT and SAT records; if any item is missing, it fails. Complete-machine release additionally includes risk assessment, control-safety validation, robot integration, and air-receiver compliance records.

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