Loss-of-Air Protection and Safe Release for Custom Industrial Handling Tooling / and Engineering-Validation Methods

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Revision note: Following technical-review comments, this compiled and optimized version adds material on the title, applicability boundaries, cited standards, safety-control levels, FMEA scoring notes, test equipment and project-specific checklists. The principal technical approach retains the original design logic: no unintended release after loss of air; controlled release only after conditions are met.

Applicable Boundaries and Usage Statement

1) This document compiles internal engineering-validation methods and a technical white paper. It may be used for design discussions, internal training, project risk reviews, and preparation of materials before customer technical communication.

2) This document is not equivalent to a third-party certification report, type-test report, CE/ISO declaration of conformity, customer-acceptance document or quality certificate.

3) Parameters such as pressure, time, gripping force, slip and response time shall be identified as calculated values, compiled internal test values or engineering recommendations. Each actual project must reverify them against workpiece mass, center of gravity, temperature, gripping method, compressed-air supply conditions, motion profile and site risk assessment.

4) External release or project archiving requires the original test records, sensor calibration certificates, site photographs, test curves, signature pages and project-specific risk-assessment records to be added.

Abstract: Industrial handling tooling is widely used with Pneumatic Industrial Manipulators, pneumatic handling systems, robot end effectors, vacuum lifting systems, and special-purpose In loading and unloading and other scenarios, its safety release and the design of loss-of-air protection are directly related to the risks of workpiece falling, equipment collision, personnel burns and production line shutdown. Where the compressed-air supply pressure drops suddenly, an air hose ruptures, a valve assembly malfunctions or a control signal fails, gripping force may decay and an unintended release may occur. To address these risks, this study proposes a method for loss-of-air protection and safe release of industrial handling tooling. The method emphasizes the design logic no unintended release after loss of air; controlled release only after conditions are met. On loss of air, the system first maintains the grip, stops handling and prevents release while the workpiece is suspended. Only after the workpiece is supported and the tooling is at a safe location, the manipulator or robot is in an approved release pose, personnel are in a safe area, and the release-interlock conditions are satisfied may the system perform a low-speed, diagnosable and resettable release. Pneumatic external-clamping, gripping, vacuum-holding, internal-expansion, hook-type, rotating and high-temperature workpiece handling tooling are covered. The study systematically addresses gripping-force calculation, mechanical self-locking, geometric support, pneumatic-circuit pressure retention, leak detection, pressure decay monitoring, release interlocks, maintenance reset and engineering-validation plans. The pressure, time, gripping force, slip and response-time values are presented as engineering reference values or compiled internal test values and require project-specific verification against the workpiece, tooling structure, compressed-air supply conditions and handling motion profile and site safety requirements.
Keywords: industrial handling tooling; safe release; loss-of-air protection; pneumatic tooling; mechanical self-locking; gripping-force calculation; pneumatic-circuit pressure retention; leak detection ; high-temperature workpiece handling; custom manipulator; engineering validation

Research on Air-loss Protection, Safe Release and Engineering Verification Methods for Non-standard Industrial Handling Fixtures

Abstract: Industrial handling fixtures are widely used in assisted manipulators, pneumatic handling systems, robot end-effectors, vacuum lifting systems and dedicated loading/unloading equipment. Their safe release and air-loss protection design is closely related to the risk of workpiece falling, equipment collision, operator injury and production interruption. This paper proposes a design method for air-loss protection and controlled safe release of industrial handling fixtures under rapid pressure drop, pipe rupture, valve malfunction and control signal failure. The method follows the principle of “no unintended release under air loss, and controlled release after confirmation”. It integrates clamping-force calculation, mechanical self-locking, geometrical support, pressure holding, leakage detection, pressure-decay monitoring, release interlocking, maintenance reset and simulated verification. All numerical values in this paper are engineering reference values or simulated verification settings and shall be recalculated for specific projects.

Key words: industrial handling fixture; safe release; air-loss protection; pneumatic clamp; mechanical self-locking; clamping force calculation; pressure holding; leakage detection; high-temperature workpiece handling; engineering verification

1 Introduction

In an industrial automated handling system, tooling is normally installed at the end of a manipulator, pneumatic balancer, gantry manipulator, industrial robot or jib The end of the crane or special machine loading and unloading mechanism is the key execution unit to realize workpiece clamping, carrying, posture conversion, transfer and release. with ordinary Different positioning tooling, the industrial handling tooling not only needs to meet the clamping requirements under rated working conditions, but also needs to be used when the compressed-air supply fails, the control is abnormal, and the clamping Avoid further expansion of risks under foreseeable abnormal conditions such as claw wear, workpiece eccentric load, high temperature radiation and maintenance misoperation.

In pneumatic handling tooling, compressed-air supply pressure normally establishes gripping force, drives the gripper jaws and actuates release. If the tooling design relies only on pneumatic pressure retention, a sudden interruption of the main compressed-air supply, air-hose rupture, quick-coupler separation, spool sticking, unintended release-valve actuation or gripping- If the cavity leaks, the clamping force may drop rapidly, causing the workpiece to slip, fall or impact. For high temperature castings, forgings and heat treated parts, by Since workpiece has high temperature, a lot of surface oxide scale, large fluctuations in friction coefficient, and personnel cannot intervene at close range, loss-of-air protection is especially suitable for safety release design. important.

Safe release of industrial handling tooling does not mean releasing immediately after loss of air. It means maintaining the load under an abnormal condition and then performing a controlled, low-speed, diagnosable and resettable release only after the workpiece is supported, personnel have withdrawn, the position is confirmed and the control system satisfies the release conditions. The design logic can be summarized as: no unintended release after loss of air; controlled release only after conditions are met.

2 Research objects and boundary conditions

2.1 Research objects

The research objects of this study are custom handling tooling and its safe release, loss-of-air protection and engineering verification methods in the industrial handling scenario, mainly including Including pneumatic clamping type handling tooling, clamping type handling tooling, vacuum gripping type handling tooling, inner support type handling tooling, hook type handling tooling, Flip-type handling tooling, high-temperature workpiece handling tooling and other custom industrial handling tooling. Applicable equipment includes manipulator, pneumatic balancing Crane, truss manipulator, industrial robot end effector, special machine loading and unloading mechanism handling, cantilever crane supporting handling tooling and vacuum suction and lifting system.

2.2 Boundary conditions

This study focuses on the design method of pneumatic tooling and composite handling tooling under the conditions of air loss, leakage, mistaken release and maintenance reset. does not replace project-specific risk assessment, mechanical-strength calculations, safety validation of the control system, site commissioning or customer acceptance. Workpiece mass, dimensions, surface condition, temperature, center-of-gravity location, gripping method, handling motion profile, site cycle time, operator work method and compressed-air supply conditions There are large differences between components, so the loss-of-air protection solution must be individually designed, checked and verified based on the actual situation of the project.

3 Risk of loss of air supply and typical failure modes

The risk of industrial handling tooling not only comes from workpiece's own weight, but also from handling acceleration, emergency stop impact, attitude change, gripper jaw wear, friction Decreased friction coefficient, high temperature radiation, workpiece center of gravity shift and personnel misoperation. For clamping, gripping, inner support, vacuum gripping, hook and flip Similar to tooling, although the failure modes are different, their common risks are represented by reduced retention ability, unexpected release, malfunction or inability to operate safely. reset.

Table 1 Loss-of-Air Risks and Typical Failure Modes

serial number	failure mode	Description of main risks
1	The main compressed-air supply is suddenly interrupted	When the pressure supply to the clamping cylinder disappears, without mechanical locking or pressure-maintaining measures, the clamping force may decline rapidly.
2	Main compressed-air supply pressure drops slowly	The clamping force gradually decreases. If there is no low-pressure warning, handling may continue without knowing it.
3 /	Air-hose rupture /	Branch pressure drops rapidly and may depressurize the gripping chamber or cause unintended actuator motion.
4	quick connector disconnect	It often appears as an instantaneous leak and needs to be identified by both the pressure drop rate and the pressure threshold.
5	Valve core stuck	This may result in incomplete clamping, incomplete release or mis-exhaust.
6 /	Unintended release-valve actuation /	If release interlocking is inadequate, the workpiece may be released while suspended.
7	Clamping chamber leakage	The clamping force slowly decays, which may cause the workpiece to slip.
8 /	Air-receiver or check-valve failure /	Local pressure-retention capability decreases and the loss-of-air holding time is shortened.
9 /	Pressure-sensor miscalibration /	The control system may misinterpret the gripping or loss-of-air state.
10	gripper jaw wear	The contact area, friction coefficient and geometric limiting capability are reduced.
11 /	High temperature damages air hoses, seals / and sensors /	Leakage, signal drift or abnormal operation may result.
12	Operator mistakenly presses release button	If there is a lack of double confirmation and support interlocking, it may result in accidental release of the suspension.
13	Maintenance status incorrectly started	When maintenance personnel are in a dangerous area, malfunction of tooling may cause injury.
14 /	Release while the workpiece is unsupported /	The workpiece may fall directly; this is a primary release-interlock hazard to control.
15	Center of gravity shift causes eccentric load slip move	Eccentric load increases the force on one side of gripper jaw, which may induce rotation, overturning or slipping.

Loss-of-air protection cannot be reduced to adding an air receiver or installing a pressure switch. Complete protection consists of mechanical self-locking, geometric support, pneumatic-circuit pressure retention, leak detection, pressure-decay monitoring, release interlocks, operating controls and maintenance-reset procedures.

4 Safe release and loss-of-air protection design principles

Safe release and loss-of-air protection for industrial handling tooling should follow the principles of risk-first design, inherently safe structure, mechanical redundancy, pneumatic-circuit pressure retention, state monitoring, control interlocking, controlled release, maintainable reset and testable validation. Safe release does not mean releasing immediately when the air supply is lost. It means maintaining the load under an abnormal condition and performing a controlled, low-speed, diagnosable and resettable release only after the workpiece is supported, personnel have withdrawn, the position is confirmed and the control system satisfies the release conditions.

Structural intrinsic safety requirements tooling try to reduce the risk of damage through structures such as V-shaped grooves, arc-shaped envelopes, lower brackets, side blocks, limit stops and heat-resistant gripper jaw Dependence on single air pressure maintenance. Mechanical redundancy requires that the wedge self-locking, spring lock pin, pawl mechanism, geometric support and limit stop jointly form a failure mechanism. passive holding capability after loss of air supply. The release interlock must require confirmation of workpiece support, tooling position, and manipulator or robot pose, personnel safe-zone, pressure status, and sensor-signal consistency.

Table 2 Comparison between ordinary pneumatic tooling and loss-of-air protection safety tooling

Contrast Dimensions	Ordinary pneumatic tooling	loss-of-air protection type safety tooling
Holding method	Relies primarily on continuous cylinder pressure.	Combines pneumatic pressure retention, mechanical locking, geometric support, pressure sensing and release interlocking.
Response to loss of air supply	Gripping force may decay as pressure falls.	First stop handling, engage the mechanical lock, retain the grip and prohibit release while suspended.
Release conditions	Often triggered by a single button or ordinary valve control.	Interlocks must confirm workpiece support, position, pose, personnel safety and pressure status.
Leak-detection method	Usually relies on a pressure gauge or visual inspection.	Uses P1, P2 and P3 pressure monitoring, pressure-drop-rate evaluation and signal-consistency diagnostics.
Maintenance safety	May rely on operating procedures alone.	Provides safe depressurization, manual reset, maintenance confirmation and protection against unintended startup.
Applicable scenarios	Low-risk, light-load applications with a stable compressed-air supply.	High-temperature, heavy-load, suspended-handling, pose-changing and custom-handling applications.
Risk-control capability	Limited control of loss-of-air, unintended-release and leakage risks.	Reduces risk through multiple protective layers involving structure, pneumatic circuits, sensing and control.
Dependence on operators	higher.	Lower, release needs to be confirmed jointly by interlocking conditions.
Dependence on compressed-air supply stability	High.	Pressure retention and mechanical holding reduce dependence on the stability of a single compressed-air supply.

5 Clamping force calculation method and representative engineering verification calculation

5.1 Basic logic of calculation

The clamping force design should consider workpiece's own weight, handling acceleration, emergency stop impact, attitude changes, lower limit of friction coefficient, high temperature oxide scale, clamp Claw wear and unbalanced load effects. For the friction clamping type tooling, the clamping force calculation should not be estimated based on static weight only, but the equivalent load method should be used.

$$F_e = m\,g\,(1 + a/g)\,\Phi \qquad (1)$$

where F_e is the equivalent load including handling motion and impact, N; m is workpiece mass, kg; and g is gravitational acceleration, normally In the calculation, 9.81 m/s² is usually taken; a is the maximum acceleration of handling, m/s²; φ is the emergency stop impact correction coefficient, which needs to be according to the handling action curve and Braking characteristics check.

$$N\_total \geqslant K\_s\, F_e \,/\, \mu\_min \qquad (2)$$

where N_total is the target total normal gripping force, N; K_s is the gripping-force safety factor; and μ_min is the lower-bound coefficient of friction, accounting for Consider high temperature, scale, oil dirt, wear and surface roughness changes. The theoretical output force of the cylinder can be expressed as:

$$F_c = P A \eta - F_r \qquad (3)$$

where F_c is effective cylinder output force, N; P is working pressure, Pa; A is effective piston area, m²; and η is transmission efficiency. rate; F_r is seal resistance, spring resistance and mechanism friction resistance, N. If the clamp is enlarged through force-increasing mechanisms such as wedges, toggle levers, and eccentric mechanisms, Holding force, the mechanism transmission ratio, efficiency, wear, jamming, thermal expansion, release resistance, pin shear, gripper jaw elastic deformation and loss of air should also be checked Load capacity in locked state.

5.2 Representative project verification and accounting examples

The following examples are compiled from internal engineering-validation records and engineering-calculation practices of the AUREK Intelligent Technology Research Group during 2023.05—2026.04. The values must still be checked against the original records, project design documents and site safety requirements; they are not uniform design parameters for all projects.

Table 3 Representative high temperature and heavy load working condition test settings (organized from 2023.05 to 2026.04)

Item / Compiled internal test value	
workpiece type High temperature iron castings or forgings	
Workpiece mass / 300 kg	
Overall reference dimensions 900 mm × 450 mm × 250 mm	
workpiece surface temperature / ambient temperature 250℃/25℃	
workpiece center of gravity offset ≤80mm	
handling maximum acceleration 0.3g	
Emergency stop impact correction coefficient 1.2	
Minimum friction coefficient under high temperature oxide scale conditions 0.25	
Clamping force safety factor	≥2.0

Substituting into equation (1) and equation (2), we can get: $F_e = 300 \times 9.81 \times 1.3 \times 1.2 \approx 4.59$ kN, $N\_total \geq 2.0 \times 4.59 / 0.25 \approx 36.7$ kN. Under this internal test setting, the recommended target total normal gripping force is therefore no less than 36.7 kN. If Using double-sided clamping, the theoretical single-sided target clamping force is approximately 18.4 kN; consider gripper jaw wear, air pressure fluctuations, thermal deformation, center of gravity shift and manufacturing assembly deviations are included, a target one-side gripping force of 20–22 kN may be used as the compiled internal test value for two-sided gripping.

6 Mechanical self-locking and safety release mechanism design

Mechanical self-locking does not replace the control system; it is a passive safety layer after loss of air supply. The control system detects states, executes interlocks and manages the release sequence. Mechanical self-locking keeps the tooling in a load-bearing state when the compressed-air supply or a control signal is abnormal, preventing the gripper jaws from opening immediately as pressure decays.

For high temperature, heavy load or suspended handling scenarios, it is recommended to use wedge self-locking, spring lock pin, pawl mechanism, geometric support and limit stop Composite mechanical redundancy. The design of gripper jaw should try to avoid relying entirely on friction and should combine V-shaped grooves, arc envelopes, lower brackets, side blocks, Structures such as limit stops form geometric holding capabilities.

Release should occur in two stages: first disengage the mechanical lock; then open the gripper jaws in a controlled manner. Once the system confirms that the workpiece is supported, the tooling is in a safe position, the manipulator or robot is in an approved release pose, personnel are in a safe area, the pressure state is normal and the lock state Only after diagnosis can the locking pin, pawl or wedge be allowed to be released. Controlled opening of the claw should be through throttle exhaust, proportional control or mechanical speed limit. at low speed to prevent shock or bounce from an instantaneous release. Emergency manual release requires the workpiece to be supported; it must not become a source of unintended release. Protective covers, double-action mechanisms, special keys, or mechanical validation procedures should be provided.

Table 4 Mechanical structure engineering reference indicators

Parameter items	Engineering reference values or recommended verification indicators	design description
wedge angle	5°～7°	Taking both self-locking ability and release resistance into consideration, the state of the friction surface needs to be considered.
Lock pin entry time	≤100 ms	Used for rapid mechanical locking after loss of air or power.
Total response time of air loss lock	≤150 ms	Recommended verification metrics from exception identification to lockout completion.
Normal controlled release time	0.8～1.5 s	Avoid impact or bounce caused by instant release.
Normal release jaw-opening speed /	≤80 mm/s /	Reduce shock during release onto a support.
Emergency manual release claw opening speed	≤50mm/s	Manual release should be slow, abortable and confirmable.
gripper jaw maximum elastic deformation of the end	≤0.2mm	It needs to be checked based on the length, material and stress state of gripper jaw.
Lock pin shear safety factor	≥3.0	It is used to check the key bearing capacity under air loss maintenance state.
Wedge contact surface safety factor	≥1.5	Contact stress, wear and lubrication conditions need to be considered.
Maximum equivalent stress of main load-bearing parts	≤60% of the allowable stress of the material	As a reference boundary for structural strength design.

High-temperature workpiece tooling must also account for insulation pads, heat-resistant gripper jaws, metal hoses, heat-shielded wiring and sensor protection. Air hoses, seals and sensors should be arranged on the weak side of thermal radiation as much as possible, and the risk of thermal damage should be reduced through metal hoses, thermal insulation sheaths or thermal insulation panels.

7 Pneumatic-Circuit Pressure Retention and Leak Detection

Pneumatic-circuit pressure retention and leak detection should cover supply filtration, local pressure retention, abnormal-circuit isolation, pressure monitoring, controlled exhaust and maintenance depressurization. A typical protective unit includes a filter-regulator, check valve, pressure-retention valve, air receiver, safety shutoff valve, flow-controlled exhaust valve, safety exhaust valve, main pressure sensor P1, branch pressure sensor P2, gripping-chamber pressure sensor P3, pressure-drop-rate evaluation and leak-level Identification, safe exhaust and maintenance pressure relief and air hose protection in high temperature areas.

An air receiver is not complete loss-of-air protection. It only supplies local compressed air or buffers a pressure drop for a limited time. Complete loss-of-air Protection should also consist of mechanical locking, pneumatic circuit pressure holding, pressure detection, control interlocking and operating procedures.

Table 5 pneumatic system engineering reference values and compiled internal test values

Parameter items	Engineering reference value or compiled internal test value	Description
Rated compressed-air supply pressure / 0.5–0.7 MPa / Typical industrial compressed-air conditions; verify against the site supply.		
Test initial air supply pressure 0.60 MPa Used for internal testing initial state setting		
Low-pressure warning threshold / P1 < 0.45 MPa for ≥200 ms / Detect insufficient compressed-air supply and inhibit the start of a new cycle.		
loss-of-air protection trigger pressure P1 < 0.35 MPa or P2 < 0.35 MPa Trigger stop handling, mechanical lock and inhibit release.		
Rapid-leak trigger / Pressure-drop rate ≥0.08 MPa/s / Detect sudden leaks such as air-hose rupture or coupler separation.		
Pre-clamping pressure 0.18MPa Approximately 30% of rated clamping pressure for soft contact phase.		
Normal clamping pressure 0.60 MPa Used to simulate normal clamping conditions.		
Pressure control allows fluctuations ±5%, about ±0.03 MPa As a recommended verification indicator for pressure stability.		
Reference volume of small air receiver / 3 L / Recalculate for the pneumatic-circuit volume and loss-of-air holding requirement.		
Initial air-receiver pressure / 0.65 MPa / Simulate local pressure-retention capability.		
Pressure sampling period ≤20 ms For pressure decay and rapid leak identification.		
Data-recording frequency / ≥50 Hz / Record loss-of-air, leakage and release processes.		
Abnormal sensor differential / |P1-P2| > 0.08 MPa for ≥300 ms / Detect an abnormality between the main compressed-air supply and the branch circuit.		
Clamping cavity abnormality judgment	|P2-P3| > 0.10 MPa, lasting ≥300 ms	Identify clamping chamber leaks or valve block abnormalities.

$$R\_p = -\Delta P / \Delta t \qquad (4)$$

In the formula: R_p is the pressure decay rate, unit MPa/s; ΔP is the pressure change; Δt is the sampling time interval. When the pressure drop rate reaches When it reaches or exceeds the internal test trigger value of 0.08 MPa/s, it can be used as a rapid leak trigger condition. For slow leakage, it can be determined according to the actual project pneumatic circuit volume, sealing form and holding time establish graded alarm thresholds. If there is an abnormal pressure difference between P1, P2, and P3, and the duration If the recommended value is exceeded, it should be determined that the sensor, valve group or pneumatic circuit is abnormal, and the system should enter a conservative and safe state.

8 Control logic and release interlock conditions

Release conditions must include, at minimum, workpiece-support confirmation, tooling-position confirmation, manipulator or robot-pose confirmation, gripping-state confirmation, lock- state confirmation, personnel safe-zone confirmation, release-command confirmation, pressure-state confirmation and sensor-signal-consistency confirmation. While the workpiece is unsupported, the system must reject a release command. If sensor signals conflict, the system must enter a conservative safe state: stop handling, maintain the grip and prohibit release.

Table 6 Loss of air supply response logic

response level	Trigger condition System response	
Level One warning / P1 < 0.45 MPa for ≥200 ms / Low-pressure alarm; inhibit new-cycle start.		
Secondary protection P1 < 0.35 MPa or P2 < 0.35 MPa Stop handling, mechanically locked and prohibited from release.		
Level Three emergency stop / Pressure-drop rate ≥0.08 MPa/s or abnormal gripper-jaw displacement / Stop immediately, insert the locking pin, retain the grip and prohibit release while suspended.		
Reset conditions	Pressure restored, leak eliminated, workpiece supported, manual confirmation completed, lock state reset, sensor states consistent, work area safe	Allows access to controlled release, re-clamping or manual handling flow process.

The control logic should follow the principle of "exceptions must be retained first and release must be confirmed". Especially in high temperature workpiece or heavy load workpiece handling scenarios, It is prohibited to directly equate interruption of air supply with a release command.

9 Risk Analysis and FMEA

FMEA can be used to identify key risks in the loss-of-air protection design, prioritize risks and formulate improvement measures. This study uses severity S, occurrence degree O, detection degree D and risk priority number RPN are used for internal engineering assessment, RPN = S × O × D. The scores in the table below are for companies Example of internal engineering assessment model used for scenario comparison and risk ranking, subject to re-evaluation on a project-specific basis.

Table 7 Example FMEA for Loss-of-Air Protection of Industrial Handling Tooling

failure mode	Possible reasons	possible consequences	S	O	D	initial RPN	Improvement measures Improve after RPN	
Sudden interruption of main compressed-air supply / Main-supply failure or valve closure / Gripping-force decay, workpiece slip or drop / 5 / 4 / 4 / 80 / Check valve, pressure-retention valve, mechanical lock, and release prohibited after loss of air / 20								
Slow decrease in main compressed-air supply / Insufficient compressed air or abnormal filter-regulator assembly / Insufficient gripping force; continued handling presents risk / 4 / 3 / 4 / 48 / Low-pressure warning, inhibit new cycle, monitor pressure trend / 16								
Air-hose rupture / High-temperature aging or mechanical wear / Rapid pressure loss and unintended tooling motion / 5 / 3 / 4 / 60 / Pressure-drop-rate detection, metal hose, hose-restraint device and mechanical lock / 15								
Quick-coupler separation / Coupler not locked or contacted by vibration / Rapid branch-pressure drop / 5 / 3 / 4 / 60 / Locking coupler, P2 monitoring and anti-separation restraint / 15								
Unintended release-valve actuation / Spool sticking or electrical-signal interference / Unintended release while suspended / 5 / 3 / 4 / 60 / Support interlock, two-step release confirmation and safety-output monitoring / 12								
Gripper-jaw wear / Long service or high-temperature abrasion / Lower coefficient of friction and workpiece slip / 4 / 4 / 3 / 48 / Replaceable wear blocks, wear indicator and periodic inspection / 18								
Locking pin not fully engaged / Spring fatigue or foreign-matter obstruction / Reduced holding capability after loss of air / 5 / 3 / 3 / 45 / Dual in-position detection, dust protection and handling inhibited on fault / 15								
Pressure-sensor miscalibration / Drift, blockage or wiring fault / Misinterpretation of the gripping or loss-of-air state / 4 / 3 / 4 / 48 / P1/P2/P3 cross-check and periodic calibration / 16								
Air hose damaged by high-temperature radiation / Heat source too close or insufficient insulation / Leakage, hose burst or abnormal signal / 5 / 3 / 3 / 45 / Metal hose, thermal-insulation sleeve and temperature recording / 15								
Unintended manual release / Accidental button actuation or inadequate access control / Workpiece drop and personal injury / 5 / 3 / 4 / 60 / Protective cover, two-action control, dedicated key and support confirmation / 12								
Unintended startup in maintenance mode / Missing lockout/tagout or reset procedure / Tooling motion injures personnel / 5 / 3 / 3 / 45 / Maintenance mode, lockout/tagout and manual reset confirmation / 15								
Release command while workpiece is unsupported / Accidental operation or program error / Release while suspended / 5 / 3 / 4 / 60 / Support sensor, position interlock and rejection of release command / 10								
Gripping-chamber leakage / Seal aging or valve-assembly leakage / Pressure decay and reduced gripping force / 4 / 4 / 3 / 48 / P3 monitoring, pressure-drop-rate evaluation and graded leak alarm / 16								
Air-receiver or check-valve failure	Spool contamination or seal failure	Reduced local pressure-retention capability	4	3	4	48	Pressure-retention test, periodic check-valve inspection and loss-of-air holding test	16

The RPN score is an enterprise's internal engineering assessment model, used for program comparison and risk ranking, and is not used as a third-party certification conclusion.

10 Test verification plan

This document does not substitute unverified data for original measured records. The following material follows the compilation convention used for internal engineering-validation records by the AUREK Intelligent Technology Research Group and supports design validation, parameter correction and risk review before project delivery.

Table 8 Enterprise recommended verification scheme

test items	Test purpose	Test method	It is recommended to record data	Acceptance concerns
Rated gripping test / Verify gripping capacity under rated conditions / Grip a test workpiece of the specified mass and hold for the specified time P1/P2/P3, gripper jaw displacement, workpiece Slip amount There is no abnormal slip, and the deformation of gripper jaw is within the allowable range. within the perimeter.				
Dynamic handling test Verify acceleration and emergency stop impact maintain ability Test maximum handling acceleration and emergency stop action Acceleration, pressure curve, displacement, Slip amount workpiece has no obvious slip and the locking state is stable Determined.				
Air-supply interruption test / Verify main compressed-air supply interruption logic / Shut off the main supply or exhaust rapidly / Pressure-decay curve, lock response time and gripper-jaw displacement / Stop handling, mechanically lock and prohibit release.				
slow leak test Verify low pressure warning and leak identification Set up controllable micro-leakage Pressure drop rate, alarm time, system Status It can alarm in different levels and prohibit new cycles.				
Rapid-leak test / Verify response to air-hose rupture or coupler separation / Simulate rapid pressure decay or branch leakage / P2/P3 curves, emergency-stop state and locking-pin state / Trigger emergency stop, retain the grip and prohibit release while suspended.				
Support-interlock test / Verify rejection of release without confirmed support / Issue a release command while the workpiece is suspended / Support signal, valve output, gripper-jaw state / System rejects the release command.				
Controlled-release test / Verify low-speed release after support is confirmed / Release after a valid support confirmation / Release time, jaw-opening speed and workpiece offset / Smooth release without appreciable shock or bounce.				
High temperature radiation test Verify component status in high temperature environments Use a heat source or high temperature test workpiece continued exposure Air-hose temperature, sensor temperature and gripper-jaw state / No appreciable thermal damage or abnormal alarm.				
Life-cycle test / Verify durability of gripper jaws, locking pins, valve assembly and seals / Cycle at the project cycle rate / Cycle count, wear condition and pressure stability / No abnormal wear or functional failure of critical parts.				
Maintenance reset test	Manual confirmation after verification failure and Reset process	Performing a maintenance reset after triggering a fault	Pressure, locking, sensing before and after reset device status	Automatic circulation is prohibited before reset, and the status after reset is Consistent.

11 Engineering Validation by the AUREK Intelligent Technology Research Group

This section compiles internal engineering-validation records from the AUREK Intelligent Technology Research Group of Jiangsu Aurek Intelligent Technology Co., Ltd. for custom manipulators, pneumatic handling systems and industrial handling-tooling design. It is presented as an internal enterprise method for design validation, engineering-validation practice and project pre-delivery risk review. The content is an internal compilation; without the original records, it does not constitute third-party certification, customer acceptance or Unified Performance Commitment.

In custom manipulator and industrial handling-tooling design, the research group conducted the following work during 2023.05—2026.04: engineering validation and record compilation covering whether the tooling retains the grip as compressed-air supply pressure falls, and whether protection is triggered promptly after a rapid air-hose leak or coupler separation; The protection can be triggered in time; whether the mechanical locking structure can assume the holding function in the state of air loss; whether the controlled release can avoid the workpiece hanging error release; whether interlocking conditions such as support confirmation, position confirmation, and personnel safety confirmation are valid; air receiver, one-way valve, pressure maintaining valve and throttle valve combination whether the combined air receiver, check valve, pressure-retention valve and flow-control valve meet safe-shutdown and controlled-release requirements; and whether gripper jaws, air hoses, sensors and insulation meet safe-use requirements under high-temperature conditions.

The internal engineering-validation platform may comprise a manipulator or tooling test frame, adjustable compressed-air supply, filter-regulator assembly and check valve, pressure-retention valve, flow-control valve, air receiver, P1/P2/P3 pressure sensors, gripper-jaw displacement sensing, lock-in-position sensing and support-confirmation sensor, test-load tooling, data-acquisition module, emergency-stop and safe-release control circuits, audible/visual alarm, manual reset and maintenance-depressurization interfaces.

In the company's internal engineering verification, the research team used 300 kg high-temperature workpiece as a representative test load and set an initial supply of 0.60 MPa. air pressure, and through operating conditions such as low pressure, air cutoff, rapid leakage, accidental release and controlled release, the tooling's retention ability, mechanical locking response and release-interlock logic. The values above are compiled values from internal engineering-validation records. Each actual project must be reverified against workpiece mass and gripping method

, cylinder specifications, gripper-jaw material, pneumatic-circuit volume, handling motion profile and customer safety requirements. External release or project archiving requires The pressure decay curve, gripper jaw displacement curve, locking response time, slip amount, release time, instrument calibration information and original signature should be supplemented. Scheme design → Clamping force calculation → pneumatic circuit protection design → Test load test → Air shut-off/leakage test → Interlock release verification →

Data recording → Risk review → Parameter correction → Confirmation before project delivery

12 Engineering Application Analysis

The proposed loss-of-air protection and safe-release method applies to high-temperature forging handling, casting cleaning and transfer, heat-treatment loading and unloading, robot end-effector tooling, large-panel or enclosure handling, custom tooling for manipulators, pneumatic-balancer tooling, vacuum-holding tooling, automotive Components handling and workpiece handling scenes such as motor stator, box, plate, tire, battery compartment, etc.

For custom manipulator and industrial handling-tooling projects, AUREK can design tooling around workpiece mass, overall dimensions, surface condition, temperature, center-of-gravity location, handling pose, site cycle time and compressed-air supply conditions. Tooling forms may include external clamping, hooks, vacuum holding, Internal support, flip, lower support, heat-resistant gripper jaw and composite tooling, etc. This expression is used to explain the engineering practice background and does not constitute an evaluation of all project indicators. unified commitment.

From the perspective of engineering application, the tooling solution should not only be designed based on "can be clamped", but should also consider whether to maintain and mis-release when losing air. Whether it is interlocked and intercepted during release, whether the controlled release is smooth, whether the maintenance status can be safely reset, and whether high temperature, dust, oil pollution and compressed-air supply waves fluctuation may reduce design margin. Vacuum-holding tooling also requires attention to vacuum retention, suction-cup aging, surface roughness and leak monitoring. Hook-type tooling requires anti-unhooking protection, workpiece center-of-gravity control and pose constraints. Rotating tooling requires attention to inertial loads and secondary locking. Internal-expansion tooling requires attention to contact-surface wear, decay of expansion force and variation in workpiece bore size.

13 Conclusion and outlook

(1) The primary objective of loss-of-air safety design is to retain the grip, not release immediately. If the compressed-air supply is abnormal, industrial handling tooling must first stop handling, maintain load and prohibit hanging release. (2) Mechanical self-locking, geometric support and pneumatic-circuit pressure retention should be combined. Pneumatic pressure retention alone cannot cover air-hose rupture, coupler separation, valve-assembly Complex working conditions such as abnormality and control signal failure. (3) The clamping force design should consider dynamic impact, lower limit of friction coefficient, high temperature effect and gripper jaw wear. For high temperature oxide scale and heavy load handling Scenario, it should be calibrated according to the more conservative friction coefficient and safety factor. (4) loss-of-air protection should adopt multi-signal diagnosis and should not rely on a single pressure gauge. P1, P2, P3 pressure monitoring, pressure drop rate judgment, gripper jaw Displacement, locking in place and support confirmation should all be involved in safety decisions. (5) Safe release must be based on confirmation that the workpiece is supported and personnel are safe. Until support, position and pose are confirmed and When the interlock condition is released, the system should reject the release command. (6) Test validation shall cover loss of air supply, leakage, dynamic handling, controlled release and maintenance reset. The relevant pressure, time and slip and response time should be documented and reviewed as proposed validation metrics. (7) AUREK engineering verification practice can be used as a reference method for enterprise internal program verification, parameter correction and project risk review, but the specific guidelines The bids need to be verified individually based on the project conditions and should not be regarded as a unified commitment for all equipment.

Follow-up research can further focus on high-temperature friction coefficient identification, gripper jaw wear status monitoring, pressure decay curve modeling, and digital test records. Recording, predictive maintenance and safety control performance verification are carried out. For complex production lines, tooling release interlock can be incorporated into the entire line safety control architecture. provide coordinated validation among the tooling, manipulator, support tooling, personnel safe zone and maintenance mode.

This research can be used as a reference for the enterprise's custom handling tooling program design, internal technical specification preparation and project risk review.

14 Disclaimer

This document compiles industrial handling-tooling safety design and internal engineering-validation records. It does not replace project-specific risk assessment, mechanical-design calculations, control-system safety validation or site acceptance. Loss-of-air protection must be designed and validated separately for each workpiece, tooling form and environment. Pressure, time, gripping force, slip and response-time parameters are engineering reference values or compiled internal test Value, not as a unified commitment indicator for all devices.

Appendix A Compiled Internal Engineering-Validation Records of the AUREK Intelligent Technology Research Group (2023.05—2026.04; names redacted)

This appendix is compiled from internal engineering-validation records of the AUREK Intelligent Technology Research Group for 2023.05—2026.04. It illustrates the format, data organization and risk-review language used in internal enterprise engineering-validation records. Because the original test records, sensor calibration certificates, site photographs and signed originals are not attached, the archived originals govern the project identifiers, test objects, test data and conclusions. This appendix is not a third-party certification report, customer-acceptance document or quality certificate.

A.1 Test objects and system configuration (internal arrangement)

Table A1 Basic information of project verification objects (internal arrangement)

Project Test settings	
File number ARK-RT-TR-HT300-2026-001 (internal arrangement number)	
tooling name High temperature and heavy load pneumatic clamp type handling tooling	
tooling form Double-sided clamping + wedge self-locking + spring lock pin + pneumatic circuit pressure maintaining	
Test workpiece 300 kg high temperature iron castings or forgings, reference size 900 mm × 450 mm × 250 mm	
temperature conditions workpiece surface 250 ℃, environment 25 ℃	
critical detection P1 main pressure, P2 branch pressure, P3 clamping chamber pressure, gripper jaw displacement, lock in place, support Confirm	
Data attributes / Compiled internal engineering-validation records; verify against the originals	
test cycle 2023.05-2026.04	
Record status	Names redacted; external use requires original records, calibration files, site photographs and signed originals

A.2 Summary of engineering verification conditions and records

Table A2 Summary of engineering verification working conditions and judgments (2023.05-2026.04)

No. / Test condition / Key setting / Recorded result / Internal acceptance				
1 / Normal gripping with air supply / P=0.60 MPa; hold for 15 min / Slip after 15 min: 0.28 mm; P3 approximately 0.594 MPa / Meets the internal acceptance criterion				
2 / Low-pressure warning / P1 < 0.45 MPa for ≥200 ms / Alarm after P1=0.446 MPa persisted for 236 ms / Meets the internal acceptance criterion				
3 / Gradual decrease of main supply / P1 decreases from 0.60 MPa to 0.35 MPa within 10 s / Level Two protection entered at 10.2 s; locking completed / Meets the internal acceptance criterion				
4 / Sudden cutoff of main supply / P1 decreases to 0 MPa within 0.5 s / Total locking response: 104 ms; slip after 5 min: 0.62 mm / Meets the internal acceptance criterion				
5 / Rapid leak in gripping branch / P3 decreases from 0.60 MPa to 0.25 MPa within 3 s / Pressure-drop rate approximately 0.116–0.118 MPa/s; Level Three emergency stop / Meets the internal acceptance criterion				
6 / Quick-coupler separation / P2 decreases to 0.10 MPa within 1 s / Time for P2 to reach 0.35 MPa: approximately 496 ms; locking pin engaged / Meets the internal acceptance criterion				
7 / Unintended release-valve actuation / Workpiece suspended; support confirmation invalid / No release output; tooling remains gripping / Meets the internal acceptance criterion				
8 / Release after workpiece support / Release time 0.8–1.5 s / Controlled jaw-opening time 1.12 s; maximum opening speed 68 mm/s / Meets the internal acceptance criterion				
9 / High-temperature radiation test / 250 ℃ heat source for 30 min / Air-hose surface temperature 57 ℃, sensor enclosure 48 ℃, no abnormal alarm / Meets the internal acceptance criterion				
10	Maintenance-reset simulation	Pressure restored to 0.60 MPa; manual confirmation valid	Automatic cycle inhibited before reset; states consistent after reset	Meets the internal acceptance criterion

A.3 Recommended data recording

For each test, record initial compressed-air supply pressure, main-supply pressure P1, pressure downstream of the valve island P2, gripping-chamber pressure P3, pressure-drop rate, gripper jaw displacement, workpiece slippage, locking response time, controlled release time, alarm triggering time, emergency stop response status, whether hanging is prohibited Status before and after release and reset, air hose surface temperature, sensor temperature, gripper jaw deformation or wear status.

A.4 Examples of exception and deviation records

Table A3 Engineering verification exception and deviation records
(internal arrangement)

serial number	anomaly or deviation	test record Handling suggestions	
1 / Small differential between P1 and P2 / Maximum difference 0.007 MPa / Project records must include sensor calibration and review of pneumatic-circuit pressure loss.			
2 / Air-hose surface temperature rise during high-temperature test / Reached 57 ▯ after 30 min / Project records must confirm hose temperature rating, distance from heat source, and insulation measures.			
3 / Small workpiece offset after supported release / Offset 0.7 mm / Reduce by optimizing the support locating face and release speed.			
4	P3 remains at a higher pressure than P2 after loss of air supply	Related to the pressure-retention valve and check-valve isolation	Project records must confirm pneumatic-circuit isolation direction and the maintenance-depressurization procedure.

A.5 Suggestions for expressing engineering verification conclusions

Recommended wording: Within the compilation scope of internal engineering-validation records for 2023.05—2026.04, the high-temperature, heavy-load pneumatic clamping The handling tooling solution can adopt measures such as mechanical locking, pneumatic circuit pressure holding, pressure monitoring, pressure drop rate judgment, support confirmation and release interlocking. provide layered control of loss-of-air, leakage and unintended-release risks. This conclusion means only that the test scheme has engineering-validation value under the stated internal-record compilation conditions. External release, customer acceptance or use as a quality certificate remains governed by the original test records, instrument calibration files and signed originals.

A.6 Signature page

Form A4 Signature Page (Compiled in 2026.04)

role	name	sign Date	
Test leader [redacted] 2026-04			
Mechanical design manager [redacted] 2026-04			
pneumatic system person in charge [redacted] 2026-04			
Electrical Control Manager [redacted] 2026-04			
safety reviewer [redacted] 2026-04			
Project leader	[redacted]	[redacted]	2026-04

15 Supplement: Relevant standards and compliance references

This section improves the engineering rigor of the document. The following standards are reference frameworks only for design, review and validation. Applicability, applicable clauses and any conformity conclusion must be determined jointly from the project risk assessment, safety-control-system design, site validation and customer requirements. Unless formal test, calculation and signed records are available, do not state that this document complies with a particular standard.

Category Reference standards/documents In tooling safety release design focus of Suggested writing method			
Machinery Safety Risk Assessment ISO 12100/GB/T 15706 Hazard identification, risk estimation, risk Risk reduction and residual risk description. Conduct risk assessments in conjunction with projects.			
Safety related control systems ISO 13849-1, IEC 62061 Release interlock, lock in place, support Acknowledgment, emergency stop and diagnostic review cover. Determine PL by project risk or SIL target.			
Pneumatic-system safety / ISO 4414 / Applicable GB/T pneumatic-system safety requirements Interruption of compressed-air supply, release of stored energy, pressure retention, exhaust, maintenance depressurization and prevention of unintended motion. The pneumatic circuit needs to be project confirmed Recognize.			
Robotics and collaborative safety ISO 10218, ISO/TS 15066 and GB/T related standards Robot posture and personnel safety zone Domain, end effector release link lock. The safety logic of the entire line needs to be jointly verified Certificate.			
Internal regulations of the enterprise	Project risk review form, test notes Recording, FMEA, inspection maintenance procedures	Closed loop of internal responsibilities and ownership of testing Backup, Maintenance Reset and Residual Risk Confirm.	As a pre-delivery internal review resource Material.

16 Supplement: Safety control level and release interlock description

A tooling-release action should not be triggered directly by one ordinary button. For heavy-load, high-temperature or suspended handling, or where personnel may enter a hazardous area, signals for release-valve output, lock-pin engagement, workpiece support, tooling position, robot/manipulator pose, personnel safe zone and pressure state should be incorporated into a safety PLC, safety relay or equivalent safety-control architecture according to the risk assessment.

security features Typical input Typical output/response Recommendations when the stakes are higher			
No hanging release allowed Support confirmation, position confirmation, position posture confirmation The release valve inhibits output and keeps the clamp hold Dual Channel Support Confirmation or Support+ Position cross-validation.			
Loss-of-air holding / P1/P2/P3, pressure-drop rate and gripper-jaw displacement / Stop handling, mechanically lock and alarm / Cross-check pressure sensors and confirm locking-pin engagement.			
controlled release workpiece Supported, personnel safety, lock Stop status, release double confirmation Release lock and open claw at low speed Release output monitoring, valve feedback, Speed limit.			
Maintenance reset	Maintenance mode, manual confirmation, pressure recovery and consistent sensor states	Inhibit automatic cycling and permit only the reset procedure	Lockout/tagout, key-controlled authorization and pre-reset state-consistency check

A target PL or SIL shall not be assigned in a general article; each project shall determine it from injury severity, exposure frequency, possibility of avoidance, system architecture, diagnostic coverage and component reliability. This document provides a method and does not replace project-level safety-control-system validation.

17 Supplement: FMEA scoring description and risk closed loop

To keep FMEA from remaining only a displayed table, project files should define S/O/D scoring, RPN thresholds, corrective-action owners and post-correction review records. The following is an internal enterprise template example.

Points Severity S Occurrence degree O Detection D			
1 Minor impact, no injuries involved damage or workpiece falling. Rarely happens. It is almost guaranteed to happen before the action Now.			
2 Minor equipment impact may be recoverable Often. Low probability of happening. Easier to pass sensor or inspection Discover.			
3 May cause shutdown and damage to workpiece or minor security risk. Occasionally. Requires combined testing or manual inspection Discover.			
4	May cause major equipment damage,	more likely to happen.	Difficult to detect in advance.

	workpiece falls or someone gets injured Risk.		
5 May cause serious personal injury, Major equipment damage or high temperature workpiece Fall. It is likely to occur under certain working conditions. It's hard to detect before it fails.			

RPN range Recommended disposal methods	
RPN ≥ 50 Corrective measures must be formulated and retests or special reviews must be completed before proceeding. into delivery.	
30 ≤ RPN < 50 A project review is required to identify risk reduction measures, responsible persons and residual Risk identification.	
RPN < 30	May be tentatively accepted, but shall be included in inspection, maintenance and project archiving records.

18 Supplement: Test equipment and calibration record template

For external release, customer acceptance or internal archiving, add test-equipment and calibration information. If no calibration certificate is available, explicitly state: Data are provided only as a compiled internal reference.

Equipment/Instruments Suggested record content Example		
Pressure sensor P1/P2/P3 Model, range, accuracy, installation location, calibration accurate date 0-1.0 MPa, the accuracy level is filled in according to actual write.		
Displacement sensor Range, resolution, sampling position gripper jaw displacement, workpiece slippage.		
Data acquisition module Sampling frequency, number of channels, time synchronization method ≥50 Hz, pressure sampling period ≤20 ms.		
Temperature-measurement equipment / Measurement method, measurement-point location and ambient temperature / Workpiece surface, air-hose surface and sensor enclosure.		
Test load / Mass verification method, dimensions, center-of-gravity offset and surface condition / 300 kg workpiece or equivalent test load.		
field notes	Photos, videos, testers, reviewers Member, signature date	The original on file shall prevail.

19 Supplement: Project-based application checklist

The following checklist can be used as a basic template for project initiation, program review, assembly commissioning and pre-delivery confirmation. Actual projects can be customized according to customer site and equipment risk level additions and deletions.

1. Have the workpiece mass, dimensions, surface condition, temperature and center-of-gravity location been confirmed?

2. Check whether the clamping force is differentiated between static, dynamic, emergency stop, eccentric load and attitude change conditions;

3. Whether the clamping method includes mechanical self-locking, geometric support or other non-pneumatic single-point dependent measures;

4. Whether P1/P2/P3 pressure monitoring, pressure drop rate judgment and sensor consistency diagnosis are configured;

5. When the workpiece is unsupported, is the release command rejected by hardware or safety logic?

6. Whether the tests for air loss, rapid leakage, slow leakage, accidental release, controlled release and maintenance reset have been completed;

7. In the high-temperature workpiece scenario, whether the air hose, sensor, seal and cable have completed the heat insulation protection verification;

8. Whether the FMEA has completed the rectification closed loop, and whether the RPN has been re-evaluated after the rectification;

9. Whether test curves, photos, calibration certificates, signature pages and risk assessment records are archived;

10. Do public-facing documents explicitly state that they do not replace third-party certification, customer acceptance or a quality certificate?