VD40 gripper — required cup vacuum and pump size for loose cups

Simulation study · 2026-10-28 · gripper MuJoCo model + vacuum model V3_effective_area · results not yet experimentally validated

Question

How much vacuum must the attached cups have so that a 15 kg carton stays on the gripper while the robot accelerates at up to 8 m/s² in any direction, with 0 to 10 cups loose (starting at the sides)? And which pump and cup-hole size deliver it?

Approach

Step 1, gripper simulation. For each grip and number of loose cups the lowest cup vacuum that keeps the carton held was found by bisection, under gravity plus a sustained 8 m/s² gripper acceleration in the worst of 26 directions (refined in 15° and 7.5° steps), and for the worse of two loose-cup orders (symmetric from both sides, or all from one side).

Two criteria. Does not drop (100 mm / 30°): the carton stays on the gripper: no floor contact, at least one cup attached, not creeping, and only gross limits on sag/tilt. **Held in place** (25 mm / 10°): the carton also stays within the plan's sway limits. Both also require that the carton does not creep away.

Step 2, vacuum model. The required vacuum gives the highest allowed pressure inside the attached cups (p_u = 1000 mbar − vacuum). The calibrated 32-cup vacuum model then gives the smallest pump that keeps p_u at or below it, per cup-hole size, with the loose cups open to the room.

Key findings

- **Top grip, chamber A only** — *Does not drop* needs 45–72 kPa for 0–4 loose cups; from 5 loose cups not even at 100 kPa (all cups stay attached, but the carton slowly creeps away). With **today's (printed)** holes 140 m³/h covers **up to 3 loose cups** (0 loose: < 20 m³/h); the current pump (40 m³/h) covers 1 loose with today's holes. *Held in place* needs 65–87 kPa for 0–2 loose cups; from 3 loose cups not even at 100 kPa (all cups attached, but the remaining cups stretch too far). With **today's (printed)** holes 140 m³/h covers **only the case without loose cups** (0 loose: 36 m³/h); the current pump (40 m³/h) covers 0 loose with today's holes.
- **Side + bottom, end face** — *Does not drop* needs 39–74 kPa for 0–10 loose cups. With **1.75 mm** holes 140 m³/h covers **up to 7 loose cups** (0 loose: 23 m³/h); the current pump (40 m³/h) covers 1 loose with today's holes, 3 loose with 1.75 mm holes. *Held in place* needs 51–90 kPa for 0–4 loose cups; from 5 loose cups not even at 100 kPa (all cups attached, but the remaining cups stretch too far). With **2.0 mm** holes 140 m³/h covers **up to 2 loose cups** (0 loose: 33 m³/h); the current pump (40 m³/h) covers 0 loose with today's holes, 0 loose with 2.0 mm holes.
- **Side + bottom, long face** — *Does not drop* needs 17–36 kPa for 0–10 loose cups. With **2.5 mm** holes 140 m³/h covers **up to 10 loose cups** (0 loose: < 20 m³/h); the current pump (40 m³/h) covers 4 loose with today's holes, 6 loose with 2.5 mm holes. *Held in place* needs 19–47 kPa for 0–10 loose cups. With **2.0 mm** holes 140 m³/h covers **up to 10 loose cups** (0 loose: < 20 m³/h); the current pump (40 m³/h) covers 3 loose with today's holes, 6 loose with 2.0 mm holes.
- **Held in place is limited by cup stretch, not by vacuum,** for the top grip and the end-face grip: with few cups left the remaining cups stretch tens of millimetres, so the carton sags or tilts beyond 25 mm / 10° while still attached. More vacuum makes the cups stiffer, but only to a point.
- **The top grip with one chamber is the weakest grip:** 16 cups carry everything, and with 5 or more cups loose on one side the carton is not held at any vacuum.
- **The results are thresholds, not design values.** Add a margin (e.g. +20% force, about 1.2 × the required vacuum) before selecting a pump.

Study inputs

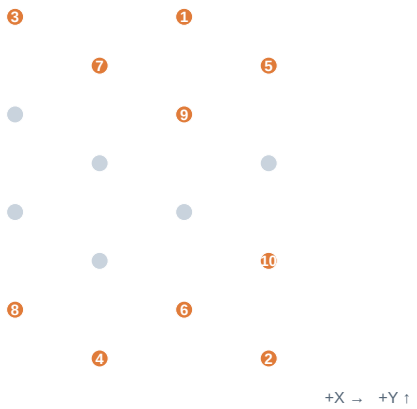
Item	Value
Carton	15 kg; 600 × 300 × 300 mm; centre of mass in the middle

Item	Value
Grips	Top grip, chamber A only: Top only · 180°, chamber A only (16 cups), box centred under A Side + bottom, end face: Side + bottom · 90°, side chamber on the 300 × 300 end face (box 600 mm deep) Side + bottom, long face: Side + bottom · 90°, side chamber on the 600 × 300 long face (box 300 mm deep)
Acceleration	8 m/s² vector on top of gravity, sustained after a 0.6 s ramp; each test 6 s at 0.5 ms timestep
Loose-cup orders	symmetric: outer columns along the box sides (±Y) first, alternating +Y / −Y, then inward one-sided: one side (+Y) first, column by column towards the other side
Held when	Does not drop: no floor contact, ≥ 1 cup attached, peak displacement over the last second ≤ 100 mm, tilt ≤ 30°, creep ≤ 2 mm/s; extra cups may let go Held in place: no floor contact, ≥ 1 cup attached, peak displacement over the last second ≤ 25 mm, tilt ≤ 10°, creep ≤ 2 mm/s; extra cups may let go
Cup vs vacuum	office cup; pull-off limit, friction capacity and load-stretch curve scale with vacuum / 60 kPa (hypothesis; only 60 kPa is measured)
Cup failure rules	pull-off; peeling above 30° cup tilt; sliding never detaches a cup by itself (slip limit at the simulator maximum, 100 mm; friction still limits shear)
Vacuum search	1–100 kPa, resolution 0.5 kPa (reported value holds)

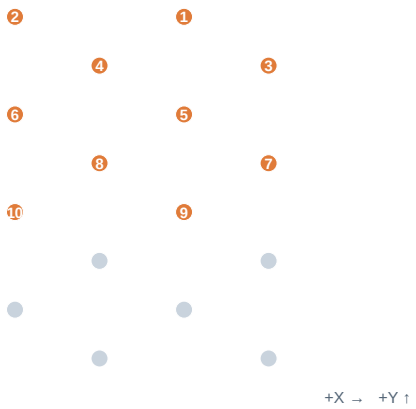
1. Required cup vacuum — Top grip, chamber A only

Top only · 180°, chamber A only (16 cups), box centred under A. Directions: X along the 600 mm box length (the two chambers lie side by side along X), Y across the box, Z up. The direction is the gripper acceleration (e.g. +Z = accelerating upwards).

loose order: symmetric



loose order: one-sided



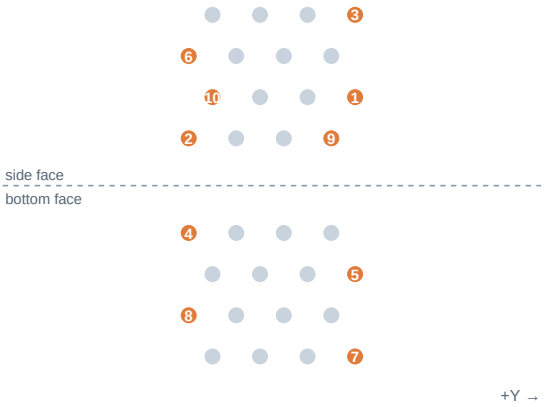
Orange, numbered: the first loose cups in each order (n loose = the first n).

Loose cups	Does not drop vacuum [kPa]	Does not drop max p_u [mbar]	Held in place vacuum [kPa]	Held in place max p_u [mbar]	Does not drop worst direction	Does not drop what fails just below
0	44.8	552	65.0	350	+X (+0.98, +0.17, +0.09) symmetric order	Pull-off, Sliding seal carton fell (floor contact, all cups released)
1	50.1	499	73.8	262	+X +Y (+0.97, +0.26, -0.00) symmetric order	Pull-off, Sliding seal carton fell (floor contact, all cups released)
2	57.9	421	86.8	132	+X +Y (+0.97, +0.26, -0.00) symmetric order	Peeling, Pull-off carton fell (floor contact, all cups released)
3	62.0	380	> 100	—	+Y (+0.09, +0.99, +0.09) one-sided order	Pull-off, Sliding seal carton fell (floor contact, all cups released)
4	71.5	285	> 100	—	+Y (+0.18, +0.98, +0.05) one-sided order	Peeling, Pull-off carton fell (floor contact, all cups released)
5	> 100	—	> 100	—	+X +Y (+0.71, +0.71, +0.00) one-sided order	not held at any vacuum at 100 kPa: creeping 2.0 mm/s; all cups stay attached
6	> 100	—	> 100	—	+Y (+0.00, +1.00, +0.00) one-sided order	not held at any vacuum at 100 kPa: carton reached floor; total detachment; displacement 52847 mm; tilt 177.2°; creeping 15230.4 mm/s; 10 cups lost; Peeling, Pull-off
7	> 100	—	> 100	—	+Y +Z (+0.00, +0.71, +0.71) one-sided order	not held at any vacuum at 100 kPa: carton reached floor; total detachment; displacement 1646 mm; tilt 90.9°; 9 cups lost; Peeling, Pull-off
8	> 100	—	> 100	—	+Y +Z (+0.00, +0.71, +0.71) one-sided order	not held at any vacuum at 100 kPa: carton reached floor; total detachment; displacement 1215 mm; 8 cups lost; Peeling
9	> 100	—	> 100	—	−X +Z (-0.71, +0.00, +0.71) one-sided order	not held at any vacuum at 100 kPa: creeping 2.5 mm/s; all cups stay attached
10	> 100	—	> 100	—	−X +Z (-0.71, +0.00, +0.71) one-sided order	not held at any vacuum at 100 kPa: carton reached floor; total detachment; displacement 1073 mm; tilt 96.0°; 6 cups lost; Sliding seal

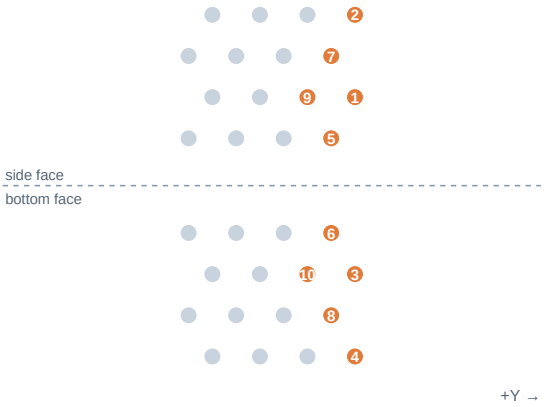
1. Required cup vacuum — Side + bottom, end face

Side + bottom · 90°, side chamber on the 300 × 300 end face (box 600 mm deep). Directions: X points from the box towards the side chamber (normal to the gripped face), Y across, Z up. The direction is the gripper acceleration (e.g. +Z = accelerating upwards).

loose order: symmetric



loose order: one-sided

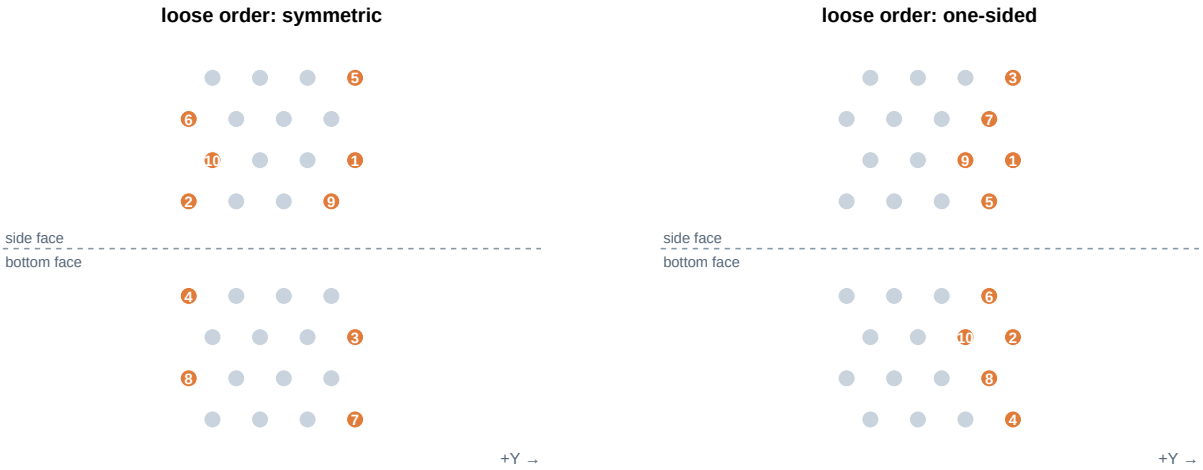


Orange, numbered: the first loose cups in each order (n loose = the first n).

Loose cups	Does not drop vacuum [kPa]	Does not drop max p_u [mbar]	Held in place vacuum [kPa]	Held in place max p_u [mbar]	Does not drop worst direction	Does not drop what fails just below
0	38.9	611	51.1	489	+X +Y +Z (+0.68, +0.26, +0.68) symmetric order	Peeling, Pull-off carton fell (floor contact, all cups released)
1	41.0	590	56.4	436	+X +Z (+0.55, +0.18, +0.81) symmetric order	Peeling, Pull-off carton fell (floor contact, all cups released)
2	44.4	556	66.7	333	+X +Z (+0.55, +0.18, +0.81) one-sided order	Peeling, Pull-off carton fell (floor contact, all cups released)
3	46.0	540	74.2	258	+X +Z (+0.55, +0.18, +0.81) symmetric order	Peeling, Pull-off carton fell (floor contact, all cups released)
4	47.2	528	90.3	97	+X +Z (+0.55, +0.18, +0.81) symmetric order	Peeling, Pull-off carton fell (floor contact, all cups released)
5	48.4	516	> 100	—	+X +Z (+0.55, +0.18, +0.81) symmetric order	Peeling, Pull-off carton fell (floor contact, all cups released)
6	51.5	485	> 100	—	+X +Z (+0.55, +0.18, +0.81) symmetric order	Peeling, Pull-off carton fell (floor contact, all cups released)
7	57.2	428	> 100	—	−Y (+0.00, -0.99, +0.13) symmetric order	cups stay attached displacement 100 mm
8	63.3	367	> 100	—	−Y (-0.09, -0.99, +0.09) symmetric order	cups stay attached displacement 100 mm
9	66.8	332	> 100	—	+Y +Z (-0.00, +0.97, +0.26) one-sided order	cups stay attached displacement 102 mm
10	74.2	258	> 100	—	+Y +Z (-0.00, +0.97, +0.26) one-sided order	cups stay attached displacement 103 mm

1. Required cup vacuum — Side + bottom, long face

Side + bottom · 90°, side chamber on the 600 × 300 long face (box 300 mm deep). Directions: X points from the box towards the side chamber (normal to the gripped face), Y along the 600 mm face, Z up. The direction is the gripper acceleration (e.g. +Z = accelerating upwards).



Orange, numbered: the first loose cups in each order (n loose = the first n).

Loose cups	Does not drop vacuum [kPa]	Does not drop max p_u [mbar]	Held in place vacuum [kPa]	Held in place max p_u [mbar]	Does not drop worst direction	Does not drop what fails just below
0	16.6	834	18.6	814	+X +Y (+0.26, +0.97, +0.00) symmetric order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
1	17.5	825	19.5	805	+X +Y (+0.26, +0.97, +0.00) symmetric order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
2	19.0	810	21.0	790	+X +Y (+0.26, +0.97, +0.00) one-sided order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
3	19.9	801	22.9	771	+X +Y (+0.26, +0.97, +0.00) one-sided order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
4	25.0	750	28.0	720	+X −Y (+0.26, -0.97, -0.00) one-sided order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
5	24.5	755	27.5	725	+X −Y (+0.26, -0.97, -0.00) one-sided order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
6	25.4	746	29.9	701	+X +Y (+0.26, +0.97, +0.00) one-sided order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
7	31.2	688	35.7	643	+X −Y (+0.26, -0.97, -0.00) symmetric order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
8	33.3	667	41.6	584	+X −Y (+0.26, -0.97, -0.00) symmetric order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
9	32.7	673	42.0	580	+X −Y (+0.26, -0.97, -0.00) symmetric order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)
10	35.9	641	46.6	534	+X +Y (+0.26, +0.97, +0.00) one-sided order	Peeling, Pull-off, Sliding seal carton fell (floor contact, all cups released)

2a. Minimum pump [m³/h] — Top grip, chamber A only — does not drop (100 mm / 30°)

Smallest pump (Becker VT 4.40 curve shape, scaled; same 150 mbar ultimate pressure) that keeps the attached cups at or below the required cup pressure. ✔ with green background = within 20–140 m³/h. * = above 140 m³/h (indicative). "> 280" = not reached even at 280 m³/h. "not held" = the gripper simulation does not hold the box at any vacuum. Bold = lowest pump in the row. Chamber B's 16 cups are plugged (no leak).

Loose cups	Max p_u [mbar]	as now (printed)	2.5 mm	2.0 mm	1.75 mm	1.5 mm	1.25 mm	1.0 mm
0	552	✔ **< 20**	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ < 20	> 280
1	499	✔ 29	✔ 26	✔ 24	✔ **23**	✔ 23	✔ 26	> 280
2	421	✔ 59	✔ 48	✔ 39	✔ 37	✔ **37**	✔ 47	> 280
3	380	✔ 127	✔ 84	✔ 60	✔ 54	✔ **54**	✔ 96	> 280
4	285	> 280	> 280	> 280	**266***	> 280	> 280	> 280
5	—	not held	not held	not held	not held	not held	not held	not held
6	—	not held	not held	not held	not held	not held	not held	not held
7	—	not held	not held	not held	not held	not held	not held	not held
8	—	not held	not held	not held	not held	not held	not held	not held
9	—	not held	not held	not held	not held	not held	not held	not held
10	—	not held	not held	not held	not held	not held	not held	not held

2a. Minimum pump [m³/h] — Side + bottom, end face — does not drop (100 mm / 30°)

Same layout as above.

Loose cups	Max p_u [mbar]	as now (printed)	2.5 mm	2.0 mm	1.75 mm	1.5 mm	1.25 mm	1.0 mm
0	611	✔ **22**	✔ 22	✔ 22	✔ 23	✔ 23	✔ 25	✔ 36
1	590	✔ 32	✔ 29	✔ 27	✔ 27	✔ **27**	✔ 28	✔ 44
2	556	✔ 47	✔ 41	✔ 35	✔ 33	✔ **32**	✔ 34	> 280
3	540	✔ 66	✔ 52	✔ 42	✔ 38	✔ **36**	✔ 38	> 280
4	528	✔ 96	✔ 67	✔ 49	✔ 44	✔ **41**	✔ 42	> 280
5	516	162*	✔ 89	✔ 59	✔ 51	✔ **46**	✔ 46	> 280
6	485	> 280	154*	✔ 79	✔ 65	✔ **57**	✔ 58	> 280
7	428	> 280	> 280	155*	✔ 109	✔ **91**	✔ 109	> 280
8	367	> 280	> 280	> 280	> 280	**274***	> 280	> 280
9	332	> 280	> 280	> 280	> 280	> 280	> 280	> 280
10	258	> 280	> 280	> 280	> 280	> 280	> 280	> 280

2a. Minimum pump [m³/h] — Side + bottom, long face — does not drop (100 mm / 30°)

Same layout as above.

Loose cups	Max p_u [mbar]	as now (printed)	2.5 mm	2.0 mm	1.75 mm	1.5 mm	1.25 mm	1.0 mm
0	834	✔ **< 20**	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ < 20
1	825	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ **< 20**	✔ < 20	✔ < 20
2	810	✔ 20	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ **< 20**	✔ < 20
3	801	✔ 25	✔ 22	✔ < 20	✔ < 20	✔ < 20	✔ **< 20**	✔ < 20
4	750	✔ 37	✔ 30	✔ 24	✔ 21	✔ < 20	✔ **< 20**	✔ < 20
5	755	✔ 43	✔ 34	✔ 26	✔ 23	✔ 20	✔ **< 20**	✔ < 20
6	746	✔ 53	✔ 40	✔ 29	✔ 25	✔ 22	✔ **20**	✔ 20
7	688	✔ 87	✔ 57	✔ 39	✔ 33	✔ 28	✔ **26**	✔ 27
8	667	✔ 135	✔ 73	✔ 46	✔ 38	✔ 32	✔ **29**	✔ 30
9	673	191*	✔ 83	✔ 49	✔ 40	✔ 33	✔ **29**	✔ 30
10	641	> 280	✔ 126	✔ 61	✔ 48	✔ 39	✔ **34**	✔ 36

2b. Minimum pump [m³/h] — Top grip, chamber A only — held in place (25 mm / 10°)

Same layout as above.

Loose cups	Max p_u [mbar]	as now (printed)	2.5 mm	2.0 mm	1.75 mm	1.5 mm	1.25 mm	1.0 mm
0	350	✔ **36**	✔ 36	✔ 38	✔ 41	✔ 49	> 280	> 280
1	262	179*	146*	**142***	183*	> 280	> 280	> 280
2	132	> 280	> 280	> 280	> 280	> 280	> 280	> 280
3	—	not held	not held	not held	not held	not held	not held	not held
4	—	not held	not held	not held	not held	not held	not held	not held
5	—	not held	not held	not held	not held	not held	not held	not held
6	—	not held	not held	not held	not held	not held	not held	not held
7	—	not held	not held	not held	not held	not held	not held	not held
8	—	not held	not held	not held	not held	not held	not held	not held
9	—	not held	not held	not held	not held	not held	not held	not held
10	—	not held	not held	not held	not held	not held	not held	not held

2b. Minimum pump [m³/h] — Side + bottom, end face — held in place (25 mm / 10°)

Same layout as above.

Loose cups	Max p_u [mbar]	as now (printed)	2.5 mm	2.0 mm	1.75 mm	1.5 mm	1.25 mm	1.0 mm
0	489	✔ **32**	✔ 32	✔ 33	✔ 33	✔ 35	✔ 42	> 280
1	436	✔ 57	✔ 52	✔ 48	✔ **48**	✔ 50	✔ 67	> 280
2	333	> 280	183*	✔ 137	✔ **136**	180*	> 280	> 280
3	258	> 280	> 280	> 280	> 280	> 280	> 280	> 280
4	97	> 280	> 280	> 280	> 280	> 280	> 280	> 280
5	—	not held	not held	not held	not held	not held	not held	not held
6	—	not held	not held	not held	not held	not held	not held	not held
7	—	not held	not held	not held	not held	not held	not held	not held
8	—	not held	not held	not held	not held	not held	not held	not held
9	—	not held	not held	not held	not held	not held	not held	not held
10	—	not held	not held	not held	not held	not held	not held	not held

2b. Minimum pump [m³/h] — Side + bottom, long face — held in place (25 mm / 10°)

Same layout as above.

Loose cups	Max p_u [mbar]	as now (printed)	2.5 mm	2.0 mm	1.75 mm	1.5 mm	1.25 mm	1.0 mm
0	814	✔ **< 20**	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ < 20
1	805	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ **< 20**	✔ < 20	✔ < 20
2	790	✔ 22	✔ < 20	✔ < 20	✔ < 20	✔ < 20	✔ **< 20**	✔ < 20
3	771	✔ 29	✔ 24	✔ < 20	✔ < 20	✔ < 20	✔ **< 20**	✔ < 20
4	720	✔ 42	✔ 33	✔ 26	✔ 24	✔ 22	✔ **21**	✔ 22
5	725	✔ 49	✔ 38	✔ 28	✔ 25	✔ 23	✔ **21**	✔ 22
6	701	✔ 66	✔ 47	✔ 34	✔ 29	✔ 26	✔ **24**	✔ 25
7	643	✔ 119	✔ 70	✔ 45	✔ 38	✔ 33	✔ **30**	✔ 34
8	584	> 280	✔ 120	✔ 63	✔ 51	✔ 43	✔ **39**	✔ 55
9	580	> 280	169*	✔ 72	✔ 56	✔ 46	✔ **41**	✔ 60
10	534	> 280	> 280	✔ 107	✔ 75	✔ 59	✔ **52**	> 280

3. Numerical checks at the requirement (worst direction)

Holds with 10 kPa more vacuum (more vacuum does not hurt); holds with half the timestep and a 12 s test (not a short-test or timestep artefact); fails 2 kPa lower in that finer, longer test (a sharp threshold). “no” in the last column means the true threshold is up to ~2 kPa lower than reported, so the reported value is on the safe side.

Criterion	Grip	Loose cups	+10 kPa holds	Half timestep, 12 s holds	−2 kPa fails
Does not drop	Top grip, chamber A only	0	yes	yes	yes
Does not drop	Side + bottom, end face	0	yes	yes	yes
Does not drop	Side + bottom, end face	5	yes	yes	yes
Does not drop	Side + bottom, end face	10	yes	yes	yes
Does not drop	Side + bottom, long face	0	yes	yes	yes
Does not drop	Side + bottom, long face	5	yes	yes	yes

Criterion	Grip	Loose cups	+10 kPa holds	Half timestep, 12 s holds	−2 kPa fails
Does not drop	Side + bottom, long face	10	yes	yes	yes
Held in place	Top grip, chamber A only	0	yes	yes	no
Held in place	Side + bottom, end face	0	yes	yes	yes
Held in place	Side + bottom, long face	0	yes	yes	yes
Held in place	Side + bottom, long face	5	yes	yes	yes
Held in place	Side + bottom, long face	10	yes	yes	yes

Assumptions and limits

- **Vacuum scaling of the cup is a hypothesis.** Pull-off (4.2 kg per cup at 60 kPa), friction capacity and the cup's load-stretch curve are scaled linearly with vacuum; only the 60 kPa behaviour is measured. The stretch law strongly affects the sag and tilt results.
- **Rigid carton, fixed gripper, sustained acceleration.** Real robot moves are shorter, so these results are conservative for slow sliding; cardboard bending, porosity and crushing are not modelled.
- **Cup failure rules:** pull-off, and peeling above 30° cup tilt. Sliding never releases a cup by itself; “Sliding seal” only appears in the failure lists once a falling carton has dragged a cup 100 mm.
- **Uniform cup vacuum.** All attached cups share the same vacuum, as in the vacuum model. In the gripper simulation a loose cup carries no force; its air leak is handled in step 2.
- **Vacuum model V3_effective_area** (printed holes behave like clean ≈2.9 mm holes; pump = full Becker curve; leak per attached cup 0.35 mm², background leak 4.7 mm², hose 26 mm × 10 m with fitted extra loss K = 41). The 32-cup gripper is extrapolated from the 17-cup measurements; the background leak is kept constant.
- **Re-drilled holes** are clean short channels with Cd = 0.8. The cup pressure is p_u = 1000 mbar − vacuum (ambient taken as 1000 mbar).
- **Cylinder force monitor:** the side + bottom simulations report a pneumatic-cylinder overload (Side + bottom, end face, Side + bottom, long face). That is a separate actuator limit of the folding mechanism, not a vacuum result, and needs its own check.
- **Not a lifting-safety certification.**

Recommended checks

- Measure the free-air flow of the current pump to confirm V3 (≈40 m³/h) before buying a pump.
- Measure the pressure inside one attached cup on the real gripper, before and after re-drilling.
- Test held / not held on the real gripper at one or two vacuum levels, and measure how far the carton sags, to check the vacuum-scaling and cup-stretch assumptions.