# *Controlling Cabin and Envelope Air Flows & Pressure Differentials*

## To control envelope moisture and related problems

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## This paper develops ventilation system design criteria to prevent envelope condensation, address envelope fires and IAQ (Walkinshaw et al, 2001, 2011) and thereby:

1 **Improve** aircraft skin **structural safety**
- Dry envelope.

2 **Improve** electrical **fire safety**.
- Exhaust envelope smoke,
- Extinguish fire directly.

3 **Reduce fuel consumption**
- Reduce envelope condensate accumulation.

4 **Improve cabin RH and IAQ** conditions
- Warmer liner.
- Lower envelope MVOCs.
- Higher cabin RH by reducing condensate losses.

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## Some background events

| | |
|---|---|
| 1987,'89,' 98, '00 | Smoking banned on US flights a) < 2 hours, b) <6 hours, c) all domestic flights, d) all flights. |
| | Decreased bleed air per person raises RH and envelope condensation. |
| 1988 | Aloha airlines loses a large section of upper fuselage during flight. |
| 1995 | Inject dry air into envelope to address condensation. Nordstrom *et al* |
| 1998 | Swiss Air Flight 111. 229 lives lost due to electrical fire/smoke movement in envelope. |
| 1999 | Seal liner, add flow blocker(s). Inject dry air to offset stack pressures. Exhaust envelope to remove smoke. Walkinshaw , Mitalas, McNeil, Preston |
| 2007 | Influenza transmission increases with decreasing RH. Lowen *et al* |
| 2011 | Southwest airlines loses some upper fuselage during flight. |

# Envelope condensation and premature metal fatigue

**April 28, 1988.** Aloha airlines jet lost a major portion of the upper fuselage near the front of the plane, in full flight at 24,000 feet, sweeping a flight attendant to her death while the pilot managed to land the plane. Multiple fatigue cracks were subsequently detected in the remaining aircraft structure in the holes of the upper row of rivets in several fuselage skin panel lap joints. Inspection of other similar aircraft revealed disbonding, corrosion and cracking in the lap joints.

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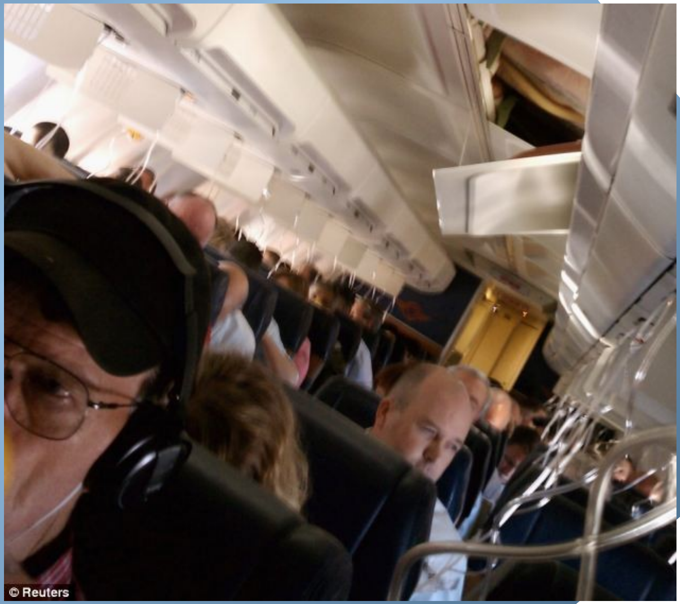
# Envelope condensation and premature metal fatigue

**April 1, 2011.** Southwest Airlines passengers said they are lucky to be alive and spoke of their terror the moment a three-foot hole 'exploded' in their plane's fuselage, forcing them into a terrifying descent and emergency landing. Engineers expect the fuselage skin lap joints to endure 60,000 flight cycles. This failure was at 39,871 flight cycles.



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# Envelope condensation – the main cause is:

## Stack pressure differentials

across the cabin insulation are created by temperature differentials and cause:

1 Cabin air to circulate between the envelope and the cabin, depositing **water vapor condensate in the envelope** (space between the cabin liner & aircraft skin).

2 **Inability to economically raise cabin humidity to normal levels**.

3 Envelope air to move longitudinally: a) to the front in nose-down attitude (**fire emergency safety problem** taking smoke in envelope to cockpit – Swiss Air flight).

# Stack pressure calculation

$$dp = (\rho 2 - \rho 1)*g*h \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

dp = Stack pressure differential, Pa

$\rho 2 - \rho 1$ = air density differential – from behind to in front of the insulation (kg/m3)

g = acceleration due to gravity (9.8 m.s-2)

h = height above the neutral plane (m)

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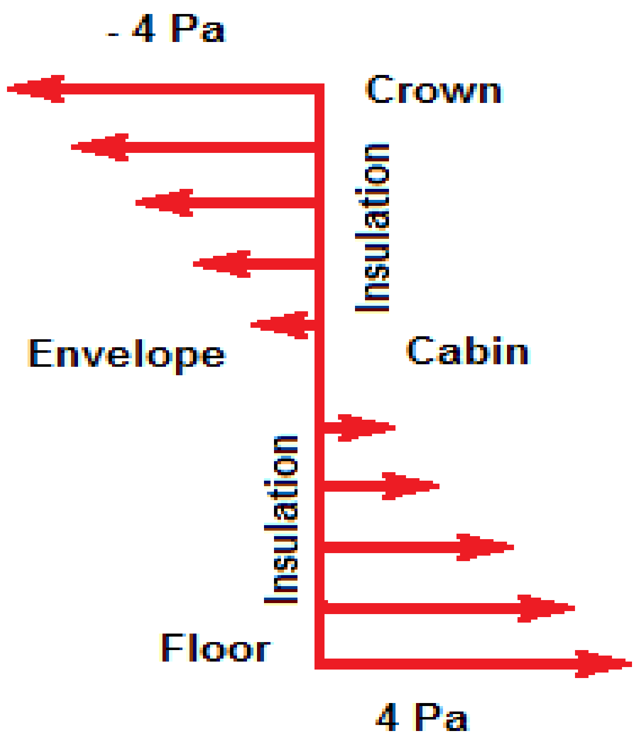
# Stack pressure variation with elevation at cold soak between the crown and the cabin floor with a flow blocker



4 Pa = 0.00058 psi or 0.016 inches wc at 4C

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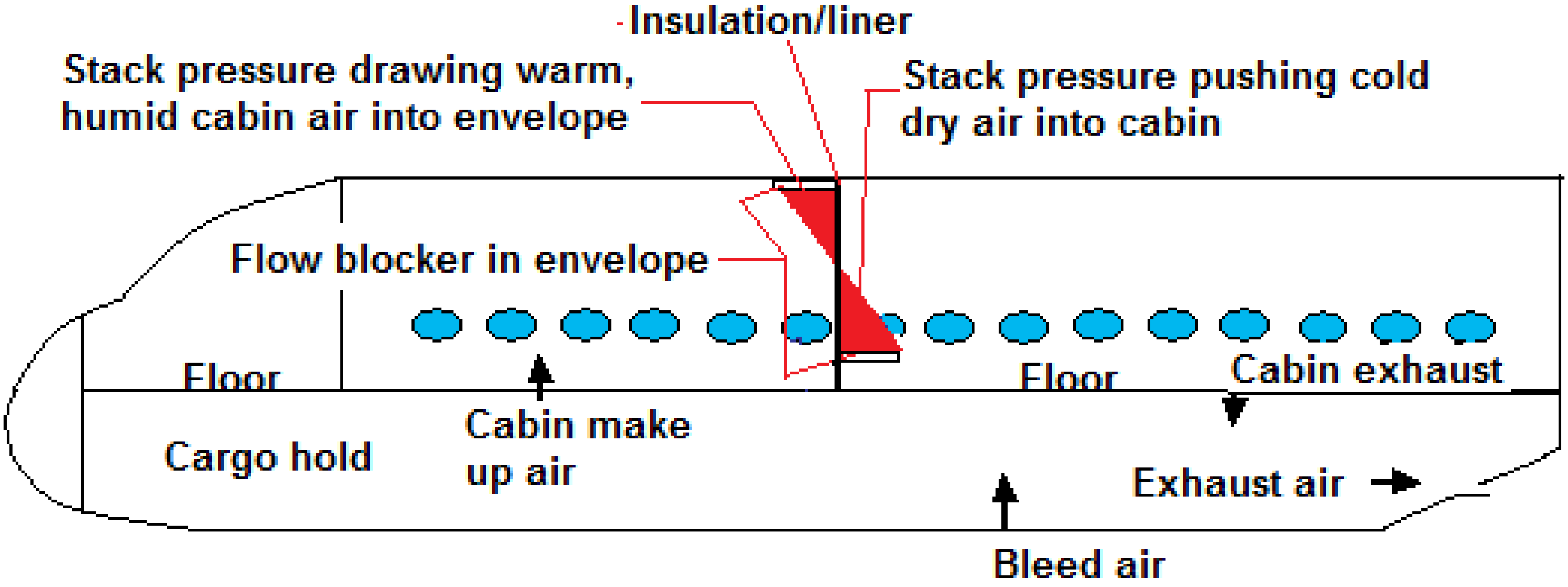
## Stack pressure profile while flying at level attitude



- Window level flow blocker.
- The stack pressure profile will be the same the length of the cabin.

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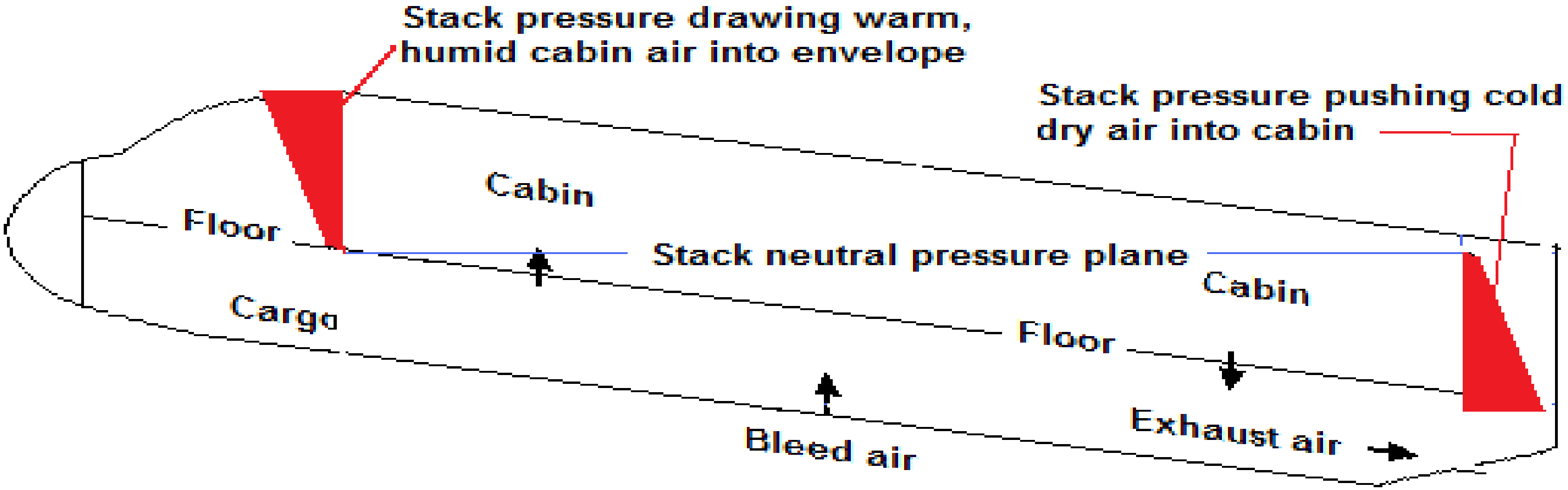
# Stack pressure profile in the nose up attitude



- Floor flow blocker.
- Unrestricted envelope air movement fore and aft.

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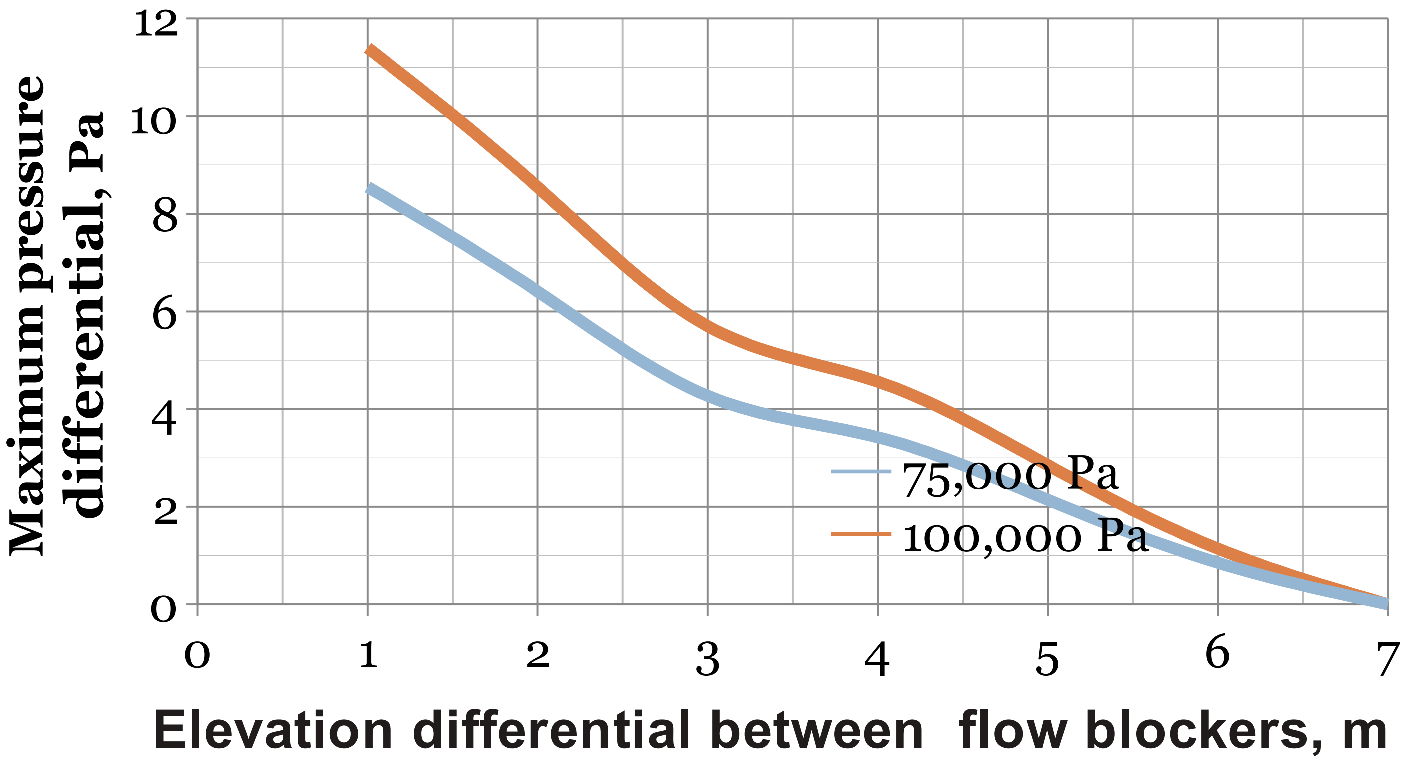
# Stack pressure across the insulation vs height, h



Temperature differential = 22C to -50C.
Cabin pressures = 75,000 Pa (8000 ft) & 100,000 Pa

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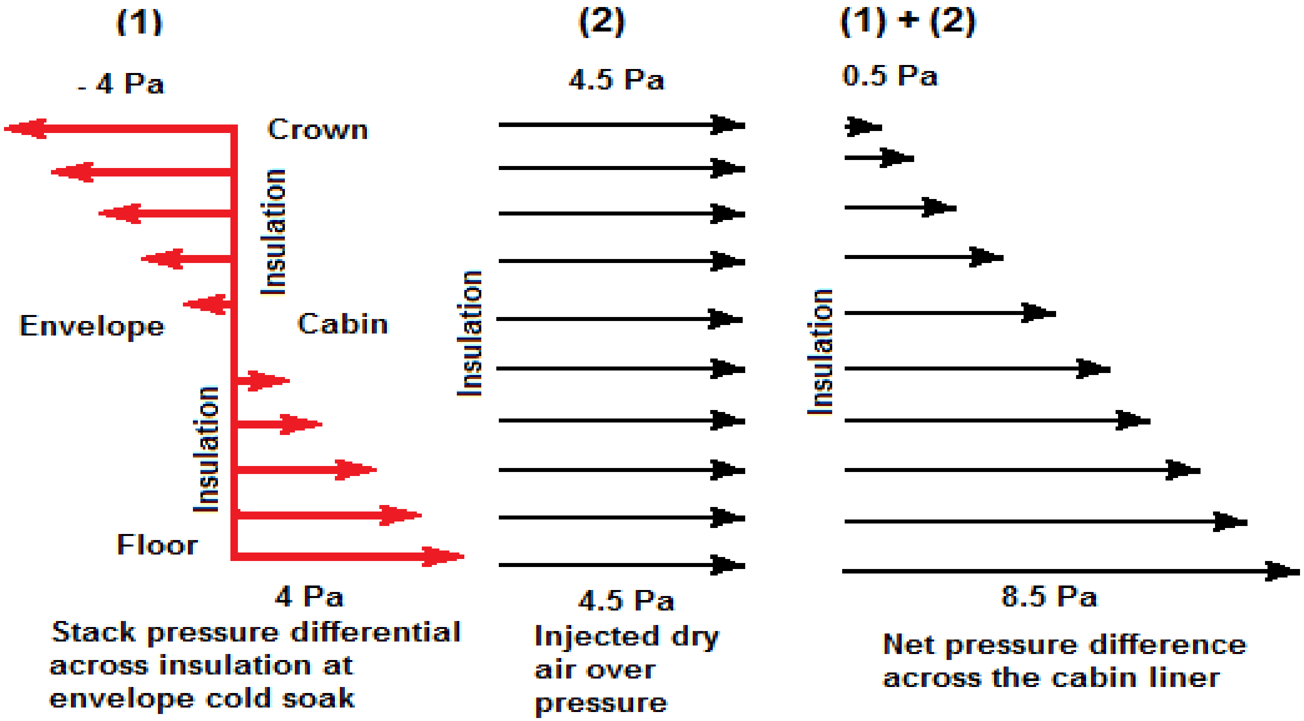
# Offsetting stack pressures through dry air injection



Dry injection air = trim bleed air or dehumidifier air.

Dry air Injection flow rate, adjusted to ELA and stack pressure profile, creates an envelope air outflow into cabin at all leakage areas.

In tightly insulated envelopes an air distribution system is needed.

PAPER # 2011-01-2689

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# To make this ventilation solution cost efficient:

1 **Install envelope flow blockers** at the cabin floor and at head height to reduce the stack pressures and cause injection air to flow back into the cabin as ventilation air .

2 **Seal the liner and add flow blockers** to reduce the injection flow rate requirement.

3 **Make liner leakage paths long** to minimize cabin water vapor upstream diffusion into the pressurized envelope.

# Calculating liner and flow blocker air tightness and ELA

$$Q=Cd*ELA*(2*dp/\rho a\ )\ 0.5\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Q = The dry air injection flow, m3/s

Cd = discharge coefficient = 0.6 for small openings

ELA = equivalent leakage area (m2)

ρa = air density (kg/m3)

dp = pressure differential across the liner (Pa)

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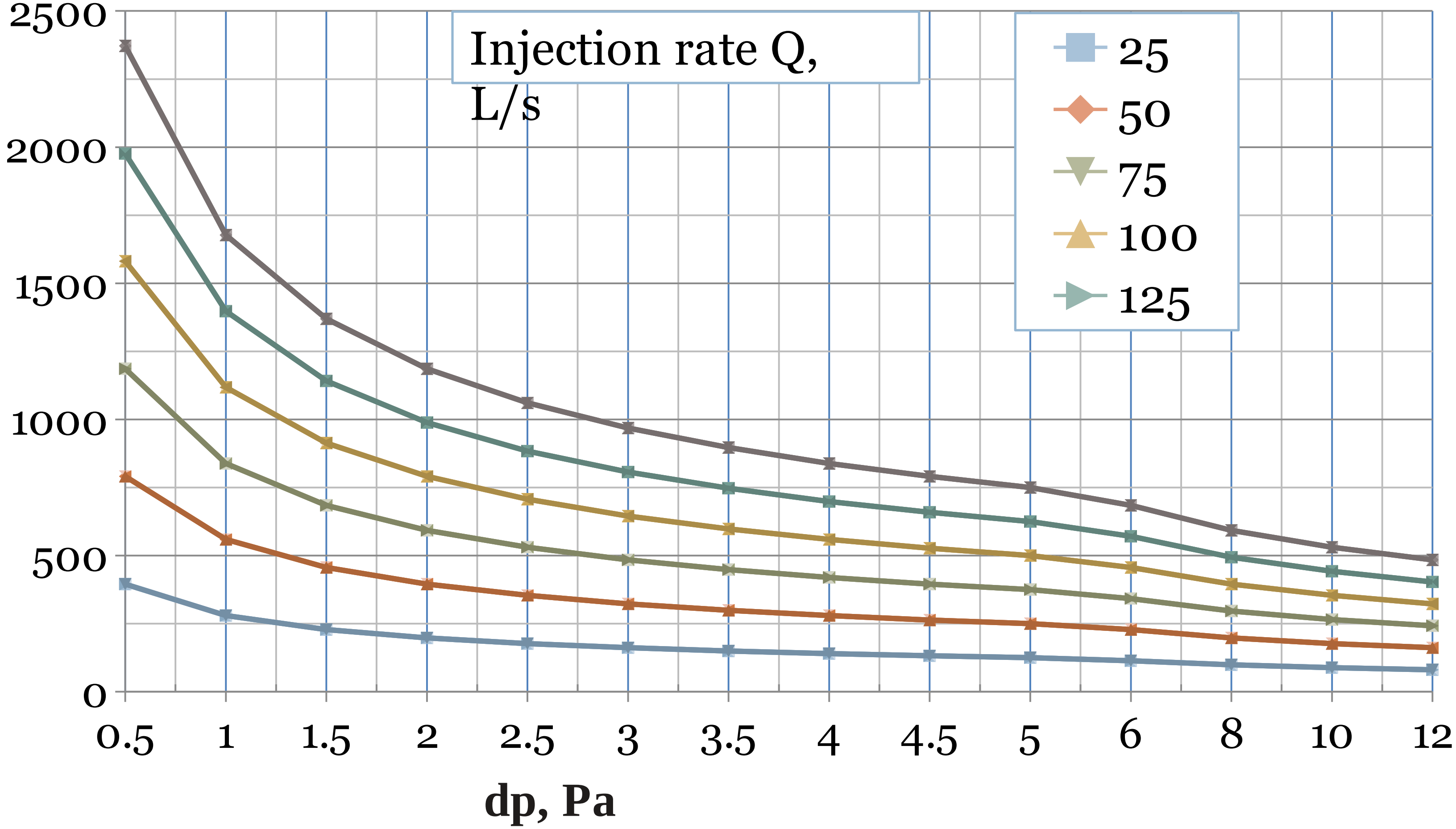
# Injection rate required versus ELA and dp for Cd=0.6 and an 8000 ft cabin elevation.



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# Calculating cabin moisture diffusion from the cabin into the envelope through liner leakage

$$Md = D * (\rho 2 - \rho 1) * A/L \text{ ..............................} (4)$$

**Md = Molecular diffusion of water vapor** from cabin into envelope through leaks, mg/s

**D = mass diffusivity** for the water vapor in air = 2.42*10-5 m2/s

ρ2 - ρ1 = partial density **gradient of water vapour- cabin to behind insulation,** mg/m3

A = cross sectional **area over which diffusion takes place** (ELA), m2

L = **length over which diffusion occurs** (e.g. liner thickness), m

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# Water vapor density in the cabin and the envelope from ASHRAE psychrometric charts

| T, oC | RH, % | Water vapor density, mg/m3 |
|---|---|---|
| 20 | 60 | 10,800 |
| 20 | 40 | 6,960 |
| 20 | 30 | 5,280 |
| 20 | 20 | 3,480 |
| 0 | 65 | 2,940 |
| -40 | 65 | 48 |

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## Calculating convective moisture outflow from a dry air pressurized envelope through leakage

**Mc = C1 * Q...................................(5)**

Mc = **Convective water vapor transfer**, from the envelope into the cabin through leaks, mg/s

C1= **concentration of the water vapor** in the envelope (e.g. 48 mg/m3)

Q = **air flow injection rate** into the envelope (m3/s)

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## Will convective moisture flow from the pressurized envelope overcome cabin air vapor diffusion into the envelope, both through the same leaks but in opposite directions?

Examples: Cabin = 20C, insulation cold side = -40C, crack length = 0.635 cm.

| Cabin RH | 20% | 20% | 30% | 30% |
|---|---|---|---|---|
| **Dry air injection rate** Q, L/s | 75 | 75 | 125 | 125 |
| **Leak ELA**, cm^2 (liner & flow blockers) | 375 | 530 | 625 | 884 |
| **Design dP**, Pa (e.g. without & with a window level flow blocker, floor blocker) | 5 | 2.5 | 5 | 2.5 |
| **H2O diffusion** into envelope, mg/s | 0.69 | 0.97 | 1.75 | 2.48 |
| **H2O convective** flow from envelope, mg/s | 3.6 | 3.6 | 6.0 | 6.0 |
| **Ratio** convective flow from envelope/diffusion into envelope | 5.2 | 3.7 | 3.4 | 2.4 |

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# Control measures summary

1 Envelope (de)pressurization

-requires an envelope ventilation system supply (exhaust);
-requires air distribution mechanisms in tightly insulated envelopes;
-more efficient with flow blockers that reduce stack pressures;
-small liner and flow blocker leakage areas make efficient;
-plane attitude changes stack pressures longitudinally.

2 Flow blocker at head height

-recovers cabin ventilation air, reduces stack pressure .

3 Back diffusion

-longer leakage pathways (thicker liner joints) enable higher cabin humidity without associated condensation.

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## Control measures summary, cont'd

| | |
|---|---|
| 4 | On board dehumidifier as the envelope dry air source<br>- Can use at all stages of flight cycle or just in flight and during descent. |
| 5 | Bleed air as the envelope dry air source<br>- Can use during cruise at no energy cost;<br>- Inject on cold side of insulation to reduce pack cooling load; Inject on warm side to thermally condition cabin. |
| 7 | -Ground A/C or heater as the envelope dry air source<br>- Can use on ground as the dry air source |
| 8 | Safety blow-out panel to relieve envelope pressure<br>- For a sudden depressurization event. |
| 9 | Envelope fire<br>- Exhaust envelope smoke directly to the outdoors;<br>- Inject fire suppressant while envelope under negative pressure. |

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## Conclusion

The cabin envelope moisture problem can be improved through controlled envelope (de)pressurization made practical with sealing, flow blocking and leakage path lengthening measures.

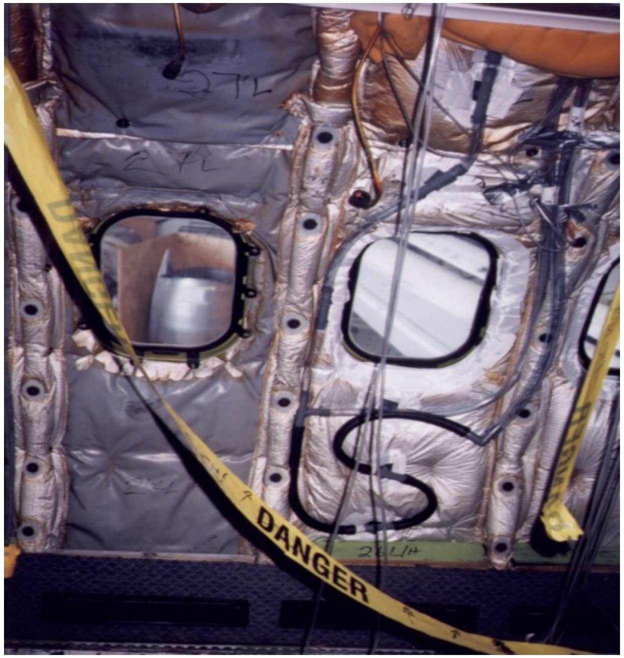

**Figure B.2** View of 3/4"ID PVC injection tubing behind the B737 cabin insulation

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