

Safety Review for Hydrogen Jet Facility

Thomas Russell¹



MONASH
University



Context

- If hydrogen jet testing is to be performed in the upstairs Shock Lab it must be done safely.
 - This is, there shall be no risk to the operators and nearby people to the lab.
- Hydrogen is a fuel and will combust readily with contact with oxygen.
- A system must be designed such that the hydrogen is extracted safely without any risk of unintended ignition.
- Appropriate fail safes must be in place to safely shut down the system in an emergency.

Key Issues

1. Hydrogen concentration leaving the jet exceeding the lower explosive limit and combusting around an ignition source.
2. Hydrogen combusting inside the extraction system
3. Hydrogen leaking outside of the designated flow path into the room
4. Being able to immediately shut the system down and safely evacuate all hydrogen from the feed system

Issue 1 – Ignition sources near hydrogen jet

The LEL of hydrogen is 4% by volume. Since no-one is in the lab when hydrogen is flowing, there is no WorkSafe requirement of concentrations. I suggest a self imposed FoS of 2 on the LEL with an additional factor of 2 for mixing variability. Giving a cumulative FoS of 4, and thus a maximum concentration of hydrogen 1% by volume for the lab concentrations levels.

Different FoS to be used for extraction*

This should eliminate need for “ex-rated” equipment and concern around ignition sources.

Flammable gases or vapours

(1) An employer or self-employed [person](#) must ensure during work in a confined space that—

(a) so far as is reasonably practicable, the concentration of any flammable gas or vapour in the atmosphere of the space is below 5% of its LEL; or

(b) if it is not reasonably practicable to comply with paragraph (a) and the concentration of any flammable gas or vapour in the atmosphere of the space—

(i) is, or is likely to be, equal to or greater than 5% but less than 10% of its LEL, any employee is removed immediately from the space unless a suitably-calibrated, continuous-monitoring, flammable gas detector is used in the space while the employee is in the space; or

(ii) is equal to or greater than 10% of its LEL, any employee is removed immediately from the space.

Issue 2 – Adequate dilution via extraction

AS/IEC 60079.10.1 discusses explosive gas atmospheres and specifically provides guidance around leaks and extraction design for these systems.

Start by classifying grade of release: I propose “primary”

3.4.2

continuous grade of release

release which is continuous or is expected to occur frequently or for long periods

Note 1 to entry: Both “frequently” and “long” are the terms which are intended to describe a very high likelihood of a potential release. In that respect, those terms do not necessarily need to be quantified.

3.4.3

primary grade of release

release which can be expected to occur periodically or occasionally during normal operation

3.4.4

secondary grade of release

release which is not expected to occur in normal operation and, if it does occur, is likely to do so only infrequently and for short periods

– 39 –

B.2.2 Sources giving a continuous grade of release

Hereunder are some typical examples:

- the surface of a flammable liquid in a fixed roof tank, with a permanent vent to the atmosphere.
- the surface of a flammable liquid which is open to the atmosphere continuously or for long periods.

B.2.3 Sources giving a primary grade of release

Hereunder are some typical examples:

- Seals of pumps, compressors or valves if release of flammable substance during normal operation is expected.
- Water drainage points on vessels which contain flammable gases or liquids, which may release flammable substance into the atmosphere while draining off water during normal operation.
- Sample points which are expected to release flammable substance into the atmosphere during normal operation.
- Relief valves, vents and other openings which are expected to release flammable substance into the atmosphere during normal operation.

B.2.4 Sources giving a secondary grade of release

Hereunder are some typical examples:

- Seals of pumps, compressors and valves where release of flammable substance during normal operation of the equipment is not expected.
- Flanges, connections and pipe fittings, where release of flammable substance is not expected during normal operation.
- Sample points which are not expected to release flammable substance during normal operation.
- Relief valves, vents and other openings which are not expected to release flammable substance into the atmosphere during normal operation.

Issue 2 – Adequate dilution via extraction

Openings must be classified according to type A, B, C and D. This experiment could be considered Type B or C, propose classifying as Type B for conservativeness.

B.8.3 Openings classification

For the purpose of this assessment, openings are classified as A, B, C and D with the following characteristics:

Type A

Openings not conforming to the characteristics specified for types B, C or D, e.g.:

- open passages for access or utilities (examples of utilities include ducts or pipes through walls, ceilings and floors);
- openings which are frequently opened;
- fixed ventilation outlets in rooms, buildings and similar openings.

Type B

Openings which are normally closed (e.g. automatic closing), infrequently opened and close-fitting.

Type C

Openings which are normally closed (e.g. automatic closing), infrequently opened and fitted with sealing devices (e.g. a gasket) along the whole perimeter; or two type B openings in series, having independent automatic closing devices.

Type D

Openings which are effectively sealed, such as in utility passages; or openings normally closed conforming to type C which can only be opened by special means or in an emergency; or a combination of one opening type C adjacent to a hazardous area and one opening type B in series.

Table B.2 shows the effect of openings on grade of release when a zone has been established upstream of those openings.

Issue 2 – Adequate dilution via extraction

The ventilation in the Shock Lab provides 19 m/s of extraction. Extrapolating on figure C.1, we have a “high” dilution rate if the release rate of hydrogen is less than 1500 L/s with factors of safety. We have “medium” dilution to effectively infinite release rate for our scenario.

$$Q_c = \frac{W_g}{\rho_g \times LFL}$$

Hi Mem,

As discussed last week, we are able to increase the airflow of the extractor arm to 8640 m3/hr as requested.

We would do this by increasing the duct diameter to 400mm with an approx. velocity of 19 m/s. We suggest using our Nederman NCF 120/15 fan which will provide the required extraction to achieve this airflow. We have included a purpose built post to support the 6m extension arm and weight. This will be a purposed design and built post including certification.

With regards to the mezzanine, we would spread the load of the system by incorporating a large place to the post.

Qty	Part no	Description	Availability
1	10507735	Extension arm 6m	4-6 weeks approx. subject to prior sale.
1	10374376	Hard duct kit D=200 ext.arm 4,2m	
1	90520328	Fan NCF 120/15, 415V 7.5kW 50Hz	
1	69000260	Flex.inlet.adap.d500,120/15,160/25	
1	69000261	Flex.ou.a.453x322d500,120/15,160/25	
1		Flex on 6m arm and duct	
1		Purpose built post	

Total for above parts only excluding mechanical installation @ \$ 20,827.17 + GST.

Installation cost subject to site inspection @ \$ 8526.00+ GST. subject to site inspection.

Should you have any queries, please do not hesitate to contact us.

Regards,

Oscar Barahona

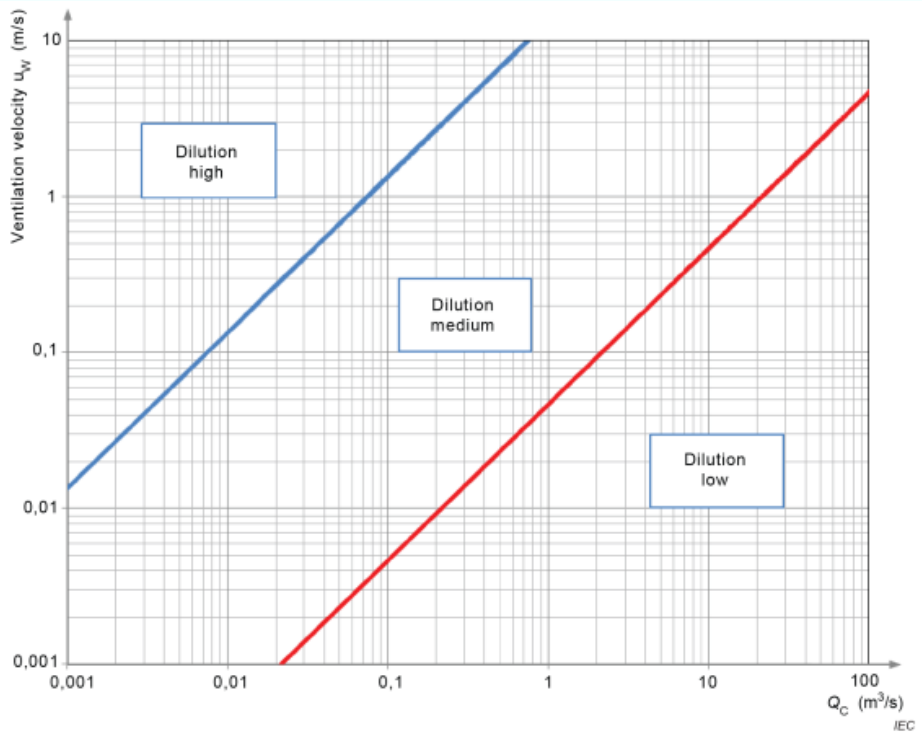


Figure C.1 – Chart for assessing the degree of dilution

Issue 2 – Adequate dilution via extraction

Now estimating the zone type using the dilution rates and ventilation quality. Our system can be assumed “Good” ventilation during operation. Using our “high” dilution and “primary” release grade, we are “Zone 1 NE”. Effectively making the area non-hazardous, ex-rated equipment not required and no explosive zone.

Table D.1 – Zones for grade of release and effectiveness of ventilation

Grade of release	Effectiveness of Ventilation						
	High Dilution			Medium Dilution			Low Dilution
	Availability of ventilation						
	Good	Fair	Poor	Good	Fair	Poor	Good, fair or poor
Continuous	Non-hazardous (Zone 0 NE) ^a	Zone 2 (Zone 0 NE) ^a	Zone 1 (Zone 0 NE) ^a	Zone 0	Zone 0 + Zone 2 ^c	Zone 0 + Zone 1	Zone 0
Primary	Non-hazardous (Zone 1 NE) ^a	Zone 2 (Zone 1 NE) ^a	Zone 2 (Zone 1 NE) ^a	Zone 1	Zone 1 + Zone 2	Zone 1 + Zone 2	Zone 1 or zone 0 ^d
Secondary^b	Non-hazardous (Zone 2 NE) ^a	Non-hazardous (Zone 2 NE) ^a	Zone 2	Zone 2	Zone 2	Zone 2	Zone 1 and even Zone 0 ^d

^a Zone 0 NE, 1 NE or 2 NE indicates a theoretical zone which would be of negligible extent under normal conditions.

^b The Zone 2 area created by a secondary grade of release may exceed that attributable to a primary or continuous grade of release; in this case, the greater distance should be taken.

^c Zone 1 is not needed here. I.e. small Zone 0 is in the area where the release is not controlled by the ventilation and larger Zone 2 for when ventilation fails.

^d Will be Zone 0 if the ventilation is so weak and the release is such that in practice an explosive gas atmosphere exists virtually continuously (i.e. approaching a 'no ventilation' condition).

'+' signifies 'surrounded by'.

Availability of ventilation in naturally ventilated enclosed spaces is commonly not considered as good.

4.4.2 Zone of negligible extent

In some cases a zone of negligible extent (NE) may arise and may be treated as non hazardous. A zone of negligible extent would also imply either a negligible release rate or a negligible release quantity and considering the volume for dispersion.

Such a zone implies that an explosion, if it takes place, will have negligible consequences. The zone NE concept can be applied irrespective of any other adjustments for risk assessment to determine EPL.

The criteria for a zone NE classification should be based on the following factors:

- i) Ignition would not result in sufficient pressure to cause harm either due to the pressure wave or due to damage that could cause flying objects or particles e.g. broken glass from windows.
- ii) Ignition would not result in sufficient heat to cause harm or a fire from surrounding materials.
- iii) For gas distributed at pressures above 1 000 kPag (10 barg) consideration shall be given to a specific risk assessment
- iv) A zone NE shall not be applied to gas distributed at pressures above 2 000 kPag (20 barg) unless a specific detailed risk assessment can document otherwise.

An example of zone NE is a natural gas cloud with an average concentration that is 50 % by volume of the LFL and that is less than 0,1 m³ or 1,0 % of the enclosed space concerned

3.3.5

Zone 1

area in which an explosive gas atmosphere is likely to occur occasionally in normal operation

Three levels of availability of the ventilation should be considered (see Table D.1):

- **good:** ventilation is present virtually continuously;
- **fair:** ventilation is expected to be present during normal operation. Discontinuities are permitted provided they occur infrequently and for short periods;
- **poor:** ventilation which does not meet the standard of fair or good, but discontinuities are not expected to occur for long periods.

Issue 2 – Adequate dilution via extraction

Lastly, using isentropic nozzle flow equations, the jet can be sized appropriately to ensure safe operation. Employing a FoS of 1.25 for confidence in mass flow rates from the nozzle gives the following volume flow rates.

Notice the standard does not employ an additional FoS, this FoS is chosen arbitrarily by us and must be agreed upon. This leaves us with an ideal nozzle diameter of 3.5 mm or less.

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--- Nozzle Diameter = 3.0 ---
M_dot = 1.3 g/s - Q H2 = 16.1 L/s - Q Air = 503.0 L/s - NPR 3
M_dot = 1.8 g/s - Q H2 = 21.5 L/s - Q Air = 670.7 L/s - NPR 4
M_dot = 2.2 g/s - Q H2 = 26.8 L/s - Q Air = 838.4 L/s - NPR 5
M_dot = 2.7 g/s - Q H2 = 32.2 L/s - Q Air = 1006.1 L/s - NPR 6

--- Nozzle Diameter = 3.5 ---
M_dot = 1.8 g/s - Q H2 = 21.9 L/s - Q Air = 684.7 L/s - NPR 3
M_dot = 2.4 g/s - Q H2 = 29.2 L/s - Q Air = 912.9 L/s - NPR 4
M_dot = 3.0 g/s - Q H2 = 36.5 L/s - Q Air = 1141.1 L/s - NPR 5
M_dot = 3.6 g/s - Q H2 = 43.8 L/s - Q Air = 1369.4 L/s - NPR 6


--- Nozzle Diameter = 4.0 ---
M_dot = 2.4 g/s - Q H2 = 28.6 L/s - Q Air = 894.3 L/s - NPR 3
M_dot = 3.1 g/s - Q H2 = 38.2 L/s - Q Air = 1192.4 L/s - NPR 4
M_dot = 3.9 g/s - Q H2 = 47.7 L/s - Q Air = 1490.5 L/s - NPR 5
M_dot = 4.7 g/s - Q H2 = 57.2 L/s - Q Air = 1788.5 L/s - NPR 6

--- Nozzle Diameter = 5.0 ---
M_dot = 3.7 g/s - Q H2 = 44.7 L/s - Q Air = 1397.3 L/s - NPR 3
M_dot = 4.9 g/s - Q H2 = 59.6 L/s - Q Air = 1863.1 L/s - NPR 4
M_dot = 6.1 g/s - Q H2 = 74.5 L/s - Q Air = 2328.8 L/s - NPR 5
M_dot = 7.4 g/s - Q H2 = 89.4 L/s - Q Air = 2794.6 L/s - NPR 6
    
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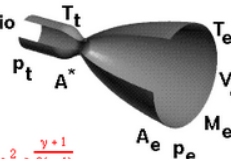
$$Q_c = \frac{W_g}{\rho_g \times LFL}$$



Rocket Thrust Summary



Known:
 p_t = Total Pressure γ = Specific Heat Ratio
 T_t = Total Temperature R = Gas Constant
 p_o = Free Stream Pressure A = Area



Mass Flow Rate: $\dot{m} = \frac{A^* p_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$

Exit Mach: $\frac{A_e}{A^*} = \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \left(1 + \frac{\gamma-1}{2} M_e^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}$

Exit Temperature: $\frac{T_e}{T_t} = \left(1 + \frac{\gamma-1}{2} M_e^2\right)^{-1}$

Exit Pressure: $\frac{p_e}{p_t} = \left(1 + \frac{\gamma-1}{2} M_e^2\right)^{-\frac{\gamma}{\gamma-1}}$

Exit Velocity: $V_e = M_e \sqrt{\gamma R T_e}$

Thrust: $F = \dot{m} V_e + (p_e - p_o) A_e$

Issue 3 – Leaking into lab

Issue 3 leads directly on from issue 2, background concentrations must be looked at. Referring back to the AS/IEC 60079.10.1 standard. Taking the conservative approach and assuming no local extraction and just general room extraction we fail the background concentration calculations ($X_b = 63\%$ of LEL which means $X_b > X_{crit} = 25\%$ of LEL).

A zero background concentration should be considered only outdoors or in regions with local extraction ventilation which controls the movement of flammable substance near the source of release. A negligible background concentration, described as $X_b \ll X_{crit}$, may be considered in highly ventilated rooms or enclosures. X_{crit} is an arbitrary value below LFL, e.g. the value at which a gas detector is set to alarm.

The safety factor f , ventilation inefficiency, is a measure of the degree to which the air in the enclosure outside of the release zone is well mixed and is the mean background concentration X_b in the room divided by the concentration at the ventilation outlet (dimensionless).

$f=1$: the background concentration is essentially uniform and the outlet is distant from the release itself, so that the concentration at the outlet reflects the mean background concentration.

$f>1$: there's a gradient of background concentration in the room due to inefficient *mixing*, and the outlet is distant from the release itself, so that the concentration at the outlet is smaller than the mean background concentration. f may be between 1.5 for mildly inefficient mixing and 5 for very inefficient mixing.

Given the origin of the cases $f=1$ or $f>1$, this value may be denoted as a safety factor related to the inefficiency of mixing (as progressively larger values reflect progressively less efficient mixing of air within the room). This factor allows for imperfections of air flow patterns in a real space with obstructions and where ventilation openings may not be ideally positioned for maximum ventilation (see C.5). The degree of dilution should be taken as being low if the background concentration exceeds 25 % of the LFL or if indicated through an assessment based on Figure C.1.

For indoor releases it is necessary to specify the room background concentration, X_b , which embodies the effects of ventilation. Background concentration is the average concentration of flammable substance within the volume under consideration (room or building) after a period of time during which a steady state has been established between the release and the flow of air induced by ventilation.

Q_1 volumetric flow rate of air entering the room through apertures (m^3/s);

Q_g volumetric flow rate of flammable gas from the source (m^3/s);

$Q_2 = Q_1 + Q_g$ volumetric flow rate of air/gas mixture leaving the room (m^3/s);

$$X_b = \frac{f \times Q_g}{Q_g + Q_1} = \frac{f \times Q_g}{Q_2} \text{ (vol/vol)}$$

and the air change frequency and ventilation flux are related by:

$$Q_2 = CV_0 \text{ (m}^3/\text{s)}$$

Issue 3 – Leaking into lab

However, this is overly conservative, and the standard specifically references local extraction. With local extraction the background concentration can be considered “zero”. Furthermore, the standard specifically references this calculation is for some specified time after reaching steady-state. We will not be running continuous and thus do not meet this condition either.

Meeting these conditions, I propose we accept a “zero background concentration” and thus this issue is resolved. Additionally, we should have hydrogen detectors around the room which will be set to 25% of LEL for alarm in case of an accidental leak.

Lastly, if deemed necessary, at 32.8 L/s (3 mm nozzle at NPR 6) with a 1.25 FoS for error margin, for a 3x3x2m room, we can run for ~3.5s before exceeding 25% LEL without any extraction.

A zero background concentration should be considered only outdoors or in regions with local extraction ventilation which controls the movement of flammable substance near the source of release. A negligible background concentration, described as $X_b \ll X_{crit}$, may be considered in highly ventilated rooms or enclosures. X_{crit} is an arbitrary value below LFL, e.g. the value at which a gas detector is set to alarm.

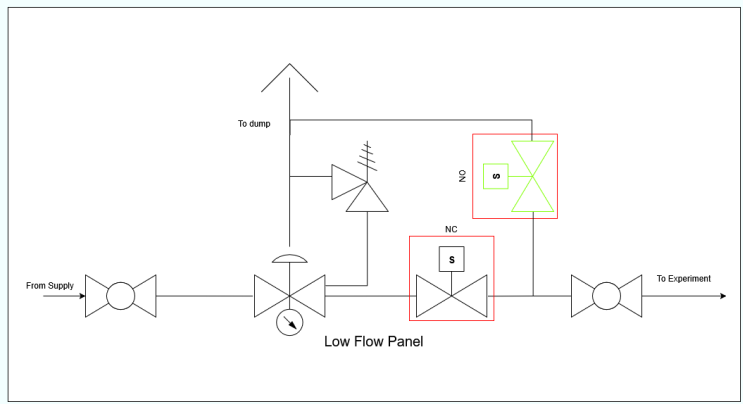
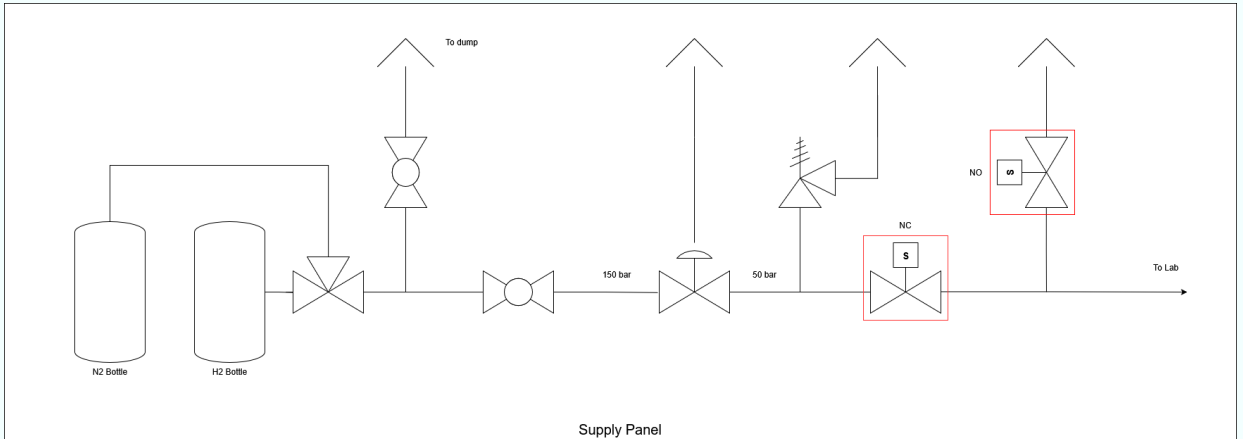
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Issue 4 – Emergency stop procedures

Issue 4 will be addressed with a “e-stop” system routed directly to the operators control station that will automate and abort sequence. Additionally, software controls can be added for non-emergency situations.

Red = Connected to e-stop

Green = New component



Order of Operations

Initial nitrogen purge and regulator setpoints:

1. Start extraction
2. Switch supply 3-way valve to nitrogen
3. Enter lab and close both manual ball valves on low-flow panel
4. Ensure pneumatic lines connect to valves and pneumatics are on
5. Exit lab and ensure manual dump valve is closed
6. Ensure pneumatic lines connect to valves and pneumatics are on
7. Open manual fill ball valve on supply side
8. Open nitrogen bottle
9. On control station run “supply regulator set” opening the two pneumatic valves on the supply panel
10. Set supply regulator to target pressure
11. Stop the process to return both pneumatic valves to closed
12. Close nitrogen bottle
13. Open the manual dump valve and close after venting complete
14. Enter lab and open manual ball valve on the supply side of the low flow panel
15. Exit the lab and open the nitrogen bottle
16. On control station run “low flow panel regulator set” opening the in-line pneumatic valve on the supply panel and the two pneumatic valves on the low flow panel
17. Adjust the regulator set point to target pressure
18. Open the experiment side manual ball valve on the low flow panel to purge the jet into the extraction, close after 5 seconds.
19. Exit the lab and close the nitrogen bottle
20. On the control station stop the process. The system should be purged and vented.

Order of operations

Running experiment:

1. Assume initial nitrogen purge has just been completed
2. Ensure both manual ball valves on supply panel are closed
3. Switch 3-way valve on supply to hydrogen bottle, ensure bottle valve is closed before this is done
4. Open hydrogen bottle
5. Set experiment duration
6. On control station run “Start experiment run” opening the in-line pneumatic valve on the supply panel for 3 seconds before opening the in-line pneumatic valve on the low flow panel for the specified duration
7. After the experiment conclusion the supply side in-line pneumatic valve will close, waiting for 3 seconds before closing the low flow panel in-line pneumatic valve
8. Close the hydrogen bottle
9. Open the manual dump valve on the supply panel, wait for vent and then close

Order of operations

Shutdown procedure:

1. Swap 3-way valve on supply panel to nitrogen bottle
2. Open the nitrogen bottle
3. On control station run “nitrogen purge” opening the in-line pneumatic valves on the supply and panel and low flow panel for 3 seconds before closing
4. Close the nitrogen bottle
5. Open manual dump valve on supply panel, wait for vent, then close
6. Close the manual fill valve on supply panel
7. Enter lab and close both manual ball valves on the low flow panel
8. Exit lab and stop extraction

Order of operations

Emergency stop mid run:

1. Press e-stop
2. Wait for vent of system
3. Close hydrogen bottle
4. Open manual dump valve on supply panel wait for vent and then close
5. Close manual fill valve on supply panel
6. Switch 3-way valve to nitrogen bottle
7. Open manual fill valve on supply panel
8. On control station run “nitrogen purge” opening the in-line pneumatic valves on the supply and panel and low flow panel for 3 seconds before closing
9. Close the nitrogen bottle
10. Open manual dump valve on supply panel, wait for vent, then close
11. Close the manual fill valve on supply panel
12. Confirm hydrogen levels on leak detector at acceptable levels before entering lab and close both manual ball valves on low flow panel
13. Exit lab and stop extraction

Acknowledgements

- Funding agencies
- Collaborators (not named on title slide)
- Data providers

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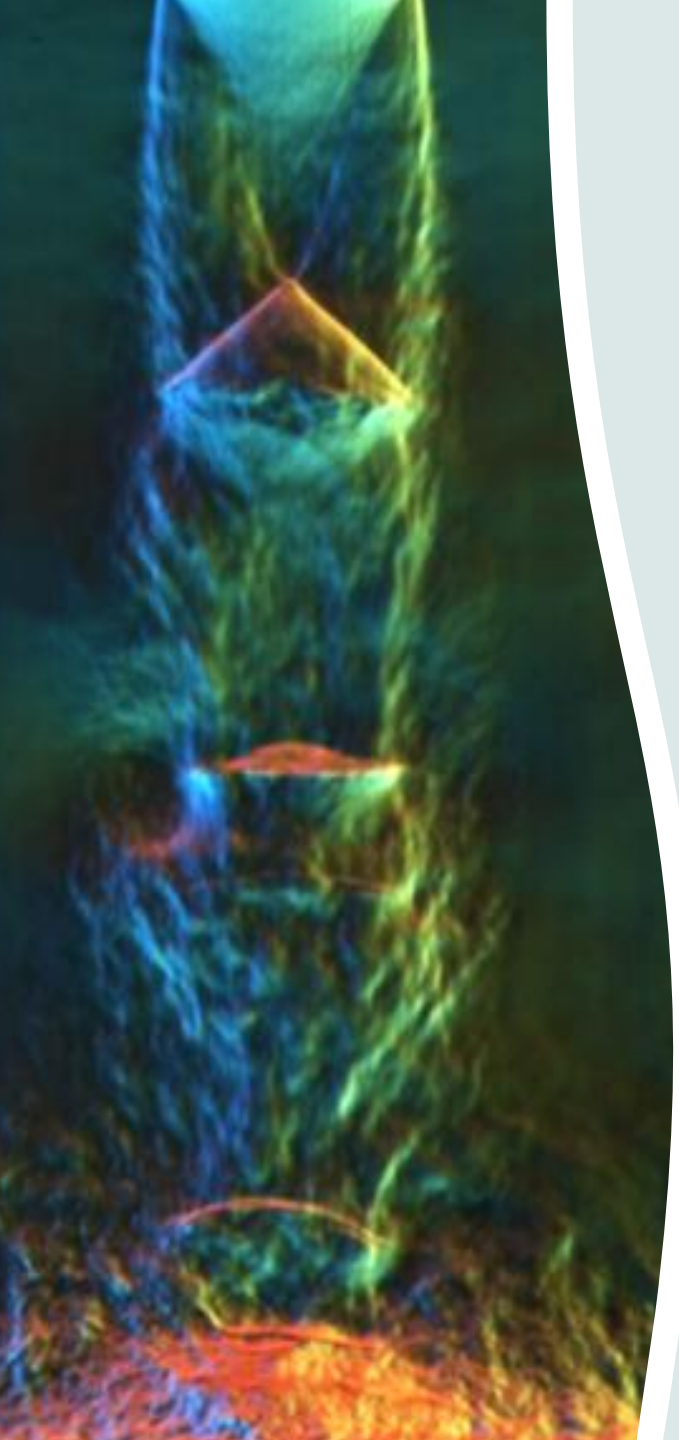
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Jet noise bad (more than two lines for a title is too large)

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