King Abdullah University of Science and Technology
Thuwal 23955-6900 Saudi Arabia

KAUST COMPRESSED GAS SAFETY PROGRAM

KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

March 2022 Health, Safety, and Environmental Department

KAUST Compressed Gas Safety Program

1. Scope

The Compressed Gas Safety Program, specifies minimum requirements for safe storage, use, and handling of compressed gases at King Abdullah University of Science and Technology (KAUST) to protect all personnel from potential physical and chemical hazards associated with using compressed gases at KAUST. This program applies to all KAUST properties and research spaces.

2. Introduction

Compressed gases are commonly used for a number of different operations. While compressed gases are very useful, they have the potential for creating hazardous working environments for these reasons:

- Gas cylinders may contain gases that are flammable, toxic, corrosive, asphyxiants, or oxidizers.
- Unsecured cylinders can be easily knocked over, causing serious injury and damage. The impact can shear the valve from an uncapped cylinder, causing a catastrophic release of pressure leading to personal injury and extensive damage.
- Mechanical failure of the cylinder, cylinder valve, or regulator can result in rapid release of the pressurized contents of the cylinder into the atmosphere; leading to explosion, fire, runaway reactions, or burst reaction vessels.

This program contains important information regarding the safe use of all types of compressed gases, liquefied gases and cryogenic gases at KAUST. It covers operational as well as engineering measures to ensure safety. The engineering requirements should also serve as a design basis for new construction and renovations.

The required safety measures mainly depend on the hazard classification of the gases. For gases that have multiple hazard properties, such as carbon monoxide, which is toxic and flammable, the applicable requirements for both "flammable gas" and "toxic gas" must be met.

Requirements also depend on quantity, concentration, distance from incompatibles/exposures as well as size and type of package.

Package Types	Examples
High pressured compressed gases	Hydrogen, helium, methane
Liquefied gas cylinders	Ammonia, butane, carbon dioxide, chlorine, CFC's, nitrous oxide, propane
Dissolved gas cylinder	Acetylene
Cryogenic liquefied gases	Liquid nitrogen, liquid argon, liquid helium
Non-refillable, single-use cylinders, lecture bottles, propane cartridges	Wide range of gases
User-refillable cylinders	High pressure cylinders intended for refilling and preparation of gas mixture by the user
Sub-atmospheric container	SDS cylinders for phosphine and arsine

For gas mixtures, the hazard properties of the mixture as a whole will determine the classification – for example, a dilute mixture of flammable gas with concentration below the Lower Explosive Limit (LEL) in an inert gas may be considered non-flammable as a whole.
This program is jointly developed by KAUST Health, Safety and Environment (HSE) Research Safety Team (RST), Planning, Design, Engineering & Construction department (PDEC), Facility Management Toxic Gas Monitoring Team (TGM) and laboratory stakeholders. Questions and comments regarding this standard should be addressed to hse@kaust.edu.sa.

3. Roles and Responsibilities

The section below provides an outline of various roles and responsibilities across campus:

3.1. Principal Investigator

The Principal Investigator (PI) of a laboratory, or supervisor of an area using gases, is responsible for compliance with this standard in the area(s) under his/her control and has primary responsibility for gas-use in the lab.

It is responsibility of the PI/supervisor/Director of Core Lab Facility that:

- Lab and gas specific standard operating procedures are developed and implemented along with risk assessments being conducted.
- Specific operational, equipment or gas specific training is provided.
- Adequate training (including hands-on) is provided to all users in the use and maintenance of compressed gases.

In addition, HSE offers basic compressed gas safety training via SALUTE. Hands on training must be conducted by the PI/supervisor.

3.2. All compressed gas users

All personnel involved in the handling of compressed gases must be competent and comply with relevant requirements contained in this program as well as specific procedures (e.g. SOPs) established by the lab PI or supervisor, lab specific safety plan and attend required trainings.

Other responsibilities of compressed gas users include but are not limited to:

- Understand the hazards while working with compressed gases.
- Wear appropriate personal protective equipment.
- Notify their supervisor of any injury directly related to a compressed gas cylinder.
- Inform their supervisor of a leaky, rusted, cracked or corroded cylinder or piping system if discovered.
- Notify their supervisor of any damage to or missing labels on cylinders.

3.3. Research Safety Team

The Research Safety Team (RST) is responsible for monitoring compliance through regular inspection and audits. Serious cases of non-compliance and violations may result in disciplinary actions, suspension of operation, and removal of the hazardous material concerned.

The RST is also responsible for conducting hazard evaluations and providing technical advice on the safe handling of hazardous gases.

Other responsibilities of RST includes:

- Approval for purchase of toxic, highly toxic, and pyrophoric gases.
- Provides general training of compressed gas safety training to lab users.
- Approval for toxic and flammable gas use requirements and controls.
- Review lab design projects prepared by Engineering and Project Management and provide comments to the design.
- Assists, advises, and instructs lab users in hazard evaluations to determine appropriate controls

Contact hse@kaust.edu.sa for any questions.

3.4. Fire Loss Prevention

Fire Loss Prevention (FLP), are the authority having jurisdiction for all matters pertaining to fire and life safety within KAUST. FLP provides formal interpretation and application of the applicable codes and standards. Contact FLP at hse@kaust.edu.sa for any questions.

3.5. Fire Department

Fire Department primary role is to respond to and take command of all incidents requiring an emergency attendance. Fire department respond to high level gas alarms coming from the TGM systems and reports from 911.Contact fire.captain@kaust.edu.sa for any questions.

3.6. Procurement Department / Planning and operations team

The department in KAUST in charge of the procurement of compressed gases and manages gas supplier contracts for all compressed or liquefied gases. Contact Procurement.research@kaust.edu.sa for any questions.

3.7. Procurement Department / Chemical Warehouse

Specialized facilities within KAUST to receive compressed gases from the supplier and capable to stock inert gases. Contact WHSOrder@kaust.edu.sa or call (0)12-808-5664 for any questions.

3.8. Procurement Department / Site Services

The team responsible for delivering compressed gases to the laboratories and collecting empty gas cylinders from the labs. Contact WHSOrder@kaust.edu.sa or call (0)12-808-5664 for any questions.

3.9. Planning, Design, Engineering and Construction Department

The KAUST group responsible for coordinating the design and commissioning of new laboratories and modification to existing lab spaces. Assists in the selection, installation, and startup of maintainable and reliable safety systems that support gas use operations. Facilities Management Project Request Form.

3.10. Facilities Management Department / Maintenance and Operations

Department responsible for maintaining gas systems and repairs to gas system components (gas manifolds, gas distribution systems, gas cabinets).
Contact fmcallcenter@kaust.edu.sa for any questions.

3.11. Facilities Management Department / TGM Team

The Toxic Gas Monitoring (TGM) Team provides maintenance and calibration to fixed gas detectors and automation controls. They are also responsible for preventive and corrective maintenance to gas monitoring systems.

On call Contact numbers: TGM 1 – 0545860225
TGM 2 – 0545863960

4. Compressed Gas Cylinder General Requirements

Compressed gas cylinders used for a variety of purposes on campus have the potential to create hazardous conditions for employees, students, and damage to facilities. The purpose of this section is to inform users of general requirements for storage, labeling, handling, use, and transportation of compressed gas cylinders at KAUST.

4.1. Storage

The following storage requirements apply to all gas cylinders:

- Gas cylinders shall not be stored in exits or dedicated exit passageways, exit stairways or other dedicated exit routes.
- Gas cylinders shall only be stored or used in approved locations.
- Always store gas cylinders in well-ventilated areas.
- Do not store gas cylinders in damp areas, near salt or corrosive chemicals, vapors, heat, or directly exposed to the weather.
- Always store gas cylinders in an upright condition and properly secured. They must be secured to a wall, table or lab bench using an appropriate chain or strap holder as purchased from a laboratory equipment supplier or custom made by the machine shop. The use of rope or cable-ties to secure cylinders is not permitted.
- Secure gas cylinders with a chain or appropriate belt above the midpoint, but below the shoulder of the cylinder. Laboratory cylinders less than 45 cm (18 inches) tall may be secured by approved stands or wall brackets.
- Cylinders must be capped when not in use.
- Oxidizing gases must be stored at least 6.1 meters (20 feet) away from flammable gases, or the storage areas must be separated by a barrier of non-combustible construction that interrupts the line of sight between the containers with a fire resistance rating of at least 30 minutes. This applies to other incompatible gases as well. Example, Ammonia (basic) and Hydrogen Chloride (acidic) are incompatible.
- Keep cylinders away from locations where they might form part of an electrical circuit, such as next to electric power panels or electric wiring.
- Cylinders should be stored such that cylinders are used in the order in which they are received.

- Do not store cylinders for longer than one year without use. Contact the chemical warehouse to return unused cylinders.
- Keep full cylinders separated from empty cylinders and properly labeled with a tag indicating: Full / In Use / Empty.
- **C**ompressed gas cylinders are not to be stored on hand trucks/carts. Labs requesting such special arrangements must get documented permission from HSE.

Tag available from chemical warehouse: SAP Code number 3000011743

- Cylinders of all gases having a health hazard rating of 3 or 4 (by NFPA 704) or have a LC_{50} < 4999 ppm (1hr) must be kept in a continuously mechanically ventilated hood or other continuously mechanically ventilated enclosure.

Methods of Securing Gas Cylinders

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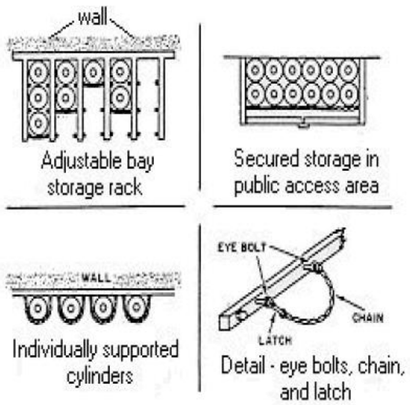

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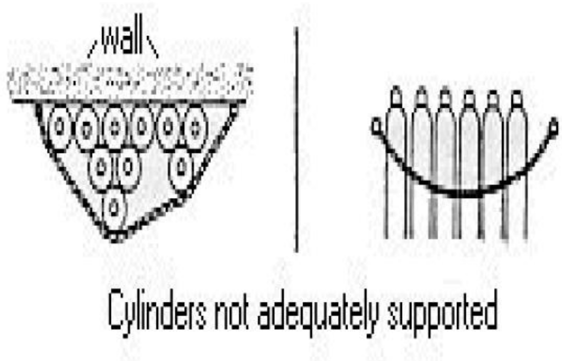


4.2. Labelling

The following labeling requirements shall apply to all gas cylinders:

- All gases shall be clearly labeled with the contents of the cylinder. Compressed gas cylinders that do not clearly identify its contents by name should not be accepted for use and returned to the supplier.
- Use only the vendor label for positive identification of contents of the cylinder. Be aware that color coding may be inconsistent from vendor to vendor.
- Labels shall be readable at all times while in service and content confirmed before using a cylinder.
- Empty cylinders shall be labeled with the word “empty” or identified by using the cylinder status tag.
- If the labeling on the gas cylinder becomes unclear or defaced so that the contents cannot be identified, the cylinder should be marked “contents unknown” and the manufacturer must be contacted regarding appropriate procedures for removal.

4.3. Transportation

The following requirements shall apply to the transport of gas cylinders:

- Do not move compressed gas cylinders by carrying, rolling, sliding, or dragging them across the floor.
- Transport cylinders with a hand truck designed for the transport of cylinders. Secure the cylinder to the hand truck with a chain or strap. **Note:** Hand trucks/carts are not for storing compressed gas cylinders on, only transporting. Labs requesting such arrangement must get documented permission from HSE.
- Cylinder caps shall be secured during transport. Never transport a cylinder while a regulator is attached.
- Leave the valve protection cap on until the cylinder is secured against a wall or bench or placed in a cylinder stand, and is ready for use.
- Prevent damage to cylinders - locate cylinders where they will be protected from physical damage by striking or falling objects, corrosion, or damage from public tampering.
- Do not transport oxygen and combustible gases at the same time.
- Use the spine in level 0 and the service elevators to transport safely compressed gases across campus.

4.4. Connections

Threads on cylinder-valve outlet connections have been standardized by the Compressed Gas Association (CGA) and are not the same on all cylinders. This prevents accidental mixing of incompatible gases from an interchange of connections. Left hand fittings for flammable and some oxidizing gases (some oxidizing gases use left hand thread, some do not) have a cut mark (notch) through the nut. Regardless, the notch indicates left hand thread.

Left Hand Thread

Right Hand Thread

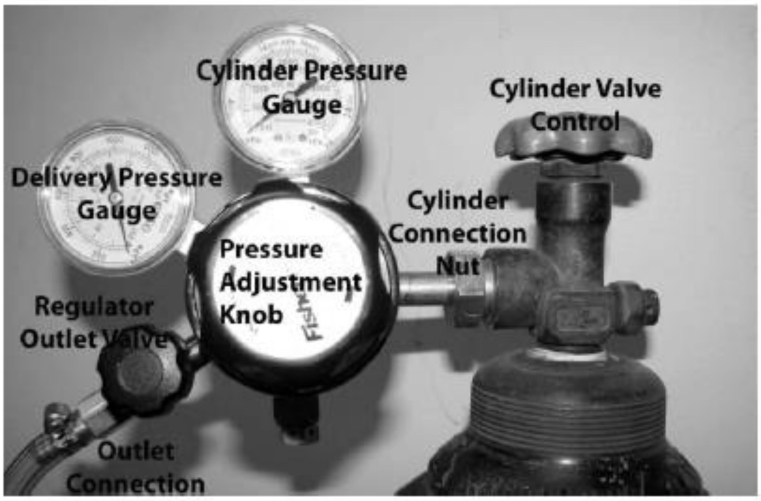
Never lubricate, modify, force, or tamper with cylinder valves. Especially do not put oil or grease on the high-pressure side of a cylinder containing oxygen, chlorine, or any oxidizing gas. An auto ignition or explosion could result. Unlike larger cylinders, non-refillable lecture bottles have identical valve threads, irrespective of the gas contained within. Refillable lecture bottles use standard regulator fittings.

4.5. Manifolds, Valves, and Regulators

The following information applies to the use of manifolds, valves and/or regulators:

- Where compressed gas containers are connected to a manifold, the manifold and its related equipment, such as regulators, shall be of proper design for the product(s) they are to contain at the appropriate temperatures, pressures, and flows.

- Use only approved valves, regulators, manifolds, piping and other associated equipment in any system that requires compressed gas. Care must be taken to ensure that pressure gauges on regulators are correct for the pressure of the gas cylinder used. With the exception of lecture bottles, threads, configurations and valve outlets are different for each class of gases to prevent mixing of incompatible gases.
- All gas piping must be compatible with the gases used, a good source of information is the materials compatibility guide from Matheson Gas Company.
- Valves and regulators should undergo periodic maintenance and repair. A visual inspection should be performed before each usage to detect any damage, cracks, corrosion or other defects. Long term maintenance or replacement periods vary with the types of gases used, the length of use, and conditions of usage. Consult the cylinder, regulator or gas supplier for recommended valve and regulator maintenance schedules.
- Valves and regulator maintenance histories should be known before usage. Valves that pass visual inspection are still subject to failure, therefore it is critical that toxic or poisonous gases are used only in ventilated enclosures and have local exhaust ventilation in place for downstream pressure relief valves, etc.
- Valves and regulators should only be repaired by qualified individuals. Valve and regulator manufacturers, gas supply companies, or valve and regulator specialty shops should be consulted for any repair needs.



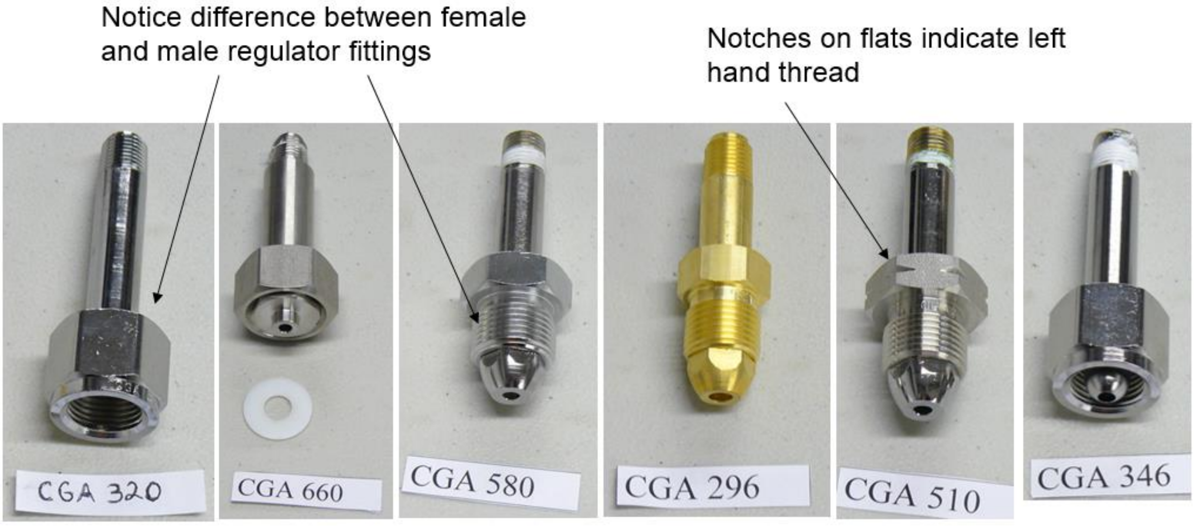
Pressure Reducing Regulator

Regulators are gas-specific which limits interchange and adds safety. Special installation processes, not mentioned here, are used for toxic or high purity gases. Always make sure that the regulator and valve fittings are compatible.

To select the appropriate regulator:

1. Determine the gas pressure needed.
2. Determine the maximum pressure the system might require.
3. Select a delivery pressure range so the required pressures are in the 25%-90% range of the regulator delivery pressure.
4. Check with the gas supplier about compatible connections and regulators.

Examples of different types of regulator fittings:



Note the difference between the male and female regulators. Also note the different types of material for different types of gas. Notched flats mean a left hand thread. Used for flammable and some oxidizing gases.

The correct procedure for installing a regulator onto a cylinder is as follows:

1. Make sure the threads on both the regulator and the cylinder valve are clean and in good condition.
2. Do NOT use adaptors or Teflon tape to attach regulators to gas cylinders. Do NOT use oil or lubricants on connections.
3. Holding the regulator upright, horizontally insert the regulator into the cylinder head, connect it to the cylinder valve by closing the thread finger-tight. The thread should move very easily, if it does not it is either damaged or you are not holding it at right angle, i.e. you are damaging it as you try to force it in. Using a wrench, tighten the connection with a maximum of one turn. Never use excessive force to tighten the connection.
4. Always stand to the side when opening valves as the gauge may shatter.
5. Close all valves and then carefully open only the cylinder valve control a small amount. The cylinder valve does NOT need to be fully open. Cylinder pressure gauge should move and indicate the internal pressure of the cylinder.
6. Leak check your connection using either commercially available Snoop® mixture or other suitable means.
7. To use the cylinder:
    a. Ensure the pressure adjustment knob is closed.
    b. Slowly open the pressure adjustment knob to the desired pressure.
    c. To shut off the gas:
        i. Close the cylinder valve.
        ii. Open the pressure adjustment knob to relieve the pressure.

More information regarding regulators can be found from the manufacturers, a good guide is available from Matheson Gas Products.

4.6. Handling, Use and Good Practices

The following good practices shall be required during the handling and use of gas cylinders:

- Compressed gases shall be handled only by properly trained persons with their training documented.
- Cylinders shall not be subjected to extremely low temperatures (< -20ºC) without approval from the supplier.
- Cylinders shall not be used for any purposes other than as originally intended.
- Damaged or leaking cylinders must be reported to 911 (landline) or 012-808-0911 (cell phone) immediately.
- When using more than one gas, be sure to install one-way flow valves (check valves) from each cylinder to prevent mixing, otherwise accidental mixing can cause contamination of a cylinder.
- Close valves on gas cylinders when a system is not in use.
- Shut-off valves must not be installed between pressure relief devices and the equipment they are to protect.
- Use pressure relief valves in downstream lines to prevent high pressure buildup in the event that a regulator valve does not seat properly and a tank valve is left on.
- Relief valves should be vented to prevent potential buildup of explosive or toxic gases.
- Never allow flames or concentrated heat sources to come in contact with a gas cylinder.
- Pressurize regulators slowly and ensure that valve outlets and regulators are pointed away from all personnel when cylinder valves are opened.
- Cylinders which require a wrench to open the cylinder valve shall have the wrench left in place on the cylinder valve while it is open. Use adequately sized wrenches to minimize ergonomic stress when turning tight cylinder valves. Never apply excessive force when trying to open valves. Cylinders with “stuck” valves should be returned to suppliers to have valves repaired.
- Do not attempt to open a corroded valve; it may be impossible to reseal.
- Valves should only be opened to the point where gas can flow into the system at the necessary pressure. This will allow for quicker shutoff in the event of a failure or emergency.
- Use a cylinder cap hook to loosen tight cylinder caps. Never apply excessive force or pry off caps. Return the cylinder to the supplier to remove “stuck” caps.

SAP Code number: 3000012020 and 3000012019

- Release pressure from systems before connections are tightened or loosened and before any repairs.
- Never use adapters or exchange fittings between tanks and regulators.
- After an experiment is completed, turn the cylinder valve off first, and then allow gas to bleed from the regulator. When both gauges read “zero”, remove the regulator and replace the protective cap on the cylinder head.
- Do not allow a cylinder to become completely empty. Leave at least 25 psi of residual gas to avoid contamination of the cylinder by reverse flow.
- When the cylinder is empty, mark it as “Empty”, and store empty cylinders separate from full cylinders.

4.7. Lecture Bottles

Lecture bottles are smaller compressed gas cylinders that usually have an internal volume of 0.4 liters and can contain ~50 liters of a desired gas. There are two types of lecture bottles: refillable and non-refillable. The refillable type of lecture bottles can be distinguished by their ability to use standard regulators that are used for full sized cylinders. The non-refillable lecture bottles can be distinguished by their use of smaller regulators (CGA-170/180). See the picture below to identify the differences. Non-refillable lecture bottles are highly discouraged due to their high disposal cost so if possible avoid their use unless only a small amount of gas is needed. The refillable lecture bottles can be incredibly useful especially for very specialized gases that are needed in small quantities such as tritium (^{3}H) or carbon-13 carbon monoxide (^{13}CO).

Notice lecture bottle on left uses CGA-170/180 regulators (disposable lecture bottles use small inlets). Lecture bottle on right uses standard regulators (larger inlet indicates refillable lecture bottle).

See Appendix 6 for more information on lecture bottles. Lecture bottle holders are available in the chemical warehouse. SAP Code number 3000007945.

5. Classification of Compressed Gases

The required safety measures for use of compressed gases will mainly depend on the hazard classification of the materials. Gases can be classified (according to Globally Harmonized System - GHS) into Flammable, Toxic, Corrosive, and Oxidizing. Inert refers to gases that do not react under normal conditions. Inert is not a hazard class under the GHS system. However, inert does not equal non-hazardous. Inert gases can pose an asphyxiation hazard under the right conditions (i.e. confined spaces). For gases that have multiple hazard properties, such as carbon monoxide, which is toxic and flammable, the applicable requirements for both “flammable gas” and “toxic gas” need be met. For gas mixtures, the hazard properties of the mixture as a whole will determine the classification – for example, a dilute mixture of flammable gas in an inert gas may be considered non-flammable as a whole.

5.1. Toxic Gases

Toxic Gas: A gas with a median lethal concentration (LC_{50}) in air of more than 200 parts per million (ppm) but not more than 2,000 ppm by volume of gas or vapor. Examples of toxic gas are chlorine, hydrogen sulfide (H_2S) and hydrogen fluoride (HF).

Highly Toxic Gas: A chemical that has a median lethal concentration (LC_{50}) in air of 200 ppm or less by volume of gas or vapor. Examples of highly toxic gas are arsine, phospine (PH_3), and nitric oxide (NO).

In many jurisdictions/universities, toxic gases are classified based on their acute toxicity measured as median lethal concentration (LC_{50}). KAUST adopts the current classification scheme detailed in the Toxic Gas Ordinance (TGO) into four categories: Class I, Class II, Class III and NR (not rated), with Class I being the most hazardous. The classification of commonly used gases can be found in Appendix 3.

Table 1. List of Toxic gases and their TGO Class

Chemical Name	CAS Number	Toxic (LC_{50})	TGO Class	Diluted to Class II (%)	Diluted to Class III (%)	Diluted to Not Rated (%)
Ammonia	7664-41-7	4000	III			80.00
Antimony pentafluoride	7783-70-2	30	I	14.9	1.0	0.60
Arsenic pentafluoride	7784-36-3	178	I	88.6	5.9	3.56
Arsenic trifluoride	7784-35-2	178	I	88.6	5.9	3.56
Arsine	7784-42-1	20	I	10.0	0.7	0.40
Boron trichloride	10294-34-5	2541	II		84.7	50.82
Boron trifluoride	7637-07-2	864	II		28.8	17.28
Bromine chloride	13863-41-7	290	II		9.7	5.80
Bromomethane	74-83-9	850	II		28.3	17.00
Carbon monoxide	630-08-0	3760	III			75.20
Carbonyl fluoride	353-50-4	360	II		12.0	7.20
Carbonyl sulfide	463-58-1	1700	II		56.7	34.00
Chlorine	7782-50-5	293	II		9.8	5.86
Chlorine pentafluoride	13637-63-3	122	I	60.7	4.1	2.44
Chlorine trifluoride	7790-91-2	299	II		10.0	5.98
Chlorotrifluoroethylene	79-38-9	2000	II		66.67	40.00
Cyanogen chloride	460-19-5	350	II		11.67	7.00
Cyanogen chloride	506-77-4	80	I	39.8	2.67	1.60
Deuterium chloride	5-7-7698	3120	III			62.40
Deuterium selenide	13536-95-3	51	I	25.4	1.70	1.02
Deuterium sulfide	13536-94-2	710	II		23.67	14.20
Diazomethane	334-88-3	1	I	0.5	0.03	0.02
Diborane	19287-45-7	80	I	39.8	2.67	1.60
Dichlorosilane	4109-96-0	314	II		10.47	6.28
Diethyl zinc	557-20-0	10	I	5.0	0.33	0.20
Diphosgene	503-38-8	2	I	1.0	0.07	0.04
Ethylene oxide	75-21-8	2900	II		96.67	58.00
Fluorine	7782-41-4	185	I	92.0	6.17	3.70
Germane	7782-65-2	620	II		20.67	12.40
Hexachloro-1,3-butadiene	87-68-3	370	II		12.33	7.40
Hexafluoroacetone	684-16-2	470	II		15.67	9.40
Hexafluoro-2-butyne	692-50-2	Not Available				
Hydrogen bromide	10035-10-6	2860	II		95.33	57.20
Hydrogen chloride	7647-01-0	2810	II		93.67	56.20
Hydrogen cyanide	74-90-8	140	I	69.7	4.67	2.80
Hydrogen fluoride	7664-39-3	1307	II		43.57	26.14

Hydrogen iodide	10034-85-2	2860	II		95.33	57.20
Hydrogen selenide	7783-07-5	51	I	25.4	1.70	1.02
Hydrogen sulfide	7783-06-4	712	II		23.73	14.24
Hydrogen telluride	07783-09-7	51	I	25.4	1.70	1.02
Methanethiol	74-93-1	1350	II		45.00	27.00
Methyl bromide	74-83-9	850	II		28.33	17.00
Methyl chlorosilane	993-00-0	600	II		20.00	12.00
Methyl isocyanate	624-83-9	3	I	1.5	0.10	0.06
Nickel tetracarbonyl	13463-39-3	20	I	10.0	0.67	0.40
Nitric oxide	10102-43-9	115	I	57.2	3.83	2.30
Nitrogen dioxide	10102-44-0	115	I	57.2	3.83	2.30
Nitrogen trioxide	10544-73-7	57	I	28.4	1.90	1.14
Nitrosyl chloride	2696-92-6	35	I	17.4	1.17	0.70
Oxygen difluoride	7783-41-7	2.6	I	1.3	0.09	0.05
Ozone	10028-15-6	9	I	4.5	0.30	0.18
Phosgene	75-44-5	5	I	2.5	0.17	0.10
Phosphine	7803-51-2	20	I	10.0	0.67	0.40
Phosphorous pentafluoride	7647-19-0	261	II		8.70	5.22
Phosphorous trifluoride	7783-55-3	436	II		14.53	8.72
Selenium hexafluoride	7783-79-1	50	I	24.9	1.67	1.00
Silicon tetrafluoride	7783-61-1	922	II		30.73	18.44
Stibene	7803-52-3	178	I	88.6	5.93	3.56
Sulfur dioxide	7446-09-5	2520	II		84.00	50.40
Sulfur pentafluoride	5714-22-7	1	I	0.5	0.03	0.02
Sulfur tetrafluoride	7783-60-0	40	I	19.9	1.33	0.80
Sulfuryl fluoride	2699-79-8	3020	III			60.40
Tellurium hexafluoride	7783-80-4	25	I	12.4	0.83	0.50
Tetrafluoroethylene	116-14-3	2000	II		66.67	40.00
Trifluoroacetyl chloride	354-32-5	10	I	5.0	0.33	0.20
Tungsten hexafluoride	7783-82-6	218	II		7.27	4.36

LC_{50} Values from **ISO 10298:2018**(E) or manufacturers SDS

Table 2. LC_{50} and Classification of Gases

	Median Lethal Concentration LC_{50} (ppm)
Class I	200 or less
Class II	201 to 2999
Class III	3000 to 4999
NR (not rated)	> 5000

5.2. Gases not Considered Toxic

Silane, nitrous oxide and sulfur hexafluoride are specifically not rated under the TGO as toxic. Some additional gases commonly used in KAUST laboratories are also NOT considered toxic under the TGO. In order to maintain a high degree of consistency between this program and the TGO, some gases are not considered toxic. Examples include but are not limited to: hydrogen, oxygen, nitrogen, helium, nitrous oxide, sulfur hexafluoride, argon, methane, propane, and ethylene to name a few. However, although these gases are not considered toxic, they can still be hazardous. Accumulation of excess quantities could result in explosion, asphyxiation and other dangers. See manufacturer's Safety Data Sheet (SDS) or Appendix 3 to identify the hazards of the compressed gas you are working with.

5.3. Flammable Gases

According to the Globally Harmonized System (GHS) the criteria for a flammable gas is defined as:

Category	Criteria
1	Gases, which at 20 °C and a standard pressure of 101.3 kPa: (a) are ignitable when in a mixture of 13% or less by volume in air; or (b) have a flammable range with air of at least 12 percentage points regardless of the lower flammable limit.
2	Gases, other than those of Category 1, which, at 20 °C and a standard pressure of 101.3 kPa, have a flammable range while mixed in air.

Refer to Appendix 3 Hazard Overview of Compressed Gases for the LEL and UEL of flammable gases.

5.4. Pyrophoric Gases

Pyrophoric gases, such as silane, germane, phosphine, etc. can spontaneously ignite when in contact with air at ambient temperatures. An even more serious danger is that under certain conditions, a leak of a pyrophoric gas might not immediately ignite but instead form a super-critical-mixture which subsequently can explode violently. The definition of pyrophoric gases is given in NFPA 45 as a material which can ignite spontaneously in air at a temperature of 130°F (54.4°C) or below.
By the Globally Harmonized System (GHS), pyrophoric gases are classified together with flammable gases. See Appendix 3 Hazard Overview of Compressed Gases to identify pyrophoric gases (they are highlighted in red).

5.5. Other Hazardous Gases

5.5.1. Oxidizing Gases

Oxidizing gases are defined by OSHA as a "Chemical other than a blasting agent or explosive as defined in [29 CFR] 1910.109(a), that initiates or promotes combustion in other materials, thereby causing fire either of itself or through the release of oxygen or other gases". The main concern with oxidizers is their compatibilities with other gases. See manufacturers SDS or Appendix 3 to identify the hazards of the compressed gas you are working with.

Nitrous oxide is an oxidizing gas which has additional risk. When nitrous oxide is heated in an enclosed container, auto-decomposition can lead to explosion. Inhalation of low concentrations of nitrous oxide can lead to euphoria, while higher concentrations mixed with air can induce anesthesia.

5.5.2. Corrosive Gases

Corrosive gases are defined by OSHA as "*Corrosive materials* are chemicals that cause visible destruction of, or irreversible alterations in, living tissue by chemical action at the site of contact".

Characteristics of which can be; low pH (acidic) or high pH (basic), may react with incompatible materials to produce heat, gas, or fire, and may corrode or degrade materials upon storage, especially metal. Therefore corrosive gases should not be stored for more than a year. See manufacturers SDS or Appendix 3 to identify the hazards of the compressed gas you are working with.
Common corrosive gases include ammonia, hydrogen chloride, chlorine, fluorine, and hydrogen fluoride.

5.5.3. Water Reactive Gases

Water reactive gases are defined as substances that react with water and may release a gas that is either corrosive, flammable, or toxic. The main concern with water-reactive materials is their incompatibility with water vapors. See manufacturers SDS or Appendix 3 to identify the hazards of the compressed gas you are working with.

5.5.4. Inert Gases

Inert gases are defined (International Union of Applied Chemistry – IUPAC Compendium of Chemical Terminology) as "a non-reactive gas under particular conditions. For example, nitrogen at ordinary temperatures and the noble gases (helium, argon, krypton, xenon, and radon) are unreactive toward most species". Inert gas refers to gases that do not react under normal conditions. However, inert does not equal non-hazardous. Inert gases can still pose an asphyxiation hazard under the right conditions (i.e. constricted spaces) by displacing oxygen. Degrees of asphyxia can occur when the oxygen content of the working environment is less than 20.9% by volume. Effects from oxygen deficiency become noticeable at levels below ~18% and sudden death may occur at ~6% oxygen content by volume.

Table 3. Degrees of Asphysia

From **Physics Division – Cryogenic Safety Manual** (Argonne National Laboratory, 2001)	
% Oxygen	**Effects**
17%	Night vision reduced Increased breathing volume Accelerated heartbeat
16%	Dizziness Reaction time for novel tasks doubled
15%	Impaired judgement and coordination Intermittent breathing Rapid fatigue Loss of muscle control
12%	Very faulty judgement Very poor muscular coordination Loss of consciousness Permanent brain damage
10%	Inability to move Nausea and Vomiting
6%	Spasmatic breathing Convulsive movements Death in 5-8 minutes

CGA-580 regulator fitting commonly used for many inert gases

Contact hse@kaust.edu.sa for additional requirements for other hazard classes not mentioned in this Compressed Gas Safety Program. See manufacturers SDS or Appendix 3 to identify the hazards of the compressed gas you are working with.

5.5.5. Cryogenic liquids

Cryogenic liquids are liquefied gases with temperatures below -73°C (-100° F). Cryogenic liquids commonly used include:

- Liquid argon
- Liquid helium
- Liquid nitrogen
- Liquid oxygen

The hazards of cryogenics liquids include: asphyxiation and burn hazards, operational hazards, fire and explosions

Asphyxiation and Burn Hazards

Cryogenic liquids and their boil-off vapors rapidly freeze human tissue. Contact with cryogenic liquids results in painful cold burns. Boiling and splashing will occur when the cryogen contacts warm objects.

Liquid helium, argon or nitrogen may displace air and create oxygen deficiency atmospheres. Liquefied cryogenic gases have large volume expansion ratios. One liter of spilled liquid nitrogen will evaporate into approximately 696 liters of gaseous nitrogen. Liquid nitrogen spilled in a small, poorly ventilated room can quickly cause unconsciousness and death.

Table 4. Temperature and Volume Expansion Ratios of Liquefied Cryogenic gases

Liquefied Gas	Boiling Point (°C)	Volume Expansion Ratio
Oxygen (O_2)	-183°C	860
Argon (Ar)	-186°C	847
Nitrogen (N_2)	-196°C	696
Hydrogen (H_2)	-253°C	851
Helium (He)	-269°C	757

Avoid storing cryogenics in cold rooms, environmental chambers, and other areas with poor ventilation. If necessary, install an oxygen monitor/oxygen deficiency alarm and/or toxic gas monitor before working with these materials in confined areas.

Table 5. Separation of Portable Cryogenic Containers from Exposure Hazards

From **Table 3204.3.1.2.1** *International Fire Code* (2009)	
Exposure	**Minimum distance**
Building exits	10 feet (3 meters)
Wall openings	1 feet (0.3 meters)
Air Intakes	10 feet (3 meters)
Lot lines	5 feet (1.5 meters)
Combustible materials such as paper, leaves, weeds, dry grass or debris	15 feet (4.6 meters)
Other hazardous materials	In accordance with Chapter 27

Operational Hazards

Boil-off vapors can rapidly cause embrittlement of many common materials and cause them to shatter.

Excessive ice buildup can result in the discharge of cold gas or structural damage to the cryogenic container or its surroundings.

Fire and Explosion Hazards

Fire or explosion from oxygen condensation in operational equipment such as cold traps or storage dewars is a serious concern.

Liquid oxygen (boiling point 183°C, 90K) has a pale blue color and will condense in a bucket of liquid nitrogen or form on a liquid nitrogen-cooled surface. It may collect into a dangerous quantity and lead to an explosion or fire. Similarly, argon gas will condense and liquefy at liquid nitrogen temperatures (see Table 4 above). If liquid nitrogen is being used as a coolant when a system is under an argon atmosphere, the argon gas will liquefy and when brought to a higher temperature, the argon will rapidly boil off and over pressurize a system, thereby possibly causing an explosion.

Oil or grease may ignite spontaneously and violently in the presence of high oxygen concentrations.

Many materials not usually combustible in air burn fiercely in an oxygen-enriched atmosphere. Remove all sources of ignition in areas where oxygen enrichment is likely to occur.

General cryogenic handling guidelines

The following information applies to the use and handling of cryogenics:

- Use appropriate personal protective equipment (PPE) including insulated gloves and eye protection (goggles and a face shield) during any transfer of cryogenic liquid.
- Shirt sleeves should be rolled down and buttoned over glove cuffs, or an equivalent protection such as a lab coat, should be worn in order to prevent liquid from spraying or spilling inside the gloves. Trousers without cuffs should be worn.
- Use the buddy system when filling and transporting cryogenic liquids. Never transport cryogenic liquid using a passenger elevator.
- Vessels being filled must not be left unattended.
- Use only equipment, valves and containers designed for the intended product and service pressure and temperature.
- Do not use or store cryogenic liquids in poorly ventilated spaces such as cold rooms.
- Transfer operations involving open cryogenic containers such as dewars must be conducted slowly to minimize boiling and splashing of the cryogenic fluid.

- All cryogenic systems including piping must be equipped with pressure relief devices to prevent excessive pressure build-up. Pressure reliefs must be directed to a safe location.
- The caps of liquid nitrogen dewars are designed to fit snugly to contain the liquid nitrogen, but also allow the periodic venting that will occur to prevent an over-pressurization of the vessel. Do not ever attempt to seal the caps of liquid nitrogen dewars.
- Do not tamper with pressure relief valves or the settings for the valves.
- Do don't dispose cryogenics down the drain, this might cause damage to the facilities.
- Do not "walk," roll, or drag dewars across a floor. Use carts or containers with wheels and follow the procedure Transport of Liquid Nitrogen in the Elevators in service elevators.
- In the event of skin contact with a cryogenic liquid, do not rub skin; place the affected part of the body under warm (not hot) water. Never use dry heat to treat cryogenic burns. For any accidents or injuries, and complete an accident report using the online ReportIt system.
- If clothing becomes soaked with cryogenic liquid, it should be removed as quickly as possible and the affected area should be flooded with water as above. Where clothing has frozen to the underlying skin, cold water should be poured on the area, but no attempt should be made to remove the clothing until it is completely free.

6. Requirements for Flammable, Pyrophoric, and Toxic Gases

6.1. Toxic Gases

Handling and use of toxic gases in KAUST requires administrative and procedural controls as well as engineering and design requirements. Any deviation from these requirements must be specifically approved by hse@kaust.edu.sa and PDEC on a case-by-case basis. See Table 1. List of Toxic Gases and Their TGO Class to identify the toxic gas, the concentration and the TGO class of the toxic gas you are using. Laboratories wishing to move toxic gas usage (and cylinders) from one lab to another must update their standard operating procedures with HSE review.

Table 6. Minimum Safety Requirements for Toxic Gases

Procedural and Administrative Requirements	**Class I**	**Class II**	**Class III**	**Dilute to NR or small Quantities**
General compressed gas requirements for storage and use	X	X	X	X
Prior approval from HSE	X	X	X	X
SOP	X	X	X	X
Leak testing – at delivery	X	X	X	X
Plugs and caps in place during transportation	X	X	X	
Written emergency response plan	X	X	C	C
Emergency drills with user participation	X	X	C	
Annual maintenance – safety tests	X	C	C	C
Restrictive flow orifices at cylinder head	X	C	C	C
Engineering and Design Requirements				
All welded gas supply pipe	X	C		
Coaxial pipe	X			
Alarm/Automatic shut off for:				

Gas detection in cabinet	X	X	C	
Manual emergency shut-off	X	C		
Controller power failure	X	C		
Remote shut down at fire panel	X			
Exhaust ventilation failure	X	C	C	
Activation of manual fire alarm	X	C		
Excess flow	X			
Local Shut Off button in area of use	X	X		
Gas detection system at point of Use	X	X	C	
High level alarms to be relayed to Fire Department automatically (auto dialer)	X	X	C	
Abatement system (scrubber or burn box)	X	X	C	
Mechanically ventilated gas cabinet	X	X	C	
Exhausted enclosure (experiment location)	X	X	C	C
Inert gas purge system in cabinet	X	X		
X=Required, C=Conditional, determined by Research Safety Team review				

See Appendix 5 for more information on Restrictive Flow Orifices.

6.2. Small Quantity Exemptions for Toxic Gases

Consistent with the TGO, use of small quantities of toxic gases in laboratories may be exempted from engineering and design requirements. Use of these quantities must still fulfill administrative and procedural controls listed in Table 6.

Table 7. Small Quantity Exemptions

Toxic Gas Classes	Small Quantities
NFPA Health Hazard 4, TGO Class I, GHS category I, DOT Poison A	≤ 500g
All other Toxic classes	≤ 1 kg

See Appendix 7 for information on Sub-Atmospheric Containers.

6.3. Dilute Mixture of Toxic Gases

Consistent with the TGO, classification of dilute mixtures of toxic gases are based on the LC_{50} of the mixture as a whole. Therefore, a dilute mixture of a toxic gas in air or in another inert gas may be classified to a lower toxicity class or even considered not-rated (NR). It must be emphasized that "NR" does not mean the gas or gas-mixture is harmless or "not-regulated". For example, pure hydrogen sulfide, having an LC_{50}, of 712 ppm, is a Class II toxic gas. When diluted to 23.7% and 14.2%, hydrogen sulfide becomes Class III and NR respectively. This does not mean hydrogen sulfide at 14.2% is harmless; it only means that, at 14.2%, the hydrogen sulfide mixture as a whole has a toxicity (LC_{50}) below 5000 ppm. Suitable control measures, such as keeping the work and all potential leak points inside a fume hood, are still required to minimize personal exposures. In general, exposure to toxic chemicals at work must be minimized as much as possible and always below acceptable limits. For example, the permissible exposure limit (PEL) for hydrogen sulfide is 20 ppm (8 hour TWA). Contact hse@kaust.edu.sa if you require additional information on controlling chemical exposures. See Table 1. List of Toxic Gases and Their TGO Class to determine the TGO class of the toxic gas you are using.

6.4. Flammable and Pyrophoric Gases

Requirements on flammable and pyrophoric gases are classified into four groups of materials or situations: (1) Pyrophoric gases, (2) Flammables gases above Maximum Allowable Quantities (MAQ), (3) Flammable gases that requires distance separation from exposures/incompatibles and (4) Flammables gases below MAQ. Many of the requirements mentioned in this section refer to the International Fire Code standards.

Table 8. Control Grouping of Flammable and Pyrophoric Gases

Group	Description
Group 1	Pyrophoric
Group 2	Above MAQ
Group 3	Require separation from exposures / incompatibles
Group 4	Below MAQ

Group 1

Pyrophoric gases (as well as water reactive gases) are arguably one of the most hazardous classes of materials to deal with. Therefore their handling and use must demand the utmost in meticulous engineering controls and procedures.

Group 2

Flammable gases being used above their MAQ (Group 2) is highly discouraged but sometimes maybe necessary. If such work is deemed necessary then many requirements must be met according to International Fire Code/International Building Code guidelines. Those extra requirements can be very challenging and expensive to obtain but revolve around ensuring explosion control (good venting and barricades being in place) and that all static producing equipment must be grounded. See Chapters 27 and 35 of International Fire Code for reference.

Group 3

Flammable gases that require distance separation (Group 3) from exposures and incompatibles is dependent on the volume of the space in question and distance between the objects being stored. In general laboratory terms, Group 3 refers to flammable gases being stored in small rooms where normal safe storage distances are impossible or difficult to obtain. See Chapter 35 of International Fire Code for reference.

Group 4

Flammable gases (excluding pyrophoric and water reactive gases) being used and stored below their MAQ and in full sized laboratories (Group 4) is how most flammable gases should be stored and handled in KAUST Laboratories. Therefore their requirements are minimal but never forget they are still flammable and can cause great property damage and harm if misused.

General Requirements for all flammable gases:

- Flammable gases must be separated by 20 ft (6.1 m) from all pyrophoric and oxidizing gases.
- The 20 ft (6.1 m) distance shall be reduced without limit when materials are separated by a barrier of noncombustible materials that interrupts the line of sight between the containers with a fire resistance rating of at least 30 minutes.
- Flammable and pyrophoric gases with pressure-relief devices shall be stored separately from cylinders without pressure-relief devices. (Note: some toxic and highly toxic gases are without pressure-relief device, but they are required to be inside gas cabinets.)

Table 9. Minimum Safety Requirements for Flammable and Pyrophoric Gases

Procedural and Administrative Requirements	Group I Pyrophoric	Group 2 Above MAQ	Group 3 Distance separation	Group 4 Below MAQ
General compressed gas requirements for storage and use	X	X	X	X
Prior approval from HSE	X	X	X	
SOP	X	X	X	X
Leak testing – at delivery	X	X	X	X
Plugs and caps in place during transportation	X	X	X	
Written emergency response plan	X	X	X	C
Emergency drills with user participation	X	X	X	
Annual maintenance – safety tests	X	X	X	C
Restrictive flow orifices at cylinder head	X	X	X	C
Engineering and Design Requirements				
All welded gas supply pipe	X	C	C	
Coaxial pipe	X			
Sprinkler in cabinet	X	C	C	
Emergency power to ventilation	X	C	C	
Alarm/Automatic shut off for:				
Gas detection in cabinet	X	C	C	
Manual emergency shut-off	X	C	C	
Controller power failure	X	C	C	
Remote shut down at fire panel	X	C	C	
Exhaust ventilation failure	X	C	C	
Activation of manual fire alarm	X	C	C	
Excess Flow	X	C	C	
Local shut off button in area of use	X	C	C	
Gas detection system at point of use	X	X	C	
High level alarms to be relayed to Fire Department automatically	X	X	C	
Fire (UV/IR) detector	X	C	C	
Mechanically ventilated gas cabinet	X	X		
Exhausted enclosure (experiment location)	X	X	C	
Inert gas purge system in cabinet	X	X		
Abatement system (scrubber or burn box)	X			

X = Required, C= Conditional, determined by Research Safety Team review

See Appendix 7 for information on Sub-Atmospheric Containers.

It is important that areas where flammable gases are stored are well ventilated. Ventilation, natural or mechanical, must be sufficient to limit the concentration of flammable gases or vapors to a maximum level below the Lower Explosive Limit (LEL).

Subject to Maximum Allowable Quantity (MAQ) limits and requirements for segregation of incompatible materials, flammable gas cylinders are allowed to be used inside the laboratory area without gas cabinets or exhausted enclosures. When flammable gases are stored or used without dedicated exhaust enclosure, restrictive flow orifices at the cylinder head are required.

Table 10. Maximum Allowable Quantities (MAQ)

Maximum Allowable Quantity (MAQ) for Flammable, Oxidizing, and Corrosive (liquefied and nonliquefied) gases in sprinklered Control Areas. See Appendix 4.		
Gas type	**No exhausted enclosure (automatic sprinkler)**	**Exhausted enclosure (automatic sprinkler)**
Flammable (liquefied)	600 lb (272 kg)	1200 lb (544 kg)
Flammable (nonliquefied)	4000 ft^3 (112 m^3) ~16 K sized cylinders	8000 ft^3 (224 m^3) ~32 K sized cylinders
Oxidizing (liquefied)	600 lb (272 kg)	1200 lb (544 kg)
Oxidizing (nonliquefied)	6000 ft^3 (170 m^3) ~24 K sized cylinders	12,000 ft^3 (340 m^3) ~48 K sized cylinders
Corrosive (liquefied)	600 lb (272 kg)	1200 lb (544 kg)
Corrosive (nonliquefied)	3240 ft^3 (92 m^3) ~13 K sized cylinders	6480 ft^3 (184 m^3) ~26 K sized cylinders

A control area is defined as "Spaces within a building where quantities of hazardous materials not exceeding the maximum allowable quantities per control area are stored, dispensed, used or handled." In KAUST, Control Areas are designated by Fire Loss Prevention using the International Fire Code standards and NFPA 55 as the reference document and only Fire Loss Prevention can make the determination of what constitutes the boundaries of the Control Area. Once the Control Area is determined and identified, see Table 10 (above) to identify the maximum allowable quantity (MAQ) of gas allowed.
In most KAUST laboratories the maximum laboratory Control Area (called lab zones) roughly equals ~10,000 ft^2 (929 m^2). Some buildings have different sized Control Areas. It is important to understand that a Control Area may not be a single laboratory. It may be the case, in most instances, that a Control Area is composed of multiple laboratories. Most laboratory Control Areas (lab zones) in KAUST are sub-divided into 5 laboratories (e.g. 2910, 2920, 2930, 2940, 2950) which the quantities stated in Table 10 must be divided into.

Note: The MAQ cylinder count cited above is interpreted as meaning that labs can have a maximum of 16 cylinders of flammable gas (32 if in ventilated enclosure) and 24 cylinders of oxidizing gas (48 if in ventilated enclosure) simultaneously per control area. Separation requirements for incompatible gases still apply.

6.5. Liquefied Gases

Many common gases used in laboratories are liquefied gases. These include carbon dioxide, ammonia, chlorine, nitrous oxide, propane, butane, and many fluorocarbon CFCs.

To achieve higher gas-phase flow-rates and pressures, some liquefied cylinders may require heating. This can only be done with appropriate safeguards and extreme caution. ALL operations that require deliberate heating of a compressed gas cylinder or a liquefied gas cylinder must be reviewed and approved by hse@kaust.edu.sa on a case-by-case basis. Many liquefied gas cylinders, such as propylene tanks, have pressure relief valves designed to vent excess pressures when the cylinder is exposed to high temperatures. The vented gas can cause fire and explosions.

Some cylinders have special valves and dip-tubes for accessing the liquid-phase directly. Obtaining the liquid phase directly from a high pressure cylinder must be done with extreme care and with proper equipment and procedures. If you plan to access the liquid phase directly from a high pressure cylinder, please obtain detailed instructions from the supplier and consult hse@kaust.edu.sa for additional advice. Appendix 8 contains additional information on this topic for your reference.

The working pressure of a liquefied gas cylinder may be much lower than a typical compressed gas cylinder. Tragedies have occurred in other countries when people tried re-filling these cylinders beyond their rated pressures. **In general, lab users are not allowed to refill compressed gas cylinders except with special permission.** Compressed gas re-filling is NOT allowed in KAUST laboratories except with special permission from hse@kaust.edu.sa. Examples of permissible refilling of compressed gas cylinders would be for SCBAs (Self Contained Breathing Apparatus) used by fire departments or SCUBA (Self Contained Underwater Breathing Apparatus) in Coastal and Marine Resources (CMOR).

Acetylene
Acetylene is an inherently unstable compound. The carbon to carbon triple bond contains a lot of energy and it is sensitive to pressure, temperature, and shock. Therefore, acetylene gas is dissolved in liquid acetone which makes it more stable. Acetylene cylinders contain a porous filler material filled with acetone. Therefore, acetylene cylinders are rather unique among compressed gas cylinders. Below are important safety rules regarding acetylene:

- Never attempt to store or inject acetylene gas into any type of vessel, tank or enclosure. Improperly stored acetylene is unstable and may explode.
- Acetylene gas regulators should not exceed 15 psig.
- In welding, brazing and work involving flames, flame arrestors and check valves must be installed. For other operations, contact hse@kaust.edu.sa for advice.
- Acetylene cylinders must be properly secured and kept upright at all times. Movement of cylinders must be done with care and cylinders must be protected from heat.

6.6. Other Hazardous Gases

6.6.1. Oxidizing Gases

Oxidizing gases must not be stored with incompatible materials. Flammable and oxidizing gases cannot be housed in the same gas-cabinet and must be separated from one another by 6.1m (20 ft).

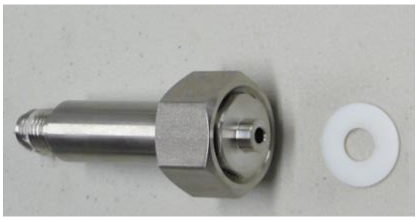
Their storage, use and handling are discussed in the previous chapter Compressed Gas Cylinder General Requirements. In addition, like flammable gases, there is a maximum allowable quantity for oxidizing gases in laboratories as well. See Table 10. Maximum Allowable Quantities (MAQ) to determine your labs MAQ.

Regulator fitting for flammable and some oxidizing gases – note notches on flats which indicate left-hand thread.

6.6.2. Corrosive Gases

Most corrosive gases are also toxic so the health and safety requirements for toxic gases are applicable, in addition, ducts and valves for corrosive gases must be of compatible materials. The main concern with corrosive gases (in addition to their toxicity) is their incompatibility with other gases. Incompatible materials must not be stored together. Their storage, use and handling are discussed in the previous chapter Compressed Gas Cylinder General Requirements.

Always keep and utilize plastic seal gaskets that come with regulators for corrosive gases.



If possible, clean regulators and other metal parts after using corrosive gases. This will help prevent regulators, valves and other equipment from becoming “stuck-open or closed” or corroded onto the cylinder head. Examples of corrosive gases include hydrogen chloride, ammonia and chlorine.

6.6.3. Water Reactive Gases

Water reactive gases should only be utilized under anhydrous conditions and may require handling techniques very similar to gases such as silane (Group 1 flammable gas). Water reactive gases must not be stored together with incompatible materials.

7. Gas Monitoring and Control System

Gas monitoring equipment in KAUST falls into two categories, (1) portable detectors and (2) fixed monitors (often called Toxic Gas Monitoring (TGM) Systems in KAUST). The two categories have different functions and they are intended for different purposes.

7.1. Portable Detectors

These are usually battery-operated hand-held devices. They usually provide a visual (flashing light) and audible alarm but they cannot automatically trigger external events such as shutting down of gas supplies, notifying the Fire Department, etc. They are very useful for locating leaks, as personal monitors during emergency response. Portable detectors may be used as area-monitors only if the operation is continuously attended to. They are not suitable for safeguarding unattended operations involving hazardous gases. **TGM system does not provide maintenance and calibration to portable gas detectors, this is a laboratory responsibility**.

7.2. Fixed Monitors

Fixed monitors include gas sensors installed inside gas cabinets, lab equipment, ventilation ducts, or areas where hazardous gas might be released. Signals (gas leakage level and sensor status) from a fixed sensor are normally sent to a control system to activate alarm and mitigating actions.

7.3. Gas Monitoring Control System

When a pre-determined level of gas is detected by a fixed sensor, a signal is sent to a controller which may be configured to actuate a number of mitigating actions automatically. These actions may include sounding of alarms, shutting off gas supplies, ramping up exhaust ventilation, and notifying emergency services. The controller may also be configured to actuate selected mitigating actions in response to other input signals such as exhaust ventilation failure, excesses flow of the gas, power failure of the controller, or activation of building fire alarm. This configuration of a controller is called the "Cause and Effect Matrix".

7.4. Hazard Evaluation and "Cause and Effect Matrix"

To determine the "cause-and-effect-matrix" concerning hazardous gases requires detailed evaluation of possible scenarios and the most appropriate actions for each. This is normally done at the design stage of a laboratory and implemented prior to lab operation. Any change or deviation from the original design must be evaluated by the Research Safety Team, and properly documented. Below is the summary of the cause and effect matrix for all current and future labs at KAUST (as applicable depending hazard class and flammability levels).

Signal	Green Strobe	Clear Strobe	Blue Strobe	Siren	Equipment Shutdown	Report Alarm	Escalation
Normal conditions	X						
TGM sensor fault		X				X	
Area/Equipment/Exhaust TGM sensor pre-alarm		X				X	
Area/Equipment/Exhaust TGM sensor alarm			X	X	X	X	X
Equipment (gas cabinet or VMB) low ventilation alarm.		X			X	X	

Building fire alarm (manual shutdown from fire command room) or lab Emergency Gas off (EGO)			X	X	X	X	X
Equipment alarm		X			X		
Gas line coaxial alarm			X	X	X	X	X

7.5. Gas Detectors in Gas Cabinets

Gas cabinets housing pyrophoric gases, Class I and Class II toxic gases are required to have fixed gas monitors (pyrophoric require flame detectors - UVIR) installed inside the gas cabinet. Upon detection at the high-alarm level, the gas monitor shall, at a minimum, cause the automatic shutdown of the gas supply at the cylinder valve and a local alarm (audio and visual) to be activated. If the cylinder valve does not allow for this function, a pneumatic or solenoid valve on the high pressure side of the regulator manifold should be shut off automatically. All such valves must fail-to-safe in case of loss of power or loss of pressure in the pneumatic system. Gas sensors in gas cabinets, valve manifold boxes, or ventilated research equipment using Class I and Class II gases may be connected to the TGM central system of the lab or directly to the equipment controller with the possibility of dual reporting in the second case.

7.6. Fixed Detectors for Other Gases

Gases other than pyrophoric, Class I and Class II toxic gases, if housed in a gas cabinet, normally DO NOT require fixed monitors inside the cabinet. The need for fixed gas monitors inside gas cabinets shall be determined by the Research Safety Team.

7.7. Area or Point of Use Monitors

The need for gas monitors apart from those inside of gas cabinets (Table 4.1 and 4.4), as well as the number and locations of the sensors, alarm levels, etc, shall be determined by the Research Safety Team based on hazard properties of the gas, plausible worst-case release rates, size and ventilation rate of the affected areas, as well as other factors. Room monitors and area monitors shall be connected to an alarm system to signal the evacuation of the affected room or area when the detected gas level is higher than a pre-determined “high-alarm-level”. Room or area monitors should be located at risk free areas and easy access for emergency response by TGM and Fire teams.

7.8. Toxic and Flammable Gas Alarm Set Points

If a fixed monitor is installed, automatic shutdown shall occur upon gas detection at the **high-alarm-level**. For toxic gases, high alarm levels must not be set higher than PEL or Threshold Limit Value (TLV) for occupied areas.

Section 7.1.6.3.2 from NFPA 318 version 2018 provides a good guide to set up alarm points:

- Immediately dangerous to life or health (IDLH) values when the monitoring point is within an exhausted enclosure.
- PEL levels when the monitoring point is in an area outside an exhausted enclosure.
- For flammable gases, twenty five percent of LEL when the monitoring point is within or outside an exhausted enclosure.

Gas detector high alarms for pyrophoric, flammable, Class I and Class II toxic gases must be automatically relayed to the main building fire alarm control panel which is then relayed to 911 SOC for immediate emergency response. Pre-alarm levels could trigger only a local alarm and do not need to trigger complete building evacuation.

Alarm levels may be set to levels lower than PEL, TLV, IDLH and 25% LEL for more sensitive detection of leaks. However, alarm levels that are set too low may be prone to frequent false-alarms and service interruptions. Pre-alarm and alarm set points can be changed from the HMI (Human Machine Interface) screen or from the TGM workstation with the right access level. Set points should be changed only after getting Research Safety Team approval via Management of Change process (MOC). To initiate this process please contact hse@kaust.edu.sa.

Gas monitors shall be able to detect gases with sensitivity to provide **low alarm level** (warning):

- For pyrophoric and flammable gases, at 10 percent (10%) of LEL (Lower Explosive Limit)
- For toxic, highly toxic and corrosive gases, low level alarms at 1/2 Immediately Dangerous To Life or Health (IDLH) Values
- For oxygen deficiency alarms Low Limit at 20 percent (20%) oxygen$_2$, High Limit at 19.5 percent oxygen.

Gas Name	Gas Formula	Low Alarm (ppm)	High Alarm (ppm)
Ammonia	NH3	25	50
Carbon Dioxide	CO2	2500	5000
Carbon Monoxide	CO	25	50
Chlorine	CL2	0.5	1
Combustible gases	CH	10% LEL	25% LEL
Diborane	B2H6	0.05	0.1
Germane	GeH4	0.1	0.2
Hydrogen	H2	4000	10000
Hydrogen Sulfide	H2S	10	20
Hydrogen Chloride	HCL	2.5	5
Methane	CH4	5000	12500
Nitrogen Dioxide	NO2	2	5
Nitrogen Oxide	NO	12.5	25
Oxygen	O2	20%	19.50%
Ozone	O3	0.1	2.5
Phosphine	PH3	0.15	0.3
Silane	SiH4	2.5	5
Sulfur Dioxide	SO2	2.5	5

8. Preventive Maintenance and Calibration of Gas Sensors

The TGM Team is responsible for preventive and corrective maintenance to gas monitoring systems.

Some of the main responsibilities for the TGM system include: maintaining TGM gas manifolds, gas valve manifold box, TGM control panels, TGM cabinets and sensors, TGM horn and strobes, auto dialers units and local display units.

- Containment and distribution systems for toxic and pyrophoric gases, including gas cabinets and associated piping and valves must be checked at least annually.

- Gas sensors, including portable and fixed sensors, must be calibrated or replaced according to the manufacturer's maintenance guideline or as least annually. **Note:** Every lab that desires to use portable detectors is responsible for their own calibration and maintenance.

- Function of the gas monitoring controllers must be checked periodically in accordance with the manufacturer's instructions.
- Any maintenance or repair on the monitoring device should be only performed by the TGM team.
  TGM Contact details:
  fmcallcenter@kaust.edu.sa
  TGM 1 – 0545860225
  TGM 2 – 0545863960

9. Design Considerations

When designing new labs, consider using Programmable Logic Controllers (PLC) for the TGM system with open protocol interface with existing TGM central system (WinCC). All new systems shall have 25% spare input/output capacity for future use and each lab shall have its HMI (Human Machine Interface) for local monitoring in addition to alarm acknowledge/reset push buttons. Emergency Gas Off (EGO) push buttons shall be installed near the lab doors and at the building fire command room. Horn/Strobes shall be installed inside the lab at visible height and outside the lab doors. Central system supports auto paging feature, however, having an Auto-dialer dedicated for each lab is still required. Area sensors shall be installed at suitable height based on the molecular weight of each gas to ensure an early detection in case of any leakage. Gas cabinets and ventilated research equipment using Class I and Class II gases shall be equipped with ventilation monitoring sensors (exhaust sensor) to ensure adequate exhaust is being achieved at all times, exhaust alarm shall be reported to TGM system.

TGM system design and sensors specifications shall be based on the KAUST Project Specifications, Section 25 80 00 - Gas monitoring and control system.

Deviation from the design specifications shall be approved by the Research Safety Team and TGM Team.

9.1. Emergency Power (Alarm, Detector, Ventilation)

In Class I and Class II Toxic gases and pyrophoric gases, emergency power must be provided for these systems:

- Exhaust ventilation (including the power supply for treatment systems)
- Gas cabinet ventilation
- Exhausted enclosure ventilation
- Gas-detection
- Emergency alarm

9.2. Auto Dialer

The auto dialer is a device which is interconnected to a telephone line and is programmed to transmit a signal by a voice or text messages that indicates either an emergency condition exists or the need for an emergency response is required or operational maintenance issues in the TGM System. An auto dialer is required for flammable and pyrophoric gases Group 1 and Group 2 and for toxic gases Class I and Class II. The escalation process, notifications, pre-alarm and high alarm settings need to be approved by the Research Safety Team and TGM team in agreement with the lab users.

Any changes to the auto dialer call system needs approval via Management of Change process (MOC).

9.3. Gas Cabinets/Valve Manifold Box

All Class I and Class II toxic gases and Group 1 and Group 2 pyrophoric and flammable gases must be kept in an mechanically ventilated gas cabinet at all times.

Gas cabinet cylinder storage/use requirements:

- Be provided with self-closing limited access ports or non-combustible windows to give access to equipment controls.
    - Average face velocity at the face of the access ports or windows shall not be less than 200 feet per minute (3.3 feet/s) or 61 meters per minute (1.01 m/s) with a minimum of 150 feet per minute (2.5 feet/s) or 46 meters per minute (0.8 m/s) at any 1 point of the access port or window.
- Connected to an approved exhaust system.
- Equipped with automatic fire sprinkler system protection, and must be constructed and ventilated according to code requirements.
- Be provided with self-closing doors.
- Gas cabinet shall be equipped with an Excess Flow Switch (EFS) to shut down the cabinet in case of line rupture.
- Gas cabinet/Valve Manifold Box (VMB) shall be able to report its status (Healthy/Alarm) to the central monitoring system and shall receive remote shutdown command from the system in case of emergency.
- Gas cabinet and (VMB) outlet shall be equipped with a coaxial gauge switch when using double wall pipe.

9.4. Gas Treatment

All Class I and Class II toxic gases and pyrophoric gases must be treated before discharge to the atmosphere.
Treatment systems must be designed to reduce the maximum allowable discharge concentration of the gas to 1/2 IDLH at the point of discharge to the atmosphere.
When more than one gas is emitted to the treatment system, the treatment system must be designed to handle the worst-case release based on the release rate, the quantity, and the IDLH for all the gases stored or used.
Gas treatment system can be dry absorbers (cartridges) or scrubbers (thermal-wet or flame type).

9.5. Compatible Piping

Piping, tubes, valves, fittings, and related components must be:

- Designed and fabricated from materials compatible with the gas to be contained.
    - Hydrogen – Use only stainless steel piping and fittings.
    - Oxygen – Use steel, brass, copper or stainless steel (as per National Fire Protection Association regulations).
    - Arsine, phosphine, ammonia – Use only stainless steel piping and fittings.
- Of adequate strength and durability to withstand the pressure, structural and seismic stress, and exposure to which they are subject.
- Identified in accordance with nationally recognized standards to indicate the material conveyed.
- Compatible cylinder connection seal (gasket) with the material to be used.
- Compatible with the CGA number of gas cylinder and connections in the equipment.

9.6. Purge System

The ability to purge the area between the cylinder valve and the regulator with an inert gas prior to maintenance or cylinder change out is required for flammable and pyrophoric gases Group 1 and Group 2 and for Class I and Class II toxic gases.

Fully automated gas cabinets reduces the risk of exposing the user to gases while replacing the gas cylinder.

10. Purchasing Control, Inventory and Disposal

Prior approval from hse@kaust.edu.sa is required for the purchase of toxic and pyrophoric gases. Approval shall not be given unless hse@kaust.edu.sa is satisfied that the lab is suitably equipped and ready for the handling of toxic and pyrophoric gas(es) being purchased. Once approved, delivery of toxic gas cylinders must be conducted through the Chemical Warehouse, which maintains a record of all deliveries. Labs must contact Chemical Warehouse (contact details below) to inform them of impending orders to be delivered. This is for coordination purposes.

***Important note:** Always retain the purchase order number for each compressed gas cylinder to facilitate the ease to return the cylinder back to the supplier.

Similar to any chemical, an accurate and up-to-date inventory of pyrophoric and toxic gases (and their whereabouts) should be maintained by all labs that use compressed gases. As for reasons stated above, toxic and pyrophoric gases must NOT be transferred to other labs without prior approval from hse@kaust.edu.sa.

Once researchers are done utilizing a compressed gas cylinder whether it is full, partially full or empty, they must contact the Chemical Warehouse (contact details below) to arrange for proper disposal. Spent cylinders should normally be sent back to the supplier through the Chemical Warehouse. The contact information for the Chemical Warehouse is:

Call Chemical Warehouse: (0)12-808-5664

Email Chemical Warehouse: WHSOrder@kaust.edu.sa

Non-refillable cylinders (*i.e.* lecture bottles and disposable gas cylinders) should be disposed through the hazardous waste management system, see the Laboratory Hazardous Waste Management Manual or contact HSE Hazardous Waste Specialist for details.

11. Compressed Gas Leaks and Emergencies

11.1. Preplanning

Despite strict adherence to laboratory safety practices, accidents involving gases may occur in the laboratory. The amount of damage sustained by personnel and property from these accidents will be directly related to the quality of the laboratory's emergency plan and procedures. Users of compressed gas cylinders must be familiar with necessary safety precautions. Standard Operating Procedures (SOPs) for experiments using compressed gases shall include a discussion of possible accident scenarios, appropriate employee responses and should take into account the following factors:

- The nature of the operation (e.g., experimental design, equipment used, etc.).
- The potential location of a release or spill (e.g., outdoors versus indoors, in a laboratory, corridor or storage area, on a table, in a hood, or on the floor).
- The quantities of material that might be released and the type of containment (i.e., compressed gas tank size, manifold systems, etc.).
- The chemical and physical properties of the compressed gas (e.g., its physical state, vapor pressure, and air or water reactivity).
- The hazardous properties of the compressed gas (e.g., its toxicity, corrosivity and flammability).
- The availability and locations of emergency supplies and equipment.
- A contingency plan which identifies building evacuation routes, emergency telephone numbers, chemical containment procedures, fire extinguisher usage, etc., should be posted in the lab.

11.2. Emergency Response

- In the event of personnel skin contamination, wash contaminated area with water and remove contaminated clothing.
- In the event of personnel eye contamination immediately flush the exposed area using an eye wash or water for 15 minutes.
- In the event of personnel exposure via inhalation, remove the victim to fresh air.
- Call 911 from a KAUST landline or 012-808-0911 from a mobile phone.
- Report the incident using ReportIt.

11.3. Minor Leaks

Occasionally a gas cylinder or one of its component parts may develop a leak. Most of these leaks occur at the top of the cylinder in areas such as the valve threads, pressure safety device, valve stem and valve outlet. The following information applies to the remediation of minor leaks:

- If possible, verify suspected leaks using a portable gas detector or soapy water solution (a flame should not be used for detection). If the leak cannot be stopped by tightening a valve gland or packing nut, emergency action procedures should be initiated by calling 911 from a campus phone or 012-808-0911 from a mobile phone.

Most likely leak points on a cylinder:

- For flammable, inert or oxidizing gases, move the cylinder to an isolated, well-ventilated area (e.g., within a fume hood) away from combustible materials. Post signs that describe the hazard.
- For corrosive and toxic gases, move the cylinder to an isolated, well-ventilated area (e.g., within a fume hood) and use suitable means to direct the gas into an appropriate chemical neutralizer. Post signs that describe the hazards.

11.4. Major Leaks

In the event of a large gas release or if an accident takes place in which readily available personal protective equipment (PPE) is inadequate to ensure worker safety, activate the following Emergency Procedures:

- Immediately call 911 from a KAUST landline or 012-808-0911 from a mobile phone and report the incident.
- Activate building and area fire alarms (or chemical safety alarms if applicable).
- Evacuate the area, securing entrances and providing assistance to others on the way out.
- Provide emergency response officials with details of the problem upon their arrival. The KAUST Fire Department will respond to gas emergencies.

Leaks from cylinders of toxic or flammable gases require immediate attention. Decisions of how to handle the problem will depend on the kind of gas, the size of the leak, the area where the cylinder is located, and other factors. Rely on KAUST Fire Department and emergency responders to deal with major leaks and release of toxic and flammable gases.

11.5. TGM Alarms

Some laboratories fitted with TGM systems at KAUST have emergency lights outside the lab. The color code is explained below:

- Blue: Gas leak emergency – Building evacuation alarm.
- White: Gas detector fault / Maintenance required / TGM isolation – Not required to evacuate the building.
- Green: TGM system operational – Normal operations.
- For questions and troubleshooting regarding TGM system please contact the following contact numbers: TGM 1 – 0545860225, TGM 2 – 0545863960

11.6. Odor Reports

Odors can come from many sources, the first minutes are essential to identify the source.
The majority of indoor air quality complaints can be tied to the Heating, Ventilation, and Air Conditioning, "HVAC" system or plumbing. HVAC systems are designed primarily for controlling temperature, humidity, odor control, and air quality.

For extremely strong and acutely irritating odors, strong burning smells or visible smoke call 911 from a KAUST landline or 012-808-0911 from a mobile phone. For chemical, gas, electrical burning smells, and any other odors call 911 from a KAUST landline or 012-808-0911 from a mobile phone.

For humidity smells, musty odors, drainage or sewage smells call 959.
When reporting an unusual or abnormal odor, be prepared to provide the following information:

- Description of odor.
- Time(s) of detection.
- Abnormal conditions, activities, or materials at the time of detection.
- Location, provide building number, level and room number.
- Possible source(s).

Appendix 1 - Glossary

CGA – Compressed Gas Association

Class I Toxic Gas
A material that has a median lethal concentration (LC_{50}) in air of 200 ppm or less by volume of gas or vapor, or 2 milligram per liter or less of mist, fume or dust, when administered by continuous inhalation for one hour, or less if death occurs within one hour, to albino rats weighing between 200 and 300 grams each.

Class II Toxic Gas
A material that has a median lethal concentration (LC_{50}) in air more than 200 ppm but not more than 3000 ppm volume of gas or vapor, or more than 2 mg per liter but not more than 30 mg per liter of mist, fume or dust, when administered by continuous inhalation for one hour, or less if death occurs within one hour, to albino rats weighing between 200 and 300 grams each.

Class III Toxic Gas
A material that has a median lethal concentration (LC_{50}) in air more than 3000 ppm but not more than 5000 ppm volume of gas or vapor, or more than 30mg per liter but not more than 50vmg per liter of mist, fume or dust, when administered by continuous inhalation for one hour, or less if death occurs within one hour, to albino rats weighing between 200 and 300 grams each.

DOT
The U.S. Department of Transportation (DOT) governs the packaging, labeling and transportation of dangerous substances, including compressed gas cylinders. The DOT classification of dangerous material is in-line with the international (UN) classification scheme.

Gas Cabinets
Gas cabinets for toxic gases must meet specifications detailed in NFPA 55. The material must be made of minimum of 12-guage steel, operated under negative pressure, have self-closing doors, and connected to a treatment system if dilution alone cannot reduce a worst-case release to half IDLH at the point of release to the atmosphere.

GHS
The Globally Harmonized System GHS of Classification and Labeling of Chemicals is a system for standardizing and harmonizing the classification and labeling of chemicals. It is a logical and comprehensive approach to:

- Defining health, physical and environmental hazards of chemicals;
- Creating classification processes that use available data on chemicals for comparison with the defined hazard criteria; and
- Communicating hazard information, as well as protective measures, on labels and Safety Data Sheets (SDS).

IKAS

Integrated KAUST Automation System (IKAS) is a campus-wide information network for monitoring status of various building services including hazard alarms.

IDLH

An acronym for **Immediately Dangerous to Life or Health**, and is defined by the US National Institute for Occupational Safety and Health (NIOSH) as exposure to airborne contaminants that is "likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment."

LC_{50}

Median Lethal Concentration (LC_{50}) is the concentration of a gas (or gas mixture) in air administered by a single exposure (usually one hour) to a group of young adult albino rats (male and female) which leads to the death of half of the animals within 14 days. **LC_{50}** values are used for classifying toxic gases.

LC_{LO}

Lowest Reported Lethal Concentration (LCLo) value is the lowest concentration of a material in air reported to have caused the death of animals or humans. When **LC_{50}** values are not available, LC_{LO} values are sometimes used as reference.

LCS

Lab Control System (LCS) is a logic controller which monitors and control essential utilities such as HVAC, lighting, hazard monitoring, and alarms in the laboratories.

LEL

Lower Explosive Limit (LEL): The lowest concentration (percentage) of a gas or a vapor in air capable of producing a flash of fire in presence of an ignition source. LEL concentrations vary greatly between combustible gases. Concentrations lower than LEL are "too lean" to burn.

NFPA Hazard Rating

NFPA Rating is defined in NFPA 704, a standard maintained by the National Fire Protection Association. It defines the colloquial "**fire diamond**" for quickly and easily identifying the risks associated with hazardous materials. This original aim was to help emergency responders determine what protective equipment should be used, procedures followed, or precautions taken during an emergency response.

PEL

Permissible Exposure Limits are similar to TLVs, these levels are established and enforced by the U.S. Occupational Safety and Health Administration (OSHA). PELs are regulatory limits on the concentration of substances in the air in a workplace.

P&ID

Piping and Instrumentation Diagram (P&ID) are symbols used in the design, blueprints, and diagrams of gas piping systems as dictated in ANSI/ISA-5.1-2009 Instrumentation Symbols and Identification.

TGM

Toxic Gas Monitoring System (TGM) is a loose terminology used in KAUST to refer to fixed gas detection and control systems in the laboratories. The gases being monitored may include toxic and flammable gases as well as oxygen levels where large quantities of inert gases are used.

TGO

Toxic Gas Ordinance was a model code first developed by Santa Clara County Fire Chiefs Association in the 1980s as a guideline to address highly hazardous gases used in the semiconductor industry. National codes and laws often lag-behind technological development. It has been adopted by many Bay Area Municipalities as enforceable standards and has been revised and refined from time to time.

TLV

The **threshold limit value** (**TLV**) of a chemical substance is the concentration in air to which it is believed almost all workers can be exposed day after day for the entire working lifetime without adverse health effects. TLV is established by of the American Conference of Governmental Industrial Hygienists (ACGIH).

UEL

Upper Explosive Limit (UEL): Highest concentration (percentage) of a gas or a vapor in air capable of producing a flash of fire in presence of an ignition source (arc, flame, heat). Concentrations higher than UEL are "too rich" to burn.

Appendix 2 - References, Codes and Standards

1. **Toxic Gas Ordinance**, Chapter XIV Toxic Gas Storage, Division B11 of the Santa Clara County Ordinance Code

2. **Toxic Gas Ordinance Consensus Guidelines**, http://www.unidocs.org/hazmat/gases/un-027.pdf Accessed May 2018

3. **Common Toxic Gases as Defined by the Toxic Gas Ordinance and CFC,** http://www.unidocs.org/hazmat/gases/un-015.pdf, accessed May 2018

4. **NFPA 45 Standard on Fire Protection for Laboratories Using Chemicals**, 2015 Edition

5. **NFPA 55 Compressed Gases and Cryogenic Fluids Code**, 2010 Edition

6. **NFPA 704 Standard System for the Identification of the Hazards of Materials for emergency Response**, 2012 Edition

7. **NFPA 318 Standard for the Protection of Semiconductor Fabrication Facilities**, 2018 Edition

8. **International Fire Code**, 2009 Edition

9. **Toxic Gases**, Stanford University, https://ehs.stanford.edu/topic/hazardous-materials/toxic-gas#santa-clara-countys-toxic-gas-ordinance Accessed May 2018

10. **Gas Monitoring Program**, North Carolina State University, https://ehs.ncsu.edu/laboratory-safety/compressed-gases/ Accessed May 2017

11. **Compressed Gases,** UC San Diego University**,** http://blink.ucsd.edu/safety/research-lab/chemical/gas/index.html Accessed May 2018

12. **Guide to Compressed gases or liquefied gases in laboratories**, Northwestern University, https://researchsafety.northwestern.edu/compressed-or-liquefied-gases-laboratories/guide-compressed-or-liquefied-gases-laboratories Accessed May 2018

13. **UN Recommendations on the Transport of Dangerous Goods - Model Regulations, Seventeenth revised edition,** United Nations, 2011

14. **CGA P-20-2017, Standard for Classification of Toxic Gas Mixtures**, Fifth Edition, Compressed Gas Association, Inc.

15. **BS ISO-10298:2018, Determination of Toxicity of a Gas or Gas Mixture**, Third Edition, International Standard Institute.

16. **California Fire Code (CFC)**
    Article 51 – Semiconductor Fabrication Facilities
    5101.10.4 Continuous gas-detection systems

17. **Article 80 Hazardous Materials**
    8003.3.1.6 Gas detection - Storage - Toxic and Highly Toxic Compressed Gases - Indoor
    8004.2.3.7.6 Gas detection Storage, Use, Dispensing and Handling - Indoor – Closed Systems - Special Requirements for Highly Toxic and Toxic Compressed Gases

18. **Section 25 80 00 - Gas monitoring and control system, KAUST PDEC**

Appendix 3 - Hazard Overview of Compressed Gases

Chemical Name	CAS Number	Corrosive	Flammable (LEL-UEL)	Oxidizer	Toxic (LC_{50})	Water Reactive
Acetaldehyde	75-07-0		4.0 - 60%			
Acetyl fluoride	557-99-3	X				
Acetylene	74-86-2		2.5 - 81%			
Allene	463-49-0		2.1 - 13%			
Ammonia	7664-41-7	X	15 - 25%		4000	
Arsenic pentafluoride	7784-36-3				178	
Arsine	7784-42-1		4.5 - 100%		20	
Argon	7440-37-1					
Boron Trichloride	10294-34-5	X			2541	
Boron Trifluoride	7637-07-2	X			864	
Bromine chloride	13863-41-7	X		X	290	
Bromomethane	74-83-9				850	
Bromotrifluoromethane	75-63-8					
1,3-Butadiene	106-99-0		2 - 11.5%			
Butane	106-97-8		1.8 - 8.4%			
1-Butene	106-98-9		1.6 - 9.3%			
cis-2-Butene	590-18-1		1.7 - 9.7%			
trans-2-Butene	624-64-6		1.6 - 9.7%			
1-Butyne	107-00-6		2.5 - 80%			
Carbon dioxide	124-38-9					
Carbon monoxide	630-08-0		12 - 75%		3760	
Carbon tetrafluoride	75-73-0					
Carbonyl fluoride	353-50-4	X			360	
Carbonyl sulfide	463-58-1		6.5 - 29%		1700	
Chlorine	7782-50-5			X	293	
Chlorine pentafluoride	13637-63-3			X	122	
Chlorine trifluoride	7790-91-2	X		X	299	X
Chloromethane	74-87-3		7 - 17.4%			
Chlorotetrafluoroethane (refrigerant 124)	1-3-63938					
2-Chloro-1,1,1-Trifluoroethane	75-88-7					
Chlorotrifluoroethylene	79-38-9		8.4 - 38.7%		2000	
Chlorotrifluoromethane	75-72-9					
Cyanogen	460-19-5		6.6 - 32%		350	
Cyanogen chloride	506-77-4				80	
Cyclopropane	75-19-4		2.4 - 10.4%			
Deuterium	7782-39-0		4 - 74.2%			

Deuterium bromide	13536-59-9	X				
Deuterium chloride	5-7-7698	X			3120	
Deuterium selenide	13536-95-3		Unavailable		51	X
Deuterium sulfide	13536-94-2		4 - 46%		710	
Diborane	19287-45-7		0.9 - 98%		80	
Dibromodifluoromethane	75-61-6					
Dichlorodifluoromethane (R-12)	75-71-8					
Dichlorofluoromethane	75-43-4					
Dichlorosilane	4109-96-0	X	4.1 - 98.8%		314	
1,2-Dichlorotetrafluoroethane	76-14-2					
Diethyl zinc	557-20-0		Unavailable		10	X
1,1-Difluoroethane	75-37-6		4.3 - 17.4%			
1,1-Difluoroethylene	75-38-7		5.5 - 21.3%			
Dimethylamine	124-40-3	X	2.8 - 14.4%			
Dimethyl ether	115-10-6		3.4 - 27%			
2,2-Dimethylpropane	463-82-1		1.4 - 7.5%			
□-Diphenylphosphino ethyltriethoxysilane	18586-39-5					
Diphosgene	503-38-8	X			2	
Enflurane	13838-16-9					
Ethane	74-84-0		3 - 12.4%			
Ethylamine	75-04-7		3.5 - 14%			
Ethyl chloride	75-00-3		3.16 - 15%			
Ethylene	74-85-1		2.7 - 36%			
Ethylene oxide	75-21-8		3 - 100%		2900	
Ethylsilane	2814-79-1		1.3 - 88.9%			
Fluorine	7782-41-4	X		X	185	
Fluoromethane	593-53-3		Unavailable			
Germane	7782-65-2		Unavailable		620	
Halon 1310	75-63-8					
Helium	7440-59-7					
Hexachloro-1,3-butadiene	87-68-3	X			370	
Hexafluoroacetone	684-16-2	X			470	
1,3-Hexafluorobutadiene	685-63-2		7 - 73%			
Hexafluoro-2-butyne	692-50-2				Unavailable	
Hexafluoroethane	76-16-4					
Hexafluoropropene	116-15-4					
Hydrogen	1333-74-0		4 - 75%			
Hydrogen bromide	10035-10-6	X			2860	
Hydrogen chloride	7647-01-0	X			2810	
Hydrogen cyanide	74-90-8	X	5.6 - 40%		140	
Hydrogen fluoride	7664-39-3	X			1307	
Hydrogen iodide	10034-85-2	X			2860	
Hydrogen selenide	7783-07-5		Unavailable		51	X

Hydrogen sulfide	7783-06-4	X	4.3 - 46%		712	
Hydrogen telluride	07783-09-7		Unavailable		51	X
Krypton	7439-90-9					
Methane	74-82-8		5 - 15%			
Methanethiol	74-93-1		3.91 - 21.8%		1350	
Methyl acetylene propadiene (MAPP)	Mixture		2 - 13%			
Methylamine	74-89-5	X	4.9 - 20%			
Methyl bromide	74-83-9				850	
3-Methyl-1-Butene	563-45-1		1.5 - 9.1%			
Methyl chloride	74-87-3		8.1 - 17.2 %			
Methyl chlorosilane	993-00-0	X	Unavailable		600	X
Methyl isocyanate	624-83-9		5.3 - 26%		< 1	
2-Methylpropane	75-28-5		1.4 - 8.3%			
2-Methylpropene	115-11-7		1.8 - 9.6%			
Methyl silane	992-94-9		1.3 - 88.9%			X
Methyl vinyl ether	107-25-5		2.6 - 39%			
Neon	13981-34-5					
Nickel tetracarbonyl	13463-39-3		2 - 34%		20	X
Nitric oxide	10102-43-9			X	115	X
Nitrogen	7727-37-9					
Nitrogen dioxide	10102-44-0	X		X	115	
Nitrogen trifluoride	7783-54-2			X		
Nitrogen trioxide	10544-73-7	X		X	57	
Nitrosyl chloride	2696-92-6				35	X
Nitrous oxide	10024-97-2			X		
Octafluorocyclobutane	115-25-3					
Oxalyl bromide	15219-34-83	X				X
Oxygen	7782-44-7			X		
Oxygen difluoride	7783-41-7	X			2.6	
Ozone	10028-15-6			X	9	
Perfluoropropane	76-19-7					
Phosgene	75-44-5	X			5	
Phosphine	7803-51-2	X	Pyrophoric		20	
Phosphorous pentafluoride	7647-19-0				261	X
Phosphorous trifluoride	7783-55-3	X			436	X
Propane	74-98-6		2.1 - 10.1%			
Propylene	115-07-1		2 - 11.1%			
Propyne	74-99-7		2.5 - 80%			
Radon	10043-92-2					
Selenium hexafluoride	7783-79-1	X			50	
Silane	780-62-5		1.5 - 98%			
Silicon tetrafluoride	7783-61-1	X			922	X
Stibine	7803-52-3		Unavailable		178	X
Sulfur dioxide	7446-09-5				2520	

Sulfur hexafluoride	2551-62-4					
Sulfur pentafluoride	5714-22-7			X	< 1	
Sulfur tetrafluoride	7783-60-0	X			40	
Sulfuryl fluoride	2699-79-8				3020	
Tellurium hexafluoride	7783-80-4	X			25	X
Tetrafluoroethylene	116-14-3		10 - 50%		2000	
Trichloromonofluoromethane	75-69-4					
Trifluoroacetyl chloride	354-32-5	X			10	X
Trifluoroiodomethane	2314-97-8					
Trifluoromethane	75-46-7					
Trimethylamine	75-50-3	X	2 - 11.6%			
Trimethylantimony	594-10-5	X	Pyrophoric			
Tungsten Hexafluoride	7783-82-6	X			218	
Vinyl acetylene	689-97-4		2 - 100%			
Vinyl bromide	593-60-2					
Vinyl chloride	75-01-4		4 - 22%			
Vinyl fluoride	75-02-5		2.6 - 21.7%			
Xenon	7440-63-3					

Gases highlighted in red are pyrophoric.

Note: Gases with no GHS hazard class of Corrosive, Flammable, Oxidizing, or Toxic are typically inert under normal conditions. However, inert does not equal non-hazardous. Given the right conditions they can be reactive. Example: nitrogen gas is typically non-reactive but will react with lithium, hence why many lithium compounds are utilized under argon instead. All values are from ISO 10298:2018(E) and manufacturers SDS

Appendix 4 - Gas Storage Maximum Allowable Quantities

Taken from Table 6.3.1.1 from NFPA 55 (2016 edition)

Table 6.3.1.1 Maximum Allowable Quantity (MAQ) of Hazardous Materials per Control Area

			Storage			Use — Closed Systems			Use — Open Systems	
Material	**Class**	**High Hazard Protection Level**	**Solid Pounds**	**Liquid Gallons**	**Gas[a] scf (lb)**	**Solid Pounds**	**Liquid Gallons**	**Gas[a] scf (lb)**	**Solid Pounds**	**Liquid Gallons**
Cryogenic fluid	Flammable	2	NA	45[b,c]	NA	NA	45[b,c]	NA	NA	45[b,c]
	Oxidizing	3	NA	45[d,e]	NA	NA	45[d,e]	NA	NA	45[d,e]
	Inert	NA	NA	NL	NA	NA	NL	NA	NA	NL
Flammable, gas[f]	Gaseous	2	NA	NA	1000[d,e]	NA	NA	1000[d,e]	NA	NA
	Liquefied	2	NA	NA	(150)[d,e]	NA	NA	(150)[d,e]	NA	NA
	LP	2	NA	NA	(300)[g,h,i]	NA	NA	(300)[g]	NA	NA
Inert gas	Gaseous	NA	NA	NA	NL	NA	NA	NL	NA	NA
	Liquefied	NA	NA	NA	NL	NA	NA	NL	NA	NA
Oxidizing gas	Gaseous	3	NA	NA	1500[d,e]	NA	NA	1500[d,e]	NA	NA
	Liquefied	3	NA	NA	(150)[d,e]	NA	NA	(150)[d,e]	NA	NA
Pyrophoric gas	Gaseous	2	NA	NA	50[d,j]	NA	NA	50[d,j]	NA	NA
	Liquefied	2	NA	NA	(4)[d,j]	NA	NA	(4)[d,j]	NA	NA
Unstable (reactive) gas	Gaseous									
	4 or 3 detonable	1	NA	NA	10[d,j]	NA	NA	10[d,j]	NA	NA
	3 nondetonable	2	NA	NA	50[d,e]	NA	NA	50[d,e]	NA	NA
	2	3	NA	NA	750[d,e]	NA	NA	750[d,e]	NA	NA
	1	NA	NA	NA	NL	NA	NA	NL	NA	NA
Unstable (reactive) gas	Liquefied									
	4 or 3 detonable	1	NA	NA	(1)[d,j]	NA	NA	(1)[d,j]	NA	NA
	3 nondetonable	2	NA	NA	(2)[d,e]	NA	NA	(2)[d,e]	NA	NA
	2	3	NA	NA	(150)[d,e]	NA	NA	(150)[d,e]	NA	NA
	1	NA	NA	NA	NL	NA	NA	NL	NA	NA
Corrosive gas	Gaseous	4	NA	NA	810[d,e]	NA	NA	810[d,e]	NA	NA
	Liquefied		NA	NA	(150)[d,e]	NA	NA	(150)[d,e]	NA	NA
Highly toxic gas	Gaseous	4	NA	NA	20[e,k]	NA	NA	20[e,k]	NA	NA
	Liquefied		NA	NA	(4)[e,k]	NA	NA	(4)[e,k]	NA	NA
Toxic gas	Gaseous	4	NA	NA	810[d,e]	NA	NA	810[d,e]	NA	NA
	Liquefied		NA	NA	(150)[d,e]	NA	NA	(150)[d,e]	NA	NA

NA: Not applicable within the context of NFPA 55 (refer to the applicable building or fire code for additional information on these materials).
NL: Not limited in quantity.
Notes:
(1) For use of control areas, see Section 6.2.
(2) Table values in parentheses or brackets correspond to the unit name in parentheses or brackets at the top of the column.
(3) The aggregate quantity in use and storage is not permitted to exceed the quantity listed for storage. In addition, quantities in specific occupancies are not permitted to exceed the limits in the building code.
[a]Measured at NTP [70°F (20°C) and 14.7 psi (101.3 kPa)].
[b]None allowed in unsprinklered buildings unless stored or used in gas rooms or in approved gas cabinets or exhausted enclosures, as specified in this code.
[c]With pressure-relief devices for stationary or portable containers vented directly outdoors or to an exhaust hood.
[d]Quantities are permitted to be increased 100 percent where stored or used in approved cabinets, gas cabinets, exhausted enclosures, gas rooms, as appropriate for the material stored. Where Footnote e also applies, the increase for the quantities in both footnotes is permitted to be applied accumulatively.
[e]Maximum quantities are permitted to be increased 100 percent in buildings equipped throughout with an automatic sprinkler system in accordance with NFPA 13. Where Footnote d also applies, the increase for the quantities in both footnotes is permitted to be applied accumulatively.
[f]Flammable gases in the fuel tanks of mobile equipment or vehicles are permitted to exceed the MAQ where the equipment is stored and operated in accordance with the applicable fire code.
[g]See NFPA 58 for requirements for liquefied petroleum gas (LP-Gas). LP-Gas is not within the scope of NFPA 55.
[h]Additional storage locations are required to be separated by a minimum of 300 ft (92 m).
[i]In mercantile occupancies, storage of LP-Gas is limited to a maximum of 200 lb (91 kg) in nominal 1 lb (0.45 kg) LP-Gas containers.
[j]Permitted only in buildings equipped throughout with an automatic sprinkler system in accordance with NFPA 13.
[k]Allowed only where stored or used in gas rooms or in approved gas cabinets or exhausted enclosures, as specified in this code.

Appendix 5 - Restrictive Flow Orifices

Restrictive Flow Orifices

The Restrictive Flow Orifice (RFO) is for use in conjunction with high purity compressed gas applications in both the semiconductor and allied chemical industries. Matheson Tri-Gas pioneered the development of RFO technology.

Restrictive Flow Orifices are used to limit the potential danger of an uncontrolled flow from a compressed gas cylinder. Unchecked, the instantaneous flow from a 44 liter compressed gas cylinder filled to 2,000 psig can be as much as 20,000 liters per minute. By inserting an RFO into the outlet of the CGA connection the flow rate could be reduced by a factor of 100 to approximately 200 liters per minute.

The Restrictive Flow Orifice is designed to thread into the outlet of most CGA connections that have external male threads. This would include the family of DISS face seal connections (CGA 630 and 710) that are used in high purity semiconductor applications.

The RFO has no moving parts. It is about 3/8" long and is generally constructed of 316LSS. The orifice opening usually varies from 0.006" to 0.060". It is possible to have orifices that are as small as 0.004" and as large as 0.150" depending upon the application.

The orifice is generally unfiltered. A KEL-F gasket is provided as part of the assembly to help create a seal between the restrictor and the valve body. Refer to Figure 1.

The flow rate through an orifice is a function of the following variables:

- Pressure
- Temperature
- Specific Gravity
- Orifice Opening

Correlations assist in predicting the flow of a particular gas or mixture through an RFO. This is done by first determining the flow through the same RFO at the required pressure with a reference gas and then adjusting the specific gravity accordingly.

The pertinent equation is presented below.

$$\text{Flow} = \text{The Flow Rate of } N_2 \text{ at the Same Pressure} \sqrt{\frac{1}{\text{Specific Gravity}}}$$

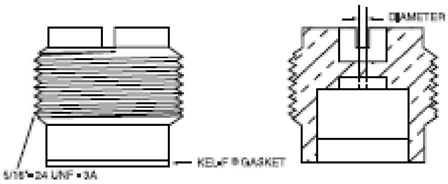


Figure 1: Restrictive Flow Orifice

Typical nitrogen flows for different orifice signs at different pressures can be found in Table I.

By using this table, a reference flow rate for nitrogen can be determined and then the reference equation can be used with this value.

For a mixture a "weighted" or "averaged" specific gravity can be used by multiplying the volume or mole fraction of each component by its specific gravity and then summing.

Table II summarizes some of the gases that can be offered with restrictive flow orifices.

In addition to providing safety features that have been mandated by various local and state codes, the restrictive flow orifice also results in a lower flow rate, which is desirable in many semiconductor applications. While the RFO was not designed to be a modulator or control valve, it will as its name implies, substantially reduce the flow rate under a specific set of pressure and temperature conditions for a given gas.

More detailed information on restrictive flow orifices is available from your local Matheson Tri-Gas Sales Engineer.

TABLE I Orifice Flow Rate at Varying Pressures

Orifice	Pressure-PSIG			
Size	0	500	1000	2000
0.006 in.	0 slpm	7 slpm	15 slpm	29 slpm
0.010 in.	0 slpm	18 slpm	36 slpm	73 slpm
0.031 in.	0 slpm	150 slpm	310 slpm	—
0.040 in.	0 slpm	245 slpm	485 slpm	—
0.052 in.	0 slpm	535 slpm	—	

TABLE II Gases offered with Restrictive Flow Orifices Specific Gravity @ 70° (1 atm), CGA and DISS Connections

Gas	Specific Gravity	CGA STD	CGA DISS
Ammonia	0.593	660	720
Argon	1.376	-	718
Arsenic Pentafluoride	6.090	-	642
Arsine	2.718	-	632
Boron Trichloride	4.045	660	634
Boron Trifluoride	2.375	330	642
Carbon Dioxide	1.527	320	716
Carbon Monoxide	0.967	350	724
Chlorine	2.479	660	728
Diborane	0.950	350	632
Dichlorosilane	3.473	678	638
Disilane	2.149	-	632
Germane	2.634	350	632
Halocarbon 11	4.770	660	-
Halocarbon 115	5.568	660	716

Gas	Specific Gravity	CGA STD	CGA DISS
Halocarbon 116	4.820	660	716
Halocarbon 12	4.262	660	716
Halocarbon 13	3.610	660	716
Halocarbon 14	3.075	-	716
Halocarbon 23	2.436	660	716
Helium	0.138	-	718
Hydrogen	0.070	350	724
Hydrogen Bromide	2.780	330	634
Hydrogen Chloride	1.266	330	634
Hydrogen Fluoride	0.689	670	638
Hydrogen Selenide	2.771	350	632
Hydrogen Sulfide	1.192	330	722
Krypton	2.900	-	718
Neon	0.696	-	718
Nitrogen	0.967	-	718

Gas	Specific Gravity	CGA STD	CGA DISS
Nitrogen Trifluoride	2.460	670	640
Nitrous Oxide	1.528	326	-
Oxygen	1.105	540	714
Perfluoropropane	6.652	660	716
Phosphine	1.190	350	632
Phosphorus Pentafluoride	4.310	330	642
Silane	1.120	350	632
Silicon Tetrachloride	5.833	-	636
Silicon Tetrafluoride	3.615	330	642
Sulfur Hexafluoride	5.105	-	716
Trichlorosilane	4.666	-	636
Tungsten Hexafluoride	10.674	670	638
Xenon	4.558	-	716

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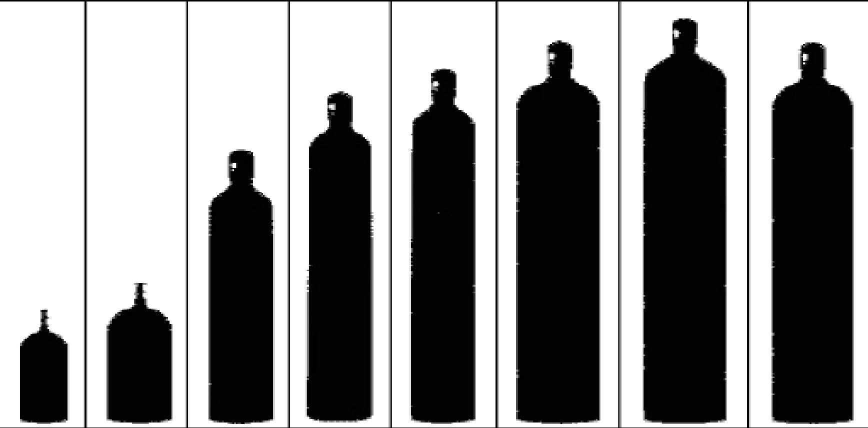
Thuwal 23955-6900 Saudi Arabia

Appendix 6 - Small-size Portable Cylinders and Lecture Bottles

Lecture bottles or “portable cylinders” are small compressed gas cylinders, typically 12-18 inches long and 2-3 inches in diameter. Content of a typical lecture bottle is around 50 standard liters – which is about ~0.7% of a full size (6909 liters) cylinder at 200 bars. This quantity is often more than enough for many research applications. The small quantities contained in portable cylinders limit their potential hazards. They are therefore usually exempt from most complicated regulatory requirements.

Use of small-size, portable cylinders is highly encouraged in KAUST whenever applicable. Nowadays, suppliers of specialty gases for research have many different sizes to choose from. While the initial purchase cost per cubic foot may be lower when hazardous gases are purchased in full sized cylinders the overall cost of experimental setup which may require local ventilation, gas cabinets, stainless steel piping and purging systems may offset the apparent saving from buying hazardous gases in full sized cylinders.

High Pressure Cylinders



Size	R	RR	Q	LD	S	K	T	KHP
Height (In)	14	17	32	43	47	51	55	51
Weight (Lbs)	11	24	46	58	61	113	139	188
Nominal Volume (CU FT)	20	40	80	122	150	244	330	N/A

Use of small-size is NOT without their associated risks, especially for highly toxic gases. In KAUST, they are exempt from most engineering controls but they still require adequate administrative controls such as SOPs, training, etc.

Safety Requirements for lecture bottles:

(1) Inspect the lecture bottle and regulator prior to use. Never use lecture bottle or regulators that are damaged or corroded.

Corroded valve on a hydrogen chloride lecture bottle.

(2) Only use regulators and tubing that are appropriate for the gas. For example, stainless steel regulators and tubing must be used for corrosive gases. Using the wrong regulator can compromise the gas purity, cause equipment failure and cause injury to laboratory personnel.

(3) Lecture bottles must be properly secured during use and lecture bottles containing hazardous gases (corrosive or poison) must be used in a fume hood, ventilated cabinet or gas cabinet.

Lecture bottle stand and work station available from Sigma Aldrich.

(4) Lecture bottles must be stored in an upright position. Lecture bottles stored on their side are more susceptible to damage, corrosion and leaks.

(5) Segregate incompatible gases, such as flammable and oxidizing gases. Store poisonous gases in a fume hood or a ventilated gas cabinet.

(6) Regulators must be removed during storage. It is a good idea to label the regulator with the gas it is used for to prevent accidental misuse in the future.
(7) Lecture bottles must be properly labeled. Re-label the lecture bottle if the label becomes illegible or falls off.

Example of proper lecture bottle storage.

Lecture bottle holder available from Fisher Scientific or Sigma Aldrich.

Examples of **improper** lecture bottle storage:

LECTURE BOTTLE PURCHASE AND DISPOSAL

Unlike other gas cylinders, most lecture bottles are not refillable and are purchased outright by the laboratory. Some suppliers do not take back lecture bottles. Lecture bottles are considered hazardous waste and may be costly to dispose of. Contact whsorder@kaust.edu.sa for disposal of old or unneeded lecture bottles. **As much as possible, choose a supplier who will take back spent lecture bottles.**

Special precaution with anhydrous hydrogen fluoride

Anhydrous hydrogen fluoride reacts over time with the iron in the steel to form iron fluoride and hydrogen. The hydrogen pressure can build up to the point where it ruptures the cylinder. Anhydrous hydrogen fluoride lecture bottles must be disposed of within 2 years of purchase.

Old anhydrous hydrogen fluoride lecture bottle exploded in another university.

Appendix 7 - Sub-Atmospheric Containers

For many applications that required highly toxic gases such as phosphine and arsine, commonly used as semiconductor dopants, the gases are used in minute quantities and always under vacuum.

Researchers are encouraged to consider Sub-Atmospheric when it is compatible to their research needs. These cylinders have pressures below one atmosphere and the gas they contained is adsorbed in a porous material and it can only be extracted under a vacuum. These cylinders are therefore inherently safe compared to compressed gas cylinders.

Below is a description of sub-atmospheric containers from one specialty gas supplier.

Ultra-High Purity Process Gases–Isotopically Enriched ^{11}Boron Trifluoride

UpTime® Sub-Atmospheric Delivery System

A safe, cost-effective dopant gas delivery system for ion implanters

Increase productivity with the *UpTime®* delivery system – OEM qualified, production proven

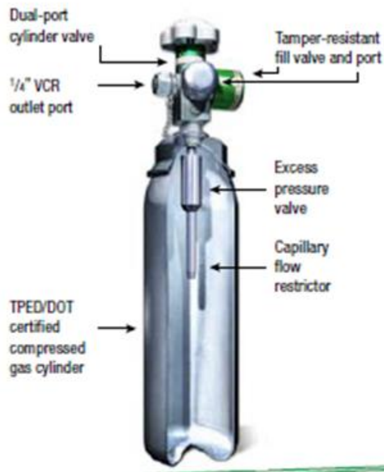
The *UpTime®* sub-atmospheric delivery dopant gas delivery system is designed as an alternative to existing adsorbent-based technology used in ion implanters. Compared to the existing technology, the *UpTime* system offers industry leading product capacity, higher product purity and a lower cost of ownership.

The *UpTime* system is comprised of an internal vacuum actuated valve in series with a specially designed capillary flow restrictor. The *UpTime* device is designed for safety with two different types of safeguards, mechanical actuator and flow restrictor.

The *UpTime* product family includes six primary ultra-high purity gases for ion implantation – isotopically enriched ^{11}boron trifluoride, arsine, phosphine, enriched ^{72}germanium tetrafluoride, germanium tetrafluoride and silicon tetrafluoride.*

Features:

- Sub-atmospheric delivery
- Internal capillary flow restrictor limits flow to 266 sccm
- SEMI® S2 and S8 compliant
- Highest equivalent-cylinder product capacity
- High product utilization
- Robust safety features
- Ultra-high purity gas



US Patent Numbers: 5,937,895; 6,007,609; 6,045,115
*Additional ultra-high purity gases are available upon request.

PRAXAIR ELECTRONICS
www.praxair.com/electronics

Ultra-High Purity Process Gases–Isotopically Enriched ^{11}Boron Trifluoride

Enabling next-generation technology
Praxair Electronics specializes in developing high performance cost-effective products to meet next-generation semiconductor manufacturing.

About Praxair Electronics
Praxair Electronics is dedicated to helping semiconductor manufacturers lower costs, improve productivity, enhance technology and reduce environmental impact by serving as a single, integrated source for a variety of process gases, materials, and related equipment and services.

Our commitment to materials science and gas technology is focused in three areas:

Process Consumables
- Ultra-high purity semiconductor process gases
- Sputtering targets
- ALD/CVD precursors
- CMP consumables

Fab Infrastructure and Services
- Bulk and on-site gas production
- Analytical systems and services
- Process gas delivery systems
- Total gas and chemical management services
- Integrated supply chain management services

Process Tool Solutions
- Electrostatic chucks
- Performance coatings
- Chamber components

Products specifications

Cylinder Specification

Cylinder Size	Overall Height (A)	Height to Connection (B)	Cylinder Body Height (C)	Diameter (D)	Content Fill Weight
UT-SSELB	16.7" 423mm	13.9" 354mm	11.9" 301mm	2.0" 51mm	64g
UT-5	18.3" 457mm	15.3" 389mm	13.7" 348mm	4.4" 111mm	335g
UT-6	22.5" 571mm	19.7" 500mm	17.5" 445mm	6.25" 159mm	1029g

Isotopically Enriched ^{11}Boron Trifluoride ($^{11}BF_3$) Specification, 3.0 grade
- Fill pressure 600 psig
- Internal capillary flow restrictor limits flow to 266 sccm

Component	Value
Boron-11 Isotopic Enrichment	>99.7%
Argon + Oxygen	50 ppm
Carbon Dioxide	25 ppm
Hydrogen Fluoride	25 ppm
Nitrogen	25 ppm
Sulfur Dioxide	25 ppm

Shelf life: 36 months

Gas Stick Requirements
- 1/4" FVCR cylinder connection
- Vacuum pressure required at cylinder connection between 100 and 500 torr
- Low-pressure, pressure transducer (ideally 0-1000 torr range)
- Vacuum pressure mass flow controller
- Normally closed pneumatic isolation valve suitable for service ≥600 psig that automatically closes if pressure exceeds working pressure of low-pressure components
- All components not protected by an isolation valve are suitable for service ≥600 psig

Gas Box Requirements
- Toxic gas monitoring of the gas box exhaust
- Gas box exhaust interlocked and abated

	North America	Europe – Process Gases	Europe – Sputtering Targets	Asia
Phone	1 800 446 8765	+32 14 250 480	+33 561 435005	+886 3 554 3538
Fax	1 800 447 5040	+32 14 250 424	+33 561 435028	+886 3 554 3539
E-mail	info@praxair.com			

PRAXAIR ELECTRONICS
www.praxair.com/electronics

Appendix 8 - Liquefied Gas Cylinders

AIR PRODUCTS

Safetygram #30

Handling Liquefied Compressed Gas

General

A liquefied compressed gas can be defined as a gas, which when compressed in a container, becomes a liquid at ordinary temperatures and at pressures ranging from 25 to 2500 psig. Liquefied gases have boiling points that range from –130 to 30°F (–90 to –1°C). At 70°F (21.1°C) the cylinder contains both liquid and gas. Cylinder pressure, or the "vapor pressure" of the gas, is directly affected by ambient temperature. Increases or decreases in the temperature will cause the vapor pressure to increase or decrease, respectively.

Liquefied gases are packaged under their own vapor pressure and are shipped under rules that limit the maximum amount that can be put into a container to allow for liquid expansion with rising temperatures. (The various transportation regulatory agencies have established very detailed requirements for the filling limits of liquefied compressed gases to prevent the possibility of container overpressurization. Consult the regulations for your region for more information.)

Typical liquefied compressed gases are listed in Table 1.

Containers

Liquefied compressed gases come in a variety of containers.

Because the product exists in both the liquid and gas phases in the container, many containers are equipped to access both phases. This is accomplished by the use of full-length eductor tubes (dip tubes) and gooseneck eductor tubes (see Fig. 1).

Cylinders with a full-length eductor tube, or what is sometimes called a full-length dip tube, have a tube that runs from the inlet of the cylinder valve to the bottom of the cylinder. When a cylinder with this valve configuration is in the upright position, the inlet of the tube is immersed in liquid and the liquid phase will be removed.

Some cylinders are equipped with two valves: one having a full-length eductor tube for liquid withdrawal and the other a valve without an eductor tube for gas withdrawal or inert gas padding (see Fig. 2 and section on liquid-phase withdrawal).

Another type of valve configuration is called the gooseneck eductor tube. The gooseneck goes only a short distance into the cylinder and then bends to the cylinder side opposite the valve outlet. In the upright position, the gooseneck is above the liquid level and provides gas. To remove the liquid, the cylinder is placed on its side with the valve outlet facing up. This puts the gooseneck into the liquid.

Figure 1

(left) Cylinder with gooseneck dip tube. (right) Cylinder with full-length dip tube.

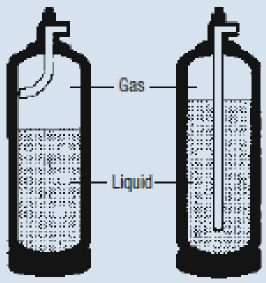
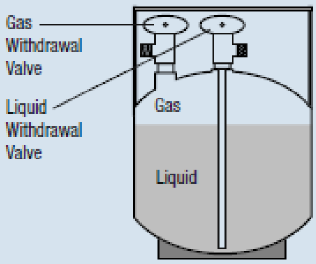


Figure 2

Some cylinders are equipped with two valves, one with and one without an eductor tube.



Responsible Care®
Good Chemistry at Work

In horizontal containers, such as "Y" cylinders, "tonners," and tube trailers (see Figs. 3, 4, and 5), dip tubes are required to access both the liquid and gas phases.

"Y" cylinders use what is referred to as a "C" configuration. This configuration is very similar to the gooseneck, but the inlet to the gooseneck is oriented in the same direction as the valve outlet. The product flows into the dip tube and out the valve outlet in a flow path shaped like the letter "C." This means when the valve outlet is pointed up, the gas phase is accessed, and when the valve outlet is pointed down, the liquid phase is accessed.

Tonner containers have two valves. The container is oriented so the valves are one above the other. The valves are connected to dip tubes that run to the cylinder sides. The top valve will have the dip tube in the vapor and the bottom valve will have the dip tube in the liquid.

On tube trailers with liquefied compressed gases, gooseneck dip tubes are used, but the dip tube orientation is determined by the end of the tube trailer that is being accessed. Typically all valve outlets will be aimed downward on a tube trailer. Normally, gas can be withdrawn from the rear of the trailer with all dip tubes oriented upward (to the vapor phase). Liquid can be withdrawn from the front of the trailer where the dip tubes will be oriented downward into the liquid phase.

The most common type of liquefied gas container uses a standard cylinder valve. In the upright position the liquid level is well below the valve inlet, preventing liquid from being removed. If liquefied gas is to be withdrawn, the bottom of the cylinder must be elevated above the valve to allow the liquid phase to be in contact with the valve inlet. Special inversion racks are usually used to provide a safe method for cylinder inversion.

Table 1

Some Common Liquefied Gases*

Gas	Vapor Pressure @ 70°F (21.1°C)
Ammonia	114 psig (7.76 atm)
Carbon Dioxide	830 psig (56.5 atm)
Chlorine	86 psig (5.85 atm)
Hydrogen Chloride	613 psig (41.7 atm)
Hydrogen Sulfide	247 psig (16.8 atm)
Methyl Chloride	59 psig (4.01 atm)
Monomethylamine	44 psig (2.99 atm)
Nitrous Oxide	745 psig (50.7 atm)
Sulfur Dioxide	34 psig (2.31 atm)
Sulfur Hexafluoride	298 psig (20.3 atm)
Tungsten Hexafluoride	2.5 psig (0.17 atm)

* Liquid petroleum gases, such as propane and butane, have not been included as they are too numerous to mention.

How to Withdraw Product Safely

Product withdrawal should be carefully supervised by qualified people with the proper equipment. Personnel should be aware of the associated hazards of the product and equipment and thoroughly understand applicable safety regulations and emergency procedures.

There are two different methods of product withdrawal from a liquefied compressed gas container: as a vapor (gas) or as a liquid (liquefied gas).

Vapor-Phase Withdrawal

Liquefied compressed gases in a cylinder or any container exist in liquid and gaseous form at a pressure equal to the vapor pressure of the particular gas (see Table 1 for specific vapor pressures). The cylinder pressure will remain constant at the vapor pressure of the material as long as there is any liquid remaining in the cylinder. When the contents of the cylinder are withdrawn to the point that no liquid remains, the pressure in the cylinder will begin to diminish as the remaining vapor is used.

The first step for removing vapor is to orient the package to access the vapor phase of the product.

Figure 3

"Y" cylinders use a C configuration dip tube.

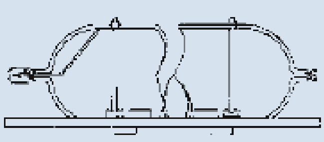


Figure 4

Tonner containers have two valves, each connected to a dip tube.

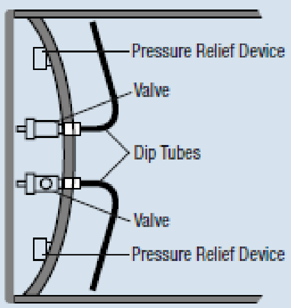
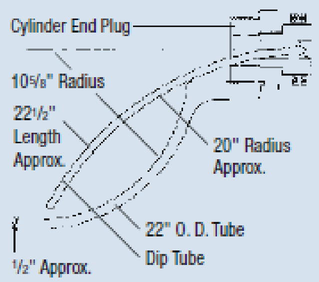


Figure 5

Tube trailer front dip tube configuration.



Special Warnings Regarding Vapor-Phase Withdrawel

CAUTION! EXCESSIVE TEMPERATURE CONSIDERATIONS: Any enhanced vapor withdrawal method listed here that involves heating should be controlled to prevent exposure of the container to temperatures exceeding 125°F (52°C).

DANGER: Never heat an aluminum cylinder with electrical resistance elements. Only cylinders made of steel should be electrically heated. Aluminum cylinders can be severely damaged by excessive temperature exposure.

CAUTION! ELECTRICAL REQUIREMENTS: All electrical systems for indirect heating and monitoring for a flammable gas supply system should be designed to comply with the applicable national or local electrical code requirements. Typical electrical code requirements include classification for instruments and/or limiting the surface temperature of heated resistance elements to a specified fraction of the autoignition temperature for the flammable gas.

AIR PRODUCTS' POSITION ON CODES: Various national and/or local codes prohibit the general direct heating of containers. However, these codes are interpreted as only pertaining to heating systems that apply heat energy directly onto the containers.

This interpretation is based on the examples of prohibited heating methods cited in various code references: radiant flame, steam impingement on the container, immersion in a heated water bath or electrical resistance heater elements in direct contact with the container.

Nonheated, flow-enhancing options should be evaluated as a first preference. If none are suitable, a properly engineered and approved **INDIRECT** heating system is acceptable for liquefied compressed gas containers. Direct heating methods such as flames, steam impingement, electrical resistance elements, water bath immersion, hot plates, and ovens should not be used.

Water-bath immersion is not recommended: The direct immersion of a cylinder into a water bath is **NOT RECOMMENDED** as a heating method, since repeated or prolonged exposure to heated and agitated water can degrade the cylinder's external surface and can eventually compromise the cylinder's mechanical integrity. Use of acidic or alkaline water or the use of conditioning salts and other materials has caused cylinder failures when used in water baths.

When vapor is removed from the cylinder, the temperature and pressure equilibrium is disturbed and both will decrease. Liquid will vaporize to replace the gas that was removed, absorbing the heat of vaporization from the remaining liquid and the container. This heat can usually be recovered from the ambient air surrounding the cylinder. If the withdrawal rate of the gas is such that the energy required to vaporize the liquid cannot be recovered from the surrounding air, the liquid phase will begin to cool.

The phase equilibrium is a function of the system temperature. As the temperature of the liquid phase increases, so will the vapor pressure; the converse is also true. If the liquid cannot recover enough heat from its surroundings to keep up with the demand for gas, the liquid will cool. This is called "sub-cooling" or "auto-refrigeration." It is common for vapor withdrawal to cool the cylinder to the point where moisture condenses on the external cylinder, valve, and piping surfaces. If the surfaces are chilled below water's freezing point, the condensed moisture can solidify into ice.

If the rate of withdrawal of vapor is excessive, serious safety problems can arise. Sub-cooling can cause the vapor pressure to collapse to the point where the cylinder pressure is below that of the process. This pressure inversion can cause backflow of the process materials into the cylinder, or "suckback." It is also possible to cool a cylinder enough to actually embrittle the metal, potentially leading to a cylinder failure. Ice formation on the cylinder and especially on the valve and piping, coupled with the decrease in flow as the cylinder pressure drops, is sometimes misinterpreted as blockage in the valve. This can lead to users applying excessive heat to the valve, possibly creating leakage at the outlet connection, the valve packing, and especially from a fusible metal relief device if the valve is so equipped.

How Can One Improve the Gas-Phase Withdrawal Rate?

Depending on the cylinder or container geometry and ambient conditions, some method might be necessary to enhance product withdrawal from liquefied compressed gas cylinders to maintain required flow rates. This is especially true with small cylinders and nearly empty larger containers.

Product withdrawal enhancement methods have a definite preference of selection based on inherent safety considerations and consequences of system failure. This Safetygram presents the recommended methods in order of preference and their associated requirements.

1. **Use a Larger Container:** This will increase the outer surface area of the container to allow more heat transfer from the environment.

2. **Vaporization:** The user can withdraw liquid phase through an external vaporizer, thereby converting the liquid to gaseous product. This is the preferred method for high flow requirements. This method requires liquid-phase withdrawal from the container using an eductor tube. The liquid is then vaporized via a standard vaporizer, tubing coil, or other vaporization means. This method can provide the highest withdrawal rates, but may not be suitable for high-purity applications. It also creates the highest release flow rate potential due to downstream leakage or operator error, which should be adequately addressed for hazardous products. Overpressure protection should be provided on any lines, including the vaporizer circuit, in which liquid product can be trapped by isolation valves, check valves, or other system components.

3. **Container Switching:** This method uses two or more identical containers or banks of containers that can be switched to the on-line position either manually or automatically. When the primary, active container vapor pressure drops below the threshold capable of supplying the desired gaseous flow rates, the secondary, alternate container is brought on-line in place of the previously active container. This permits the first container to rewarm by absorbing ambient heat. The switching sequence is repeated throughout the high flow demand. This method may not be feasible if the ambient temperature conditions do not provide adequate heat to rewarm the off-line container within an acceptable period of time.

4. **Container Manifolding:** Manifolding a number of liquefied, compressed gas containers in parallel permits the user to achieve the required gas-

eous flow rate by withdrawing product from all containers simultaneously. This method benefits from the larger thermal mass of the manifolded cylinders and product and provides additional container surface area for ambient heat transfer, thus enhancing total gaseous withdrawal capability. However, manifolding may not be adequate if ambient temperature conditions do not yield sufficient heat flow or product vapor pressures within the containers.

Warning: Manifolding liquefied compressed gas cylinders together without good engineering practices to prevent product migration of one cylinder's contents into another cylinder may result in:

1. Container rupture.
2. Major property damage.
3. Serious injury or death.
4. Noncompliance with local, national or international shipping and fire/occupancy regulations.

CAUTION, Cylinder Heating Considerations: Any equipment used to heat a cylinder of liquefied compressed gas must include redundant over-temperature protection, such as a system temperature controller (thermostat) with a maximum setpoint of 125°F (52°C) along with a separate, independent over-temperature shutdown device, such as a fusible link, in the power supply to the heater. The over-temperature shutdown must be installed between the heat source and the cylinder.

5. **Convective Conditioning:** Gas withdrawal can be enhanced by heating the atmosphere surrounding the container to provide additional thermal convective heating of the containers and their contents to increase product vapor pressure. This approach is best accomplished if the container is held within an enclosure or small room and it provides gradual, controlled heating of the container contents. However, this system may not prove feasible for containers located outdoors, within a large room, or in a highly ventilated/exhausted enclosure.

6. **Radiant Conditioning:** Heat lamps (or equal) can be used to provide radiant heating of the container contents to increase container pressure for enhanced gas withdrawal capability. The heat source must not directly heat the container valve since the valve, connection, and relief device components can be damaged by excessive temperatures. This method is best utilized for indoor systems with no obstructions around the containers and provides gradual heating of the container contents. The system may not be feasible for containers located outdoors or in congested areas.

7. **Temperature-Controlled Jacket:** This method encloses the container in a removable, temperature-controlled jacket that contains a "closed-loop," recirculated heat transfer fluid connected to a separate electric heater unit. This design separates the heating element from the container and also allows for heating or cooling the containers, depending on the process pressure requirements. The electric heater should have a heat output rated for the maximum product withdrawal rate requirements, without excessive overcapacity. This design is widely used for multiple container systems where there is sufficient space to locate the heating unit adjacent to the containers.

8. **Electrically Heated Blanket:** The container can be encased in a removable blanket that contains electrically heated resistance elements operated by a temperature controller. Blankets should have an integral covering permanently attached to their inner surface to prevent direct contact of the heating elements with the container. The power input to the blanket should be limited, based on maximum withdrawal rate requirements to restrict worst-case heat input to the container during temperature controller runaway.

Liquid-Phase Withdrawal

Just as in vapor-phase removal, the first step in liquid-phase removal is to orient the package to gain access to the liquid phase. The liquid is pushed from the cylinder by the vapor pressure of the product. As the liquid is removed, it increases the volume of the vapor space of the cylinder. Some liquid will vaporize to fill the additional space, but usually not enough to excessively subcool the cylinder.

Sometimes the vapor pressure of the product is not high enough to push the liquid out at the required rate. When this is the case, a method called padding can be used to pressurize the liquid. This enhances the rate at which the liquid can be pushed from the cylinder. Padding is the addition of an inert gas to the vapor space in the cylinder to raise the cylinder pressure. When adding the inert gas to the cylinder, the cylinder pressure rating must never be exceeded. This pressure rating is part of the regulatory stamping on the cylinder. The maximum allowable working pressure (MAWP) of the cylinder is stamped into the cylinder. In the United States the stamping may read DOT3AA480, where 480 psig is the MAWP. In Europe the stamping may read FP25BAR, where 25 BAR is the MAWP. Furthermore, certain cylinder relief devices may vent the cylinder contents at pressures below the pressure rating of the cylinder. If you are not sure how to interpret the DOT stamping, or for guidance concerning padding a cylinder, contact your supplier.

How the inert gas pressure is added depends upon the cylinder. If the cylinder has dual valves, the inert gas can be added through the gas-phase valve. Be sure the inert gas source is regulated to not exceed the pressure rating of the cylinder and is protected from backflow minimally by a check valve. If the cylinder has one valve, the inert gas can be added while the cylinder valve is oriented to the vapor phase, then the inert gas source can be disconnected before orienting to the liquid phase. Again, care must be taken not to exceed the pressure rating of the cylinder. Some applications use air in place of the inert gas for padding. For some products, unloading with air padding may be prohibited by regulations. **NEVER USE AIR TO PAD FLAMMABLE PRODUCTS.** When air padding is allowed and appropriate, it is imperative that clean, oil-free, cooled, dry compressed air be introduced into the vapor space through its vapor valve to transfer the liquid. **NEVER** use a plant air system for air padding since vapors may backflow into the plant air system.

Extreme care must be taken when handling the liquid phase of any liquefied compressed gas. Unlike gas, the liquid does not compress. Therefore, the liquid must always have a space to expand, especially as it warms. In the cylinder this expansion space is provided by the vapor space or head space.

The filling limits/fill density for liquefied compressed gases were described earlier. These limits were set to prevent the cylinder from becoming liquid full at normal storage and use temperatures. If a vessel or system becomes liquid full, any increase in temperature would cause the liquid to try to expand with no space for the expansion. The liquid's incompressibility would result in a rapid increase of hydrostatic pressure. These pressures can build very rapidly and can quickly cause overpressurization of the equipment. Overpressurization of a system takes place when its pressure rating is exceeded. This can result in a rupture of the system. Systems using liquefied gases as liquids should be adequately protected by pressure relief devices, especially where there is a chance to trap liquid between valves or in other components that can be isolated.

Important Considerations

1. **NEVER** allow any part of a liquefied gas container to be exposed to temperatures greater than 125°F (51°C).
2. **NEVER** fill any cylinders without the owner's written consent.
3. **NEVER** heat an aluminum cylinder with electrical resistance heaters.
4. **ALWAYS** refer to the Material Safety Data Sheet for specific chemical properties.

Manufacturers of Systems to Enhance Withdrawal Rates

Consult the *Thomas Register* to locate vendors of cylinder heating systems or vaporizers. Or contact the Air Products Gases and Equipment Technical Information Center at +1-800-752-1597.

AIR PRODUCTS

Emergency Response System

- Call: +1-800-523-9374 (Continental U.S. and Puerto Rico)
- Call: +1-610-481-7711 (other locations)
- 24 hours a day, 7 days a week
- For assistance involving Air Products and Chemicals, Inc. products

Product Safety Information

- For MSDS www.airproducts.com/msds/search.asp
- For Safetygrams www.airproducts.com/Responsibility/EHS/ProductSafety/ProductSafetyInformation/Safetygrams.htm
- For Product Safety Information www.airproducts.com/Responsibility/EHS/ProductSafety/ProductSafetyInformation/

Technical Information Center

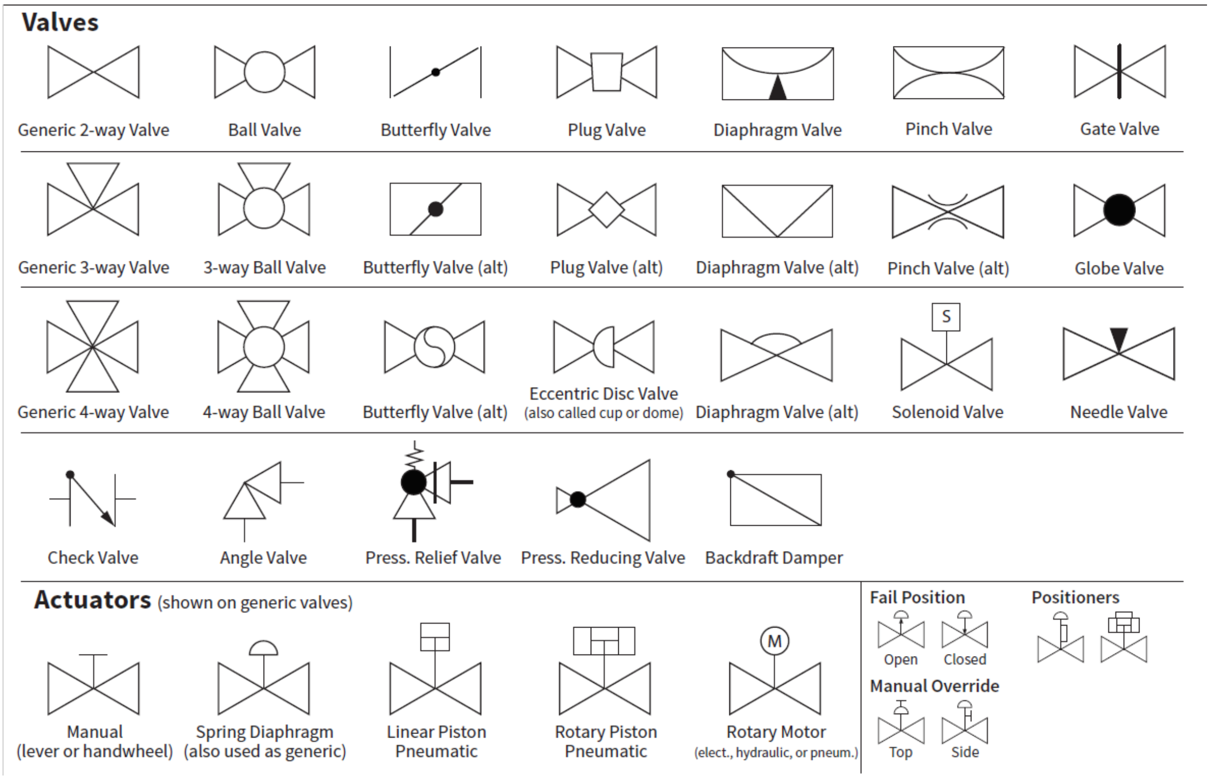
- Call: +1-800-752-1597 (U.S.)
- Call: +1-610-481-8565 (other locations)
- Fax: +1-610-481-8690
- E-mail: gasinfo@apci.com
- Monday–Friday, 8:00 a.m.–5:00 p.m. EST

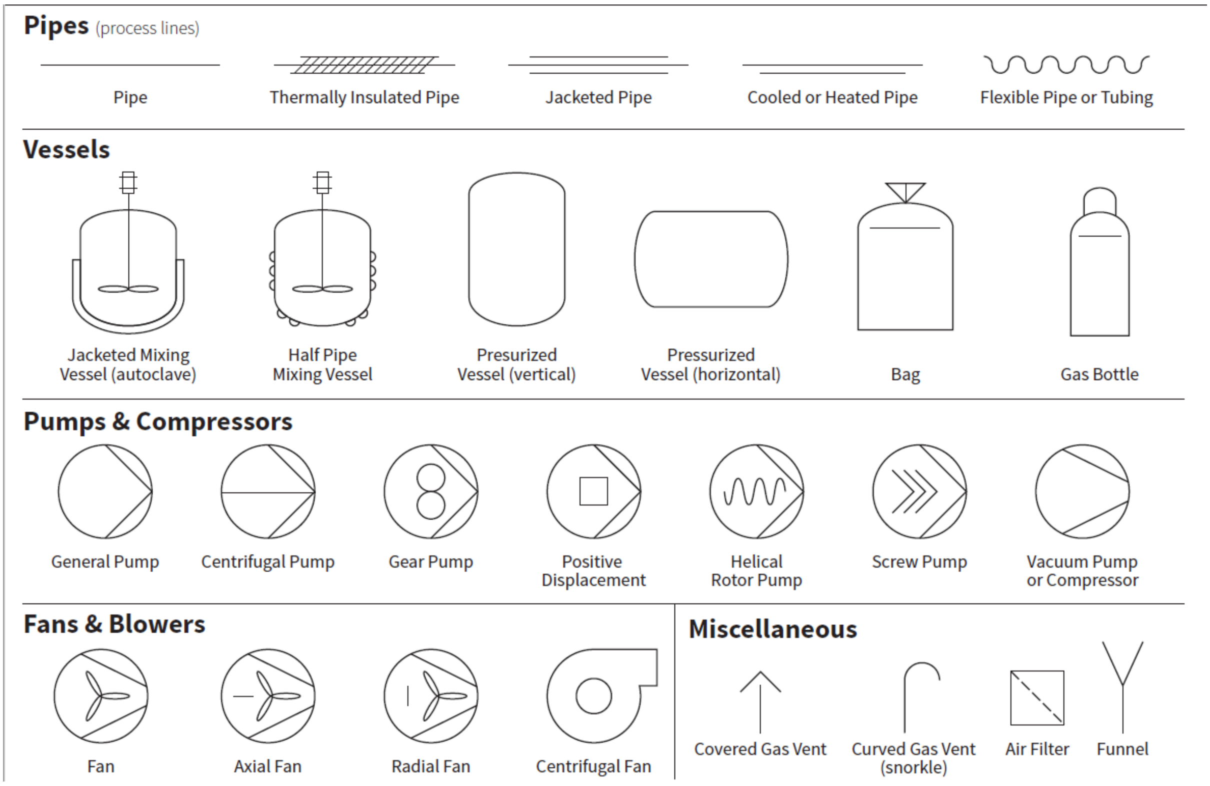
Information Sources

- Compressed Gas Association (CGA) www.cganet.com
- European Industrial Gases Association (EIGA) www.eiga.org
- Japanese Industrial Gases Association (JIGA) www.jiga.gr.jp/english
- American Chemistry Council www.americanchemistry.com

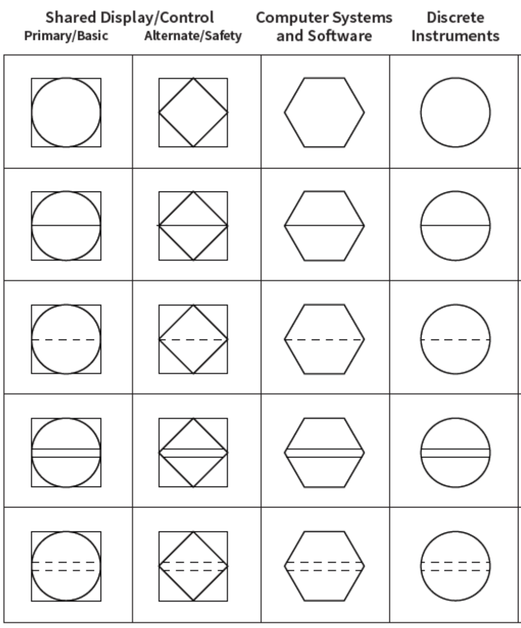
Appendix 9 - Piping and Instrumentation Diagram (P&ID) Symbols

Below is a description of the P&ID symbols based on the ANSI/ISA-5.1-2009 Instrumentation Symbols and Identification standard. Researchers are encouraged to use these symbols to help reduce confusion and create commonality throughout KAUST.





Instrumentation Bubbles



- Located in the Field
- Not Panel, Cabinet, or Console Mounted
- Visible at Field Location
- Normally Operator Accessible

- Located on Front of Main Control Panel
- Visible on Front of Panel or Video Display
- Normally Operator Accessible at Panel

- Located Behind Main Control Panel
- Located in Cabinet Behind Panel
- Not Visible on Control Panel or Video Display
- Not Normally Operator Accessible

- Located on Secondary Control Panel
- Visible on Front of Panel or Video Display
- Normally Operator Accessible

- Located Behind Secondary or Local Control Panel
- Located in Field Cabinet
- Not Visible on Control Panel od Video Display
- Not Normally Operator Accessible

Tag Numbers

Inside these bubbles there will be letters that identify the function of the instrument on top. There are also numbers on bottom that identify the process loop. Together these letters and numbers make up the **Tag Number** of the component.

Common Identifying Letters

1st letter (property being measured)
F = flow rate **P** = pressure
T = temperature **L** = level

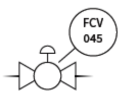
2nd letter (modifier)
D = differential **F** = ratio
simply omit if no modifiers apply

3rd letter (passive/readout function)
A = alarm **R** = record
I = indicator **G** = gauge

4th letter (active/output function)
C = controller **T** = transmit
S = switch **V** = valve

5th letter (function modifier)
H = high **L** = low
O = open **C** = closed
simply omit if no modifiers apply

Use these bubbles to represent instruments and to label final control elements like valves as shown here.



The information in this document is based on the standard: **ANSI/ISA-5.1-2009 Instrumentation Symbols and Identification.**
The complete standard is available at: **https://www.isa.org/store/products/product-detail/?productId=116630**