

Life cycle of medical oxygen from production to consumption

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ABSTRACT

Oxygen is used extensively in illnesses involving respiratory system. In emergencies such as the one created by the flare of Covid-19, oxygen consumption has increased tremendously. This article aims to improve our understanding about the medical oxygen, its production (air separation unit, pressure swing adsorption, oxygen concentrators), the supply chain, storage methods, and the final delivery system to the patient. This article also provides a comprehensive review on the additions in the medical infrastructure during the time of oxygen crisis in India along with the introduction of certain novel approaches towards oxygen production and conservation. We aim to minimize the panic among our readers by giving them an insight about the course behind the oxygen supply in that oxygen mask.

Keywords: Covid-19, cryogenic air separator unit, cylinders, medical oxygen, oxygen, PSA (Pressure Swing adsorption)

Introduction

Oxygen is the most common element and is vital for continuance of any life form on Earth. In the plight of Covid-19 pandemic, oxygen becomes the critical consumable resource. The production of oxygen and its sudden high demand are important factors responsible for resource depletion. However, lack of transportation and storage facilities of the resource (oxygen) is as critically an important factor as the other obvious ones. The purpose of this article is to discuss the logistics starting from commercial oxygen production to its final delivery to the patient, acknowledging the rise in the infrastructure and to understand the current state of oxygen demand and supply in India.

Oxygen- Its importance to human life form

The human body is dependent on oxygen for its survival. Every tissue and organ of the body requires oxygen for its effective

functionality. For example, human brain requires 20% oxygen at rest. Every time we take a breath, the oxygen, from the air, enters into our lungs and through the vasculature in the alveoli, enters the blood stream. In the blood, red blood cells bind oxygen and transport it to the tissues. Oxygen in the tissues and organs assist in energy production through multiple pathways directly or indirectly. In a situation when these end organs do not receive enough oxygen, they develop a condition called hypoxia that causes suboptimal cellular function. In toto, oxygen is the one crucial element for human health. About 95–100% oxygen saturation is considered the normal blood oxygen level.^[1]

Oxygen production

Oxygen is one of the main gases present in the air. Grossly, environmental air comprises 78% nitrogen, 21% oxygen and 1% of other gases. Oxygen is produced in bulk through air separation process in an Air Separation Unit (ASU). Up till now, the primary large-scale consumers of oxygen produced from air separator units through cryogenic distillation process were steel, petroleum and chemical industries until the rise of Covid-19, when sudden oxygen demand increased in the medical use. This

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makes it important for us to understand the process of extraction of oxygen from air and its usability for medical purposes. Oxygen produced through cryogenic process in an ASU accounts for up to 99% purity, thereby making it suitable for medical use. This technique has been used over the past 75 years and is designed for high volume production of oxygen (approximately 5000 tons per day).

Cryogenic Air Separation Unit^[2]

In this process, air is first, pre-treated to remove all gross impurities like heavy hydrocarbons, carbon dioxide, etc., Then, the pre-treated air is passed through a multi-stage compressor to reach the cooling plant, which condenses and removes water vapours. From here, the air passes through a molecular sieve absorber made of zeolite and silica gel-type absorbents, which trap the remaining carbon di oxide, water vapours and hydrocarbons. Now, the air enters the fractional distillation chambers that separate it into its three major components: nitrogen, oxygen and argon. As the process of distillation works on the basic principle of boiling a liquid to separate its components, a cryogenic section is required before distillation to convert the gaseous component to liquid form, and hence the name, cryogenic air separation unit. This process is possible because of the differences in the boiling points of each gas.

The air stream that is now partially liquid and partially gas enters the high-pressure fractionating chambers. As the air rises up, separation process commences. The oxygen starts to liquify at the bottom of the column, and nitrogen and argon rise up as vapours to the top of the column. The liquified oxygen is collected from the bottom, later on cooled and fed to the low-pressure column thereby further distilling oxygen from the remaining argon and nitrogen. This liquified oxygen is now of 99.5% purity. Purity of oxygen is based on the presence of nitrogen or argon. By adding another step of distillation and increasing the temperature to 186°C, argon is vapourised leaving behind liquid oxygen of 99.8% purity. [Figure 1] shows a simplified diagrammatic representation of a Linde Double Column System ASU. The liquified oxygen from here can be

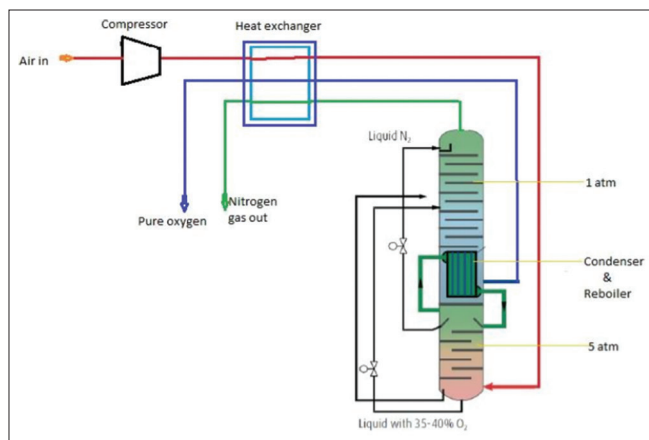


Figure 1: Diagrammatic representation of the separation process in a Cryogenic Air Separation Unit

stored as it is or can be warmed to an ambient room temperature and stored in the gaseous form.

Oxygen concentrators

Oxygen generator is a device that concentrates oxygen from the ambient air by removing nitrogen through a sieve. Different devices use different types of sieve. While some use Ion Transport membrane, others use zeolite. With this process, 90–95% purity of oxygen is generated. The process includes using room air, compressing it, removing nitrogen through a sieve and finally delivering oxygen. Drawbacks in its use are primarily because of malfunctioning of sieve, or presence of water vapours compromising nitrogen absorption. Smaller oxygen concentrator units can be used as a portable device, although they are not the primary choice of oxygen delivery system in moribund patients, but may be used in patients requiring long-term oxygen therapy at home^[3] or in times of crisis. This device produces 0.5–15 litres of oxygen per minute depending on low-flow or high-flow oxygen concentrators.^[4,5] The major benefit of this device is that it is independent of the commercial oxygen producer’s supply. All one needs for this device to work is a continuous electricity supply and room air.

Commercially, oxygen concentrators are used for large scale oxygen production by using various technologies for oxygen production namely Pressure Swing Adsorption (PSA) or Membrane Technology. While PSA technology uses zeolite, membrane technology uses Ion Transport Membrane to selectively absorb nitrogen and release oxygen-rich gas. With the advancement in the field of oxygen generation, these technologies can release oxygen with 95–99% purity.^[6]

Pressure Swing Adsorption (PSA) plant^[7]

PSA works on the principle that when air is passed under high pressure through a vessel containing an adsorbent bed of zeolite (hydrated aluminium silicates of the alkaline earth metals) that attracts nitrogen more strongly than oxygen, part or all of the nitrogen will get absorbed by the adsorbent bed and the gas exiting the vessel will be richer in oxygen, as depicted in [Figure 2]. Although PSA plants do not produce as high volumes of oxygen as a cryogenic plant, knowledge about its functioning is important as this type of plants can be assembled around a

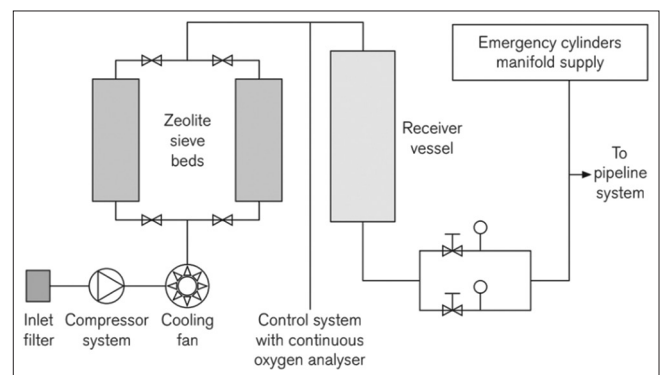


Figure 2: Schematic representation of In-Hospital PSA Plant

hospital facility to cater to the urgent high demands of oxygen supply in that hospital. PSA plants are sized according to output capacity, in cubic metres per hour (m³/hr) of oxygen, where 1 m³ = 1000 litres of oxygen. PSA plants need a constant power supply for uninterrupted production of oxygen.

Vacuum Pressure Swing Adsorption (VPSA) plant

VPSA is a cost-effective method of on-site oxygen production. Until now, this technology was extensively used in steel, chemical or mining industry. In the current scenario, VPSA plants can be built in remote areas to cope up with the oxygen demand—supply imbalance. In a VPSA plant, a cyclic swing between overpressure and vacuum occurs (Vacuum Pressure Swing Adsorption). To reduce energy consumption, the pressure is equalised between the production (overpressure) and regeneration (vacuum) steps. When the compressed air passes through the adsorbent bed, moisture and carbon dioxide are captured at the entrance and nitrogen gets adsorbed continuously throughout the column leaving behind oxygen-rich air, with then passes through the buffer for final collection. Vacuum pump is used to desorb the adsorbed nitrogen.

Deployable Oxygen Concentration System (DOCS)^[8]

This is another method of portable oxygen production using molecular sieve technology. This system is primarily used in defence and aerospace industries especially in disaster relief situation. DOCS operate by adsorbing water and nitrogen from filtered air. Depending on the unit size, the resulting gas has increased oxygen at flow rates from 30 to 500 litres per minute. This device is prepared to deliver oxygen up to 93% (90–96%). Although the Safe Medical Device Act statement states that the oxygen supplied by this device is supplemental and not to be considered life-supporting or life sustaining, and that the failure of the device would not have any serious consequences to the user’s health.

Comparison among various oxygen production technologies^[9]

Over all, cryogenic production of oxygen is a cheaper mode of oxygen production for the purest form of oxygen in larger volumes. However, the construction of such a mass-scale plant takes a lot of planning and time. In times of emergency, PSA plant is a more constructible option, although it is costlier for larger volumes of pure oxygen. [Table 1] summarises the comparison of various oxygen production technologies.^[9]

Medical oxygen and Industrial oxygen- What’s the difference?

Medical Oxygen (Medical grade IP 2010) is one of the purest forms of oxygen (99.0–100% purity), certified to be used by

humans as a treatment or support against various illnesses. It is free from halogen, polymer and oxidising substance and moisture. It has a particulate count of carbon monoxide less than 5 parts per million (PPM) and not more than 300 PPM. It is expected to not cause damage to gas cylinders, pipe lines, anaesthesia machines or ventilators.^[10] However, World health organization (WHO) states that medical oxygen should be at least 82% pure, free from any contamination and generated by oil-free compressor.^[11]

Whereas, industrial oxygen is the oxygen required in the industries to support mechanical or chemical processes like combustion/oxidation. The method of production of medical oxygen is not any different from that of the industrial oxygen. However, industrial oxygen may have a comparatively higher percentage of impurities (mixture of other gases or particulate impurities), whereas medical oxygen is in its purest form (with negligible amount of impurities, mainly mixture of other gases).

Distribution, storage and supply of medical oxygen

Distribution

1. Primary plant is the primary production house of oxygen. The distribution of oxygen from the primary plant to the secondary plant occurs in different forms of oxygen (gaseous form or liquid form) based on the storage capacity of the secondary plant.
2. Secondary plants are usually reservoirs to the primary plant, which are closer to the terminal consumers. They have the capacity to store oxygen in liquid or gaseous form, although storage in liquid form is both cost and quantity effective. They either supply liquid oxygen (LOX) to the customers or vapourise LOX to form gaseous oxygen and then supply it to the consumers in gas cylinders.
3. Customers are local gas vendors, hospitals, etc., who take the supply in gaseous form or LOX form, depending upon their storage facility.

Storage

Oxygen is stored either as LOX or in gaseous form. Usually LOX is stored in large vacuum insulated, double-walled tanks made of austenitic steel on the inner wall and carbon steel on the outer wall with an anti-corrosive layer on the outside topped with environment friendly paint. The space between the two layers of steel has vacuum or insulating powder (perlite). The containers must be maintained in a way such that they keep natural evaporation rate to less than 1%. Liquid medical oxygen container capacity is approximately 990 litres–10,000 litres.^[10] Gaseous oxygen is stored in cylinders. Their body is

Table 1: Summary of the comparison of various oxygen production technologies^[9]

Comparison	Cryogenic	PSA	Membrane technology
Running Cost for purity <99%	Costlier	Cheaper	Cheaper
Running cost for purity >99%	Cheaper	Costlier	Cheaper
Volume production	High volumes	Low volumes	Low volumes
Purity ^[7]	99% and above	95-99%	45-99% (Matured plant to research and development phase)

made of either steel (heavier in weight, yet cheaper in cost) or aluminium (lighter in weight and costly compared to steel cylinders). Nowadays, composite cylinders are available that are much lighter but not cost effective in medical environment. In India, gas cylinders are Indian Standards Institute marked (IS mark) to IS 7285 (Part 2):2004, approved from Chief controller of explosives (CCOE), Nagpur.

Supply

Gaseous oxygen is liquified at a temperature of -183°C. So, when 1 litre of LOX is evaporated, it expands to 860 litres of gaseous oxygen.^[12] This is now compressed in smaller containers (cylinders) for transport to remote facilities. The commonly used cylinder categories with their size, pressure and capacity are listed in [Table 2]. The most commonly used sizes in portable variety are D and E.^[13] Larger size cylinders can be placed on the bedside and be directly attached to the patient or a centralised oxygen source can be built, called as a manifold, connected to a web of copper pipelines supplying oxygen throughout the hospital facility. [Figure 3] is a diagrammatic representation for the reservoir unit of LOX from the reservoir gets converted to gaseous form through vapourisation, which gets collected in oxygen cylinders in a manifold and through pipelines, this gaseous oxygen is supplied to the end point from where end users use oxygen delivery devices for the final use.

Oxygen delivery system

Oxygen delivery systems are categorised into low-flow and high-flow systems. Low-flow systems provide oxygen flow lower than the actual inspiratory flow (~30 L·min⁻¹), whereas high-flow oxygen delivery systems provide higher oxygen flows than the actual inspiratory flow. [Table 3] enlists the various oxygen delivery system used on a day-to-day basis in hospitals and ICU facilities.^[14] It also highlights the oxygen delivering capacity of each of the devices along with their percentage of Inspiratory oxygen fraction (FIO₂).

Crisis in India

India faced a serious crunch in medical oxygen during the second wave. This unforeseen crisis rose due to the abundance of patients

requiring oxygen in a very short span of time. Media made headlines like “hospitals gasp for oxygen on hour-to-hour basis” and narrated the horror stories of oxygen cylinders being shared to unavailability of oxygen supply on hospital beds. The major challenge was to find a way to move the oxygen from states with less necessity to states with increased necessity. The Central and the State governments handled the crisis by running special trains to supply liquid oxygen from one state to another. Hospitals were sanctioned permission to establish oxygen plants in their compounds. From 62,458 oxygen supported beds, 27,360 Intensive care units (ICU) beds and 13,158 ventilators in April 2020, medical infrastructure in India grew substantially with 1,57,344 oxygen supported beds, 36,008 ICU beds and 23,619 ventilators by 28th Jan 2021. This data was generated from the hospital facilities in the public sector by the ministry of health and family welfare of India.^[15]

India has had a daily production capacity of 7127 metric ton (MT) of oxygen per day. As of 12th April 2021, the medical oxygen consumption in India was 3842 MT, which is 54% of the daily production capacity.

WHO COVID-19 Essential Supply Forecast Tool (ESFT)

This formula is designed by the WHO, which enables the decision makers to estimate how much oxygen supply in litres per minute (l/min) is needed in a hospital facility.

Table 2: List of various types of cylinders available for medical use along with their size and capacity

Cylinder type	Size	Service Pressure (psi)	Cubic Feet	Litres
PORTABLE	B	2,015	5.8	164
	C	2,015	8.8	249
	D	2,015	14.7	416
	E	2,015	24	679
	M	2,015	110	3,113
FIXED	H	2,015	220	6,226
	K	2,015	266	7,528

Table 3: The various types of oxygen delivery systems, the amount of oxygen and the percentage of FIO₂ delivered by each^[15]

Type of oxygen delivery system	Amount of oxygen delivered (Litres per minute)	Inspiratory oxygen fraction (FIO ₂ %)
LOW FLOW SYSTEMS:		
Nasal Cannula	1-6	24-40%
Simple face mask	5-10	35-55%
Non-breather mask *	10-15	Variable
Transtracheal Oxygen catheter	0.5-4	-
HIGH FLOW SYSTEMS		
Artificial manual rebreather mask	-	100%
Venturi Mask	2-15	24-50%
High flow nasal cannula (HFNC)	UP TO 60	Up to 100%

*Non-Breathable masks uses a reservoir bad (~1000 ml) to deliver high concentration of oxygen. FIO₂ depends on the patient's breathing pattern

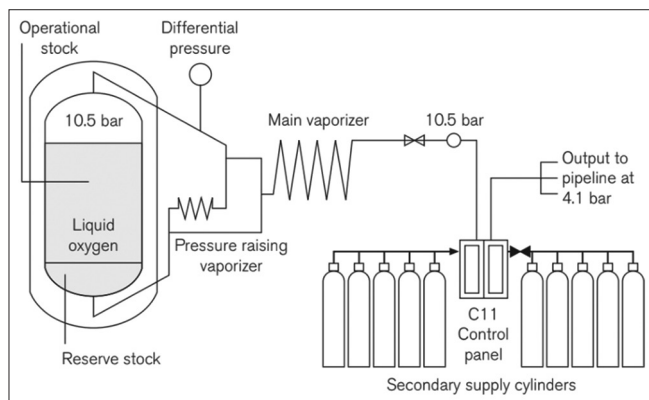


Figure 3: In-hospital construction of Storage and supply of LOX system

Formula:

Total oxygen in l/min = (Number (No.) of beds except ICU and OT \times 0.75 l/min) + (No. of beds in OT \times 7 l/min) + (No. of beds in ICU \times 30 l/min).

Example:

In a 100-bedded hospital with 25% ICU beds (n = 25), and five Operation theatres (n = 5), we can calculate the oxygen requirement by using the formula:

Total Oxygen (l/min) = [(100-(25 + 5)) \times 0.75] + (5 \times 7) + (25 \times 30) = 841.25 l/min.

This calculation remains fairly valid for all oxygen delivery systems except when HFNC is used, which delivers oxygen up to 60 l/min, in which case a higher oxygen supply will be needed. Also, in COVID care units, the flow rate varies. In adults suffering from Covid-19, oxygen requirement in severe condition (oxygen requirement needed, ICU support not required) is at 10 l/min flow rate and in critical condition (requiring ICU support) is at 30 l/min. Therefore, the total oxygen flow rate for the hospital or that particular ward or floor changes. To understand the gravity of the consumption of oxygen in severely infected COVID patients requiring oxygen is that a regular E size oxygen gas cylinder would be consumed in approximately 1.5 hours if flow rate of 10 l/min has to be maintained.

Oxygen conservation practices

Clearly, the way to reduce this surplus demand of oxygen is by reducing the number of persons infected by COVID-19 for which the government has placed advisories all over the country through every possible mode of communication. It is the duty of the people of the country to halt the spread of the infection and stop worsening the condition. With this being the pivotal point, certain measures can be taken by the administrators of the hospital facilities or oxygen plants or government-appointed officials to have a regular check on the leakage in the oxygen plants, storage facilities, pipelines, or final delivery systems. Within the hospital, the staff should regularly check for unused oxygen masks with open oxygen circuit especially at times when a patient is being shifted from that bed. Portable oxygen concentrators may be encouraged for people who require oxygen support but can monitor their condition at home. Patients should be prioritised for the oxygen requirement. Demand oxygen delivery system should be used where indicated as these works on the principle of delivering oxygen as per the demand generated during inspiration and interrupts the supply during exhalation when oxygen is technically wasted.^[16] Reservoir nasal cannulas reserve oxygen during exhalation thereby making it an oxygen conserving device. A newer device developed by Defense Research and Development Organization (DRDO) is an oxygen delivery system based on SPO₂ levels in a patient thereby making it a highly efficient oxygen conserving unit. It delivers oxygen in 2/5/7/10 l/min and can be used in patients with moderate

COVID infection at home.^[17] Finally, Oxygen saturation should be targeted at 92% rather than 95%.

Improving oxygen perfusion

Oxygen perfusion can be improved most effectively by improving the oxygen carrying capacity of blood. A rise of haemoglobin from 8 gm/dl to 10 g/dl will increase its oxygen carrying capacity by 25%. Studies suggest that massage increases the muscle blood flow and therefore, oxygenation, in people with lower back pain who drive frequently.^[18] However, the benefits of massage therapy are short term and disappears when therapy ends.^[19] The positive effects of Coenzyme Q 10 in increasing blood flow and in turn improving oxygen perfusion have been studied in patients with fibromyalgia, who suffer from musculoskeletal oxygenation alteration.^[20] Extracts from the leaves of Ginkgo Biloba have known to improve oxygen perfusion. In a human study, Ginkgo biloba combined with hyperbaric oxygen either resolved or improved tinnitus in approximately 80% of the patients (P = 0.046).^[21] Juice from Beetroot (Beta vulgaris) is another substance that has shown beneficial effects with its ability to increase levels of nitric oxide, which subsequently improves blood flow.^[22]

Conclusions

Whatever emergency contingency a decision-making committee decides to adopt, one thing is clear—when a disaster happens people create panic that creates an exaggerated picture of the actual scenario. In the hour of emergency, what one does not possess cannot be made available quickly. Planning for oxygen reserves and attempting to anticipate oxygen requirements during such emergencies is not an easy task. There is a limit to the amount of oxygen cylinders that can be stockpiled in case of a such an outbreak. Rather than blaming one another for the crisis, we must join hands and work towards the common goal—rebuild a safe, COVID-free nation.

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Conflicts of interest

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