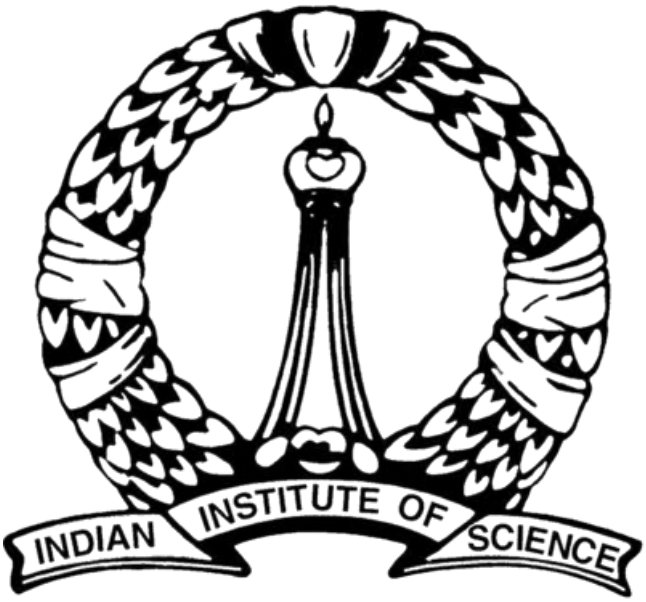
S^3

Medical Oxygen Generator



Design Document for 3 Nm^3/h Medical Oxygen Generation System

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I n s e r v i c e o f h u m a n i t y

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As part of our open-source endeavour, we are making available the design documentation for a 3 Nm^3/h medical oxygen prototype system, designated S^3 (S-Cube). The current documentation is self-sufficient to build the said prototype and any additional information as and when available will be updated on the web page. A fully functional prototype has been setup at out laboratory based on the design document. It may however be noted that the system has not been tested or approved for use in any application, clinical or otherwise. This document was prepared as an account of work to support the cause of oxygen availability shortage, which was noticed during the 2020 pandemic. Neither the Indian Institute of Science nor any agency thereof, nor any of their employees, makes any warranty, express or implied or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, products, or process disclosed or represents that is used would not infringe privately owned rights. Reference herein to specific commercial product, process, or service by trade name, trademark, manufacturer or otherwise, does not necessarily constitute or imply its endorsement, recommendation or favouring by any agency thereof.

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Preamble

Patients with compromised lung conditions require supplemental Oxygen due to reduced ability of the lungs to absorb Oxygen. The supplemental Oxygen, known more commonly as medical Oxygen has a concentration of 93 ± 3 vol% Oxygen. Atmospheric air has approximately 21% Oxygen and 79% Nitrogen with other trace gases and medical Oxygen can be generated by separating Nitrogen from air to get the prescribed purity of Oxygen.

Currently, most of the medical Oxygen in India is met through centralized largescale systems adopting cryogenic technology. Medical Oxygen is then transported to hospitals / end use locations in high pressure bottles. Some large medical facilities host adsorption technique based in house medical Oxygen generation facilities. In pandemic like situation when the requirement for medical Oxygen spikes from multiple locations, the transport logistics introduces substantial delays in reaching the medical Oxygen to the needy. Availability of decentralized medical Oxygen generation facilities ensures immediate and on demand availability of medical Oxygen.

As a response to the need for such decentralized medical Oxygen generation systems, the thermo-chemical conversion group at Combustion Gasification and Propulsion Laboratory, Indian Institute of Science, Bangalore has evolved the design for a low-pressure swing adsorption-based system for the generation of Medical Oxygen. Based on the design, a 3 Nm^3/h medical Oxygen generation system has also been assembled and tested at the institute. For the benefit of the society, the complete design of the 3 Nm^3/h system is being released under Open-Source License through this document. It is hoped that through localized initiatives, many such systems can be built and installed across the country, particularly in the rural hinterlands. Indian Institute of Science will be pleased to extend all technical help towards realization of such systems.

Together we can and together we will

Medical Oxygen
Quality specifications as per Indian regulations

The Indian Pharmacopeia 2018 laid down the following monograph pertaining to the quality of medical grade oxygen:

- Oxygen purity: 93 ± 3 vol%
- CO: < 5 ppm
- CO_2: < 300 ppm
- Water vapour: < 67 ppm
- SO_2: 0 ppm
- NO_x: 0 ppm

Other requirements:

- Each module should be able to produce medical grade oxygen with dew point temperature of minus 73 deg C. The product oxygen should be supplied through oxygen outlet at minimum pressure of 4.2 – 6 bar-g at all times of operations of the generator.
- The oxygen generator should have all necessary certifications and approvals like US FDA, CE tag, ISO 13485:2016, ISO 10083/ENISO7396-1/EN737-3 European Standards and medical device directives 93/42/EEC etc.
- Automatic shut off valve should be installed to control the medical oxygen purity and pressure.
- The plant should have silencer to reduce air discharge noise to less than 65dBA.

Medical Oxygen generation principle
Pressure Swing Adsorption

The medical oxygen generation plant – S^3 works on the basis of Pressure Swing Adsorption (PSA) principle. Air from the ambient is drawn through a filter using a compressor operating at about 7 bar-g pressure. At the exit of the compressor, a refrigerated air dryer removes any moisture in the gas and also condenses any undesirable compounds. If the temperature of the compressed dried air is above 35 deg C, the air needs to be cooled using an appropriate heat exchanger to maintain the temperature below 35 deg C. The ideal temperature for the operation of adsorbers is 25 deg C. The dry cool air is further conditioned in the hybrid bed containing activated carbon and activated alumina. This bed ensures removal of any trace contaminants present in the gas, specifically if oil lubricated compressor is employed for compression. The clean cool and dry gas is now passed through particulate matter filters (PM1 and PM0.01) to remove any carry over particulate matter. The air exiting the particulate matter filter is finally sent though a pair of adsorber columns switching cyclically and undergoing a well-defined process to generate medical grade Oxygen at the rate of 3 Nm^3/h. The generated medical grade Oxygen is discharged into the oxygen surge vessel where the Oxygen is stored at ≥ 4.2 bar-g as per the requirement of Indian pharmacopeia. Oxygen is discharged from the surge vessel through a sterile bacterial filter to meet the specifications. The system operation requires a connected load of about 4.5 kWe and draws in air at the rate of about 40 Nm^3/h to generate 3 Nm^3/h of medical grade Oxygen.

Process description

The oxygen generator works based on the principle of pressure swing adsorption. The overall system basically contains two adsorbers filled with alumina (for moisture adsorption) and main adsorbent (for nitrogen adsorption) to generate medical grade oxygen. The generated oxygen is stored in a surge vessel and fulfils the requirements prescribed by Indian Pharmacopeia. The continuous process involves five cyclic steps as described below.

Step – 1: Feed Pressurization: In this step, the feed air is sent into one of the adsorption columns/adsorbers to raise its pressure to the desired level. During this step, the output valve is kept in closed position and only air is allowed to enter into the adsorber column.

Step – 2: Adsorption: At the end of feed pressurization, the outlet valve of the adsorber column is opened while maintaining the air inlet flow. In this step, air continues to enter the adsorber column and simultaneously Oxygen continues to exit the column while maintaining the pressure of the column. This is the principal step where gas separation takes place, and the oxygen of desired purity is made available at the outlet. During the separation of Oxygen from air, the bed material starts accumulating Nitrogen and over a certain period, the bed material will not be able to hold all the Nitrogen. Just before this stage is reached, the adsorption process is stopped by closing the Oxygen discharge valve.

Step – 3: Desorption: On completion of the adsorption step, the Nitrogen accumulated in the bed needs to be flushed out. This is done by connecting the column to the atmosphere while keeping the air inlet and the Oxygen outlet closed. On connecting the column to the atmosphere, all the adsorbed Nitrogen is flushed to the ambient completing the desorption step.

Step – 4: Purging: In the desorption step while most of the Nitrogen from the column is flushed, some residual Nitrogen remaining in the column voids and adsorbed to the surface of the bed material needs to be removed. This is done by sending pure Oxygen being generated from the other column undergoing adsorption step.

Step – 5: Pressure Equalization: During this step, both the adsorbers are connected from the top to each other to equalize pressure. This is performed to increase the oxygen recovery of the system.

The timing of various steps and the status of solenoid valves during these steps can be found in the control logic and valve timing description section.

Specifications, operating conditions, and recommendations

The technical specifications of various components as depicted in the process flow diagram are mentioned in table 1. The battery limits pertaining to various operating conditions are shown in table 2. Table 3 provides recommendations pertaining to some of the components.

Table 1: Technical specifications of various components

Serial no.	Component	Technical Specifications	Numbers required	Remarks
1	Compressor	Free air delivery (Nm^3/h): 40	1 (2 if one is required for standby purpose)	○ Check recommendations section for information on compressor selection.
		Delivery pressure (bar-g): 7		
		Operating inlet temperature range (deg C): minus 10 to 55		
		Inlet relative humidity - RH (%): ≤ 95		
		Maximum outlet temperature (deg C) – must be ensured by using an after-cooler: 45		
2	Refrigerated air dryer	Inlet flow rate (Nm^3/h): 40	1	○ Choose slightly over-sized capacity for the dryer to manage any process adversaries.
		Inlet pressure (bar-g): 7		
		Inlet air temperature (deg C): 45		
		Maximum ambient temperature (deg C): 50		
		Maximum dew point temperature at inlet (deg C): 3		
3	Air filters	PM – 5	1	○ PM – 5/1/0.01 (size in µm) and hybrid bed will be placed at the upstream of adsorbers. However, sterile bacterial filter is required to be placed at the outlet of surge vessel. ○ See attached drawing of the hybrid bed for its construction. Note that the carbon and alumina requirement and the dimensions of the hybrid bed are calculated considering ambient temperature (40 deg C), RH (100%) and moisture adsorption capacity of activated alumina (15% w/w).
		PM – 1	1	
		PM – 0.01	1 (2 if one is required for standby purpose)	
		Hybrid bed	1	
		Sterile bacterial filter	1	
4	Pressure gauge	Dial size: 4”	4	○ Pressure gauges filled with glycerine are better.
		Case: SS		
		Range: 0 – 10 bar-g		

		Resolution: 0.2 bar-g (min,)		○ For more accuracy and automatic operation (specially incorporating safety alarm for oxygen storage vessel pressure), transducers are preferred. ○ Pressure gauges or transducers need to be properly calibrated.
5	Safety valve / pressure relief valve	Size: 1/2” Operating pressure: 9 bar-g (hybrid bed); 6 bar-g (surge vessel) Body: SS	2	○ Pressure relief valves are to be placed on the hybrid bed and surge vessel. The valves will open in accordance with the pre-set operating pressure.
6	Flow meter	*Feed line:* Flow range: 5 – 60 Nm3/h Resolution: 0.5 Nm3/h Accuracy: +/- 1% Inlet pressure: 9 bar-g (max.) *Output line:* Flow range: 0.1 – 5 Nm3/h Resolution: 0.1 Nm3/h Accuracy: +/- 1% Inlet pressure: 6 bar-g (max.)	2	○ Flow meters are required to be placed at the input and output line of the unit. They can be of mechanical or digital type.
7	Temperature sensor with indicator	Type: T or K Temp range: 0 to 100 deg C Rod diameter: 3 mm Rod length: 150 mm (or as required) Cable length: 5 m (or as required)	1	○ Temperature sensor will sense the temperature of the feed gas at the inlet of the adsorbers. Note that this temperature ideally shall stay around 25 ^{o}C. Any kind of digital indicator can be used. In the absence of thermocouple and digital indicator, analog temperature gauge can also be employed.
8	Solenoid valves	Type: Pneumatically actuated (external air) solenoid valves Operating voltage: 24 V DC Power consumption: ~ 11 W Media: Air Body material: SS Seal and O ring: Viton or PTFE Media temperature: 0 – 100 ^{o}C Media pressure: 0 – 8 bar-g End connection: Screwed	4 (1/2”) 5 (2”)	○ The solenoid valves must have high reliability and shall remain unaffected by voltage surges. Note that all these valves shall be direction free and shall just On/off as per the set cycle sequence through the solenoid and external air.
9	Activated carbon – to be used in	Size: 4*8 mesh Type: granular Iodine value: 800 – 1100 mg/g	30 kg	○ Activated carbon will be loaded as a bottom layer in the hybrid bed to remove any oil contaminants

	the hybrid bed	Base: coconut (preferred) or coal		present in the feed gas (if oil compressor is used). ○ See attached drawing of hybrid bed for its construction. ○ Bed tapping/vibration is suggested during filling of the bed to ensure no empty spaces.
10	Activated alumina – to be used in the hybrid bed and adsorbers	Brand name: Siliporite H_2O beads Manufacturer: Arkema, France Type: Activated alumina Size: 4*10 mesh (2.0 – 5.0 mm) Crush strength: ~ 190 N Bulk density: 720 – 880 kg/m3 Water adsorption capacity: 6% (at 10% RH); 14% (at 50% RH); 21% (at 60% RH)	70 kg (in hybrid bed) 38 kg (to be divided equally in both the adsorbers)	○ 70 kg of activated alumina will be used in the hybrid bed (as its top layer) to take care of any moisture existing in the feed gas at the upstream of adsorbers. Other 19 kg will be used as a bottom layer in each of the adsorbers. The alumina should have good water adsorption capacity and strong mechanical strength. This will safeguard the main zeolites from moisture, thus increasing the efficacy and life of the plant. As per our estimates, the given quantity of alumina in the hybrid bed shall be sufficient for one day operation (without ambient desorption) [assumptions: RH: 100%, Ambient temperature: 40 deg C, refrigerated dryer moisture removal efficiency: 90%]. However, hybrid bed will get desorbed off moisture via. ambient desorption happening for 5 seconds every 5 cycles ensuring continuous operation. ○ Bed tapping/vibration is suggested during filling of the bed to ensure no empty spaces.
11	Molecular sieve – zeolite	Brand name: Airsiev OX19 Manufacturer: Arkema, France Type: Synthetic zeolite type LSX lithium N_2 adsorption capacity (25 ^oC, 1 atm): 18 – 20 Nl/kg Selectivity N_2/O_2 (25 ^oC, 1 atm): 6.0 Crush strength: 28 – 30 N Particle size: 1.2 – 2.0 mm Bulk density: 600 – 660 kg/m^3	120 kg (to be divided equally in both the adsorbers)	○ The zeolites shall have high nitrogen adsorption capacity, very high selectivity in favour of Nitrogen and strong mechanical strength. ○ Lithium doped zeolites are preferred. ○ Bed tapping/vibration is suggested during filling of the bed to ensure no empty spaces.
12	Oxygen Analyser	Measurement range: 21-96% O_2 (lower or higher acceptable) Resolution: 0.1% across all measurements Accuracy: +/- 3%	1	○ The oxygen sensor can be of Zirconium/Ultrasonic/Galvanic type ○ Sensor should be rated for use with PSA based oxygen production.

		Operating temperature: minus 10 to 50 deg C Relative humidity: 15 – 95% (atmosphere) Historical logging of all alarms Real time trending curve of oxygen purity		○ Required to be calibrated depending upon the type of sensor. ○ The sensor shall have minimum response time and fitted with alarms. Also, the data from the sensor shall continuously be acquired and can be transferred into a USB drive in excel/ASCII format.
13	PSA vessels / Adsorbers	See attached drawing (No: 2) for the construction of PSA vessel / adsorber. The bottom layer is of activated alumina and the top layer contains the main adsorbent. The empty space above column neck can be covered by using ceramic balls (5 mm) or sponge (rectangular with approx. dimensions: 50 * 40 * 25 mm)	2	○ The PSA Vessels (2) shall be designed and manufactured as per ASME VIII code or Directive 97/23/EC or equivalent for pressure vessels.
14	Oxygen storage vessel	See attached drawing (No: 3) for the construction of oxygen storage vessel.	1	○ The oxygen storage vessel is designed in such a way that it should provide stored medical grade oxygen for about 30 minutes (till pressure in the tank becomes 2 bar-g), in case of power failure. ○ The vessel shall be designed and manufactured as per ASME Section VIII Div 1 Or Equivalent. ○ A corrosion allowance of 1.6 mm shall be considered. ○ The receiver vessel shall be provided with a pressure gauge, safety pressure release valve and auto drain valve, and has a vertical floor mounted design
15	Ball valve	Size: 1/2” and 1” Body: SS Media: Air Media pressure: 0 – 9 bar-g Media temperature: 0 – 100 ^{o}C	3 (1/2”) and 2 (1”)	○ The ball valves will be fitted in the vent lines of hybrid bed, adsorbers, and surge vessel. In addition, one ball valve is required in the P.E. line before SV-4.
16	Needle valve	Size: 1/2” and 1” Body: SS Media: Air Media pressure: 0 – 9 bar-g Media temperature: 0 – 100 ^{o}C	1 (1/2”)	○ The needle valve is required to be placed at the outlet of surge vessel to fine control the flow of product oxygen.

17	Control and acquisition	Timing control of 9 (SV-1 to SV-9) solenoid valves (24 V DC) Provision to change the timing of any solenoid valve (min assigned value: 0, max. assigned value: 100 s) Panel shall be fitted with safety ON/OFF switch Shall be properly earthed and installed with all safety provisions	1	○ The control and acquisition unit must be a PLC or microprocessor-controlled completely automatic unit with all safety features in place. ○ The panel shall have a diagnostic tool to pin-point exact malfunctioned solenoid valves for fast service. ○ The oxygen concentrator system shall have PSA sieve beds with touch screen for display of size not less than 5" for constant quality control by measuring oxygen purity, outlet pressure, instruction manual, curves of oxygen pressure, basic setting, alarm facility for process a cycle failure, low oxygen pressure, maintenance alerts, process overview with valve operation and an analogue valves
18	Piping	Internal diameter: 2" and ½" Maximum pressure: 20 bar-g MOC: SS	Running meters	○ 2" pipe for feed line and desorption line, whereas 1/2" pipe for pressure equalization and output line.

Table 2: Battery limits for operating conditions

Serial no.	Parameter	Value/Range
1	Air inlet flow rate (Nm3/h):	40
2	Ambient temperature – Max. (deg C):	50
3	Feed air temperature (deg C):	< 35 (ideal: 25)
4	Adsorption pressure (bar-g):	5
5	Desorption pressure (bar-g):	0
6	Storage vessel pressure (bar-g):	4.2 – 4.7

Notes:

a) The storage vessel must be tested at different vessel pressures (4.2 – 4.7 bar-g) to arrive at the optimum condition at which the required flow rate and purity of oxygen is available.

b) The lab prototype uses Airsiev OX19 as the main adsorbent and Siliporite H_2O beads as the activated alumina. Both adsorbents are manufactured by Arkema, France. In the hybrid bed, activated carbon with iodine value 800 mg/g (4*8 mesh, coconut base) was used, which was manufactured by MM Corporation, Ahmedabad, India. The current design document is generated considering these as the working adsorbent. The change in adsorbent might demand changes in geometry too for the desired operation.

Table 3: Recommendations for some system components

Serial no.	Component	Recommendation(s)
1	Compressor	○ Screw compressor is recommended because of its low noise and oil-free operation. However, in case of its non-availability or higher cost, reciprocating type oil compressor can be used. However, for the later case, the use of hybrid bed containing activated carbon and alumina to remove any oil contaminants and moisture (if any) becomes important. ○ Compressor Package shall be enclosed in a powder coated acoustic canopy with sound absorbing material for limiting the noise level. Canopy is pressurized ensuring no pressure drop at suction filter and avoids entry for dust particles in the element in the anti-vibration mounts support electric motor and compressor unit and isolate the moving components from the rest of the structure. ○ The compressor shall have to be with all standard accessories compatible with oxygen generator. ○ The air compressor shall be manufactured to internationally acceptable standards with CE mark and ISO 9001 and ISO 13485 certification. ISO 8573-1: Compressed air – Part 1: Contaminants and purity classes. ISO 8573-2: Compressed air – contaminant measurement – Part 2: Oil aerosol content. ISO 8573-4: Compressed air – contaminant measurement – Part 4: particle content. ISO 5011: Inlet air cleaning equipment for internal combustion engines and compressors – performance testing.
2	Refrigerated air dryer	○ The dryer shall be equipped with all safety valves and be of simple plug and play concept. The pressure shall be self-regulating.
3	Air filters	○ Feed air quality of the oxygen concentrator should be conforming to ISO 8573 Class 4 and is of filtration grade of 0.01 micron.
4	Safety valve / pressure relief valve	○ The valves shall be properly tested before installation.
5	Flow meter	○ The flow meter to be placed at the outlet of oxygen storage vessel must be properly calibrated for oxygen. The flow meters are generally made for air and thus density correction for oxygen is desired. Contact manufacturer for this purpose.
6	Activated carbon	○ Every bed (hybrid and adsorbers) must be properly compacted to the correct density by means of column tapping or vibration.
7	Activated alumina	
8	Molecular sieve – zeolite	
9	Oxygen storage vessel	○ A corrosion allowance of 1.6 mm shall be considered ○ The vessel shall have vertical floor mounted design and be provided with a pressure gauge, safety pressure release valve and an auto drain valve
10	Alarm system	○ Providing main alarm panel to indicate any abnormality of gas pressure and other failures of the system (drop in oxygen purity etc.) is recommended. ○ The Alarm System consists of an isolation valve box, pressure sensors, circuit plate with LED colour indicators for visual indications. ○ The Gas Alarm system is sensitive to detect any pressure drop in the supply pipelines. ○ The Alarm System is fitted with electronic hotter/audio siren for audio indications of pressure drop. ○ The alarm is provided with the manual pressure gauge for indication of pressure in services. It shall have anti-microbial coating labels for touch control. ○ The alarm system shall be complete with digital display, sensor module and power supply. The alarm system shall be complete with all indication controls, wirings, accessories etc as required.
11	Servo voltage stabilizer	○ Servo voltage stabilizer of suitable capacity for oxygen plant and allied equipment's with input voltage range 300 – 480V and output voltage

		415+1% rating 3 phase 50Hz, micro processed based digital display suitable for unbalanced/balanced supply and unbalanced/balanced load copper wound with by-pass switch, MCCB, selector switches, complete in all respect, is recommended
12	Online UPS	○ With at least 30 min backup for PLC of the concentrator plant
13	Pressure vessels	○ All the vessels including hybrid bed, adsorbers, Oxygen storage vessel must be designed and manufactured as per ASME Section VIII Div 1 or equivalent. Appropriate corrosion/welding etc. allowances shall be provided. The maximum operating pressure in each one of these vessels are written below: ▪ Hybrid bed: 8 bar-g ▪ Adsorbers: 7 bar-g ▪ Oxygen storage vessel: 6 bar-g

CAD drawing with material of construction

The CAD drawing of the following components are presented as Annexures.

a) Hybrid bed

b) Adsorbers

c) Surge vessel

d) Full process layout

e) General assembly model

Bill of materials

The bill of materials containing most of the components not mentioned in the specifications list is written below:

Table 4: Bill of materials

Serial no.	**Part**	**Specification**	**Quantity**
1	Base frame (MS)	MS channel frame 3 m x 1.6 m x 200 mm Ht.	1
2	Hybrid bed	ID 508 mm (20") x Ht. 760 mm (30").	1
3	Adsorber	ID 330 mm (13").	2
4	Oxygen Storage Vessel	ID 712 mm (28") x Ht. 1890 mm (74 1/2").	1
5	PM Filter 1	Particulate filter 1 micron	1
6	PM Filter 2	Particulate filter 0.01 micron	1
7	Pipeline (Hybrid tank to absorber header)	2" nb x sch 40, ASA 150 class MS Flanges	1
8	Adsorber header	2" nb x sch 40, ASA 150 class MS Flanges	1
9	Adsorber outlet to surge tank	1/2" nb x sch 40, ASA 150 class MS Flanges	1
10	Adsorber outlet inter connection	1/2" nb x sch 40, ASA 150 class MS Flanges	1
11	Adsorber out to ambient	2" nb x sch 40, ASA 150 class MS Flanges	1
12	Feed and desorption line solenoid valve	2" nb pneumatically (external air) actuated solenoid valve, ASA 150 class Flanged end, SS 304 ball, CS body, 24 V DC	4
13	Inter connection (Pressure Equalization) and output line valve	1/2" nb pneumatically (external air) actuated solenoid valve, ASA 150 class Flanged end, SS 304 body 24 V DC	4
14	Hybrid bed drain valve	1/2" nb pneumatically (external air) actuated solenoid valve, ASA 150 class Flanged end, SS 304 body 24 V DC	1
15	Dain valves (adsorber)	1" nb heavy duty ball vave, thread end (SS 304)	2
16	Dain valves (Storage vessel and Hybrid tank)	1/2" nb heavy duty ball vave, thread end (SS 304)	2

20	SS ball valve	Manually operated ball valve 1/2" nb, Thread end type	2
21	Pipeline (compressor to drier)	2" nb x sch 40 pipe, 2" nb flexible pipe	1
22	Pipe from dryer to hybrid bed	2" nb x sch 40 pipe, 2" nb flexible pipe	1
23	Gaskets	3 mm nitrile rubber gasket	1 set
24	O' ring	Nitrile rubber 570 OD x 10mm dia.	1
25	O' ring	Nitrile rubber 390 OD x 10mm dia.	2
26	Fasteners Bolt, nut and double washer	HT bolt grade 8.8 M20 x 75	120
		HT bolt grade 8.8 M16 x 75	84
		HT bolt grade 8.8 M12 x 50	48
27	SS Fasteners	SS 304 Bolt and single washer	48
28	Hybrid bed flange	M20 x 75	24
29	Drain 4" flange	M16 x 75	16
30	Adsorber bottom flange (2 set)	M20 x 75	64
31	Adsorber top flange	M20 x 75	32
32	Absorber drain 4"	M16 x 75	16
33	Hybrid bed (Bolt for valve assembly)	M16 x 75	12
34	Adsorber inlet valve assembly	M16 x 75	24
35	Header connection	M16 x 75	4
36	Header dummy	M16 x 75	4
37	Outlet	M16 x 75	8
38	Outlet pipe 1/2"	M12 x 50	16
39	1/2" inter connection	M12 x 50	16
40	Oxygen storage vessel inlet 1/2"	M12 x 50	8
41	1/2" pipe Dummy	M12 x 50	8
42	Adsorber top mesh fixing	SS M6 x 20	48
43	Plated bolts (mounting of elements to Base frame)	M10 x 40	50

Control logic and valve timing description

The logical timing sequence for S^3 oxygen generator producing about 3 Nm^3/h medical grade oxygen is written below:

Table 3: Logical timing sequence

Time	Adsorber I	Adsorber II	SV* Open	SV Close
0 to 15s	FP	D	2, 8	1, 3, 4, 5, 6, 7, 9
15 to 55 s	A	D	2, 3, 8, 9	1, 4, 5, 6, 7
55 to 60 s	A	P	2, 3, 7, 8	1, 4, 5, 6, 9
60 to 62 s	PE	PE	1, 4	2, 3, 5, 6, 7, 8, 9
62 to 77 s	D	FP	5, 6	1, 2, 3, 4, 7, 8, 9
77 to 117 s	D	A	5, 6, 7, 9	1, 2, 3, 4, 8
117 to 122 s	P	A	3, 5, 6, 7	1, 2, 4, 8, 9
122 to 124 s	PE	PE	1, 4	2, 3, 5, 6, 7, 8, 9

*SV: Solenoid valve

Total cycle time = 124 s, ~ 2.1 minutes. The process will repeat (cyclic) from t = 0 after every 124 s.

Step description:

FP: Feed pressurization: to take column pressure to the desired level

A: Adsorption: main separation step in which high purity oxygen is available

D: Desorption: to desorb all adsorbed gases from the adsorbent by lowering pressure

P: Purging: cleaning the adsorbers with pure oxygen available as a product

PE: Pressure equalization: to increase the recovery of high pure oxygen

Important notes:

- All step times are required to be optimized as per the system performance. Currently, the timings are considered based on the lab prototype.
- During pressure equalization step, all the system solenoid valves excluding SV-4 and SV-1 will remain in closed position. The feed will be vented out to the ambient through SV-1. This will also desorb moisture from the hybrid bed.
- Pneumatically actuated (external air) solenoid valves are preferred.

List of bought out items with manufacturer/vendor details

NOTE: The present manufacturer/vendor list is non exhaustive and provides only an immediate guide of potential suppliers and should not be treated as a recommendation list. The design team does not vouch for any of the listed products and the responsibility of carrying out due diligence and sourcing appropriate materials as per the recommended specification rests entirely with the user of this document. It may however be noted that all the components used in the manufacturing of the lab prototype have been sourced from one or more of the vendors listed in Table 4.

Table 4: Bought out items with manufacturer/vendor details

Serial no.	**Component**	**Manufacturer**	**Suggested model**	**Manufacturer/Vendor – Address**	**Manufacturer/Vendor – Contact details**
1	Compressor	Frank	N.A.	Reach Pneumatics, #42/2, 6th cross, 5th main, Malleswaram, Bangalore	+91-80-23465570, 23496920 reachpneumatics@gmail.com www.reachpneumatics.com
		Ingersoll-Rand	N.A.	N.A.	https://www.irco.com/en-in
		ELGi	N.A.	N.A.	https://www.elgi.com/in/
2	Refrigerated dryer	Trident	Coldspell – 80	Reach Pneumatics, #42/2, 6th cross, 5th main, Malleswaram, Bangalore	+91-80-23465570, 23496920 reachpneumatics@gmail.com www.reachpneumatics.com
3	Air filter (to remove any particulate matter from the feed air,	Trident	T-100P	Reach Pneumatics, #42/2, 6th cross, 5th main, Malleswaram, Bangalore	+91-80-23465570, 23496920 reachpneumatics@gmail.com www.reachpneumatics.com
			T-100X		
			T-100A		
			BAC-50		

	and bacteria from the product oxygen)	Festo	N.A.	Festo India Private Limited Plot No.225 & 226, Bommasandra Industrial Area, Bengaluru, PIN 560 099. Karnataka.	080-22894245 thanmai.puchakayala@festo.com
4	Pressure gauge	Kains Instruments India Pvt. Ltd.	N.A.	No.9A, 1st cross, 3rd Main, Abbigere Main Road, Jalahalli West, Bangalore 560 015	91-9448615402 https://www.kains.com/ kainsindia@gmail.com
		Swagelok India	N.A.	Swagelok Bangalore #1, Doddanakkundi Industrial Area Whitefield Main Road, Mahadevapura Post Bangalore - 560048	+91-6366756548 +91-8792822596 +91-9686700134 bangalore.swagelok.com
5	Safety valve	Swagelok	N.A.	Swagelok Bangalore #1, Doddanakkundi Industrial Area Whitefield Main Road, Mahadevapura Post Bangalore - 560048	+91-6366756548 +91-8792822596 +91-9686700134 bangalore.swagelok.com
		Global	N.A.	ElectroWing Technologies Pvt. Ltd. No. 8, Puttenahalli, 24th Main, J.P. Nagar, Bangalore-560078	+91-8971467957 www.electrowingindia.com info@electrowingindia.com
6	Flow meter	Rockwin	N.A.	85/19, Sree Rangam Avenue,Pantheon Road, Egmore, Chennai - 600 008.	044 - 2852 9176/7 044 - 2852 9569 www.rockwin.com chennai@rockwin.com
		Alicat	N.A.	ElectroWing Technologies Pvt. Ltd. No. 8, Puttenahalli, 24th Main, J.P. Nagar, Bangalore-560078	+91-8971467957 www.electrowingindia.com info@electrowingindia.com

7	Temperature sensor with indicator	Elohim Instruments	N.A.	Elohim instruments, 409/1 M.E.S Road, Bangalore – 560013	+91-9448511883 elohiminstruments@gmail.com
8	Solenoid valves	Uflow		Ankur Industrial Complex, Survey No: 275/276, Plot No: 31, Nr. Intol Cast Pvt. Ltd. Shapar (Veraval) 360 024. Dist: Rajkot Gujarat (INDIA).	+91-2827254343, +91-8905907070 info@uflowvalve.com www.uflowvalve.com Vendor: +91-8971467957 www.electrowingindia.com info@electrowingindia.com
		Rotex		Rotex Automation Limited, 703, Western Edge II, Off. Western Express Highway, Borivali (East), Mumbai – 400 066, Maharashtra, India	+91 22 4211 1444 enquiry@rotexautomation.com https://rotexautomation.com/ContactUs/ReachUs Vendor(s): seatonsales1@gmail.com [+91-9886916711] puneeth.a@techsolengineers.com [+91-6366758485]
9	Activated carbon	M M Corporation	N.A.	403 Block A, Shivalik Corporate Park Shivranjani Shyamal Road, Satellite Ahmedabad 380015, Gujarat INDIA	+91-79-4006 0421/22 +91-98253 46557 www.mmcorporation.in manish.modi@mmcorporation.in
10	Activated alumina – to be used in the hybrid bed and adsorbers	Arkema	OX19	89, boulevard National 92257 La Garenne-Colombes Cedex - France arkema.com	+33 (0) 1 49 00 38 00 – Phone +33 (0) 1 49 00 38 03 – Fax. molecular.sieves@arkema.com
		Zeochem	N.A.	Zeochem LLC, 1600 West Hill Street, Louisville, KY 40210	+15026347600 https://www.zeochem.com/

		Shanghai Hengye Group Co., China	N.A.	11999 Katy Freeway Suite 588 Houstan, Texas 77079, USA	http://hengyeinc.com/ 1-844-308-3271 – toll free 1-832-288-4230 – Fax
		Jalon	N.A.	Junmin Road, Industrial Cluster District, Yanshi, Henan, China.	https://www.jalonzeolite.com/ +91 9810502962 (India) +86-13938894719 +86-379-6989 5719 info@jalonzeolite.com
		Honeywell UOP	N.A.	N.A.	https://uop.honeywell.com/en/products-and-services/adsorbents https://uop.honeywell.com/en/contact-us
11	Molecular sieve – zeolite	Arkema	OX19	89, boulevard National 92257 La Garenne-Colombes Cedex - France arkema.com	+33 (0) 1 49 00 38 00 – Phone +33 (0) 1 49 00 38 03 – Fax. molecular.sieves@arkema.com
		Zeochem	N.A.	Zeochem LLC, 1600 West Hill Street, Louisville, KY 40210	+15026347600 – Phone https://www.zeochem.com/
		Shanghai Hengye Group Co., China	N.A.	11999 Katy Freeway Suite 588 Houstan, Texas 77079, USA	http://hengyeinc.com/ 1-844-308-3271 – toll free 1-832-288-4230 – Fax
		Jalon	N.A.	Junmin Road, Industrial Cluster District, Yanshi, Henan, China.	https://www.jalonzeolite.com/ +91 9810502962 (India) +86-13938894719 +86-379-6989 5719 info@jalonzeolite.com
		Honeywell UOP	N.A.	N.A.	https://uop.honeywell.com/en/products-and-services/adsorbents https://uop.honeywell.com/en/contact-us
12	Oxygen Analyser	Uniphos	N.A.	Uniphos Envirotronic Pvt Ltd, P.O Nahuli, Tal. Umbergaon, Dist. Valsad, Gujarat – 396108, INDIA	+91-9909 994 042 / 7574 839 945 gasdetection@uniphos-envirotronic.com https://www.uniphos-she.com/index.php

					Vendor details: sales@sagixsolutions.com; customersupport@sagixsolutions.com www.sagixsolutions.com +91-9845410401
13	Ball valve / Needle Valve	Swagelok	N.A.	Swagelok Bangalore #1, Doddanakkundi Industrial Area Whitefield Main Road, Mahadevapura Post Bangalore - 560048	+91-6366756548 +91-8792822596 +91-9686700134 bangalore.swagelok.com
		Global	N.A.	ElectroWing Technologies Pvt. Ltd. No. 8, Puttenahalli, 24th Main, J.P. Nagar, Bangalore-560078	Vendor: +91-8971467957 www.electrowingindia.com info@electrowingindia.com
14	Control and acquisition	ASEC Solutions	N.A.	No. 38 Annapoorneshwari industrial area, Doddakallasandra, Kanakapura road, Bangalore – 560062	balaji@asecsolution.com +91-9886486815 https://asecsolution.com/index.htm
		ElectroWing Technologies Pvt. Ltd.	N.A.	ElectroWing Technologies Pvt. Ltd. No. 8, Puttenahalli, 24th Main, J.P. Nagar, Bangalore-560078	+91-8971467957 www.electrowingindia.com info@electrowingindia.com

Operating procedure with check list

After installation of the entire plant, following stepwise procedure can be followed for its smooth operation.

- Check cycle times given in the PLC control. Initial starting can be done by setting suggested times which further can be optimized based on the process performance.
- Check all the lines and valves. All the ball valves in the vent lines shall be in the closed position. The ball valve given at the outlet of oxygen storage vessel can also be in the closed position. This valve can be opened solely once the required pressure in the surge vessel is reached, which can take around 10 cycles.
- Switch on the pneumatic air compressor and wait till the pressure in the external air manifold reaches around 6 bar-g. Once reached, the solenoid valves are ready to operate.
- Switch on the refrigerated air dryer. Depending upon the manufacturer, the refrigerated air drier will take some time to reach desired operational temperature. Make sure the drain is set in automatic position. This will ensure automatic drainage of condensed moisture from the chiller.
- Switch on the feed air compressor. If air receiver or tank is used, this will take some time till it gets filled. Once the tank gets filled, the full unit can be started.
- Prior to sending the feed air to the adsorber columns, it is advisable to check for the operation and sequence of solenoid valves to ensure everything is in order. This can be done by just operating the solenoid valves using the PLC.
- If all the components are working fine, the unit can be started.
- Once the unit is operational, it starts discharging Oxygen into the surge / storage vessel. In the course of filling of the surge vessel, the outlet of the surge vessel should be kept closed till the pressure in the surge vessel becomes minimum 4.2 bar-g. Once the desired pressure is reached, the outlet valve can be gradually opened such that in addition to purity and flow rate, product oxygen at the desired pressure (minimum 4.2 bar-g) is made available at the outlet. Note that varying surge vessel pressure impacts both the purity and the flow rate.

- Note that during P.E. Step, all valves excluding SV-4 and SV-1 will remain in closed position. During this time, the feed gas will be vented to the ambient through SV-1. This will also ensure desorption of moisture from alumina present in the hybrid bed.
- All the filters can be periodically checked for clogging and other issues.

Prototype performance data

A full-scale lab prototype was developed and tested to generate medical grade oxygen. Some results from the preliminary studies are mentioned below:

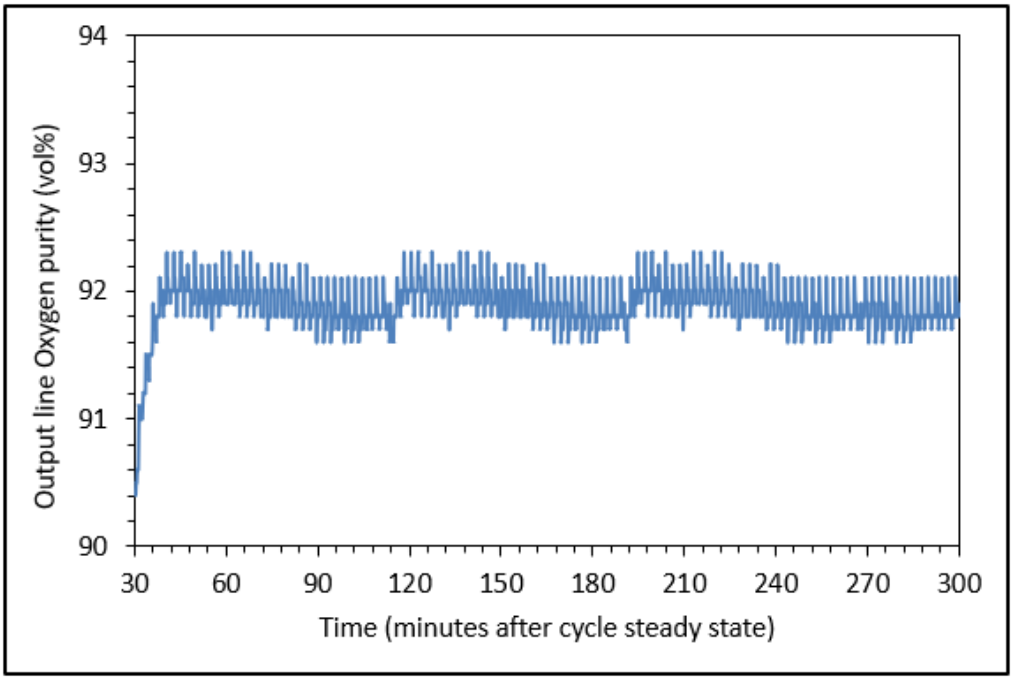


Figure 1: Variation of output oxygen purity with time during long duration testing

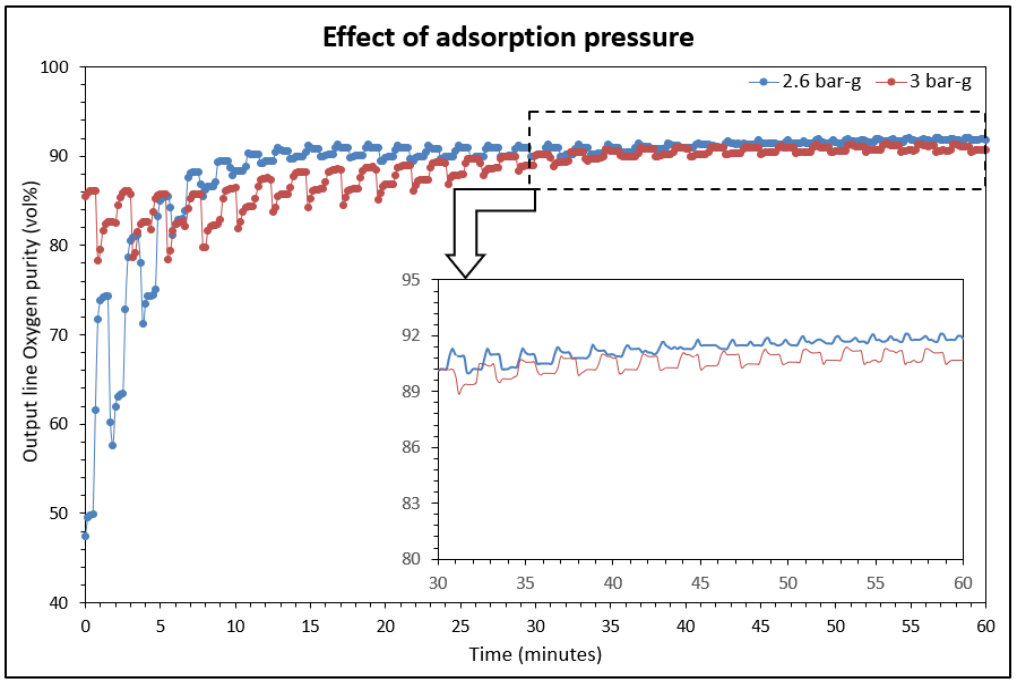


Figure 2: Effect of adsorption pressure on output oxygen purity

[Note: Purity was maintained at both the pressures and outlet flow rate was 2.4 and 2.9 $Nm^3/h\text{-}O_2$ at 2.6 and 3 bar-g respectively]

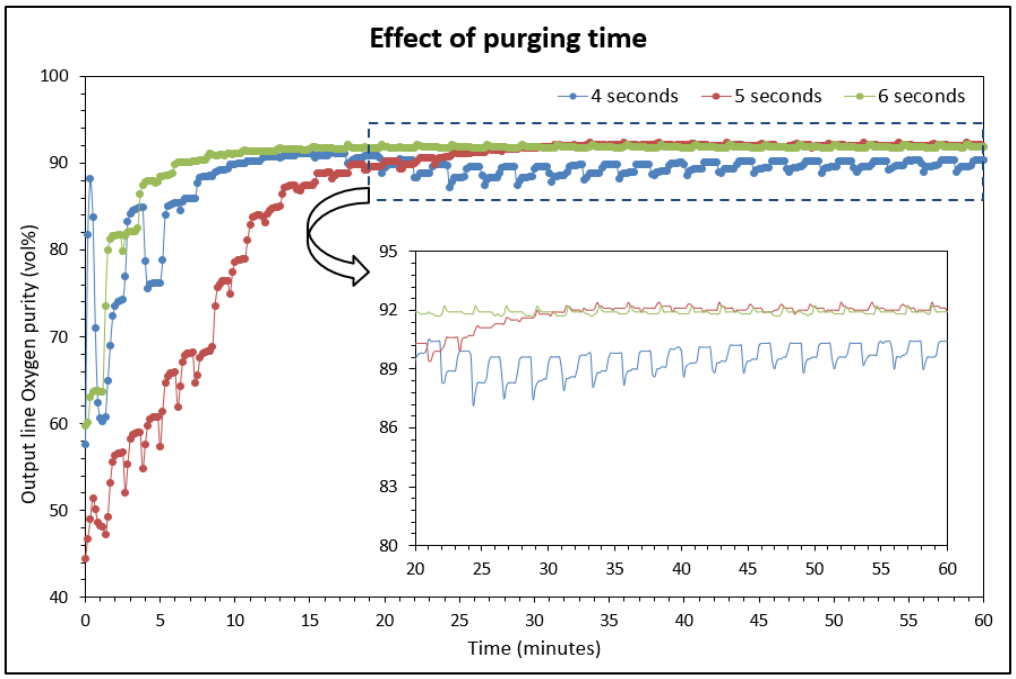


Figure 3: Effect of purging time on output oxygen purity
[Note: purity improves with purging time, however, recovery drops]

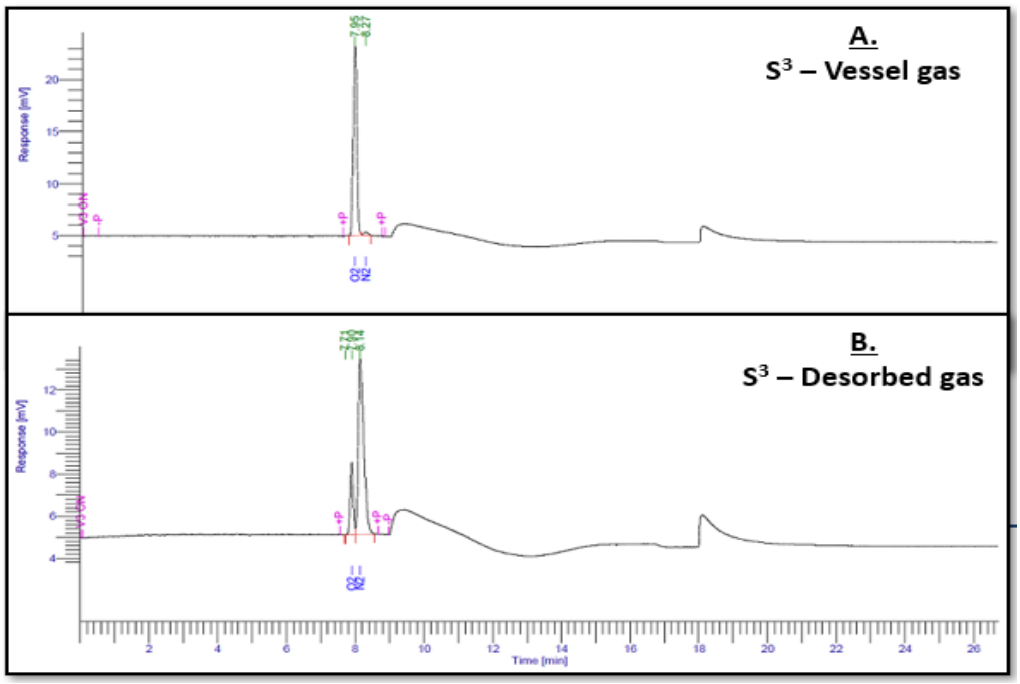


Figure 4: GC traces for a) S^3 – surge vessel composition (O_2: 92.4 vol%), b) S^3 – desorbed gas composition (O_2: 14.2 vol%)

Frequently Asked Questions

1. What is S^3?

Response] S^3 is the name given to the high purity, medical-grade, oxygen generator developed by Indian Institute of Science (IISc), Bangalore. It works on Pressure Swing Adsorption (PSA) technology.

2. What are the operating conditions?

Response] It operates at maximum ambient temperature of 50^{o}C, pressure of 5 bar-g and ambient relative humidity of ≤ 95%. All vessels are to be designed and manufactured in accordance with ASME Section VIII Div I.

3. How many beds can the system support?

Response] Equivalent number of hospital beds that can be served is 5 (at 10 LPM) – 10 (at 5 LPM).

4. What are some of the salient features built into the S^3 design?

Response] Some of the salient features of the design are:

- Five step cyclic continuous process with efficient feed dehumidification, cleaning, and increased life of adsorbents
- Fulfills the normative requirement of the quantity of oxygen for a 5 to 10 bed hospital as prescribed by the MoH&FW
- Product gas quality as per the guidelines prescribed by the Indian Pharmacopeia
- Reliable and automatic unit with all safety features
- Availability of product gas at > 4.2 bar-g pressure which can be regulated
- Uninterrupted product gas supply for 30 minutes in case of power failure
- A rugged system with ± 20% fluctuation in the input/feed flow rate allowed
- Standard accessories and components compatible with oxygen with all pipes and valves made up of SS-316L
- Continuous monitoring of product purity using online oxygen analyzer and alarms

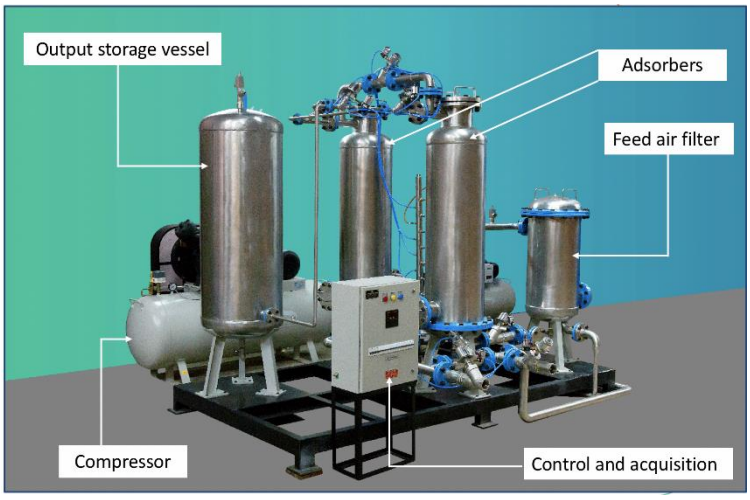
- Control and acquisition using a programmable logic controller with a provision for emergency stop
- Low noise levels (< 65 dB)
- Sterile bacterial filtration on the output line
- Can be coupled to a diesel genset, renewable power as a decentralized system (for use in remote areas)
- The general design principle can be adopted for any throughput requirement
- Low system footprint (1.5 m × 3.0 m) with maximum delivery of 3 Nm^3/h at a typical power consumption of ≤ 1.5 kWh/Nm^3, which can further be optimized.

5. What is the adsorbent used?

Response] The lab prototype uses Airsiev OX19 as the main adsorbent and Siliporite H2O beads as the activated alumina. Both adsorbents are manufactured by Arkema, France. In the hybrid bed, Activated carbon with iodine value 800 mg/g (4*8 mesh, coconut base) was used, which was manufactured by MM Corporation, Ahmedabad, India.

6. Is there an existing prototype?

Yes, firstly lab prototype was developed and tested. It has all the features to address the needs of the hospitals. Below is the picture of the lab prototype.



7. Your scope of supply and our scope and other vendor detail for procurement (if any)

Response] The IISc team is releasing the complete design, drawings and control logic as an open source for generating 3 Nm3/h oxygen. For additional requirements, team can be contacted at scube@iisc.ac.in

8. Whether IISc will supervise the entire project from erection and operation process from grounds up ?

Response] No.

9. What is the electrical unit consumption per month for 1 and 3 phase both?

Response] The unit consumes about 1.5 units of energy per Nm3 of oxygen generation. The current system employs three phase power supply.

10. What are the safety norms?

Response] Safety is of paramount importance to the team. Therefore, all vessels are to be designed and manufactured in accordance with ASME Section VIII Div I. In addition, the team has incorporated two pressure relief valves in the system to ensure pressure safety. Moreover, the quality of product oxygen is ensured by number of filters.

11. What is the requirement of space in Sq. Mtr.

Response] The current system requires about 1.5 m * 3 m land, which can be further optimized, to generate 3 Nm3/h medical grade oxygen.

12. Will the plant the erected in open space (OTS) or any covered shed / building is required?

Response] Covered shed is recommended to safeguard the system from ambient conditions. Note that system contains many electrical and electronic appliances.

13. Any water requirement?

Response] No.

14. Man power requirement for 8 hrs operation (Skilled and semi- Skilled).

Response] The plant can be designed in such a way that it can run un-attended. However, one semi-skilled labour might be required for day to day operations (to take care of power failure, etc.)

15. Whether any (identified-experienced) manufacturers are available for the fabrication of different components of the plant?

Response] The design document contains the list of experienced vendors which can supply most of the components.

16. Is there any alternative adsorbent available?

Response] The current system is tested on Airsiev OX-19 adsorbent from Arkema, France. Any other zeolite having similar characteristics as OX-19 can be used. If zeolites having characteristics different from OX-19 are used, then Oxygen throughput might vary. Some other companies which manufacture adsorbents are Honeywell UOP, Zeochem, Jalon etc.

17. What % of components are available off the self and what % the components needs to be fabricated?

Response] The main components to be fabricated are hybrid bed, adsorbers, surge vessel and the connecting lines. Nearly all other components are available as bought out items.

18. What would be the import components if any and timelines for getting the same in your estimation?

Response] As per our estimates, the only component to be imported is the adsorbent. Nearly all companies have their representatives here in India who can be contacted for the adsorbent.

Team S^3

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Dr Anand M Shivapuji

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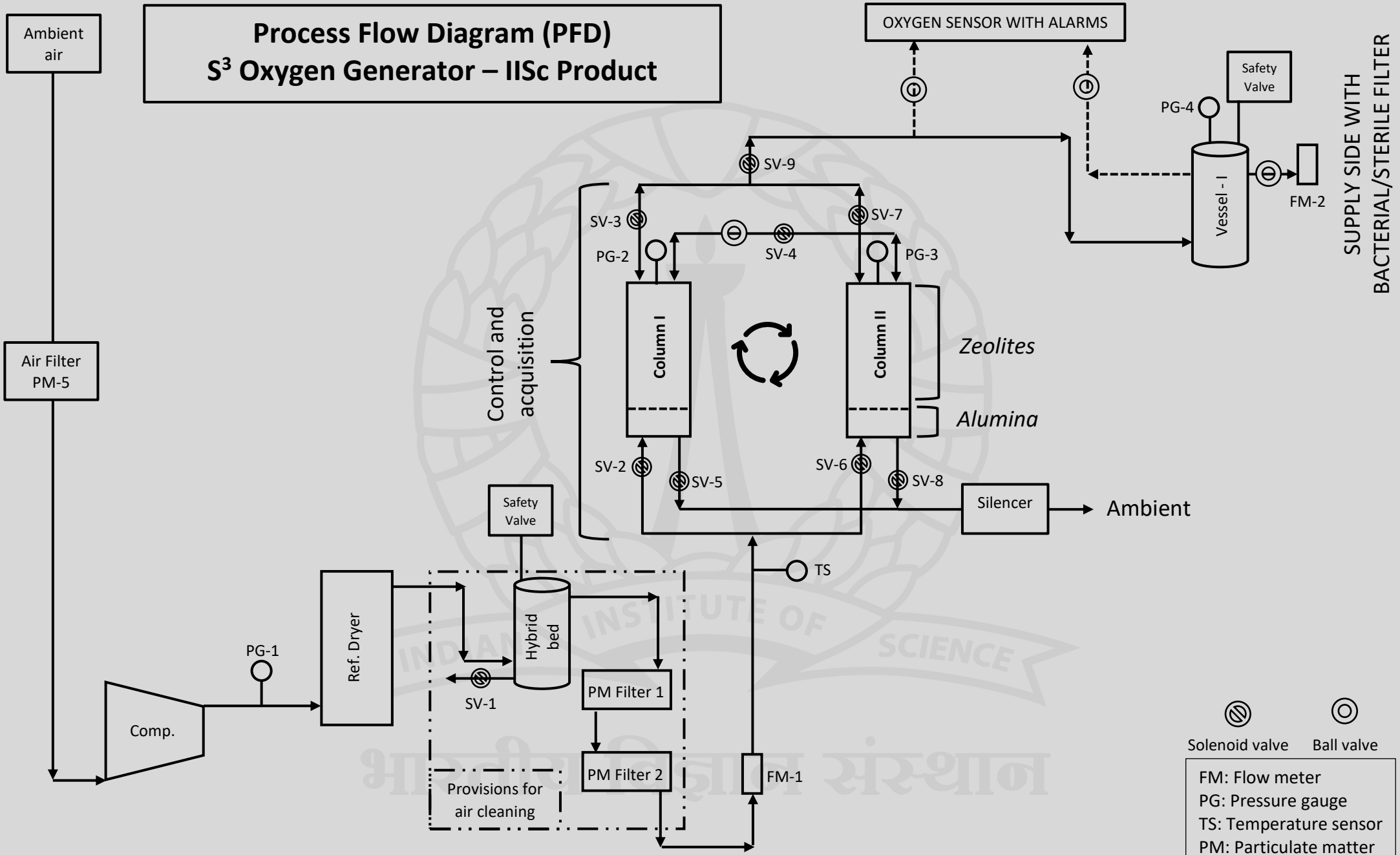
scube@iisc.ac.in

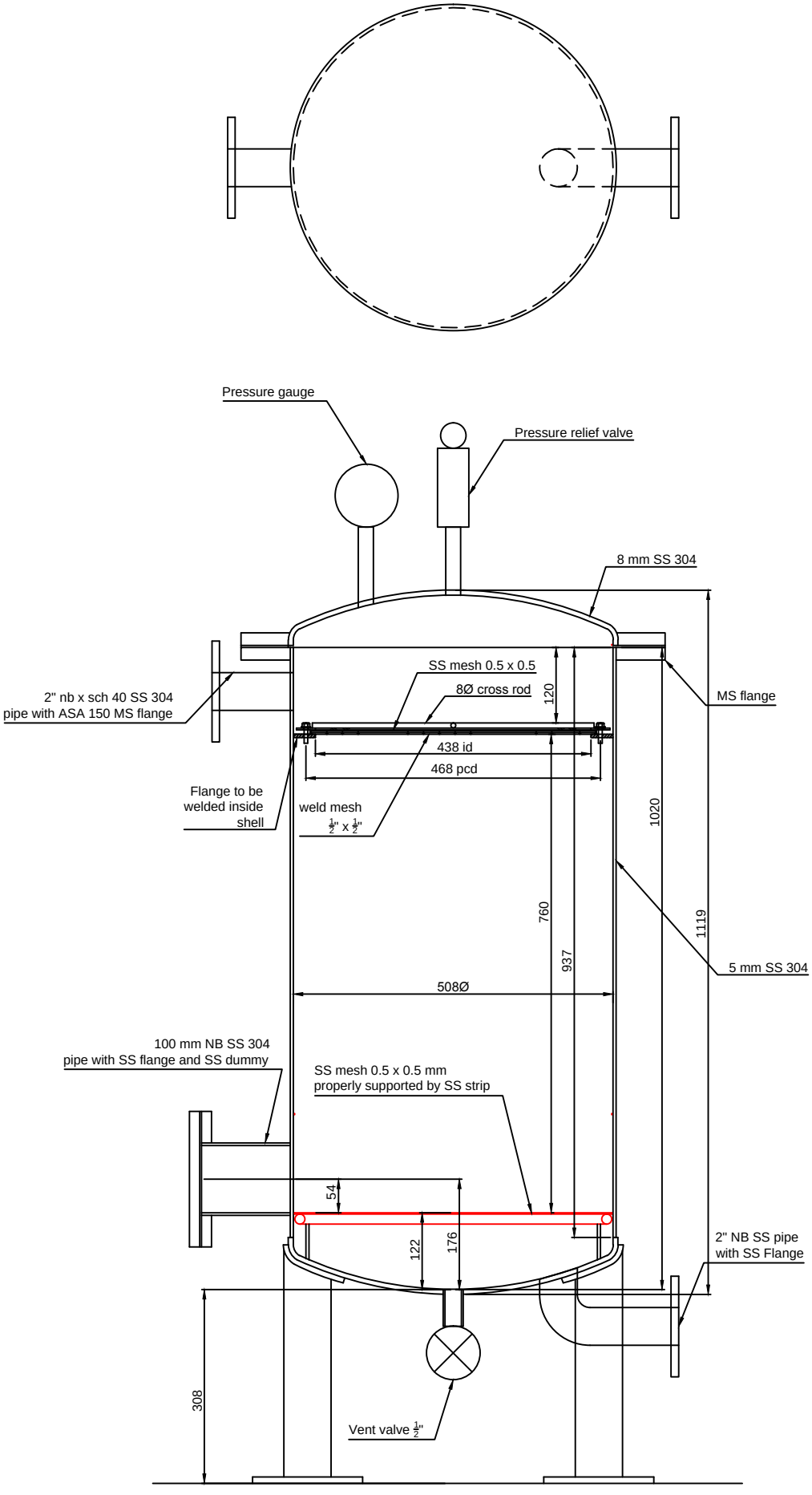
Annexures

Process Flow Diagram

Process Flow Diagram (PFD)
S^3 Oxygen Generator – IISc Product

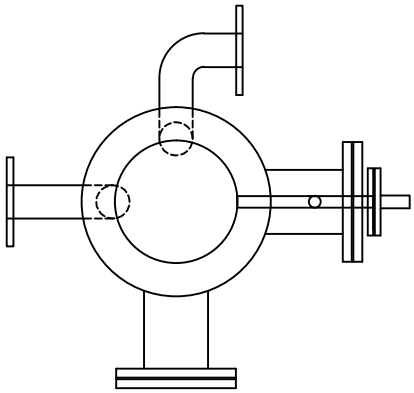


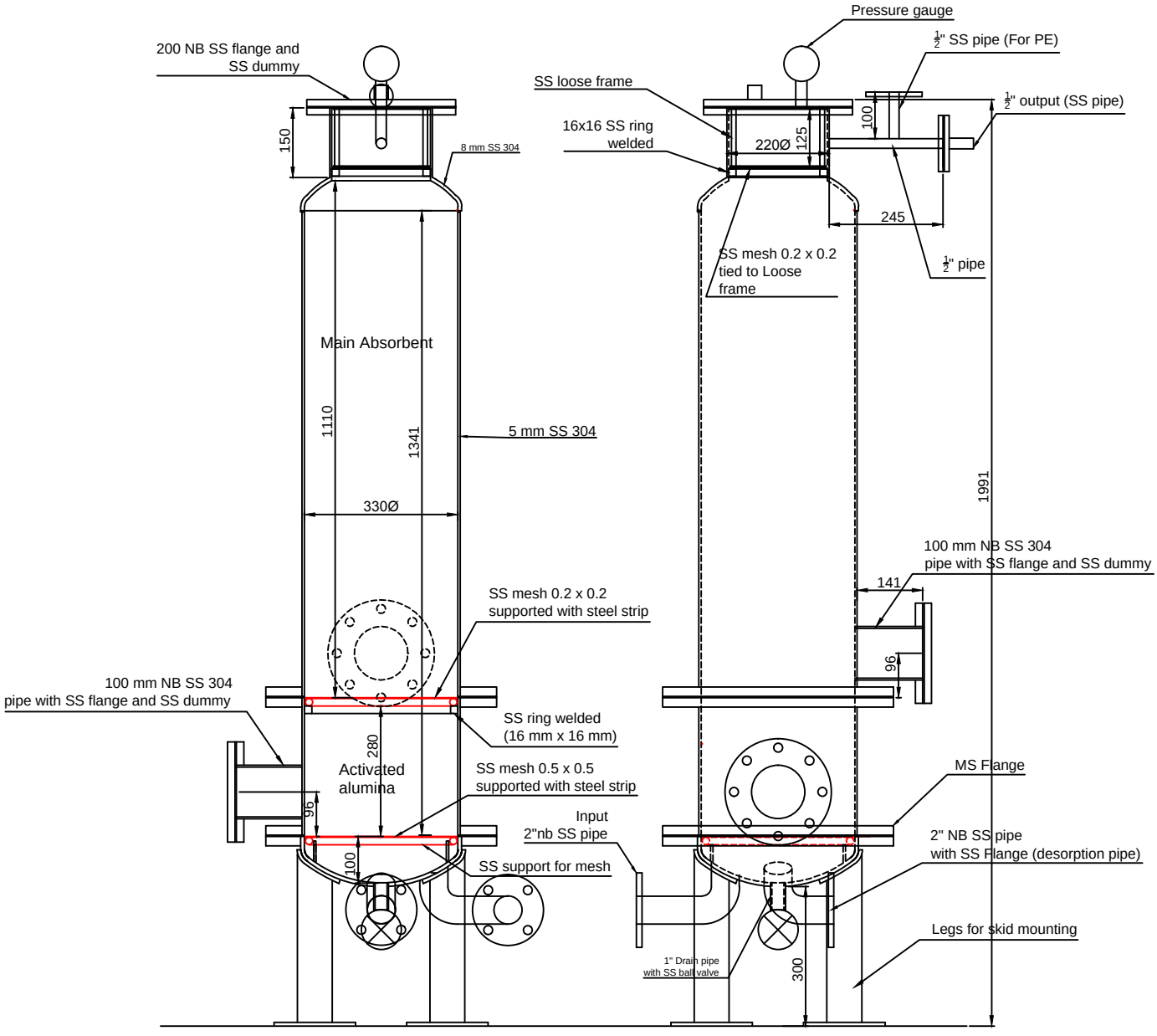
Gas Conditioning Hybrid Bed


Pressure gauge
Pressure relief valve
8 mm SS 304
SS mesh 0.5 x 0.5
8Ø cross rod
120
MS flange
2" nb x sch 40 SS 304
pipe with ASA 150 MS flange
438 id
468 pcd
Flange to be
welded inside
shell
weld mesh
½" x ½"
1020
760
937
1119
5 mm SS 304
508Ø
100 mm NB SS 304
pipe with SS flange and SS dummy
SS mesh 0.5 x 0.5 mm
properly supported by SS strip
54
122
176
2" NB SS pipe
with SS Flange
308
Vent valve ½"

HYBRID BED

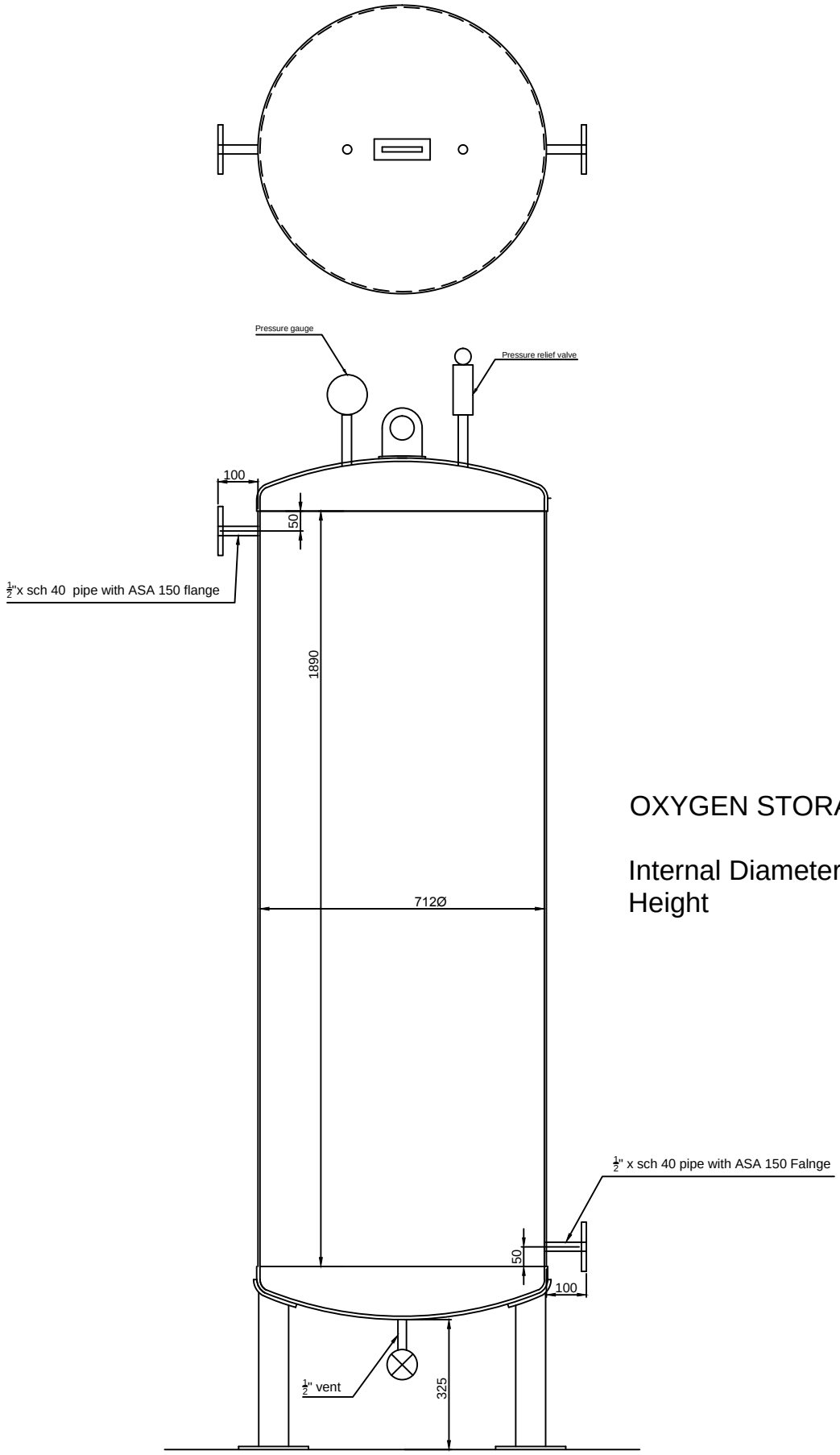
Adsorber Vessel





PSA VESSEL / ADSORBER - 2 Nos.

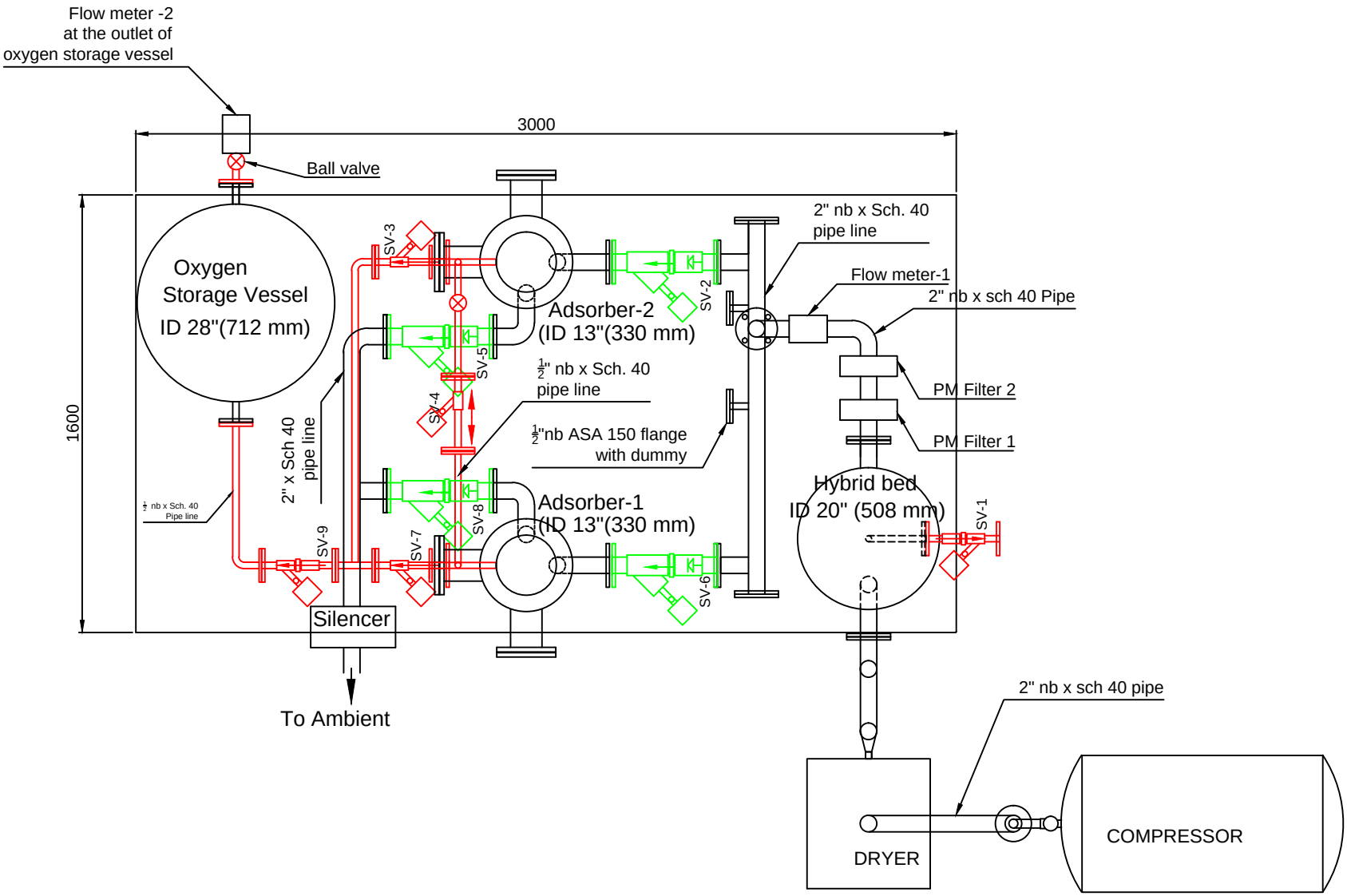
Storage Vessel



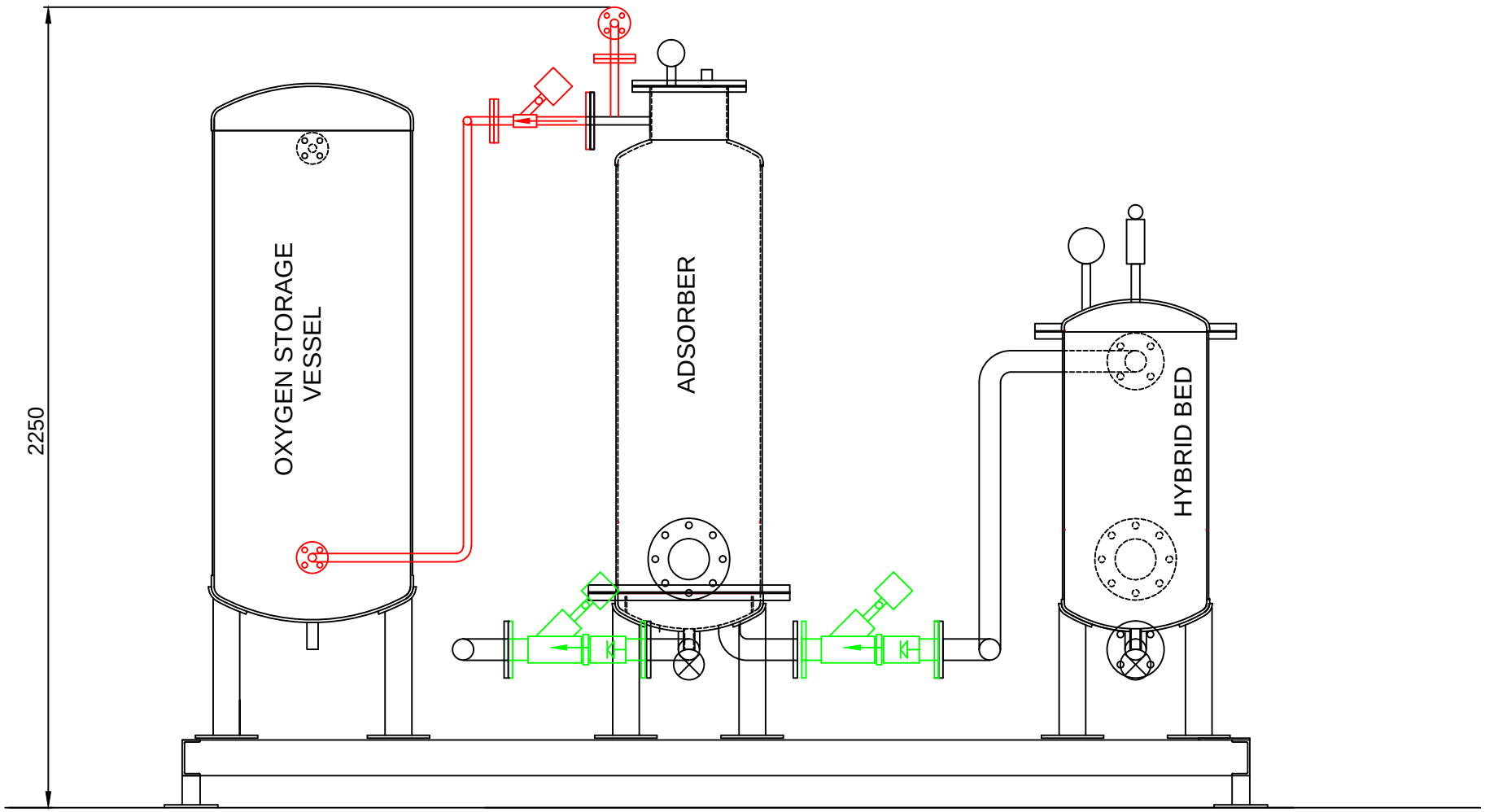
OXYGEN STORAGE VESSEL

Internal Diameter	28" (712 mm)
Height	74 1/2" (1890mm)

Plant Layout


Flow meter -2
at the outlet of
oxygen storage vessel
3000
Ball valve
1600
Oxygen
Storage Vessel
ID 28"(712 mm)
SV-3
SV-2
SV-5
SV-4
SV-8
SV-7
SV-9
SV-6
SV-1
Adsorber-2
(ID 13"(330 mm)
Adsorber-1
(ID 13"(330 mm)
2" nb x Sch. 40
pipe line
Flow meter-1
2" nb x sch 40 Pipe
½" nb x Sch. 40
pipe line
½"nb ASA 150 flange
with dummy
PM Filter 2
PM Filter 1
Hybrid bed
ID 20" (508 mm)
2" x Sch 40
pipe line
½ nb x Sch. 40
Pipe line
Silencer
To Ambient
2" nb x sch 40 pipe
DRYER
COMPRESSOR

General Assembly



ELEVATION