GREEN HYDROGEN - BALANCE OF PLANT SIZING			Flexera CONSULTING
Green Hydrogen plant capacity		5	MW
		5000	kWh
Volume of Hydrogen produced		1000	Nm^3/hr
Hydrogen produced		89.23	kg/hr
Reaction Chemistry			
H_2O	H_2 +	$0.5\ O_2$	
18	2	16	
Therotical Water rquirement		9	kg / kg of H_2
Water requirement for the rated capacity		803.07	kg/hr
Technology considered		**PEM**	
Current density		10000	A/m^2
DC current required		2391362.541	Amps
Electrochemical efficiency		75	%
		3188483.388	Amps
Electrode area requried		318.85	m^2
Electrode area required per element		2	m^2
No of elements required		159.4241694	No
		160	No
Electrolyser operating condition			
Operating Pressure		6.5	bar
Operating Temperature		80	deg.C
Cathode outlet gas composition			
Hydrogen		97.25	% v/v
Water		2.654	% v/v
Oxygen		0.096	% v/v
Separator			
Gas volumetric flow rate		1028.28	Nm^3/hr
Hydrogen		1000	Nm^3/hr
Water		27.29	Nm^3/hr
Oxygen		0.99	Nm^3/hr
Gas molar flow rate			
Hydrogen		44.61	kgmol/hr
Water		1.218	kgmol/hr
Oxygen		0.044	kgmol/hr
		45.877	kgmol/hr
Gas mass flow rate			
Hydrogen		89.23	kg/hr
Water		21.92	kg/hr

GREEN HYDROGEN - BALANCE OF PLANT SIZING		Flexera CONSULTING
Oxygen	1.41	kg/hr
	112.56	kg/hr
Gas density at NTP condition	0.11	kg/Nm^3
Gas density at operating condition	201.89	kg/m^3
Vapour Liquid Separator sizing		
Density of liquid (Water - p_L)	1000	kg/m^3
Density of vapour (Vapour - p_V)	201.8895828	kg/m^3
Gas superficial velocity (k)	0.032	m/sec
Cross sectional area of the VLS	0.356	m^2
Orientation of vapour liquid separator	Horizontal	
Diameter to length ration	2	
Diameter of the VLS	0.61	m
Length of the VLS	1.22	m
At the outlet of the VLS		
Operating Pressure	6.5	bar
Operating Temperature	70	deg.C
DEOXO system to remove Oxygen in the gas stream		
Oxygen concentration at the inlet of deoxo system	0.096	% v/v
	960	ppm
	0.044	kgmol/hr 44.0415
Oxygen concentration at the outlet of deoxo system	0.00024	% v/v
	2.4	ppm
	0.25	
Removal efficiency required	99.75	%
Reaction Chemistry		
H_2 + $0.5\ O_2$	H_2O	
2 16	18	
Oxygen involven in the reaction	0.04	kgmol/hr
	1.41	kg/hr
Equivalent hydrogen consumption	0.18	kg/hr
Water formation	1.58	kg/hr
	0.09	kgmol/hr
Resultant water at the outlet of DEOXO	1.305	kgmol/hr
Resultant Hydrogen at the outlet of DEOXO	44.53	kgmol/hr
	45.83	kgmol/hr
Resultant water concentration in the deoxo outlet	2.85	% v/v
Resultant hydrogen concentration in the deoxo outlet	97.15	% v/v
Heat release calculation		
Water formation reaction is exothermic reaction		
Heat of reation	242	KJ/mol

GREEN HYDROGEN - BALANCE OF PLANT SIZING		Flexera CONSULTING
	242000	KJ/kgmol
Heat liberated during the Water formation	10631.40	KJ/hr
	2.95	kW
Due to exothermic reaction, temperature of the product stream will raised		
Gas quantity at the inlet of deoxo	112.56	kg/hr
Temerature of the gas at the inlet	70	deg.C
Heat capacity of the gas entered to the deoxo system	2.88	kcal/hr
Heat with the feed	22653.07	kcal/hr
Heat load raised due to exothermic reaction	2539.31	kcal/hr
Resiltant heat load	25192.38	kcal/hr
Resultatn deoxo outlet temperature	77.85	deg.C
Catalyst Volume Calculation		
Catalyst volume is calculated baesed on Gas Hourly Space Velocity (GHSV) method.		
Which is the standard industrial approch for Deoxo reactor sizing.		
GHSV values are clculated based on the gas volumetric flow rate at normal condition (1 atm & 0^0C)		
Recommended GHSV values for the Deoxo system are indicted below.		
Minimum GHSV	4000	1/hr
Maximum GHSV	12000	1/hr
GHSV considered for the Palladium Catalyst	6000	1/hr
GHSV considered for the latinum Catalyst	5000	1/hr
Properties of Palladium Catalyst (Option 1)		
Particle size	3 to 5	mm
Palladium loading	0.3 to 0.5	% w/w
Design loading	0.4	% w/w
Support Matrial	Y Al_2O_3	
Bulk density	750	kg/m^3
Volume of catalyst requried (calculated)	0.17	m^3
Volume of catalyst requried (selected)	0.20	m^3
	200	lit
Vessel Sizing		
Free board volume required	20.00	%
Inl;et / distributor allownace	10	%
Vessel volume required	264	lit
	270	lit
Diameter to height ration	3	
Diameter of the vessel	0.486	m
	485.72	mm
	500	mm
Height of the vessel	1500	mm
Catalyst bed height	1.02	m
Superfical velocity at operating condition		
Volumetric flow rate at actual condition	200.64	m^3/hr

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	0.056	m^3/sec
Cross section area of the vessel	0.1963	m^2
Actual superficial velocity	0.2838	m/sec
Range must be inbetween 0.1 to 0.5 m/sec	**SATISFIED**	
Pressure drop across the Catalyst Bed (Palladium)		
Pressure drop will be calcualted by Ergun Equation		
$\Delta P/L = [150\ \mu\ u_s\ (1-\varepsilon)^2] / [d_p^2\ \varepsilon^3] + [1.75\ \rho\ u_s^2\ (1-\varepsilon)] / [d_p\ \varepsilon^3]$		
ΔP is the pressure drop in Pa		
L is the height of catalyst bed in m	1.02	m
U_S is superficaial velocity in m/sec	0.2838	m/sec
μ is viscosity in Hydrogen in Pa.s	0.0000095	Pa.s
d_p is the particle size of catalyst in m	0.003	m
p is the density of Hydrogen in kg/m^3	0.445	kg/m^3
Ɛ is the porosity of the catalyst	0.4	
	252.80	Pa/m
	196.25	Pa/m
Pressure drop across the catalyst bed ($\Delta P/L$)	449.05	Pa/m
Total pressure drop across the catalyst bed	457.40	Pa
(Note: Pressure drop should be less than 0.3 bar)	0.0046	bar
	SATISFIED	
Catalyst mass determination		
Volume of Catalyst	0.20	m^3
Mass of catalyst	150	kg
Palladium content in the catalyst	0.60	kg
	600	gram
Contact time		
Actual volumetric flow rate	200.64	m^3/hr
Retention time	0.001	hr
	3.59	sec
Acceptable range : 1 - 5 sec	**SATISFIED**	
Water removal system by Temperature Swing Adsorption (TSA)		
Gas volumetric flow rate from DEOXO	1027.29	Nm^3/hr
Composition		
Hydrogen	97.15	% v/v
	998.03	Nm^3/hr
	89.05	kg/hr
Water	2.85	% v/v
	29.26	Nm^3/hr
	23.5238	kg/hr
Outlet gas volumetric flow rate	998.53	Nm^3/hr
Water content allowed in the outlet gas	5	ppm

GREEN HYDROGEN - BALANCE OF PLANT SIZING		Flexera CONSULTING
	0.0005	% v/v
	0.0050	Nm^3/hr
	0.0040	kg/hr
Water to be removed in the TSA	23.5198	kg/hr
Operating pressure	6.4954	bar a
Partial pressure of water in the inlet gas stream	0.1850	bar
Operating temperature	77.85	deg.C
Vapour pressure water at the operating temperature	0.427	bar
Relative Humidity	43.33	% Saturation
It indicates that the water is below its saturation condition, so the water will not condense. At this condition, the water dew point will be 35.5°C		
Adsorption cycle time assumption		
Standard TSA design uses 2 vessels alternating in adsorption / regeneration		
Adsorption half cycle time slected	8	hr
Total cycle per vessel (8 hr operation + 8 hr regeneration)	16	hr
Water load per adsorption half cycle	188.16	kg/cycle
Design Margin	25	%
	235.20	kg/cycle
Recommended Adsorbent	**Molecular Sieve 3A**	
Adsorbent data		
Form	4 - 8 mesh beads	
Pore Size	3	A
BET Surface area	700	m^2/g
Bulk density	640 - 700	kg/m^3
Dynamic water capacity	12 to 16	% w/w
For design purpose	10	% w/w
Heat of adsorption	4000 to 4500	KJ/kg H_2O
Regeneration temperature	175 - 260	deg.C
Adsorbent Mass Calculation		
Design water load per cycle	235.20	kg/cycle
Adsorbent working capacity selected (77 deg.C, 6.5 bar & H2O - 2.85%)		
Water adsorption capacity (q Working)	10	% w/w
(Equilibrium capacity 14 - 16%, derated to 10% for design)	0.1	kg H_2O / kg adsorbent
Adsorbent requirement	2351.98	kg adsorbent
Add 20% for distribution loss	2822.37	kg adsorbent
Actual Adsorbent requriment	2900	kg adsorbent
Mass of adsorbent split in to different layer		
Gurad layer, used Activated Alumina (AA)	20	%
	580	kgs
Main layer (MS 3A)	2320	kgs
Bulk density for 4 - 8 beads (lower range)	670	kg/m^3

GREEN HYDROGEN - BALANCE OF PLANT SIZING		Flexera CONSULTING
Bed Volume	4.33	m^3
Vessel Diameter & Bed height determination		
Gas volumetric flow rate at NTP condition	1027.29	Nm^3/hr
Gas volumetric flow rate at actual condition	200.59	m^3/hr
	0.0557	m^3/sec
TSA H_2 range : 0.03 to 0.25 m/sec.		
Gas superficial velocity considered for the calcualtion	0.15	m/sec
Cross section area of the vessel	0.371	m^2
Diameter of the vessel	0.688	m
Calculated diameter of the vessel is seems to be small, Since the vessel volume is required around 4.5 m^3. This will indicate upnormal L/D ratio. Hence the vessel size is determined based on the L/D ratio of 3.		
Length to diameter ratio	3	
Vessel volume 12.11	4.33	m^3
Diameterr of the vessel for the specified L/D ratio	1.22	m
	1.2	m
Cross section area of the corrected diameter	1.13	m^2
Gas superficial velocity at corrected diameter	0.049	m/sec
Superficial velocity lies in the range of 0.03 - 0.25 m/sed	**SATISFIED**	
Bed height required	3.83	m
L/D ratio for adsorbent in the vessel	3.19	
Accetable range of L/D is 2.5 to 4.0	**SATISFIED**	
Vessel Tan to Tan height		
Bottom AA layer mass	580	kgs
Bottom AA layer volume	0.87	m^3
Bottom AA layer height	0.77	m
Main MS3A layer mass	2320	kgs
Main MS3A layer volume	3.46	m^3
Main MS3A layer height	3.06	m
Total adsorbent height	3.83	m
Free board required above the adsorbent bed	0.5	m
Space required below bed (inert ball & support grid)	0.3	m
Shell tan to tan height	4.63	m
Vessel dish end closure	2 : 1 Elipsoidal	
Height of dish end	0.3	m
Total vessel height	5.23	m

GREEN HYDROGEN - BALANCE OF PLANT SIZING		Flexera CONSULTING
Pressure drop across the Catalyst Bed (Palladium)		
Pressure drop will be calcualted by Ergun Equation		
$\Delta P/L = [150\ \mu\ u_s\ (1-\varepsilon)^2] / [d_p^2\ \varepsilon^3] + [1.75\ \rho\ u_s^2\ (1-\varepsilon)] / [d_p\ \varepsilon^3]$		
ΔP is the pressure drop in Pa		
L is the height of catalyst bed in m	3.83	m
U_S is superficaial velocity in m/sec	0.0493	m/sec
μ is viscosity in Hydrogen in Pa.s	0.0000095	Pa.s
d_p is the particle size of catalyst in m	0.0035	m
p is the density of Hydrogen in kg/m^3	0.445	kg/m^3
Ɛ is the porosity of the catalyst	0.37	
	44.91	Pa/m
	6.72	Pa/m
Pressure drop across the catalyst bed ($\Delta P/L$)	51.63	Pa/m
Total pressure drop across the catalyst bed	197.59	Pa
	0.0020	bar
Regeneration System Design		
Regeneration method	Hot Gas Purge	
TSA generation is performed by purging the bed with hot dry gas. A slip stream of dried product H2 is heated and directed counter currently through off line bed.		
Heat Required for the Regeneration		
Total heat required is the sum of heat of desorption, sensible heat of addsorbent, sensible heat of vessel and heat losses		
Heat of Desorption		
Mass flow rate of water removed per cycle	235.20	kg/cycle
Heat of desorption	4200	KJ/kg
	987830.96	KJ/ cycle
Sensible heat of adsorbent bed		
Intial temeparature	77.85	deg.C
Temparature required for regeneration	250	deg.C
Temparature difference	172.15	deg.C
Heat capacity of adsorbent	1.05	KJ/kg deg.K
Mass of adsorbent	2900	kg
Sensible heat of adsorbent bed	524185.95	KJ/ cycle
Sensible heat of vessel	10	%
	151201.69	KJ/ cycle
Heat loss	15	%
	249482.79	KJ/ cycle
Total heat requried	1912701.38	KJ

GREEN HYDROGEN - BALANCE OF PLANT SIZING		Flexera CONSULTING
Heater Sizing		
Heater rating required	88.55	KW
Selected heater rating	100	KW
Total heat load is splitted to 6 hours, than converted to per second.		
Total regeneration cycle is 8 hours, in that 6 hours regeneration and 2 hours cooling.		
Recirculating Purge Loop		
in the frecirculation system, a fixed H2 gas inventory circulates in closed loop. The blower maintains flow, the heater adds the heat each pass, the knock out drum removes water each pass. No product is continuously withdrawn.		
Recirculating flow sized on superficial velocity in bed during regeneration.		
Design regen superficial velocity (assumed)	0.1	m/sec
Vessel cross section area	1.13	m^2
Voluetric flow rate of regen gas flow	0.1131	m^3/sec
Hydrogen density at 280^{0}C and 6.5 bar	0.283	kg/m^3
Mass flow rate of Hydrogen	115.08	kg/hr
	57.54	kgmol/hr
Heater outlet temperature check		
Temparature refernce	40	deg.C
Temperature raise	193.72	deg.C
Heater outlet temperature	233.72	deg.C
This is well within heater element limits. Bed inlet trimmed to 280^{0}C by temp.controller.		
Water carry over per pass		
Transit time per pass	38.27	sec
	94.07	pass / hr
Water carry over	235.20	kg
	13.05	kgmol
Average water removal per pass	0.023	kgmol/pass
Mole fraction of water per pass	0.0004	
	0.04	% v/v
Mole fraction is lower than the saturation (15.6%) at 6.5 bar operating pressure		
Hydrogen loss per cycle		
Loss occurs only from the blowdown of vessel gas inventory at the end of each regen cycle.		
(once per 8 hours). Vessel gas volume at 6.5 bar & 50 deg.C		
Blowdown rate	1.32	kgmol
Duration between venting	8	hr
	0.1651	kgmol/hr
Product loss	0.37	% v/v

GREEN HYDROGEN - BALANCE OF PLANT SIZING		Flexera CONSULTING
Regen loop Euipment		
Heater		
Heater rated duty	100.00	KW
Watt density for Hydrogen Service	2	W/cm^2
Total element surface area	50000	cm^2
	5	m^2
Element sheath OD	12.7	mm
Total Element length required	125.32	m
Type of element	U - Bend	
Active length of element each	1.5	m
No of elements required	41.77	
	42.00	
Elemnet arragnment	3	Phase
Element per pahse	14	
Heater Pressure Shell		
Gas velocity inside the shell (prevent hot spot formation)	2.5	m/sec
Gas inlet temperature	40	deg.C
Hydrogen density at 40^0C and 6.5 bar	0.499	kg/m^3
Cross section area of the shell	0.0256	m^2
Diameter of the shell	0.181	m
	181	mm
Selected shell diameter	200	mm
Shell length (element zone + end boxes)	2500	mm
Blower		
Blower taking suction from the knockout drum		
Suction temperature	40	deg.C
Desnity of the gas stream at operating pressure & temperature	0.499	kg/m^3
Gas mass flow rate	115.08	kg/hr
Gas volumetric flow rate	230.50	m^3/hr
Blower head required (assumed)	350	mmWC
Blower power requried	0.81	KW
Blower rated motor	2.2	KW
Gas cooler heat load and HTA calculation		
Gas temperature at the outlet of vessel	100	deg.C
Gas cooled in the heat exchanger	40	deg.C
Temerature difference	60	deg.C
Water mass flow rate during regeneration	39.20	kg/hr
	2.175	kgmol/hr
Water composition in the gas	3.64	% v/v
Vapour pressure of water at 100 deg.C	1.0132	bar
Partial pressure of water at the operating conditon	15.59	% v/v

GREEN HYDROGEN - BALANCE OF PLANT SIZING		Flexera CONSULTING
Vapour pressure of water at 40 deg.C	0.07262	bar
Partial pressure of water at the operating conditon	1.12	% v/v
Water concentration in the outlet gas	0.0112	mol fraction
Mass flow rate of water in the outllet	11.71	kg/hr
Mass flow rate of water condensed	27.48	kg/hr
Heat Duty Calculation		
Hydrogen sensible heat load	24165.84	kcal/hr
Water vapour sensible heat load	1058.39	kcal/hr
Condensing heat load	14841.89	kcal/hr
Total cooler heat duty	40066.12	kcal/hr
Cooling water inlet temperature	32	deg.C
Cooling water outlet temperature	40	deg.C
Cooling water temperature difference	8	deg.C
Cooling water mass flow rate	5008.27	kg/hr
Overall heat transfer coefficient (assumption)	60	kcal/hr m^2 deg.C
LMTD	25.81	deg.C
Heat transfer area	25.87	m^2
Hot fluid location	Tube Side	
Cold fluid location	Shell tube	
Knockout Drum Sizing		
Drum orientation	Vertical	
Geomentry	Cylindrical, Both side dish end	
Mass flowrate of gas	230.50	m^3/hr
Gas density	0.499	kg/m^3
Liquid density	992	kg/m^3
Gas superficial velocity constant	0.04	m/sec
Gas superficial velocity	1.78	m/sec
Cross section area of the vessel	0.04	m^2
Diameter of the drum	0.21	m
	213.85	mm
Selected diameter of the knockout drum	300	mm
Knock outdrum tan to tan height	1500.00	mm
Knock out drum shall be equipped with mesh pad to prevent the liquid carry over.		