MIT Carbon Sequestration Forum VII

Pathways to Lower Capture Costs

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Oxyfuel Pathways

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Oxyfuel Technology for CO_2 Capture - Definition:

- Fuel + oxygen + diluent (optional)
- Diluent can be H_2O or CO_2
  - i.e. Flue gas recycle
- Diluent controls combustion temperature

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Oxyfuel Technology for CO_2 Capture - Characteristics:

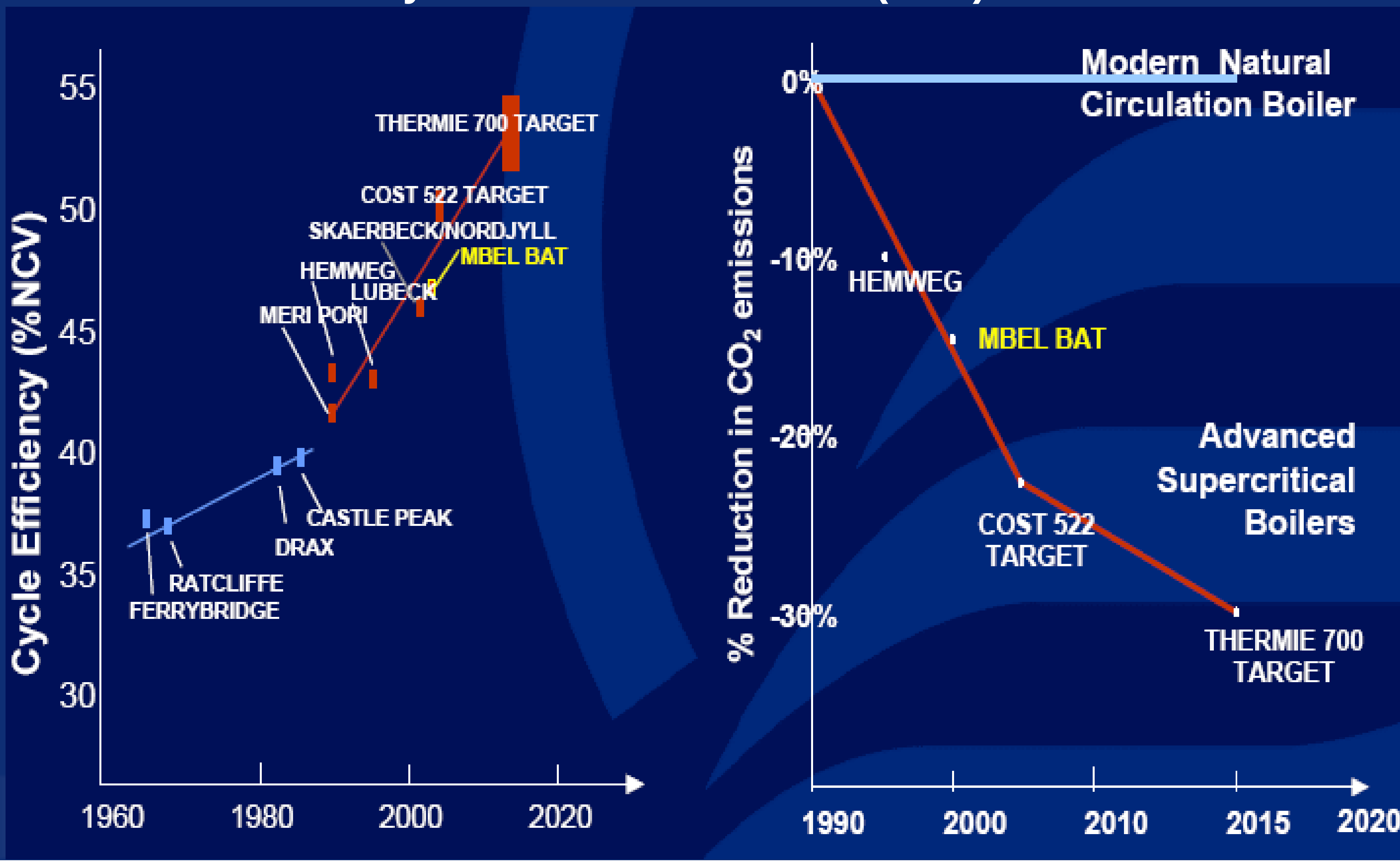
- **Minimises CO_2 impurities**
  - **N_2 and Ar from air ingress and oxygen impurities**
  - **O_2 excess from combustion**
- **Within the combustor all impurity concentrations derived from coal are increased**
  - **SO_2/SO_3, Hg, etc.**
- **Independent control of combustion temperature and excess oxygen level**

Oxyfuel Applications

- **Coal-fired boiler for power generation**
- **Oxyfuel gas turbine**
- **Oxyfuel high pressure steam generator – Clean Energy Systems**
- **Advanced Zero Emission Power Plant – Norsk Hydro**

Pulverised Coal Supercritical Steam Boilers

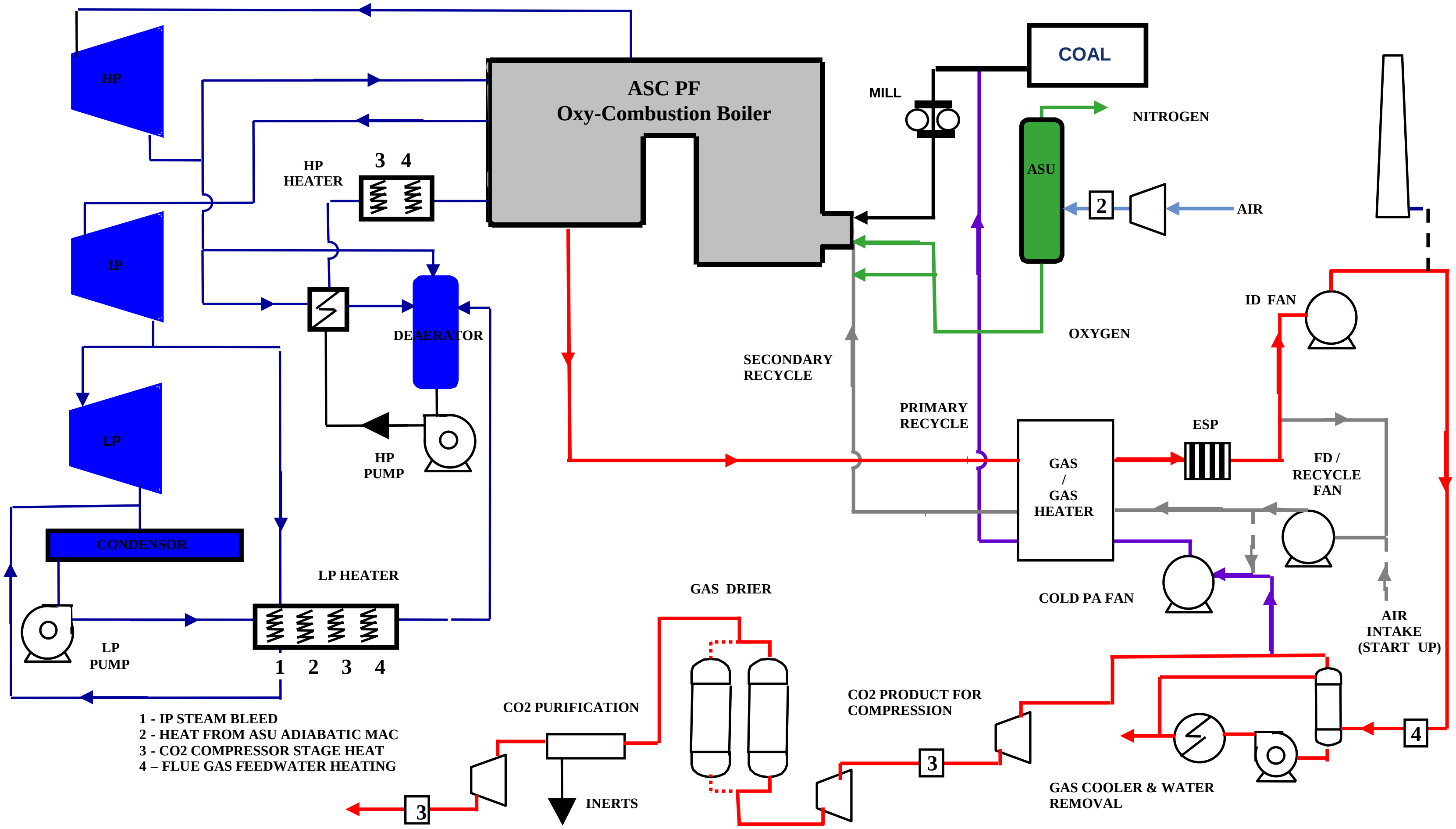
There have been rapid advances in generation efficiency.
Planned efficiency increases above 50% (LHV)



Design Study On Supercritical PF Coal Boiler With Oxyfuel

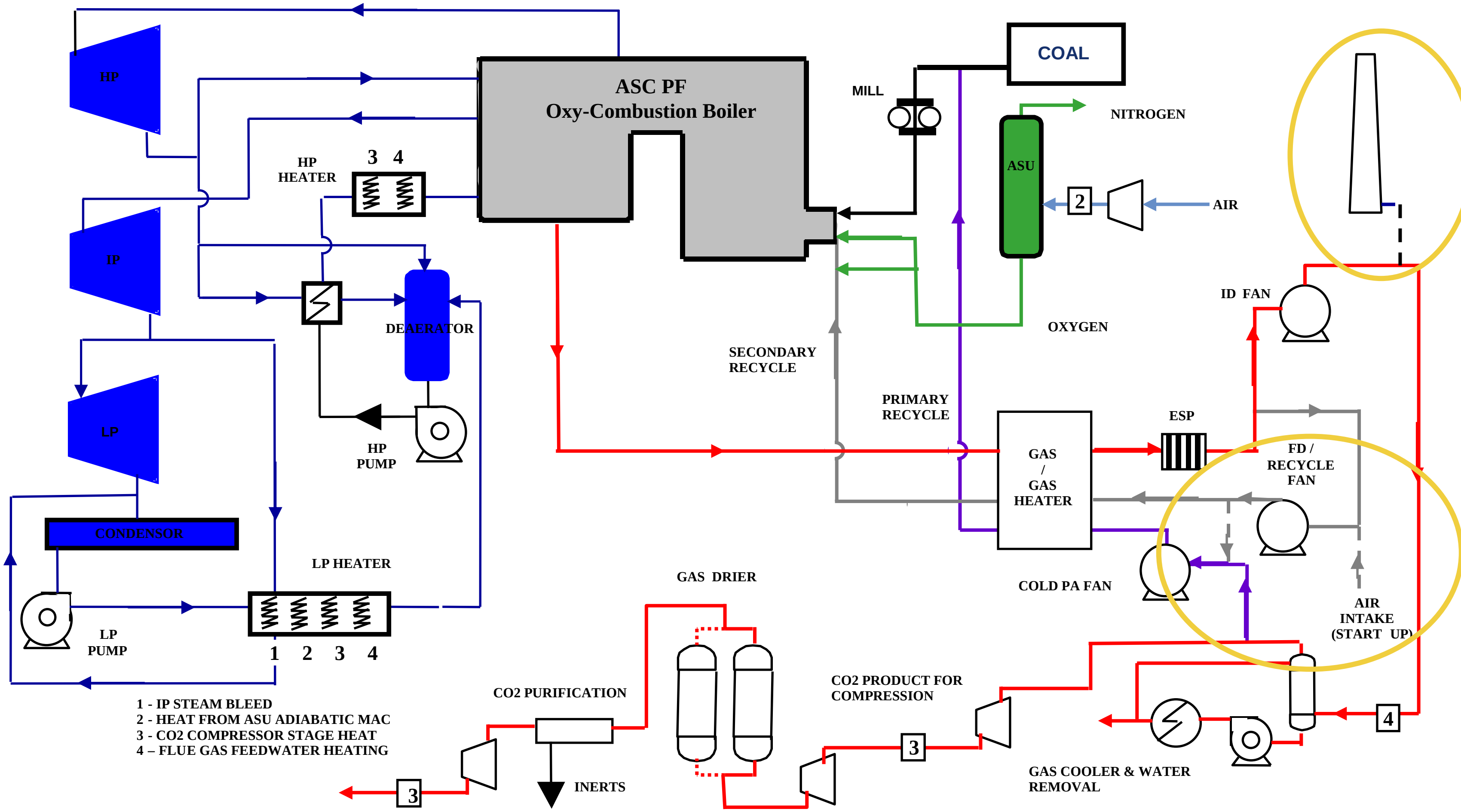
- Based on a study carried for the International Energy Agency Greenhouse Gas R and D programme
- Air fired boiler 677 MWe net output, Australian coal, new build, N. European location, SCR and flue gas desulphurisation
- Steam conditions 290 bar, 600°C/620°C, 40 mbar condenser 44.2% net efficiency (LHV)
- Oxyfuel system based on 95 mol% O_2 from 2 cryogenic air separation units each 5187 tonnes/day contained O_2 at 1.7 bara
- CO_2 purified to 98% and compressed to pipeline pressure of 110 bar

Schematic of Supercritical PF Oxyfuel Power Plant With CO_2 Capture



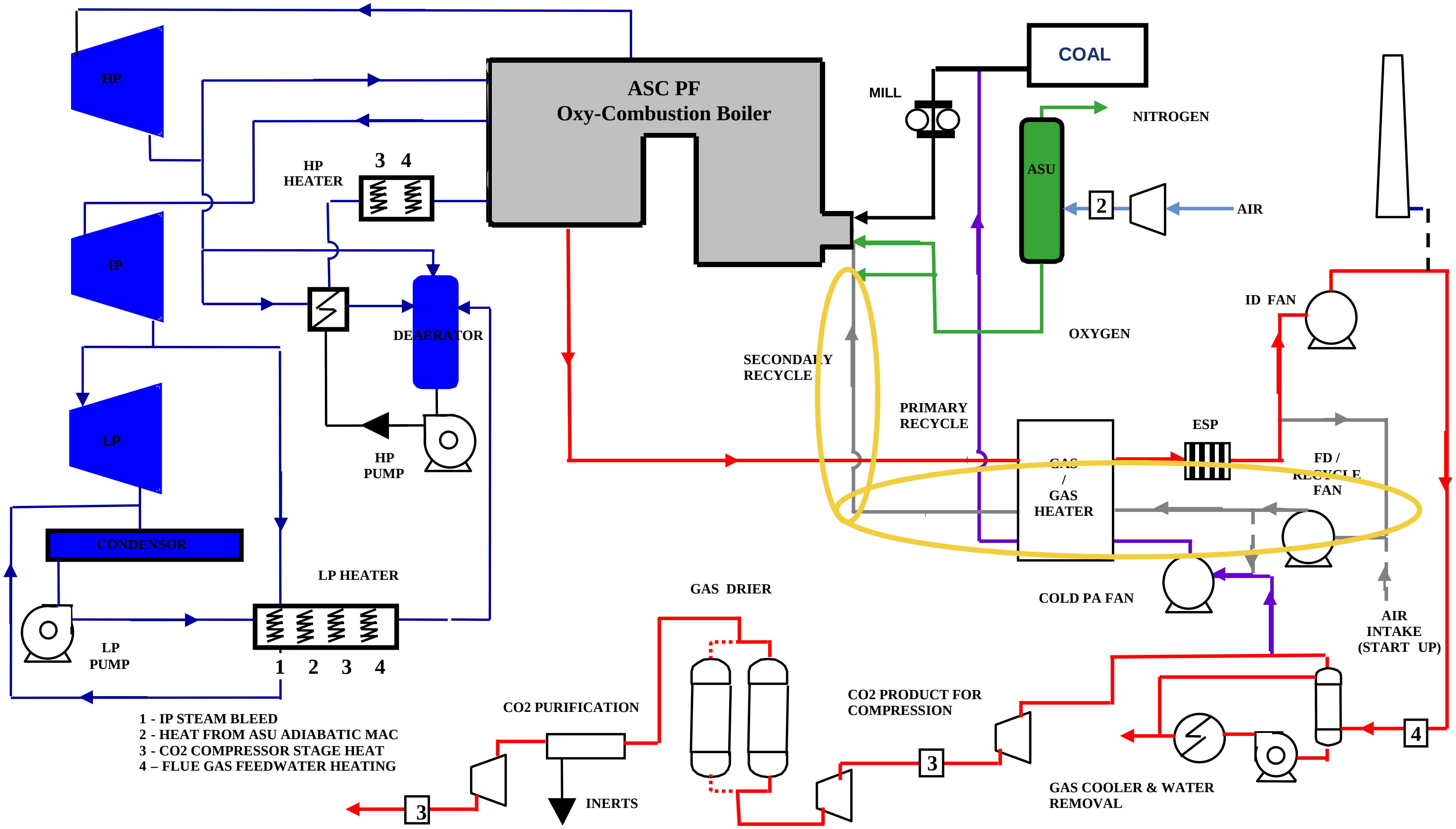
1 - IP STEAM BLEED
2 - HEAT FROM ASU ADIABATIC MAC
3 - CO2 COMPRESSOR STAGE HEAT
4 – FLUE GAS FEEDWATER HEATING

Schematic of Supercritical PF Oxyfuel Power Plant With CO_2 Capture



Capable of air or oxyfuel firing

Schematic of Supercritical PF Oxyfuel Power Plant With CO_2 Capture



Hot recycle gas for secondary flow

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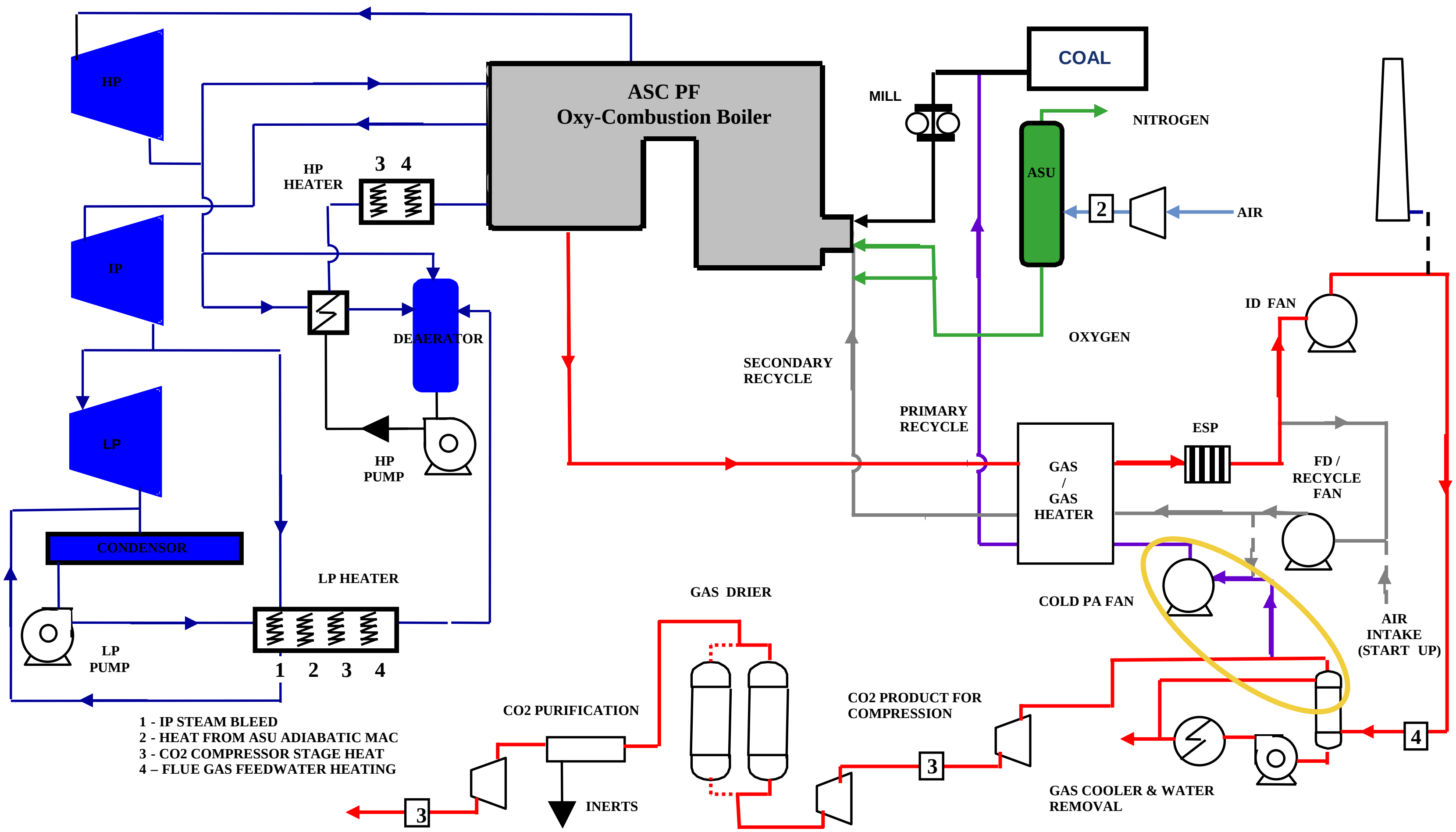
Schematic of Supercritical PF Oxyfuel Power Plant With CO_2 Capture



Cool primary recycle gas to ambient to minimise water content

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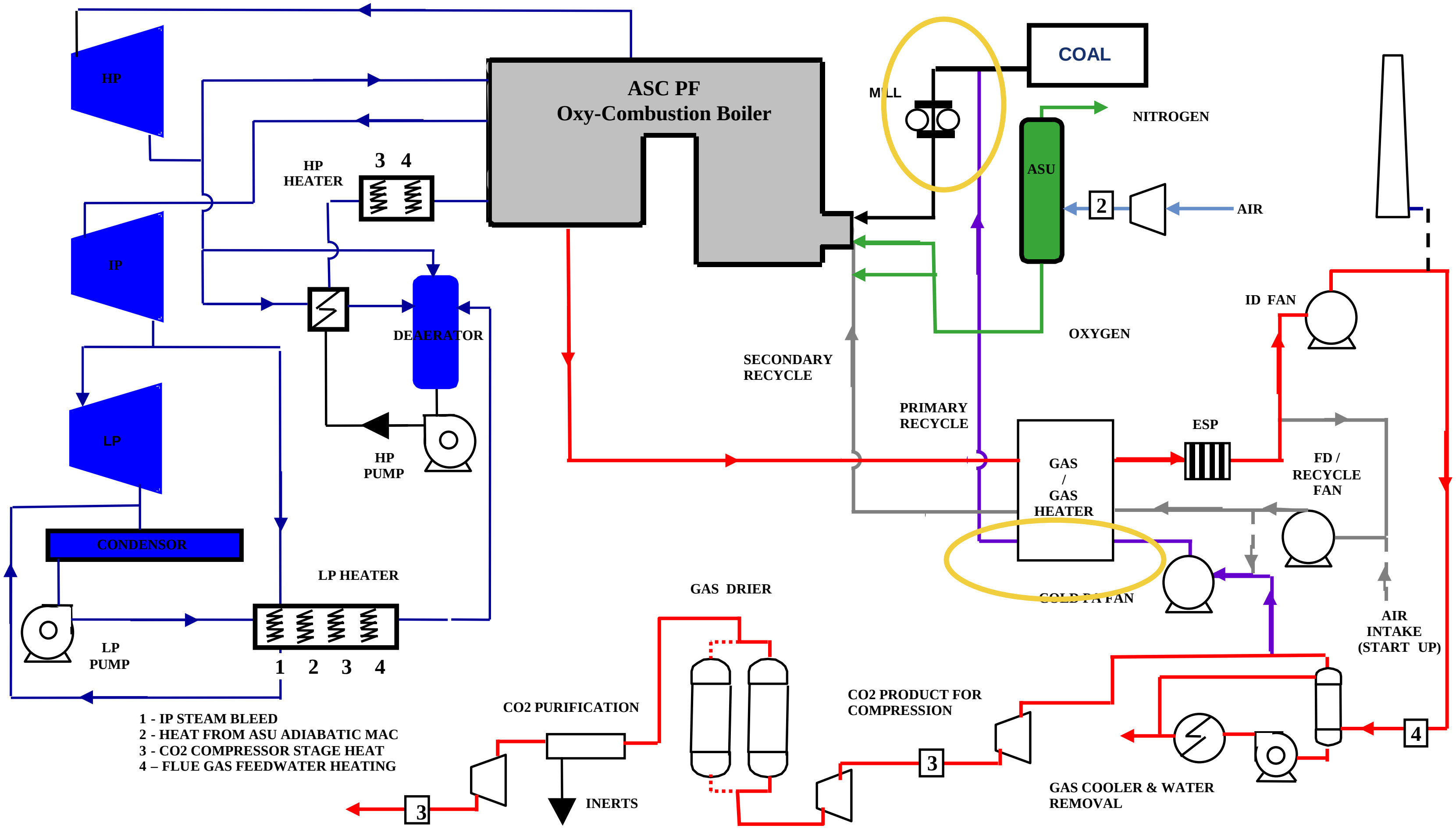
Schematic of Supercritical PF Oxyfuel Power Plant With CO_2 Capture



Heat primary gas and pass through coal mill

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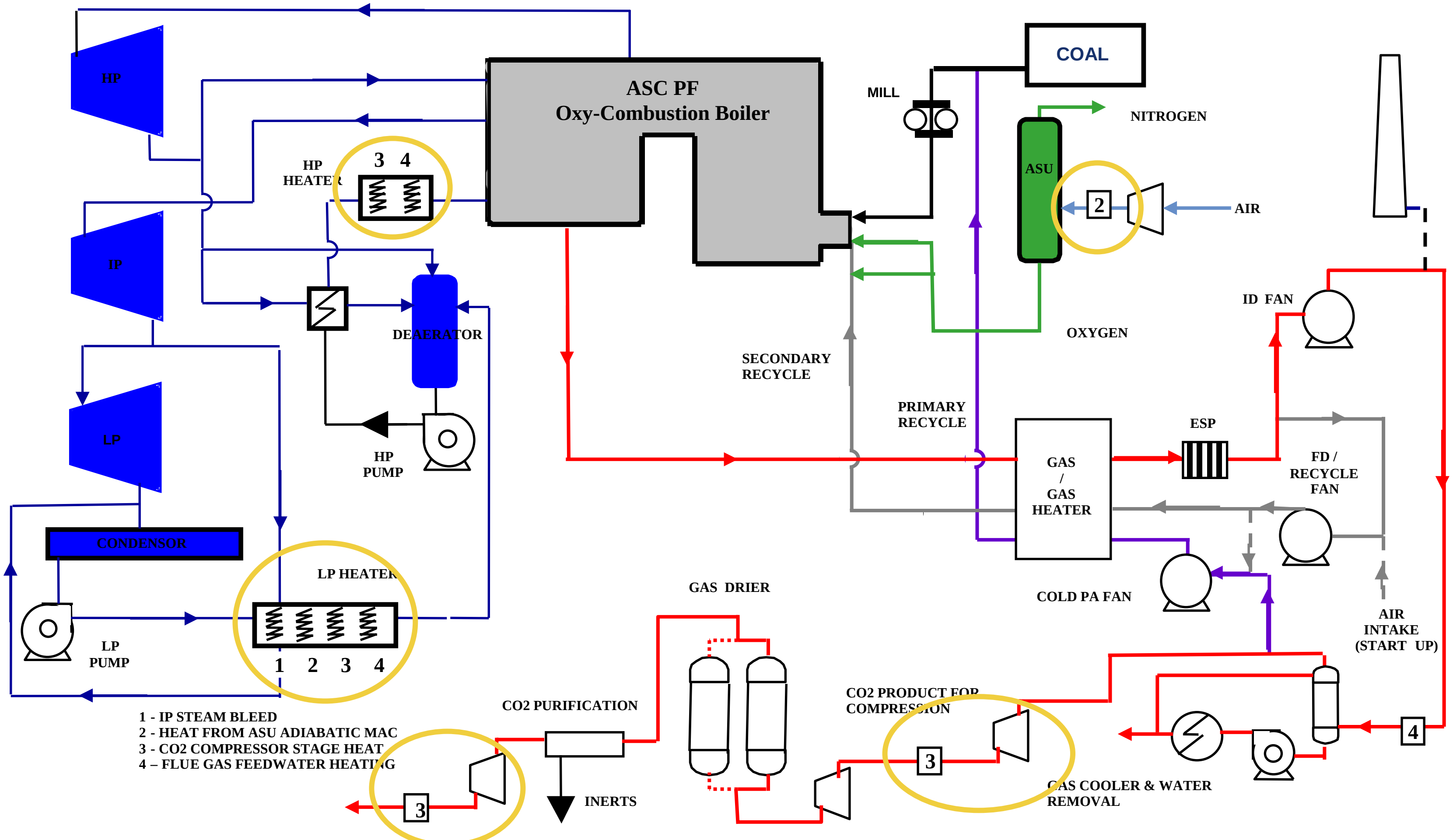
Schematic of Supercritical PF Oxyfuel Power Plant With CO_2 Capture



Use of adiabatic compression of air and CO_2 to allow heat recovery to condensate and boiler feed water

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Supercritical PF Oxyfuel Power Plant With CO_2 Capture – Summary of Features

- Capable of air or oxyfuel firing
- Hot recycle gas for secondary flow
- Cool primary recycle gas to ambient to minimise water content
- Heat primary gas and pass through coal mill
- Use of adiabatic compression of air and CO_2 to allow heat recovery to condensate and boiler feed water
- Increased radiant heat transfer in the boiler
- 3 times higher SO_2 concentration due to flue gas recycle
- Can be retrofitted to existing PF coal fired power plants

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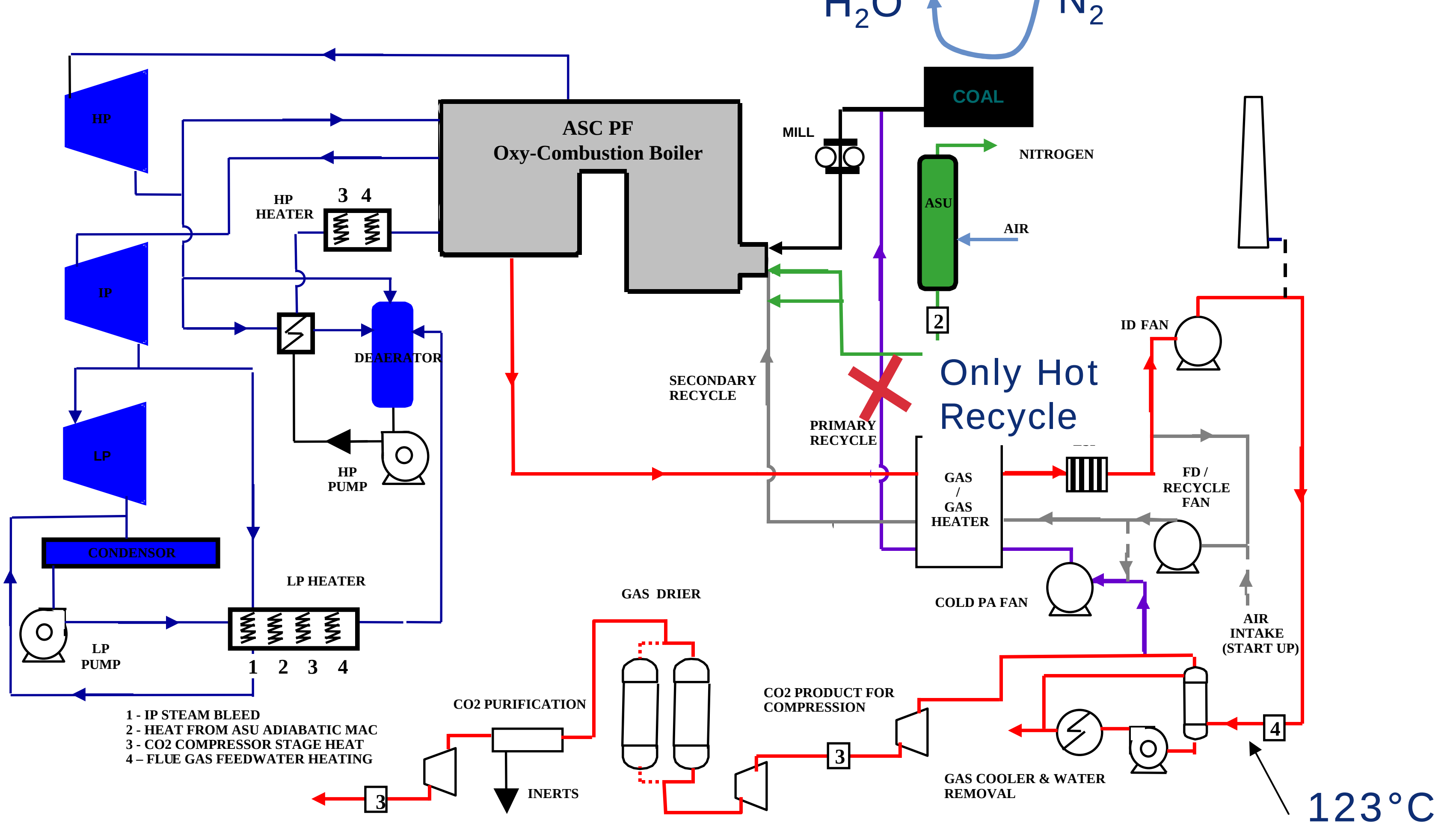
ASC PF Oxy-Combustion Power Plant – IEA GHG Study

- ASU 12% of gross power output
- ASU Optimised for low power consumption

		ASC PF Air Fired Power Plant Without CO_2 Capture	ASC PF Oxy-Combustion Power Plant With CO_2 Capture
Fuel Input	kg/s	59.19	58.09
Fuel Heating Value	MJ/kg (LHV)	25.86	25.86
Fuel Heat Input	MW_{th} (LHV)	1530.8	1502.2
O_2 Input (contained)	tonne/day	-	10,373
Gross Power Output	MW_e	**740**	**737**
ASU Power	MW_e	-	87
CO_2 Compression & Purification	MW_e	-	65
Power Plant Auxiliaries	MW_e	63	53
Net Power Output	MW_e	677	532
Gross Efficiency	% LHV	48.3	49.06
Net Efficiency	% LHV	**44.2**	**35.4**
Efficiency Reduction	**% points**	**-**	**8.8**

Optimised Oxy-Combustion Power Plant



Efficiency 35.6% 36.1% 36.3% 36.4% 36.6%

Only Hot Recycle | + Coal Drying | + O_2 Preheat with IP Steam

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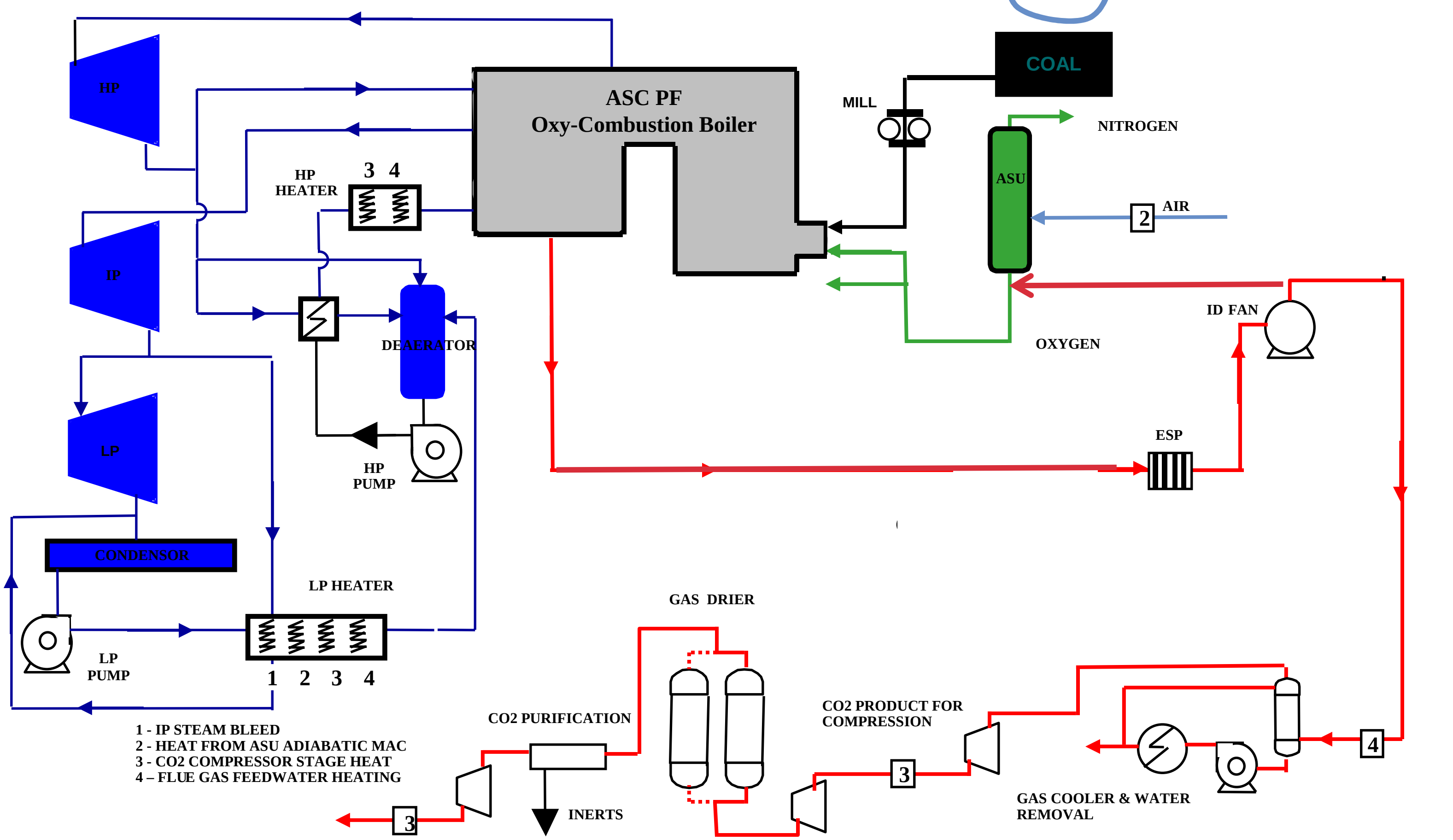
Optimised Oxy-Combustion Power Plant



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Optimised Oxyfuel Flowsheet

- **Design of the station for air and oxygen or oxygen alone**
- **Option for coal drying with dry nitrogen from the ASU**
- **Allows total hot gas recycle, removal of 2 blowers, gas-gas exchanger and improves efficiency**
- **Dust removal in a closed cycle oxyfuel system – options for ESP operation at higher temperature**
- **First estimate for the duty of the boiler/steam turbine/auxiliary system following supercritical conversion. This will enable us to complete the overall process design of the oxyfuel and CO_2 compression system and its heat integration with the base case supercritical conversion project.**

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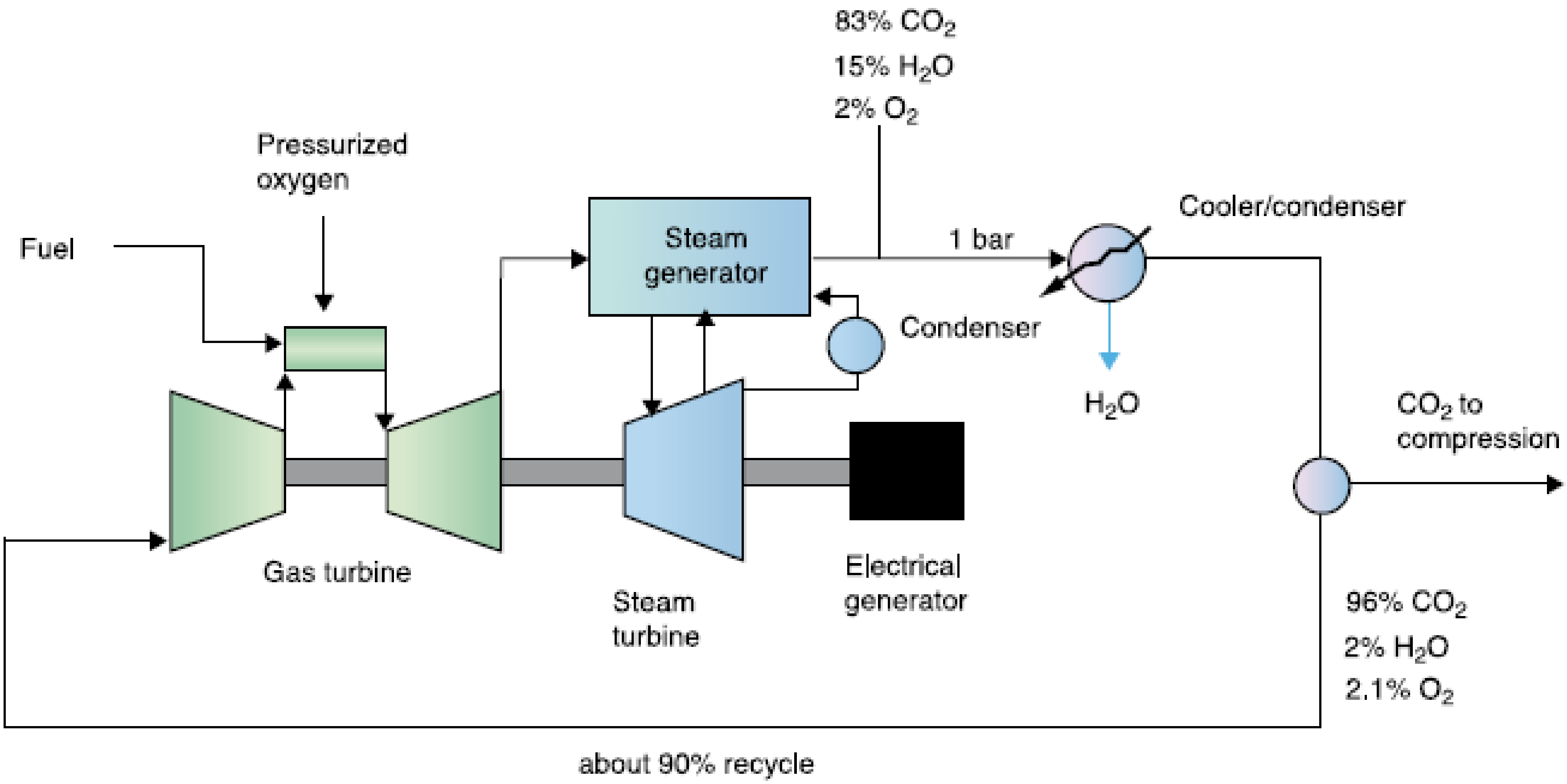
Oxyfuel Gas Turbine



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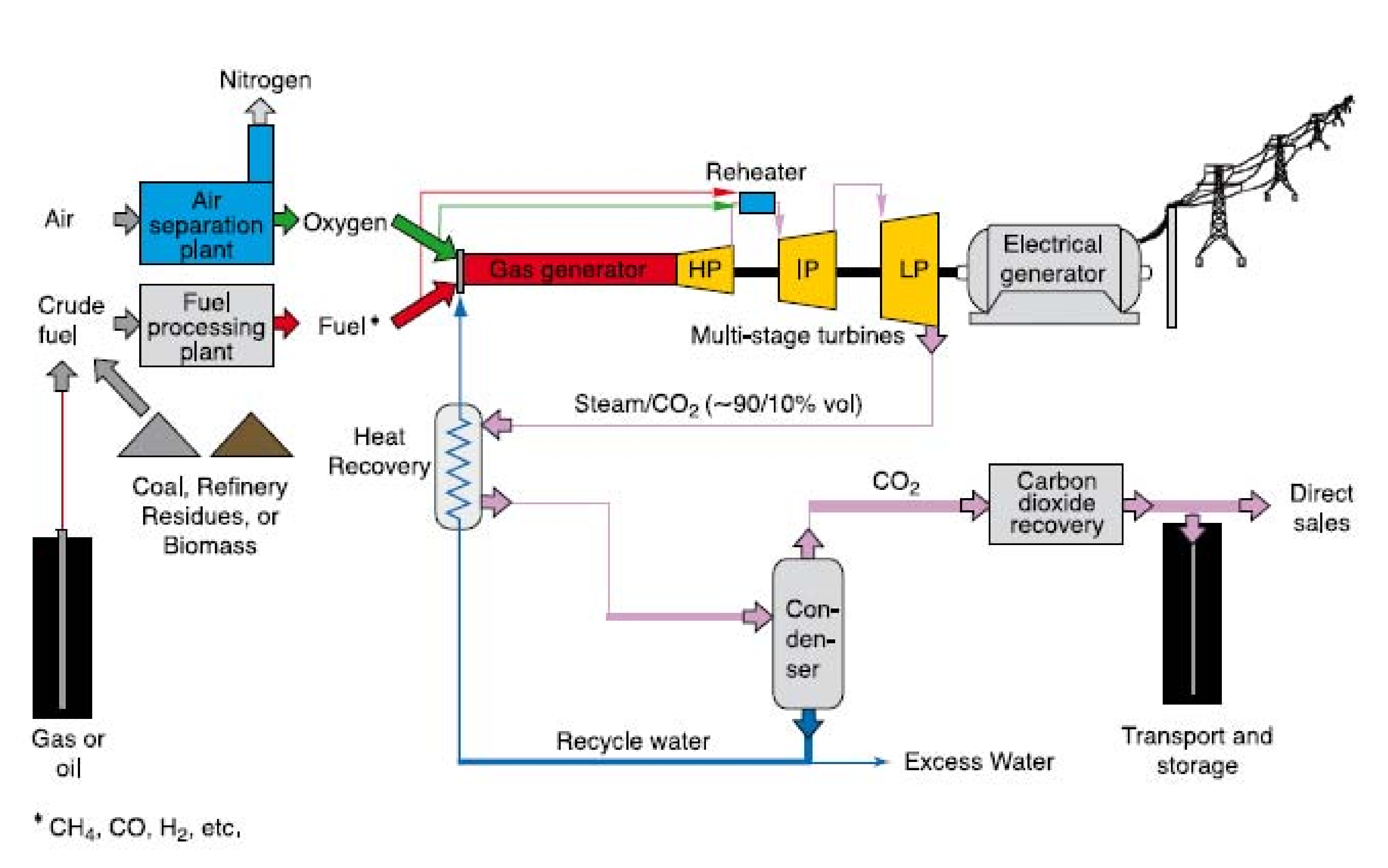
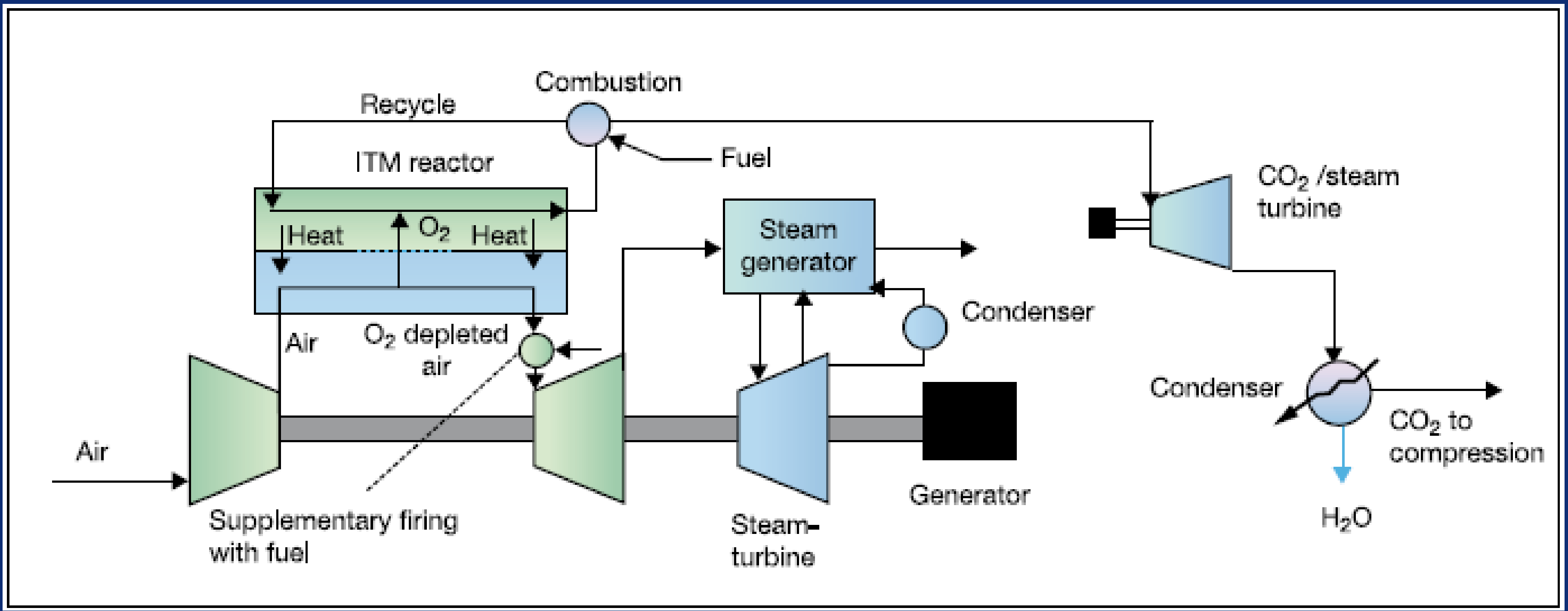
NGCC Oxy-Combustion Power Plant – IEA GHG Study

		Typical NGCC Air Fired Power Plant Without CO_2 Capture	NGCC Oxy-Combustion Power Plant With CO_2 Capture
Fuel Input	kg/s	14.77	20.32
Fuel Heating Value	MJ/kg (LHV)	46.90	48.45
Fuel Heat Input	MW_{th} (LHV)	692.9	984.5
O_2 Input (contained)	tonne/day	-	6,840
Gross Power Output	MW_e	400	575
ASU Power	MW_e	-	70
CO_2 Compression & Purification	MW_e	-	49
Power Plant Auxiliaries	MW_e	12	18
Net Power Output	MW_e	**388**	**440**
Gross Efficiency	% LHV	57.7	58.4
Net Efficiency	% LHV	**56.0**	**44.7**
Efficiency Reduction	**% points**	**-**	**11.3**

High Pressure Oxyfuel Steam Combustor – Clean Energy Systems



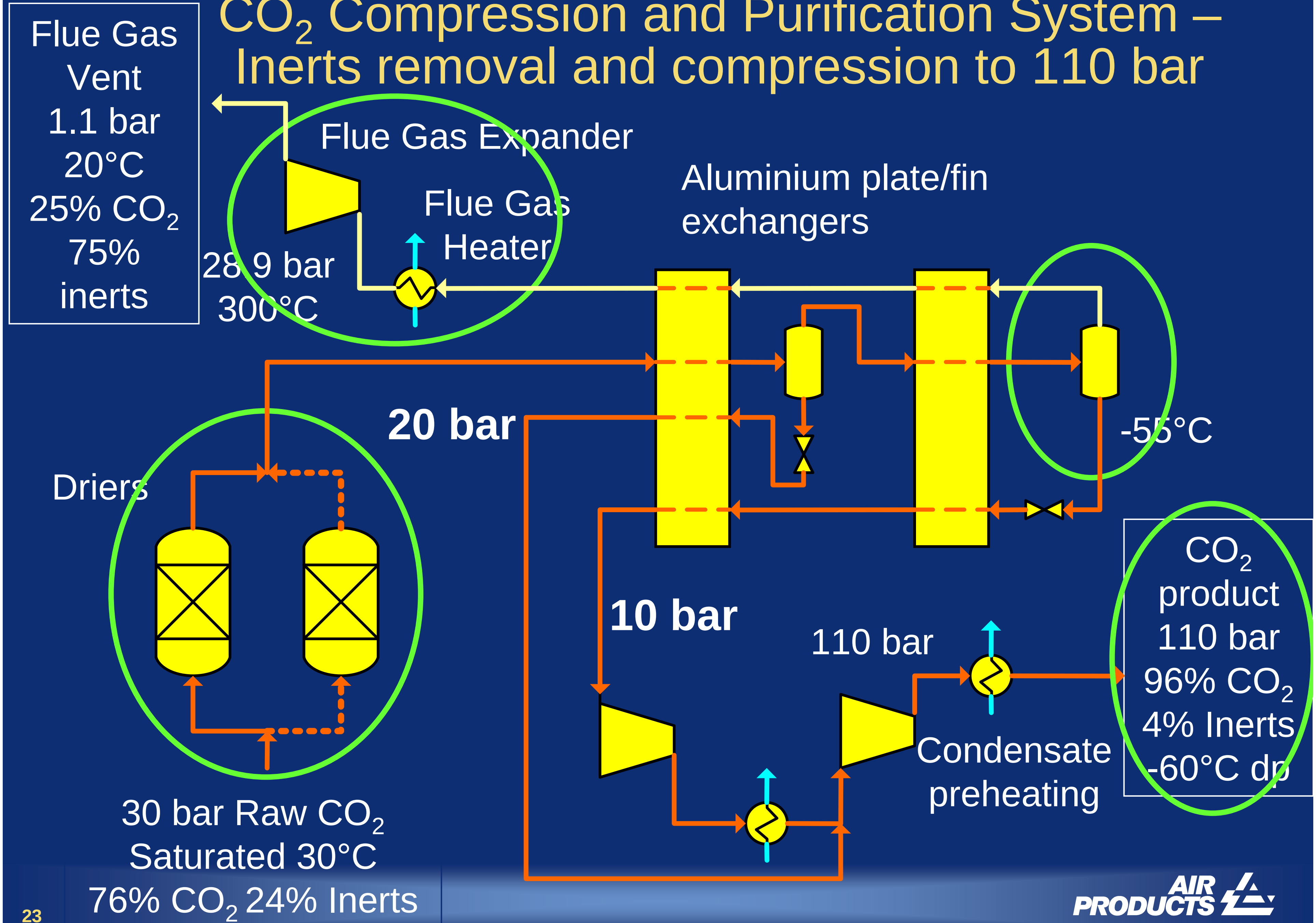
Advanced Zero Emission Power Plant – AZEP, Norsk Hydro



Purification of Oxyfuel-Derived CO_2 for Sequestration or EOR

- **CO_2 produced from oxyfuel requires purification**
  - **Cooling to remove water**
  - **Inerts removal**
  - **Compression**
- **Current design have limitations**
  - **SOx/NOx removal**
  - **Oxygen removal**
- **A new concept for purification has been developed**
  - **Includes SOx/NOx and oxygen removal**

CO_2 Compression and Purification System – Inerts removal and compression to 110 bar



Raw and Product CO_2 Compositions From IEA GHG Report – Assumed SO_2 passed through to the CO_2 Product

	Raw Flue Gas @ 35°C, 1.02 bara mol%	CO_2 Product @ 35°C, 110 bar mol% Prior Art	Vent @ 11°C, 1.1 bar mol% Prior Art
CO_2	71.5	95.8	24.6
N_2	14.3	2.0	48.7
O_2	5.9	1.1	19.4
Ar	2.3	0.6	7.1
SO_2	0.4	0.5	0
NO	400 ppm	13 ppm	1180 ppm
NO_2	10 ppm	0	0
H_2O	5.6	0	0

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CO_2 Purity Issues

	Basic Design Case	EOR Case
H_2O	< 500 ppm	< 50 ppm
CO_2	> 90% mol	> 90% mol
SO_2	From H&MB	< 50 ppm
NO	From H&MB	From H&MB
O_2	< 4% mol	100 ppm
Ar + N_2 + O_2	< 4% mol	< 4% mol

- **Regulations regarding onshore and off-shore disposal are being drafted world-wide**
- **Co-disposal of other wastes (NOx, SOx, Hg) is a sensitive issue**
- **Important that the CO_2 can be purified for disposal or EOR**

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NOx SO_2 Reactions in the CO_2 Compression System

- **We realised that SO_2, NOx and Hg can be removed in the CO_2 compression process, in the presence of water and oxygen.**
- **SO_2 is converted to Sulphuric Acid, NO_2 converted to Nitric Acid:**
  - $NO + ½ O_2 = NO_2$ (1) Slow
  - $2 NO_2 = N_2O_4$ (2) Fast
  - $2 NO_2 + H_2O = HNO_2 + HNO_3$ (3) Slow
  - $3 HNO_2 = HNO_3 + 2 NO + H_2O$ (4) Fast
  - $NO_2 + SO_2 = NO + SO_3$ (5) Fast
  - $SO_3 + H_2O = H_2SO_4$ (6) Fast
- **Rate of Reaction 1 increases with Pressure to the 3rd power**
  - **only feasible at elevated pressure**
- **No Nitric Acid is formed until all the SO_2 is converted**
- **Pressure, reactor design and residence times, and NO concentration are important**

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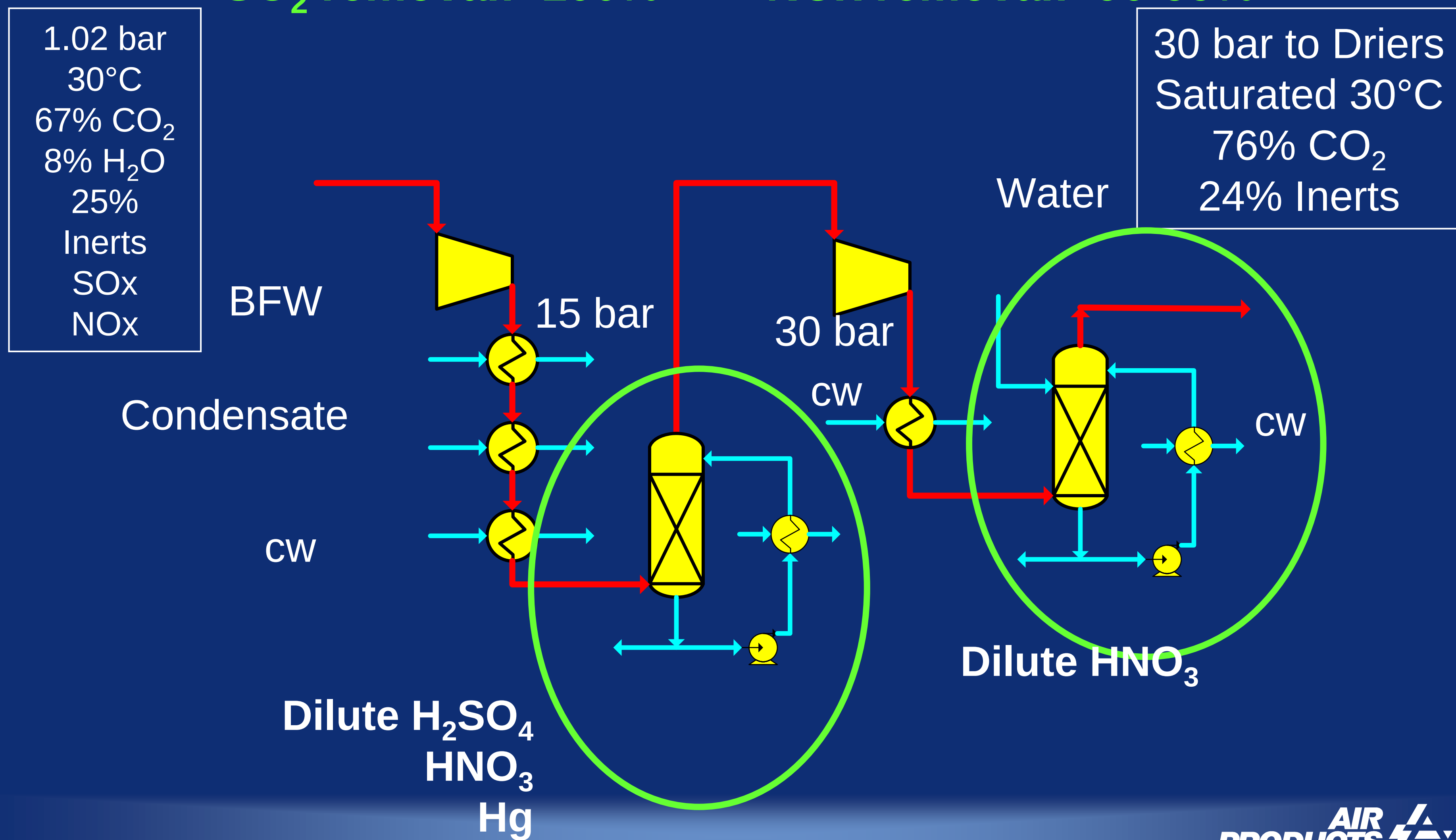
CO_2 Compression and Purification System – Removal of SO_2, NOx and Hg

- **SO_2 removal: 100%   NOx removal: 90-99%**



SOx/NOx Removal – Key Features

- Adiabatic compression to 15 bar:
  - No interstage water removal
  - All Water and SOx removed at one place
- NO acts as a catalyst
  - NO is oxidised to NO_2 and then NO_2 oxidises SO_2 to SO_3: The Lead Chamber Process
- Hg will also be removed, reacting with the nitric acid that is formed

Corrected CO_2 Purity

	Raw Flue Gas @ 35°C, 1.02 bara mol%	CO_2 Product @ 35°C, 110 bar mol% Prior Art	Vent @ 11°C, 1.1 bar mol% Prior Art	CO_2 Product @ 35°C, 110 bar mol% Corrected	Vent @ 11°C, 1.1 bar mol% Corrected
CO_2	71.5	95.8	24.6	96.3	24.6
N_2	14.3	2.0	48.7	2.0	48.7
O_2	5.9	1.1	19.4	1.1	19.4
Ar	2.3	0.6	7.1	0.6	7.1
SO_2	0.4	0.5	0	0	0
NO	400 ppm	13 ppm	1180 ppm	< 10 ppm	< 100 ppm
NO_2	10 ppm	0	0	< 10 ppm	0
H_2O	5.6	0	0	0	0

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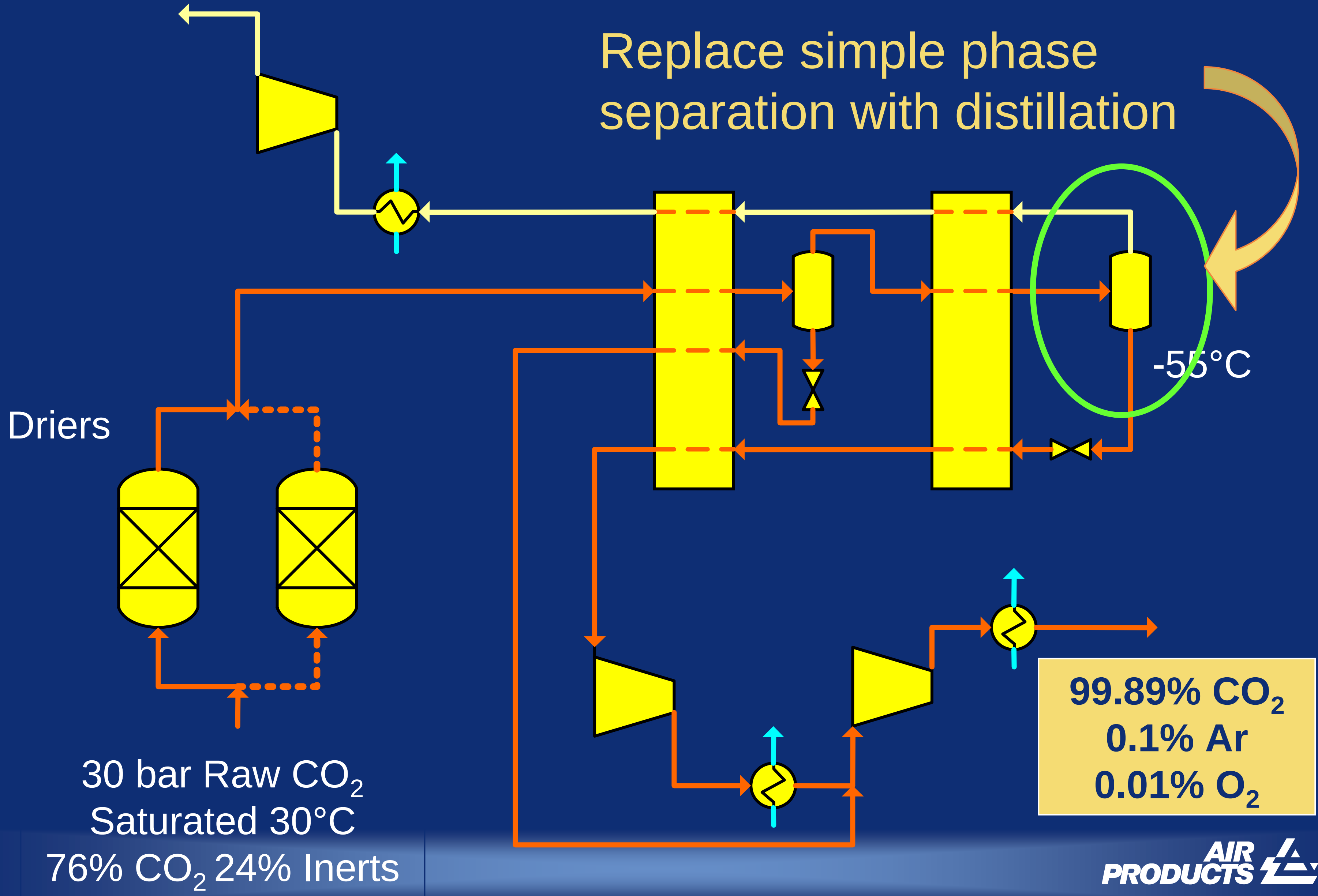
And Oxygen removal from the CO_2?



The Cost of Higher Purity CO_2

- Case 1: "Standard" dual flash system
- Case 2: Extra flash at cold end
- Case 3: Distillation at cold end
- Power is to 110 bar and uses adiabatic compression from 1 to 15 bar and from 20 to 110 bar
  - Heat is recovered to the steam system

	CO_2 Purity	Oxygen Content	CO_2 Recovery	Power kWhr/tonne
Case 1	95.9 mol%	0.9 mol%	89.0%	168.5
Case 2	98 mol%	0.4 mol%	87.0%	166.5
Case 3	99.97 mol%	10 ppmv	87.4%	177.1

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Summary of CO_2 Purification

- FGD and DeNOx systems are not required to meet tight CO_2 purity specifications
- Co-disposal of SO_2 with CO_2 is not possible
  - Compressing CO_2 with NO + SO_2 + O_2 + Water will result in H_2SO_4 production
- Low NOx burners are not required for oxyfuel combustion
- Oxygen can be removed for EOR-grade CO_2
- Large-scale demonstration is required
  - Further development is planned

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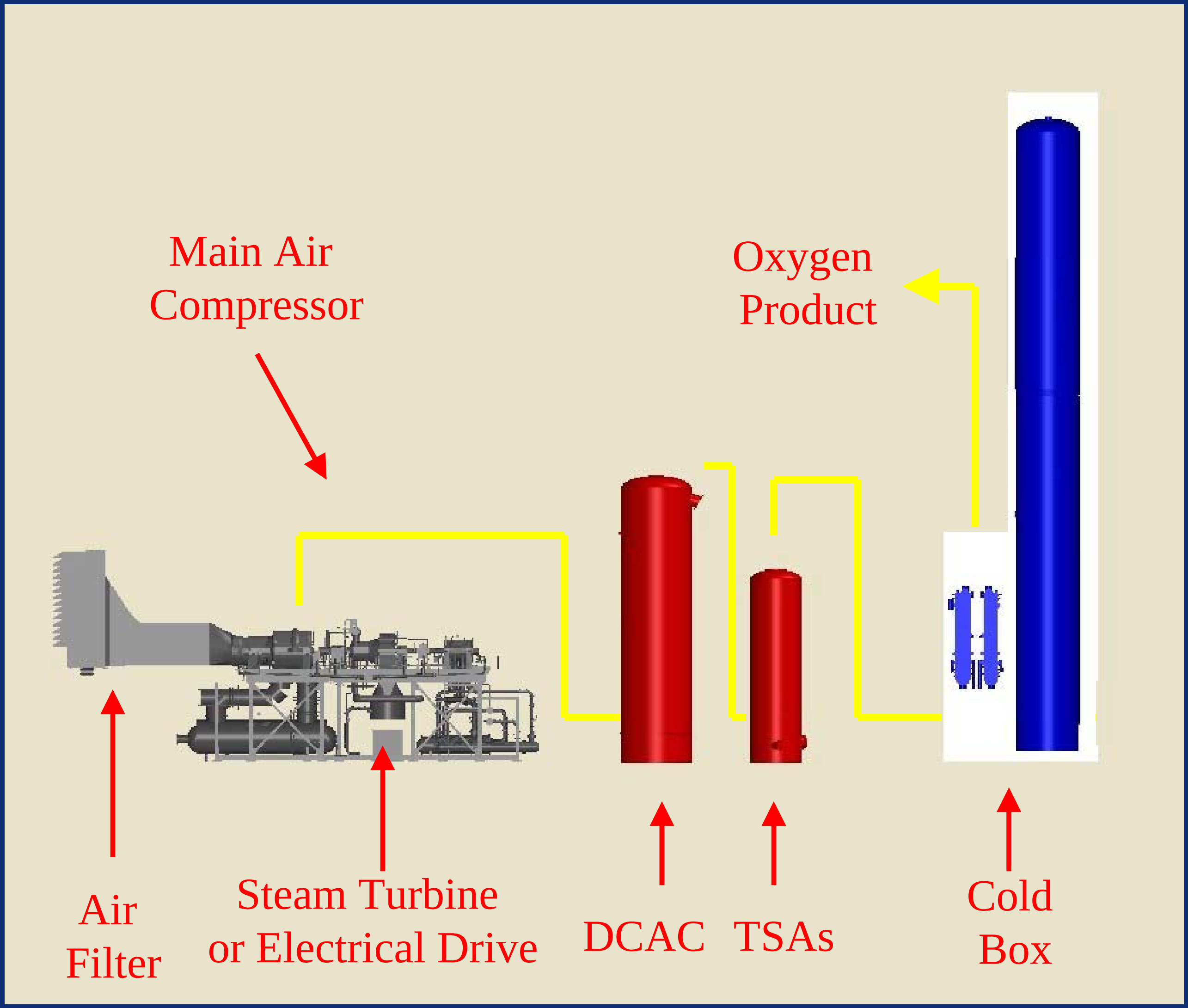
FUTURE DEVELOPMENT OF OXYFUEL ASC BOILER SYSTEM

- Studies on retrofit to existing power stations
- Efficiency increase to 36.4% by improved coal drying using warm N_2, more O_2 preheat, higher temperature gas recycle
- Air firing option can be eliminated, system simplification boiler start system needs development
- Full scale burners must be demonstrated with flue gas recycle
- Ash characteristics/fouling tendency to be verified
- Materials of construction – corrosion
- Development and simulation of effective control systems
- Further optimisation, integration and cost reduction studies

LEADING TO

- Full scale boiler supercritical/oxyfuel conversion for system demonstration

Basic Cryogenic Air Separation Process



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Large size single train plants – 3500 tonne/day for Qatar

Prefabricated modularised design


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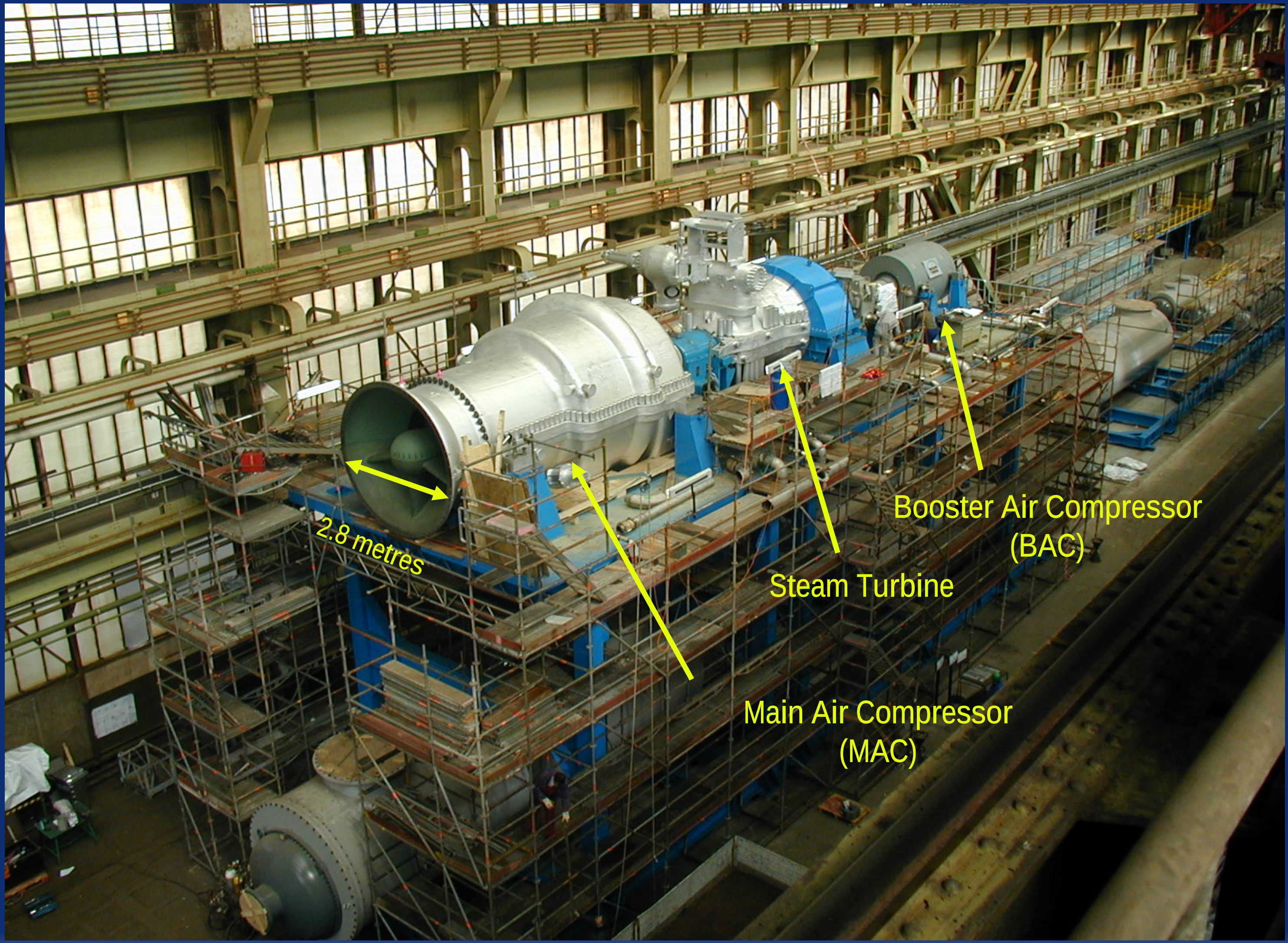
Proven Machinery Systems – Double-ended Steam Turbine



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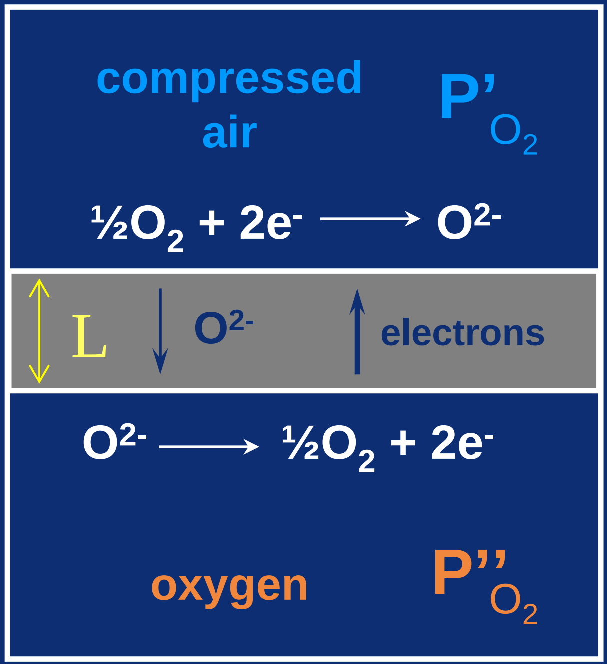
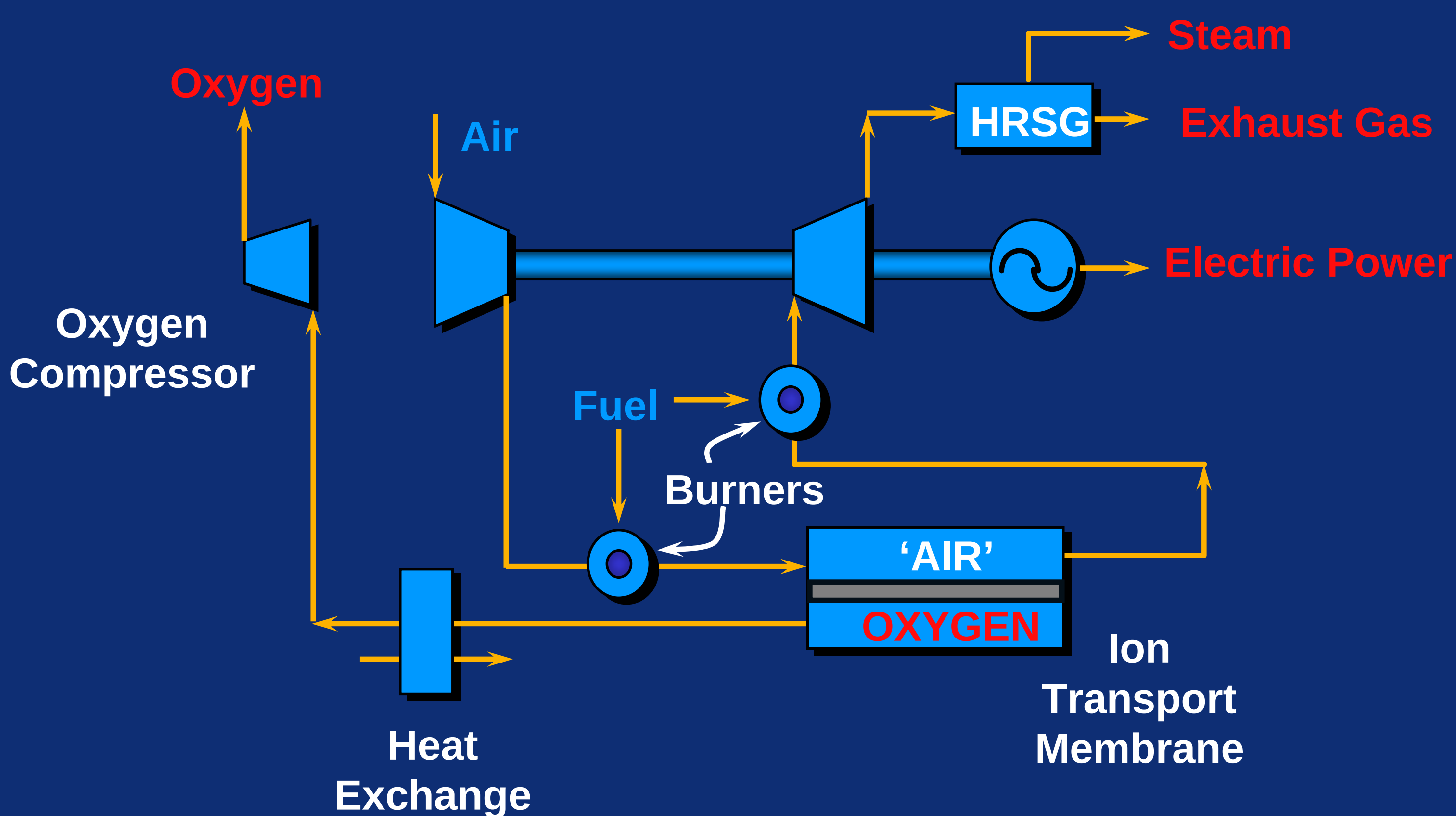
Ion Transport Membranes (ITM): High-flux, High-purity Oxygen

- **Mixed-conducting ceramic membranes (non-porous)**
- **Typically operate at 800-900 °C**
- **Crystalline structure incorporates oxygen ion vacancies**
- **Oxygen ions diffuse through vacancies**
- **100% selective for O_2**
- $O_2 Flux \propto \frac{1}{L} \ln\left(\frac{P'_{O2}}{P''_{O2}}\right)$



Gas Turbine ITM Integration



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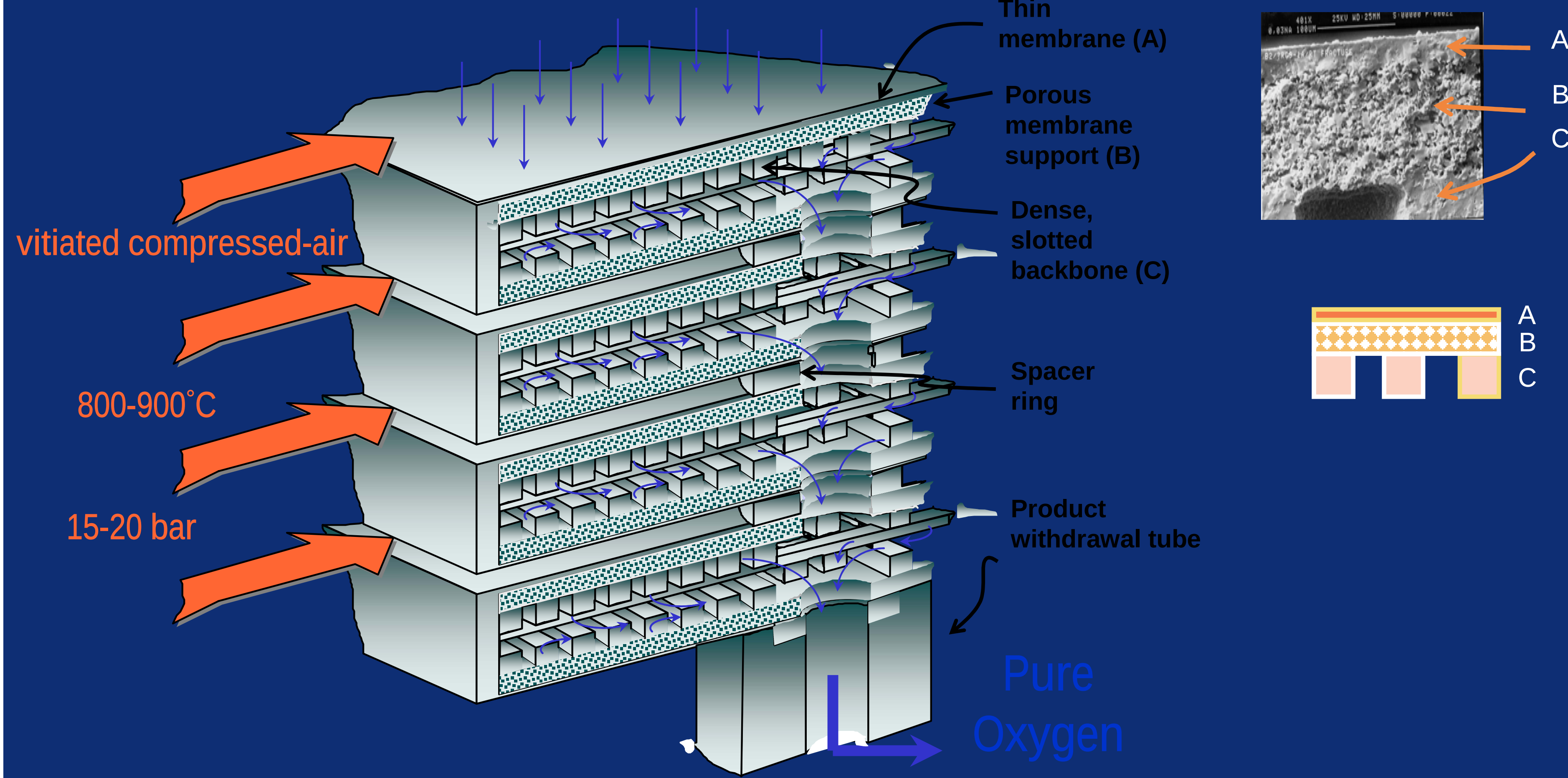
Ion Transport Membrane For Low Cost Oxygen Production



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