

Development in the Air Separation Unit Addressing the Need of Increased Oxygen Demand from the Oxy-Blast Furnace

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AIR PRODUCTS

Outline

- Cryogenic ASU introduction
- ASU developments
- Application of developments to iron & steel with CCS
- Conclusions

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- **Cryogenic ASU introduction**
  - **Process and equipment**
  - **Design considerations**
- ASU developments
- Application of developments to iron & steel with CCS
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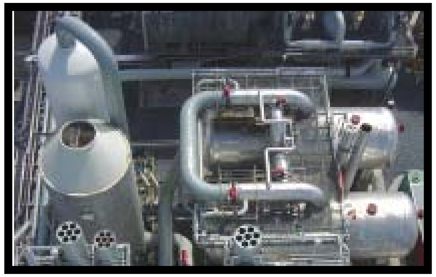
Cryogenic ASU Process and Equipment

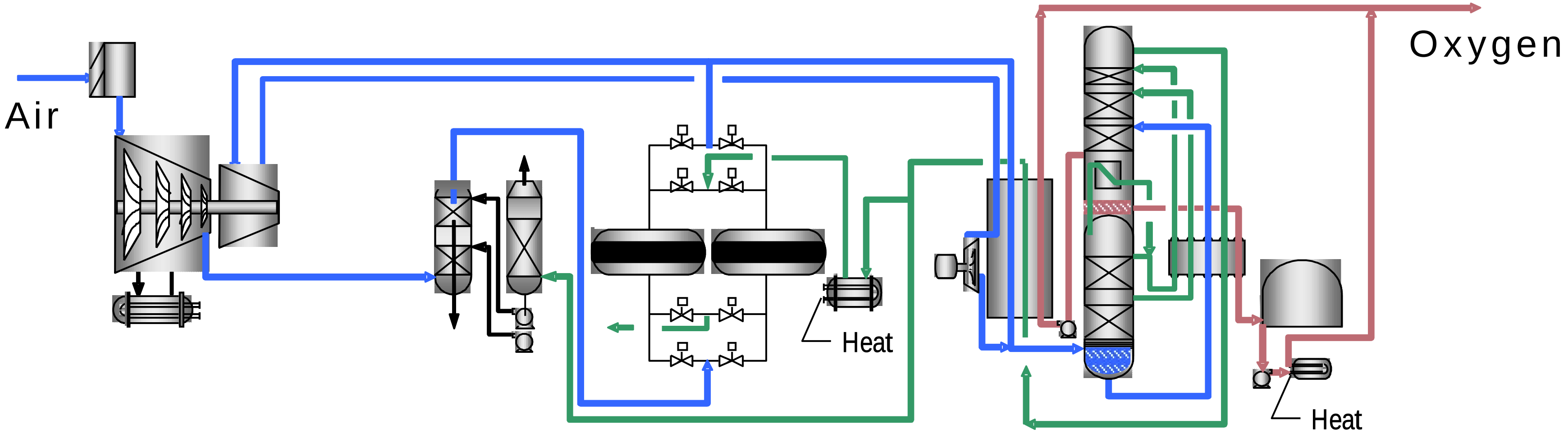
Main and Boost Air Compression

Air Cooling and Pretreatment



Cryogenic Separation

Storage



ASU design considerations

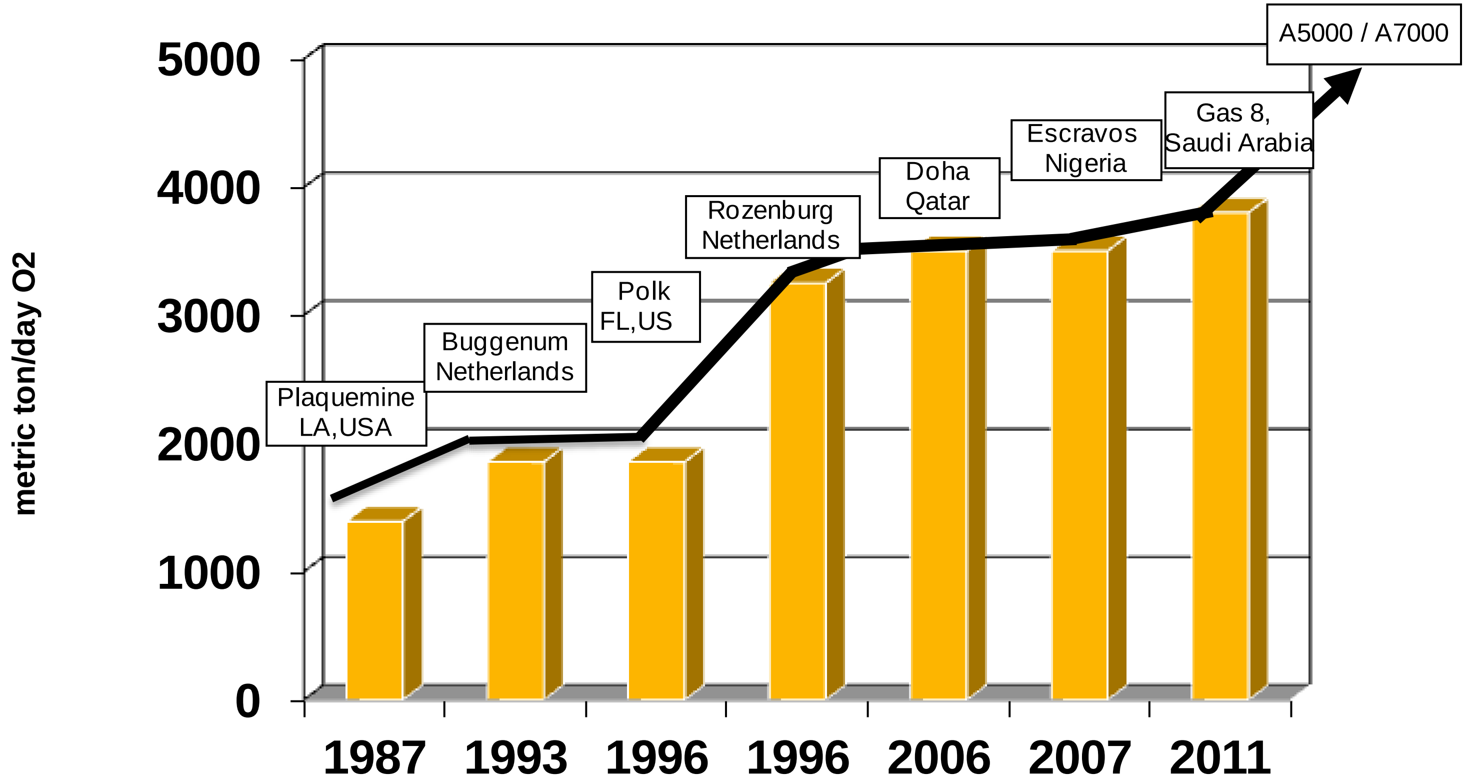
- Process selection and optimisation
  - Power vs. capital costs (€ to save 1kW)
  - Purity requirements (high or low purity oxygen)
  - Co-products (nitrogen or argon, gas or liquid)
  - Compression optimisation and integration
- Manufacturing strategy
  - Transport of components to site (e.g. columns)
  - Reducing construction / erection costs and risks
- Operability
  - Fit with customer's use patterns
    - Turndown / ramping / storage
    - Advanced control capabilities (e.g. MPC)
- Reliability
  - Extra high reliability design?
  - Liquid backup

Outline

- Cryogenic ASU introduction
- **ASU developments**
  - **Train size development**
  - **Equipment**
  - **Cycle development and selection**
- Application of developments to iron & steel with CCS
- Conclusions

Air Products ASU train size development

- **Market drives ASU scale-up**
- **Proven 70% scale-up**
- **Quoting 5000+ metric t/d today**



ASU Equipment - machinery and drives

- Significant part of ASU cost (capital and power)
  - Critical to optimise efficiency vs. capital cost
  - Improved efficiency when power value is high
- Reach referenced machinery limits as train size increases
  - Can use multiple trains for a single cold box
- Centrifugal or axial air compressors
  - Centrifugal up to ~5000 tonnes/day O_2
  - Axial up to ~8000 tonnes/day O_2
    - Blast furnace blower technology
    - GT derived units will be even larger

- Electric Motor or Steam Turbine drive
  - Motors simplify operation but may have starting issues
  - Steam turbines more efficient for power generation than mechanical drives – balances extra electrical losses

ASU equipment - front-end development

- Packing selection for DCAC and CWT
  - Reduced pressure drop
  - Minimise diameter
- New adsorbent development
  - Increased capacity (smaller vessels)
  - To remove additional contaminants (e.g. N_2O)
  - Lower cost (cost/performance ratio)
- Regeneration cycle development
  - Reduced energy input
  - Lower temperature regeneration
- Reduced pressure drops when power value is high

ASU cold box equipment development

- Main heat exchanger development and optimisation
  - Improved heat transfer
  - Lower pressure drop
  - Larger core sizes
  - Lower cost suppliers
- Distillation column development
  - Cryogenic distillation test rig
  - High capacity structured packing
  - Cost-effective internals
  - Smaller column diameters
  - Reduced pressure drop
- Reboiler development and safety
  - Safe downflow reboiler design
  - Efficient thermosyphon reboiler design

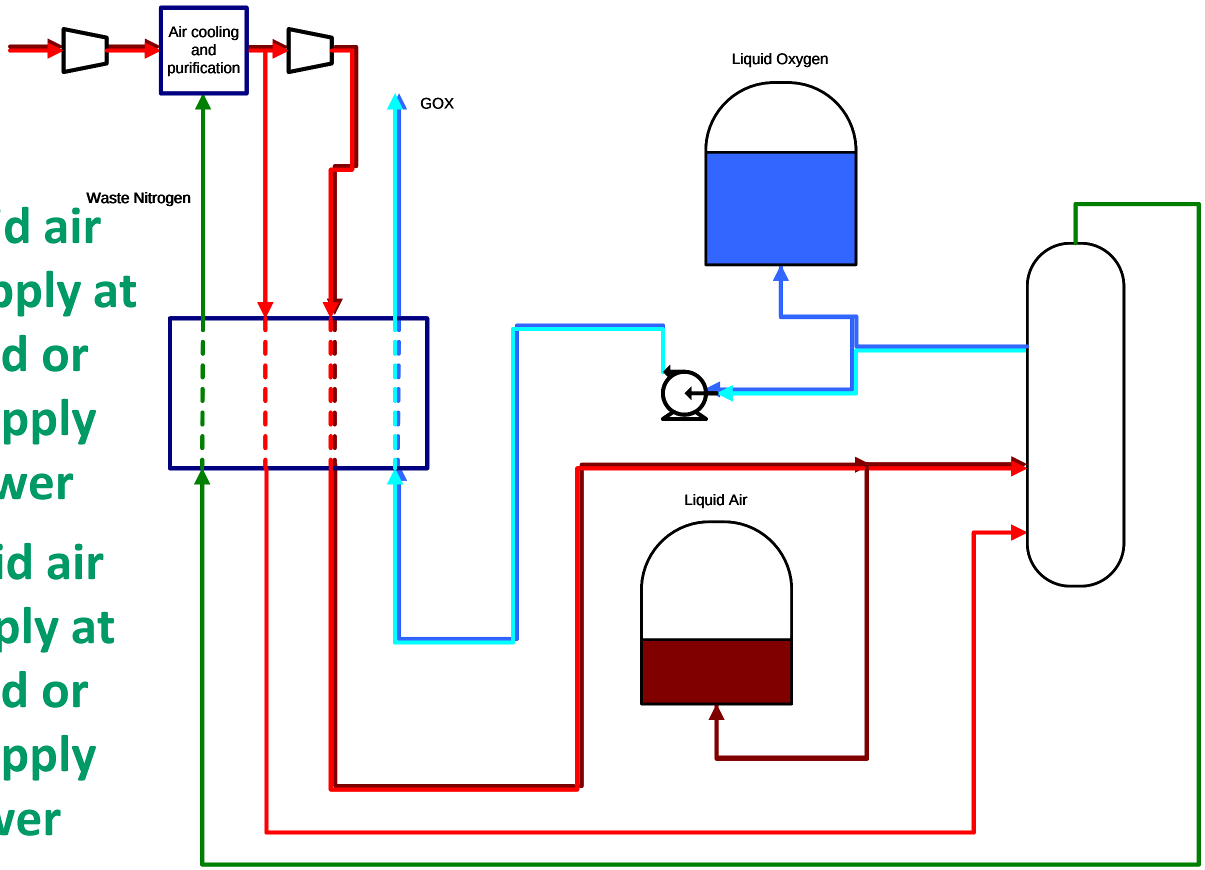
ASU cycle development and selection

- Pumped Liquid Oxygen (PLOX) (Internal Compression (IC))
  - Replaces oxygen compressor with booster air compressor
  - Can also pump other products (argon, nitrogen)
- Pure argon by distillation (<1ppm O_2)
  - Replaces deoxo, avoids H_2 consumption
- Liquid swap cycles for variable oxygen demand
  - Stored liquid oxygen swapped with liquid air or nitrogen
- Advanced cycles for low purity oxygen (<~97.5%)
  - Save power with multiple columns and/or reboilers
  - Can make some high purity O_2 or Ar at low recovery
- Integration with other processes
  - Pressurised nitrogen (e.g. GT) and heat integration
  - Nitrogen integration may allow elevated column pressures

Liquid swap for flexible oxygen supply

- Liquid storage decouples column load and oxygen supply rate
- Can deal with medium term oxygen flow variations

- **Liquid oxygen from columns is boiled by condensing air feed**
- **Inject LOX, store liquid air**
  - **Increase GOX supply at same column load or**
  - **Maintain GOX supply with reduced power**
- **Store LOX, inject liquid air**
  - **Reduce GOX supply at same column load or**
  - **Maintain GOX supply and increase power**



ASU advanced cycle comparison

- Five low purity cycles compared (in oxyfuel study)
  1) Three column cycle (IEA GHG report 2005/9)
  2) Conventional double column cycle
  3) Dual reboiler cycle
  4) Elevated pressure three column cycle
  5) Elevated pressure dual reboiler cycle
- Cycles optimised for comparison (capital vs power)
- Results given on same basis as Darde et al. (2009)
  - Oxygen separation shaft power at ISO conditions
- Intercooled compression and no heat integration
- With and without pressurised nitrogen coproduct
- More detail in our paper in IJGGC oxyfuel edition

ASU power calculation

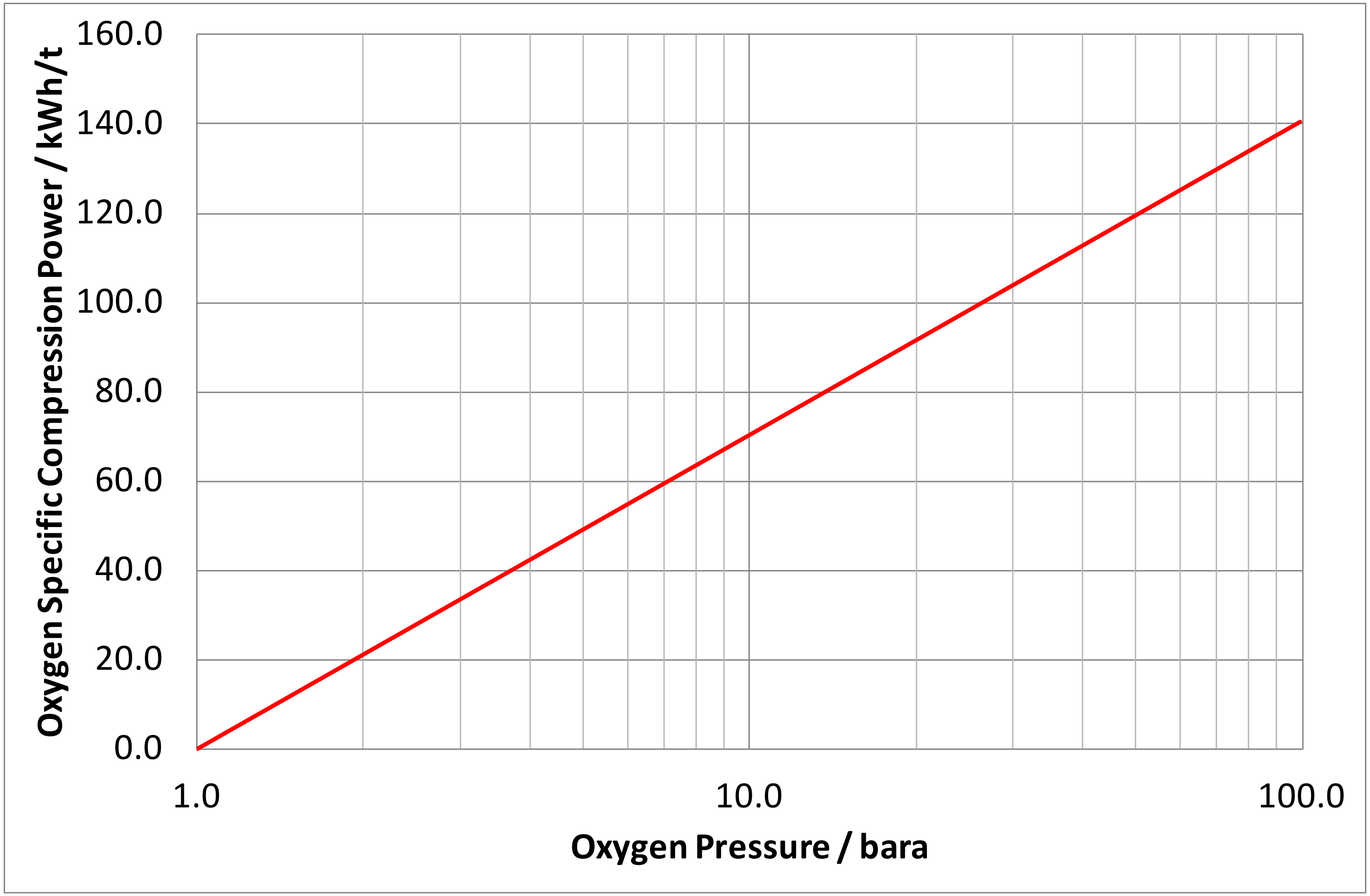
- Overall power can be expressed as sum of conceptual processes
  - Independent of actual process

  1) Separation
     - Separate air to oxygen and nitrogen at atmospheric pressure

  2) Product compression
     - Compress products to required pressures

  3) Product liquefaction
     - Cool and liquefy products if required
- Powers depend on ambient conditions, power/capital evaluation, operating conditions compared to design point
- Powers can be quoted at different points – shaft power, electric power at motor terminals, at incomer, process users only etc.
- This Comparison is **Oxygen Separation Shaft Power** only
  - Excludes compression, liquefaction, electrical losses, cooling

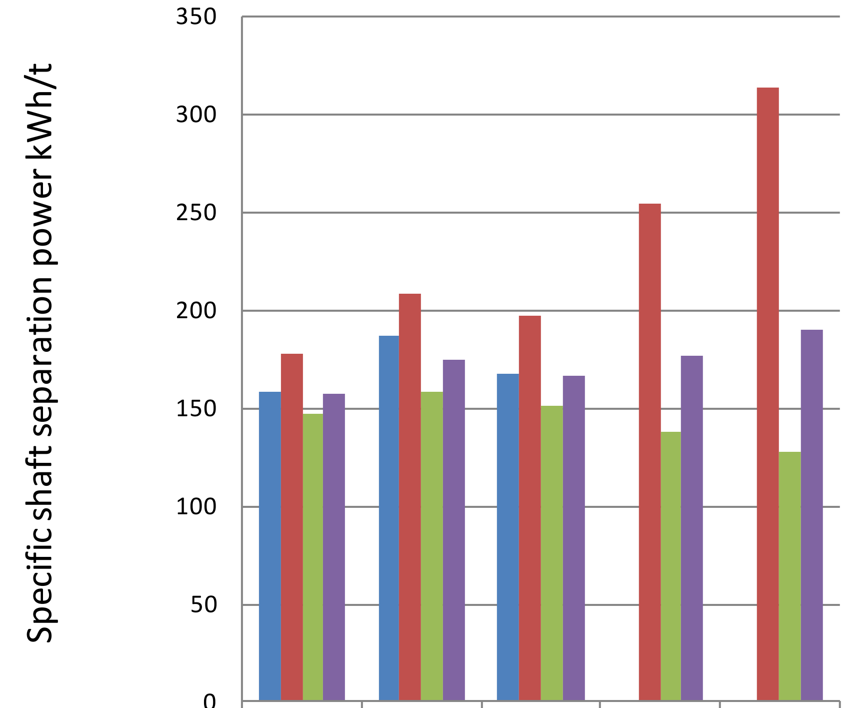
Oxygen Specific Compression Power



- Typical values at ISO conditions, based on total flow of oxygen stream

ASU Cycle Comparison Results

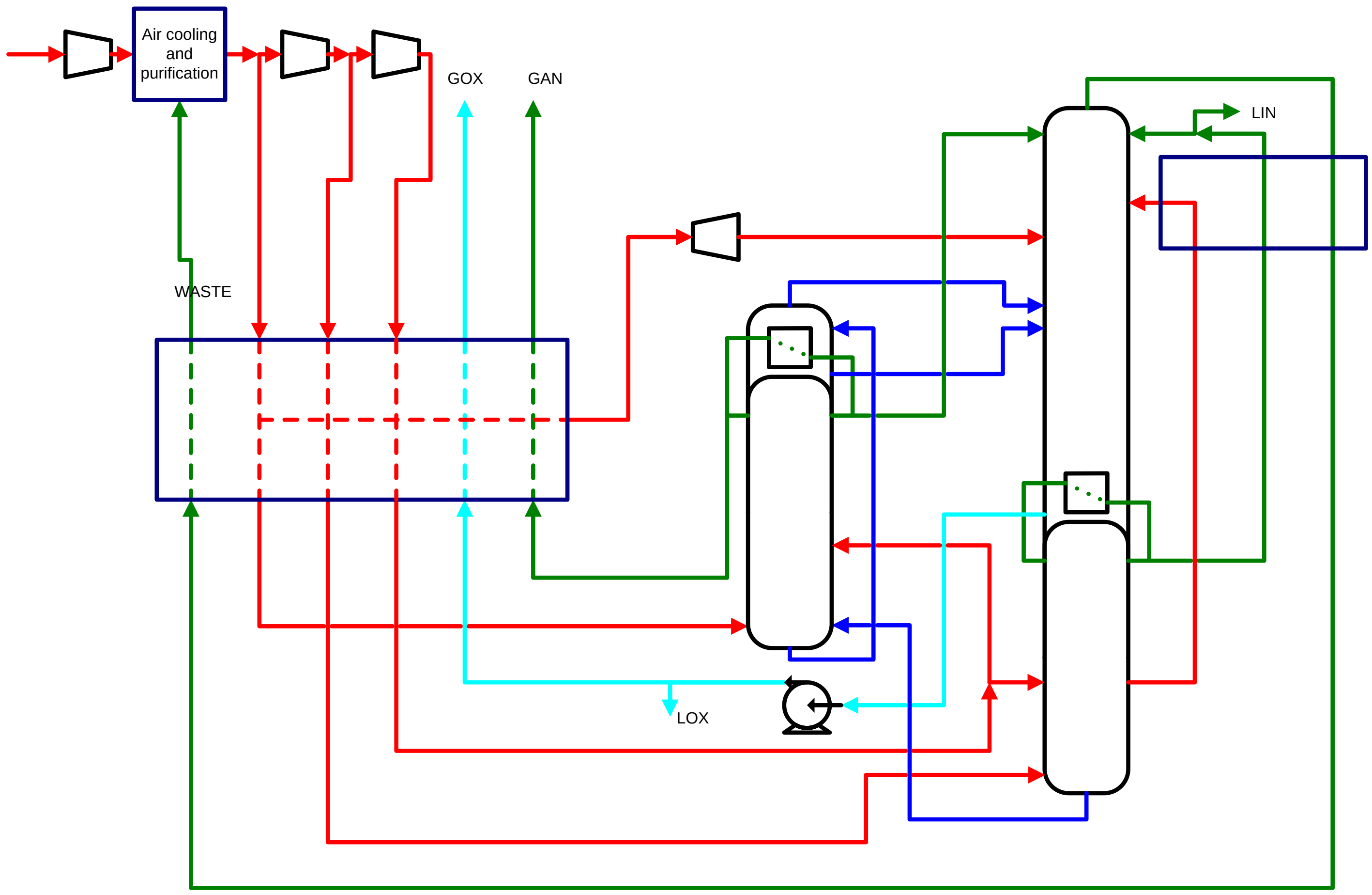
- **Without gaseous nitrogen (GAN), three column cycle is best**
  - **158 kWh/t (base)**
- **With GAN, three column cycle has lowest gross power - increases dramatically for elevated pressure (EP) cycles as they make more GAN**
- **If GAN can be used (crediting avoided compression power) EP cycles are best**
  - **3 Col (LP): 147 kWh/t (-7%)**
  - **2 Reb (EP): 128 kWh/t (-19%)**
- **If GAN has no use and power is recovered with expander (no external heat), three column cycle is still best**
  - **157 kWh/t (-1%)**



	1 - Three column	2 - Dual column	3 - Dual column dual reboiler	4 - EP three column	5 - EP dual column dual reboiler
no gaseous nitrogen (GAN)	158	187	167		
with GAN (gross power)	178	208	197	255	313
GAN used (power credit)	147	158	151	138	128
GAN power recovered	157	175	166	177	190

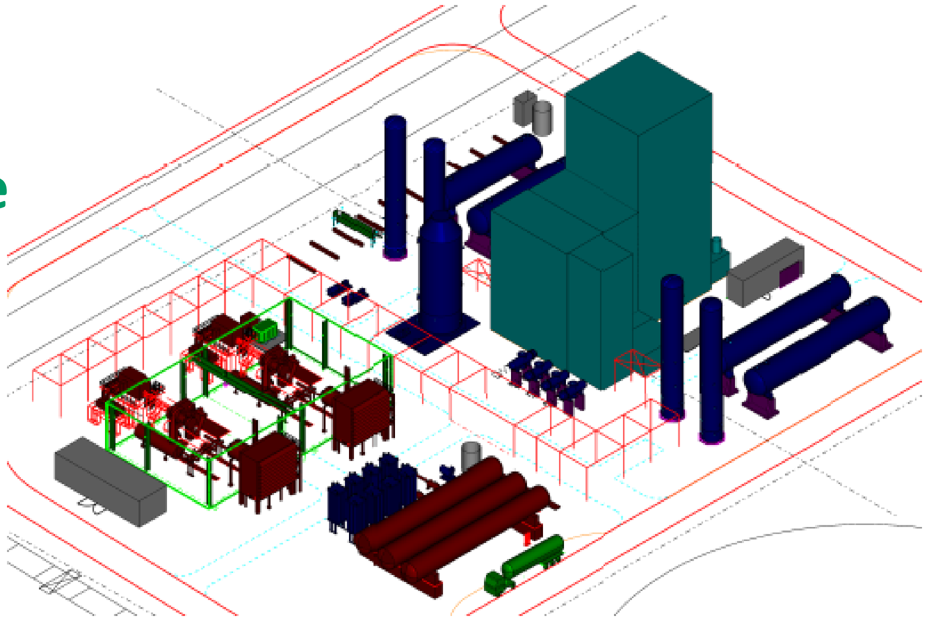
Three column, low purity cycle

- Air feeds at 3 and 5 bar(a), optional GAN at 2.5 bar(a), pumped LOX version
- High, medium and low pressure columns



Low Purity “Reference ASU”

- **Designs developed for a scalable reference plant**
- **Based on three column cycle**
- **Column diameters within manufacturing capabilities (referenced to 7000 TPD)**
- **Up to ~25% of oxygen possible at high purity**



Size TPD O_2	Main Air Compressor options
3,000 – 4,000	Centrifugal 1 or 2 train or axial 1 train
4,000 – 5,500	Centrifugal 1 or 2 train or axial 1 train
5,500 – 7,000	Centrifugal 2 train or axial 1 train
7,000 -10,000	Centrifugal or axial 2 train

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- Cryogenic ASU introduction
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- **Application of ASU developments to iron & steel with CCS**
  - **Oxygen demands for iron & steel**
  - **ASU features for current and future requirements**
  - **Power comparison for different oxygen requirements**
- Conclusions

Typical O_2 demands for 4 million tonne per year hot rolled coil integrated steelworks

Technology	Oxygen Flow / TPD	Oxygen Pressure / bara	Oxygen Purity / mol %
Steelmaking	1000	30 (for gas storage)	~99.5
Blast Furnace (some enrichment)	750	3-8	>90
BF Plus	2500	3-8	>90
Oxy Blast Furnace, Top Gas Recycle	3500	3-8	>90
COREX/FINEX	8000	3-8	>90

- Some nitrogen, argon and liquid back-up are also needed

Typical Modern Steelworks ASU

- 1500-2500 TPD Oxygen
- Moderate power evaluation
- High purity oxygen (99.5%+) with argon (high recovery)
- Pumped liquid oxygen supply at two pressures
  - ~40-50% at medium pressure (MP) for blast furnace
  - Rest at high pressure (HP) for steelmaking
- Small liquid production for backup
- Some utility nitrogen (typically << oxygen demand)
- Liquid swap scheme for peak shaving

Steelworks ASU – for all future O_2 demand

- >3500 TPD Oxygen
- High power evaluation (due to cost of CO_2 emissions)
- Dual purity oxygen (99.5%+ and ~95%) with some argon production (low recovery) – advanced cycle
- Pumped liquid oxygen supply at two pressures
  - ~80-90% at medium pressure (MP) for blast furnace
  - Rest at high pressure (HP) for steelmaking
- Small liquid production for backup
- Some utility nitrogen production
- Possible additional nitrogen demand for GT integration
- Liquid swap scheme for peak shaving

Steelworks ASU – for additional O_2 only

- >2000 TPD Oxygen
- High power evaluation (due to cost of CO2 emissions)
- Low purity oxygen (~95%), no argon production
  - Ideally suited to advanced cycle
- Pumped liquid oxygen supply at medium pressure only
- Possible liquid production for backup
- Some utility nitrogen production
- Possibility of elevated pressure cycle with nitrogen for gas turbine integration

Oxygen specific power comparison

ASU type	Press. bar	Purity %	Specific sep. power kWh/t	Auxiliaries and losses kWh/t	Comp. power kWh/t	Total specific power kWh/t	Total specific power kWh/Nm^3
Old ASU	30	99.5	250	25	110	385	0.55
Modern ASU	30	99.5	230	20	100	350	0.50
	5	99.5	230	20	50	300	0.43
Dual purity	30	99.5	165	15	100	280	0.40
	5	95	160	15	50	225	0.32
Low purity	5	95	160	15	50	225	0.32
EP, N_2 Integrated	5	95	130	10	50	190	0.27

- Total electrical power at HV incomer
- At design point at ISO conditions with no coproducts

Power comparison of ASUs for iron & steel

- Powers depend on multiple factors – powers given are
  - At ISO conditions
  - For steady operation at design point
  - With no coproducts
  - For all consumers including cooling & adsorber regeneration
  - At HV incomer
- Coproduct powers must be added, e.g. LOX for backup, LAr and 30 bar N_2 at 5% of O_2 flow could add 28kWh/t (0.04kWh/Nm^3) O_2
- High power value means lower power but increased capital cost
- Low purity process can provide some high purity O_2 efficiently
  - At little more than low purity separation power
- Future ASU could **halve** oxygen power compared to old ASU!
  - High vs low power value (15%)
  - Medium pressure vs high pressure product (13%)
  - Low purity (or dual purity) vs high purity oxygen (13%)
  - Elevated pressure with GT N_2 integration vs low pressure (10%)
  - As low as190 vs 385 kWh/t (0.27 vs 0.55 kWh/Nm^3)

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Conclusions

- Oxygen demand increases in steelworks with CO_2 capture
- Important to understand ASU possibilities in evaluation of CCS
- Increased demand is at low purity and moderate pressure
- ASU can provide oxygen at multiple pressures to save power
- Low purity enables use of advanced low power cycles
  - Also work for dual purity and low argon recovery
  - Specific power for high purity little more than for low purity
- Integration of ASU with power generation is beneficial
  - Nitrogen integration with gas turbine allows EP ASU cycle
  - Steam cycle condensate preheat in compressor coolers
- ASU scale-up is possible to 10000 TPD in a single cold box
  - At this size two machinery trains are needed
- Power consumption comparisons need care
  - Ambient conditions, operating modes, what's included