HONEYWELL UOP ZONEFLOW™ / UOP POLYBED™ PSA RECOVERYMAX

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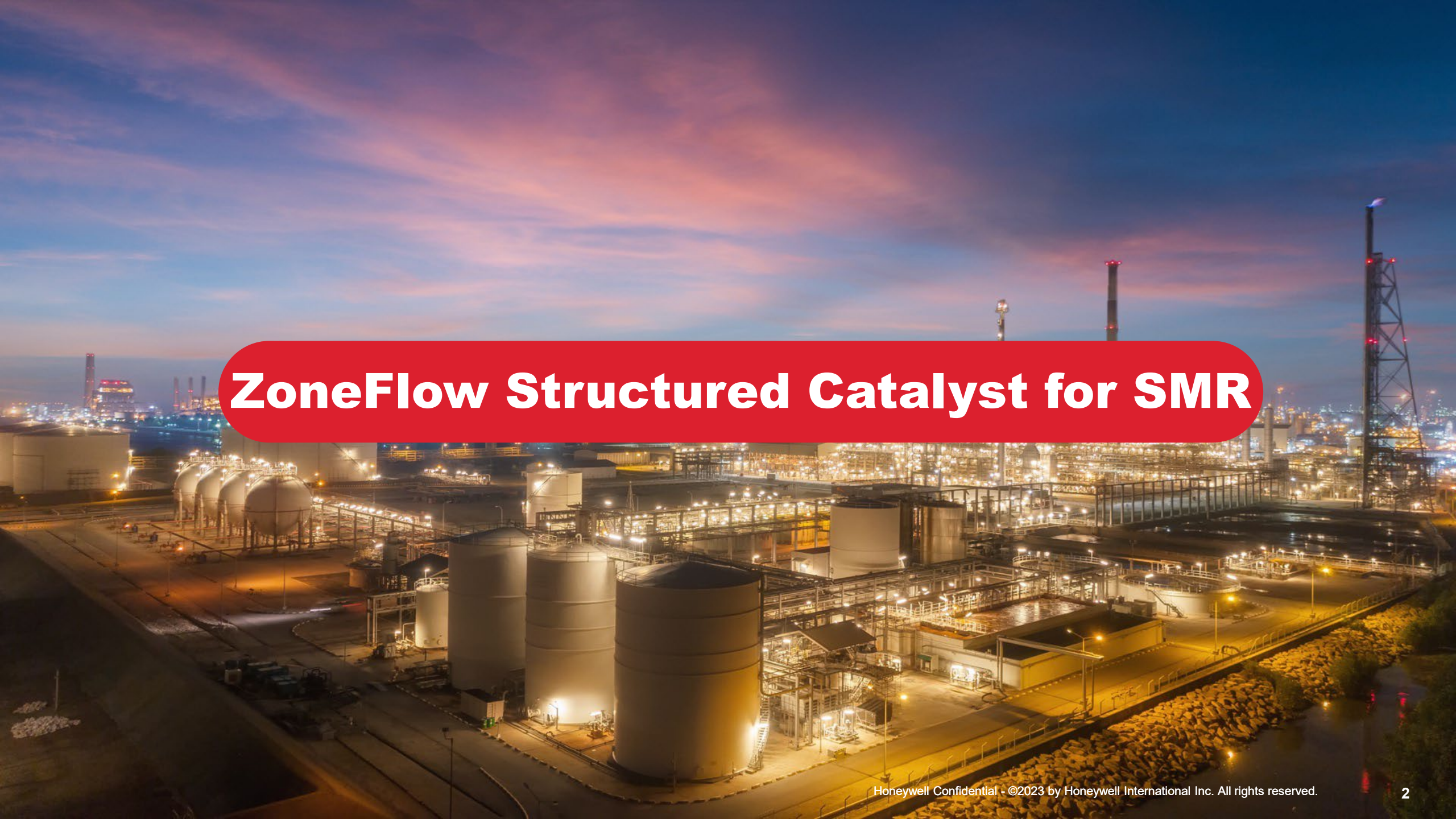
Honeywell
UOP



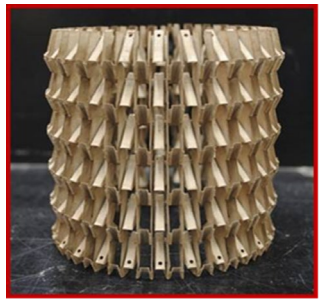
ZoneFlow Structured Catalyst for SMR

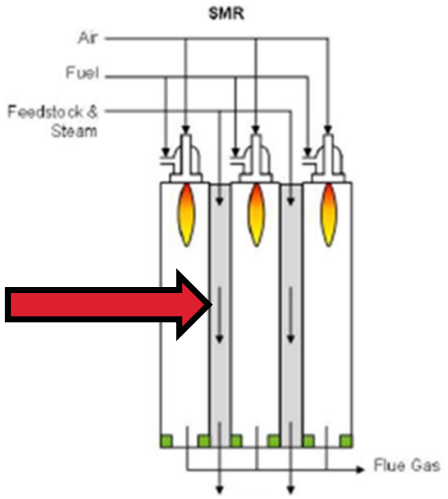
ZONEFLOW STRUCTURED CATALYST

1) Internally developed Techno Economical Analysis using Honeywell UOP developed simulation models, Unisim simulation model, standard PDD tool and optimisation. Key variables include, stream composition, utility price set, price of H2 of $1685/MT, natural gas feed of $327/MT, fuel price (HHV) of $6.6/MMBTU, and steam HP steam export of $25.28/MT , cost of capital of 12%, 350 days per year on-stream, and 2022 US gulf coast basis. Also based on the following paper; Florent Minette, Luis Calamote de Almeida, Sanjiv Ratan, Juray De Wilde, "Pressure drop and heat transfer of ZoneFlow™ structured catalytic reactors and reference pellets for Steam Methane Reforming", Chem. Eng. Journal. 417, 128080, 2021. Juray De Wilde, Gilbert F. Froment, "Computational Fluid Dynamics in chemical reactor analysis and design: Application to the ZoneFlow™ reactor for methane steam reforming", Fuel 100, p. 48-56, 2012; and the results from the Pilot Plant Test Program- Final Report, Feb 2023 delivering the results and conclusions based on detailed simulation and reconciliation of the collected data from all the test campaigns.

Conventional Pellet Catalyst

ZFRT Structured Catalyst





$$CH_4 + H_2O \rightleftharpoons CO + 3H_2$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

ZFRT STRUCTURED CATALYST PERFORMANCE

FLOW IMPINGES THE TUBE (FOR GOOD HEAT TRANSFER)

BUT NOT THE PACKING (FOR LOW PRESSURE DROP)

NO "WALL EFFECT" BYPASS (NO COKING AT <2.0 S/C)

FLEXIBLE (NO CRUSHING IN THERMAL CYCLING)

THIN CATALYTIC COATING (EFFECTIVENESS FACTOR >0.8)

2 X Increase Heat Transfer (at the same ΔP & approach to equilibrium)[1]

- 15% to 25% higher H_2 PRODUCTION at same tube temperature and higher bridge wall temperature

OR

- 20-25ºC cooler TUBES AND BRIDGE WALL at same reformer outlet temperature

Flexible → **extremely tolerant of thermal cycling, longer catalyst life[1]**

Eliminates bypass → **<2.0 S/C without coking[1]**

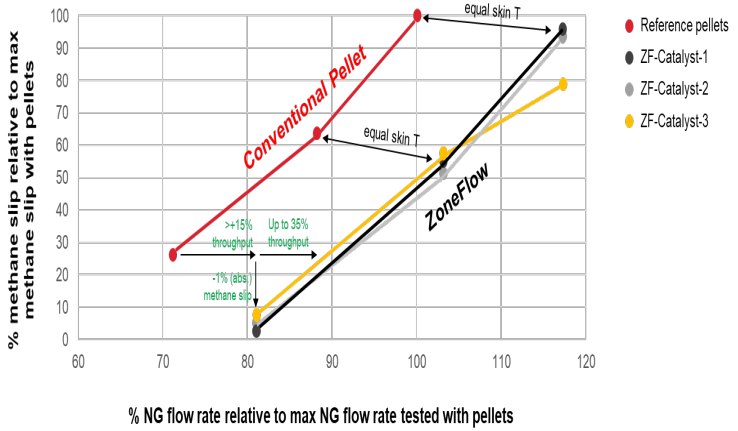
PILOT PLANT TESTING RESULTS > 15% CAPACITY INCREASE

Four campaigns (2-3 weeks each)

- Commercial reference Pellet catalyst
- Three different catalyst with ZFRT casing

Demonstrated increased capacity

- with lower methane slip;
- and same or lower max tube skin temperature;
- and Lower pressure drop



Existing SMR Plant Upgrade[1]

- 15% to 25% increase hydrogen production (lowest capital cost option)
- With
  - $25M 150yr NPV advantage versus a 15% capacity improvement with post-reformer and pellets or
    - $16M 15-yr NPV advantage versus pellets with no capacity improvement
  - Low catalyst susceptibility to thermal cycling
  - More uniform tube and gas outlet temperature

New SMR Plant[1]

- 10% to 15% lower capital costs (smaller radiant and convective zones, fin fans, etc.)
- 2% to 3% lower energy costs

Polybed PSA

UOP: THE PSA INNOVATION LEADER

UOP invented & patented the
5-STEP
PSA cycle

more than **1,150**
PSA units designed & commissioned into commercial operation worldwide

KIRKPATRICK AWARD 1979
Presented to UOP for the development of Polybed PSA

UOP invented the synthetic molecular sieve adsorbents required to obtain the **99.99+%** H_2 purity required for H_2 applications

- **PSA technology and performance leader for 50 years**
- **The first PSA in the world was commissioned in commercial service in 1966**
- **Experience with all sizes of PSA including**
  - The largest single train PSA in the world, which measures 20-beds, and was started in January 2014
  - The largest unit produces more than 253,000 Nm^3/hr (226 MMSCFD) product from SMR feed gas using a 14-bed system

After Market Revamps and Service

H2 PURIFICATION – POLYBED™ PSA

H_2 + Impurities
High Pressure

FEED GAS

PRODUCT

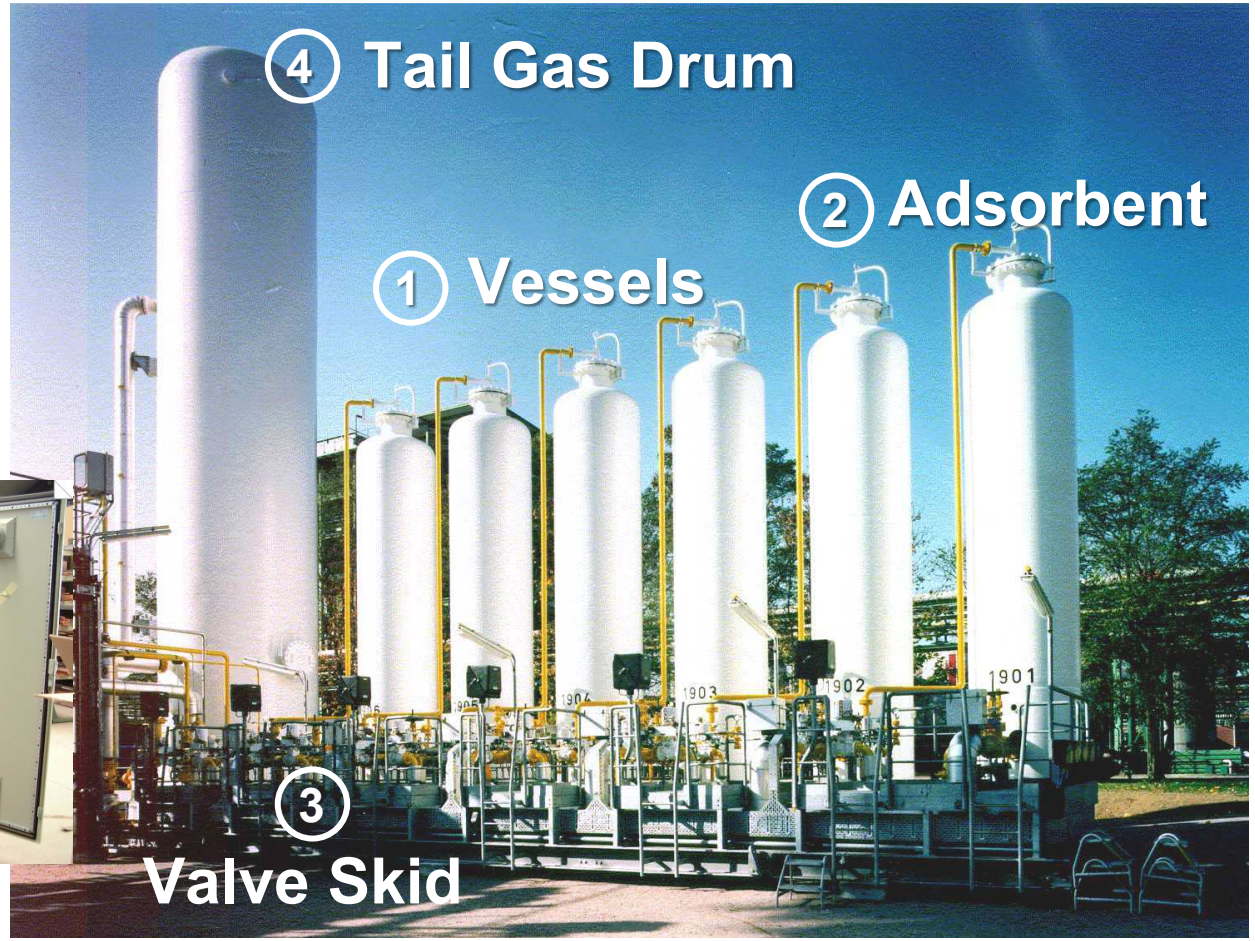
H_2 @ High Purity
High Pressure

OFF GAS

Impurities (+H_2)
Low Pressure

H_2 Purity 99.9 – 99.9999%
H_2 Recovery 80 – 90%
H_2 Feed pressure 6 - 40 bar g (90 – 580 psig)
H_2 Product pressure 5 - 39 bar g (80 – 570 psig)

COMPONENTS OF A PSA SYSTEM



5 Control System

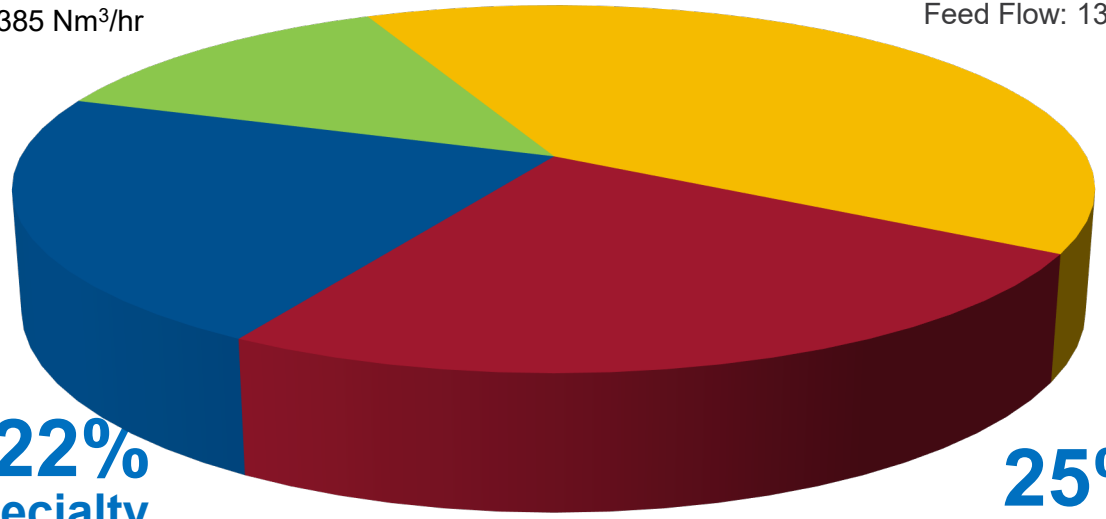
6 UOP Service and Support

PSA EQUIPMENT / MODULAR SUPPLY

HYDROGEN PSA APPLICATIONS / EXPERIENCE LIST

13%
Ethylene Off-Gas
No. of Units: 151
Feed Pressure: .03 – 44 bar
Feed Flow: 89 – 188,385 Nm^3/hr

40%
Steam Reformers
No. of Units: 465
Feed Pressure: 1.0 – 64 bar
Feed Flow: 134 – 383,650 Nm^3/hr



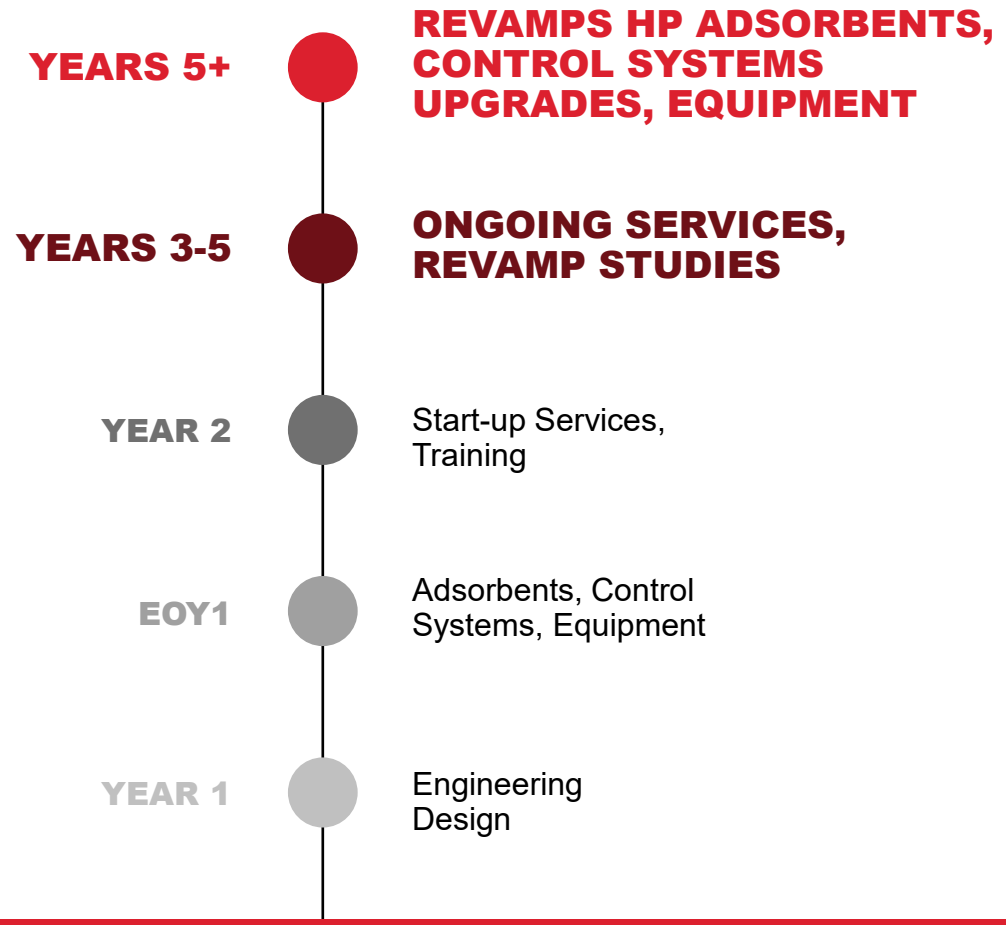
22%
Specialty Applications
No. of Units 255
Ammonia Plants
Coke Oven Gas
Gasification
Methanol Off-Gas
Misc Off-Gas

25%
Refinery Streams
No. of Units: 288
Feed Pressure: 1.4 – 46 bar
Feed Flow: 53 – 226,179 Nm^3/hr

>1,150 Polybed PSA Units UOP Supplied Worldwide

REASONS TO CONSIDER A REVAMP

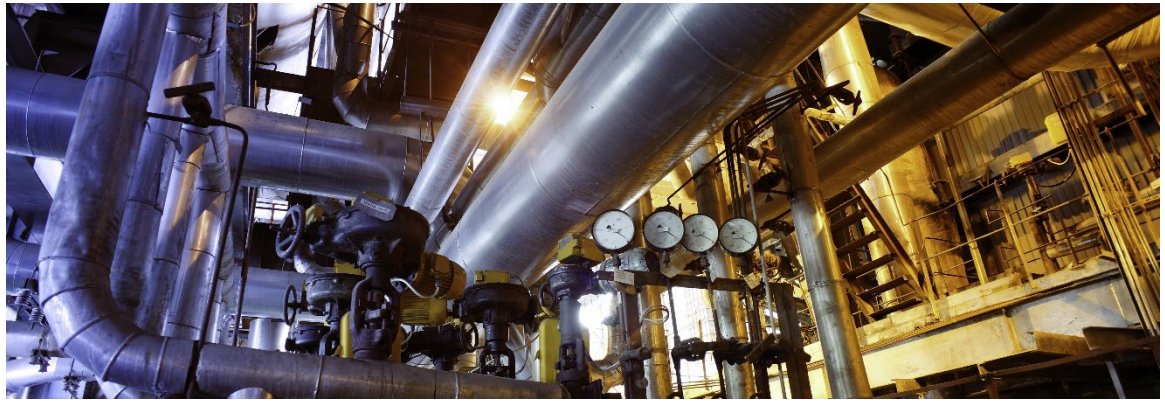
- New Product Specifications
- Change in Feed Composition
- Increase H_2 Recovery
- Increase Capacity
- Enhanced Operating Features (switchovers, …)
- Increased Reliability (older / smaller units)
- Upgrade Control System (obsolescence)
- PSA Health Check
- Vessel inspections



[1] UOP has executed over 3,500 PSA revamp projects Worldwide, which started in the 1980s, where the above benefits of the revamp project were provided or the revamp was due to the above reasons.

Revamps – The perfect way to upgrade your existing unit

REVAMP BENEFITS



REVAMP BENEFITS[1]

- Increased capacity possible with existing equipment
- Shorter schedules
- Lower capital investments

[1] These benefits have been demonstrated by UOP having executed over 3,500 PSA revamp projects worldwide starting from the 1980s, where UOP's revamp customers consistently experienced the above benefits as a result of UOP's revamp of their respective PSA units.

REVAMP DELIVERED AS

- Process Evaluations / Studies
- Adsorbent Replacement: Optimized / Make-up / Partial / Complete
- Control Systems: Upgraded Hardware / Equipment / Software
- Capacity Expansions: Additional vessels / Valves / Piping
- Periodic Health Check:
  - Adsorbent / Control Panel / Auto Valve / Overall Unit Performance

UOP has been providing on-going revamp support for more than 25 years

NEW HIGH-PERFORMANCE ADSORBENT
SMR & ROG/EOG PSA UNITS

General Observations[1]

+1% to +2% INCREASE
in H_2 recovery at same Product spec / CO slip

5 to 15 % INCREASE
in unit capacity in some cases

[1] For details on the recovery and capacity increase for the SMR (Steam Methane Reformer) applications see the following slide 11 of this presentation and for details on the recovery and capacity increase for ROG (Refinery Off-Gas) and EOG (Ethylene Off-Gas) applications see the 2nd slide from this slide - slide 12.

FIELD RESULTS – SMR PSA UNITS
NEW HIGH-PERFORMANCE ADSORBENT

UNIT A – SOUTHEAST ASIA

ORIGINAL UNIT

- 10-bed PSA system
- SMR feed
- 73 300 Nm3/h feed gas
- 24.5 bar g
- Original Design Recovery 89.0%
- 50 ppm v CO

RELOADED WITH NEW HIGH-PERFORMANCE ADSORBENTS IN MAY 2018

- Guaranteed Recovery 90.0%[1]
- 18% increase in K_F (capacity)[1]

Additional revenue of *$1.2M*[2] per year based on recovery improvement only

UNIT B – EASTERN EUROPE

ORIGINAL UNIT

- 10-bed PSA system
- SMR feed
- 65 000 Nm3/h feed gas
- 32 bar g
- Design Recovery 87.0%
- 20 ppm v CO
- Measured Recovery > 87.0%

RELOADED WITH NEW HIGH-PERFORMANCE ADSORBENTS IN SEPTEMBER 2017

- Measured Recovery 91.5%[3]
- Guaranteed Recovery 90.0%[3]
- 8.5% increase in K_F (capacity)[3]

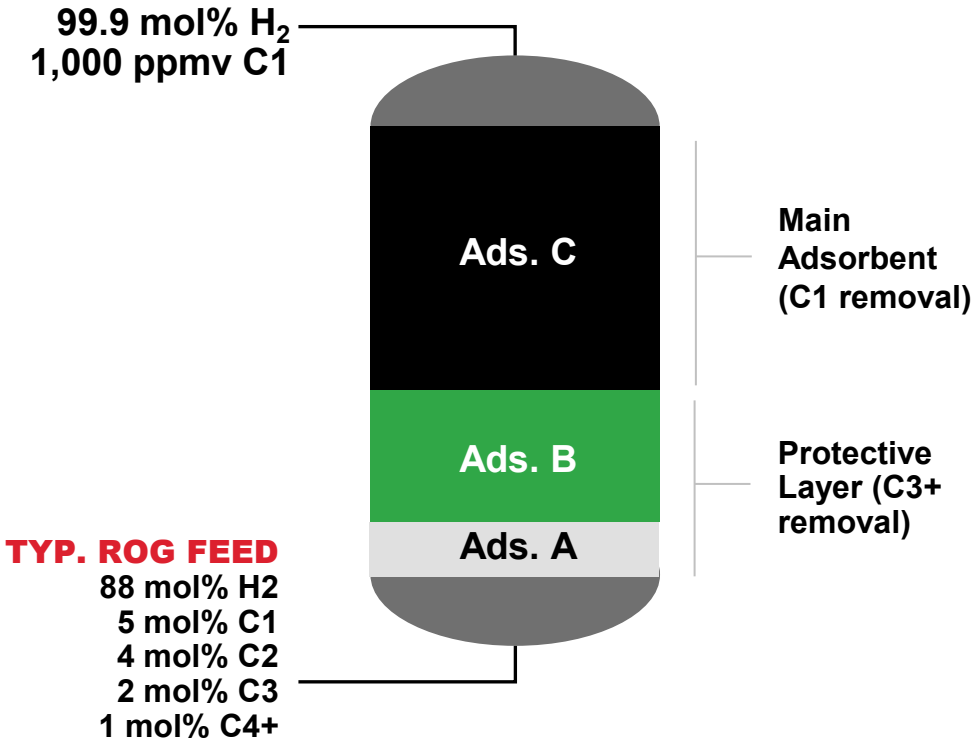
Additional revenue of *$2.0M*[2] per year based on recovery improvement only

1. Based on the guaranteed recovery and capacity performance provided by UOP on the original designed PSA unit and the guaranteed recovery and capacity performance provided by UOP on the revamp design PSA unit.
2. The additional revenue from the recovery increase only using a $1,200/MT price for hydrogen and 8400 operating hours per year.
3. Based on actual operating data from the original designed PSA unit and operating data from the revamp designed PSA unit after the adsorbent reload with high performance adsorbents. Details on the actual data from the revamp designed PSA unit was provided in a Performance Test Report.

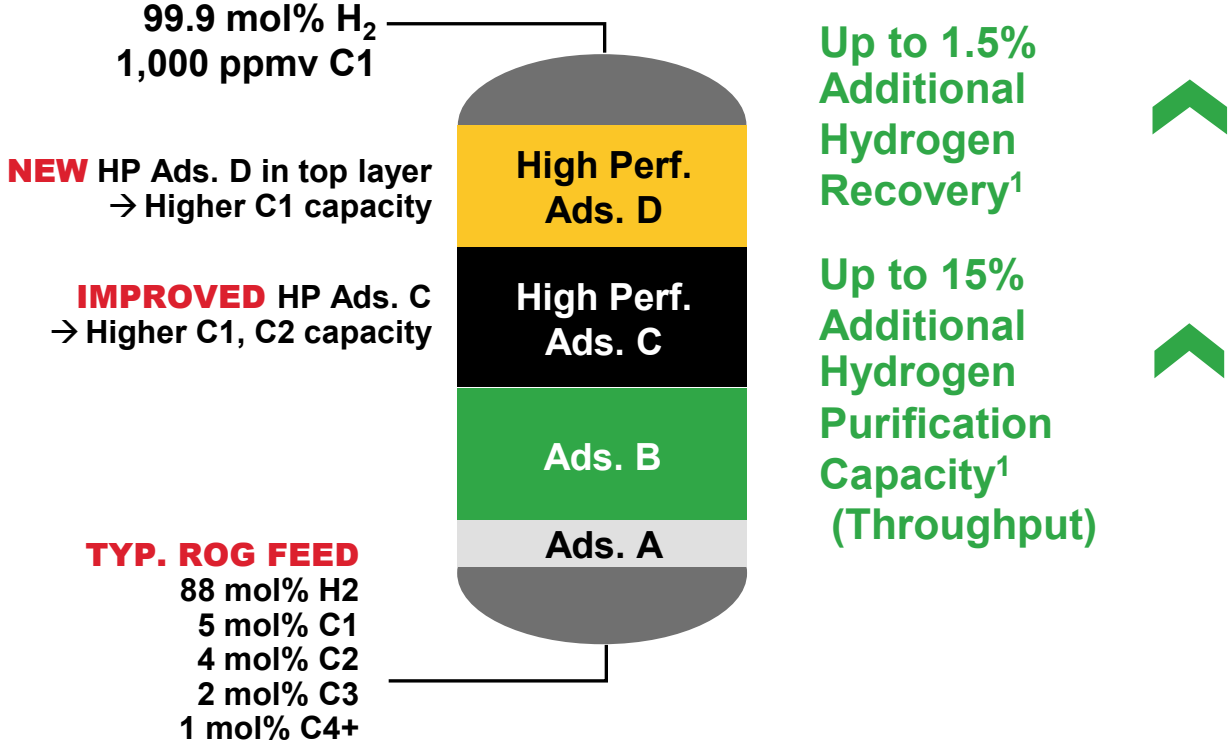
Better than original performance on Recovery by 1% & 3%

NEW HIGH-PERFORMANCE ADSORBENT ROG/EOG PSA UNITS

OPERATING UNIT



PROPOSED RELOAD



Estimated *$6.1M* of additional revenue per year (based on recovery and capacity improvement)[2]

1. Based on a UOP pilot plant tests results conducted by UOP in 2019 & 2020 at its own facilities, confirming the improved performance in terms of recovery and capacity of the high-performance molecular sieve and carbon (C1) adsorbents.
2. The additional revenue from the recovery and capacity increase using a $1,200/MT price for hydrogen and 8400 operating hours per year.

Improved Recovery & Productivity – New High-Performance Adsorbents

POLYBED™ PSA
CAPACITY EXPANSION REVAMP

UNIT A – INDIA

ORIGINAL UNIT

- 12-bed PSA system
- ROG feed
- 144,305 Nm^3/h feed gas
- 26.5 kg/cm^2 g
- Original Design Recovery 86.0%
- 99.9 mol% H_2 purity
- Supplied in 2010

NEW DESIGN

- 16-bed PSA system
- ROG feed (different concentrations)
- 191,927 Nm^3/h feed gas
- 25.8 kg/cm^2 g
- Original Design Recovery 90.0%
- 99.9 mol% H_2 purity
- Suppied in 2022

PSA CYCLE CHANGE 12-BED TO 16-BED EXPANSION

- **Increased recovery 4% points to 90% recovery[1]**
- **Increased feed capacity 33%[1]**
- **No change to adsorbent split**
- **Provided 4-bed skid extenstion**

Additional revenue of *$30M* per year based on recovery and capacity improvement[2]

Improvement on recovery versus pre-revamp Unit by ~ 4%

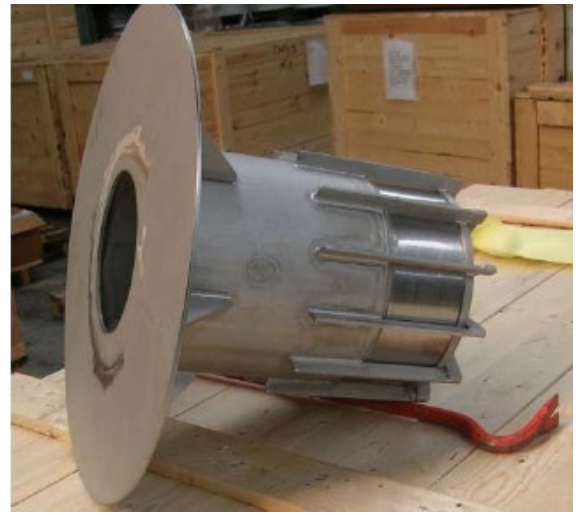
1.Based on internal simulation model and project documentation.
2.The additional revenue based on using a $1,200/MT price for hydrogen and 8400 operating hours per year.

POLYBED™ PSA
IMPROVED TOP FLOW DISTRIBUTOR

ADVANTAGES NEW VS. OLD DESIGN[1]

- Improved flow distribution
- Wedged wire screen instead of mesh
- Rugged design with reinforcements
- Even further reduced risk of a failure
- Easy one on one replacement
- No vessel modifications required

New Improved Design



HOW TO UPGRADE

- There is no direct need of immediate replacement of the existing distributors
- In order to ensure trouble free operation beyond the design life and to upgrade internals to UOP's latest offering to enhance mechanical reliability, we highly recommend replacement of the Top Flow Distributors during next scheduled vessel inspection or during an adsorbent reload

Old Design

1. Advantages of new top flow distributor design for Polybed PSA have been confirmed by the results of CFD (Computational Fluid Dynamics) performed on the improved top flow distributor modeling in March of 2009. In addition, a metallurgical examination was completed by a 3rd party (Praxair) in 2012 to verify the new top flow distributor design improvements versus the old top distributor design. In addition, UOP has supplied this new top flow distributor model on over 150 PSA units since 2013 without any known issues reported to UOP to date by the customers related to the new model of the top flow distributor.

CONTROLS
RELIABILITY AND AVAILABILITY ENHANCEMENT

CUSTOM CONTROL SYSTEM SOLUTIONS

- Full replacement or upgrade of obsolete Control System
- Fully redundant control system hardware and communications
- Fast Trending HMI station with comprehensive fault detection diagnostics

HONEYWELL EXPERION C300 SOLUTION

- Integrate PSA with Honeywell Experion PKS using UOP's Honeywell C300 control system and Experion HMI Web PSA graphics
- Fully integrated DCS control replacing PLC-DCS interface

HMI STATION UPGRADES AND SPARES

- Replacement of obsolete HMI PC and Software upgrades
- Upgrade HMI station communication set up
- Control System spares to improve process unit on-stream performance and decrease process upsets

PSA
HEALTH CHECKUP

WHY WE NEED A HEALTH CHECKUP?

- To Avoid Unexpected Shutdown
- Improve On-Time Availability
- Improve Performance
- Timely Procurement of Spare Parts
- Advance Maintenance Planning

Proactive Maintenance Has a Real Impact on Profitability

TYPICAL SCHEDULE
FOR PLANNING PURPOSES

- Adsorbents – up to 6 months of port of export
- Phase 1 (Engineering) Studies – 3 months
- Control Systems Retrofits – 12 months or more
- Control System and HMI upgrades – 4-10 months
- Phase 2 (Implementation) – 6 to 12 months

RecoveryMax

RECOVERYMAX

WHAT IS RECOVERYMAX?

- An energy efficient system to recover high value products from Platforming gases
- **Plays pivotal role for refinery H_2 balance**
- Modular supply revamp option (integrated or independent)
- 12 references, 2 of those delivered as a Modular solution

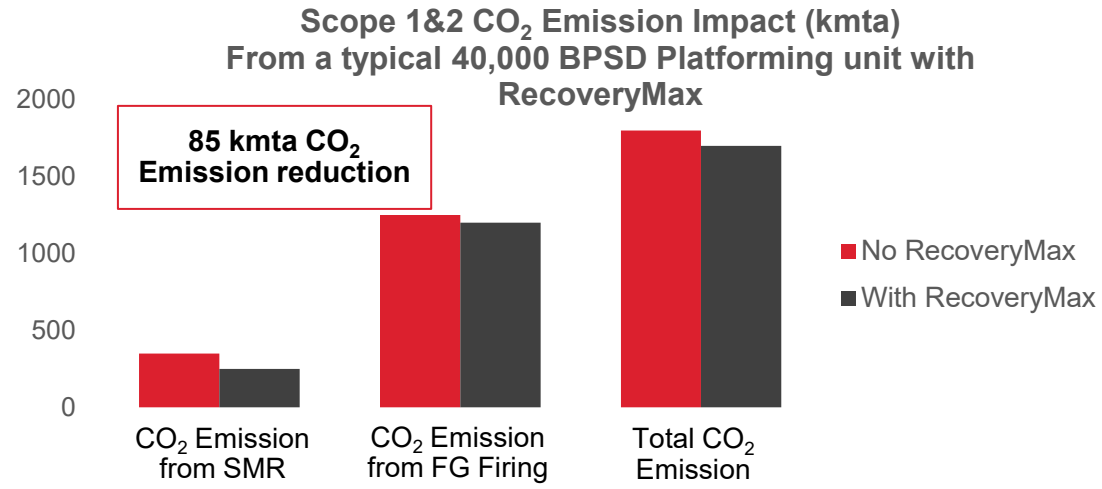
ECONOMIC RETURN AND EMISSION REDUCTION

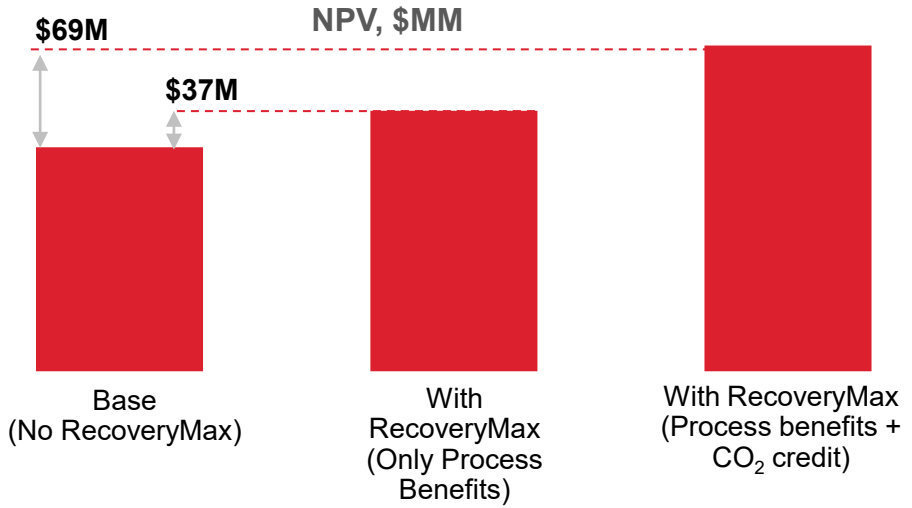
Enables higher economic return

- ~10% higher H_2 recovery
- ~30% higher LPG recovery
- ~0.5% higher reformate production

A cost-effective choice for CO_2 emission reduction[1]

- Improve H_2 supply from low-emission source and reduce need of SMR H_2
- Improve refinery fuel gas quality by enhanced C_3/C_4 recovery

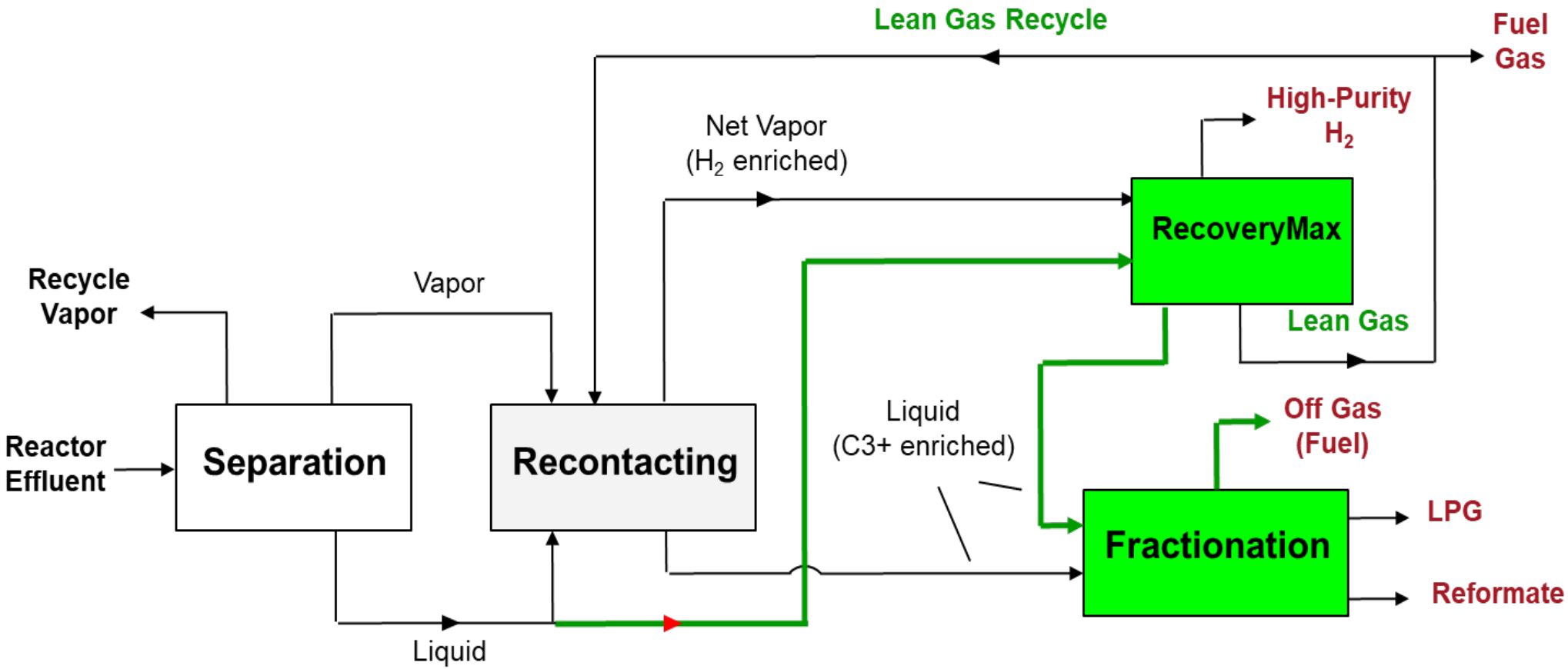




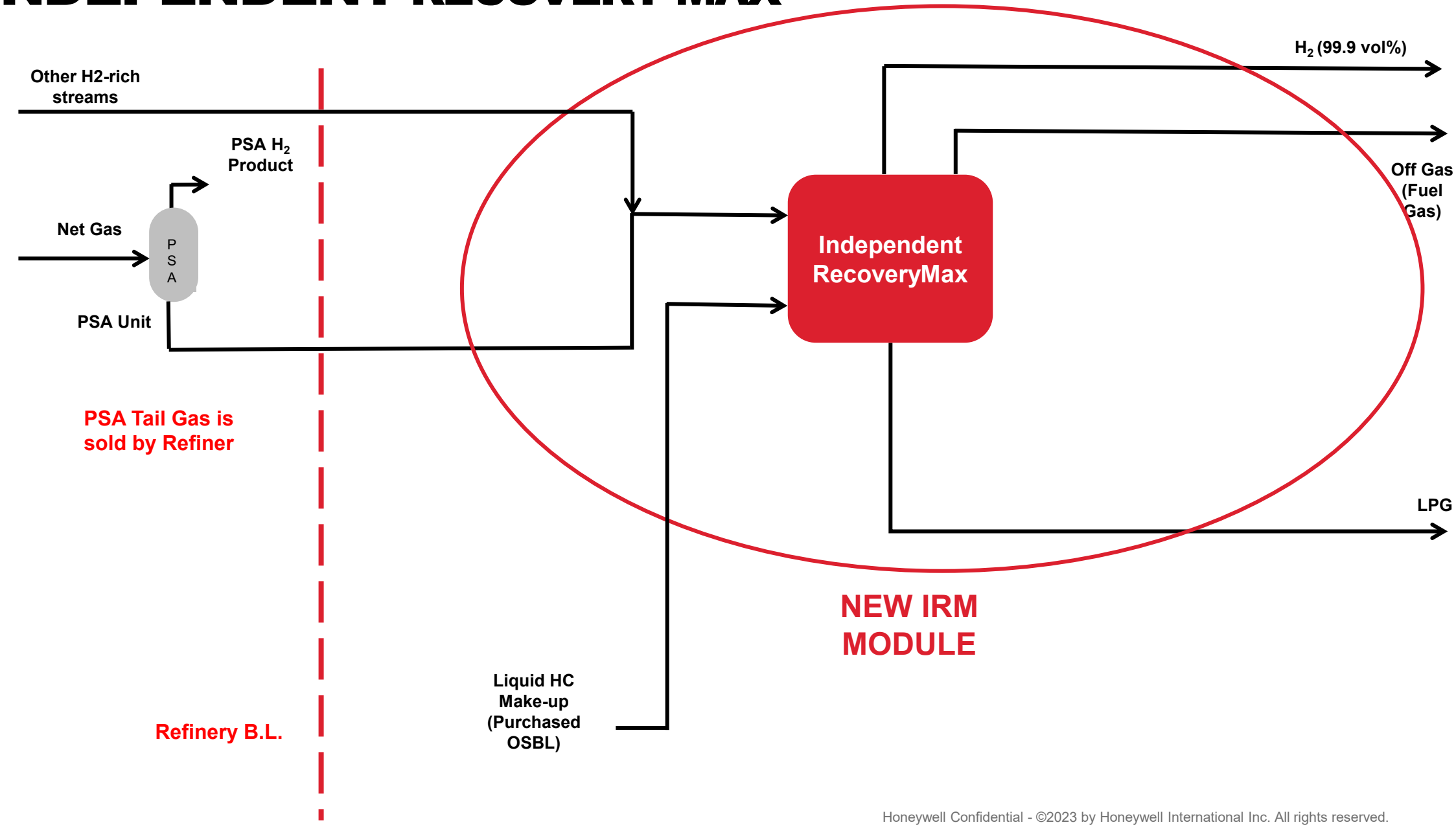
RecoveryMax Reduces Scope 1 & 2 Emissions while improving profitability

Notes:
1 Scope 1 & Scope 2 CO_2 emission. Assumed $50/mt CO_2 credit
2 For NPV assessment standard SEA price set is considered
3 85kmta CO_2 reduction is based on UOP internal calculation for a typical refinery H_2 and fuel gas balance where SMR is being fed by NG and is a primary H_2 source to meet refinery process requirements

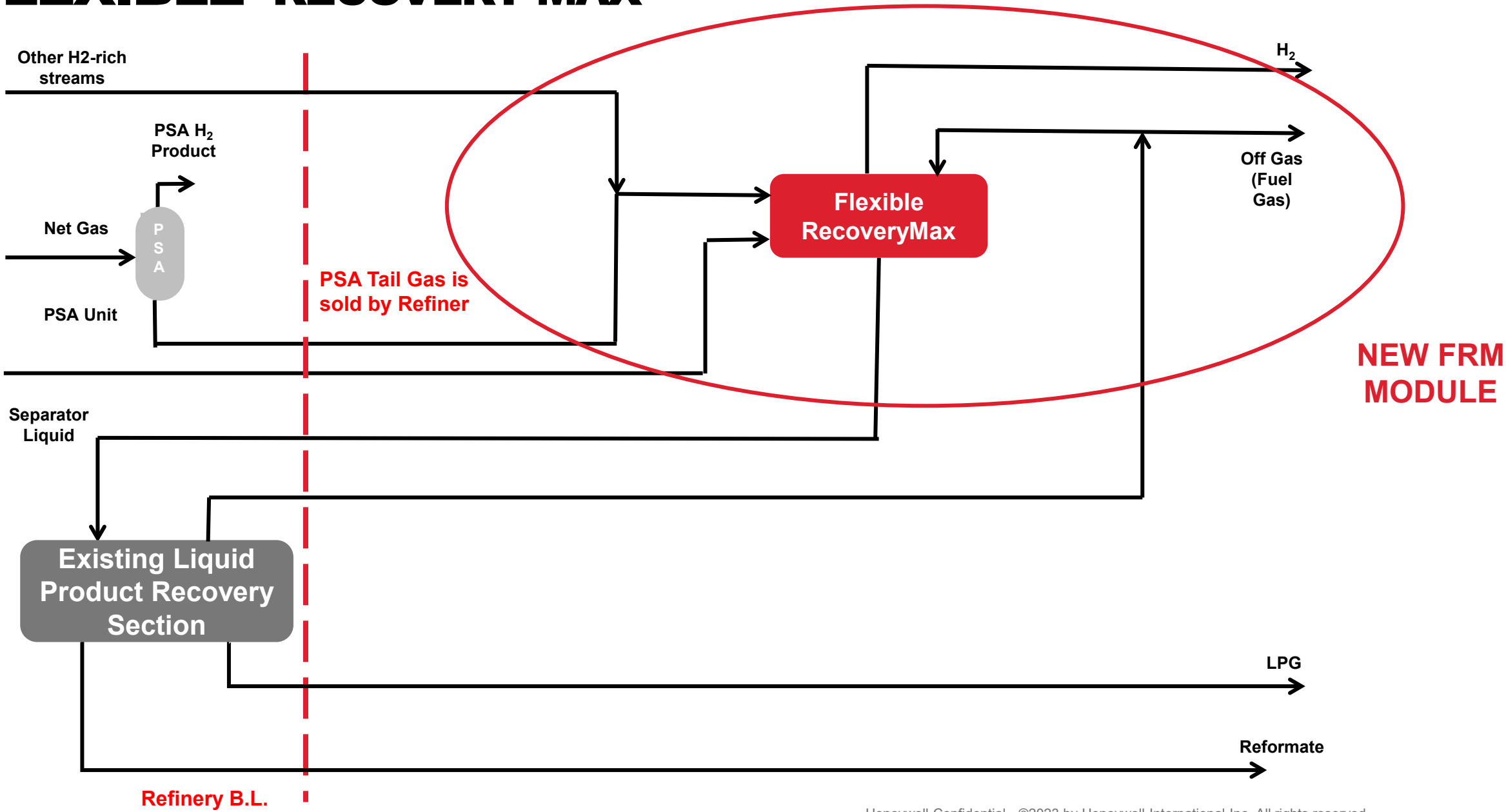
RecoveryMax™ SIMPLIFIED PROCESS FLOWS



INDEPENDENT RECOVERY MAX



FLEXIBLE RECOVERY MAX



Independent Recovery Max profitability example

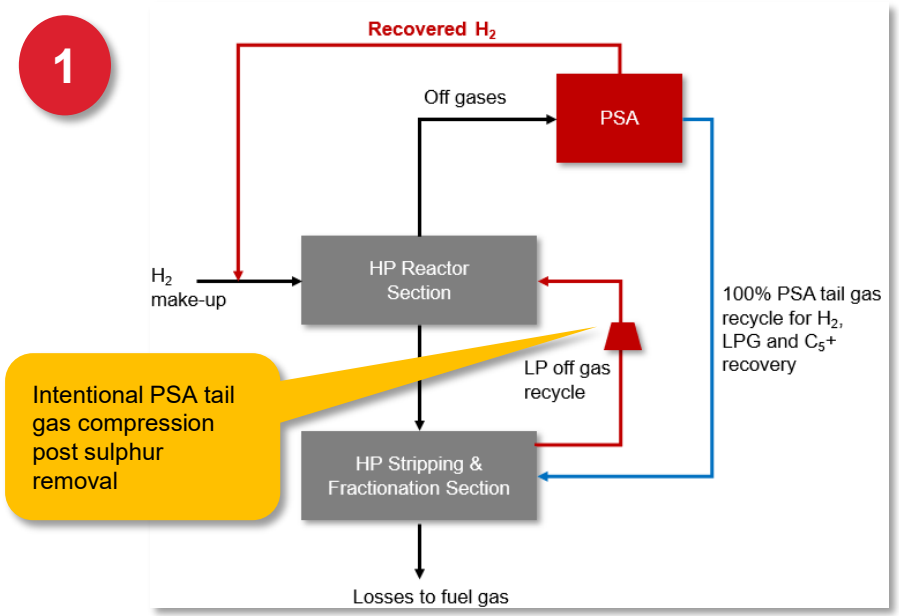
Stream	In/Out	Flow Rate, KMTA	Value $/T	Value M$/y
External Gas to IRM	In	158.5	200	31.7
Liquid Hydrocarbon Make up to IRM	In	0.1		
Hydrogen (99.9vol%) from IRM	Out	7.4	1100	8.1
Off Gas from IRM	Out	103	200	20.6
LPG from IRM	Out	48	500	24
Net Value Increase				21

- **TIC : 40 MMUSD**
- **Utility : 4 MMUSD/Y**
- **PayBack : 2.5 Years**

H_2 Management in Hydrocracking

HYDROPROCESSING (HP) H_2 MANAGEMENT

Cold Flash Drum Off Gas H_2 Recovery in RX section



H_2 in CFD off gas typically ranging between 75 – 90 vol%

Typically 84-86% H_2 recovery w/o tail gas recycle integration

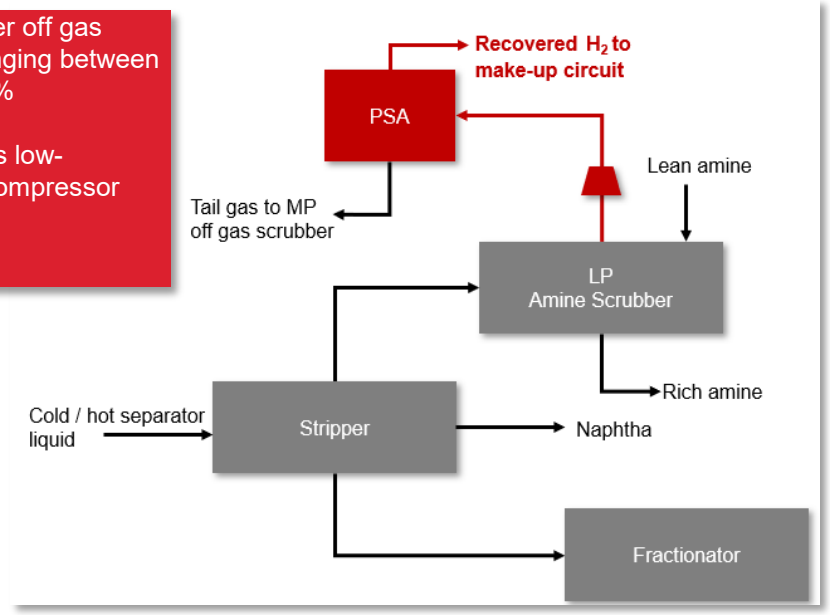
> 95% H_2 recovery w/ 50% LP off gas recycle integration

Stripper Off Gas H_2 Recovery in HP frac. section

2

H_2 in stripper off gas typically ranging between 40 – 60 vol%

LP off gas is low-pressure, compressor needed.



Hydrocracker H_2 Management Options – H_2 recovery in RX & Fractionation Section

- Option 1 - Addition of a PSA in RX and/or fractionation section
- Option 2 - Addition of a Membrane (PolySep) in RX and/or fractionation section

Endeavor combining H_2 recovery into 1 central PSA or Membrane unit

Hydroprocessing H_2 recovery is a key enabler for overall refinery profitability

HYDROCRACKER H_2 MANAGEMENT VIA H_2 RICH OFF GAS RECOVERY

- **Option 1** - PSA to process Cold Flash Drum and/or LP amine stripper off gas
  - Typical 84 – 86% H_2 recovery w/o PSA tail gas integration & >95% H_2 recovery w/ PSA tail gas integration
  - High purity H_2 (> 99.9 vol%)
  - Recovered H_2 recycled to the Makeup Gas Compressor [MUG]
  - Reduced fresh H_2 demand (make-up) by 10%
  - Increased LPG & C_5+ production by sending PSA tail gas to sponge absorber, in lieu of refinery fuel gas
  - Reduce CO_2 emissions from SMR by lower requirement on-purpose H_2 production
- **Option 2** - adding Membrane is a lower cost option
  - Typical H_2 recovery is ~ 98% (higher than PSA)
  - Hydrogen purity is lower (96 vol%)
  - Membranes need frequent element replacement and have had operational issues
- **Both PSA and membrane can be independently constructed and tied in during hydrocracker turnaround**

Hydroprocessing H_2 recovery is a key enabler for overall refinery profitability

CASE STUDY - HC CFD OFF GAS PSA ECONOMICS

- Basis 2,000,000 MTA hydrocracking unit with VGO feed
- Hydrogen requirement 2.5 wt%, 50,000 MTA
- Cold flash drum purge - 1.03 wt%, 20,624 MTA valued at $200/t as Fuel Gas
- CAPEX of PSA - $5 M

Benefit	Recovery	kMTA	Delta $ Value	$ MM/yr
H_2 Recovery	86%	6,439	$1,300	5.7
LPG recovery	86%	6,984	$200/t	1.4
C_5+ recovery	100%	1,624	$500/t	0.8
Carbon credits		53,000	$50/t	2.7
Additional utilities	-	-	-	(1.0)
Total w/o CC	-	-	-	6.9
Total w/ CC	-	-	-	9.6
Payback w/o CC				~ 7 months
Payback w CC				~ 5 months

H_2 recovery from Hydrocracking Improves Refinery Profitability

Assumptions – 1) 86vol% H_2 recovery in PSA, 2) 50% LPG in PSA tail gas and 86% recovery, 3) 10% C_5+ in PSA tail gas and 100% recovery.

THANK YOU
FOR YOUR PARTICIPATION