MOVE THE WORLD FORWARD MITSUBISHI HEAVY INDUSTRIES GROUP

KM CDR Process™ - From Notion to "World's Largest"

2018 CCUS Student Week

Golden, Colorado

October 16th, 2018

MITSUBISHI HEAVY INDUSTRIES AMERICA

January 2017 Owner's PR:

*"NRG Energy, JX Nippon complete world's largest post-combustion carbon capture facility on-budget and on-sch**e**dule[1]"*

[1]NRG press release

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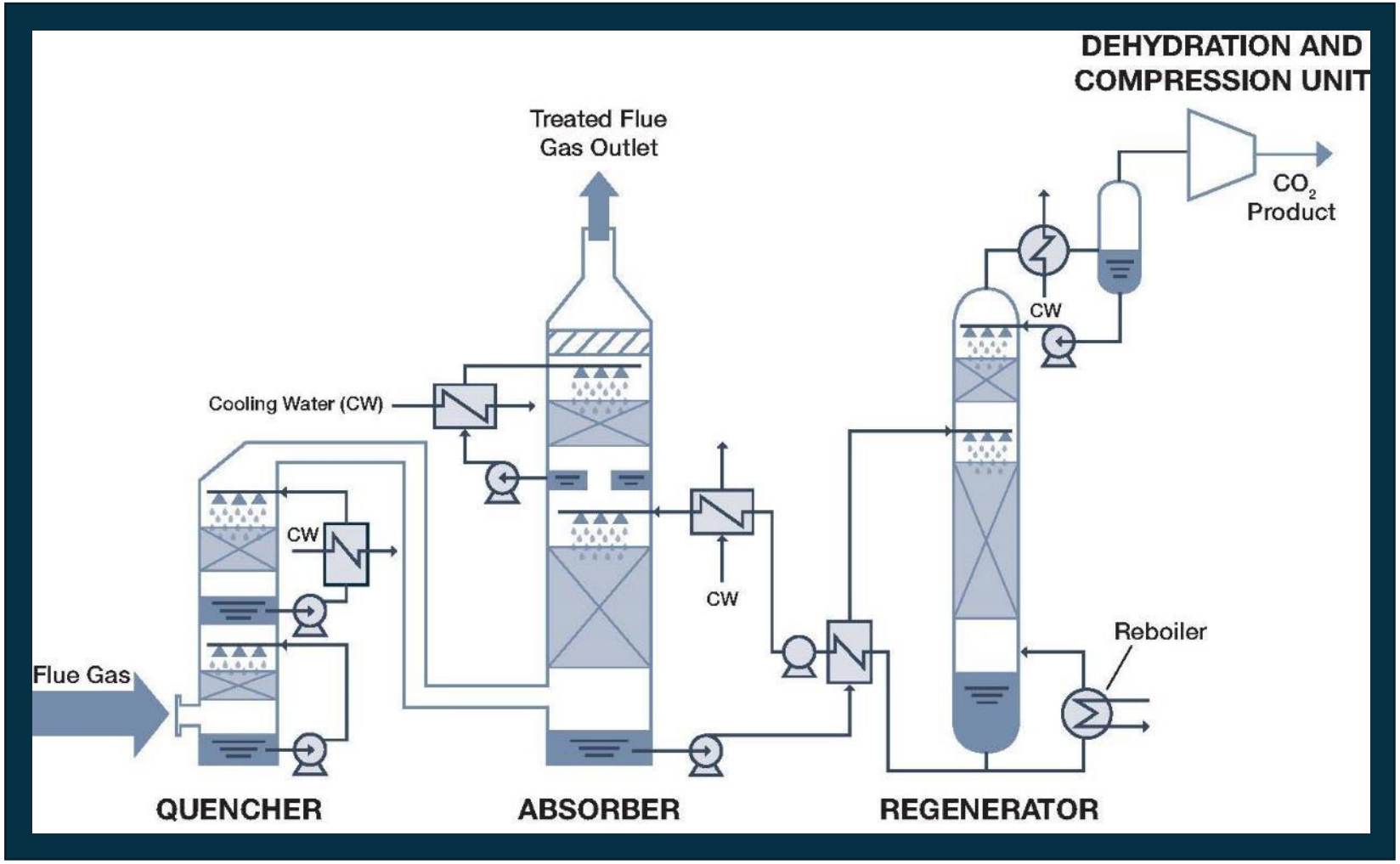
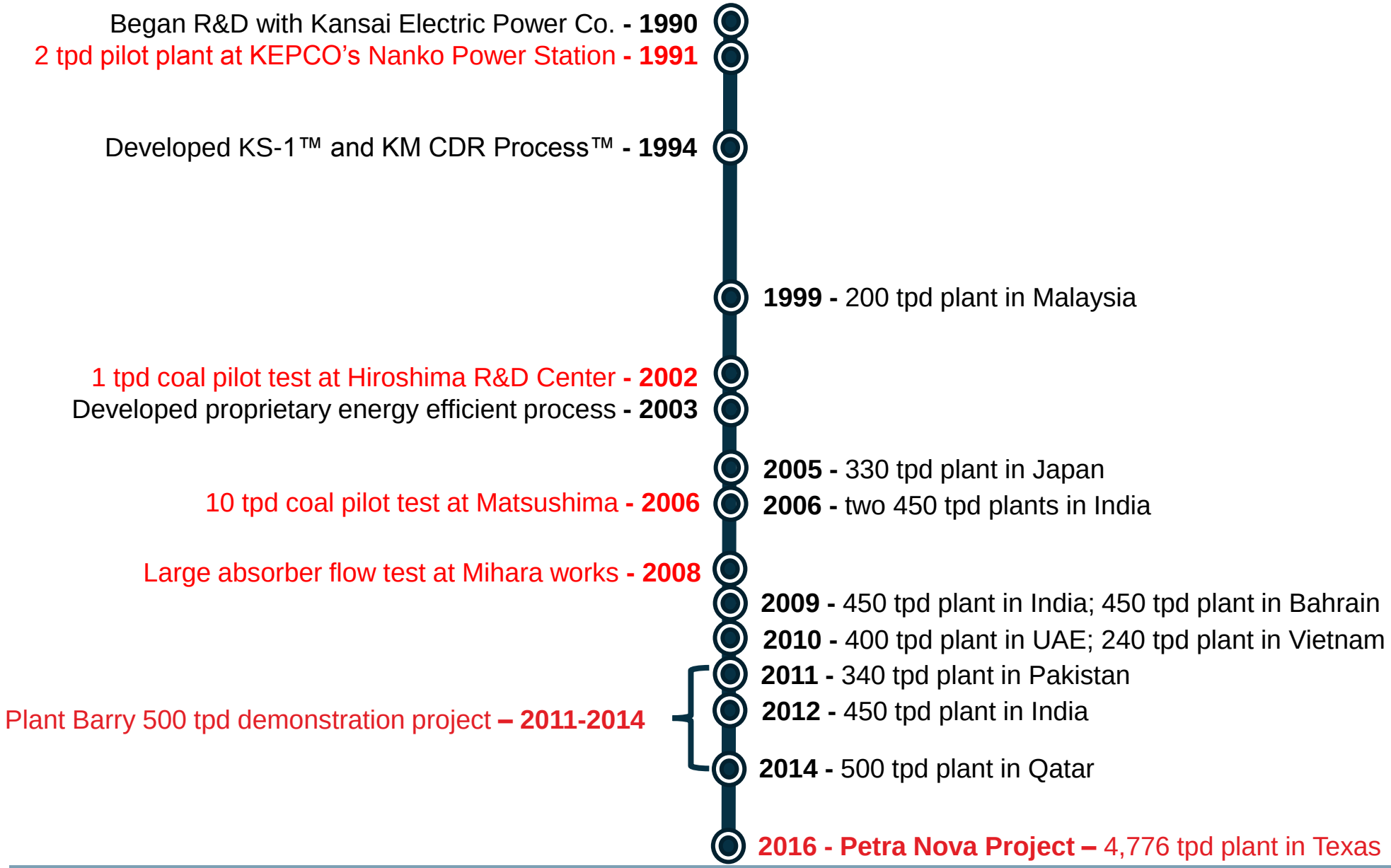
How did we get here?

KM CDR Process™ Overview



- **KM CDR Process™** = *Kansai Mitsubishi Carbon Dioxide Removal Process*
- Amine-based technology
- Proprietary features developed over 28 years of experience
- KS-1™ solvent boasts high CO_2 capacity, low degradation, and low regeneration energy
- Capable of capturing ~90+% CO_2 from combustion gas sources

KM CDR Process™ Technology Development Timeline



Nanko – Screening and Testing to develop KS-1™ and KM CDR Process™

MHI believed that CO_2 regulations would be implemented and began investigating CO_2 capture technologies for combustion gases.

- 1990 – MHI screened more than 200 solvent formations.
- 1991 – MHI tested 20 solvents at KEPCO's Nanko Power Plant (natural gas fired boiler).
- Flue gas composition can be varied with CO_2 recycle and air.
- Max CO_2 capture capacity: 2 tpd
- Over 14,000 hours of direct testing to date.
- ✓ 1994 – MHI settled on KS-1™ and KM CDR Process™

Hiroshima & Matsushima – Effects of Coal-fired Flue Gas on KM CDR Process™

Hiroshima R&D Facility
(1 mtpd)

Matsushima Pilot Plant
(10 mtpd)

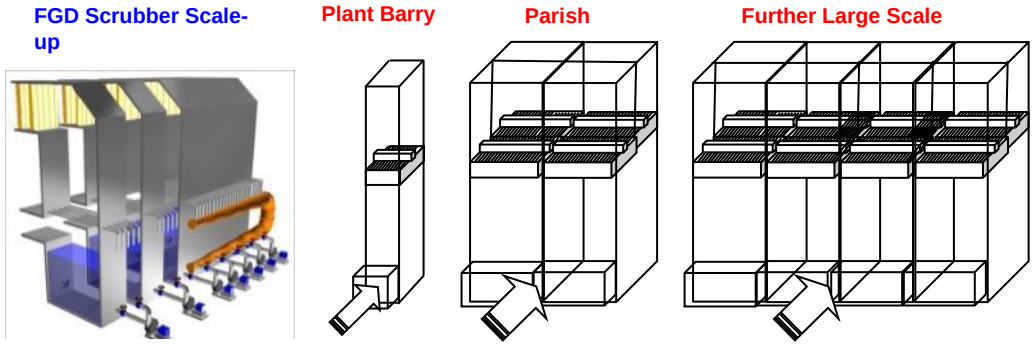
MHI understood that the impact of flue gas impurities on the solvent and process must be well-characterized before scale-up.

- 2002 – Tested on coal-fired flue gas at Hiroshima R&D.
  - Max CO_2 capture capacity: 2 tpd
  - Over 1,700 hours of direct testing to date.
  - ✓ Evaluated effects of PM, SOx, NOx, metals, and aerosols.
- 2006 – Tested at Matsushima coal fired power plant.
  - Max CO_2 capture capacity: 10 tpd
  - Completed more than 6,000 hours of solvent and process testing.
  - ✓ Demonstrated and verified long-term performance of solvent on coal exhaust.

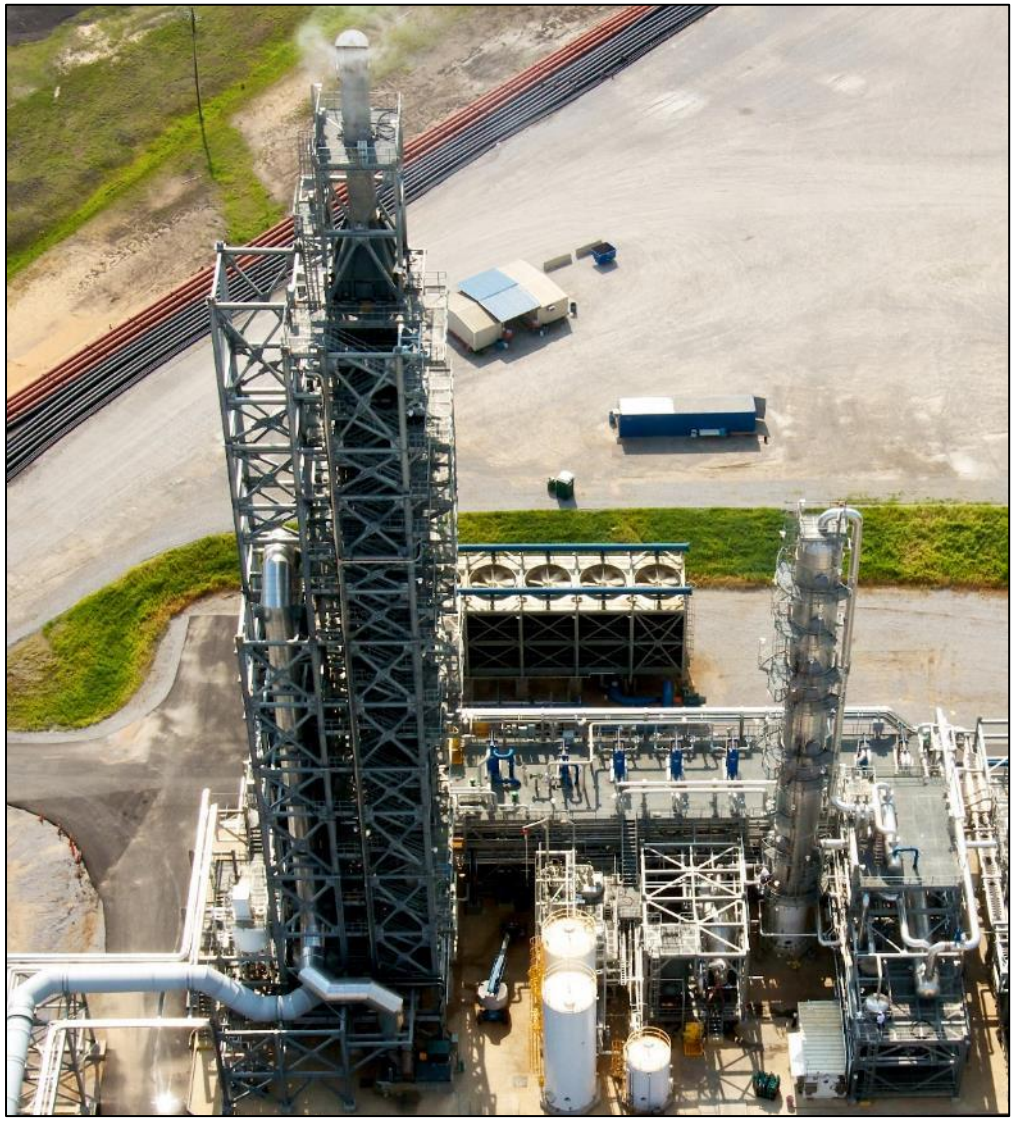
Mihara Works – Verification of Rectangular Tower and Distributors for Scale-up

High performance packing is very sensitive to liquid distribution. Without proper distribution, performance cannot be predicted.

- 2008 – tested liquid distributors
- Absorber measures ~36’L x ~18’W x 105’H
- Scaling technique is similar to that used on more than 200 commercial FGD systems.



Large-Scale Coal Demonstration Project at Plant Barry (25MWeq)



Large-scale demonstration was necessary to combine the lessons learned from the smaller pilot projects before scaling up for commercial power projects.

- Majority of funding by Southern Company and MHI.
- CO_2 capture capacity: 500 tpd
- From 2011-14: over 12,000 hours, over 250,000 tons captured, over 125,000 tons injected

✓ Tested various technologies developed from pilots.

✓ Confirmed design expectations and performance.

✓ Confirmed long-term stable system operation.

✓ Verified long-term performance under various flue gas conditions and coal characteristics.

25MW$_{eq}$ CCS Demonstration Project at Plant Barry

Verified Process Improvements

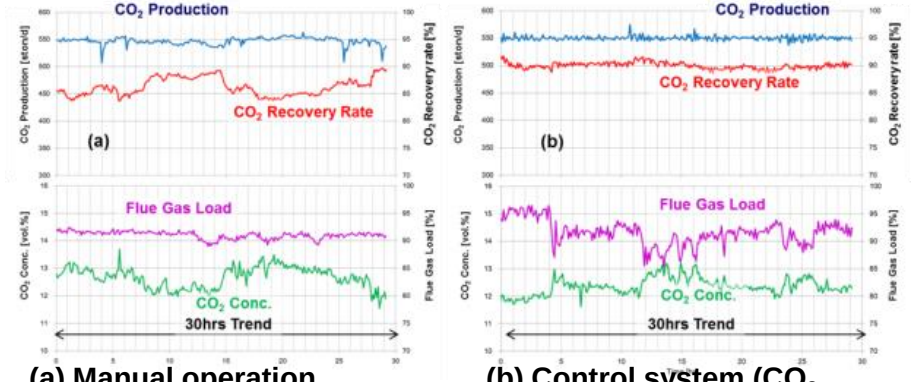
Energy Saving System
Deployed and verified an optimized system for reduced steam consumption

Automatic Load Adjustment System
Deployed and verified dynamic response simulator and automatic control system for load following

Amine Emission Reduction System
Deployed and verified countermeasures including multi-stage wash and demisters at elevated inlet SO_3 conditions.

Amine Purification System
Verified performance of batch reclaiming operation to remove coal combustion impurities from solvent

Automatic Load Adjustment System



(a) Manual operation **(b) Control system (CO_2 production control mode)**

- Automatic system control including solvent circulation and steam use depending on plant load, flue gas condition, and CO_2 demand
- Allows rapid response to changing system conditions and turndown to 50%

Amine Emissions Reduction System

MHI Plant without Amine Reduction System

MHI Plant with Amine Reduction System

Petra Nova Project – World's Largest Post-Combustion CO_2 Capture Project

Fall 2016 View of the Site

The Petra Nova project is MHI's first commercial power project and has ~10x the capacity of the Plant Barry demonstration.

- The Petra Nova project captures CO_2 from NRG's WA Parish Plant Unit 8 and transports the CO_2 to the West Ranch Oil field for EOR.
- Plant is owned by NRG and JX Oil & Gas.
- Captures 4,776 mtons/day (240 MWeq, 90% capture) from a ~37% flue gas slip stream.
- MHI - TIC consortium for full turnkey EPC delivery of the CO_2 capture and compression system and BOP.
- Successfully completed Performance Test in December 2016.

Operating the plant has provided valuable insights that can be implemented into the next projects.

- Operating parameters exceeded expectations:
  - Steam consumption, absorber performance, and CO_2 capacity exceeded expectations -> Reduce size of absorber tower.
  - Quencher and SO_2 removal system exceeded expectations -> Reduce size of quencher tower.

- Initial flue gas impurities assumptions were conservative. Actual flue gas conditions should be thoroughly considered.
  - Filtration system loading is lower than expected.
  - Reclaiming operation less frequent than expected.
  - VOC emissions lower than expected.






What's Next?

Plant Barry 500 tpd demonstration project **– 2011-2014**

- **2011 -** 340 tpd plant in Pakistan
- **2012 -** 450 tpd plant in India
- **2014 -** 500 tpd plant in Qatar
- **2016 - Petra Nova Project –** 4,776 tpd plant in Texas

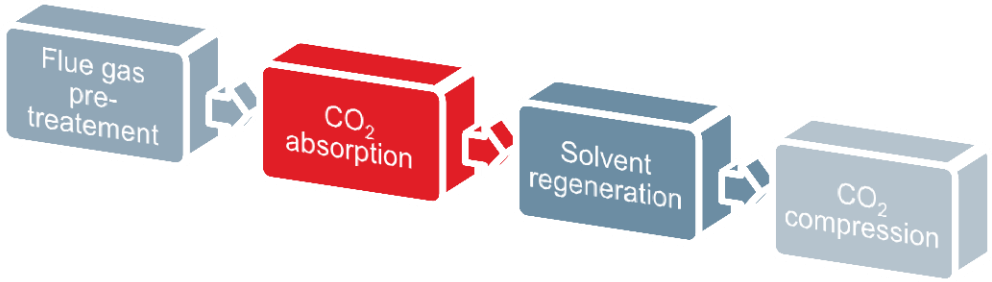
New Solvent Testing

- Multiple new solvent formulations have been evaluated.
- KS-21 appears to have advantages over KS-1™ that may help reduce overall capital and operating costs.
- Pilot testing currently underway.

Parameters	KS-1™	KS-21
Volatility	100	50-60
Thermal degradation rate	100	30-50
Oxidation rate	100	70
Heat of absorption	100	85

Design Standardization

- How will we deliver the next 10,000+ tpd systems on a timeline compliant with 45Q credits?
- MHI currently evaluating how to standardize portions of the design to reduce overall project costs and schedule.



Without large scale demonstration of the KM CDR Process™, the performance of the Petra Nova Project could not have been guaranteed.

Thoughtful technology development, extensive testing, and large scale demonstrations are essential for successful commercial projects.

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