Autothermal Cyclic Reforming and H_2 Refueling System

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This presentation does not include any proprietary or confidential information

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imagination at work

Outline

- Objectives
- Project Timeline & Budget
- DOE Targets
- Accomplishments over last year
- Safety Status
- Project Plan for Next Year
- Summary

Objectives

- Overall
  - > Design a reformer based refueling system that can meet the DOE cost (<$2.50/kg) target
  - > Fabricate and operate an integrated 60 kg of H_2/day reforming and refueling system
- Last Year
  - > Design, fabricate and operate reformer and pressure swing adsorber pilot-scale sub-systems
  - > Design the prototype reformer and pressure swing adsorber
  - > Design the compression, storage and dispensing system and collect data on sub-systems

Project Timeline – Major Milestones

- Phase I – Design and Analysis
  1. Completed conceptual design
  2. Completed economic analysis
- Phase II – Subsystem Development
  3. Operated pilot-scale reformer and PSA
  4. Completed prototype reformer and PSA design
  5. Fabrication and shakedown of prototype reformer and PSA
- Phase III – Integrated System Operation
  6. Integration of ACR with PSA
  7. Complete bench-scale catalyst durability testing
  8. Integration of H_2 generator with H_2 compressor and dispenser
  9. Operation of ACR based hydrogen refueling system

Budget

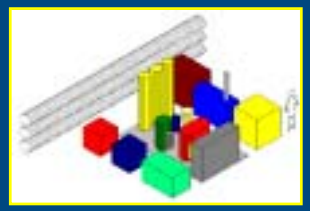
- Total: $4.8 Million
- Industry: $2.1 Million
- DOE: $2.7 Million
- FY04 Funding: $0.6 Million

Technical Barriers and Targets

- Distributed H_2 Production from Natural Gas Barriers
  - > A. Fuel Processor Capital Costs
  - > B. Operation & Maintenance Issues
  - > D. Carbon Dioxide Emissions
  - > E. Control & Safety
  - > Z. Catalysts
  - > AB. H_2 Separation & Purification
- Targets

	2003	2005	2010
Cost ($/kg)	5.0	3.0	1.5
Efficiency (LHV)	62	68	75

Prototype Hydrogen Generating & Dispensing System



Natural Gas

Water

Fueling Technologies

H_2

Dispenser

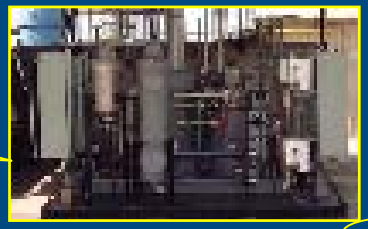
Air

Reformer

Vent

Storage Tanks

Recycle Fuel



GE

Praxair

Hydro-Pac

Comp.

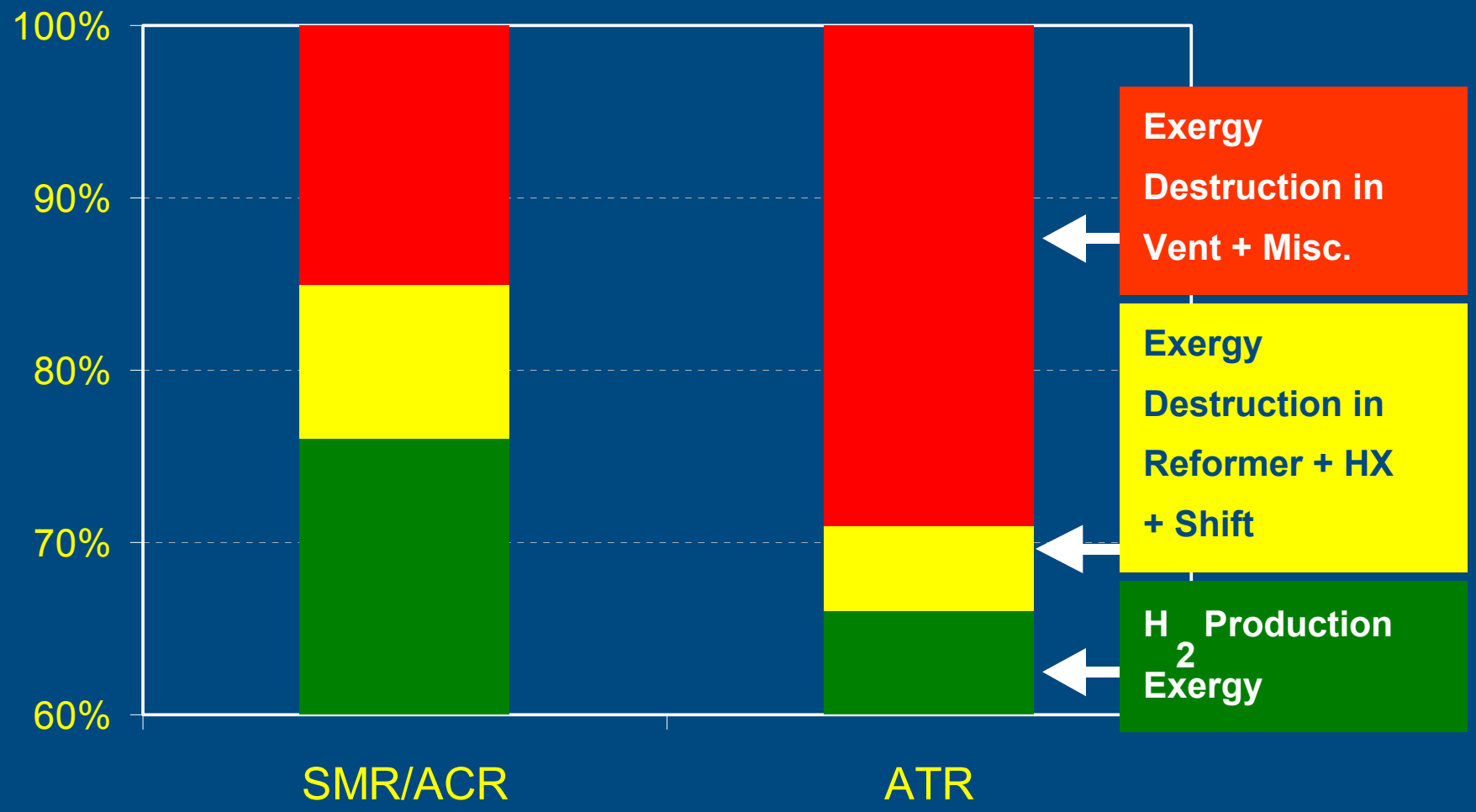
Shift Reactor

Pressure Swing Adsorber

H_2

H_2, CO, CO_2, CH_4

Exergy of Reformers for H_2 Generation

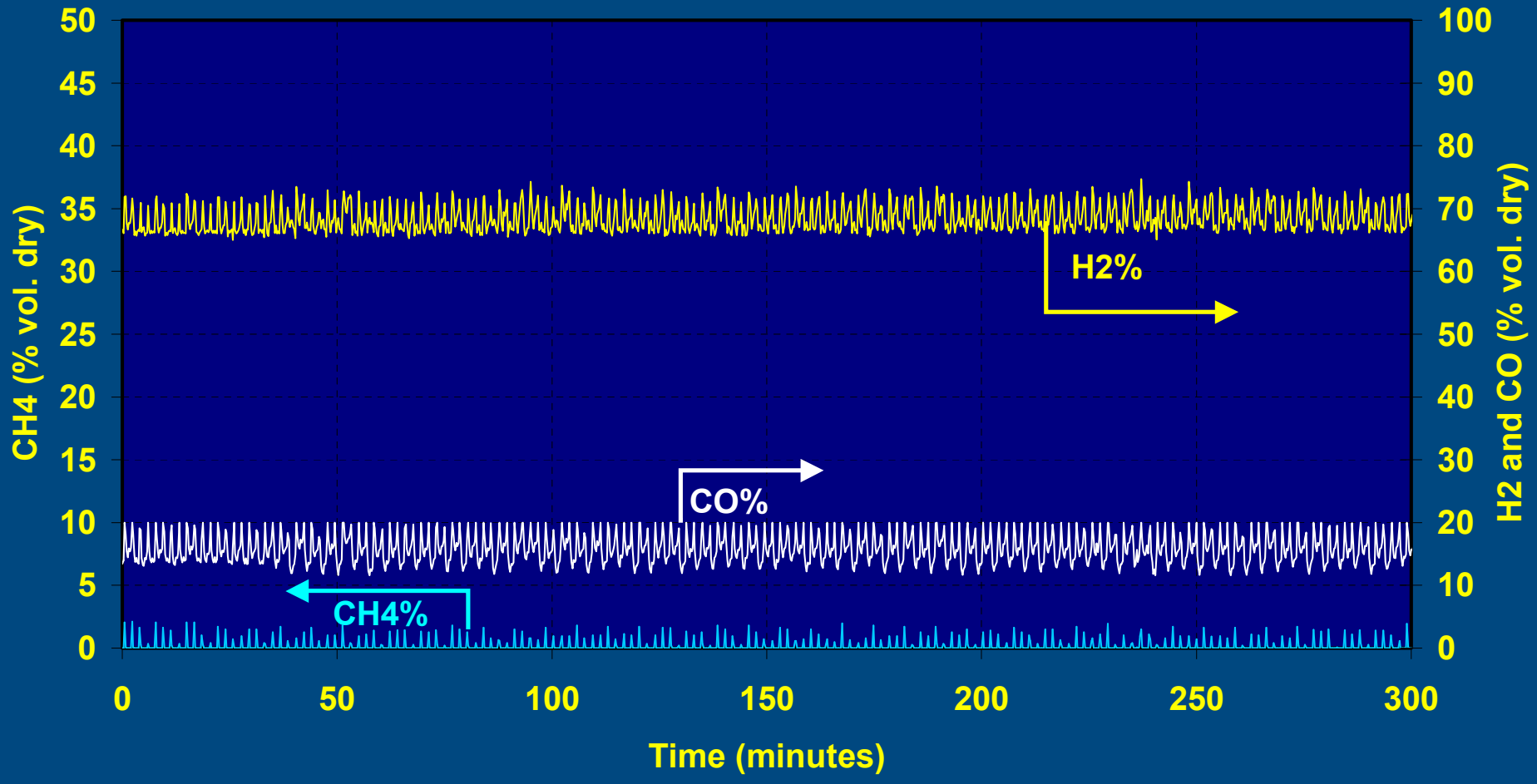


SMR – Steam Methane Reforming
ACR – Autothermal Cyclic Reforming
ATR – Conventional Autothermal Reforming

Reformer Choice Depends on Application

	Conv. SMR	Conv. ATR	ACR
%H_2 from reformer	70%	40-50%	70%
Efficiency	75%	65%	75%
Capital Cost	High	Low	Low
Fuel Flexibility	Natural Gas, Propane	Natural Gas, Propane, Diesel Fuel, Biogas	Natural Gas, Propane, Diesel Fuel, Biogas
Sulfur Tolerance	Poor	Good	Good
Turndown	Poor	Good	Good

Stable Operation of Low-Pressure Pilot-Scale ACR



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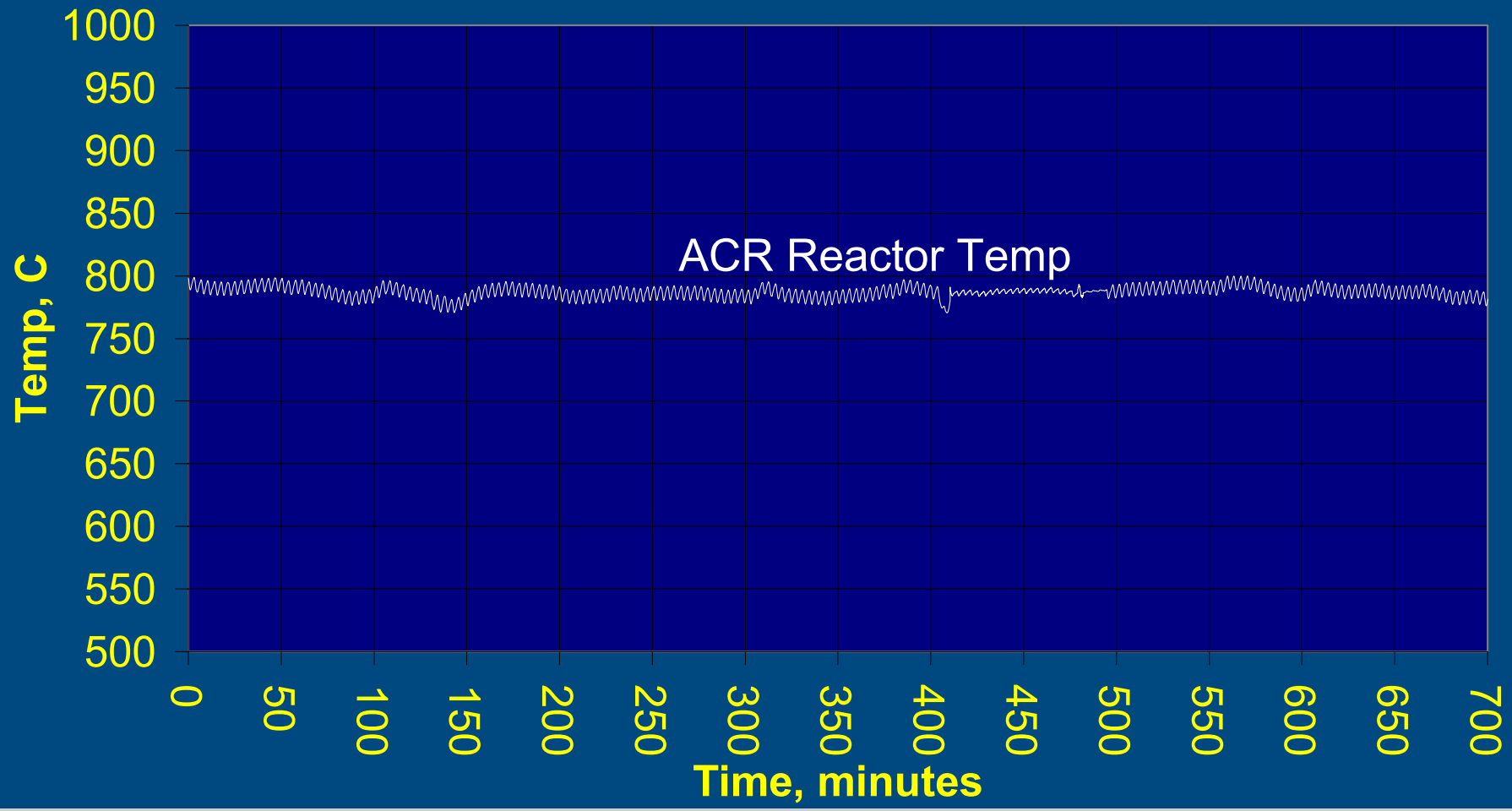
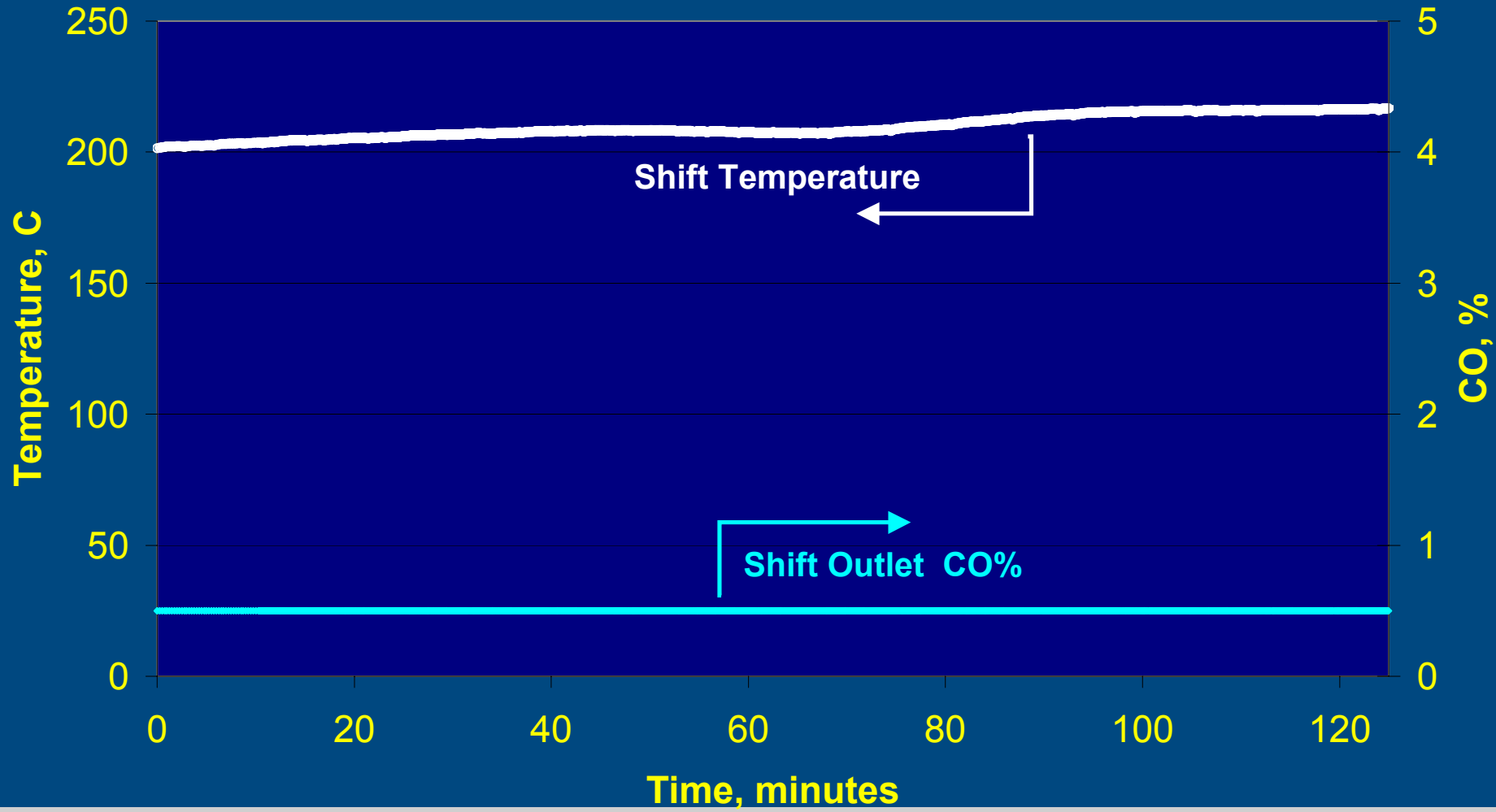


Shift Reactor Testing

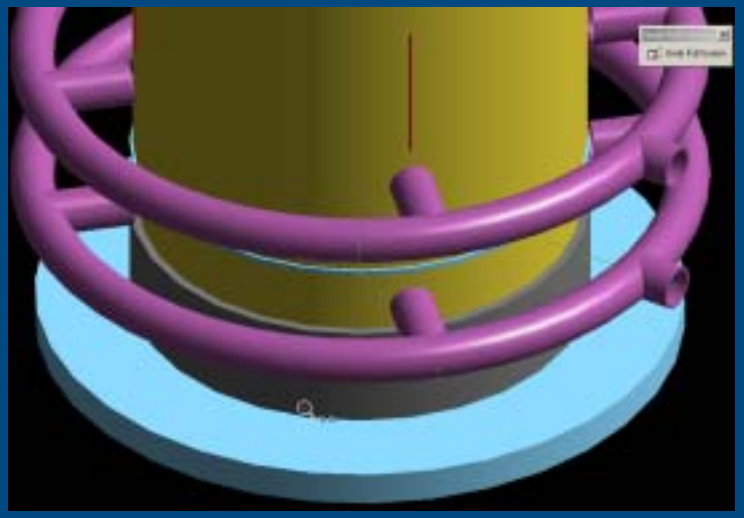
Specification: %CO < 1%

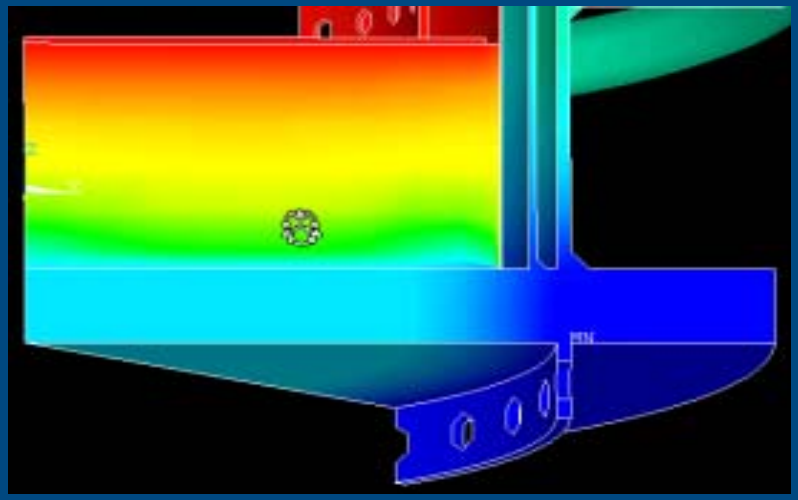


Reformer Testing Accomplishments

- Operated system with about 30 start-stop cycles
- Operated system continuously for up to 30 hours using automated controls several times.
- Demonstrated less than 0.5% CO at exit of shift reactor
- Operated system from 55 kg/day to 15 kg/day (3.5:1 load change)
- Lab scale tests for 2,000 hrs

High Pressure Reformer Reactor: 3-D Stress & Thermal Modeling





Reformer Zones	Heat Loss, kW
Top	0.4
Side	2.7
Bottom	0.3
Total	3.4
Specification	< 5.0

Critical welds	Cold-Start Cycles to failure
Hottest Internal	> 90,000
Outer Shell	> 1,000,000
Specification	> 1,000

Praxair PSA Pilot Plant Meets Requirements

Design Goals: 60 kg/day, 99.99% H_2 purity, 75% recovery

4 bed design
- > Shortened bed height
- > Reduced amount of sieve required
- > Improved recovery

3 bed design
- > Advanced sieve material
- > Proprietary 12-step cycle
- > Lowered feed pressure requirements

Praxair PSA Prototype Skid Status

- Skid design 75% complete
- Adsorbent - on order
- Logged 300,000 cycles on valves
  - > No detectable leaks using He @ 150 psig

H_2 Purity Status

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Component in the Product	DOE Targets	Current Status	Status with Future Development
H2	98% dry basis	99.99% dry basis	~ 99.9999% dry basis
CO	< 1 ppm	< 5 ppm	< 1 ppm
CO2	< 100 ppm	< 10 ppm	< 5 ppm
Sulfur	< 10 ppb	< 50 ppb	< 10 ppb
Ammonia	< 1 ppm	< 10 ppm	< 1 ppm
Hydrocarbons	< 100 ppm	< 10 ppm	< 10 ppm
O2, N2 & Ar	< 2%	~ 100 ppm	~ 100 ppm

Hydro-Pac Hydraulic H_2 Compressor

- Praxair's LAX project provided an opportunity to gain experience needed for the ACR program
- Measured incoming power and calculated the compressor efficiency during factory run test on helium

$$\eta_{adiabatic} = 67.8\%$$

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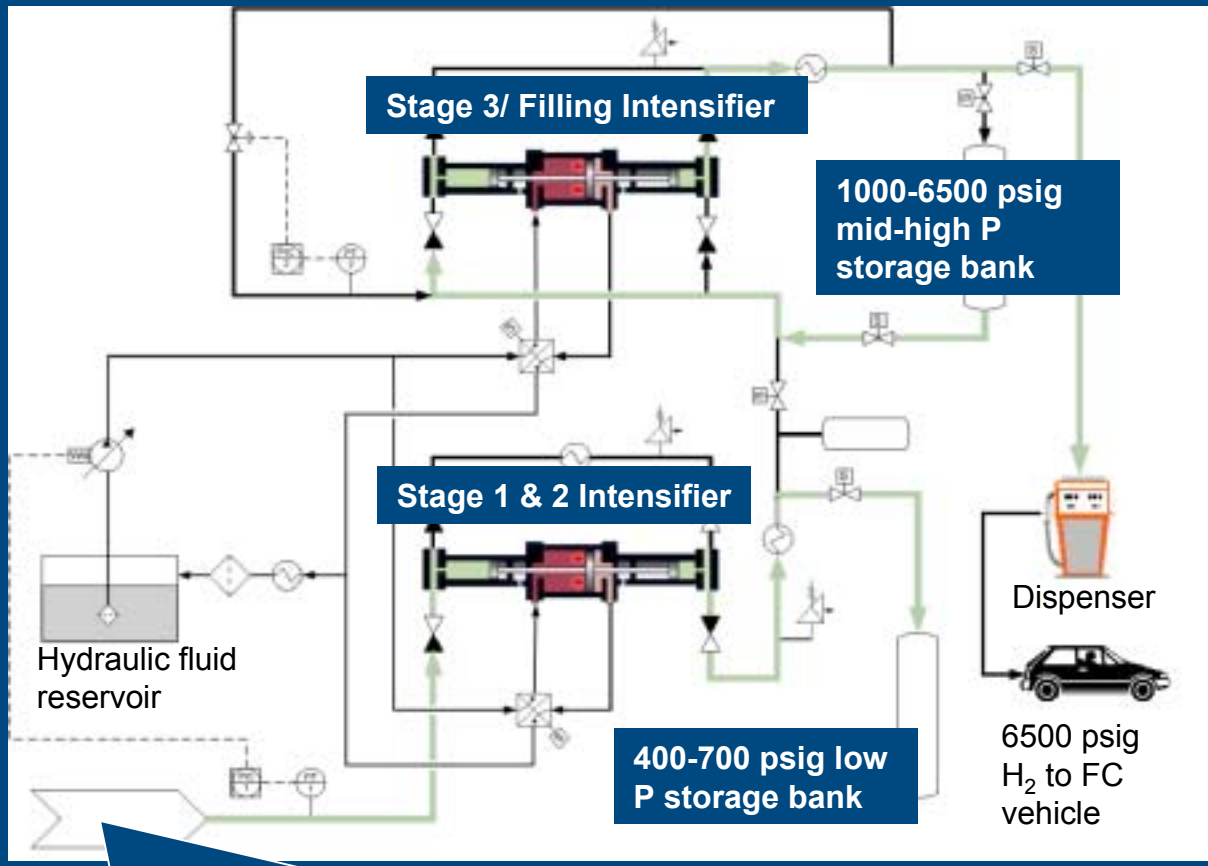
Fill Pump Dispensing with Added Low Pressure Bank (Patent Pending)

- Requires 1/3 the amount of storage than cascade dispensing
- Added low pressure storage bank to maximize utilization
- Requires only one "modified" packaged compressor by separating functionality of each intensifier during fill
  - > Stages 1 & 2 fill low pressure bank
  - > Stage 3 acts as fill pump
- Small scale testing to begin in 2nd quarter of 2004



Stationary Storage

- Plan to use ASME Section VIII, Division 1 Coded seamless steel cylinders
  - > Designed with a safety factor of 3.0
  - > Praxair has a perfect safety record when employing these vessels for H_2 service
- Work with ASME to develop new rules for composite vessels
  - > Praxair working with ASME and is actively participating in the H_2 Steering Committee for storage and transport of H_2

ASME STEEL CYLINDERS

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Praxair is working with Fueling Technologies on Dispenser

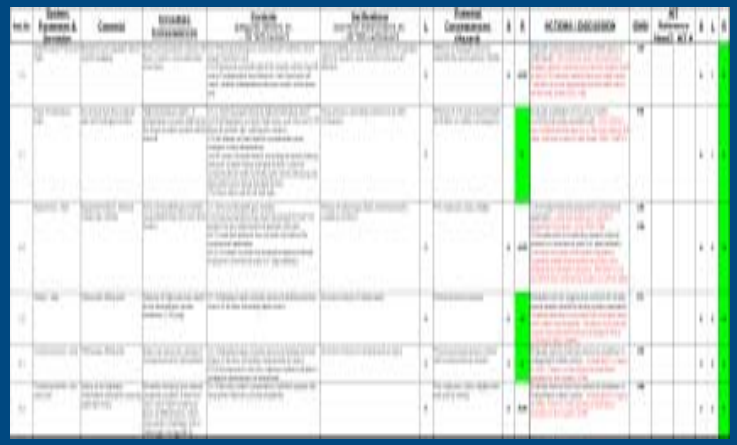
- Safety
- Additions
  - > A vibration switch terminates the fill operation in the event of vehicle contact and remains locked out until reactivated
  - > A shear frame assembly and automatic shutoff valves as a safeguard against a more severe vehicular collision
  - > FTI provided new connections to allow the use of N_2 for purging both the enclosure in an LEL shut-down event and for continuously purging the dispenser H_2 vent header

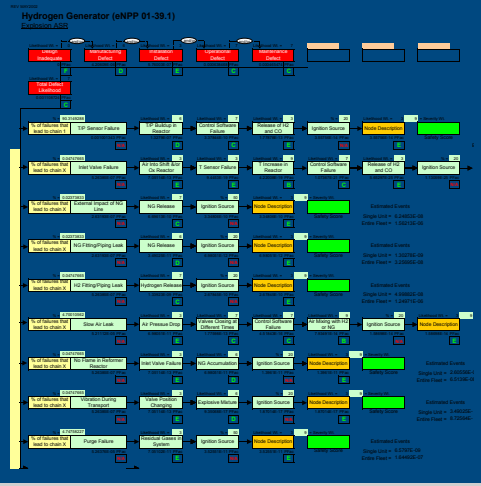
PRIORITY SEQUENCING PANEL

DISPENSER ISLAND

Project Safety

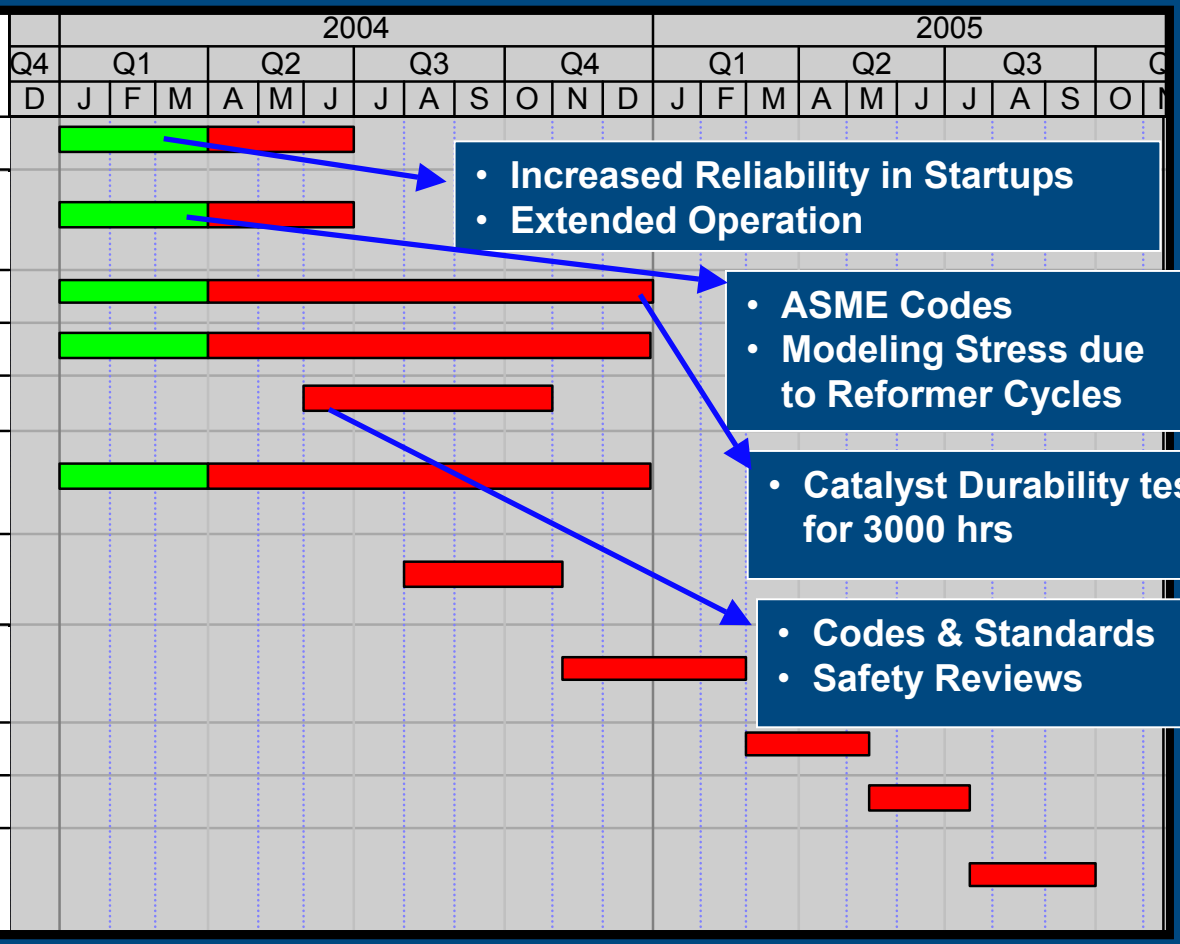
- System Component FMEA's
- Preliminary Hazard Assessment
- Haz Op (with independent review)
- Accident Scenario Review (performed review on any medium scoring item on Haz Op)





ACR Project Plan for 2004-5

#	Task Name
1	Low pressure reformer operation
2	High pressure reformer design and fabrication
3	Catalyst durability testing
4	PSA design and fabrication
5	Installation in UCI
6	Design of H2 compressor, storage and dispenser
7	High pressure ACR reactor shakedown
8	High pressure reformer start-up and operation
9	Integration with PSA
10	Integration with PEM fuel cell
11	Integration with H2 compressor, storage and dispenser

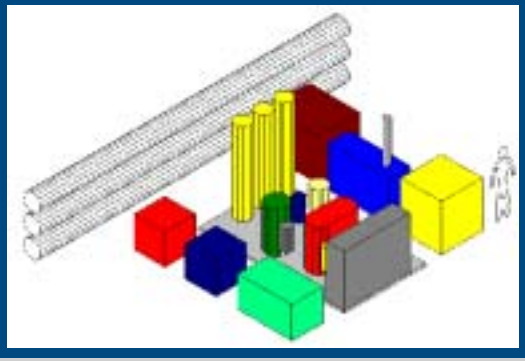


Significant Reviewer Comments

- Excellent implementation of economics; Economic analysis should include reformers from other manufacturers
  - > Working on DOE H_2A panel
  - > Supporting DOE on an apples-to-apples comparison of different reforming technologies
- Little innovation outside of GE reformer evident
  - > Praxair submitted patents on PSA and refueling system recently
  - > Novel 3-bed and 4-bed designs
  - > Some of the innovation is confidential and will be presented to DOE
- Excellent component developed and test plans; Future plans are weak
  - > Included a detailed project plan for next year

Summary

- Low-pressure pilot-scale ACR operation
  - > Stabilized for extended periods of time
  - > 30 start-stop cycles
- High pressure prototype reformer design is complete
- Prototype reformer and PSA will be fabricated and operated this year
- Reformer will be integrated with PSA, compressor and storage tanks
- Operation of integrated system in 2005



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imagination at work