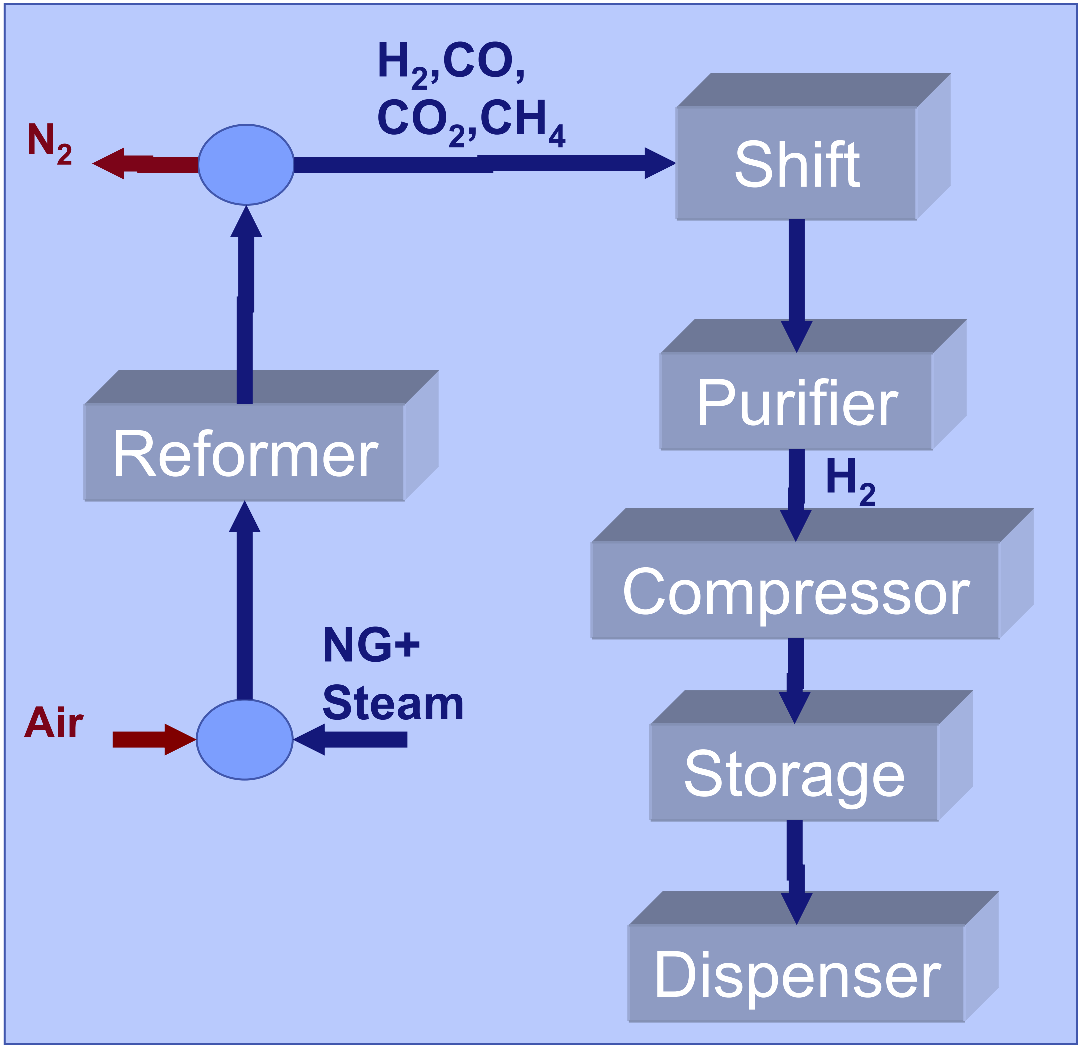
Autothermal Cyclic Reforming Based Hydrogen Generating & Dispensing System

Ravi Kumar
GE Global Research

23rd May 2005

This presentation does not contain any proprietary or confidential information



imagination at work

Project ID # PD3

Overview

Timeline

- Start - Jan 2002
- Finish - Dec 2005
- 85% Complete

Budget

- Total project funding
  - DOE - $2,382K
  - Contractor - $1,812K
- Funding received in FY04
  - $650K
- Funding for FY05
  - $650K
- Funding reduced - Fabrication & operation of H2 compressor, storage & dispenser removed from scope

Barriers

- Barriers
  - > A. Fuel Processor Capital Costs
  - > B. Fuel Processor Manufacturing
  - > C. Operation & Maintenance
  - > E. CO_2 Emissions
  - > F. Control & Safety
  - > L. Durability
  - > M. Impurities
- Targets - production & dispensing

	2003	2005	2010
Efficiency (LHV)	65	65	75

Partners

- Praxair - Purifier
- University of California at Irvine – Host Site

imagination at work

Objectives

Overall	• Design a generating & refueling system that can meet the DOE cost target of <$3.00/gge • Fabricate and operate an integrated 60 kg of H_2/day generating system
2004	• High-pressure reformer & pressure swing adsorber (PSA) – Design – Fabrication & Installation • Compression, storage & dispensing system – Design
2005	• Permitting • High-pressure reformer & PSA – Integration & Operation • Update economic analysis

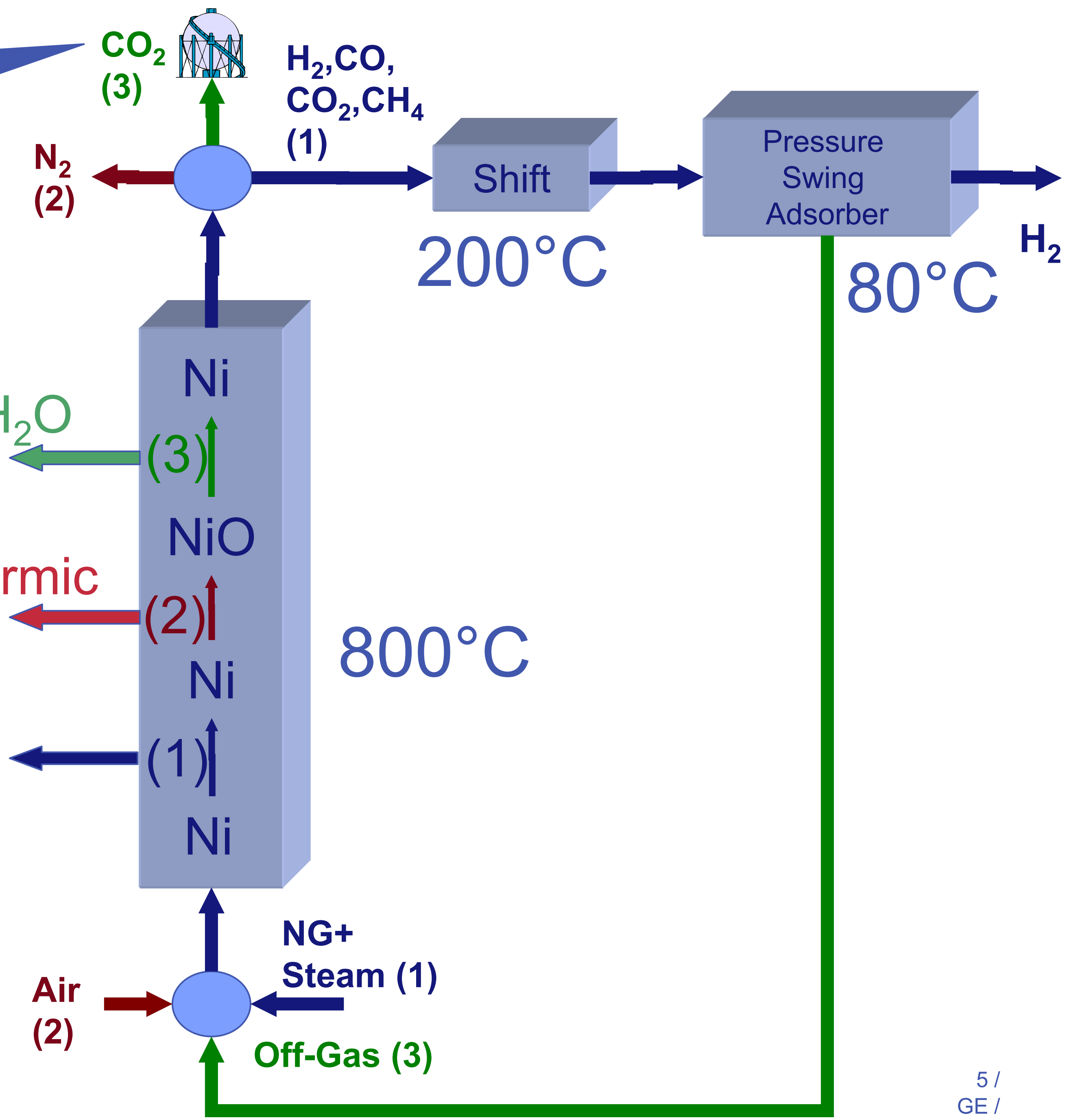
imagination at work

Technical Approach

Reformer	• Minimize capital cost • Design for 1000s of cold start cycles • Modeling of advanced control systems for stabilizing temperature and flows • Catalyst durability – thermal/RedOx cycles • Increase methane conversion
Shift	• Increase CO conversion
Pressure Swing Adsorber	• Impurities – CO, Sulfur • >75% recovery of Hydrogen
Safety & Permitting	• Gas Sensors – Lower Explosive Limit (LEL) • Seismic zone 4 classifications • Class I Div II explosion proof electrical

Autothermal Cyclic Reforming Process

Separation potential for large scales



Fuel Reduction – Mildly Endothermic

$4NiO+CH_4 \rightarrow 4Ni+CO_2+2H_2O$

$NiO+H_2 \rightarrow Ni+H_2O$

Air Regeneration - Exothermic

$Ni + 1/2\ O_2 \rightarrow NiO$

Reforming - Endothermic

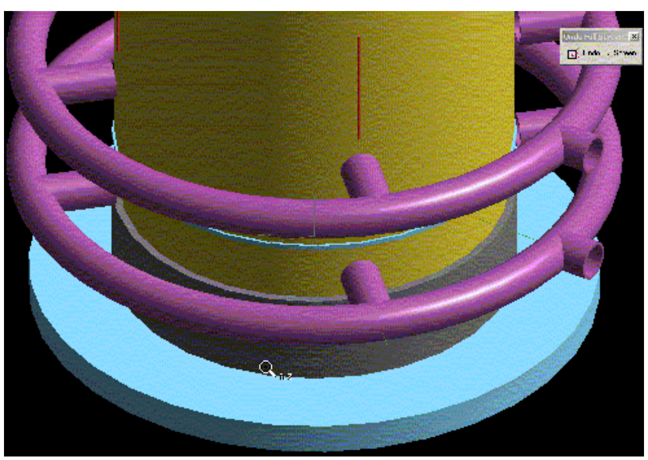
$CH_4+H_2O \rightarrow CO + 3H_2$

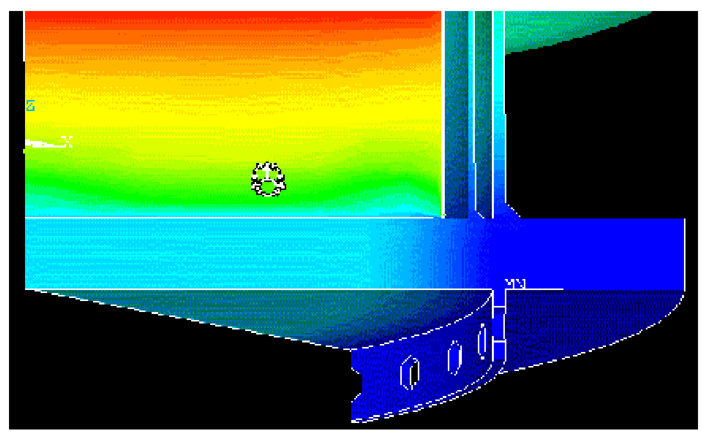
$CO+H_2O \rightarrow CO_2 + H_2$

High Pressure ACR Reactor Design Meets the Performance Targets

CTQ	Targets	Current Status (modeling)
ASME: Outer shell temperature	< 400°C	~ 300°C
Cold start cycles to failure	> 1,000	12,984
Reforming cycles	> 2E+6	5.8E+7
CH_4 slip	< 10%	< 5%
Heat loss from the reactor	< 5 kW	3.4 kW

3D Modeling
- Thermal
- Mechanical Stresses
- Reactions



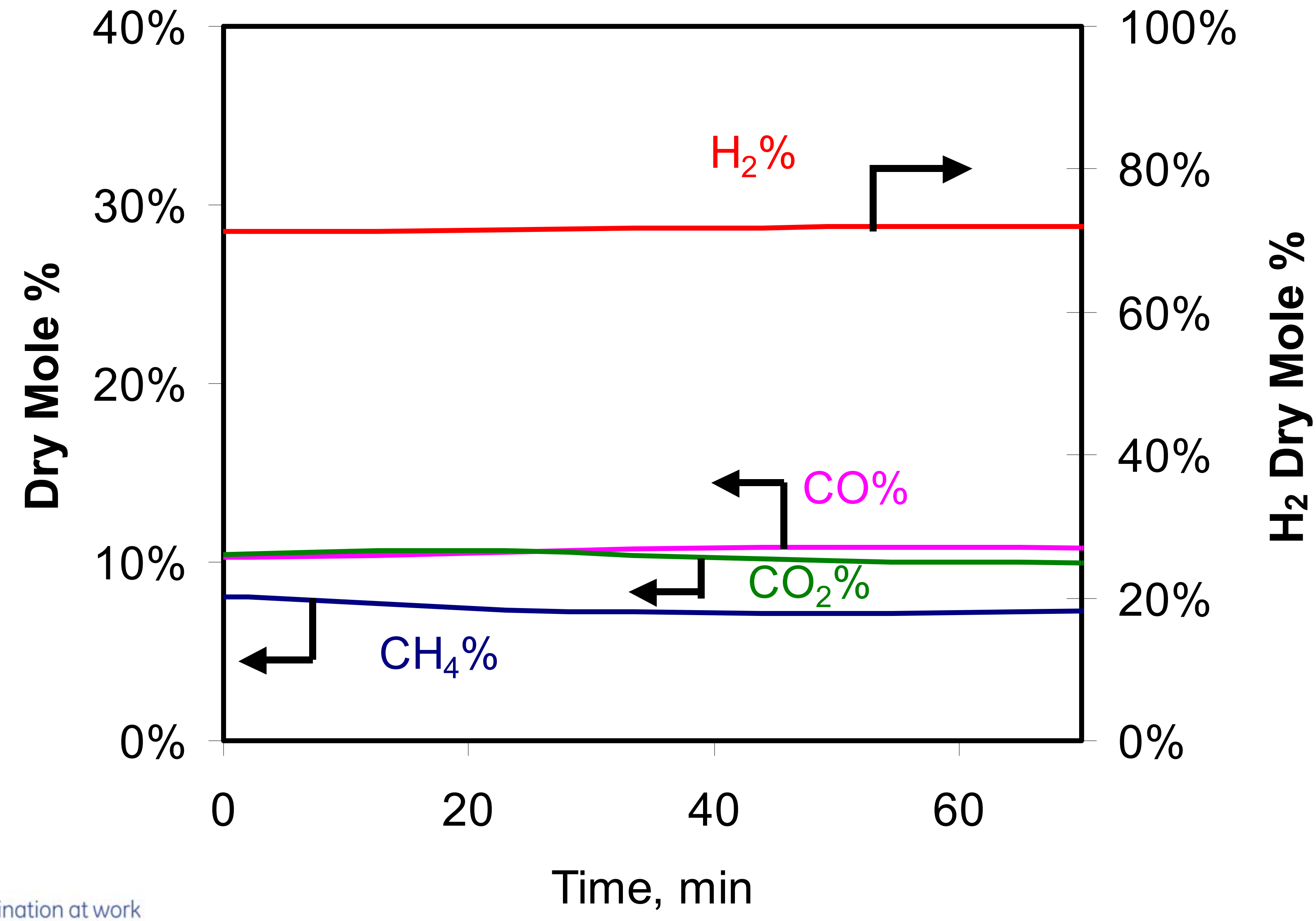


Rigorous QA on welds – Visual, X-Ray, Ultrasonic Inspection

imagination at work

Developed Dynamic Cascade Control Algorithms for Stabilizing the Process

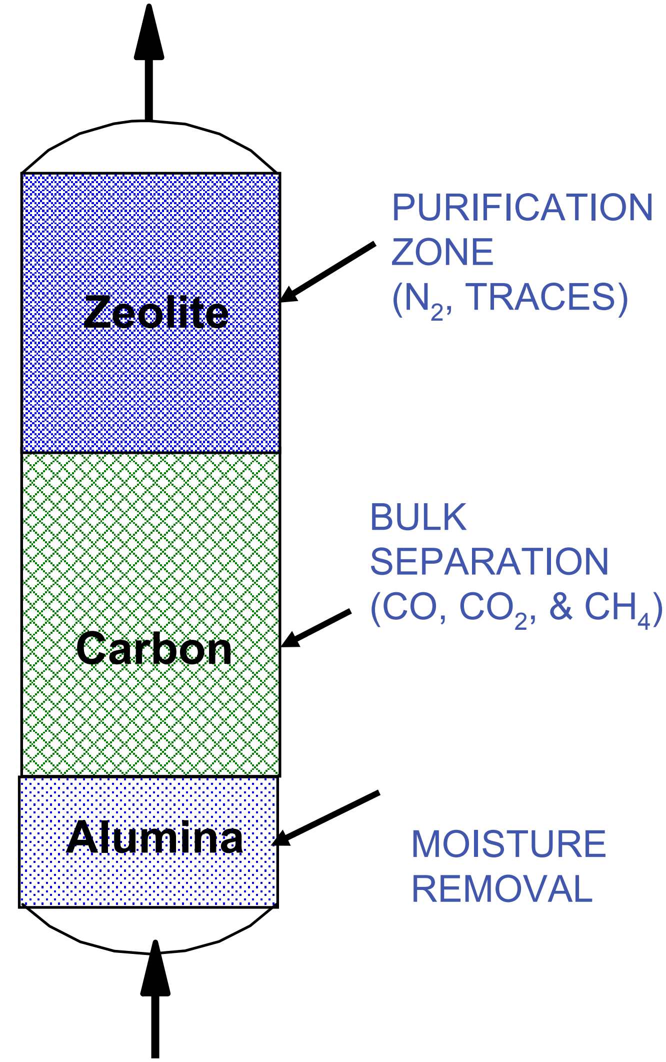
Model Results at High Pressure



imagination at work

Pressure Swing Adsorber

Product Species	DOE Targets	Current Status	Projected
H_2	> 98%	99.99%	> 99.99%
CO	< 1 ppm	< 5 ppm	< 1 ppm
CO_2	< 100 ppm	< 10 ppm	< 5 ppm
Sulfur	< 10 ppb	< 50 ppb	< 10 ppb
Ammonia	< 1 ppm	< 10 ppm	< 1 ppm
Hydro-carbons	< 100 ppm	< 10 ppm	< 10 ppm
O_2, N_2 & Ar	< 2%	~ 100 ppm	~ 100 ppm



Praxair

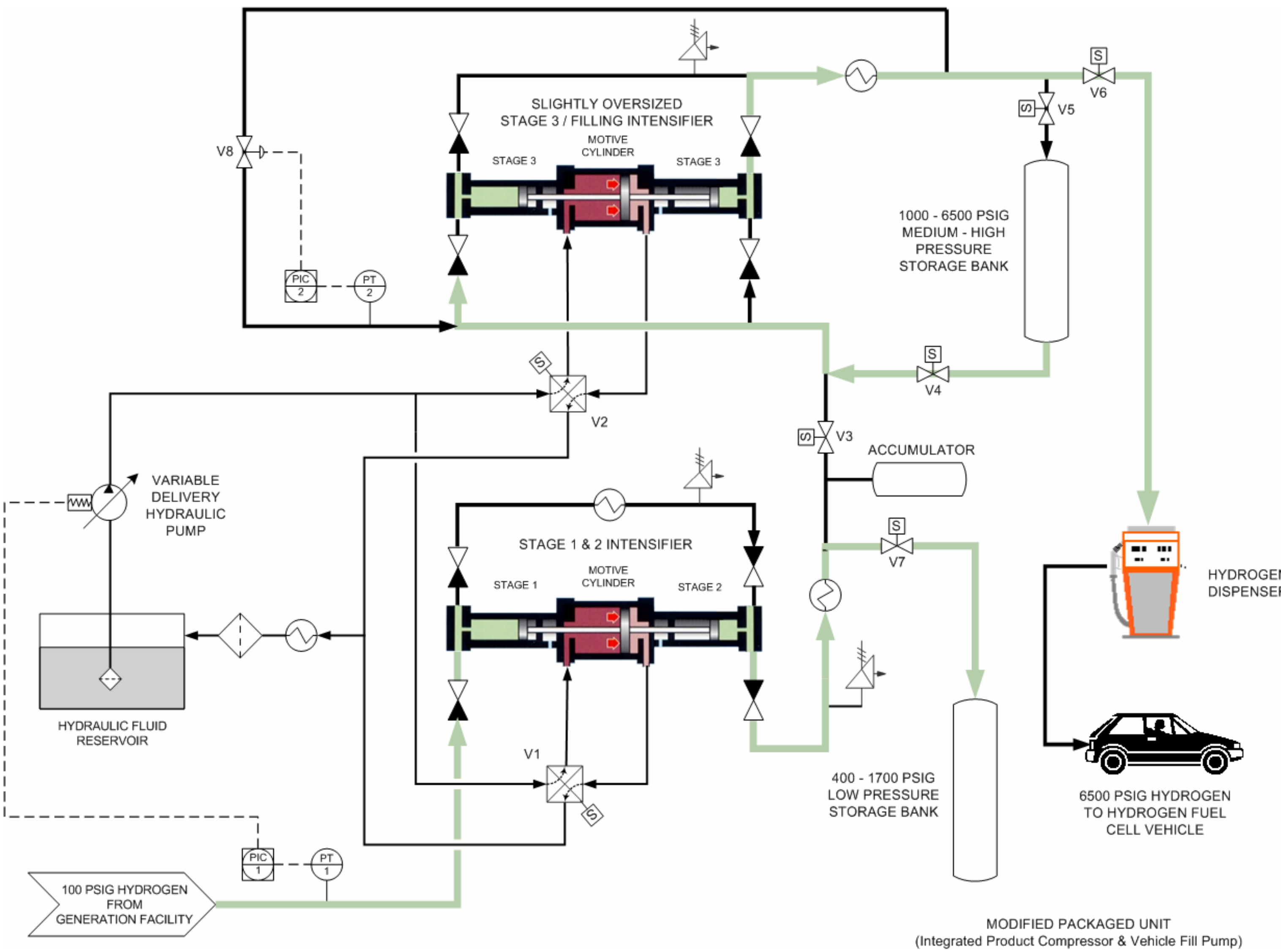
Reformer and PSA - Fabrication Status

- Next generation high pressure reformer and H_2 purifier fabricated and installed at University of California at Irvine
- Upgraded to ASME stamped pressure vessels & class I div II electrical

imagination at work

H_2 Compression & Dispensing System

- Design completed -Praxair

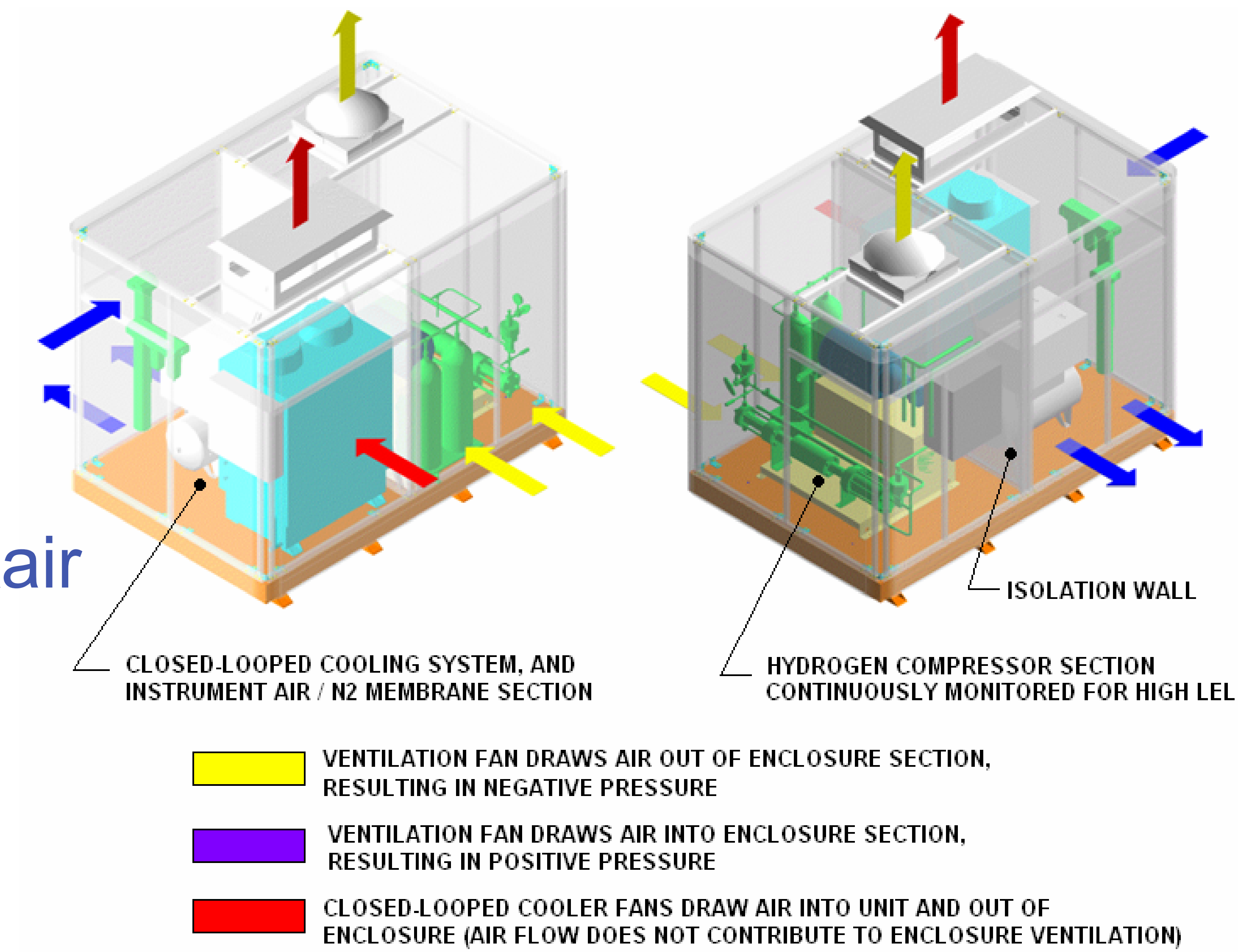


imagination at work

Hydrogen Compressor Skid Design

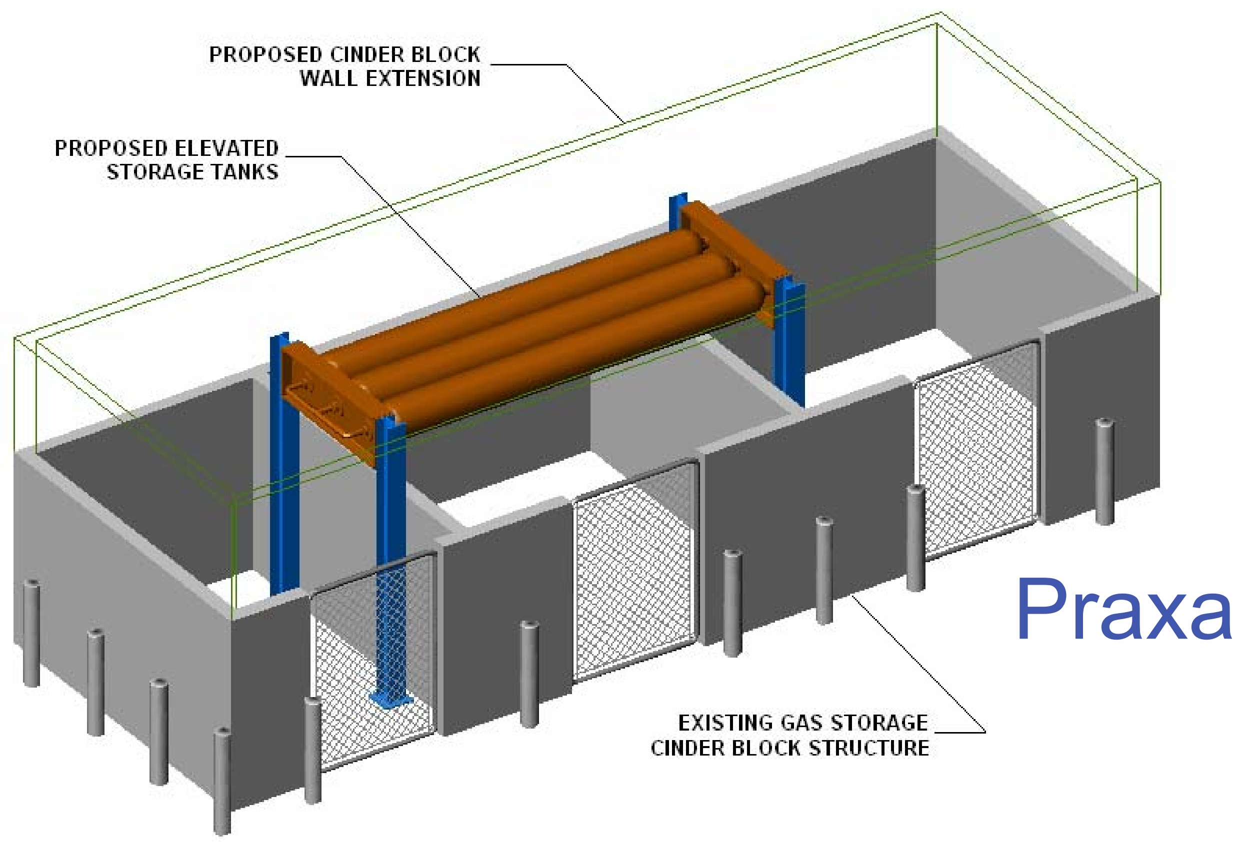
Ventilation system prevents the accumulation of H_2

Praxair



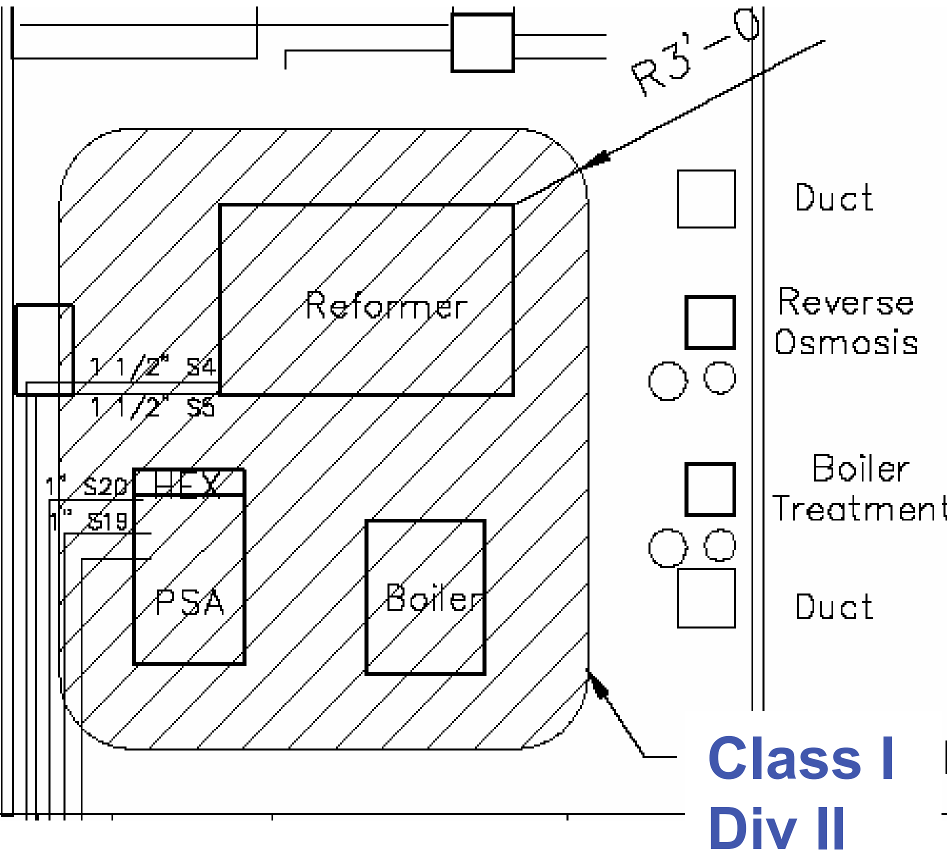
Hydrogen Storage – Elevated Design Strategy

- Leaks will quickly rise and dissipate.
- Out of the line of sight
- Design completed



Praxair

Discussed Area Classification w/ Fire Marshal
Only 3' around reformer & PSA is Class I Div II



Safety Case Studies

- Rupture of all vessels and room blower is off
  - Will reach 10% of Lower Flammability Limit (LFL)
- Sensors shut down system, if
  - 20% LFL is reached
  - Room blower is off

Permitting

- Fire Marshal
  - > Hired 4 professional engineers certified by State of California – mechanical, electrical, structural, chemical
  - > Best practices from National Fire Protection Agency (NPFA) 50A, 52 & 497
  - > 99% complete
- Campus Architect (Completed)
- South Coast Air Quality Management District (Completed)

Responses to Previous Year Reviewer's Comments

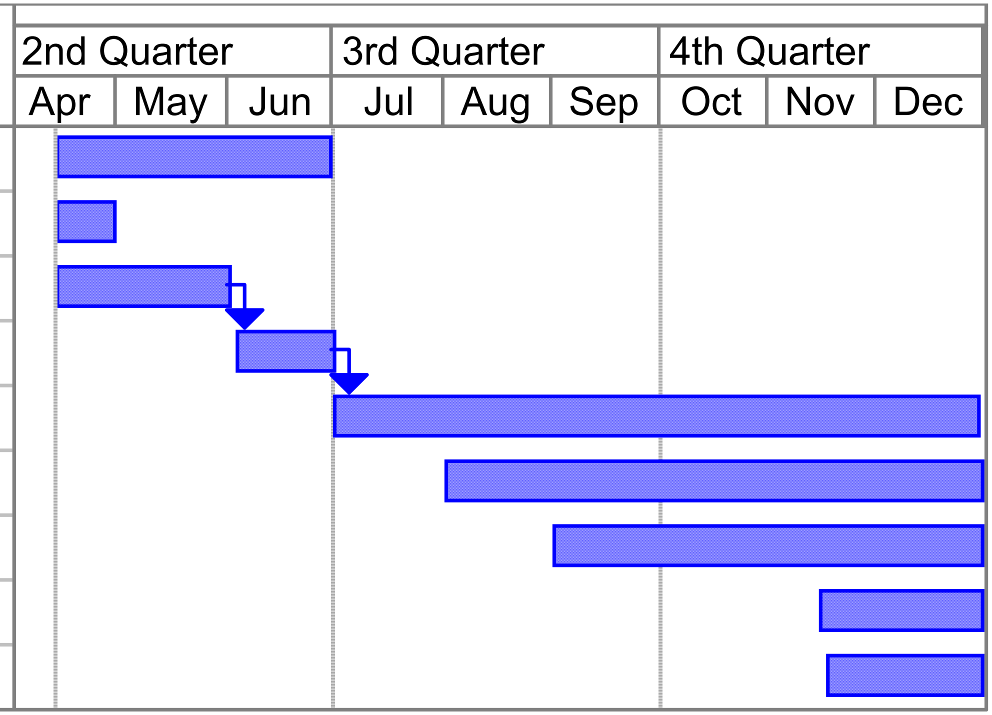
- High pressure reforming vs. low pressure reforming with compression decision
  - Compressing natural gas vs. compressing syngas is more efficient and more cost effective
- Current lifetime of catalyst is 3 months
  - Designed reactor to replace catalyst in a day
- Performance goal and detailed operation plan needs to be worked out
  - Developed advanced controls and tested them in the process model
  - Low pressure reformer was stable for extended periods of time during experimental runs

Technical Approach for 2005

Safety	• HAZOP – UCI, Praxair & GE • Independent peer review
Reformer process control	• Cascade dynamic control algorithm being optimized in a model • Monitor temperature, pressure & flows • Methane conversion
Reformer catalyst durability	• Thermal cycles • Reduction/Oxidation cycles
H_2 impurities	• CO & Sulfur
System Optimization	• Load changes – 20 to 60 kg/day • Optimize efficiency • Optimize startup times

Remaining Project Tasks - Completion by Dec 2005

ID	Task Name
1	Optimize dynamic process control model
2	Fire marshal approval
3	Fabrication - electrical/structural
4	Shakedown
5	Operation of reformer+shift
6	Integration & operation of PSA
7	System optimization
8	Update cost models
9	Final report



Supplemental Slides

Publications and Presentations

- Patent # 6,878,362 - Issued to GE
- Patent # 6,792,981 - Issued to Praxair
- World Hydrogen Energy Conference, Yokohama, Japan - June 27th – July 2nd 2004

Hydrogen Safety

- H_2, CO and natural gas leaks – electrical spark
- Pressure vessel rupture
- Piping rupture
- Earthquakes
- Structural failures
- Over-pressurization or high temperatures

Hydrogen Safety

H_2, CO and natural gas leaks	• Class I Div II electrical • Intrinsically safe electrical barriers • Lower explosive limit (LEL) sensors • CO sensors • Emergency egress lights • Alarm to 24 hr monitoring station • Electrical shunt trips
Pressure vessel rupture	• ASME stamped vessels • Design structural supports to seismic zone 4 specifications
Piping rupture	• ANSI B31.3 codes
Over-pressurization or high temperatures	• Pressure and temperature switches

imagination at work

Ackowledgements

- Department of Energy
  - Arlene Anderson, Mark Paster, Peter Devlin and Sig Gronich
- California Energy Commission
  - Avtar Bining and Art Soinski
- California Air Resources Board
  - Steve Church