

Low-Cost Hydrogen Distributed Production Systems

2005 DOE Hydrogen Program Review

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This presentation does not contain any proprietary or confidential information



PD#9

Overview

Timeline

- Contract not yet in place

Budget

- Total project funding
 - \$3.5M DOE funds
 - \$1.89M contractor share
- No funds received in FY04
- \$450k* planned for FY05

* Pending contract

Partners

- Süd-Chemie, Inc.
- Naval Research Lab

Barriers

A. Fuel Processor Capital Costs. Current small-scale distributed natural gas and renewable liquid feedstock reforming technologies have capital costs that are too high to achieve the targeted hydrogen production cost. Multiple unit operations and low energy efficiencies are key contributors to the high capital costs. Improved reforming and shift catalysts are needed to reduce side reactions and improve performance. Shift, separation, and purification costs need to be reduced. Process intensification by combining steps could significantly reduce costs. For example, combining the current two step shift and PSA separation into a onestep shift with integrated hydrogen separation could significantly reduce capital costs.

B. Fuel Processor Manufacturing. Distributed reforming units are currently designed and built one at a time, particularly for large industrial applications. Efforts such as Design for Manufacture and Assembly (DFMA) need to be applied to develop more compact, appliance-type units that can be produced using lowcost, high-throughput manufacturing methods.

C. Operation and Maintenance (O&M). O&M costs for distributed reforming hydrogen production from natural gas and renewable feedstocks are too high. Robust systems that require little maintenance and that include remote monitoring capability need to be developed.

D. Feedstock Issues. Availability of some feedstocks is limited in certain areas. Feedstock-flexible reformers are needed to address location-specific feedstock supply issues. Effects of impurities on the system from multiple feedstocks as well as the effects of impurities from variations in single feedstocks need to be addressed in the reformer design.

F. Control and Safety. Control and safety issues are associated with natural gas and renewable feedstock reforming, including on-off cycling. Effective operations control strategies are needed to minimize cost and emissions, maximize efficiencies, and enhance safety.

Table 3.1.2. Technical Targets: Distributed Production of Hydrogen from Natural Gas ^{a, b}

Characteristics	Units	Calendar Year		
		2003 ^c Status	2005 ^d Target	2010 ^d Target
Total Energy Efficiency ^e	%(LHV)	65.0	65.0	75.0
Production Energy Efficiency	%(LHV)	69.0	69.0	80.0
Storage, Compression, and Dispensing Energy Efficiency ^f	%(LHV)	94.0	94.0	94.0
Total Hydrogen Cost	\$/gge H ₂	5.00	3.00	1.50
Detailed Cost Breakdown – These calculations are for guidance only and not necessarily the research targets to achieve the total energy efficiency and cost goals.				
Capital Cost Contribution	\$/gge H ₂	2.70	1.40	0.30
Production	\$/gge H ₂	1.90	0.60	0.10
Storage, Compression, Dispensing ^f	\$/gge H ₂	0.80	0.80	0.20
Fixed O&M Cost Contribution	\$/gge H ₂	1.20	0.60	0.30
Feedstock Cost Contribution	\$/gge H ₂	0.90	0.80	0.70
Other Variable O&M Cost Contribution	\$/gge H ₂	0.20	0.20	0.20

^a Economic parameters used were for a production design capacity of 1500 kg/day of hydrogen: 20 yr. analysis period, 10% IRR after taxes, 100% equity financing, 1.9% inflation, 38.9% total tax rate, and MACRS 7-year depreciation. A 70% capacity factor was used for 2003 and 2005. A 90% capacity factor was used for 2010. The results in 2000\$ were inflated by 6% to yield 2003\$.

^b The natural gas price was set to \$4.50/MMBTU in 2000\$, based on the levelized price for natural gas between 2005 and 2025 based on the EIA AEO 2004 for industrial rates. The electricity price was set at \$.07/kWhr in 2000\$ based on the levelized price between 2005-2025 based on the EIA AEO 2004 for commercial rates.

^c For the 2003 analysis it was assumed the units would be built a few at a time.

^d For the 2005 and 2010 analysis it was assumed that Design for Manufacture and Assembly (DFMA) would be employed and that on the order of 500 units per year would be produced.

^e Energy efficiency is defined as the energy of the hydrogen out of the process (LHV) divided by the sum of the energy into the process from the feedstock (LHV) and all other energy needed. The electrical energy utilized does not include the efficiency losses from the production of the electricity.

^f Storage capacity for 1100 kg of hydrogen at the forecourt is included. It is assumed that the required hydrogen pressure for refueling is 5000 psi for 2003 and 2005. It is assumed that in 2015, the pressure for hydrogen refueling is 1500 psi.

Project Objectives

Project objective – Execute on the following specific goals as part of the overall plan to overcome the barriers identified by the USDOE and to meet the USDOE technical targets in terms of cost and energy efficiency

- Design, build and test a 565 kg/day hydrogen plant for 99.999% pure hydrogen at \$0.21/kg
- Develop a catalyst suite based on our current technology suitable for use with fuel grade ethanol to facilitate renewable hydrogen production

2005 Objectives

- Achieve at least 3 kW increased heat recovery from the reformat in the HGM-2000 reformer
- Complete the design of features needed to boost the HGM-2000 capacity to at least 141 kg/day of CGA IB grade hydrogen in an HGM-2000 (30% increase)
- Demonstrate improved reforming and water gas shift catalysts for at least 2,500 hours of field testing in a full-scale HGM-2000
- Demonstrate improved PSA adsorbent technology to yield a 10% increase in hydrogen recovery.

Approach

First steps – analysis and bench scale experiments

- Catalyst improvements
- Balance of plant improvement
- Advanced reactor design

Second step - integration and test improved technology in the existing HGM-2000 platform

1. Incremental improvements
2. Obtain long-term test data
3. Make ongoing progress towards USDOE goals

Final deliverable

1. Design 565 kg/day plant using DFMA, FMEA and other best practices based on lessons learned from second step
2. Construct 565 kg/day plant
3. Test 565 kg/day plant

Catalyst approach

1. Improve steam reforming catalyst robustness and cost-effectiveness by developing new carrier material
2. Improve thermodynamics of system by developing high selectivity water gas shift catalysts
3. Use current catalyst suite as platform for developing fuel ethanol reformer

Reforming catalyst approach

Original plan - Higher stability ceramic carrier

1. Very high surface areas with high stability
2. Lower cost synthesis route

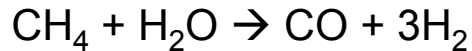
Modified plan

- High stability ceramic carrier chemistry
- More emphasis on robustness and cyclic durability to address O&M costs
- Optimization of metal loadings and deposition technique to maximize cost effectiveness in long-term operation

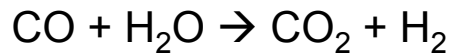
Unique focus on performance past 1,000 hours

Water Gas Shift Catalyst Approach

Steam Reforming (main H₂ generating reaction)



Water Gas Shift (WGS, cleans up CO and generates additional H₂)



Methanation (undesirable side reaction in WGS section of reactor)



Higher selectivity improves reactor output and efficiency

- More H₂ generated per CH₄ in feedgas
- opportunity to operate shift reactor hotter, with faster kinetics (lower cost per unit output)

Will improve PSA performance – recover more of the H₂ that we generate

- CO concentration is the limiting factor for PSA performance

Total projected benefits to the system

- 7% increase in H₂ production
- 4% increase in efficiency

Water Gas Shift Catalyst Approach

Technical approach

- Ceramic carrier optimization to prevent methanation
 - Use of special promoters
 - Inherently selective ceramics
- Selection of active metal species for lasting selectivity
 - Optimization of binding energies
 - Mixtures and/or Alloys of metals
 - Optimization at unique H2Gen process conditions

Development focus on stability of high performance past 1,000 hours

Ethanol Catalyst Approach

First – identify optimal ethanol fuel

- Fuel grade ethanols (often gasoline denatured)
- Partially-refined ethanols containing water (more energy efficient and cost effective?)
- Taxation issues
- Impurity issues

Second – test catalysts on optimum fuel(s)

- Screening tests < 1,000 hours
- Pilot tests over 1,000+ hours

Use results to identify and develop needed improvements

Balance of plant approach

- Greater heat recovery
 - Recovery of waste heat in reformat by preheating feed fuel and/or air
 - Recovery of waste heat in flue gas with a more efficient steam generator
- Lower electricity input
 - Lower air pressure drop reactor core (see reactor section)
 - Eliminate vacuum assist from PSA
 - Use higher pressure natural gas feedstock – 60 psig widely available in US
- Greater hydrogen recovery
 - Reduce impurity levels in raw reformat by improving catalyst, optimizing steam to carbon ratios and temperatures (global optimization)
 - Direct improvements in PSA apparatus to boost recovery
 - Adsorbent improvements (faster kinetics)
 - PSA cycle improvements
 - Optimization of system losses around PSA (pressure drops, flow variability, etc.)

Reactor approach

Metallurgy and mechanical design of HGM-2000 work, but...

- Need custom tooling
- Have relatively high air-side pressure drop
- Thermal stress problems at 565 kg/hr scale

Steps for improvement

- Design features to comply with stresses in larger format
- design for lower air-side losses
- design for use of standard production tooling
- Optimize relative size of water gas shift and reformer catalyst charges
- Optimize final mechanical design based on DFMA analysis as well as detailed reactor simulation
- Execute a development test reactor suitable for testing in the HGM-2000 platform to reduce costs and risks

System-scale testing approach

Problem – direct scale up to 565 kg/day while introducing improvements is very risky

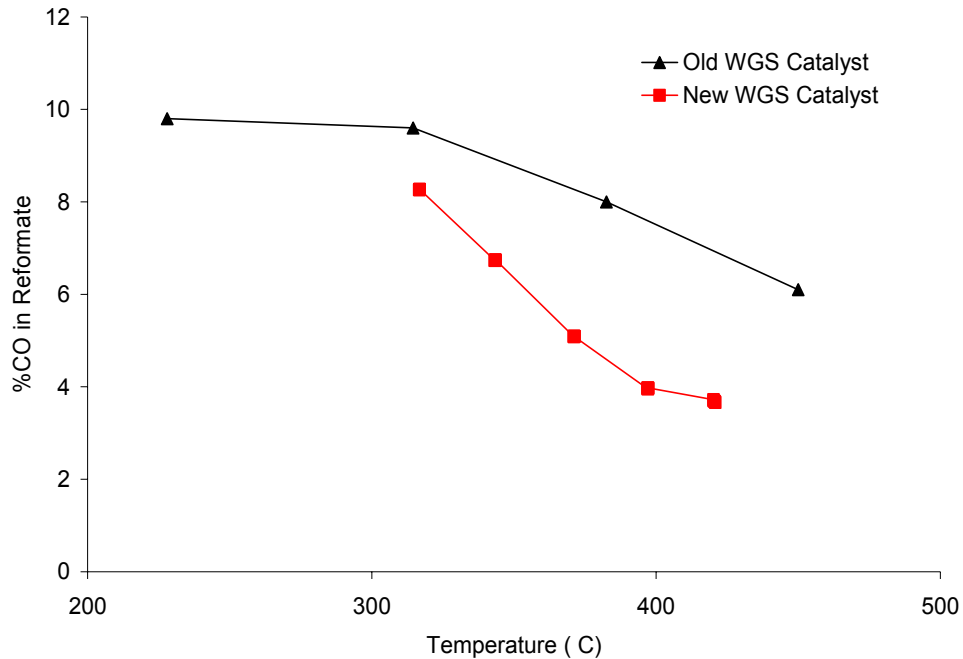
Solution – test innovations incrementally, as achieved, in the existing HGM-2000 platform

- Tests real, system-level effects
- Very cost-efficient, as dedicated test apparatus and balance of plant is not needed
- Allows collection of ongoing field data
- Greatly reduces scale-up risk to 565 kg/hr
- Approach may be altered based on results within USDOE schedule and resources – many “bites at the apple” available

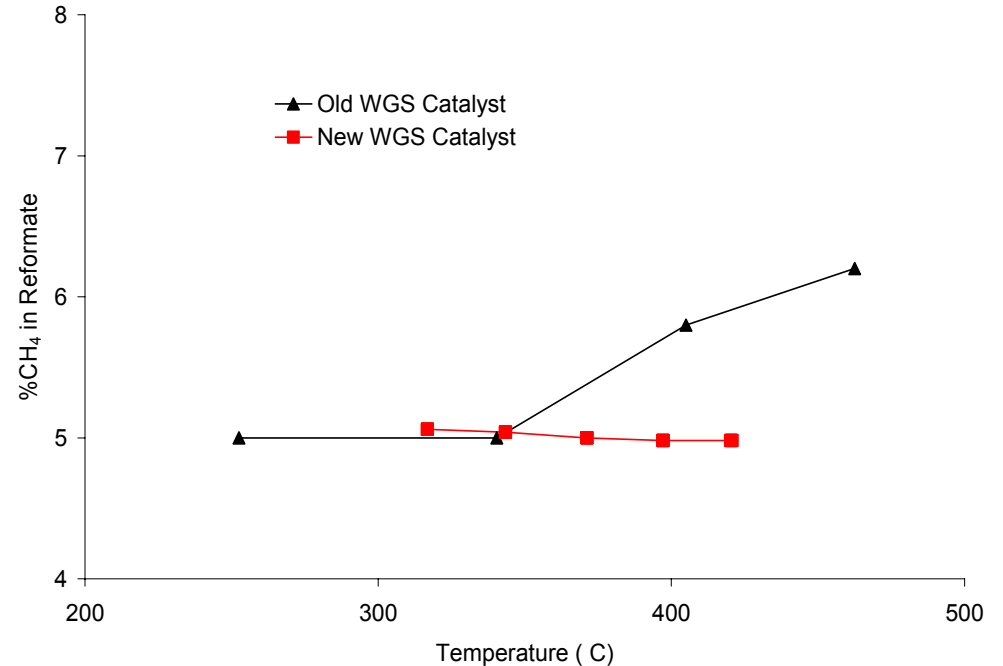
Very important! – Existing HGM-2000 is designed in accordance with applicable national and international safety rules. It has proven operability and robustness. Using this platform minimizes safety risk in the developmental testing

Water Gas Shift Catalyst Results

Comparison of CO% Left in Reformate



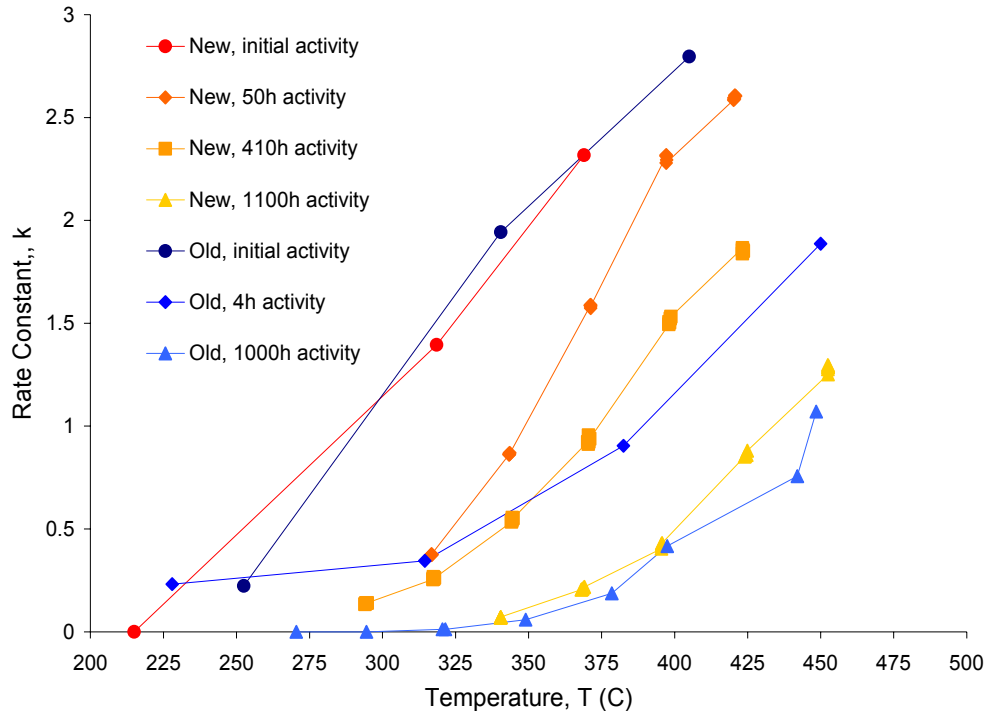
Comparison of CH₄% Left in Reformate



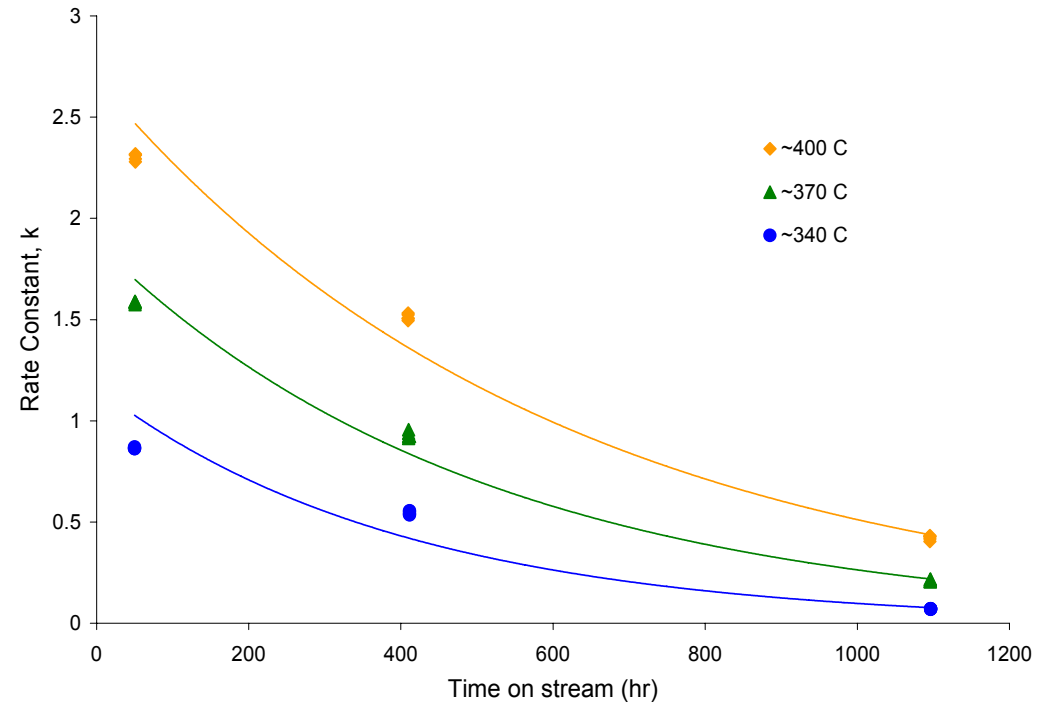
- Developed 1st generation of selective shift catalysts
- Delays methanation by over 100°C
- Facilitates much higher CO conversion in the reactor per unit reactor volume

Water Gas Shift Catalyst Results

WGS catalyst activity for various aging times



Aging Effect on the Rate Constant for HGHT-1

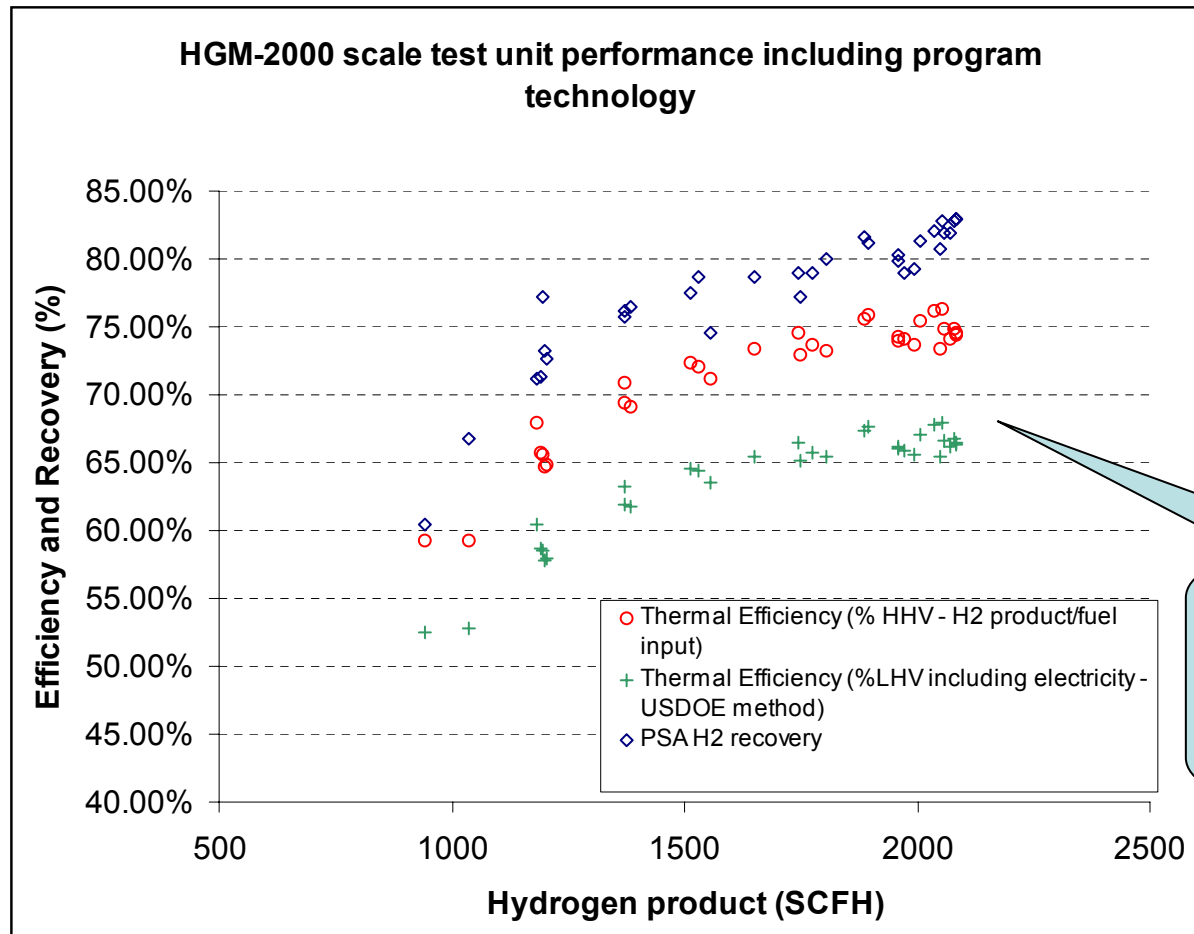


- Both new and older shift catalysts age significantly in 1,000 hours
- Aging traps expensive active metal, reducing cost effectiveness
- Aging results in a need to continuously increase reactor temperatures to keep carbon monoxide conversion constant

Other catalyst results

- Developed 1st generation of reforming catalysts on high stability ceramic carrier
- Successfully tested the 1st generation reforming catalyst for over 1200 hours in pilot-scale apparatus
- Initiated HGM-2000 scale testing in machine PC#2

System-scale testing results



- HGM-2000 scale machine constructed with three key USDOE features
 - 1st generation improved reforming catalyst
 - Improved heat recovery from reformat
 - Improved heat recovery from flue gas
- Plant is under continuous test – expect ~4,000 hours of operation in FY05

FY05 Work - Catalyst

- Reforming
 - Optimize metal loading and application method for each zone of the reformer
 - Conduct manufacturing cost studies in concert with above to optimize catalyst
 - Develop extrusion dies suitable for higher-rate production of stable carrier in desired shapes
 - Conduct long-term tests in pilot reactors
- Water gas shift
 - Vary ceramic carrier properties to combat aging
 - Optimize metal loadings and ratios to combat aging and optimize cost
 - Conduct long-term tests in pilot reactors
- Ethanol
 - Study available commercial ethanol grades to identify most promising from cost/efficiency standpoint

FY05 work – balance of plant

- Heat recovery
 - Study of impact of further reformat heat recovery on cost/performance
 - Improved flue gas heat recovery by two stages of steam generator re-design
- Electricity reduction
 - Developing and testing a 60 psig gas feed pressure system
 - Eliminating the PSA vacuum assist
- PSA
 - Characterizing fast kinetic adsorbents
 - Testing in a micro-scale PSA to generate scale-up data

FY05 work - reformer

- Design studies for improved reformer
- Operate HGM-2000 scale reformer under low air pressure loss conditions

Future work-system scale tests

- Plan two more HGM-2000 scale machines including program-developed features in FY05
- First machine
 - 1st generation selective shift catalysts
 - Improved flue gas heat recovery
 - 60 psig fuel system
 - No vacuum assist
 - Lower air system loss reformer
- Second machine
 - Final generation DFMA steam generator
 - Other changes as indicated by sub-scale work

Publications and Presentations

No publications or public presentations have resulted from the work to date.

Hydrogen Safety

The most significant hydrogen hazard associated with this project is safe disposal of the 565kg/day of hydrogen

Hydrogen Safety

Our approach to deal with this hazard is:

- Use existing hydrogen vent system designed according to CGA-5.5-1996