One Step Hydrogen Generation Through Sorption Enhanced Reforming

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Gas Technology Institute

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Project Objective

- Develop low-cost hydrogen production technology, utilizing Sorption Enhanced Reforming (SER), for large-scale commercial applications
  - Reduce cost of hydrogen by 15-20% vs. current technology
  - Reduce cost of carbon capture from natural gas feedstock
- Improve the Technology Readiness Level (TRL) from 4 to 6
- Develop a robust SER process and associated solids handling capability for circulating fine, reacting sorbent particles

Technical Innovation

- Conventional hydrogen production uses Steam Methane Reforming (SMR)
- SER combines the reforming and water-gas shift processes into one-step (i.e., in the same vessel)
  - Sorbent balances heat necessary for reforming- eliminating costly SMR firebox, convective heat exchanger, and Water-Gas Shift Reactor

Chemistry Comparison

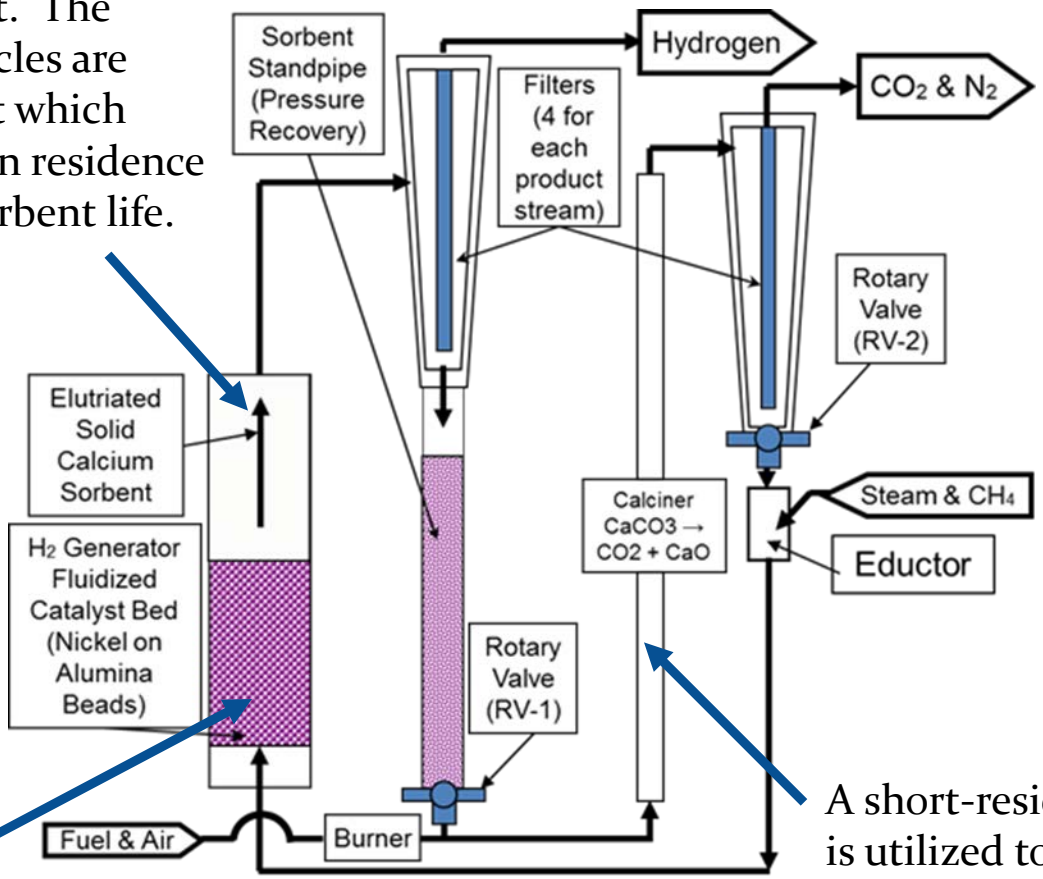
Chemistry	Heat
SMR Chemistry	
Reforming $CH_4 + H_2O \rightarrow 3H_2 + CO$	+206 KJ
WGS $CO + H_2O \rightarrow H_2 + CO_2$	-37.8KJ
Combined $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	+206 KJ/-37.8KJ
SER Process Chemistry	
$CH_4 + 2H_2O + CaO \rightarrow 4H_2 + CaCO_3$	None
$CaCO_3 \rightarrow CaO + CO_2$	178 KJ

Plant Comparison (71,000 Nm³/hr)

Plant Size	Reactor Description	Capital Cost	Efficiency % (LHV)
CHG 5x5x15 (L x W x H) meters	4m dia. x 8m tall, refractory lined, carbon-steel vessel	• 60-80% - H_2 Only • 65-85% - H_2 w/CO_2 separation	• 86% - H_2 Only • 86% - H_2 & CO_2 w/o compression
SMR 11x22x27 (L x W x H) meters	~900 15cm dia., spin cast 25-20 NiCr tubes x 18m long w/firebox	• 100% - H_2 Only • 229% - H_2 w/CO_2 separation	• 83.5% - H_2 Only w/steam export • 68% - H_2 & CO_2 w/o compression

Technical Innovation

A process which enables the sorbent to flow through a bubbling fluidized bed of catalyst. The elutriated sorbent particles are hindered by the catalyst which provides ~10x increase in residence time, thus extending sorbent life.



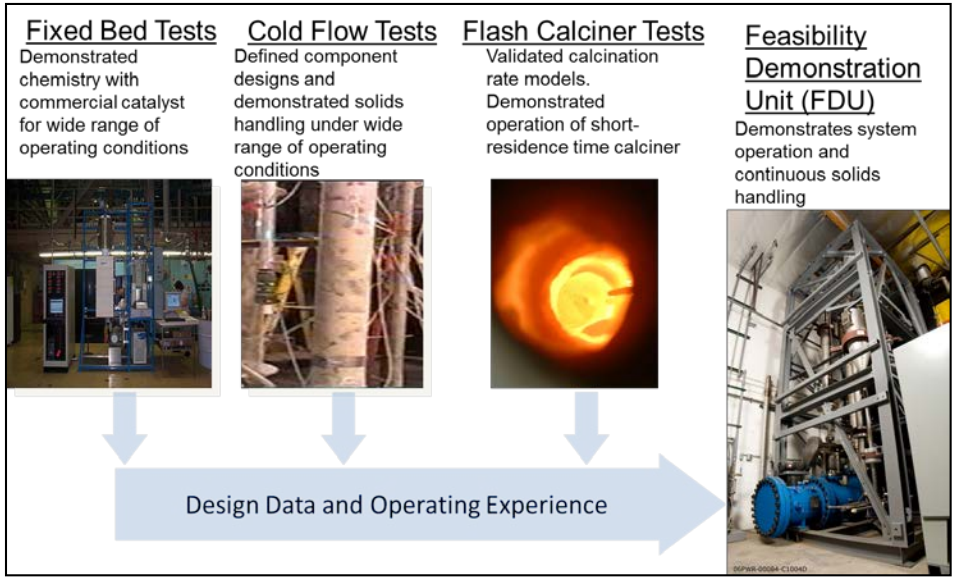
A high aspect ratio bubbling-bed, which increases the overall reaction zone

A short-residence time calciner is utilized to minimize "time at temperature" of the sorbent, and extends its reactivity (seconds vs. minutes)

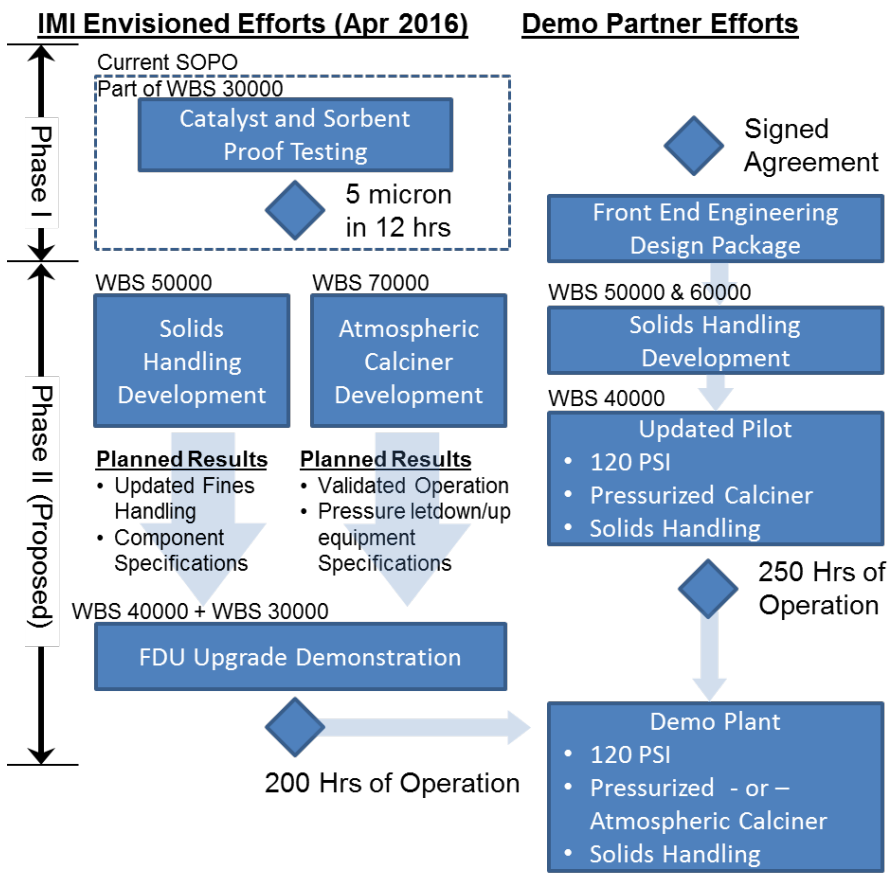
Technical Approach

- Demonstrate alternative catalyst substrates and operating conditions to assess catalyst deactivation issues
- Demonstrate alternative sorbents to increase reactivity

Technology Development History

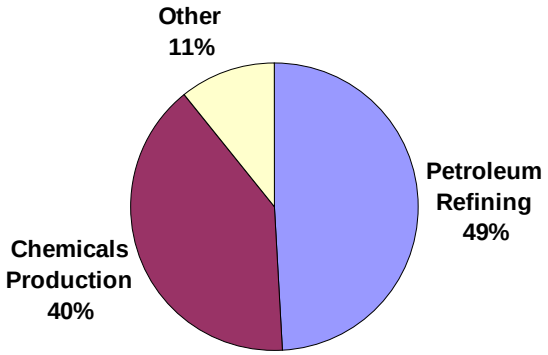


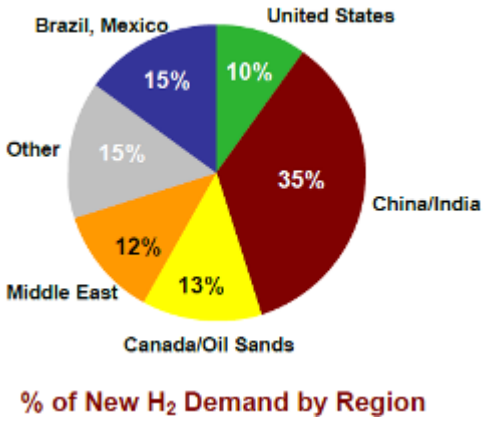
Go-Forward Approach



Transition (beyond DOE assistance)

Hydrogen Demand[3]





% of New H_2 Demand by Region

- Overall hydrogen market size is between $60B - $90B[1]
- Hydrogen equipment market size is between $3B-$4.5B
- Annual market growth ranges from 7%-15%[2]

[1] *Based on a average value of $2.00 - $3.00 Mscfd, where M represents thousands*
[2] *March 2010 Praxair CFO Presentation*
[3] *Hydrogen and Synthesis Gas, SFA Pacific, Inc., 1998 and March 2010 Praxair CFO Presentation*

- Hydrogen end-users benefit from process intensification
  - Reduced hydrogen cost through:
    - Lower capital cost and smaller footprint
    - Improved efficiency
  - No steam export and significantly reduce CO_2 capture cost

Large market, growing at steady rate

Transition (beyond DOE assistance)

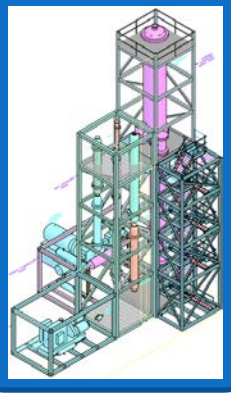
GTI and Partner Perform Technology Development → **GTI and Partner Demonstrate Technology** → **End Customers Own & Operate Plants**

Existing Pilot → Lessons Learned

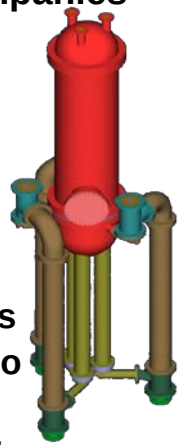
Modified Pilot w/ Atmospheric Calciner

Updated Pilot operating at commercial conditions

Demo Plant with commercial configuration



- **Industrial Gas Companies**
  - Praxair
  - Air Liquide
  - Air Products
  - Linde
- **Oil Companies**
  - ExxonMobil
  - ConocoPhillips
  - ChevronTexaco
  - Others
- **Chemical Companies**
  - PCS Nitrogen
  - Agrium



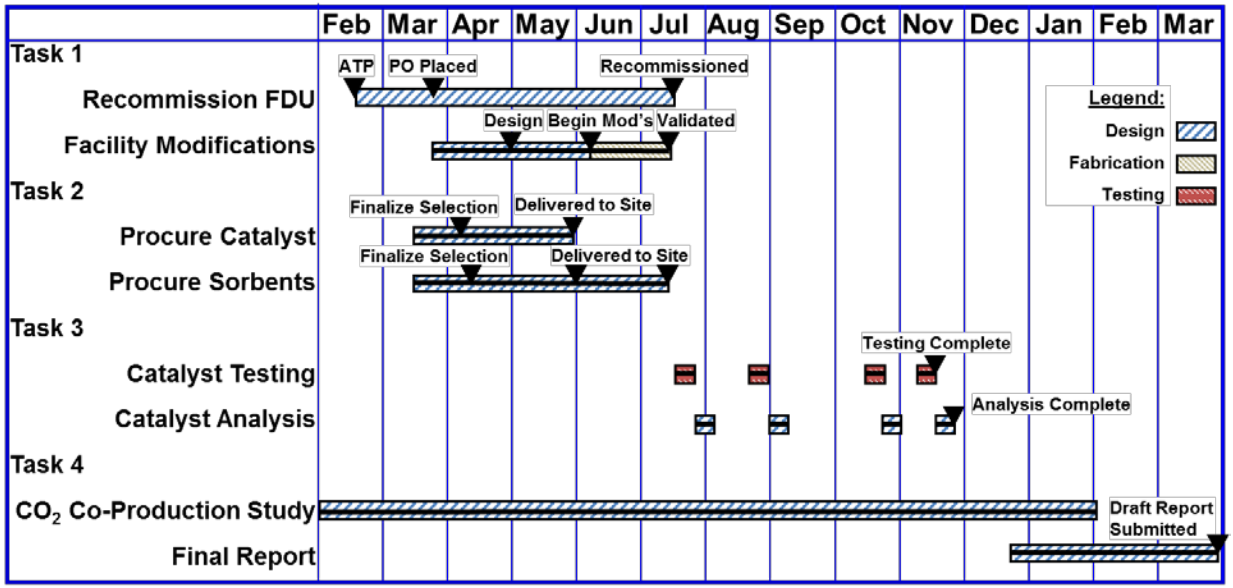
- Utilize continuous improvement process for technology sustainment

Measure of Success

- Successful deployment of CHG technology will reduce cost of hydrogen, provide lower cost CO_2 capture, and lead to additional market penetration due to compactness (e.g., debottlenecking, ammonia/urea production, and electric power with low-cost CO_2 capture)
- Success will be measured through an increase in market share against SMR's (projected to be 26% share in 10 years)
  - Equates to energy savings of 43.6 Trillion BTU/year
- Increased global marketshare results in more U.S. jobs in engineering and manufacturing of special equipment

Project Management & Budget

- Project Duration = 10 Months
- Project Performance: Project Complete. Achieved all objectives on Budget



Total Project Budget	
DOE Investment	$630,868
Cost Share	$793,666
Project Total	$1,424,533

Results and Accomplishments

- Successfully demonstrated SER chemistry and process operation, with H_2 purity and yield at or above expected levels for the sorbent feed rates used (sorbent feeding limited by mechanical systems)
  - Accumulated more than 28 hours of SER-mode operation with catalyst without degradation
  - Achieved operation at design point (3:1 S/C ratio and 20,000 SCFD)
  - Achieved 3-fold increase in sorbent feed rate
  - Assessed CO_2 Co-production benefits and pathways