2005 Annual DOE Hydrogen Program Review
Hydrogen Production & Delivery

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State of the Art
Near-term technologies

- **Distributed Natural Gas Steam Methane Reforming:** $4-5/gasoline gallon equivalent (gge) delivered

- **Electrolysis:** $4.75 – 5.15/gge delivered

Sunline HyRadix Reformer

Giner PEM Electrolyzer

DOE Hydrogen Production Technology Research Portfolio

<u>EERE</u>

- Distributed natural gas and bio-derived liquid reforming
- Electrolysis
- Reforming biomass gas from gasification/pyrolysis
- Biological hydrogen production
- Photoelectrochemical hydrogen production
- Solar HT thermochemical cycles
- Separations

<u>Office of Fossil Energy</u>

- Coal gasification with sequestration

<u>Office of Nuclear Energy</u>

- Nuclear driven HT thermochemical cycles

<u>Office of Science</u>

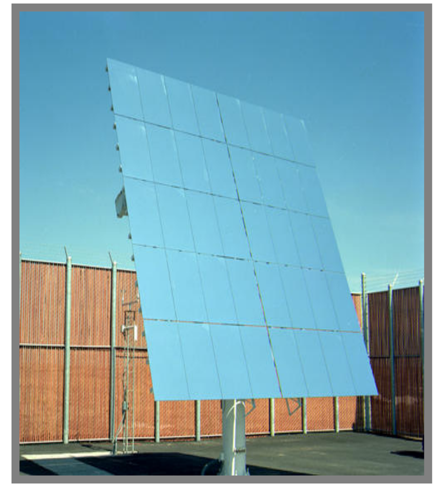
- Basic research on materials and catalysts

Hydrogen Production Barriers
Cost and Energy Efficiency

Distributed Reforming Using Natural Gas and Renewable Liquids

- Intensified, lower capital cost, more efficient NG reformer technology
- Improved catalysts and technology for renewable liquid reforming
  - Ethanol, sugar alcohols, bio-oil

H2Gen HGM 2000



NREL solar research Mesa top facility

Electrolysis

- Low cost materials and high efficiency system designs
- Integrated compression
- Integrated wind power/electrolysis systems

Solar/Photolytic

- Durable and efficient materials for direct photo-electrochemical solid state water splitting using sunlight
- Microorganisms that split water using sunlight or produce H2 through fermentation
- Thermochemical cycles, solar concentrators, receivers/reactors to split water (600 – 2000 C)
  - Effective and efficient thermochemical cycles
  - Reduced capital cost of the solar concentrator

Biomass Gasification

- Integrated gasification, reforming, shift and separations technology to reduce capital cost and improve efficiency.

New Hydrogen Cost Goal for 2015

- Pathway independent
- Consumer fueling costs are equivalent on a cents per mile basis
- Gasoline ICE and gasoline-electric hybrids are benchmarks
- Provide a "yardstick" for assessing technology performance

Hydrogen Cost Goal for 2015

Mechanics

$$\text{H2 Cost } (\$ / \text{gge}) = (\text{EIA Projected Gasoline Price in 2015}) \left[\frac{\text{Fuel Economy H2FCV}}{\text{Fuel Economy Competitive Vehicle}} \right]^{1}$$

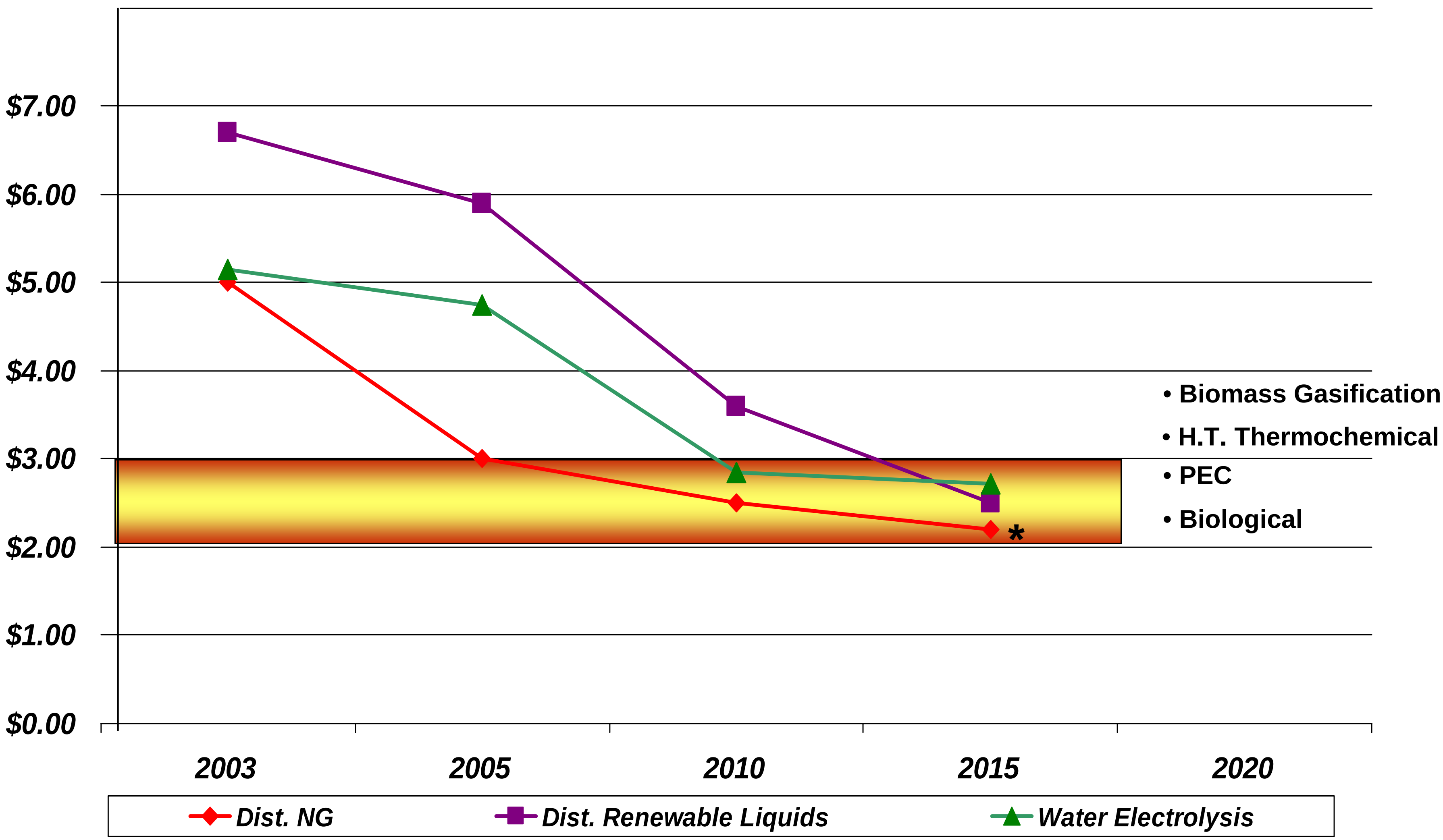
Input	Value	Source
Gasoline price projection for 2015	$1.26 / gal (untaxed, 2005 $)	EIA Annual Energy Outlook, 2005
Ratio of FCV fuel economy to evolved gasoline ICE	2.40	NRC H2 Economy Report
Ratio of FCV fuel economy to gasoline hybrid	1.66	NRC H2 Economy Report

Results

- **$ 2.00 - $3.00 / gge**

[1] Ratio of FCV fuel economy to competitive vehicle

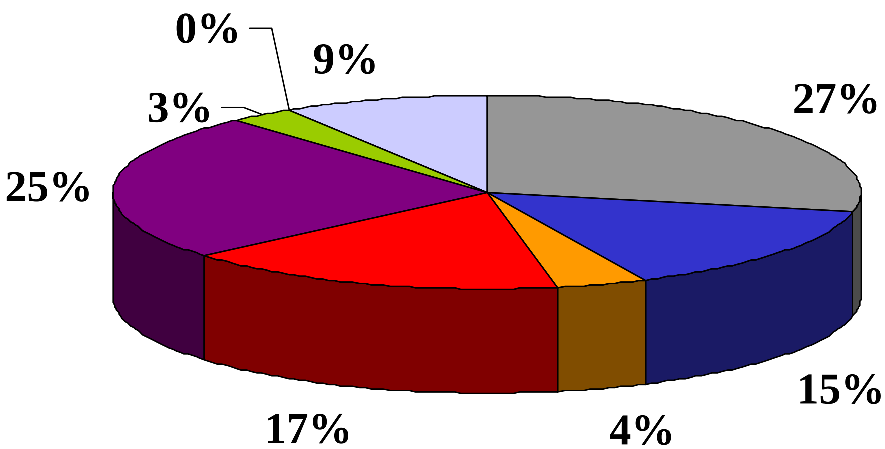
Hydrogen Production
Targets Compared to 2015 Cost Goal



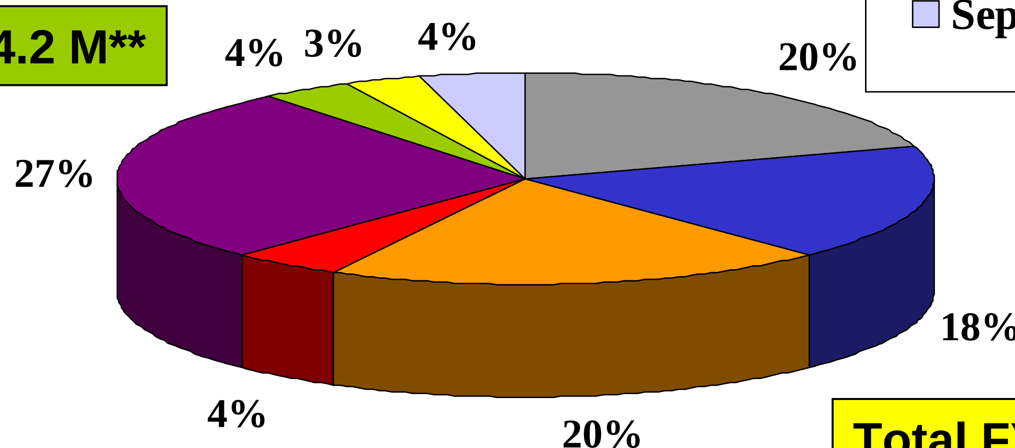
* Pending final approval by DOE Change Control Board

Hydrogen Production & Delivery Funding Distribution

FY 04 = $10.3 M*



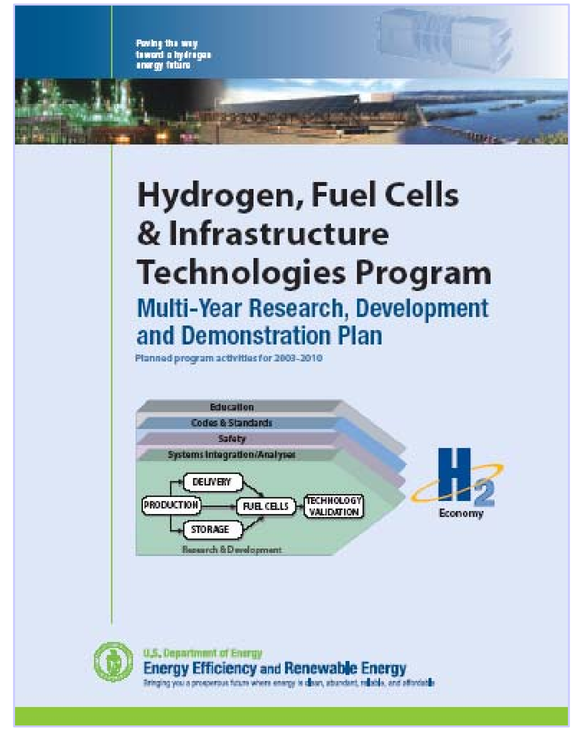
FY 05 = $14.2 M**



Total FY 06 Request = $32.0 M

*FY 04 Appropriation including earmarks = $22.6 M
**FY 05 Appropriation including earmarks = $25.3 M

R & D Plan



<u>New goals and targets</u>

- Distributed renewable liquid reforming
- Water electrolysis from central renewables
- Separations technologies: dense metallic and microporous
- Biomass (gasification/pyrolysis) reforming
- Photosynthetic bacteria and dark fermentation

<u>Detailed target guidance</u>

- Capital equipment targets separate from operations and maintenance
- Total system energy efficiency
- Specific capacity utilization factors

<u>Developed R & D targets based on common set of economic parameters</u>

- 10% IRR after taxes, 100% equity financing, 1.9% inflation, 38.9% tax rate, 7 year depreciation
- Reviewed by industry experts from 16 companies

http://www.eere.energy.gov/hydrogenanfuelcells/mypp/

Key Milestones

FY 2008

- Go/No-go: Determine if membrane separation technology can be applied to natural gas distributed reforming during the transition to a hydrogen economy.
- Down-select to a primary technology and configuration for central biomass gasification/pyrolysis clean–up, reforming, shift, separations and purification.

FY 2009

- Complete development of integrated “appliance” type distributed reforming system applying DFMA principles.

FY 2010

- Go/No-Go: Identify cost-effective transparent H2-impermeable materials for use in photobiological and photoelectrochemical systems.
- Go/No-Go: Verify the feasibility of an effective integrated high-temperature solar-driven thermochemical cycle for hydrogen projected to meet the 2010 cost goal of \$6/gge (\$4/gge delivered by 2015).

2004 & 2005 DOE Hydrogen Production & Delivery Projects

Distributed Production
MSRI
GE Energy
Air Products
GTI
PNNL
Virent Energy Systems
BOC Group, Inc.
H2Gen Inno. Inc.
GE Global Res.

Separations
Eltorn Res. Inc.
ORNL
GTI

Photobiological
U.C. Berkeley
NREL
ORNL
J. Craig Venture Institute

Biomass Reforming
United Tech. Res. Inst.

H.T. Thermochemical
Univ. of Nevada

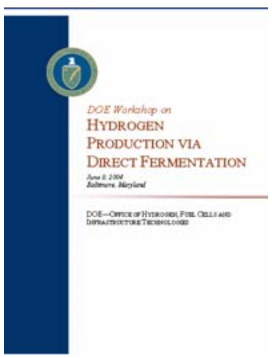
Photoelectrochemical
U. of Hawaii
NREL
U. of Cal. Santa Barbara
Midwest Optoelectronics
GE Global Research

Electrolysis
Giner
INEEL
NREL
Teledyne

Delivery
ANL
ORNL
Air Products
Secat, Inc.

Hydrogen Production R&D – Planning and Implementing

Fermentation Workshop



Separations Workshop

Production & Delivery Selections Announced

Annual Program Review

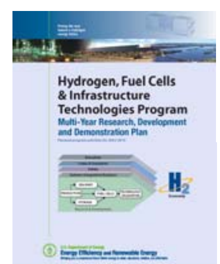
H2A Tool

May '04 | Jun '04 | Sept '04 | Oct '04 | Nov '04 | Feb '05 | May '05

Utility Electrolysis Workshop

Solar Electrolysis Workshop

R&D Plan Published

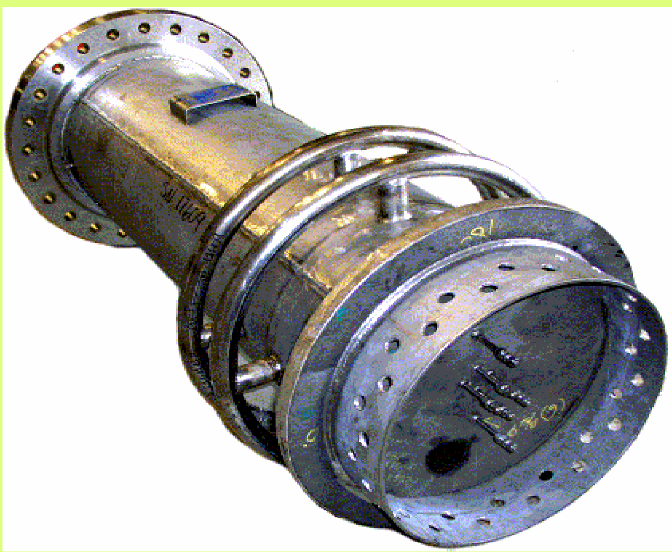


Opening Solid oxide Materials & Systems Development Solicitation

Recent Technical Accomplishments

<u>Natural Gas Distributed Reforming</u>

- Approaching $3/kg dispensed hydrogen from natural gas (690 kg/day, >100 units annually, $4/MMBTU NG, 90% utilization)
- Completed R&D for a highly efficient autothermal cyclic reformer



GE High-Pressure Autothermal Cyclic Reforming (ACR) Reactor

Teledyne HP TITAN™ HP generator

<u>Electrolysis</u>

- Achieved 2000 psi H2 production in planar electrolysis stack
- Developed new system designs with 40-50% part count reduction
- Novel stack design for alkaline system on track for achieving a hydrogen production cost <$2.85/kg by 2010.

Recent Technical Accomplishments

Biological

- Increased photobiological efficiency of absorbed sunlight energy to ~15% (5% in 2003)
- 40-50% increase in oxygen tolerance achieved

Measuring photosynthetic productivity of micro-algae (NREL)

Lab scale testing of semiconductors (NREL)

Photoelectrochemical

- Achieved 1000 hours durability (100 hour in 2003) with new gallium nitride material for photoelectrochemical
- Integrated photovoltaic electrolysis panel ready for prototype testing

Recent Technical Accomplishments

Biomass gasifier/pyrolyzer PDU (NREL)

Biomass Gasification/Pyrolysis

- Developed biomass reforming catalyst to reduce coking and attrition

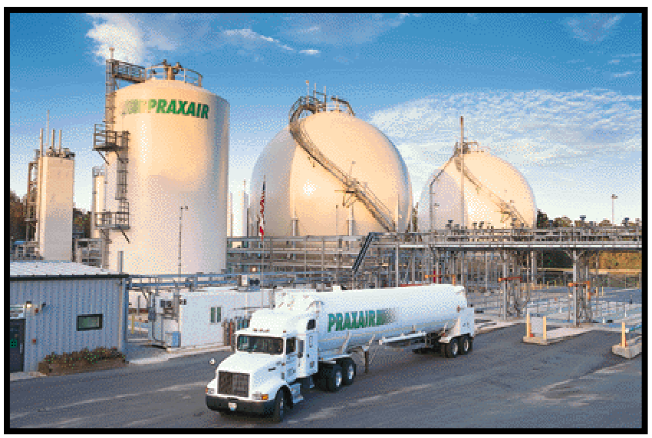
Solar HT Thermochemical

- Demonstrated lab feasibility of zinc and maganese cycles
- Selected 4 groups of cycles
  - Volatile metal
  - Metal oxide
  - Sulfate
  - Sulfuric acid

Solar HT Thermochemcial reactor (NREL)

Delivery State of the Art

- Today hydrogen is transported by cryogenic liquid trucks and gaseous tube trailers. There is also a very limited transmission pipeline infrastructure (630 miles; Gulf Coast, California, Chicago)
- Cost $4-9/gge of H2 or more depending on distance for truck transport. Pipeline transport can be <$1/gge.



Delivery Pathways and Components

– Pathways
  - Gaseous Hydrogen Delivery
  - Liquid Hydrogen Delivery
  - Carriers

  } Including mixed pathways

– Components

Pipelines	Terminals
Compression	Separations/Purification
Liquefaction	Dispensers
Liquid and Gaseous Storage Tanks	Mobile Fuelers
Carriers & Transformations	Other Forecourt Issues
GH2 Tube Trailers	Cryogenic Liquid Trucks
	Rail, Barge, Ships

Delivery Barriers

Analysis Needs

- Infrastructure options and trade-offs for the transition and long term

Compression
Transmission and Forecourt Applications

- Reliability
- Lower capital costs
- Energy efficiency

Off-Board Storage
Forecourt, Terminals, Other

- Lower cost (lower capital cost)
- Smaller footprint (Forecourt)

Pipelines

- Hydrogen embrittlement and permeability
- Lower capital costs – new materials to reduce pipeline installation costs
- Coating – to allow usage of existing NG or other pipeline infrastructure or for new pipelines
- ROW
- Can we use existing NG infrastructure for mixtures if H2 and NG?

Liquefaction

- Higher energy efficiency – current technology consume >30% of H2 energy
- Lower cost – current technology >$/gge of H2

Novel Carriers

- Discovery of novel solid or liquid carriers with sufficient H2 density
- System energy efficiency and cost

Delivery Objectives

- By **2007**, define the criteria for a cost-effective and energy-efficient hydrogen delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power.

- By **2010**, develop technologies to reduce the cost of hydrogen delivery from central and semi-central production facilities to the gate of refueling stations and other end users to <***$0.90/kg*** of hydrogen.

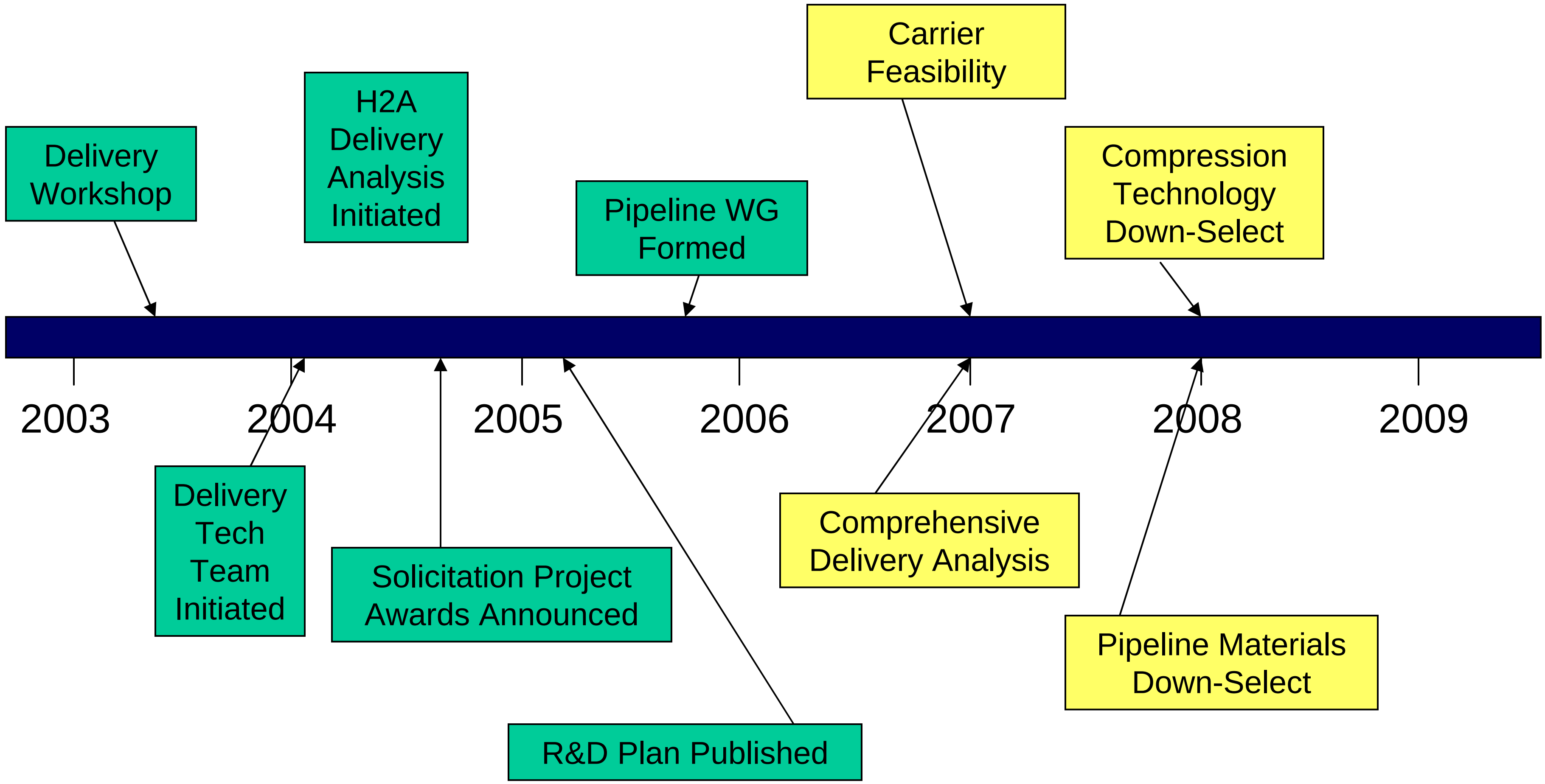
- By **2010**, develop technologies to reduce the cost of compression, storage, and dispensing at refueling stations and stationary power sites to less than ***<$0.80/kg*** of hydrogen.

- By **2015**, develop technologies to reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <***$1.00/kg*** of hydrogen in total.

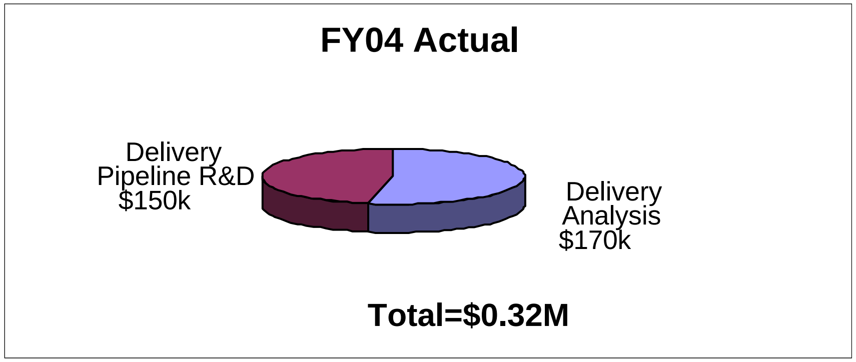
Delivery Key Targets

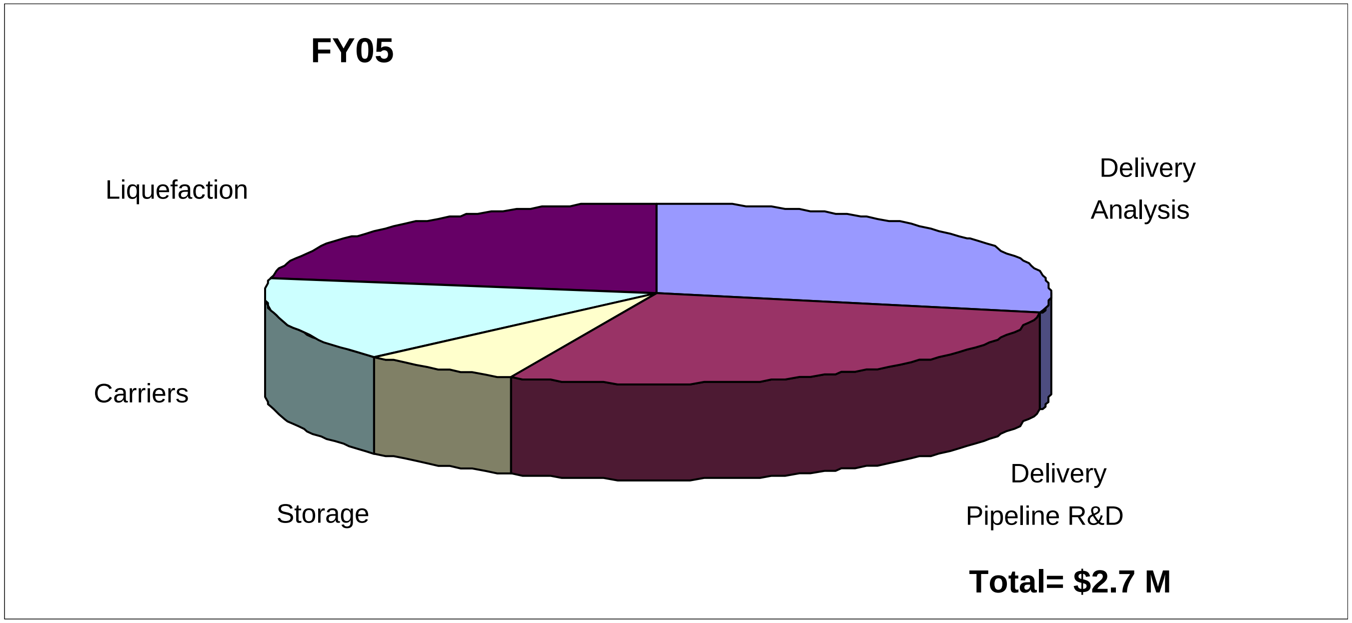
Targets	2003 Status	2015 Target
Transmission Pipeline Capital ($/mile)	$1.20	$0.80
Forecourt Compression		
Cost Contribution ($/kg of H2)	$0.60	$0.25
Reliability	Unknown	>99%
Forecourt Storage Cost Contribution ($/kg of H2)	$0.70	$0.20
Carrier (weight % H2)	3%	13%

Delivery Planning and Implementation



Delivery Funding





Delivery
Key Accomplishments

- Delivery Tech Team and Draft Roadmap
- R&D Multi-Year Plan
- H2A Delivery Analysis Tools
  - Components and Scenarios
- Initial Portfolio of Research Projects
- Pipeline Working Group

DOE Hydrogen Production Team

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