Project H
A Complete Spaceport Hydrogen Solution

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Background

- In the 1950's and 1960's, NASA and USAF requirements pushed the development of large scale liquid hydrogen technology
- Since the completion of LC 39, cryogenic technology has progressed, in many cases by two generations
  - Refrigeration systems
  - Transfer lines and disconnects
  - Compressors and valves
  - Controls and instrumentation
- Spaceport hydrogen operations are different from every other industrial gas customer, and industry is not optimized to meet our needs
  - Very large scales
  - Very unsteady demand and high peak demand
  - Strict delivery requirements
- Hydrogen has a reputation as a difficult and expensive fuel choice, but a necessary evil due to performance benefits
- KSC/CCAFS needs to upgrade its hydrogen infrastructure, optimized for unique spaceport applications and designed for minimal operations costs

Project H Goals

- Goal is to increase the efficiency of hydrogen operations to >80%
  - Current KSC practice is approximately 55%
  - Defined by mass launched/mass purchased
- Targeted hydrogen losses
  - Storage tank boil off
  - Chill down losses
  - Tanker venting recovery
  - Line drain and purge
  - Tank venting
- Local hydrogen production and liquefaction capability
  - Sized for KSC needs but allowed to sell offsite
  - Can stimulate local economy
- Propellant conditioning and densification
  - Bulk temperature to 16 K
  - Thermal energy storage for launch, load balancing
- Reduction in helium use
- Reducing in spaceport carbon footprint

Project H Elements

- Ultimate goal is a complete KSC/CCAFS hydrogen system optimized for spaceport operational demands
- Economic and energy efficiency for minimal life cycle costs
- Consists of 4 elements
  - ***Local hydrogen production system***
    - Tie into existing natural gas pipeline and electrical grid
    - Capitalize on latest plant designs
  - ***Hydrogen compression and gaseous distribution system***
    - Advanced compressors and hydrogen pipeline feeding LC 39 A and B, LC 40, LC 41, LC 37, and LC 36
    - Addition of vehicle refueling station for fleet applications (existing)
  - ***Integrated refrigeration and storage system***
    - Provides for liquefaction , conditioning, and zero loss storage and transfer
    - Hybrid cycle uses closed helium refrigerators with open cycle hydrogen expansion
  - ***High efficiency transfer lines***
    - Vapor shielded for 10x reduction in heat leak
    - Integrates vent cycle back to liquefier

- All components and subsystems are commercially available
- Major development challenge is engineering and integration, not technology development

Project H Phasing

- Although the subsystem technology is mature, at the system level operations will be very different, and there will be a learning curve associated with use
- To mitigate this risk, **Phase 1 will build a smaller scale demonstration system** (0.5 MMSCFD) to prove operations and efficiency
    - Exact sizing to be determined via trade study
    - Can utilize some existing equipment for minimal cost
    - Method of maintaining critical skills
- Upon successful completion, **Phase II will build a full scale spaceport system**
    - Allows for time to determine future Spaceport demands
    - Will need CCAFS and commercial buy in
- Phase I system has multiple continued uses
    - Can be used to shave peak loads from full scale Spaceport system
    - Can be used as a hydrogen center of excellence for energy research and education
    - Can be used by a commercial supplier for hydrogen industries, even if Phase II isn't funded
    - Can be sent to Launch Complex 36, 40, or 41, West Palm Beach or SSC for incorporation into their operational system
    - Can serve as densified propellant testbed

Local Hydrogen Production

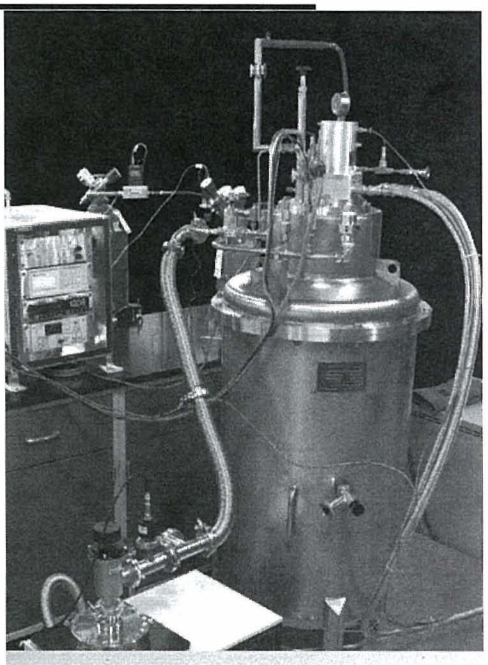
- No current hydrogen production within 400 miles of KSC
  - Currently come from New Orleans (700 miles)
  - Gap in national hydrogen production map
- Steam methane reformation (SMR) is currently the preferred method
  - Experience base allows for cost estimates with engineering certainty
  - Cost ($M) = 5.384 * Capacity (TPD)^ $^{0.6045}$
- Can take advantage of recent plant technologies for energy efficiency and economics
- Existing natural gas line sized for eventual hydrogen production at KSC
- KSC demands smaller than typical plants being built
  - Sizing fits within DoE goals for distributed scale production
  - Possible future partnership with DoE
- Other potential partners include Pratt and Whitney/Rocketdyne
  - Developed compact reformer process
  - Pilot scale plant in testing
  - One step reaction with simplified carbon capture
  - 30-40% lower capital cost compared to SMR

Hydrogen Compression and Distribution

- Hydrogen compression is a mature technology but there are efficiencies to be gained over current oil lubricated piston compressors
- Linde has recently developed ionic liquid hydrogen compressors that can be used
- Spaceport scale distribution can use gaseous pipelines between the central production facility and various launch pads for liquefaction
- Gaseous hydrogen pipelines are a mature technology with hundreds of miles of pipe in Europe and North America
  - Cost models are known with engineering certainty
  - Cost ($) = 200,000 * length (miles) * diameter (in)
- Gaseous distribution system capabilities
  - Can be used for high pressure GH2 fleet refueling
  - Gas source eliminates need for vaporizer, increases effective tank capacity
  - Serves as compression source for hybrid liquefier cycle

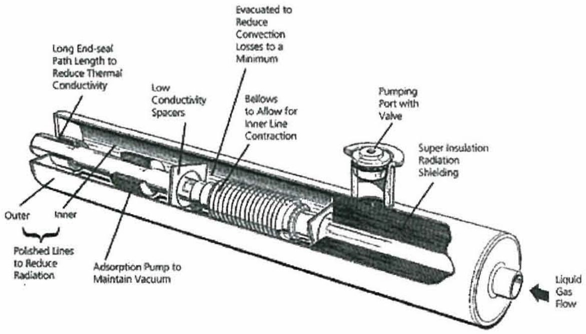
Integrated Refrigeration and Storage System

- Many past studies and projects have used active refrigeration with storage tanks
  - Early work focused on reliquefier concepts
    - Open cycle liquefiers using the ullage gas as the working fluid
  - Later NASA work used close cycle refrigerators for zero boil off applications
    - Coldhead condensers in ullage space
    - Pumps with forced liquid convection to cold heat exchanger
- Recent KSC demonstrations have proved IRAS concepts for LH2 and LOX on small scale (<100 gallons)
  - Uses close cycle refrigeration with heat exchange in liquid region of tank, will depend on natural convection
  - Hydrogen system has demonstrated liquefaction, zero boil off, and hydrogen densification
- Advantages
  - Less active systems
  - Ability to control liquid temperature
    - Allows for greater thermal storage
    - Allows for propellant conditioning and densification
    - Final stage of a single pass open cycle liquefier
- Liquefaction accomplished by a hybrid system, part open cycle liquefier and part closed cycle refrigerator.



High Efficiency Transfer Lines

- Current operational techniques lose approximately 20,000 gallons during chilldown
  - Brute force approach using only latent heat
  - Vapor is route to flare stack and burned
- In the event of scrub, lines are purged with GHe and warmed back up
  - Similar loss profile the next attempt
- Current Line Heat Leaks (1” LN2 pipe)
  - Bare Pipe (190 W/m): Foam (20 W/m) Vacuum Jacket (0.4 W/m)
- Targeted Heat Leak Values
  - Vapor Shielded Lines 0.04 W/m
  - Reduces LC39 transfer line heat leak from 1000 W to 100 W, within range of refrigeration system
- High efficiency transfer lines, based on similar helium lines for national laboratory systems, can be developed for spaceport hydrogen applications
- Lines are custom designed for individual applications
- Cost models are well known
- LH2 HETF application has unbalanced flow, extended no flow durations, higher temperatures than LHe



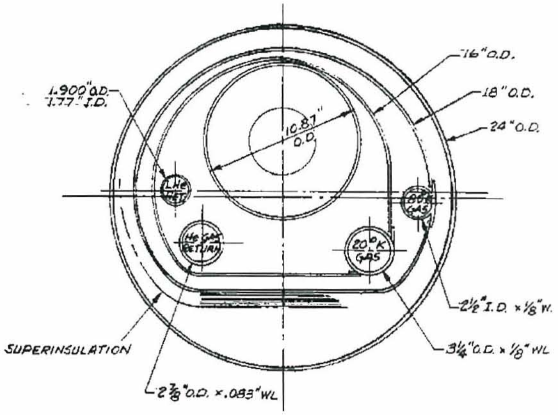


FIGURE - 1

SSC DIPOLE CRYOSTAT CROSS-SECTION

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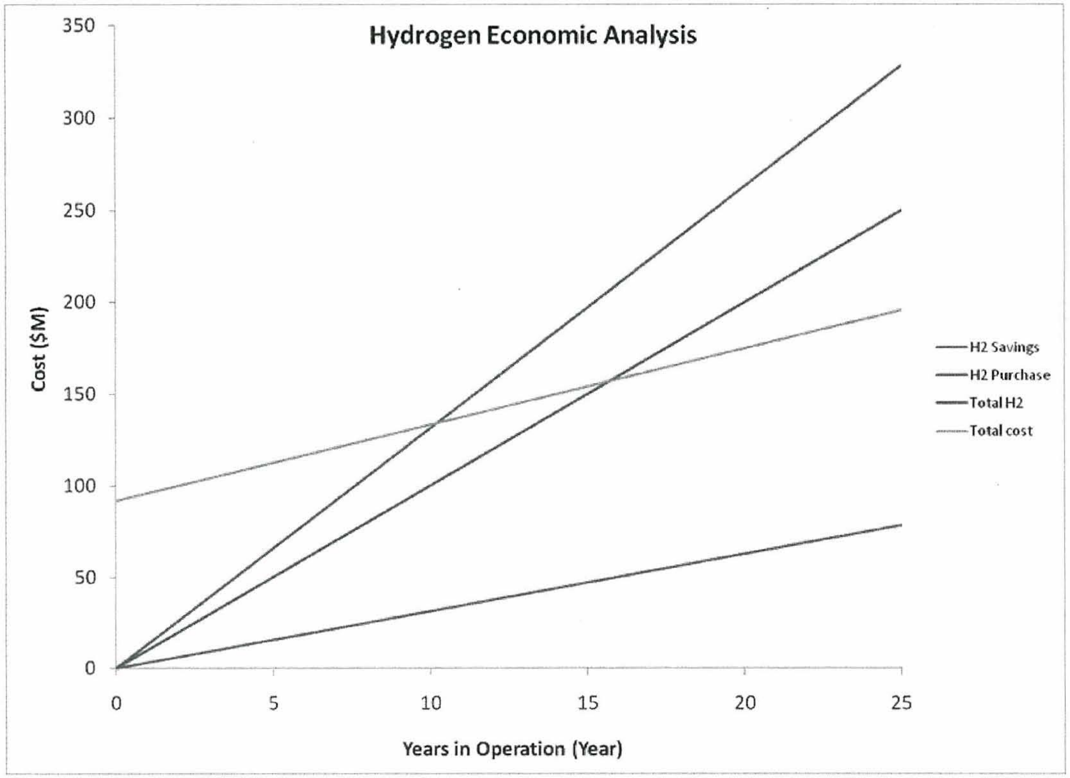
Economic Justification

- Several studies over the past 40 years have shown economic payback of hydrogen ZBO system at LC-39
- A new economic model is being developed to incorporate Project H elements
- Payback period depends on LH2 cost, electric cost, storage volume, refrigeration efficiency, hydrogen recovery modes, and capital costs
- Payback period varies from 5 years to 12 years compared to current system
- Only considers hydrogen and electrical cost, does not include labor savings
- More detailed models are currently being developed, including peak and average demand estimates



Demand Model

Current State of the Art

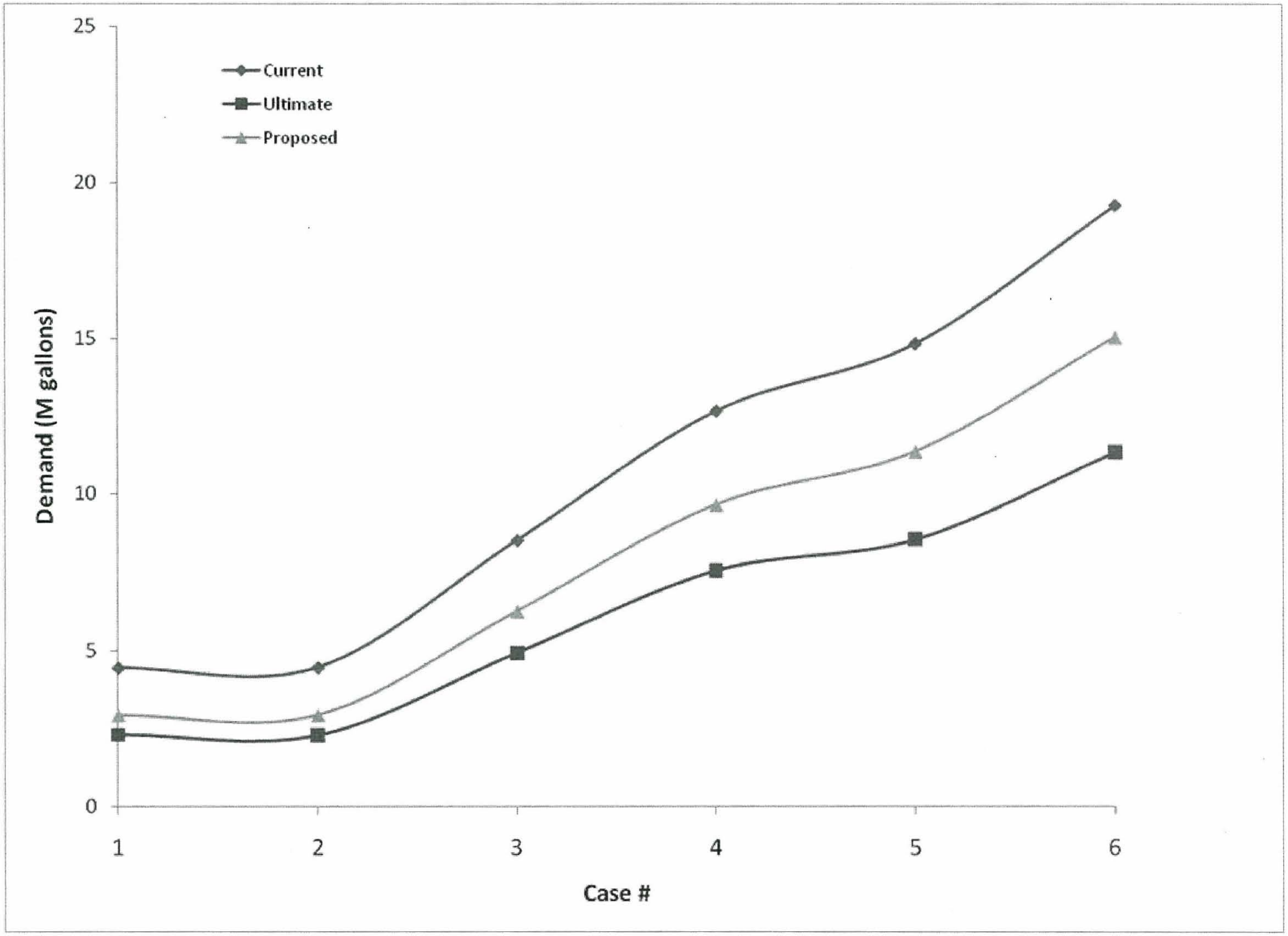
	Case A	Case B	Case C	Case D	Case E	Case F
HLV launch	0	2	4	6	6	8
HLV scrub	0	2	3	4	6	6
Delta IV medium launch	0	2	4	6	8	8
Delta IV medium scrub	0	1	2	3	4	6
Delta IV heavy launch	0	0	1	2	4	6
Delta IV heavy scrub	0	0	0	1	2	4
Atlas V launch	0	4	8	10	12	18
Atlas V scrub	0	2	4	5	6	8
Falcon X launch	0	2	6	10	12	18
Falcon X scrub	0	1	3	5	6	8
STS launch	6	0	0	0	0	0
STS scrub	3	0	0	0	0	0
PWR WPB	0	0	0	0	0	0
Total (M gal)	4.46	4.47	8.52	12.66	14.83	19.28
GPD	12208	12237	23346	34688	40628	52828
mmscfd	1.40	1.41	2.68	3.99	4.67	6.08
mmscf/yr	512	514	980	1456	1705	2217
TPD	3.45	3.45	6.59	9.79	11.47	14.91

Proposed Hydrogen System

	Case A	Case B	Case C	Case D	Case E	Case F
HLV launch	0	2	4	6	6	8
HLV scrub	0	2	3	4	6	6
Delta IV medium launch	0	2	4	6	8	8
Delta IV medium scrub	0	1	2	3	4	6
Delta IV heavy launch	0	0	1	2	4	6
Delta IV heavy scrub	0	0	0	1	2	4
Atlas V launch	0	4	8	10	12	18
Atlas V scrub	0	2	4	5	6	8
Falcon 9 launch	0	2	6	10	12	18
Falcon 9 scrub	0	1	3	5	6	8
STS launch	6	0	0	0	0	0
STS scrub	3	0	0	0	0	0
PWR WPB	0	0	0	0	0	0
Total (M gal)	2.94	2.94	6.26	9.66	11.36	15.04
GPD	8055	8062	17163	26477	31136	41216
mmscfd	0.93	0.93	1.97	3.04	3.58	4.74
mmscf/yr	338	338	720	1111	1307	1730
TPD	2.27	2.28	4.85	7.47	8.79	11.64

Estimates shown are for average demand only, peak demand calculations and load balancing is in work

Reduced Hydrogen Production



Kennedy Space Center
Cryogenic Test Laboratory

Environmental Benefits

- Hydrogen production and liquefaction is a very energy intensive operation
- Reduction in hydrogen losses will have environmental benefits
- Preliminary environmental impact estimates have been done to quantify the carbon savings associated with this proposed system
- Savings come from reduced production demands, reduced liquefaction energy demands, and transportation savings.
- Does not account for increased production efficiency or carbon capture technology during production

- **CO2 savings equate to eliminating the carbon footprint of 2100 people or eliminating 2800 cars from the road.**

	Annual LH2 Production (millions of gallons)	GH2 Production Energy Required (MWh)	Liquefaction Energy Required (MWh)	Total Energy Required (MWh)	CO2 Emitted (millions of lbs)	CO Emitted (millions of lbs)	Total Carbon Emitted (millions of lbs)
Case 1	13.76	21342	68969	90311	107.9	37.6	42.8
Case 2	10.85	16829	54384	71213	85.1	29.7	33.7

Conclusions

- Current Kennedy Space Center practice results in half the hydrogen purchased being lost
  - Leads to large economic losses
- KSC needs are different than other industrial gas customers
- The industrial gas companies are optimized for other customers needs
- KSC should modernize its liquid hydrogen systems, taking into account cryogenic advances made in the past 50 years, to optimize life cycle costs for the unique KSC application

- Project H ideas for local hydrogen production, gaseous distribution, integrated refrigeration and storage, and high efficiency transfer lines should be investigated further