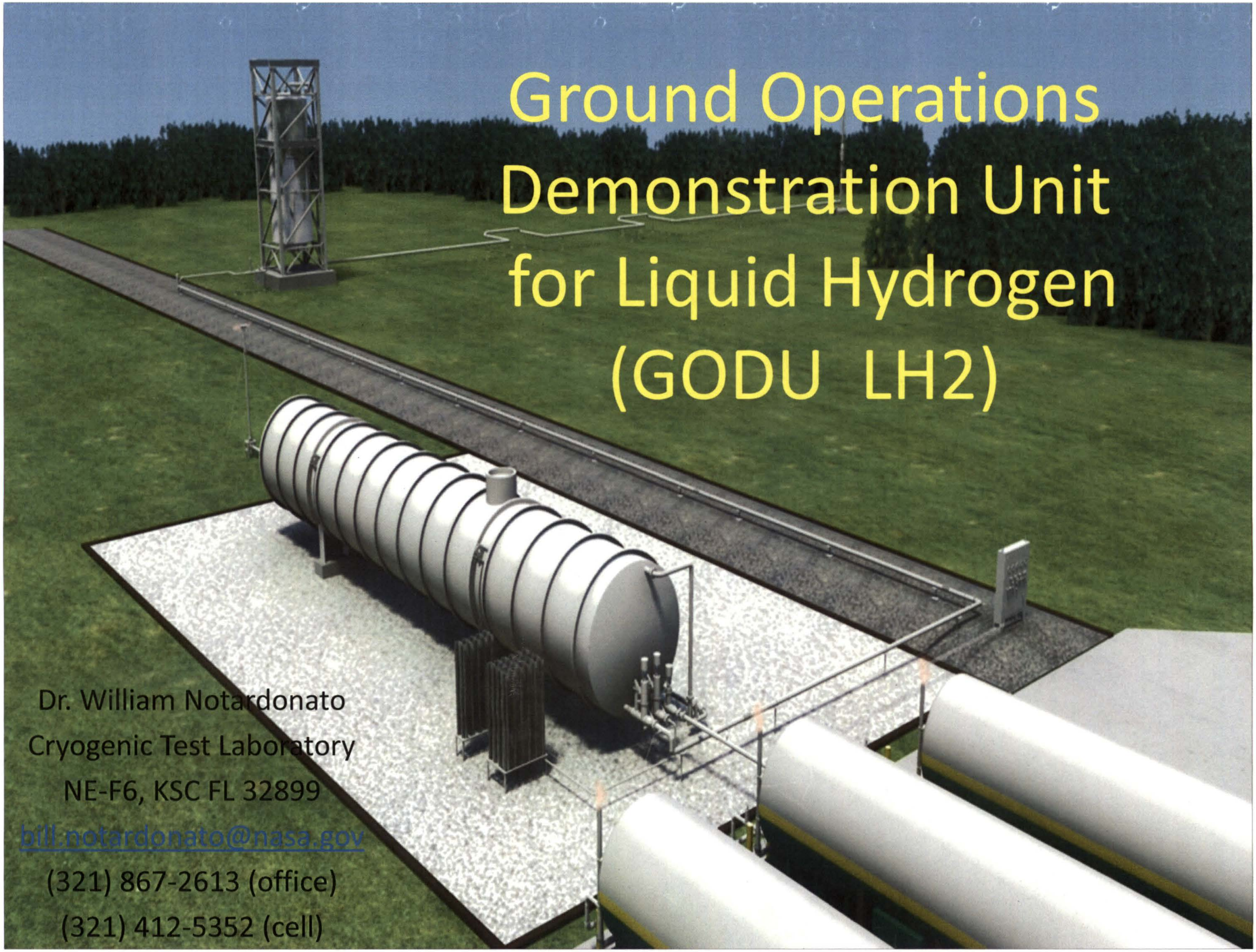

Ground Operations Demonstration Unit for Liquid Hydrogen (GODU LH2)

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  - Hydrogen and NASA
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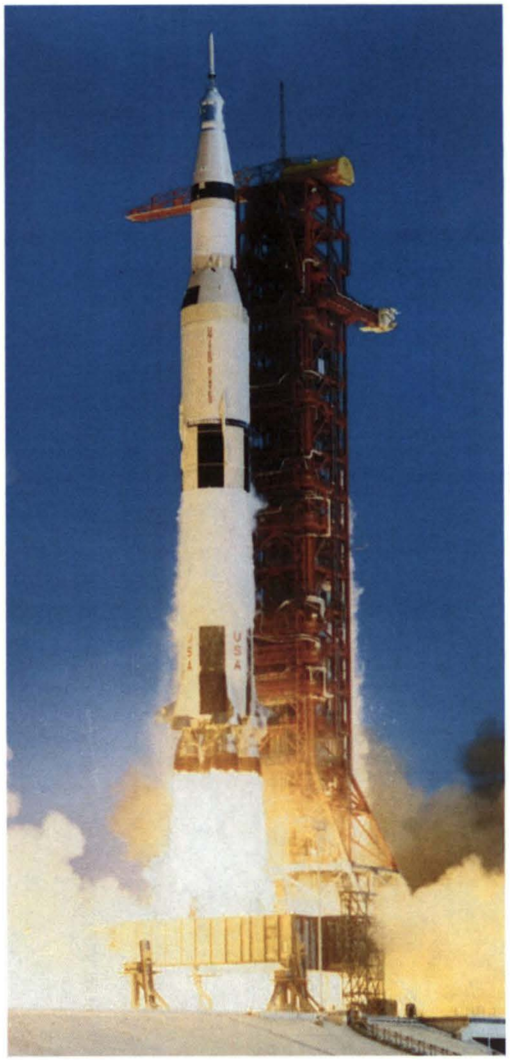
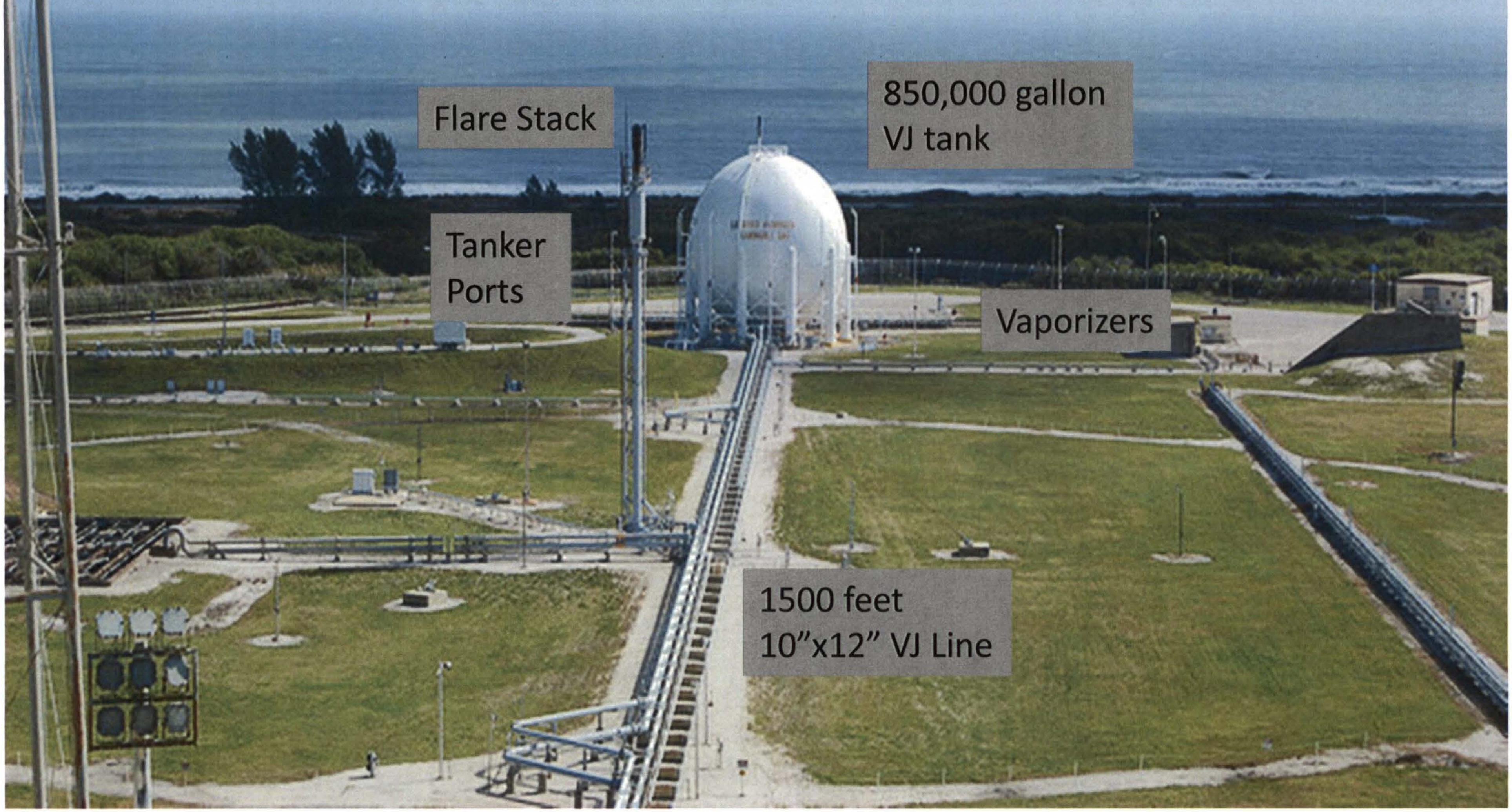


HISTORICAL CONTEXT

NASA LH2 Background

- NASA helped drive the development of large scale LH2 industry
- LC 39 built for Apollo and reused for Shuttle



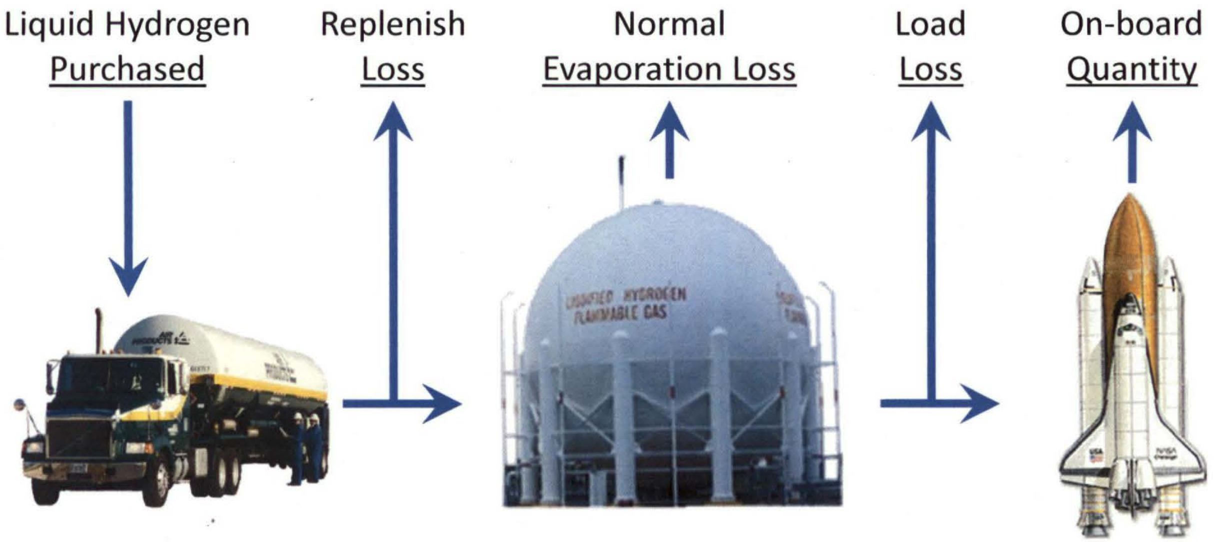
Status of KSC LH2 Systems

- 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 necessary due to performance benefits

LC-39 Use and Loss for STS Program

- Replenish
  - heat leak during transit, chill-down of transfer system, and tanker press.
  - Approx. 13% of the KSC hydrogen purchased over the Space Shuttle Program
- Normal Evaporation Loss
  - heat leak from the ambient to the ground storage tank
  - Approx. 12% of the KSC hydrogen purchased over the Space Shuttle Program
- Load Loss
  - chill-down of ground and flight system and ET heat leak during replenish
  - Approx. 21% of the KSC hydrogen purchased over the Space Shuttle Program
- On-board Quantity
  - Volume of the External Tank
  - Approx. 55% of the KSC hydrogen purchased over the Space Shuttle Program.

Historical Consumption Summary



Liquid Hydrogen Consumption over Entire Space Shuttle Program

Liquid Hydrogen Purchased	100.0%	54,200,000 lb
Replenish Loss	12.6%	6,800,000 lb
Normal Evaporation Loss	12.2%	6,600,000 lb
Load Loss	20.6%	11,200,000 lb
On-board Quantity	54.6%	29,600,000 lb

Future Spaceport LH2 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
- Propellant conditioning and densification
  - Bulk temperature to 16 K
  - Thermal energy storage for load balancing
- Reduction in helium use
- Reducing in spaceport carbon footprint

Economic Justification

- Several studies over the past 40 years have shown economic payback of hydrogen ZBO system at LC-39
- Basic economic models have been developed
- Average annual hydrogen demand for both business as usual and advanced systems scenarios is estimated
  - All losses except for loading losses are assumed to be recovered
- Capital costs for hydrogen production, distribution, liquefaction, and transfer lines are estimated
  - Well known cost models for production, distribution, and liquefaction used
  - No cost savings for smaller storage volumes included
- Operational costs only considers natural gas and electrical cost, does not include labor savings
- Payback period depends on system size, 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
- Estimates shown are for average demand only, peak demand calculations and load balancing is in work
- More detailed models are currently being developed, including peak and unsteady demand estimates

Losses

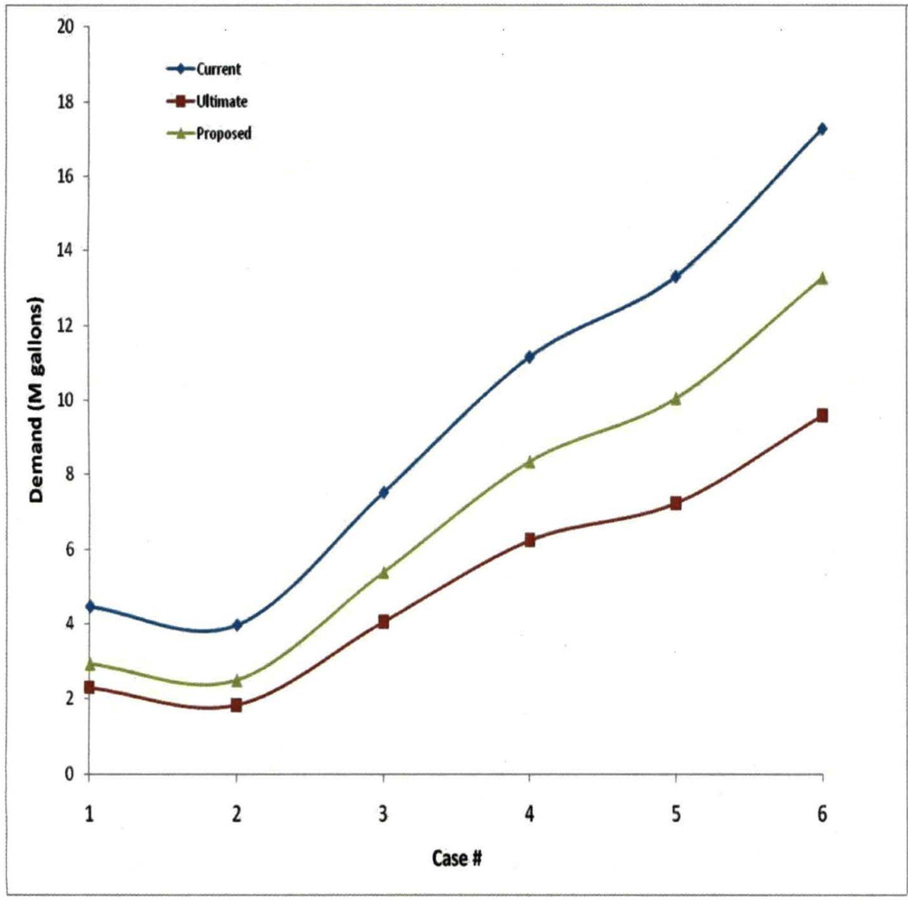
Hydrogen Sinks					
	Vehicle Requirements				
	LH2 Volume		LH2 Mass		
	Gal/launch	M^3/launch	lb/launch	kg/launch	
HLV (Ares V)	760,000	2,877	429120	195055	
Delta IV medium	125000	473	70579	32081	
Delta IV heavy	350000	1,325	197621	89828	
Atlas V	13000	49	7340	3336	
Falcon X	10000	38	5646	2567	
STS	385000	1,457	217383	98811	
	Load Loss				
	LH2 Volume		LH2 Mass		
	Gal/launch	M^3/launch	lb/launch	kg/launch	
HLV (Ares V)	190000	719	107280	48764	
Delta IV medium	50000	189	28232	12833	
Delta IV heavy	150000	568	84695	38498	
Atlas V	7000	26	3952	1797	
Falcon	5000	19	2823	1283	
STS	100000	379	56463	25665	
	Scrub Loss				
	LH2 Volume		LH2 Mass		
	Gal/scrub	M^3/scrub	lb/scrub	kg/scrub	loss factor
HLV (Ares V)	152000	575	85824	39011	0.8
Delta IV medium	40000	151	22585	10266	
Delta IV heavy	120000	454	67756	30798	
Atlas V	5600	21	3162	1437	
Falcon	4000	15	2259	1027	
STS	80000	303	45171	20532	
	Normal Evaporation				
	LH2 Volume		LH2 Mass		loss factor
	Gal/year	M^3/year	lb/year	kg/year	%/year
LC39A	146000	553	82436	37471	0.172
LC39B	365000	1,382	206091	93678	0.429
LC41	6750	26	3811	1732	0.150
LC40	4950	19	2795	1270	0.150
LC37	219000	829	123654	56207	0.258
	Supply Loss				
	LH2 Volume				
	% purchased				
LC39A	1.145				
LC39B	1.145				
LC41	1.145				
LC40	1.145				
LC37	1.145				

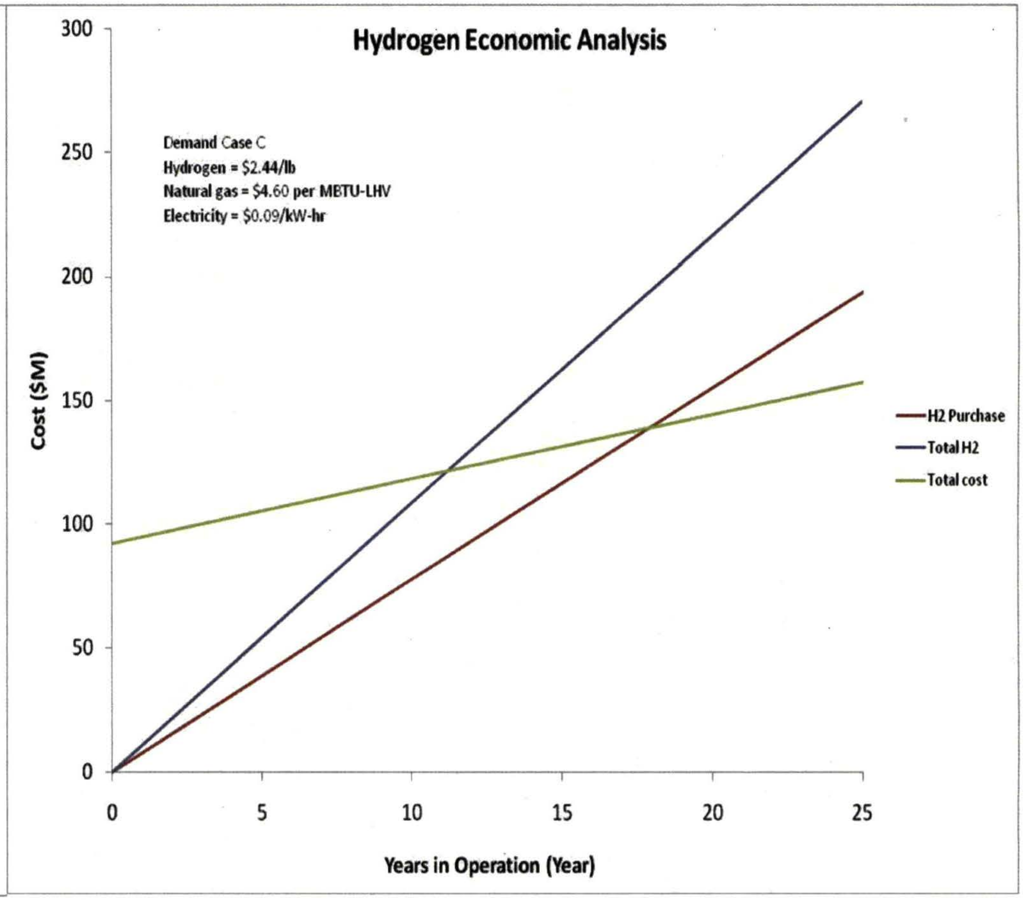
Demand

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

Reduced Demand





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 cost.
- 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

GODU LH2

Advanced Exploration Systems

- The Advanced Exploration Systems (AES) program is pioneering new approaches to **rapidly develop prototype systems** and subsystems, **mature and demonstrate key capabilities**, and **validate operational concepts** for future human missions beyond Earth orbit.
- The AES program goals will be achieved through of a set of **HSF-Works In House Activities**. The teams performing these activities will be **comprised almost entirely of NASA civil servants** to maximize the leveraging of available workforce, and will have very limited procurement funding.
- They will use innovative approaches, partnerships, and management practices, aimed at rapidly developing, building, testing and/or deploying hardware in a **skunkworks like environment**.
  – Reference Kelly's rules at http://www.jamesshuggins.com/h/u-2a/u-2_kellys_rules.htm
  – Project management team is small and is technical in nature
  – Small teams with responsibility to produce
- The activities will typically last 1 to 3 years to drive a rapid pace of progress.

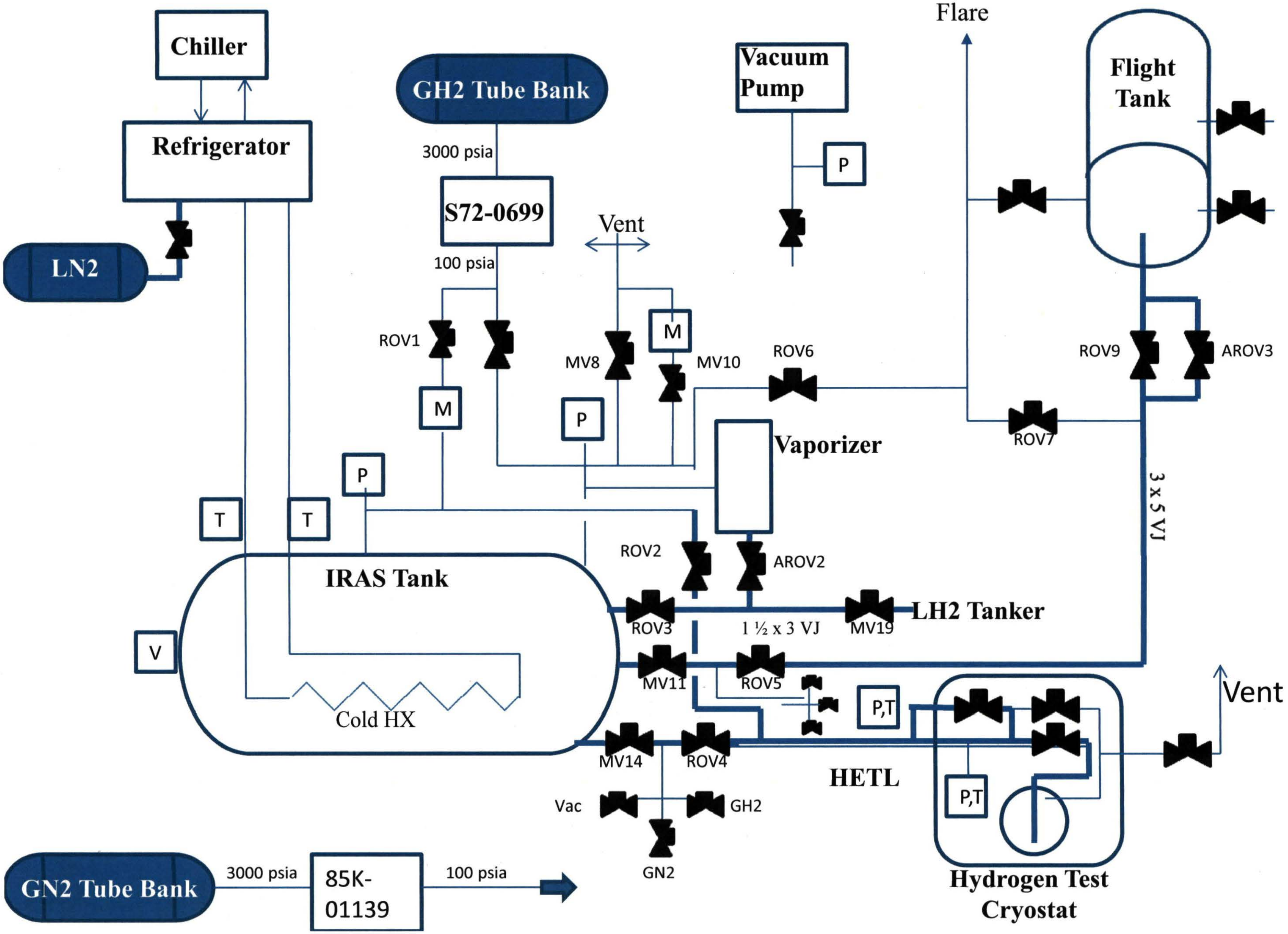
GODU- LH2 Background

- The concept is based on the principle that hydrogen losses can be eliminated if a refrigeration system is integrated into the storage tank (IRAS).
- Placing the cold heat exchanger in the liquid hydrogen allows for direct control over the liquid state.
- Oversizing the refrigerator allows for propellant densification and liquefaction.
- Lab scale operations (150 l) have been successfully demonstrated at Florida Solar Energy Center
- GODU LH2 will expand the scale and operations of the FSEC demonstration

Objectives

- Demonstrate zero loss storage and transfer of LH2 at a large scale
- Demonstrate hydrogen liquefaction using close cycle helium refrigeration
- Demonstrate hydrogen densification in storage tank and loading of flight tank
- Also includes a number of secondary objectives including creating a densified hydrogen servicing capability, maintaining critical cryogenic design and operations skills, demonstrating low-helium usage operations, and validating modern component technologies

GODU LH2 Functional Diagram



Refrigeration System

- Procurement of 850W at 20K cryogenic refrigerator (Linde R1620)
  - Helium circulation capability
  - Long pole in schedule
  - LN2 Precooling
- Procurement of commercial chiller units
- Installation and checkout at test site
- Design and installation of cold heat exchanger
- Integration with transportable skid

Test Articles

- Integrated Refrigeration and Storage Tank
  - 33000 gal tank from Cx 41
  - Modify manway for helium and instrumentation feedthru
  - Install Cold HX and supports
- Cryostat 900
  - 44” dia vacuum chamber with removable upper lid
  - Interface with HETL
- Flight tank
  - Space Act Agreement with ULA to use Centaur 3 tank
  - Used for final simulated load demonstration with densified propellants

Fluid Transfer

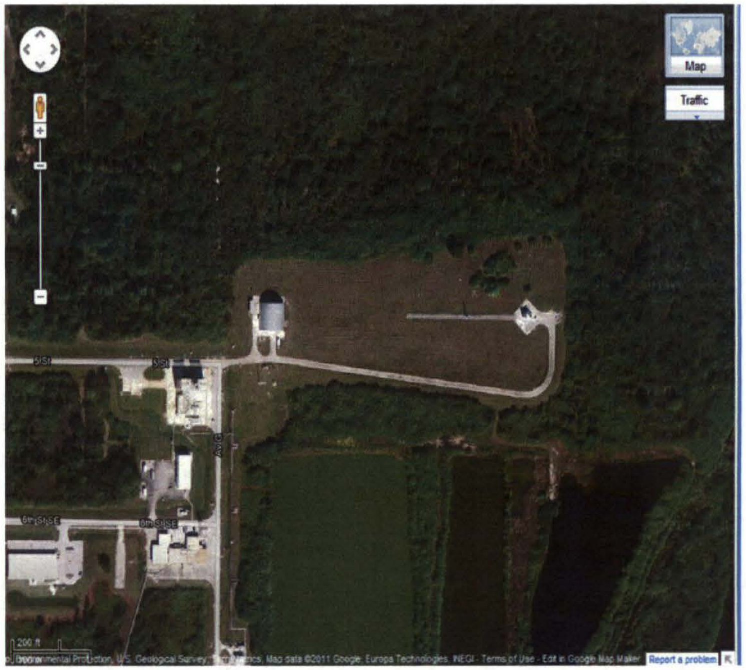
- Vacuum jacketed transfer lines
  - Reuse 240’ existing 3” x 5” VJ lines from X-33 site
  - Procure new VJ lines to interfaces
  - Design/analyze piping support system
- High efficiency transfer lines (HETL)
  - Quad axial semi flex piping
  - Need to design end connections and interfaces
- Gaseous hydrogen vent system
- Gaseous hydrogen flare system
  - Refurbish existing X-33 flare stack
  - 8” dia vent pipe from simulated flight tank
- Liquid hydrogen vaporizers
  - Reuse from NASA Plumbrook K-Site

Command and Control/DAQ

- Use of Allan Bradley PLC based hardware
- COTS hardware and software
- Local and remote control
- Need to define data requirements
- Low speed data acquisition
- Leak and fire detection

Test Site

- Site layout
  - Ground preparations (gravel, concrete)
- Access control
- Paging and area warning system
- Ground power modifications
  - Fuel cell UPS
- Pneumatics
  - Refurbish panels from LC-39, OPF, HMF
- Communication and video systems
- Process Safety Management



Modeling/analysis

- Provide design analysis as needed
  - Cold heat exchanger sizing
  - Tank and feedthru thermal analysis
  - High efficiency transfer line thermal analysis
  - Pressure vessel systems analysis
- Systems level SINDA/FLUINT modeling
  - Lumped parameter thermal and fluid model
  - Transient, open systems, two phase
- Tank stratification model
  - Modify existing LSP code with internal heat exchanger and geometrical constraints
  - Predict IRAS and flight tank temperature profile during operation

Specific Test Objectives

Objective	Operation	Current State of the Art	Full Success Criteria
Zero Loss Storage and Transfer			
Zero Boil Off Storage	Store LH2 in main storage tank	0.1% to 0.5% per day boil off	0% per day- No hydrogen venting in steady state storage operation
Zero Loss Tanker Offload	Transfer hydrogen from tanker to main storage tank	10% loss	0% loss - Offload 100% of tanker with no venting
Zero Loss Chill Down	Chill down transfer lines prior to operation	Varies by system mass	0% loss - Full recovery of all chill down vapor
Zero Loss Stop Flow	Leave transfer lines serviced between launch attempts	Lines drained and purged between launch attempts	0% loss - No hydrogen vented for two days during simulated scrub turnaround
Hydrogen Liquefaction			
In Situ Liquefaction in Main Storage Tank	Allow for local liquefaction inside storage tank	Hydrogen liquefied in New Orleans and trucked to KSC	50 gallons per day at 5% COP
Tank Pressure Control	Maintain positive pressure in tank during densification	Densification operations create subatmospheric pressure inside	15 psia with bulk liquid temp below 16K
Hydrogen Densification			
Storage Tank Densification	Use refrigeration to control state of bulk fluid in tank	Past densification systems used large quantities of hydrogen	Continuous densification inside storage tank with bulk fluid
Flight Tank Densification	Load simulated flight tank with densified hydrogen	None	Simulated tank loading with bulk fluid temperature of 17K

PART 3

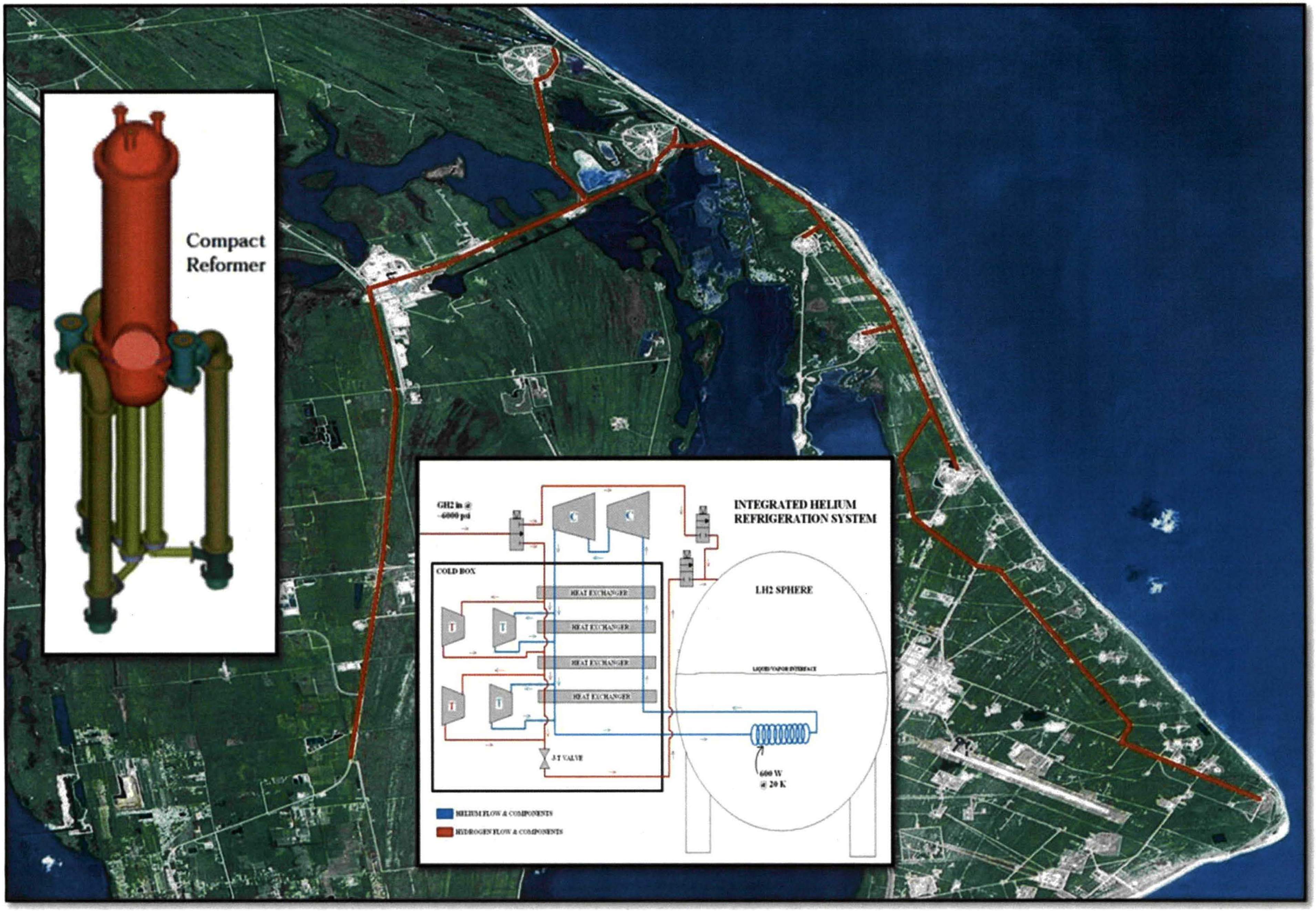
FUTURE

GODU LH2 Future Uses

- Used as a basis of a Space Hydrogen Energy research lab
  - Hydrogen fleet applications
  - Cryostat 900 testing
  - Fuel Cell and electrolysis research
  - Superconductivity
- Servicing on upper stages or test stands with densified hydrogen
- Spacecraft loading ground support equipment
- Helium refrigeration capability
  - Superconducting power transmission and generation development

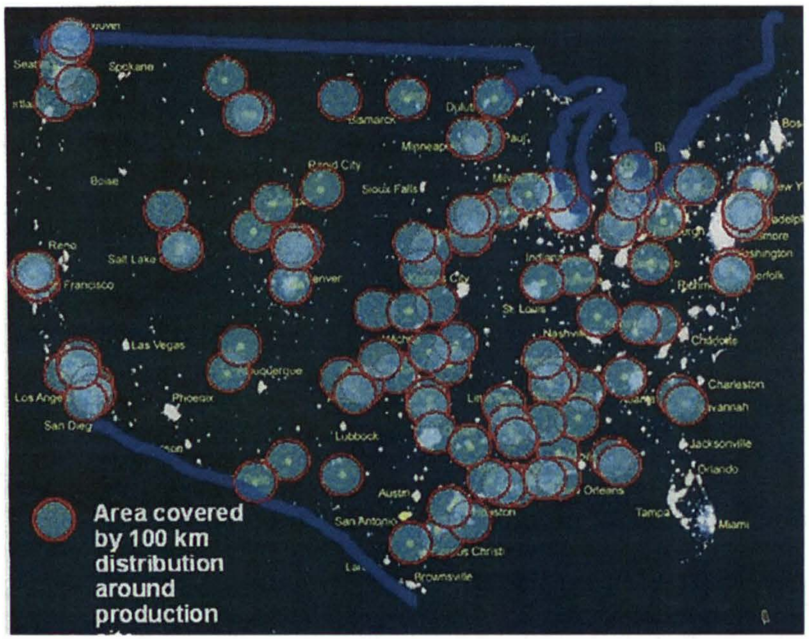
Project H Elements

- 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
  - ***Hydrogen compression and gaseous distribution system***
    - Advanced compressors and hydrogen pipeline feeding LC 39 A and B, LC 40, LC 41, and LC 37
    - Addition of vehicle refueling station for fleet applications
  - ***Integrated refrigeration and storage system***
    - Provides for liquefaction , conditioning, and zero loss storage and transfer
    - Hybrid cycle uses closed helium refrigerators for cooling hydrogen flow
  - ***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


Compact Reformer
INTEGRATED HELIUM REFRIGERATION SYSTEM
GH2 in @ ~6000 psi
COLD BOX
HEAT EXCHANGER
HEAT EXCHANGER
HEAT EXCHANGER
HEAT EXCHANGER
J-T VALVE
LH2 SPHERE
LIQUID/VAPOR INTERFACE
600 W @ 20 K
HELIUM FLOW & COMPONENTS
HYDROGEN FLOW & COMPONENTS

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)^ $^{0.6045}$
- 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



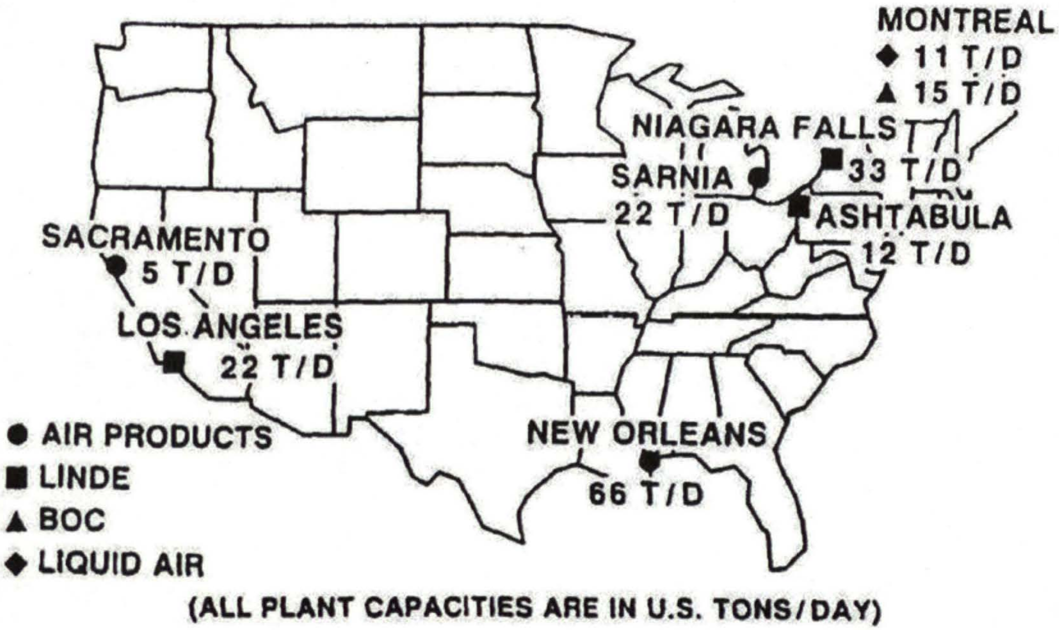


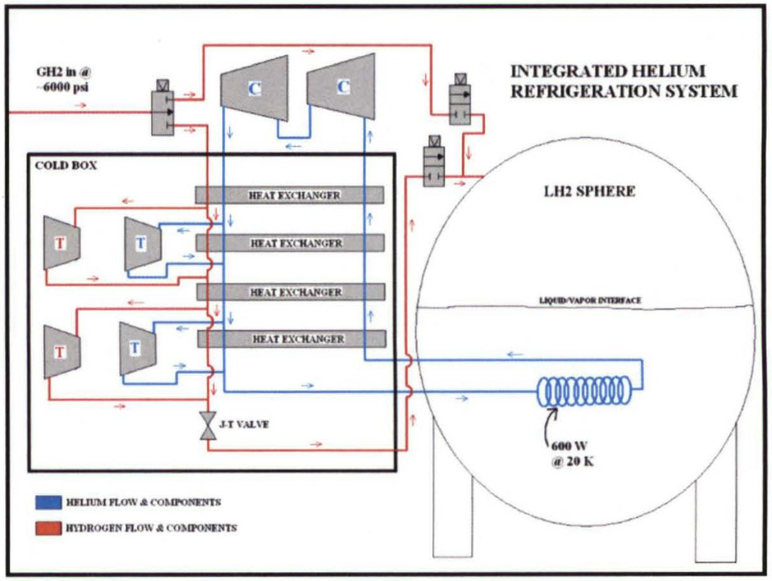
Figure adapted from *Cryogenic Engineering* by Thomas M. Flynn, Dekker:NY (1997) p. 127

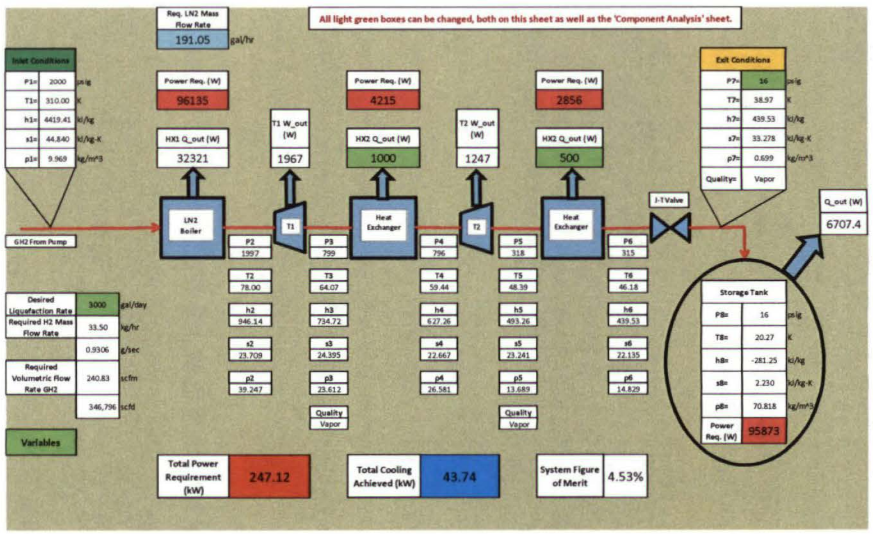
Hydrogen Compression and Distribution

- Optimal method of distributing hydrogen from production plant to refrigerator/liquefier is using gaseous hydrogen pipeline
- 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 additional 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
- It is desirable to locate the hydrogen production plant some distance away from the launch pads to mitigate launch hazards and minimize corrosion from salt.
- Keeping the refrigeration system near the launch pads is essential for storage tank and transfer line hydrogen recovery
- Compression required for pipeline distribution is used in hybrid open/closed cycle liquefier
- Compressors can be oil lubricated piston or screw compressors with appropriate downstream purification or potentially use ionic liquid compressors
- Ionic liquid compressors starting to be used in Europe for compressed hydrogen servicing of fleet vehicles

Integrated Refrigeration and Storage System

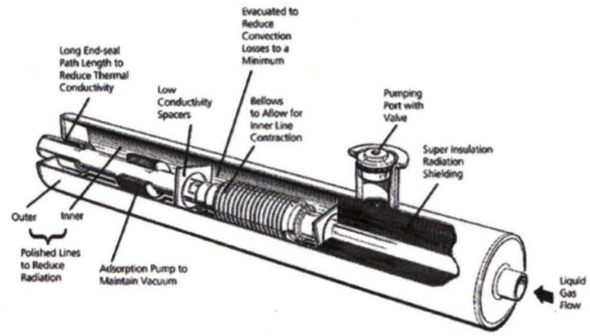
- Many past studies and projects have used active refrigeration with storage tanks
  - Early work focused on reliquefier concepts
    - Open cycle liquefiers using the ullage gas as the working fluid
  - Later NASA work used close cycle refrigerators for zero boil off applications
    - Coldhead condensers 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



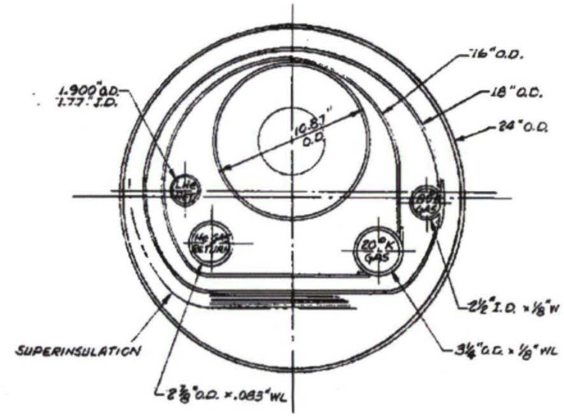


FIGURE - 1

SSC DIPOLE CRYOSTAT CROSS-SECTION

-3-

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