REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
24-10-2006

2. REPORT TYPE
Journal Article

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Hydrogen Pressurization of LOX: High Risk/High Reward (Preprint)

5a. CONTRACT NUMBER
FA9300-04-C-0008

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Andrew E. Turner (Space Systems/Loral); and Aaron Leichner (Microcosm Corporation)

5d. PROJECT NUMBER

5e. TASK NUMBER
502603BQ

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Aerojet
P.O. Box 13222
Sacramento CA 95813-6000

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-PR-ED-JA-2006-412

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-JA-2006-412

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (AFRL-ERS-PAS-2006-252)

13. SUPPLEMENTARY NOTES
Submitted to Space Times Magazine

14. ABSTRACT
Hydrogen safety has been an oxymoron in many circles since the catastrophic loss of the Hindenburg on May 6, 1937 due to a sudden fire consuming the huge 800 foot long, 100 foot diameter dirigible filled with hydrogen gas. Airship commercial service, enabled by relatively low-cost hydrogen, died along with the longest vehicle ever to fly, even though thousands of passengers had been transported without incident prior to that time. Since 1937 hydrogen has had a bad reputation, though less prominent applications such as launch vehicles, fuel cells and batteries have been safe and successful. But the passing of three generations and the maturation of certain technologies has advanced things sufficiently so that a hydrogen fuel transportation infrastructure and other uses can be discussed constructively.

One beneficial application of hydrogen is pressurization of launch vehicle propellants, in other words forcing the liquid propellants out of their storage tanks and into the combustion chamber, overcoming combustion back-pressure and other resistance along the way. Hydrogen is the most mass-efficient way to do this. However, helium is more often used as the safer and more reliable solution, though it weighs twice as much. While the use of helium is a sensible approach for high-cost, high-reliability systems, hydrogen is attractive for systems that do not require high reliability. An example is Aquarius, a new low-cost, reduced-reliability launch vehicle for low-cost consumables, for which an occasional failure will be tolerated. This article discusses pressurization of liquid oxygen (LOX) with gaseous hydrogen, something most rocket scientists would not attempt but that has now been shown to be worthy of development.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Sean Kenny
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	**Unclassified**	**Unclassified**	SAR	5	N/A

Hydrogen Pressurization of LOX: High Risk/High Reward (Preprint)

Andrew E. Turner, Space Systems/Loral
Aaron Leichner, Microcosm Corporation

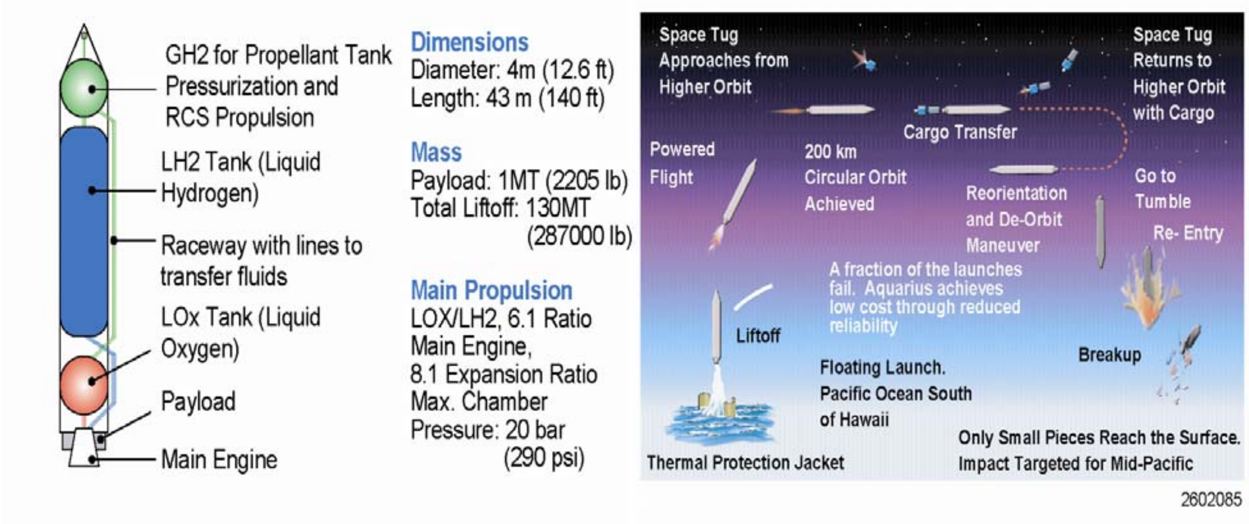
Hydrogen safety has been an oxymoron in many circles since the catastrophic loss of the *Hindenburg* on May 6, 1937 due to a sudden fire consuming the huge 800 foot long, 100 foot diameter dirigible filled with hydrogen gas. Airship commercial service, enabled by relatively low-cost hydrogen, died along with the longest vehicle ever to fly, even though thousands of passengers had been transported without incident prior to that time. Since 1937 hydrogen has had a bad reputation, though less prominent applications such as launch vehicles, fuel cells and batteries have been safe and successful. But the passing of three generations and the maturation of certain technologies has advanced things sufficiently so that a hydrogen fuel transportation infrastructure and other uses can be discussed constructively.

One beneficial application of hydrogen is pressurization of launch vehicle propellants, in other words forcing the liquid propellants out of their storage tanks and into the combustion chamber, overcoming combustion back-pressure and other resistance along the way. Hydrogen is the most mass-efficient way to do this. However, helium is more often used as the safer and more reliable solution, though it weighs twice as much. While the use of helium is a sensible approach for high-cost, high-reliability systems, hydrogen is attractive for systems that do not require high reliability. An example is Aquarius, a new low-cost, reduced-reliability launch vehicle for low-cost consumables, for which an occasional failure will be tolerated. This article discusses pressurization of liquid oxygen (LOX) with gaseous hydrogen, something most rocket scientists would not attempt but that has now been shown to be worthy of development.

Aquarius Low-Cost Launch

The Aquarius launch vehicle was discussed in two previous *Space Times* articles (May/June 2001, vol 40, issue 3, and March/April, 2006, vol 45, issue 2). Aquarius achieves low-cost launch by permitting reduced reliability of 0.67-0.80. It will transport low cost consumables and low-cost, easily replaceable spacecraft and other equipment to nominally 200-km orbits, as the mission profile shows. Since high reliability is not required, a cost per pound to orbit of $500 is feasible - an order of magnitude below that of any present launcher. Of the 20-33 losses allocated for every 100 launch attempts, loss of a few vehicles due to hydrogen fires or explosions would be acceptable if that helps keep the net cost per successful mission low.

Corresponding author: Andy Turner, turner.andrew@ssd.loral.com, (650) 852-4071



Aquarius Layout and Mission Profile

The most risky aspect of using gaseous hydrogen (GH2) is pressurization of the LOX tank, since hydrogen and oxygen are easily ignited. A literature search by Microcosm indicates that the sudden insertion of only 0.02 milli-joules of energy, equivalent to dropping a one-ounce weight a distance of 0.003 inches, could be sufficient to ignite a pressurized mix of hydrogen and oxygen. No sparks allowed here! - a typical spark contains 10 joules, 500 times the energy required for ignition. Merely allowing light to shine into the dark, cold high-pressure interior of the LOX tank might be enough to ignite its contents. Sparks and the sudden release of tiny quantities of heat are not the only risks the LOX tank faces if pressurized by hydrogen gas - the tiniest metallic particles can catalyze ignition, with disastrous results.

The use of lightweight, low-cost, metal-free, liner-less graphite composite tanks has already been planned for Aquarius. Tanks of this type produced by Microcosm were demonstrated to contain LOX without incident aboard a sounding rocket by Garvey Spacecraft on June 3, 2000. Prior to this test, and to earlier testing performed by Wilson Composite Technologies, there was concern that such tanks would ignite due to the contact of the powerful oxidizer LOX with the carbon fiber material composing the tank walls. But, following Microcosm's and Wilson's successful demos, these metal-free vessels became strong contenders for the demonstration of combustion-less GH2 LOX pressurization. Such a demonstration would pave the way for the development of hydrogen gas as an ultra-lightweight pressurant, obtainable at low cost from the liquid hydrogen already planned for use on Aquarius.

An initial tank pressurization demonstration was supported as a part of a 15-month, $1M study contract awarded in June 2005 to an team including Aerojet, ORBITEC, Space Systems/Loral, and Microcosm. The California Space Authority helped obtain support for this study through the office of Rep. Anna Eshoo (D-CA), and funding was channeled through existing Air Force Research Laboratory (AFRL) activities supporting development of advanced launch vehicles.

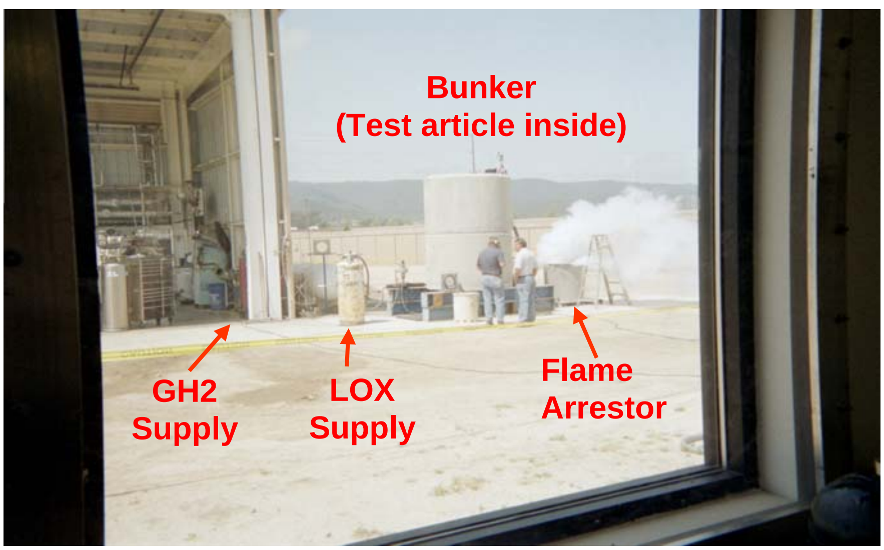
Microcosm, which produces liner-less composite tanks in a wide variety of sizes, fabricated several 10-inch diameter, 18-inch long tanks of an already proven design. Testing of hydrogen pressurization of LOX was conducted on May 9, 2006 at the Innovative Engineering Solutions

Corresponding author: Andy Turner, turner.andrew@ssd.loral.com, (650) 852-4071

.

(IES) facility in Murrieta, California, where modest quantities of explosive mixes can be safely tested. To our knowledge, this is the first time a test of this sort has ever been tried.

Sean Kenny, AFRL holds a duplicate of the tank subjected to testing while Aaron Leichner, Microcosm (left), and Tom Fanciullo, Aerojet look on



The test configuration as viewed from inside the control room. Gaseous hydrogen and LOX are supplied from tanks at left, the tank being tested is located within the bunker at center, and gases are vented at right through the flame arrestor

Corresponding author: Andy Turner, turner.andrew@ssd.loral.com, (650) 852-4071

.

The tank was loaded with 40 pounds of LOX and pressurized to 30 atmospheres (440 psi) with GH2. This pressurization condition was maintained for about 6 minutes, simulating the time between pressurization of an Aquarius launch vehicle's main propulsion subsystem and liftoff.

To simulate the tank environment during regulated pressure operation for the first two minutes of flight an expulsion test was conducted. An attempt was made to maintain constant pressure within the tank by adding GH2 the LOX was drained. However, the pressure fell from 440 to 250 psi because fresh GH2 could not be added quickly enough to maintain constant pressure.

Following the expulsion test a blow-down test was performed during which the tank was not re-pressurized with gaseous hydrogen as it was drained, simulating the second and last two-minute span of Aquarius powered flight. During this portion of the test pressure decreased more rapidly. Prior to the test conclusion the flow of LOX ceased and gaseous hydrogen and gaseous oxygen were observed to be draining from the tank. No ignition or other harmful effects were observed.

Bigger and Better

The successful completion of this test validates the general concept of hydrogen pressurization of the LOX tank for the low-cost/reduced reliability Aquarius launch vehicle and sets the stage for more ambitious testing involving larger tanks and more stringent environments that are even more representative of conditions expected during launch. It is expected that the next series of tests will involve re-use of the same tanks used in this test, but they will be mounted on a shaker table to simulate the launch vibration environment. The concept includes Microcosm manufacturing a larger tank of an already proven all-composite design with a volume of 14 cubic feet to test with a much larger volume of LOX and GH2.

Shedding the *Hindenburg* Stigma

Sensible use of hydrogen for air and space transportation is progressing as new technologies involving non-metallic, non-flammable tank materials at last help to overcome the stigma of the *Hindenburg* disaster.

For the new Aquarius launch vehicle, the fatal event that brought the greatest of all airships down in flames is not a showstopper but merely a cautionary tale and maybe a challenge. Aquarius can tolerate the risk as it will carry no people. It will carry only easily replaceable supplies and low-cost, research-class spacecraft. High reliability is not required for Aquarius economic success; in fact, the cost of high reliability could doom true low-cost access to space for low-cost payloads. Thus, accepting the risk of using hydrogen as a pressurizing gas for liquid propellants, including LOX, helps realize the reward of low-cost access to space.

Corresponding author: Andy Turner, turner.andrew@ssd.loral.com, (650) 852-4071

.