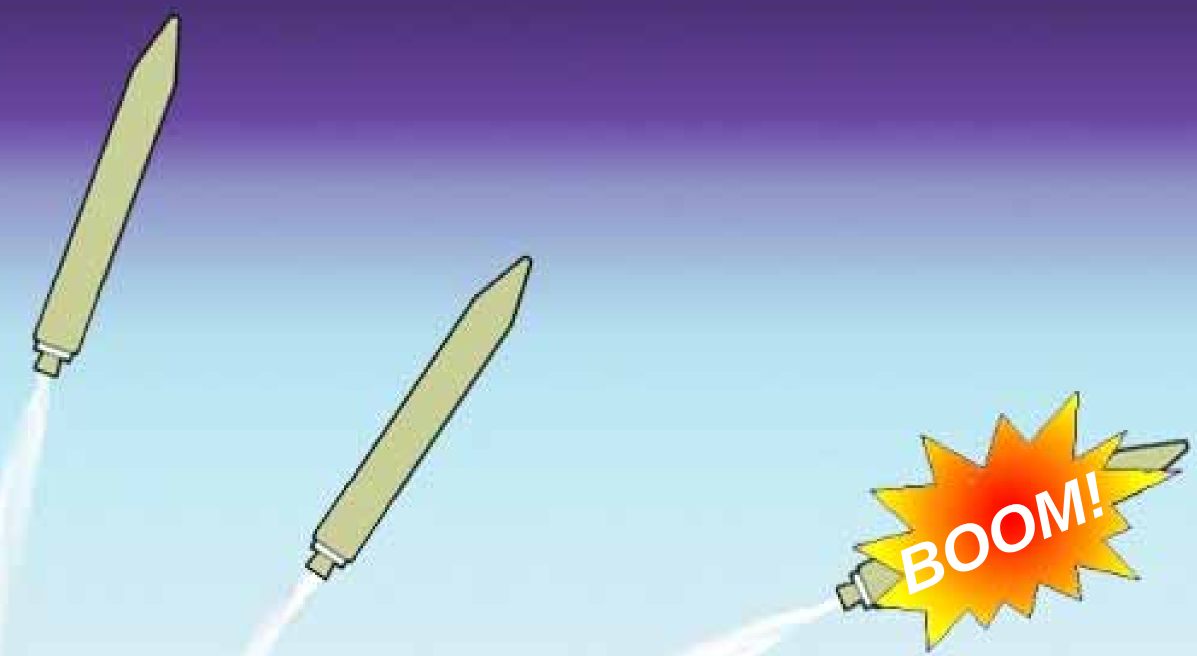

Aquarius Low Cost Launch Main Engine Study
AIAA-RS3 2005-6001

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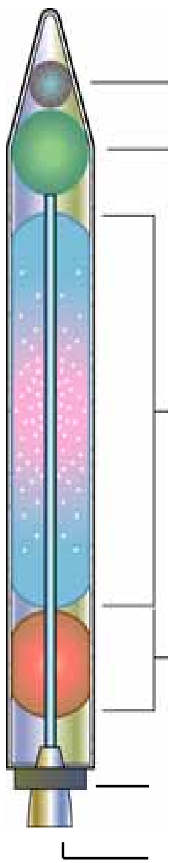
Agenda

- Introduction
- Previous Vortex Engine Development
- Vortex Engine Study
- GH2 Pressurization of LOX Study

Aquarius configuration



- **Dimensions**
  - Diameter: 4 meters (12.6 feet)
  - LH2 tank length: 21 meters (69 feet)
  - LOX tank length: 8.4 meters (28 feet)
  - **GH2 Pressurant tank length: 4 meters (12.6 feet)**
  - Total Length: 43 meters (140 feet)
- **Mass**
  - Payload: 1 metric ton (2200 pounds)
  - Total dry mass: about 10 metric tons (22000 pounds)
  - Total liftoff mass: 130 metric tons (287000 pounds)
- **Main Propulsion**
  - **LOX/LH2,**
  - **GH2 pressurant:-remains in vehicle following thrust termination and is used for cold-gas propulsion for orbit insertion, on-orbit velocity correction, and de-orbit**
- **RCS Propulsion**
  - GN2: 1 metric ton (2200 pounds)--nearly all of this mass is expended during ascent
  - Slow-acting gimbals on main engine used together with fast-acting RCS
- **Max g-load 10g**

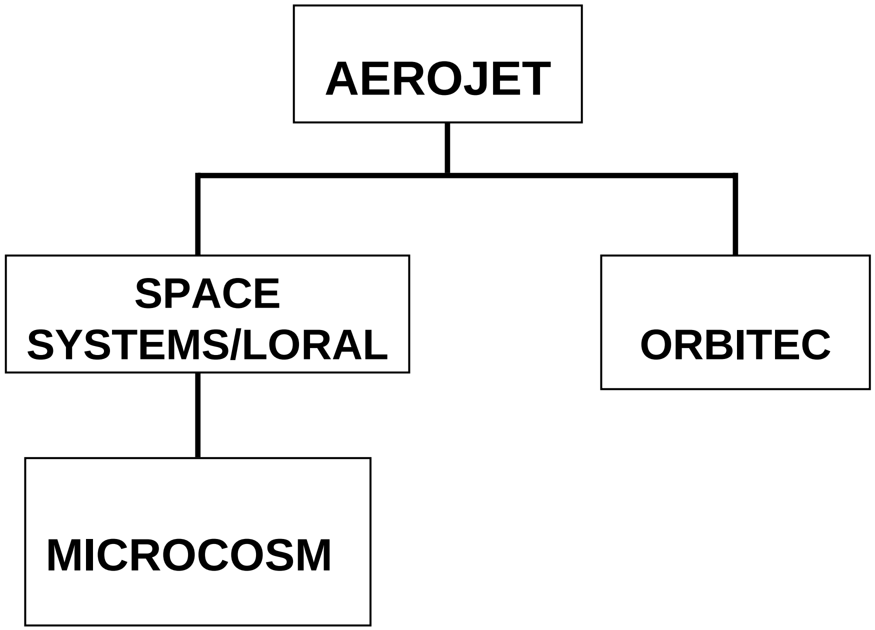
Aquarius business concept

- Low-cost, moderate-reliability launch to LEO
  - Launch cheap consumables like fuel, water, air, food, duct tape
  - Launch in advance of need
    - Replenish stock of propellant, supplies on depots
    - Permits efficient launch schedule focused on minimizing cost
  - Launch small disposable / replaceable spacecraft
  - Launch vehicle cost commensurate with payload intrinsic cost
  - Target ~$1000 per kilogram ($450 per pound)
  - Allowing failure up to one third of the time to maintain low cost
- Markets
  - Low-cost supplies for Space Station
  - Resupply to military spacecraft - DARPA ASTRO/Orbital Express concept
  - Rapid deployment of space probes & other missions
  - Low-cost deployment of swarms and constellations
  - Enables new goods and services

Aquarius technical concept

- Payload: 1 metric ton
- Reliability: 0.67
- Cost to launch: $1-2 million
- About 80 missions per year to be profitable
- Pressure-fed engine
- Liner-less composite tanks
- Might use floating launch to avoid loss of life and property from failure, or launch from remote land area as opposed to a launch pad
- Single Stage to Orbit (SSTO) shown feasible by simulation, reduces engine count to one, minimizes number of tanks
- Payload transferred by orbital tugboat to user
- Potential Modest-Cost Factory site: Central Valley, California
- Launch site: ocean south of Big Island of Hawaii

Aquarius Engine Study Team Structure



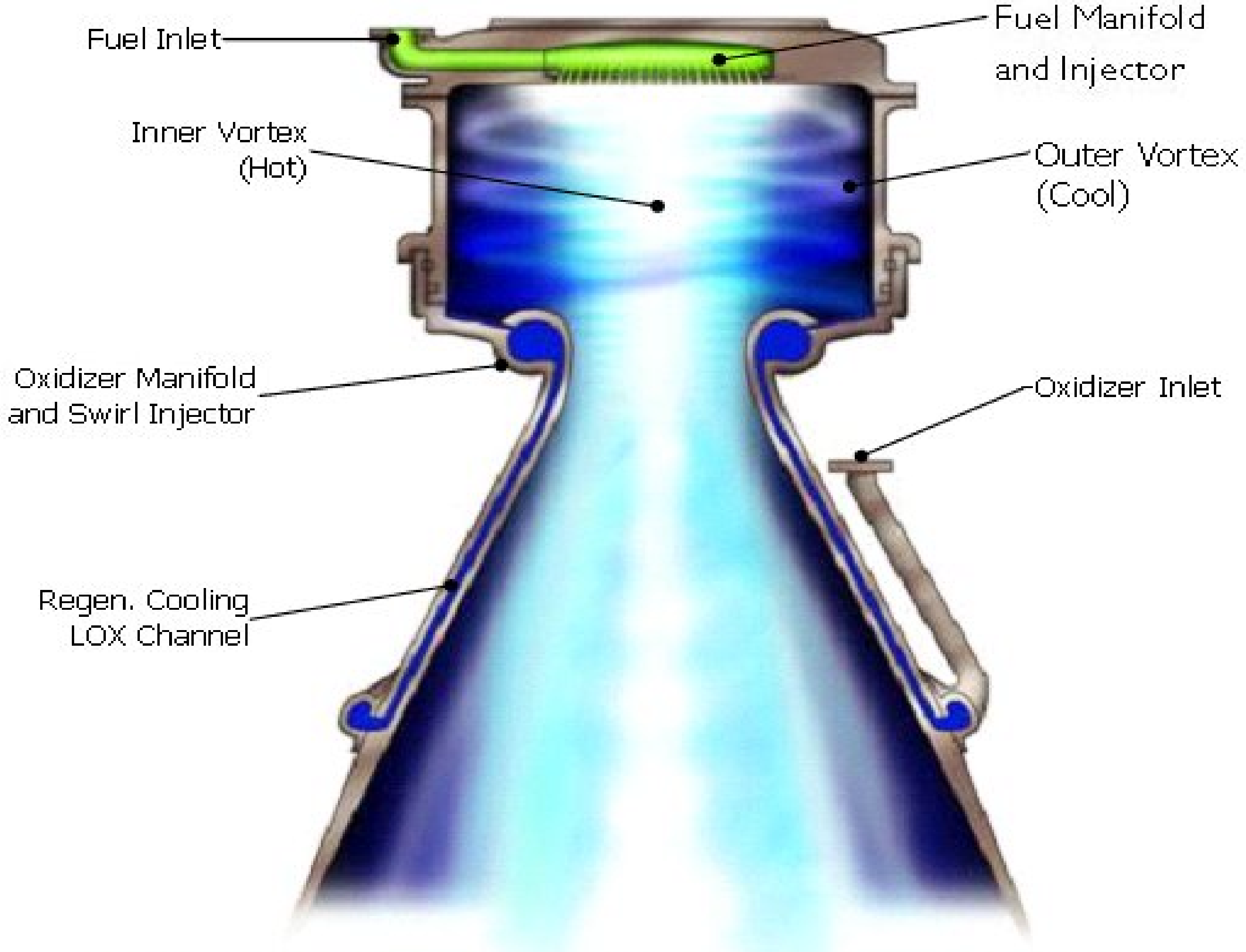
- Prime Contractor: Aerojet of Sacramento, CA
- Space Systems/Loral (SS/L) of Palo Alto, CA and ORBITEC of Madison, WI are subcontractors to Aerojet
- Microcosm of El Segundo, CA is subcontractor to SS/L

Background on the Study

- Total value $1 M
- Duration: mid-2005 through mid-2006
- Major task of study to evaluate Vortex Engine invented by ORBITEC for high-thrust use for Aquarius
  - Minimizes requirements for ablative on engine due to thermal protection of combustion chamber walls by vortex flow
  - Vortex engines are expected to be useful for other launch vehicles besides Aquarius, including high-reliability vehicles
- Second task of study to evaluate use of gaseous hydrogen (GH2) to pressurize LOX
  - GH2 desirable as pressurant for pressure-fed propulsion due to its low molecular weight
  - GH2 usable for cold-gas propulsion following main engine cutoff
  - GH2 would be low cost for Aquarius since it would be obtained as boiloff from LH2 in storage for Aquarius fuel

Previous Vortex Engine Development

Vortex Engine Configuration

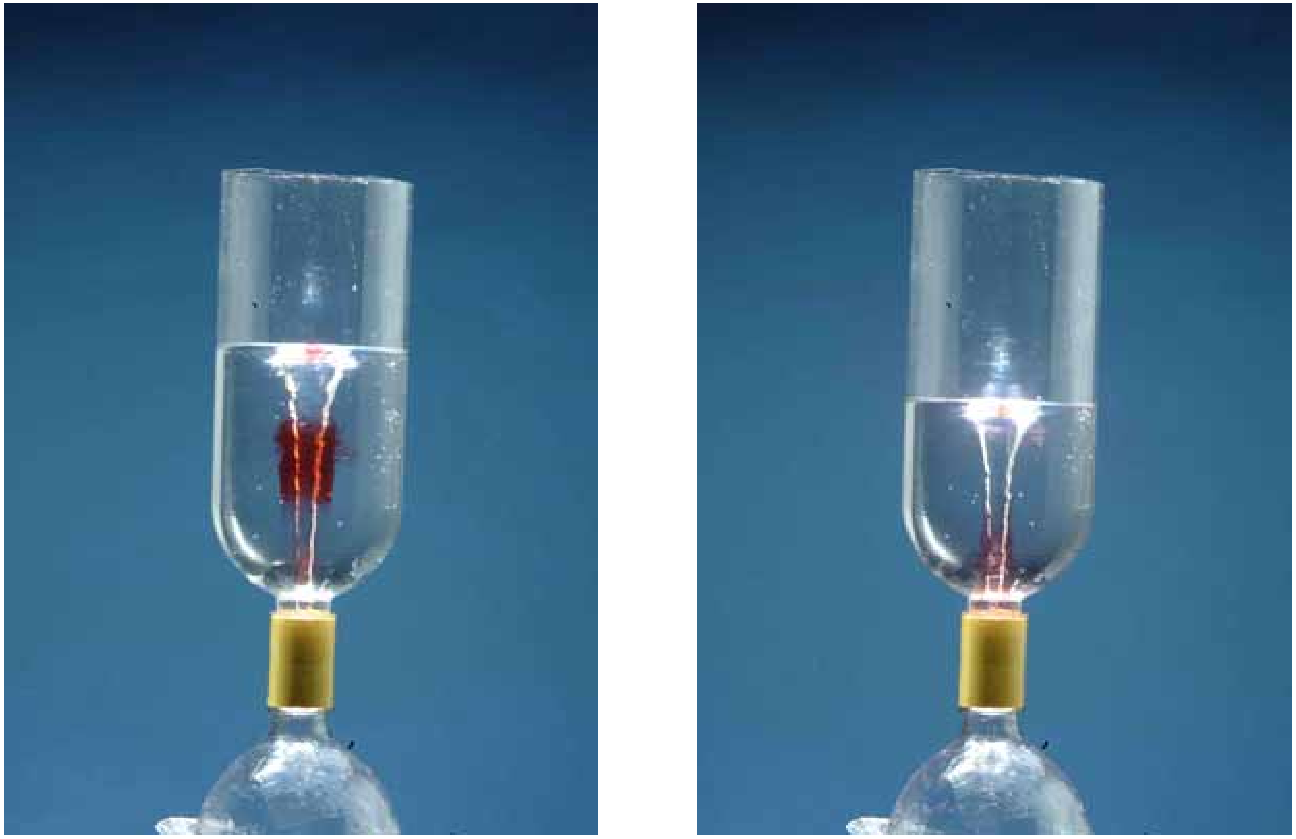


Cold Wall Vortex Combustion Thrust Chamber (Artist's Concept)

Vortex Cooled Chamber Wall (VCCW) Engine Concept

- **Flow field is controlled by design and caused to form a coaxial, co-swirling, counter-flowing vortex pair**
- **Combustion is intentionally confined to the inner vortex, and hot combustion products are prevented by the flow field dynamics from contacting the chamber wall**
  - **Chamber wall is exposed only to radiant heat**
  - **Chamber wall is convectively cooled by fresh propellant so that its temperature remains moderate**
- **Oxidizer is fed in from the base and swirls in a vortex flow field around the inner circumference of the chamber until it reaches the head end where it spirals inward to form a second discrete vortex along the chamber centerline, flowing toward the exit nozzle**
- **Fuel is injected into the center vortex where the strong swirl promotes mixing and combustion occurs**
- **Combustion occurs only in the inner vortex**
  - **Combustion products are isolated from the outer wall by buoyancy forces induced in the radial direction by the vortex flow field**

Demonstration: Vortex Engine Concept

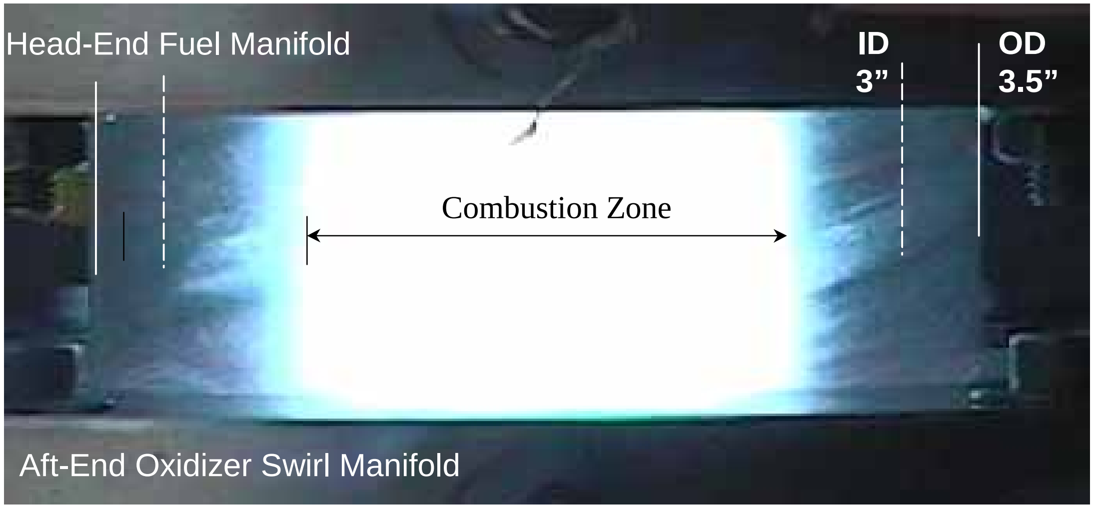


- Under rotating flow the red dye remains concentrated in the core of the vortex as the clear fluid drains

Vortex Engine Background

- Aerojet pointed out heat transfer issues for Aquarius main engine
  - Ablative material required for engine is a potential high-cost item
- ORBITEC of Madison, WI has been developing a potential low cost high-power rocket engine for several years that may resolve heat transfer issues while minimizing amount of ablative required
- ORBITEC Background
  - Founded in 1988
  - Total value of Government contracts: >$80 M
  - About 80 employees
  - Holds U.S. Patent 6,298.659, *Vortex flow field and apparatus and method for producing the same*
- Development funded by NASA-MSFC for small scale engine
- Current study is the first effort involving large scale engines

Video image of Lab-Scale VCCW chamber



- **Image shows a side view image of a cylindrical combustion chamber**
- **Combustion zone confined to the inner vortex by the coaxial flow field while an annular layer of cool, non-combusting gaseous oxygen (GOX) separates the chamber sidewall surface from the region under which combustion is taking place**
- **GOX and GH2 are undergoing combustion in the above figure**

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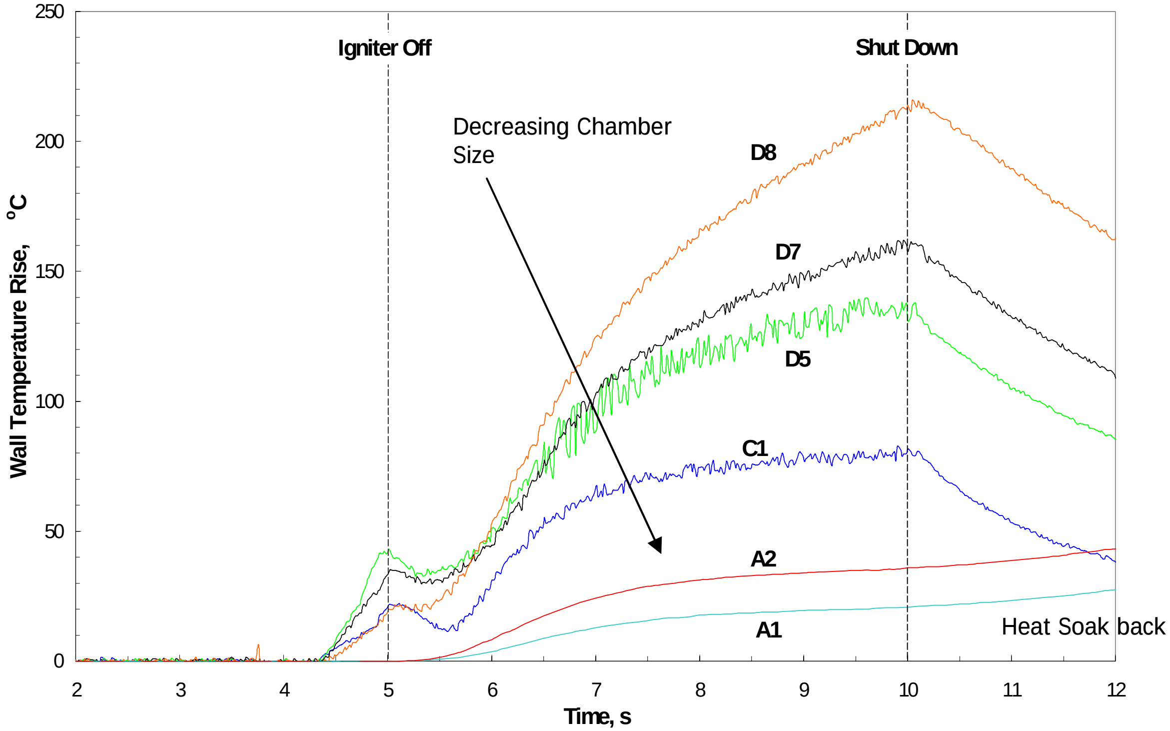
Wall Temperature Histories for VCCW using GOX/GH2



- Sidewall temperatures measured using thermocouples located about 2 mm below the "hot" side of the combustion chamber
- Reducing chamber size resulting in lowering heat rates since surface area decreased. Low heating rates were achieved in all cases as can be seen by the low wall temperature rise, which is less than 250 ºC

Previous Vortex Engine studies by ORBITEC

- NASA preliminary testing of the VCCW engine design
  - LOX/RP1
  - GOX/GH2
- NASA study
  - Computational fluid dynamic analysis of the engine flow field, design and fabrication of several thrust chamber assemblies

Vortex Engine Study

Effort under study

- Baseline design for the Aquarius launch vehicle involves a single main engine
  - Thrust level is beyond the scope of the previous vortex engine development discussed in section 2 and well beyond any effort that can be funded under this $1 million study
  - Sub-scale model will be constructed to support the development of computational fluid dynamic (CFD) models that can be scaled up to the required thrust level of the Aquarius Main Engine
  - Hot-fire testing cannot be supported, however gas flow and water cold flow testing is planned

GH2 Pressurization of LOX Study

GH2 LOX pressurization background

- **Reasons for interest:**
  - **Low molecular weight of GH**
  - **Availability of GH2 since LH2 is used as propellant**
  - **GH2 attractive for cold-gas propulsion after main engine cutoff**
- **Use of GH2 to pressurize LOX has never been tried, but appropriate**
  - **Non-metallic composite tank environment**
  - **Modest temperatures within the environment due to cryogenics**
  - **Hydrogen-oxygen mixes that do not involve some third agent do not explode spontaneously even under pressures exceeding 10 bar as long as temperature is below 400 ºC, according to: K. Kuan-yun Kuo, <u>Principles of Combustion</u>, John Wiley & Sons, New York, 1986, ISBN 0-471-09852-3.**
- **Nature of test**
  - **Temperature: 100 ºC or less, which is facilitated by the cryogenic nature of the LOX**
  - **Pressure: 30 atmospheres, corresponding to the propellant tank pressure envisioned for Aquarius**

Tank for testing: to be provided by Microcosm

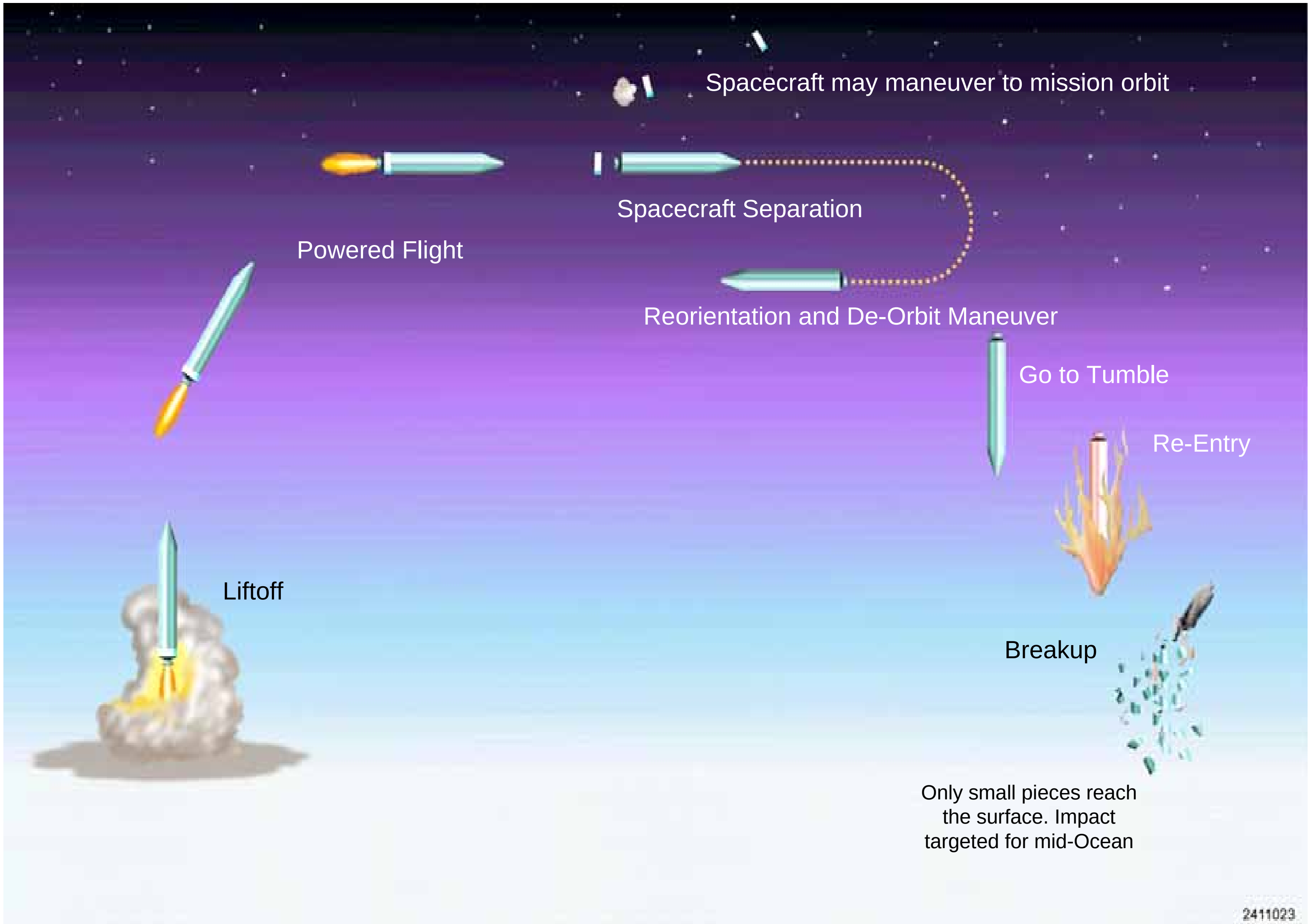
All composite LOX tank flown on the Kimbo-IV sounding rocket on 3 June 2001. This tank includes no metal liner thus LOX was permitted to contact the graphite composite material within the tank

Background to tank testing

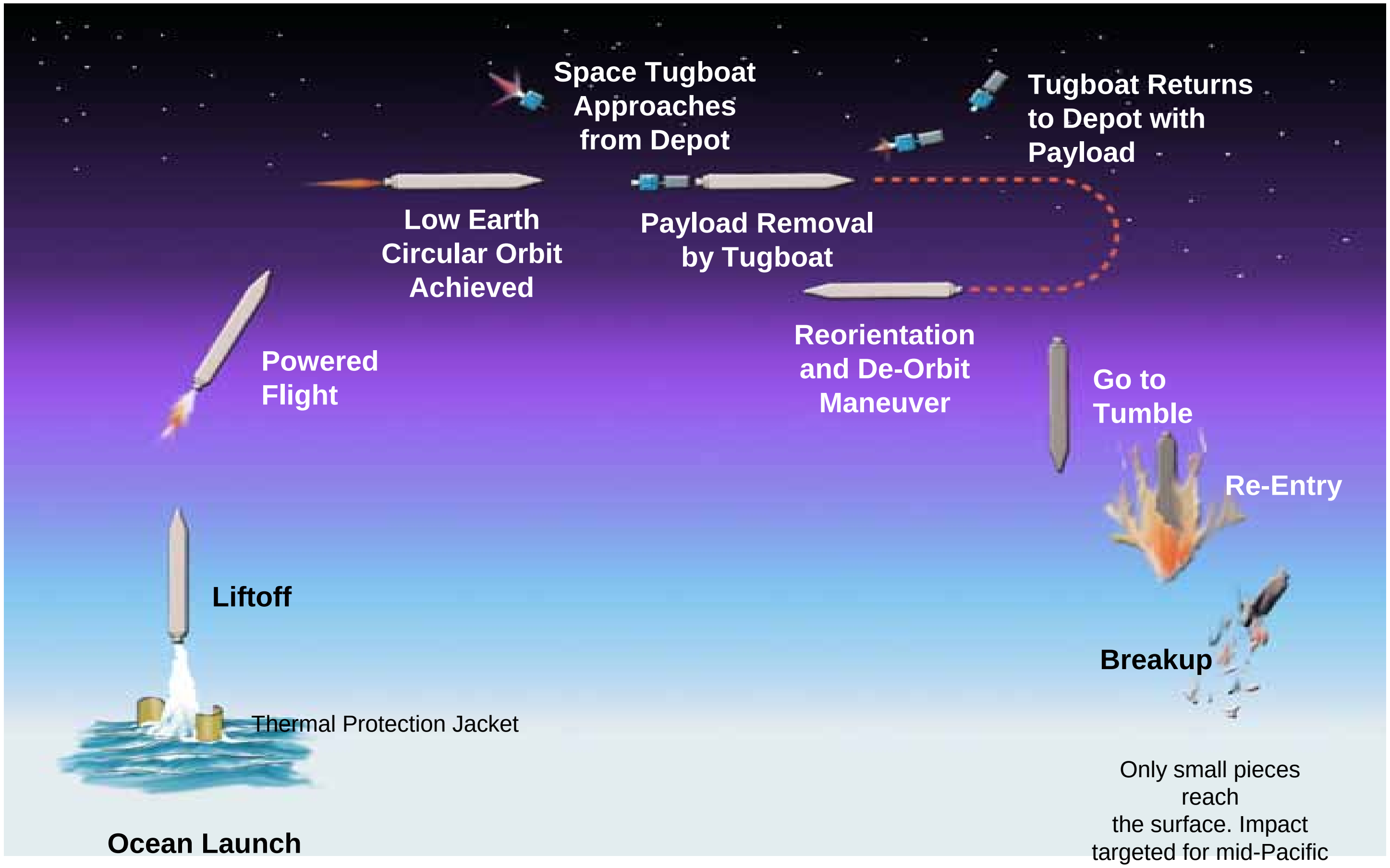
- Tank will be of similar design and construction to the graphite composite LOX tank used on the Kimbo-IV sounding rocket by Garvey Spacecraft launched on 3 June 2001
- Tank volume is expected to be about 20 liters and the total quantity of LOX appropriate to the size of the tank
- Duration of the test will be short since the LOX/GH2 mix would only be present under high pressure and moderate temperature for only a few minutes from propulsion system pressurization shortly before liftoff until main engine cutoff
- Concerns have been raised about the susceptibility of hydrogen-oxygen mixes to even modest inputs of energy. The interior of the test tank will of course not be illuminated, and no sensors will be used within the tank
- This test may be conducted at a facility in Santa Clarita, CA in which modest volumes of explosive mixes can be tested.

Hip Pocket Charts

Aquarius Mission Profile for launch of spacecraft



Aquarius Mission Profile for launch of supplies



Aquarius re-stocks a depot from which supplies can be brought to the Space Station or another user on demand. Launch can be made when it is cost-effective, not in response to demand. The response to demand is to provide items from depot stock to the end-user