Integrated Vehicle Fluids
A Combined Propulsion & Power System for Long Duration Spaceflight

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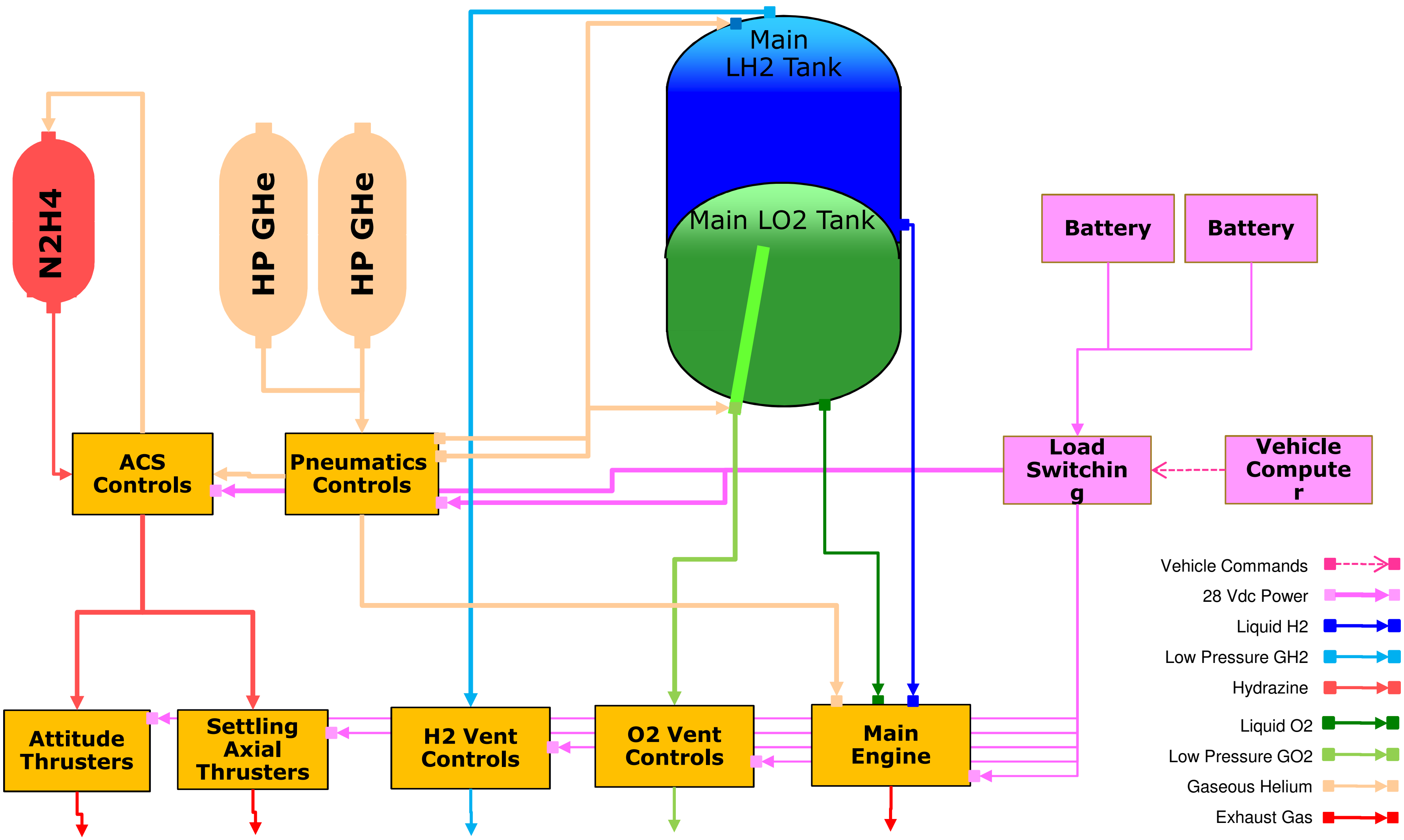
The Status Quo for In-Space Vehicles

- Independent power, attitude control, pressurization & vent systems
  - Discrete hardware with redundancy where tolerable for reliability
    - Separate storage for hydrazine, helium, hydrogen, oxygen
  - Independent, additive mass margins for working fluids
  - Individually optimized systems meet strictly bounded mission designs
    - Short duration, highly predictable engine burn times, duration & number
  - Minimal tolerance for hardware malfunction
    - Design focus on making hardware perfect & elaborate testing to assure it
    - Redundancy often compromises system function
  - Complex, safety-compromised, built-on-the-vehicle designs
    - Extensive installation labor, functional testing at top assembly
    - Hazardous ultra high pressure gases, toxic propellants, pyrotechnics
  - Require extensive engineering oversight
    - Tight margins demand elaborate mission analyses
    - Direct operational experience with flight hardware limited to brief acceptance tests

Architecture Assessment

- Dry mass roughly 15-20% of total vehicle
  - Scales directly with vehicle size, mission duration
- Brittle, point-designs with limited growth capability
- Much technology shared with no other industry
  - Hypergolic fluid loading, storage & delivery systems
  - Hypergolic thrusters
  - Single use batteries
  - Low-margin, high-capacity pressure vessels
- Small leakages, blockages or contamination potentially fatal
- Complex loading/activation processes
- Limited preflight hardware validation
- Shortcomings overcome by intensive engagement of large, highly skilled teams working under a highly disciplined control system

Typical In-Space Vehicle Systems Architecture



Technology Focus to Date

- Increase performance & reliability via:
  - Higher pressure, higher fluid density lightweight composite tanks
  - Simplified, no-friction valves, Improved assembly technologies
  - Less toxic propellants, high performance Lithium batteries
- Bottom line: Only marginal improvements can be attained with existing design approaches
  - Very high investment to realize these incremental improvements
  - Not attractive from an economics standpoint
- Biggest problem: aerospace-only solutions are built by mostly aerospace-only companies
  - High undiluted overheads, highly skilled engineering support systems
  - Low-rate production with often exotic, quality critical processes
  - Limited learning from real-world field experience
  - Inevitable high-costs

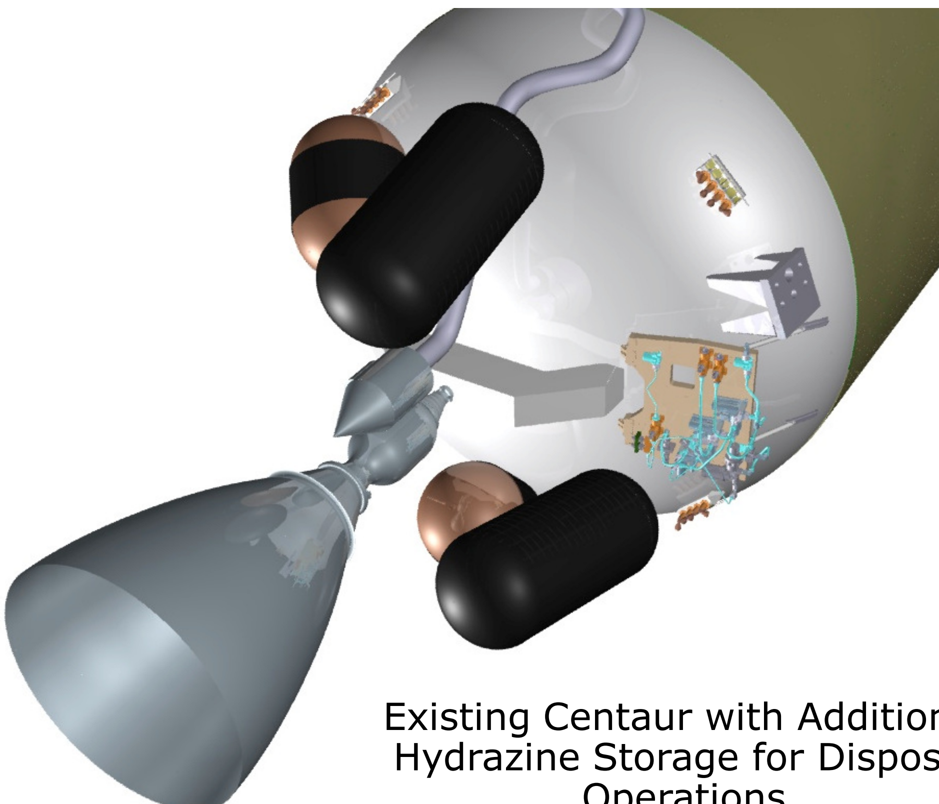
The Goals

- Slash costs by designing in the best possible system reliability
  - Get rid of GHe, Hydrazine, large Batteries & high pressures
  - Simple, commercial designs and materials, no toxic/hazardous operations
  - Extremely large functional margins, full block redundancy
- Amplify performance & mission capability
  - Performance increases of 10-20% of vehicle dry mass
  - Unlimited engine burns, low delta-V burns, built-in vehicle disposal
    - Enable disposal without cost or performance penalty
  - Eliminate restrictions to flight duration except by main vehicle propellants
- Support all likely future transport architectures
  - Anticipate larger thruster sizes, greater power demand, larger tanks
  - Enable depot based space transport
    - Vehicle replenishment, fluid transfer, thermal management
  - Support booster and upper stage re-use
    - Long system life, no-touch between flights, highest possible reliability

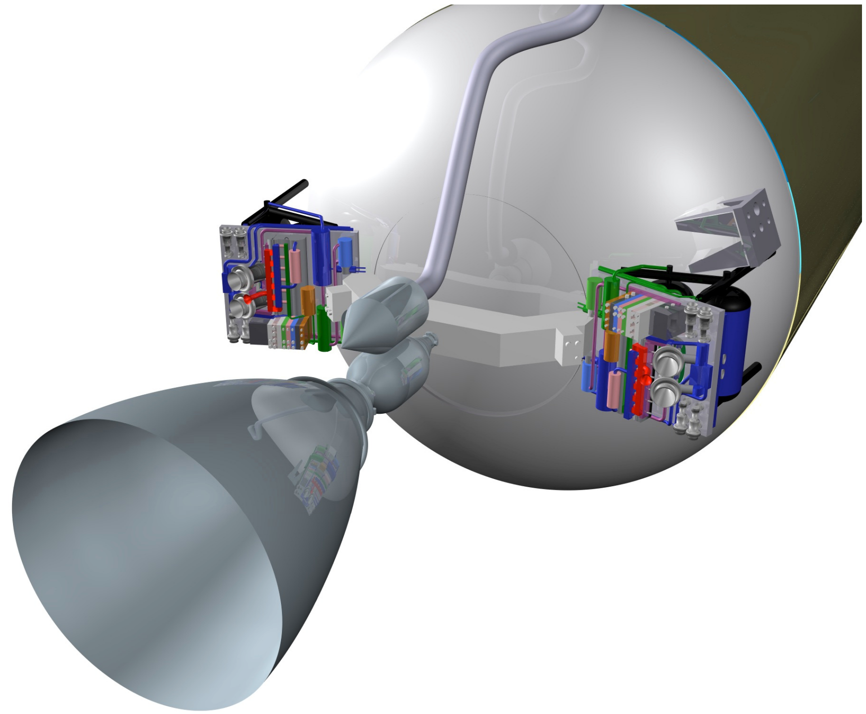
IVF Basic Concept

- Use only hydrogen and oxygen already on board for vehicle functions
  - Pressurization & Vent
  - Attitude control & Vehicle settling
  - Power
- Use waste gas whenever possible
  - H2 & O2 that would have been vented overboard on today's vehicle
- Use a small H2/O2 burning engine to provide power for all vehicle functions
  - Electrical power
  - Pump H2 & O2 up to moderate pressure as needed
    - Minimal storage capacity hence small residuals, low costs, low mass
- Block-redundant hardware to maximize margins and fault tolerance
- Eliminate risks from high pressures, leakage, material incompatibility, contamination, corrosion, short-life wearout
- Use hardware validated by non-aerospace industry experience
- Leverage companies with non-aerospace experience with critical hardware

The IVF Transformation

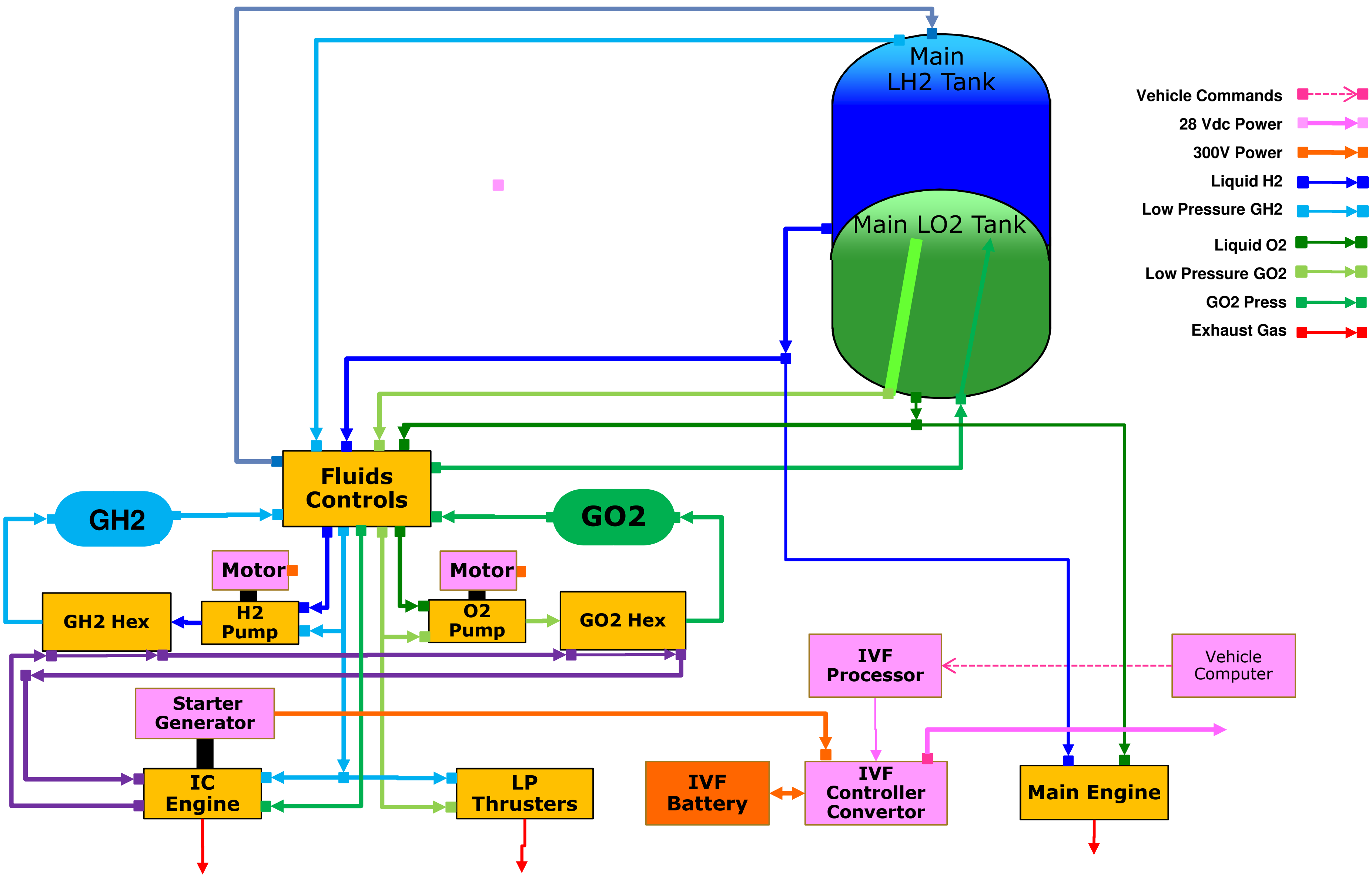


Existing Centaur with Additional Hydrazine Storage for Disposal Operations

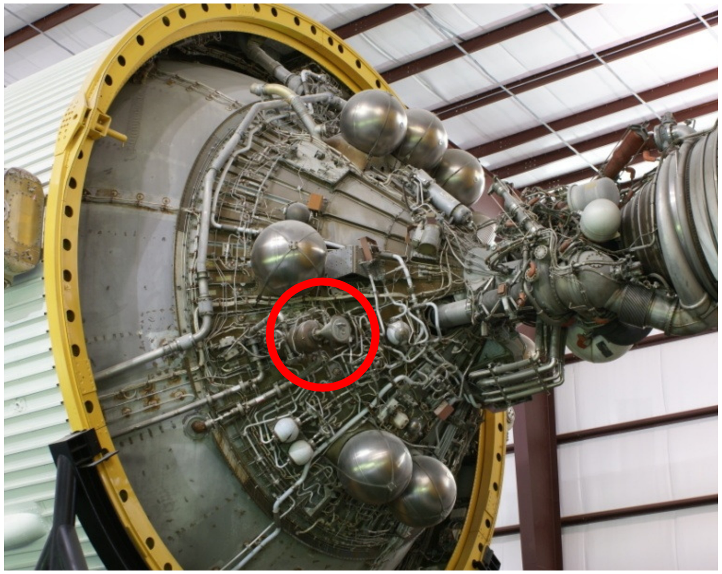


Centaur Converted to IVF
Approximate Liftoff Mass Benefit: 0.5t

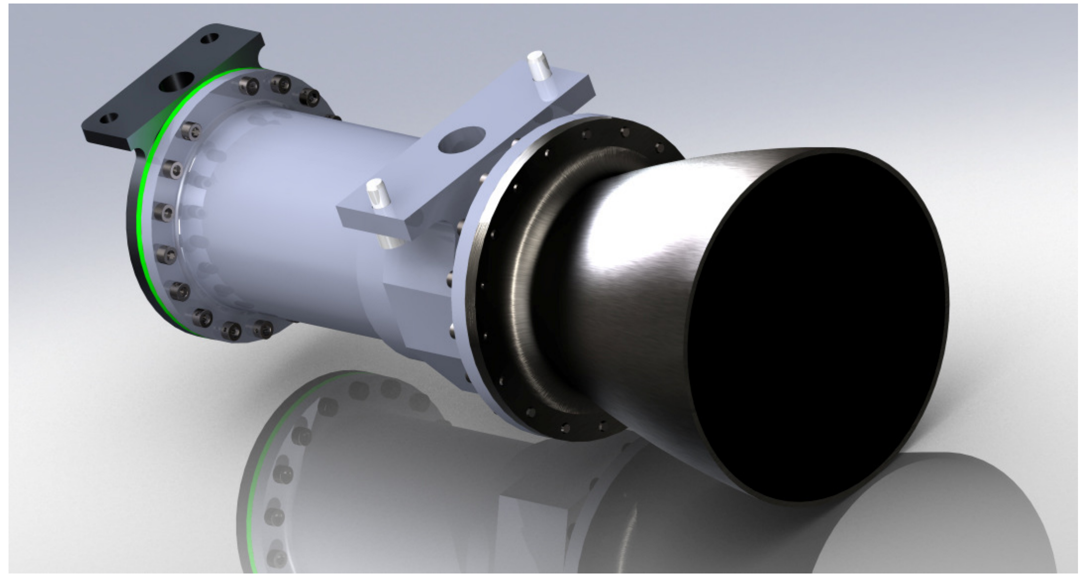
IVF Block Schematic

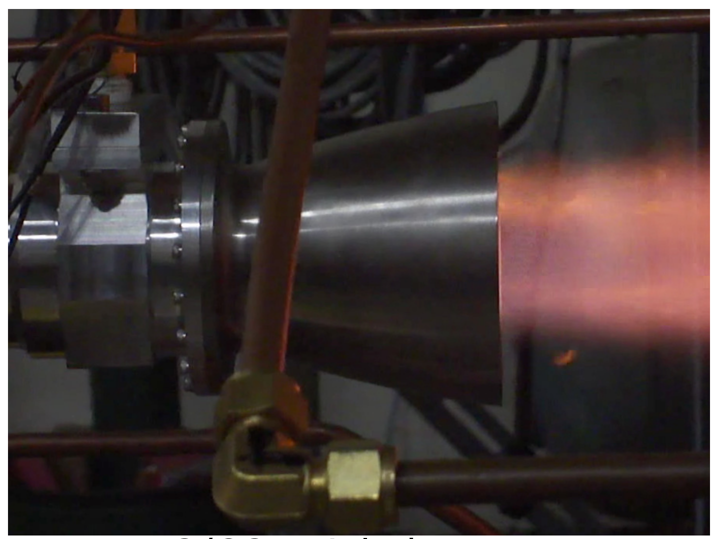


Thruster Hardware



Saturn S-IVB Ullage Burning
Settling Motor





H2/O2 Axial Thruster
Atmospheric Hotfire Testing

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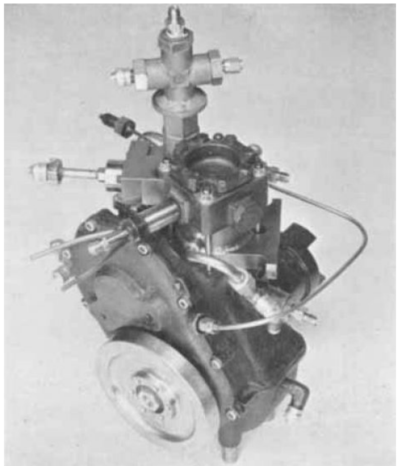
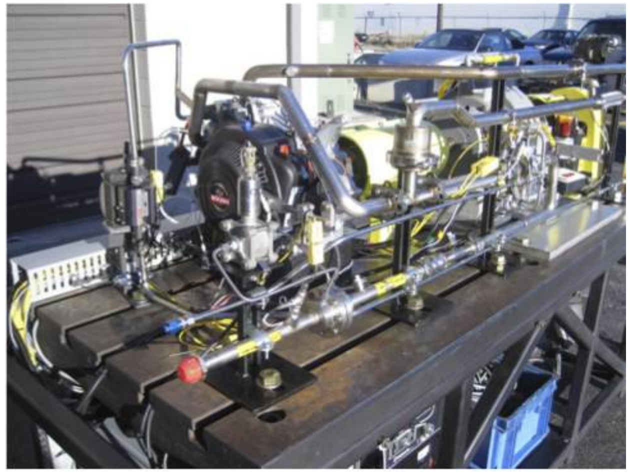
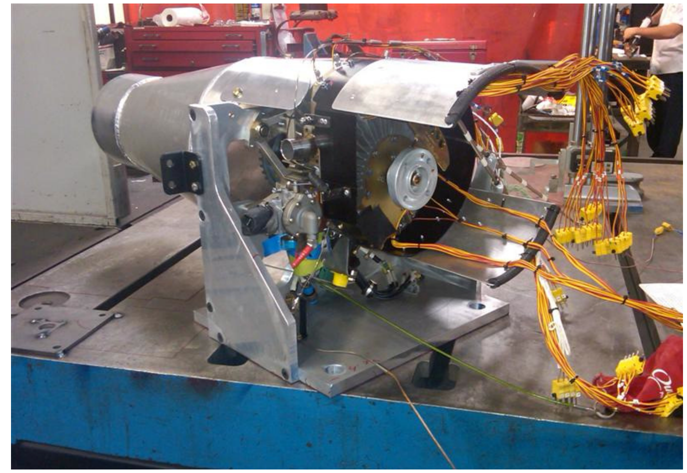
ICE/ ISG Hardware



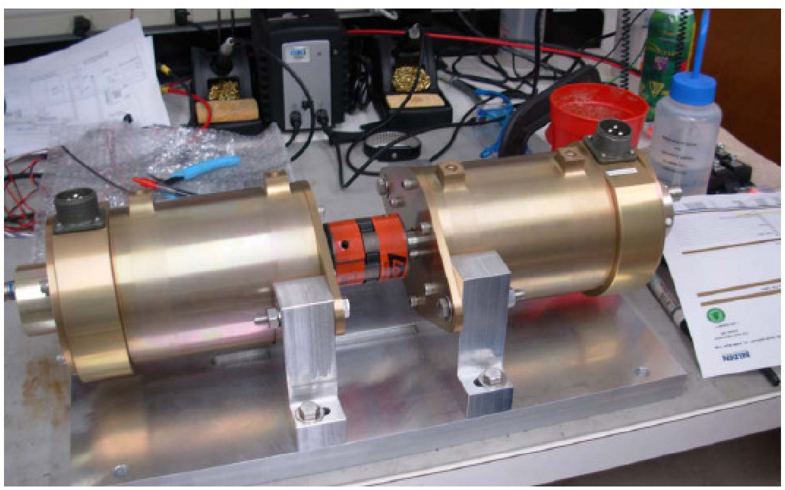
1965 Vickers H2/O2 Single Cylinder Engine



2010 Single Cylinder Engine on Dynamometer Test Stand



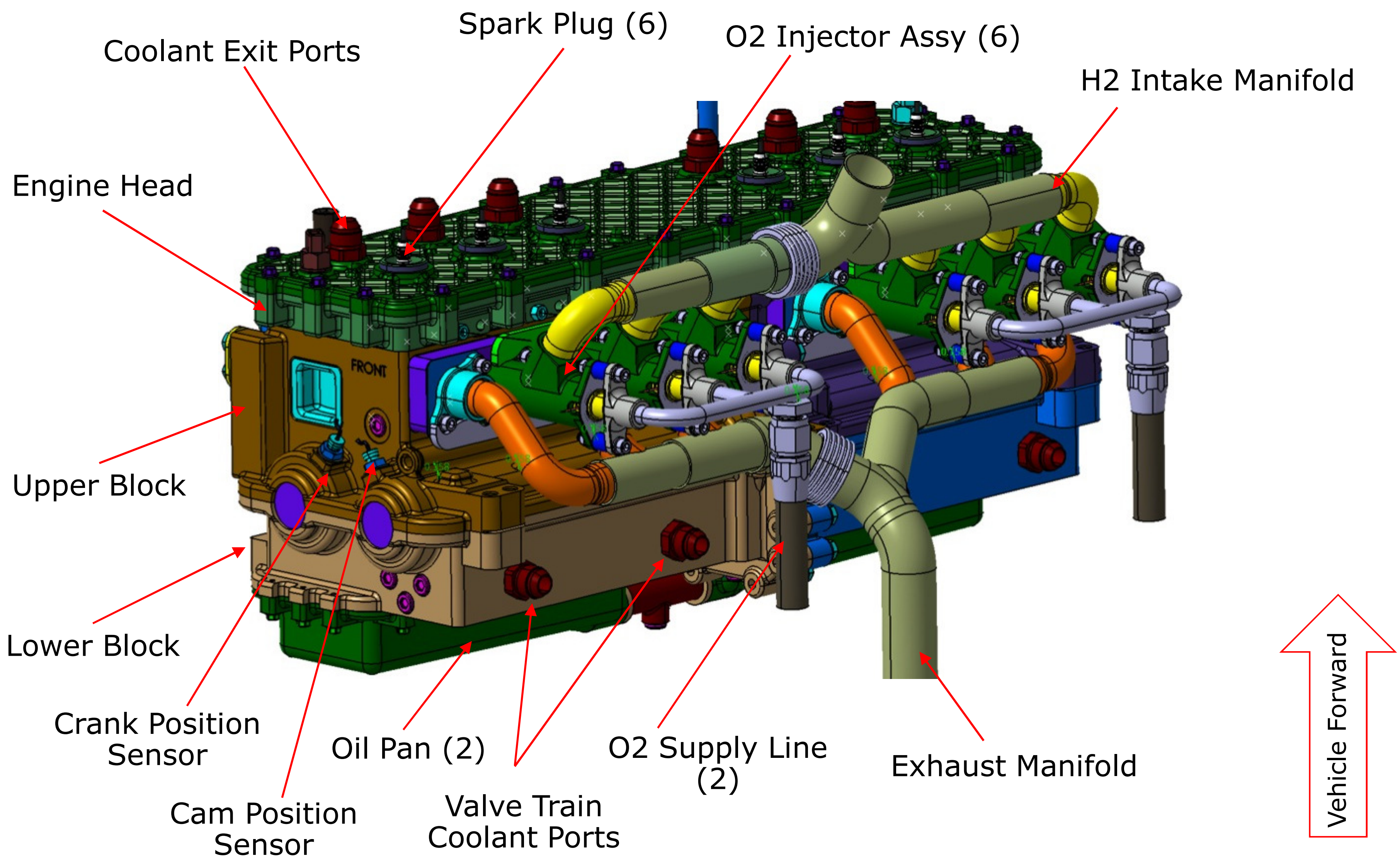
Wankel H2/O2 Engine Ready for Thermal Survey Testing



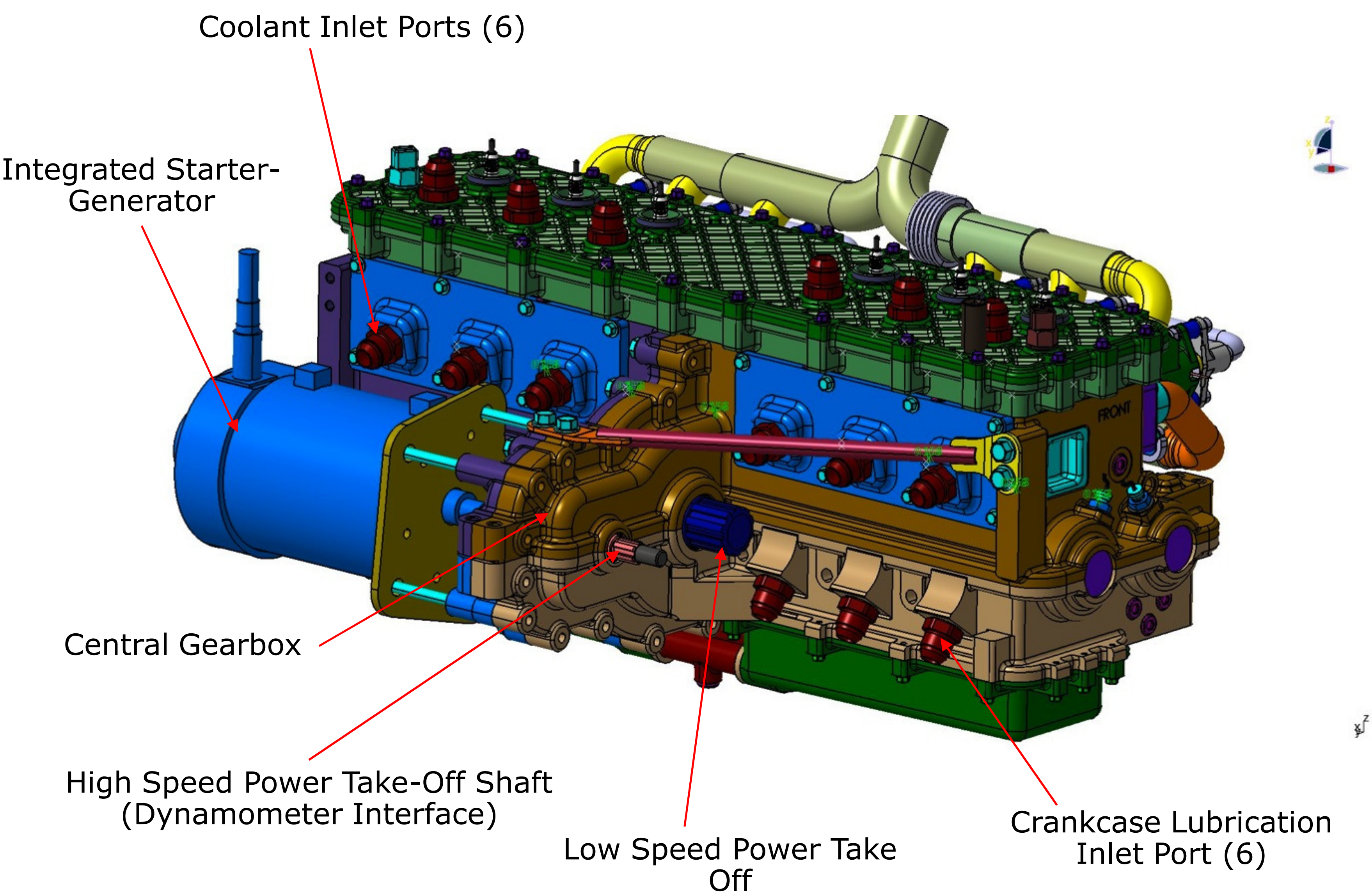
Back to Back Starter/Generators Ready to Test

Integrated Engine/Starter-Generator Load Simulation Testing

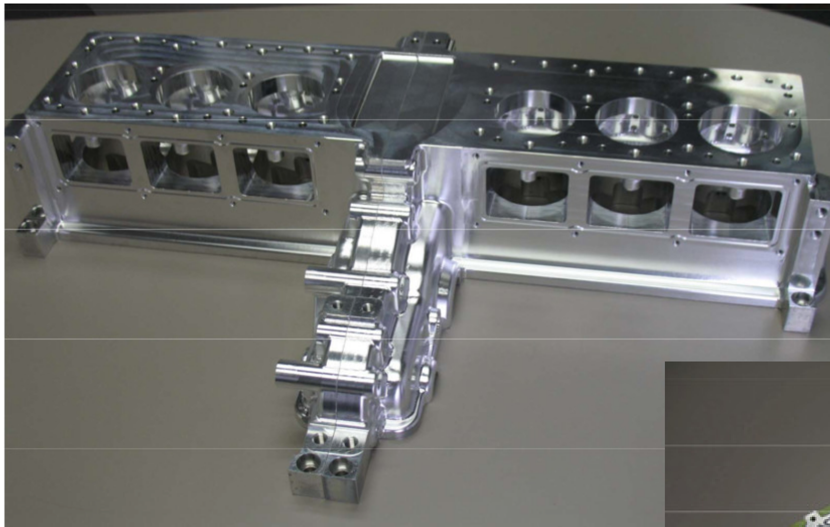
Gen1 IC Engine- Outboard View

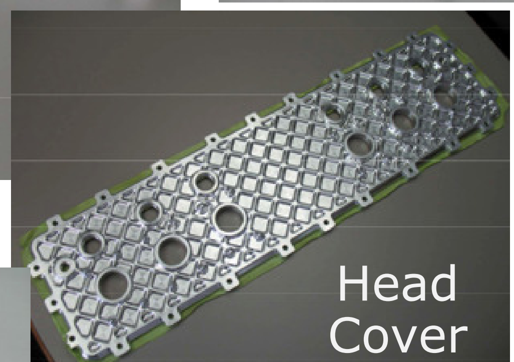


Gen 1 IC Engine- Inboard Side



Hardware Fabrication

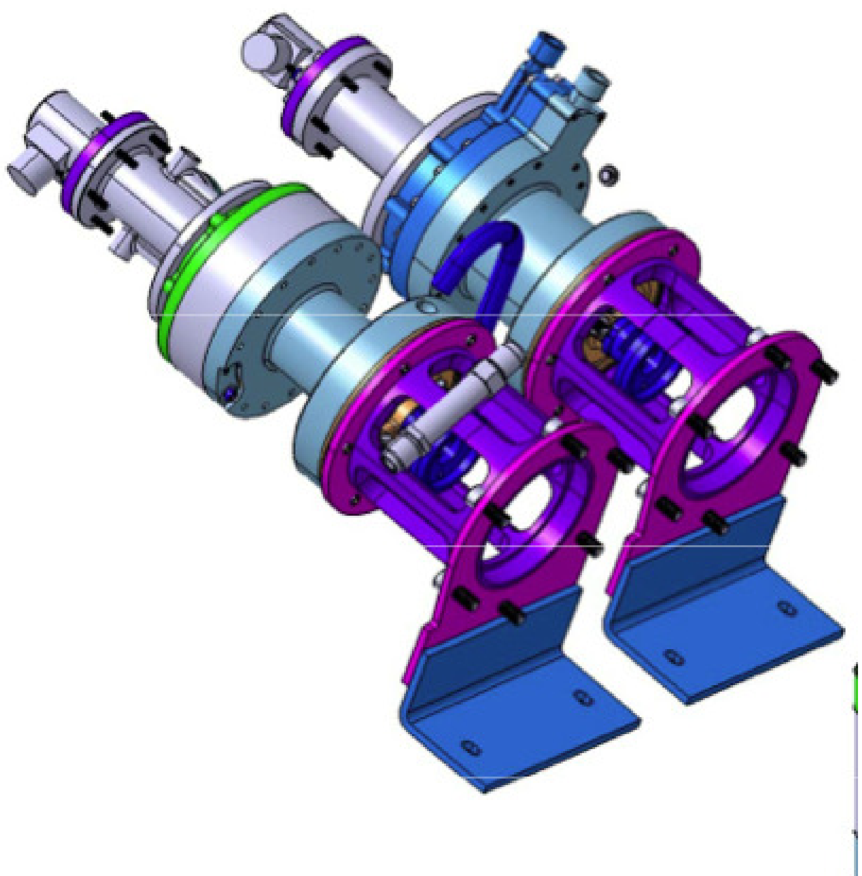




Cryopumps

Two-stage Generation 1 Design

- Leverages all prior learning
- Optimized for accelerated learning and experimentation
- Rapid hardware changeout
- Completely controllable piston motion via linear motor



IVF Foundational Ideas

- **Optimize overall vehicle design- not individual systems**
- **Store energy in one place- the main vehicle tanks**
  - **Lowest mass of hardware per energy unit**
  - **Minor energy storage in small rechargeable battery**
  - **Produce power, thrust, gases at need via simple machines**
- **Most energy is handled not as electricity but as heat**
  - **Moving/using heat efficiently more important than conversion efficiency**
- **Most mass savings come from reducing residuals/losses**
  - **Settling the vehicle is mandatory to suppress propellant losses**
  - **Controlling/reducing tank pressures starts a beneficial loop of reduced tank mass, propellant heating and propellant losses**
  - **System mass does not have to scale with vehicle size & mission complexity**
- **Elevated voltage power is a powerful tool**
  - **Lighter hardware, new device types, commonality to real-world hardware**
- **Batteries & engines sharing electrical loads benefits both their designs**
  - **Reduced mass, simplified controls, high peak capacity**

United Launch Alliance

Summary

- IVF shows a path forward to new levels of cost, reliability & capability
  - 3-Burn Centaur Flight benefits exceed 10% of dry mass
- Benefits existing vehicles but is a powerful design tool for next generation vehicles & especially crewed vehicles
  - Long operational flight duration, compact, light & modular
  - Extremely high peak power output dovetails with cruise solar power
  - Components valuable for depots, active cooling systems, in-situ propellant synthesis
  - Removable, simple and repairable in-situ with common tools
  - Components made of common materials, everyday processes
  - Works with methane & other propellants