Feasibility of Developing a Refrigerant-Based Propulsion System for Small Spacecraft

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Small Satellite Conference

August 14th 2007

UMR UNIVERSITY OF MISSOURI-ROLLA

THE UNIVERSITY OF TEXAS AT AUSTIN

Washington University in St. Louis

AIR FORCE RESEARCH LABORATORY

Outline

- Background
- Propulsion system requirements
- Propellant selection
- Engineering modeling
- Safety assessment
- Design application
  - University of Missouri - Rolla
  - University of Texas at Austin
  - Washington University in St. Louis

Background

- Small spacecraft < 100 kg
- AFRL / AFOSR / AIAA University Nanosat Program
- Nanosat 4 competition concluded March 2007
- Research collaboration – Feasibility study / safety assessment:
  - University of Missouri – Rolla
  - University of Texas at Austin
  - Washington University in St. Louis
- Collaboration goals:
  - Assess feasibility of using a refrigerant propellant in space
  - Assess feasibility/safety of exceeding sealed container status

Propulsion System Requirements

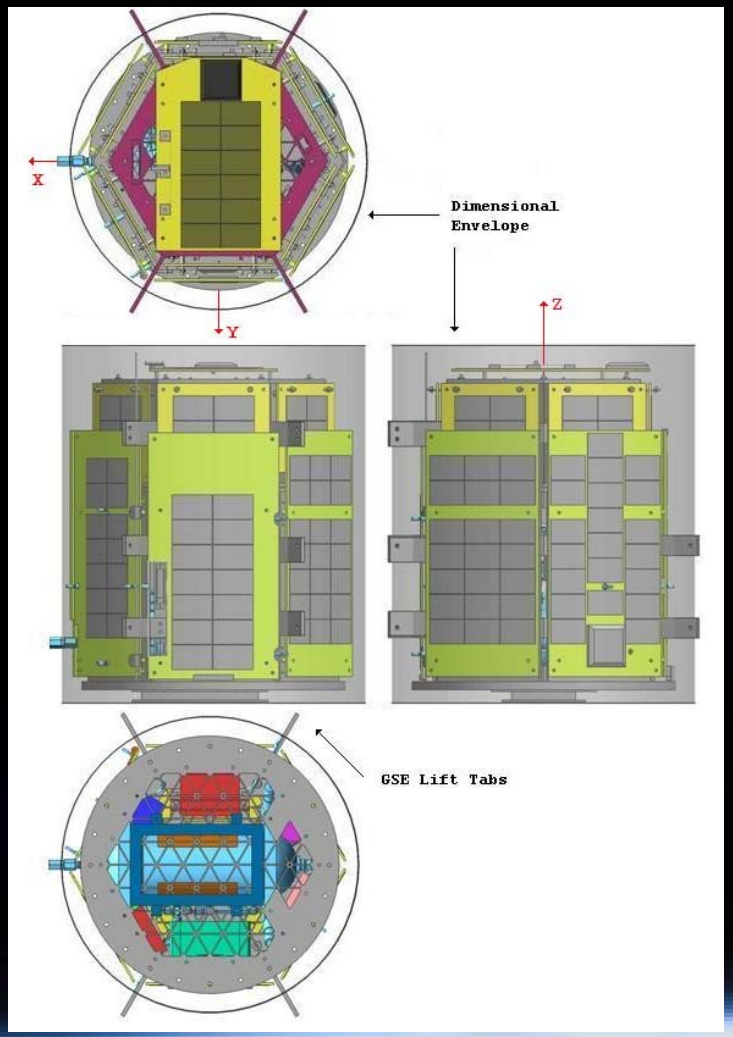
UNP requirements:

- Space Shuttle payload design
  - Most stringent requirements for spaceflight
- Sealed container requirements
  - *P* – Absolute Pressure ≤ 100 psia (689.48 kPa)
  - *U* – Internal Energy ≤ 14,240 ft-lbs (19,310 J)
  - Otherwise it is categorized as a pressure vessel
- To improve performance and meet objectives it was necessary to violate these sealed container requirements and request a waiver for the UNP competition
- Pressure vessel status can be deemed safe

Spacecraft System Requirements

- Dimensional constraints
  - 47.5 x 47.5 cm cylinder
- Spacecraft mass limitation
  - Total 30 kg

- Team requirements (typical)
  - Orbit control
  - 3 axis attitude control
  - Formation flight time
  - Integration
    - Structural
    - Power
    - Command and control



System Desired Attributes

- Low budget, utilizing commercial off-the-shelf components
- Low storage/operating pressures
- Minimal volume/size envelope
- Rapid development – 2 years
- Proven and easy to implement technology without significant prior research

Desired Attributes for the Propellant

- Nontoxic / non-flammable
- Safe and easy laboratory handling procedures
- Environmentally friendly
- Easily obtainable without the need for licensing or permits
- Simple storage requirements
- Easily transportable
- Compatible and chemically inert with common spacecraft materials

Trade Studies

- Cold gas / chemical / electric system trade off
  - Safe and practical solution → cold gas
- Saturated liquids in space
  - Higher mass storage capability
  - Utilize vapor as a common cold gas
  - SPHERES liquid CO_2
  - SNAP-1 liquid butane
  - Can-X liquid sulfur hexafluoride (SF_6)
- Refrigerants in space
  - Space Shuttle orbiter: freon-21
  - Pioneer 10 and 12: freon
  - No documented uses of a refrigerant having been used as a spacecraft cold gas propellant

Propellant Selection Process

Max conditions: 100 psia / 100 °C / 19.31 kJ
Operating conditions: 30 psia / 20 ° C
Spacecraft mass: 25 kg

Propellant	Specific Impulse (I_{SP}) s	Change in Velocity (ΔV) m/s	Critical Temperature °C	Saturated Vapor Pressure @ 20 °C psia (kPa)		Liquid Density kg/m^3
R-134a	48.52	1.15	100.9	82.98	(572.1)	1150
R-123	31.60	1.24	183.86	10.98	(75.71)	1460
H_2O – Water	132.8	2.02*	374	0.338	(2.33)	998
SF_6 – Sulfur Hexafluoride	41.79	1.38	45.5	304.72	(2101)	1880
C_4H_{10} – Butane	65.09	0.91	134.9	43.8	(302)	556
Xe	30.44	0.89	16.5	-		3057
CO_2	64.38	0.63	31.0	830.92	(5729)	763
Ar	55.53	0.48	-122.3	-		1400
N_2	75.58	0.47	-146.9	-		809
NH_3 - Ammonia	101.43	0.39	132.35	124.4	(857.8)	682

Propellant Selection Process

EPA Regulations and Legality

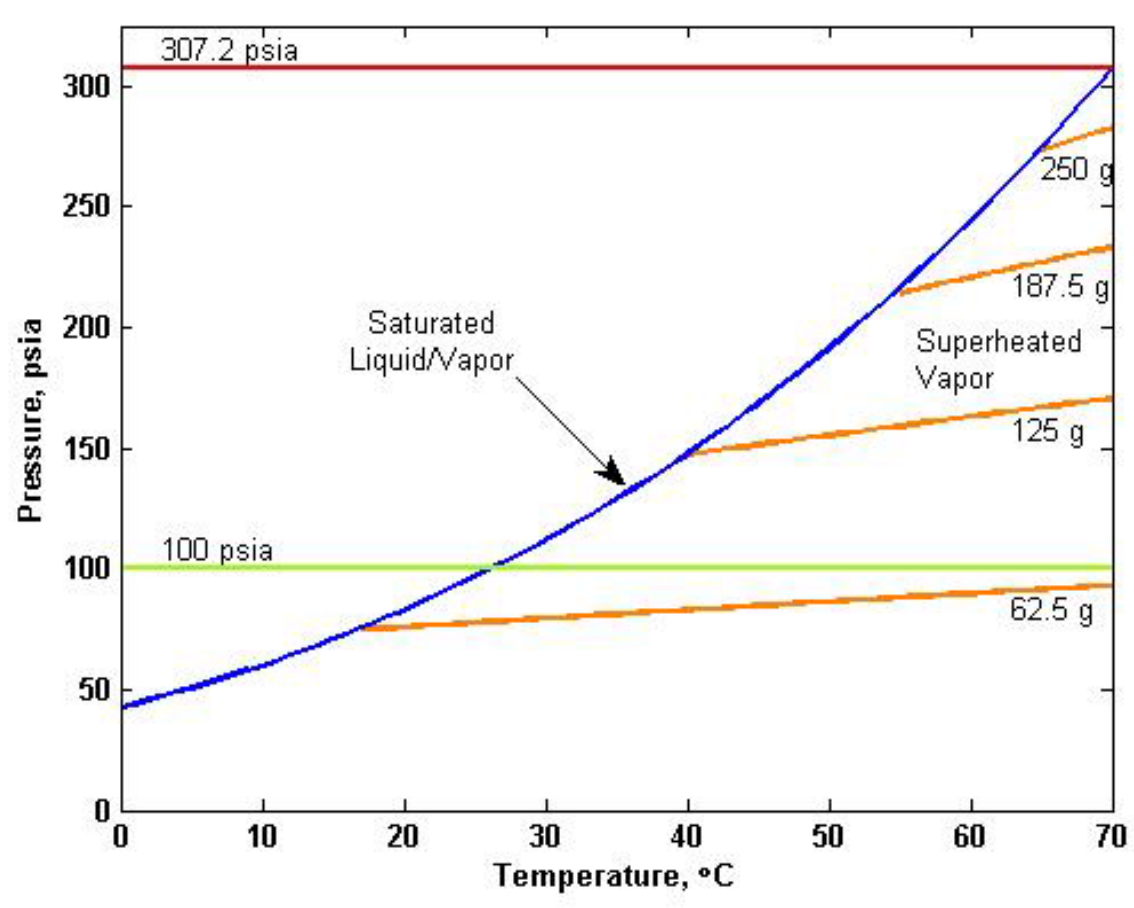
- R-123 – HCFC
  - EPA definition: Class II substance
  - Sale and production illegal after 2015
  - License restrictions
- R-134a – HFC
  - EPA definition: Alternate refrigerant
  - Friendlier to environment and humans
  - No restrictions on small quantity purchases
  - Release as a refrigerant must be recaptured

Hardware Compatibility

- Seals need to be compatible and meet outgassing regulations
- Use seals only when absolutely necessary
- R-134a has limited compatibility data

Two-Phase Dimensional Application

R-134a Pressure and State Envelope – 2.5 L Tank



Refined Engineering Model (R134a)

Maximum Tank Pressure at 70 ºC psia (kPa)		Propellant Mass g	Internal Energy kJ	Total Thrust Exhaust Duration min	Change in velocity ΔV m/s
100	(689.5)	67.6	19.1	7.9	1.05
200	(1379.0)	152.7	42.0	17.9	2.38
300	(2068.4)	277.0	72.9	32.5	4.33
307.2	(2118.2)	1388.9*	229.0*	162.9*	22.2*

Spacecraft mass: 25 kg

Operating conditions: 30 psia / 20 ° C

*Calculated with an initial tank propellant quality of 10%

Safety Assessment

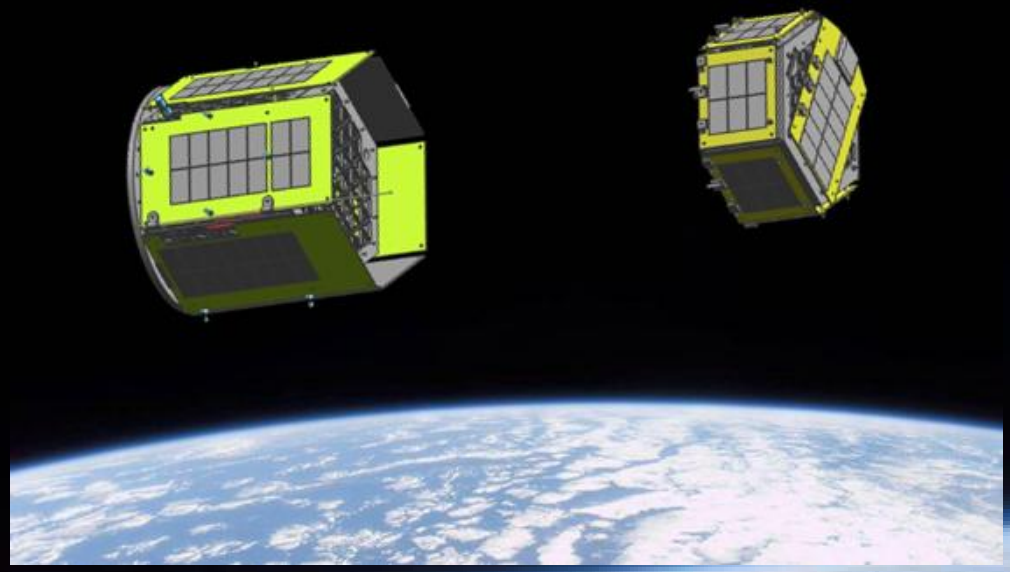
- Aim
  - Ensure the propellant will operate within the guidelines set by the university developers
  - Identify and classify hazards associated with the propellant, the risks assessed and mitigating solutions found
- Identification
  - Qualitative analysis of a general system using a two-phase propellant
  - Focused on worst-case conditions
- Classification
  - **Catastrophic** - A catastrophic hazard is defined as any single or multiple system failure which has the potential to cause damage/harm not only to the spacecraft, but to surrounding equipment/personnel as well
  - **Critical** - A critical hazard is defined as any system failure which results in damage/harm to the spacecraft and/or has the potential to negatively impact mission objectives to the point of failure
  - **Tolerable** - A tolerable hazard is defined as any system failure which results in minimal damage to the spacecraft/mission

Safety Assessment

- Acceptable Risk for Flight
  - Defined as operating the system with known hazards classified as tolerable or with hazards which can be mitigated by use of the appropriate safety devices and measures
- Catastrophic hazards
  - Temperature rise / latent heat effects
  - Thermal expansion / fatigue
- Critical hazards
  - Propellant freezing
  - Chemical reactivity
- Tolerable hazards
  - Asphyxiation and skin irritation to personnel

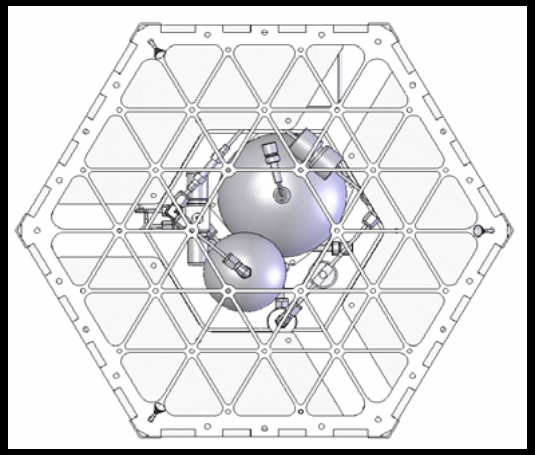
University of Missouri - Rolla

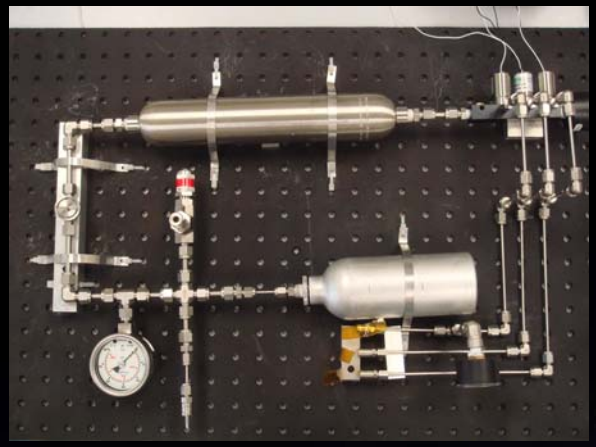
- Satellite pair - MR and MRS SAT
- Study autonomous formation flight 50 m ± 5 m

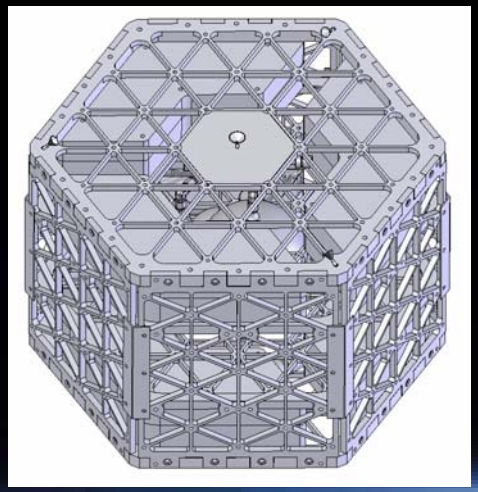


University of Texas at Austin

- ARTEMIS – Satellite pair
- Separate on-orbit and autonomously rendezvous within a target distance of 50 m

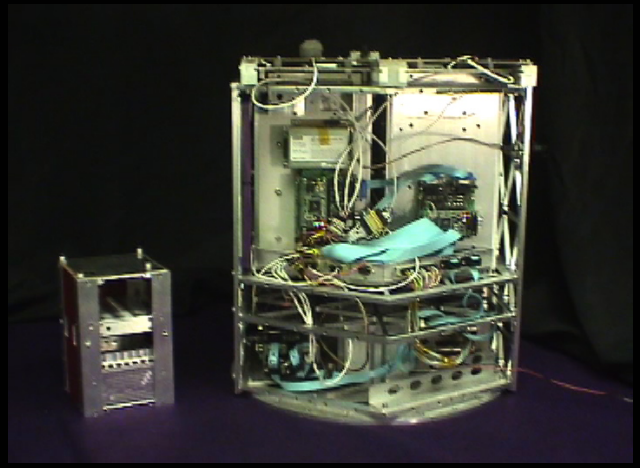


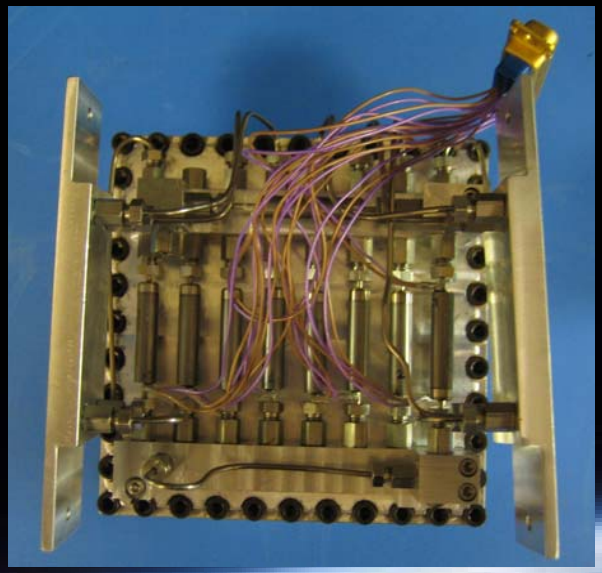


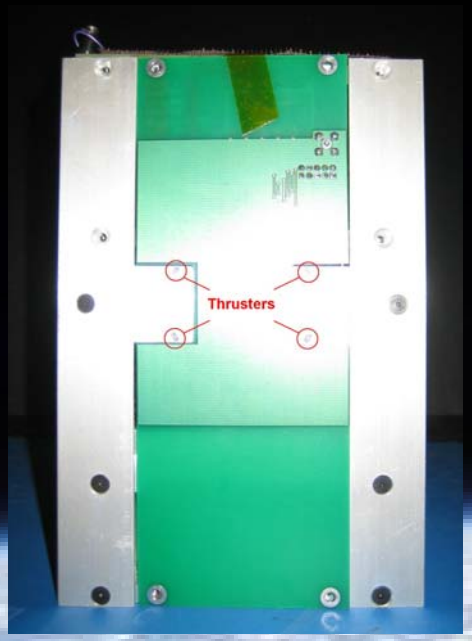


Washington University in St. Louis

- Two spacecraft
  - 3 kg free-flyer (Bandit)
  - 29 kg host (Akoya)
- Flight-test proximity operations technologies, including:
  - Repeatable docking
  - Navigation within 5 m of a target
  - Image-based navigation





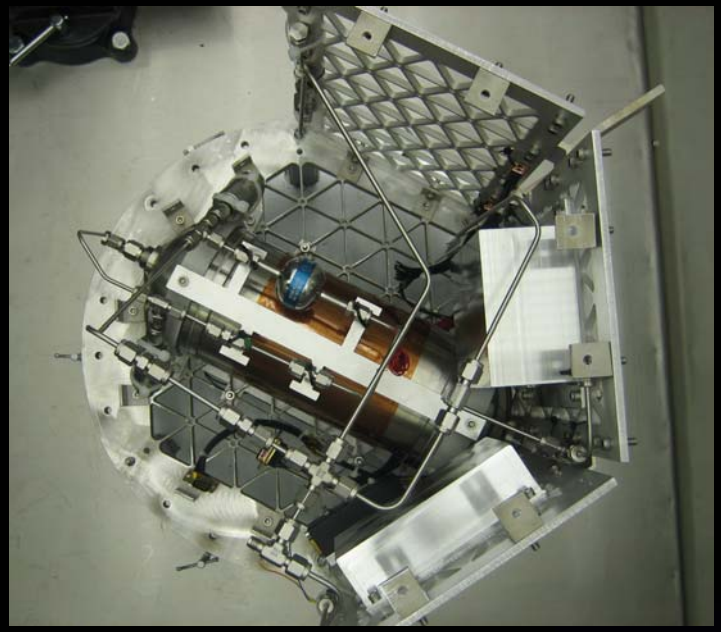


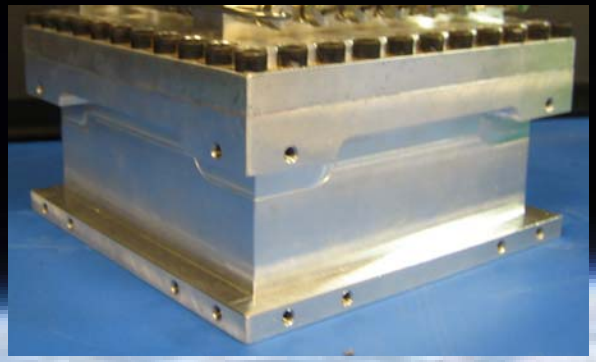
Summary - Small Spacecraft Propulsion Solution

Universal design methodology

R-134a provides:

- A feasible propellant option for small spacecraft
- Can be safely operated above the sealed container status
- Safe and practical for low-budget developers
- Allows easy system development and test
- Performance comparable to traditional cold gas propellants





Questions ?

SSC07-III-4 “Feasibility of Developing a Refrigerant-Based Propulsion System for Small Spacecraft”