National Aeronautics and Space Administration

Summary & Status of Green Monopropellant Power Units at MSFC

marshall

Joel Robinson / MSFC

Apr 23, 2019

Agenda

- NASA Interest
- Air Force Interest
- Green Propellant Choices
- NASA/MSFC Testing Results
- Green Propellant TIM Summary
- SERDP Scope
- DLA Scope
- Proposed Future Scope
- Conclusion

What's in a name?

- What is "Green" Propellant?
  - Are there environmental issues with production?
  - How well does it transport/off-load?
  - What are the bi-products of combustion?

- Performance and Characteristics:
  - Storable Liquid monopropellant
  - High Specific and Density Impulse
  - Good pulse performance

- Safety:
  - Low Sensitivity & Toxicity
  - Non Carcinogenic
  - Environmentally Benign

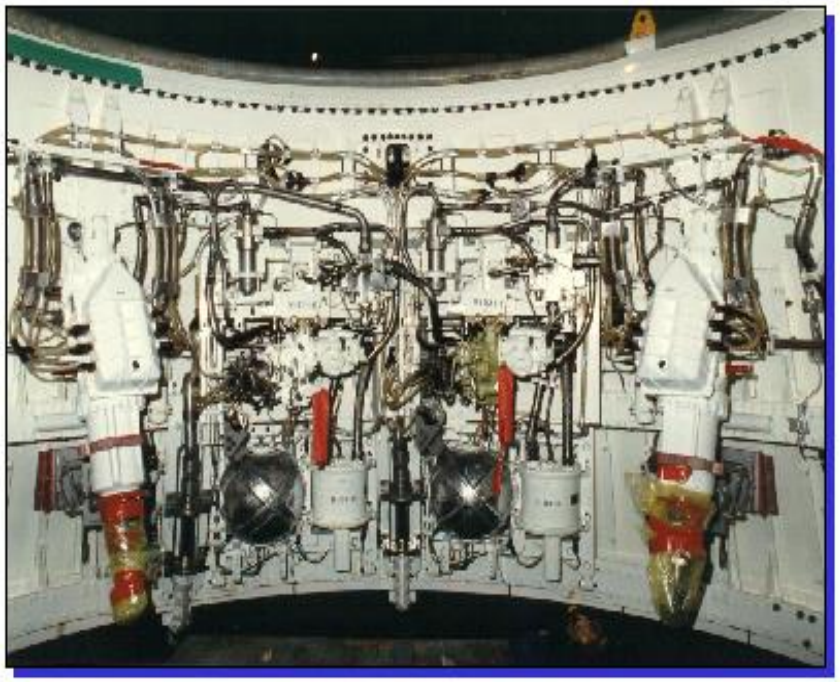
- Lower overall mission cost:
  - Easier to handle and transport
  - Compatible with available COTS

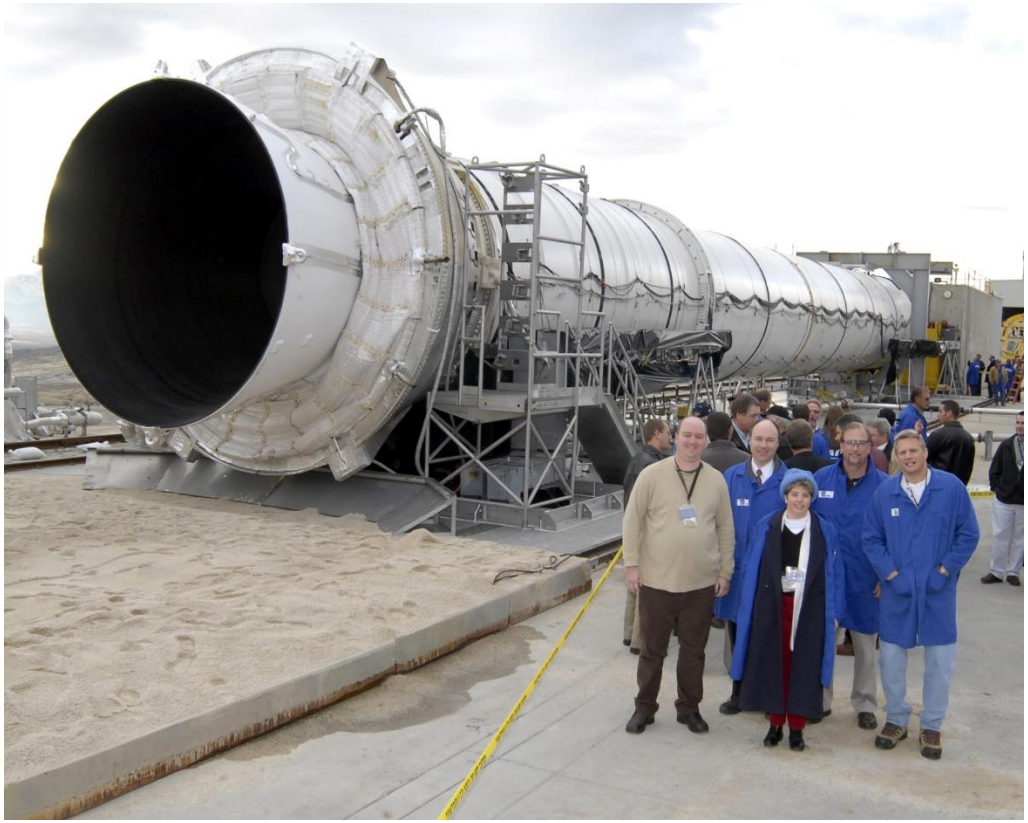
Introduction

- NASA is pursuing use of green monopropellant alternatives to Hydrazine.
- The 2 leading green props are the LMP-103S and the AF-M315E.
  - The Swedish PRISMA mission was launched in 2010 and ECAPS has flown multiple spacecraft from the US (Skybox sats and STPSat-5).
  - The AF propellant is scheduled to fly on the NASA funded GPIM spacecraft this year.
- While the Agency and its Field Centers have been concentrating on thruster technology, I began in 2012 to focus on power unit applications.
- For the Space Launch System, the Program will continue to use Hydrazine for gimballing during the first 2 minutes of flight.
  - I focused activities on the use of the F-16 EPU as surrogate hardware.
- This briefing will summarize the path and results of MSFC testing for full scale, F-16 EPU hardware obtained from DMAFB.

Shuttle Heritage Auxiliary Power Unit

- Three APU's flew on each Shuttle and provided vehicle power on ascent and descent (activation of cargo bay doors).
- A pair of APU's were located in the Aft Skirt of each SRB for gimbal of nozzles.





Motivation for Green Propellant

- In January 2012, NASA released a Technology Demonstration Mission (TDM) synopsis focused on hydrazine replacement.
  - Beyond performance improvements, green prop offers safety enhancements (no SCAPE).
  - Demonstrations could include launch vehicle power generation via ground testing.

- One of the proposals submitted was to demonstrate application of green prop to APU systems while minimizing design changes to existing APU hardware.
  - The 2 leading green propellants require their own, unique catalyst material for maximizing performance characteristics.
  - Both propellants also require catalyst bed heating for spacecraft thruster operation.

- While MSFC was not selected for TDM funding, the Center continued to make internal investments in the area of green propellant power units.
  - Acquired F-16 EPU's from Davis-Monthan AFB and tanks from Hill AFB.
  - Obtained Shuttle-heritage hardware from KSC and WSTF.

- By Dec 2013, MSFC awarded Center Innovation Fund money to investigate USAF green prop testing in an F-16 EPU gas generator.
  - Can a heated green propellant be operated with the H-70 catalyst material?

USAF Interest

- Based on discussions with the F-16 SPO in 2012 (Paul Hoth and Mary Wyderski), they had expressed interest in a green “drop-in” replacement.
- Recent SPO discussions have suggested minor modifications to existing platform may be allowed.
- Compared to the current use of H-70, green propellants could result in reduced environmental impacts and associated costs:
  - reduced potential for harmful worker exposure and health screening costs
  - labor for inspection and maintenance of PPE and propellant trailer
  - training related to occupational health requirements
  - hydrazine response team training/monitoring
  - shipping costs for tanks and H-70, and disposal costs
- There are 25 domestic & 5 international F-16 bases and 11 hydrazine refueling locations.
  - Significant cost savings could be attained as existing fire departments can respond to green propellant EPU activations and spills.
- Potential to use for the U-2 Emergency Start System.

Potential replacement to Hydrazine

Performance/Environmental/Safety Challenge

Hydrazines are SOTA spacecraft fuel:

- Increased Operations Costs:
  - Carcinogenic Vapor (Respiratory Route)
  - Dermal Toxicity
  - Strong Reducing Agent
  - Flammable (LEL = 4.7%, UEL = 100%)
- On-Orbit Propulsion Systems Affected

System	Mission
FltSatCom	Communications
STARDUST	Deep Space Probe
INTELSAT	Communications
HEAO-B	X-Ray Astronomy

- Hundreds of Satellites Use Hydrazine for RCS & ACS

2011 Tommy Hawkins/AFRL Briefing to Partners in Environmental Technology Conference

Hawkins cont'd

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'Greener' Chemical Propulsion- ILs in Advanced Monopropellants

ADN (M.P. 92°C) is also an Energetic Ionic Liquid

- ADN-based monopropellant (LMP-103S) from ECAPS, Swedish Space Corporation
- High performance 'green' propellant (30% Improved Isp*Density vs. hydrazine)
- 1 N Thruster using thermal and catalytic ignition flight qualified and flown (PRISMA)

AF-M315E is US Air Force IL-Based Monopropellant

- Significant physical property and performance advantages (50% improved Isp*Density)
- Ongoing hardware developments

Constituents	Weight %
ADN	60-65
Methanol	15-20
Ammonia	3-6
H_2O	balance

* Sjoberg et.al., Insensitive Munitions & Energetic Materials Technology Symp. Proc.,Tucson, USA, May 11-14, 2009

Properties	LMP-103S	AF-M315E	Hydrazine
Isp_{vac},lbf sec/lbm (e = 50:1 Pc = 300 psi)	252 (theor.) 235 (del)	266 (theor.) ~ 250 (del)	242 (theor.)
Density , g/cc	1.24	1.465	1.01
Vapor Pressure (torr)	Ammonia Methanol H_2O	<0.1 (w/o H_2O)	14.3

* Hawkins et.al., Proc. 4th International Association for the Advancement of Space Safety, Huntsville AL, 19 May 2010; Hawkins et.al., Proc. Fourth International Conference on Green Propellants for Space Propulsion, Noordwijk, The Netherlands, 20-22 June 2001.

MSFC Testing of Green GG

- Of the two leading green propellants, the Air Force prop burns hotter.
  - So a watered-down version was chosen to emulate a blend similar to H-70 to obtain lower combustion temperatures.
- MSFC worked with AFRL/Edwards on modifying the prop.
  - Conducted mini-pino tests followed by ignition delay.
- MSFC never tested any version of the LMP propellant but would like to in the future.

Agreements Reached with AFMC

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS OGDEN AIR LOGISTICS CENTER (AFMC)
HILL AIR FORCE BASE, UTAH

11Apr 2012

MEMORANDUM FOR NASA/MSFC/ZP31
ATTN: Mr. Joel Robinson

FROM: OO-ALC/GHBWB
6061 Gum Lane, Bldg 1224
Hill AFB, UT 84056-5826

SUBJECT: Request for F-16 Emergency Power Unit (EPU) Availability for possible future NASA Demonstrations and Testing

1. In an effort to help support NASA with a possible cross cutting effort to replace the current hydrazine propellant with a "green" propellant that would be safer and more cost effective, USAF agrees to provide two F-16 EPU systems for demonstrations and testing from aircraft that are earmarked for disposal at the Aircraft Maintenance and Regeneration Group (AMARG).

2. The hardware contributed to this activity is $311,475.02. NASA project team is responsible for costs associated with purging, cleaning and shipping of the hydrazine tanks, which are located at Hill AFB, UT. The hydrazine shipping caskets will need to be returned. The total shipping cost will be an estimated $433. The estimated purge and clean cost is $3168. The 309th AMARG labor costs are not included.

3. The parts will be in "As is, Where is" condition, since we do not have testing capability at AMARG. By providing these assets, it does not obligate the DoD, USAF or the F-16 System Program Office (SPO) to any costs incurred by this testing nor any follow-on support to the reclaimed assets.

4. For additional information, please contact Nettie Marsh, OO-ALC/GHBWB, 801-777-0133 (DSN 777-0133) or nettie.marsh@hill.af.mil.

//Signed/nfm//
NETTIE F. MARSH
F-16 SPO Fleet Manager

DEPARTMENT OF THE AIR FORCE
309TH AEROSPACE MAINTENANCE AND REGENERATION GROUP (AFMC)
DAVIS-MONTHAN AIR FORCE BASE, ARIZONA

10 Apr 2013

MEMORANDUM FOR Joel W. Robinson, NASA, MSFC/CS10

FROM: 309 AMARG/OB
4860 S. Superior Ave.
Davis-Monthan AFB, AZ 85707-4305

SUBJECT: 309 AMARG Project Estimate for Reclaiming and Preparing to Ship Two (2) Each F-16A EPUs

1. The estimated cost to complete the project is $ 8,025.00. This estimate refers to the project described in the attached agreement and/or Statement of Work (SOW) as applied to standard industrial practices. It is meant to be an estimated cost of the project barring any changes in the scope of work.

2. Scheduled start and completion dates of April 29, 2013 and May 31, 2013 respectively are contingent upon applicable resources being positioned and funds being received by 309 AMARG prior to April 22, 2013. The cost includes the estimated hours and material to complete the project and a mandatory 9.4% surcharge determined annually by the Office of the Under Secretary of Defense for unfunded civilian retirement, post-retirement health benefit and post retirement life insurance costs.

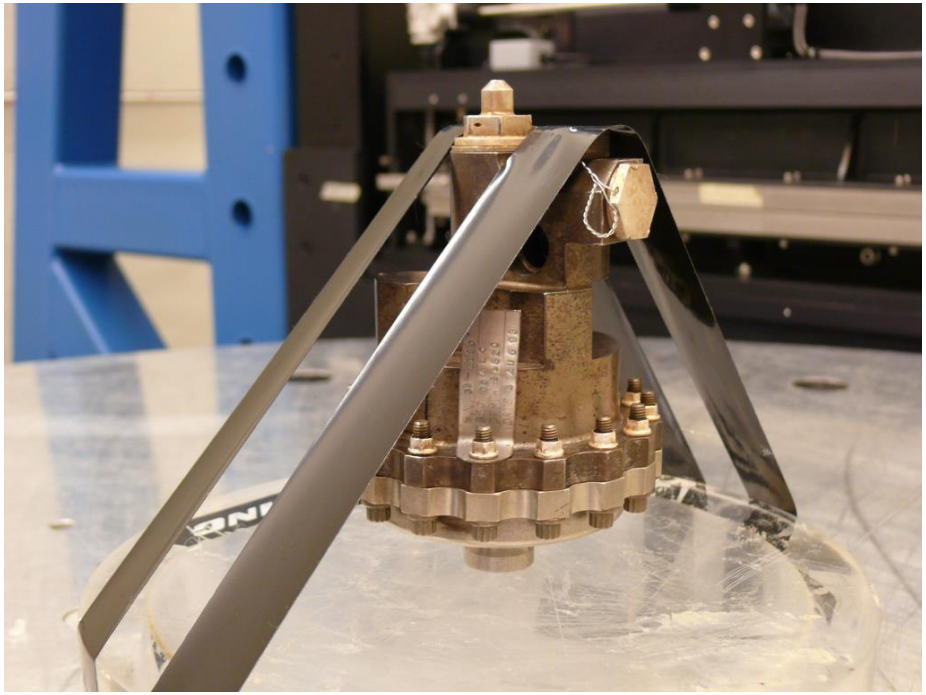
3. This estimate does **NOT** include the cost of shipping the items to their destination.

4. Further funding coordination can be made by email to 309AMARGFUNDS@dm.af.mil or by calling the Customer Funds Office at area code (520) 228-8215 or 228 8340.

5. This estimate will expire 90 days from the date of this memorandum or September 30th of the current year, whichever comes first. If you have any questions or concerns about this quote please contact Jerry L. Peterson, 520-228-8954, (DSN 228-8954) or e-mail jerry.peterson@dm.af.mil.

//Signed//
JERRY L. PETERSON
309th AMARG/OBW

Hardware Status

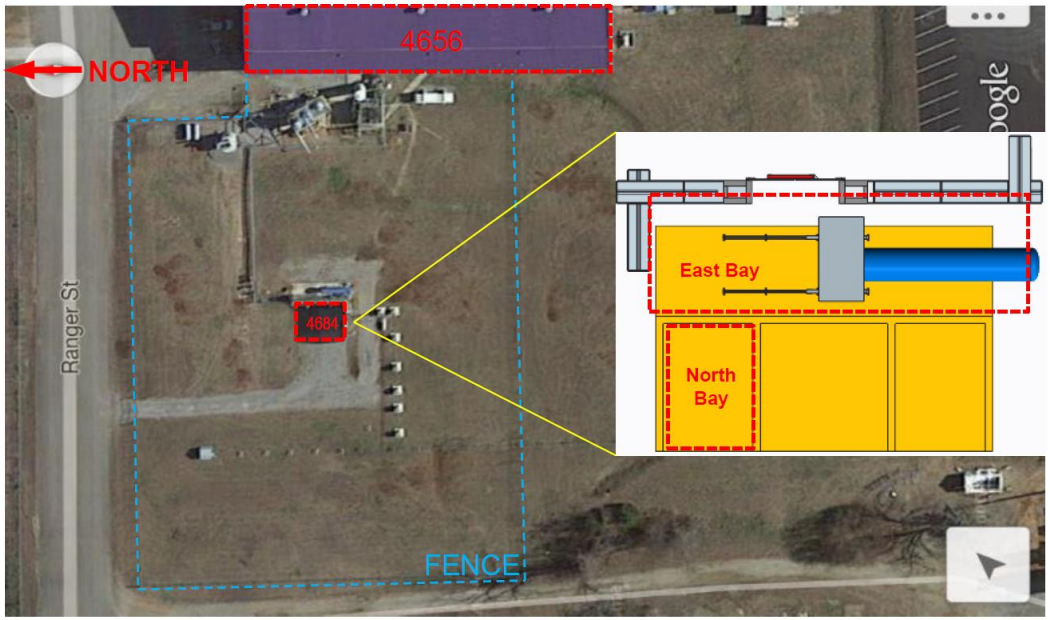


- MSFC did not know the condition of the EPU's that were located at DMAFB.
- That is why MSFC decided to obtain two units to increase chance of valid hardware and potential spare.
- Jan 2014 pre-test CT scan showed that the gas generator
  a) Had catalyst material
  b) No obvious voids, so intact for our use

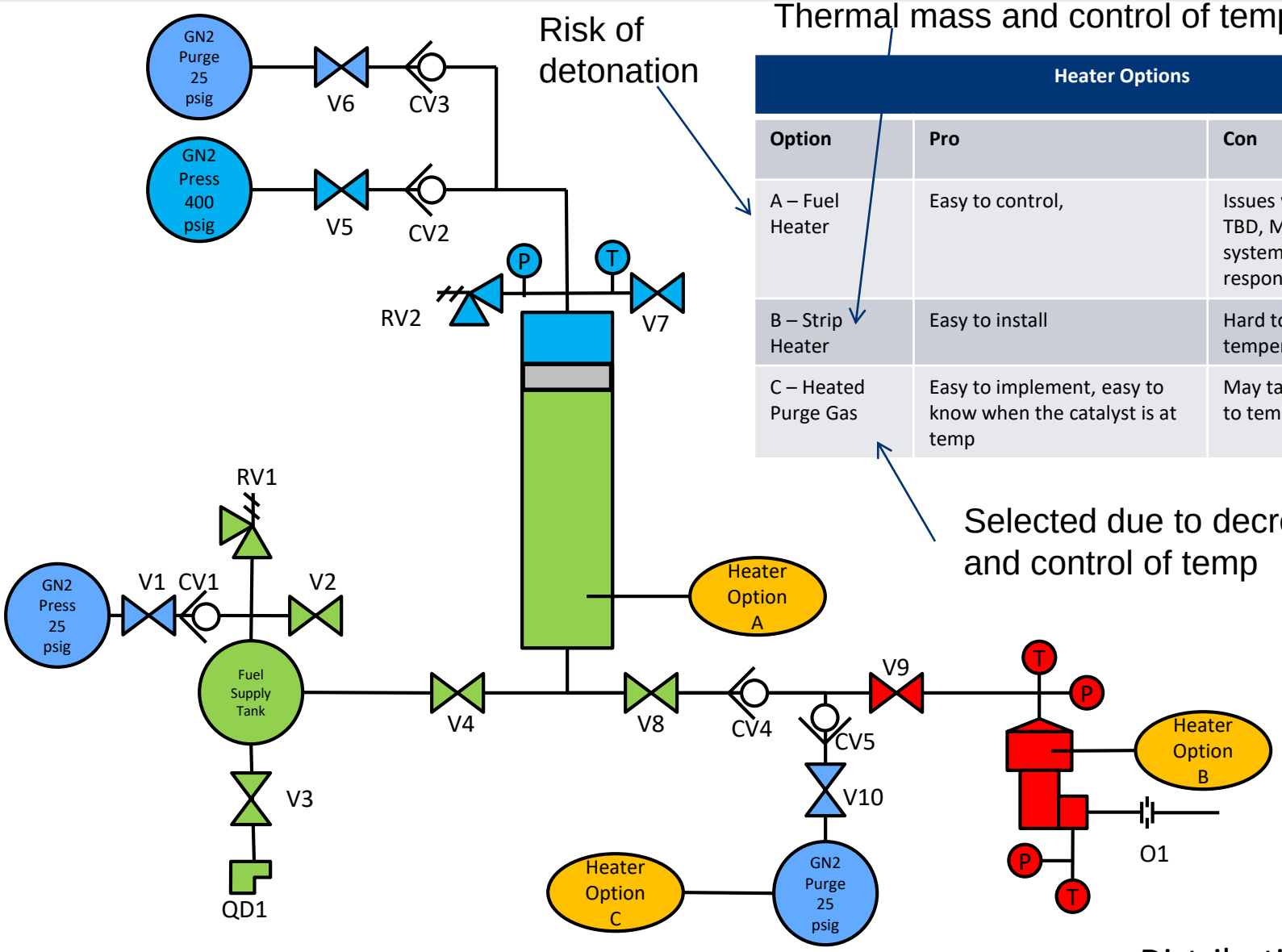
MSFC Component Development Area

- Existing test facilities and propellant storage that was used for the 2014 testing at MSFC can be re-used.

- Accommodations have been made for the MSFC laboratories to conduct the compatibility testing we will be performing in the next few months.



General Layout at Test Bunker



Risk of detonation

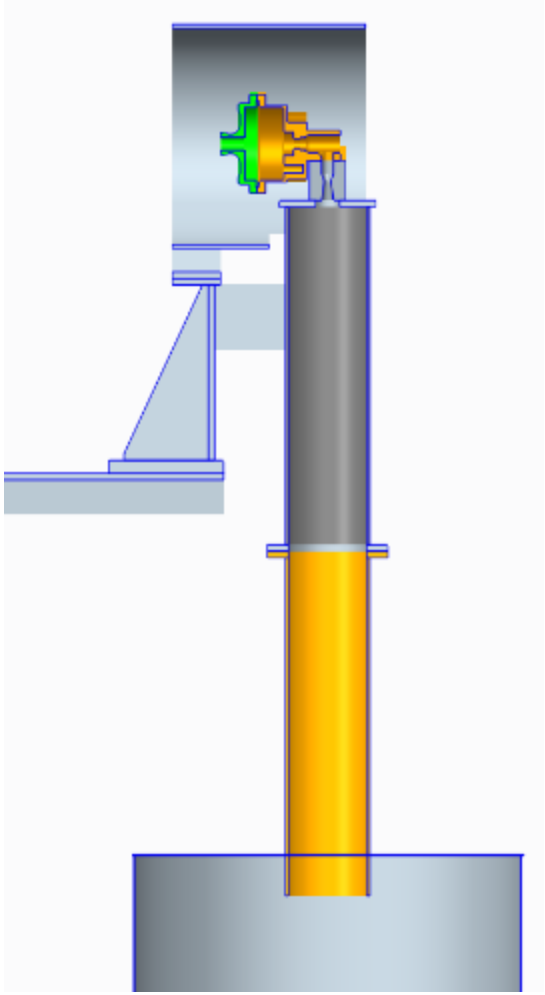
Thermal mass and control of temp

Heater Options		
Option	**Pro**	**Con**
A – Fuel Heater	Easy to control,	Issues with reaction are TBD, May require a bleed system, potentially slow response.
B – Strip Heater	Easy to install	Hard to tell the catalyst temperature
C – Heated Purge Gas	Easy to implement, easy to know when the catalyst is at temp	May take the longest to get to temp.

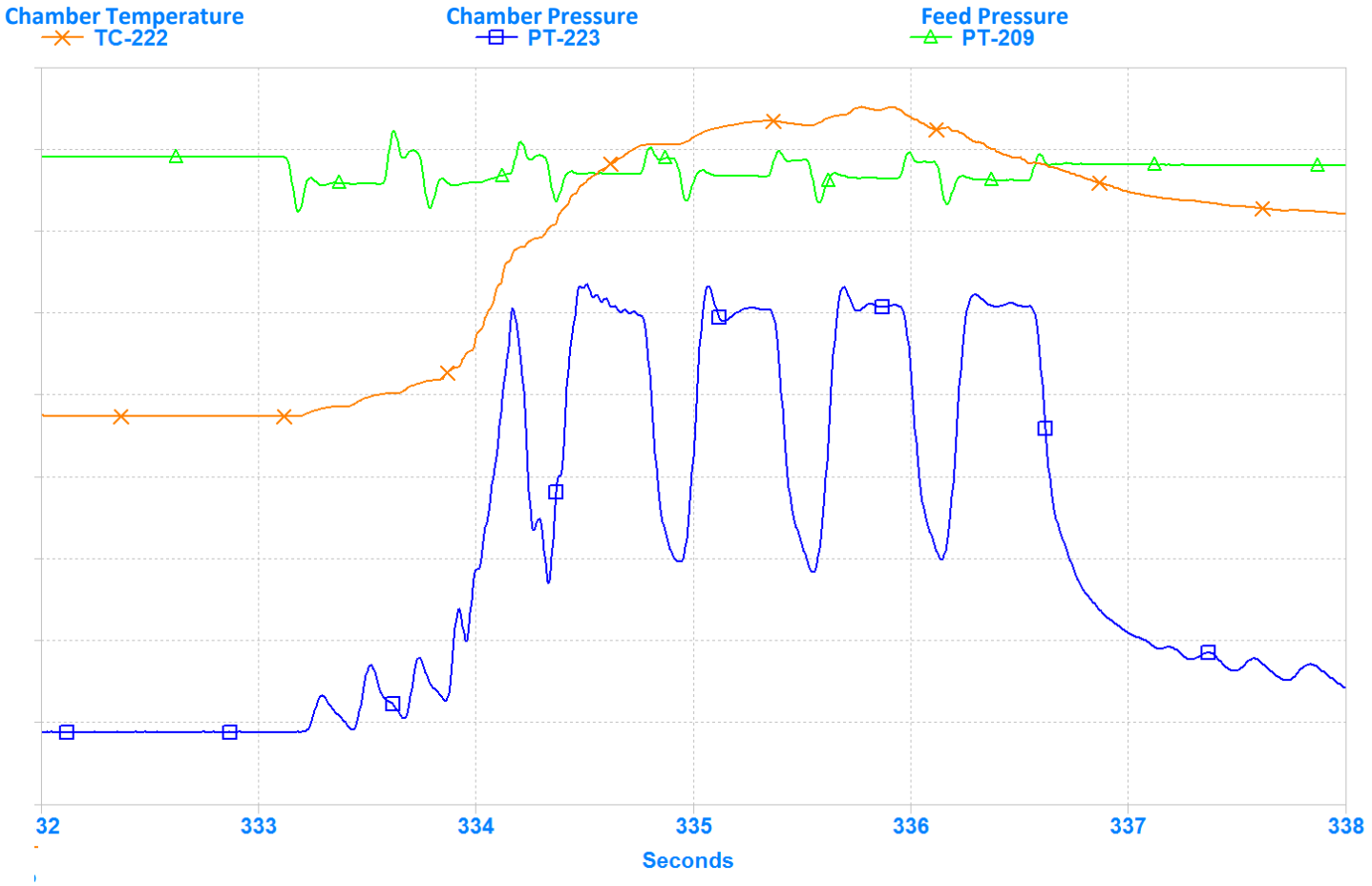
Selected due to decreased risk and control of temp

Testing Summary (Nov 2014)

- Used basic F-16 configuration
  - Including F-16 GG and control valve
  - Added preheat source
- Testing
  - 2 days testing
  - 55 lbs of AF-M315EM (~5 gal)
  - 64 pulse sequences
- Results
  - Equivalent chamber pressure
  - Peak chamber temperatures reveal near complete combustion



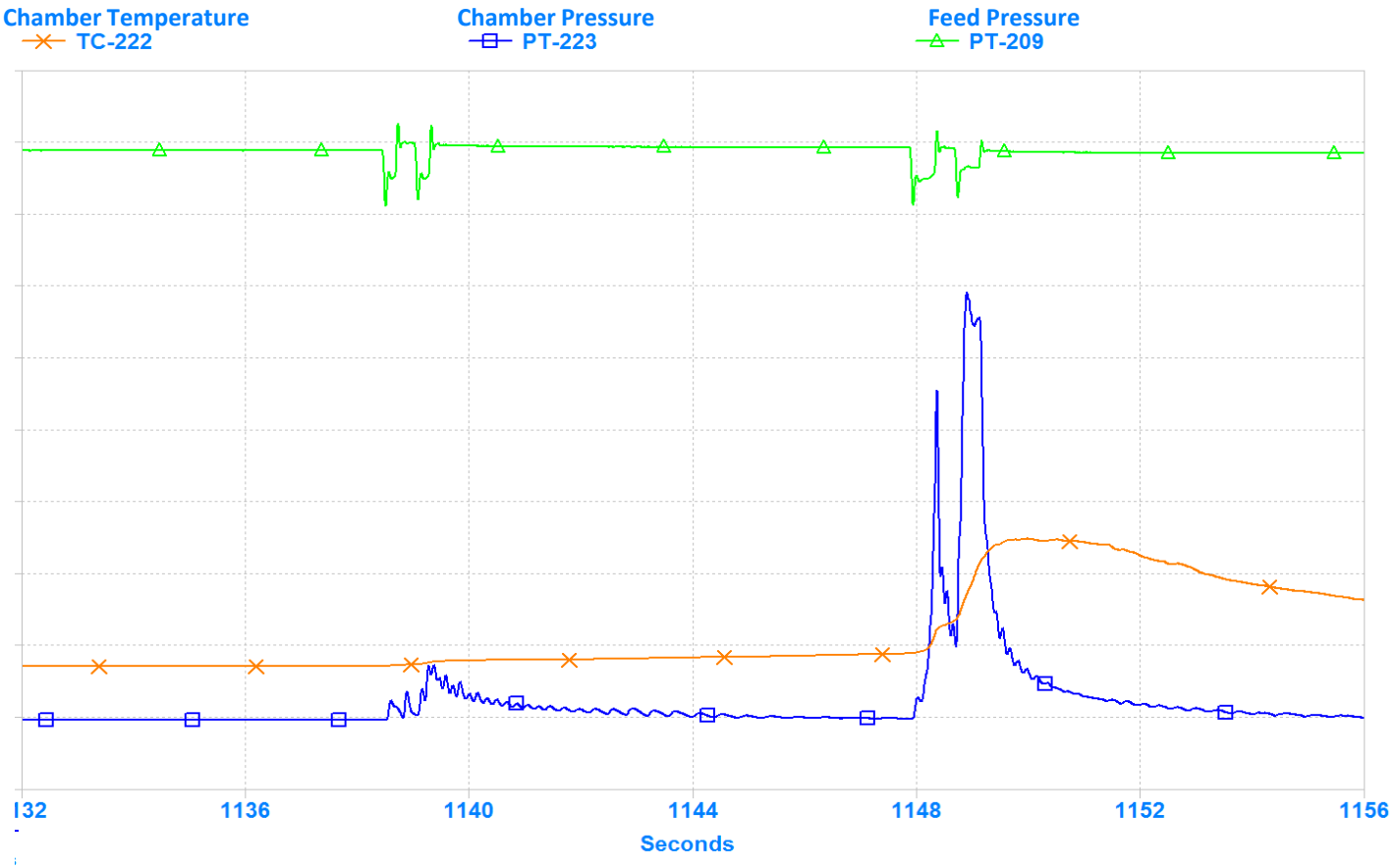
Key Accomplishments – Video 1



- Demonstrated that AF-M315EM can be decomposed using Shell 405 (Hydrazine catalyst).

Key Accomplishments – Video 2

- Demonstrated that lower temperature decomposition can be achieved by pulsing.



*Note: Accuracy of temperature measurements have not been verified.

Coordination of Community (TIM)

- MSFC has led previous workshops and technical interchange meetings on green monopropellants.
- Most notably, we had a successful JANNAF TIM in Aug 2015.
  - 4 Universities, 8 NASA organizations, 7 DoD locations and 28 Companies
  - Thruster development: Aerojet, ATK, Busek, Moog, ECAPS
  - Catalyst and ignition development:
    - Sienna – Dr. Ender Savrun
    - Ultramet – Dr. Art Fortini
    - Systima – Ms. Stephanie Sawmill
    - PSI – Dr. Prakesh Joshi
    - Plasma Processes Inc. – Dr. Tim McKechnie
    - Honeywell – Mr. Gary Seminara
  - Valves and components: Moog, Vacco
  - Primes: Boeing, LM, Loral, ATK, Ball
- As a result of the JANNAF TIM, I led the development of a joint NASA/DoD roadmap with 24 other gov't colleagues across multiple Centers and DoD Research Facilities.

ESTCP and SERDP Funding

- In 2015, I approached Mary Wyderski for pursuit of DoD funding to continue activities.
  - We submitted against a call to the Environmental Security Technology Certification Program (ESTCP).
  - Our focus was to test at the EPU system level, conduct tank compatibility testing and conduct a ground demo with aircraft but did not get selected to pursue formal proposal.
- In 2017 based on feedback from the SPO, we took out the ground demo and replaced it with new scope.
  - Penn State University had previously demonstrated microwave ignition on green props under previous AFOSR funding.
  - Our proposal team was selected to provide a formal proposal (Step 2) but was not chosen.
- Instead our team was provided funding from a sister organization, Strategic Environmental Research and Development Program (SERDP).
  - That activity was awarded in Feb 2019 through NASA for Penn State's continued work.

Penn State Scope

- Previous research in 2013 at Penn State achieved rapid microwave ignition of AF-M315E at a simulated altitude > 47,000 ft and LMP-103S at atmospheric pressure without a catalyst.
- 2019 scope will demonstrate solid-state ignition device (SSD) at PSU.
  - Focused on optimizing ignition power with the use of a smaller device that requires less power from the aircraft battery for implementation and without heating the catalyst material for AF-M315EM and LMP-103S/T.
- Preliminary test results will be shown at the JANNAF Conference in Dayton, OH, the week of June 3rd.

AF-M315E at ~47,000 ft pressure altitude.

LMP-103S at atmospheric pressure.

DLA Scope

- Assess green propellant compatibility of EPU material at MSFC.
  - Conduct surface optical and electron microscopy on tank materials and perform metallographic cross sectioning to evaluate if any material degradation occurred.
  - Perform mechanical hardness, tensile, and dynamic mechanical analysis on metal tank and soft goods to determine compatibility.
- Agreement paperwork is currently being processed and we anticipate a funding MIPR very soon.
  - Our plan is to test one tank with AF-M315EM and the other tank with LMP-103S/T.
  - The LMP-103S/T blend is new to the market and has higher water content, therefore lower combustion temp.

- Status updates from SERDP and DLA scope will be provided to the SPO.
  - Additional presentations can be made to U-2 SPO based on their interests.
- Products delivered will highlight lessons learned, procedural steps and safety documentation that will be critical to SPO transition.
  - Including Lockheed Martin (plane) and Honeywell (EPU vendor).

F-16 EPU – Suggested Next Steps

	COMPLETED	PLANNED	FUTURE
1. Reactivity with existing catalyst	✓ MSFC Funded		
2. Ignition Source w/o Pre-Heat		✓ SERDP Funded	
3. Tank Compatibility		✓ DLA Funded	
4. Power Generation Levels			SPO Funded?
5. Downstream H/W Compatibility			SPO Funded?

1. To test power generation levels:
   A. MSFC could test the PSU SSD with EPU system with AF-M315EM propellant.
   B. MSFC could test the PSU SSD with EPU system with LMP-103S/T propellant.
2. Downstream hardware could be tested for compatibility.
3. A ground demo with an aircraft in the loop could be performed.
4. Any other testing requested by the SPO.

SPO Ground Demo A/C in the Loop

- MSFC has had previous conversations with EAFB for ground demo.
  - Test cart fabricated with mechanical and electrical routed outside of the test aircraft.
  - The aircraft would be placed on test jacks to execute landing gear swings and control surface sweeps.

- F-16 Ground Demo Turnaround Timeline at EAFB
  - Remove hydrazine tank at Fuels facility: 1 day
  - Remove hydrazine EPU at Hush House facility: 2 days
  - Move aircraft to/from test location: 1 day total
  - Green propellant EPU tests: 2 days
  - Hydrazine tank and EPU re-installation/checkout: 4 days

Aircraft downtime synonymous with standard 400-hr maintenance check

- The SPO could consider other test locations instead of EAFB.
  - ANG Air Force Reserve Test Center in Tucson, AZ, with proximity to Davis-Monthan.
  - The 85th Test & Evaluation Squadron at Eglin AFB in Florida for refrigerated testing.
  - The 422nd Test & Evaluation Squadron at Nellis AFB in Nevada.
  - The 457th Fighter Squadron at NAS Ft Worth to be closer to LM/Plant 4.
  - Could be tested on aircraft at Hill AFB and/or at EPAF base overseas.

Conclusions

- MSFC has demonstrated that the use of Green propellant with existing Shell-405 catalyst is feasible for EPU usage.
- We have acquired funding to investigate ignition without heating the catalyst and are preparing to perform compatibility testing on EPU tanks.
- Additional testing would be required to optimize and characterize performance at the EPU system level.
- MSFC can set up a reimbursable Space Act Agreement with the DoD to pursue further testing, leading to EPU system demonstration and eventual aircraft test.

Backup

ESTCP Review Comments

1. Provide a discussion on the benefits to the F-16 Program and if other platforms have been identified for potential implementation.

Response – One of the tasks outlined in the ESTCP proposal was to quantitate a comprehensive savings/benefits that can be gained from implementation using green propellant in place of hydrazine (H-70). As the proposal team prepared for Step 2, additional data were located that were documented in the proposal that show current estimates of benefits. The other DoD program that could benefit from this application would be the U-2 ESS used for the emergency re-start of the engine at altitude.

ESTCP Review Comments

2. Explain why the F-16 is the most reasonable program for a demonstration.

Response – Over 4,600 F-16s have been delivered to the United States military and foreign entities. Of this total, 913 still fly for the USAF, Reserves and ANG whereas the U-2 platform has significantly less aircraft in operation. In April 2017, the USAF decided to increase the F-16 operating hour limit from 8,000 hours to 12,000 hours. According to a 2004 study by the Air Force Logistics Management Agency, F-16 engine failure is the leading cause for F-16 Class A mishaps over the decade from 1994-2004. With a 150% increase in operating hours and increasing age of the platform, there is a higher probability/potential that engine failures could occur that would result in the use of an EPU.

ESTCP Review Comments

3. Do you currently have support or a commitment from the F-16 Program?

Response – The ESTCP Co-Principal Investigator, Lt. Col. Russell, recently moved from the Test Pilot School at EAFB to the F-16 SPO at HAFB. He would be our conduit into the SPO at Hill to give them updates as progress was made. Likewise, Mary Wyderski would provide updates to SPO personnel at WPAFB. The proposal was updated with a letter of support from Chris Zearley, F-16 Development Chief Engineer of the WPAFB F-16 SPO.

ESTCP Review Comments

4. Describe the potential for a hydrazine replacement for F-16 or other DoD programs.

Response – With the success of the planned ESTCP scope, the only modification required would be to add the solid state ignition device across the fleet. This mod for green propellant could be performed during a standard 400-hour maintenance break or could be incorporated into the Service Life Extension Program upgrades currently planned. With the DLA funding, the team will be able to explore both propellants (AF-M315EM and LMP-103S/T), as the Swedish propellant could have utility for Foreign Military Sales (FMS) of F-16s to European commands. The ESTCP scope does not address application-specific questions about the U-2 based upon security clearances required to proceed further.