Certification Testing Approach for Propulsion System Design

Henry Rodriguez[*].
The Boeing Company, Huntington Beach, California, 92647-2099

and

Chris Popp[†]
Marshall Space Flight Center (MSFC), Alabama, Huntsville, 35808

The Certification of Propulsion Systems is costly and complex which involves development and qualification testing. The desire of the certification process is to assure all requirements can be demonstrated to be compliant. The purpose of this paper is to address the technical design concerns of certifying a system for flight. The authors of this paper have experience the lessons learned from supporting the Shuttle Program for Main Propulsion and On Orbit Propulsions Systems. They have collaborated design concerns for certifying propulsion systems. Presented are Pressurization, Tankage, Feed System and Combustion Instability concerns. Propulsion System Engineers are challenged with the dilemma for testing new systems to specific levels to reduce risk yet maintain budgetary targets. A methodical approach is presented to define the types of test suitable to address the technical issues for qualifying systems for retiring the risk levels.

I.   Introduction

The purpose of development testing is to address those areas of flight hardware where performance cannot be address by analysis, design and/or by similarity. Mathematical modeling and verification by similarity are tools that can be used when environmental and geometrical conditions of specific systems are similar. Solving the extent of the amount of testing and the level of fidelity (flight hardware) are economical challenges for the customers and developer. On one end of the budget spectrum, one can require a full development test article that has identical fluid geometries (tube bends, component geometry and system attachments) and is tested to representative environmental conditions (i.e. altitude, thermal, vibration and shock conditions), and on the other end, development testing can be considered to satisfy minimum ambiguities of the design (e.g. low inlet pressures to induce chugging). The following questions are topics that deserve discussion to guide the design team to determine the types of testing and the fidelity of the hardware required to assure requirements can be demonstration.

II.   Test Considerations

Development testing is performed to address ambiguous design areas that cannot be addressed by analysis/similarity and to demonstrate requirements can be met with minor hardware modifications. If major hardware changes are made to existing hardware, testing is required because many variables that influence the interaction of components are difficult to account for in modeling. Many design concepts are attempted to be verified by analysis and similarity; however, evaluating the need for a test, specifically for propellant systems, identifies whether requirements can be demonstrated. Answering the questions for why should a test be conducted identifies the magnitude of the test required:

1.   Is the system significantly different than what has been tested or flown?
2.   Are there areas of the design significantly different that complex fluid, thermal and combustion conditions cannot be characterized by analysis, by analytical modeling or by test similarity?

---

[*] Principal Engineer/Scientist, Advance Vehicle Systems.
[†] Senior Engineer/Scientist, Liquid Propulsion Systems.

1

If differences in system design and environments cannot be modeled or similarity cannot be applied, testing is required to address the above questions. If these questions are answered to the level that analysis, geometrical and environmental conditions cannot be predicted, test is required to the level of demonstrating requirements to within a desire envelope to retire risks. Defining the need for a test, is driven by requirements that cannot be satisfied by analysis or test similarity. Complex operations (e.g. addressing combustion instability) can be produced during a test to characterize the ambiguous design areas then show by math models that these ambiguous areas can be avoided by system design. Resolving what areas of the design should be tested and why are discussions and trades that are addressed a team that has procure applicable hardware and has analyzed the areas of concern. The following are subsystem areas of design concern:

A. Pressurization Systems

There are several techniques used to pressurize propellant storage systems (e.g. mechanical pressure regulators or a pressure modulating system with electrical isolation valves) which present short and long term storage issues. When ullage pressure and thermal sensitivities with respect to low inlet engine pressure are distinctively different than previous systems, system level testing may be needed depending on the engine burn required. If the engine burn is long were helium temperature drops to negative temperatures, sufficient helium mass to meet ullage pressure will result in low engine inlet. This design area is defined by the sensitivity of the Mission Duty Cycles required and the qualification demonstration of the engine at low inlet pressures. If heavy pulse operation for long durations is required and if low inlet engine pressure is sensitive to the engine, subassembly level testing is required to address thermal effects with respect to overshoot and undershoot for small and large ullage volumes, respectively. Test should be defined to demonstrate the pressure control requirements for long heavy duty cycle pulses and long engine burns. If long steady state burns are required, analytical methods can be used to provide verification by analysis and similarity.

Other sensitive issues related to pressure regulating systems are specific to the types of propellant used. If MMH and N2O4 types propellants are used, propellant particles and propellant vapor migration tend to react with the seating areas of the isolation mechanism which lead to internal leakage and hardware deterioration. These type of issues cannot be addressed by mathematical modeling; but can be assessed by long term exposure tests where hardware is exposed propellant vapors are used. Materials can be selected based on the experience gain from other systems; however, the relating mechanism is required to demonstrate long term exposure to propellant vapor migration.

B. Propellant Tankage Systems

Micro-gravity tanks are complex in design and are required to supply propellant under dynamic environments (e.g. micro-gravity and/or torque disturbances). Several creditable tank manufactures have proven many design concepts. Although each tank is different with respect to Design Reference Missions (DRMs), new tanks require the development and qualification path to verification. If the verification process demonstrates requirements and passes qualification successfully, flight type tanks are not needed to perform system level testing. CFD analyses can demonstrate or determine the fluid location during micro-gravity conditions. When sufficient margin (5 to 10% of propellant required) is embedded in into the propellant budgets, a low micro-gravity test is not required CFD tools demonstrate fluid positions for the flight environments and no development testing is recommended for demonstrating expulsion techniques or requirements. If minimum propellant margin is driven to reduce weight and propellant consumption accuracies are questionable, KC-135 low-gravity tests can be used to ascertain limited expulsion efficiencies. Although real space environments will not be addressed until a mission is executed, minimum propellant margins are recommended within 3 to 5% of propellant volume. Because of this position, a high fidelity propellant gauging system will be required to offset the low propellant margin.

For addressing system ground tests, Run-type (ground) tanks can be used to simulate a storage vessel. When thermal control is uncertain or ambiguous, fail-on heater control, environmental heating during station keeping or re-entry effects impact propellant conditions, evaluated propellant temperatures with helium solubility affects are recommended to understand the interaction between propellant feed and combustion effects. If the heating environment is long in duration or erratic, ullage pressure control should be demonstrated within the pressure design limits. Large bulk volumes of propellant (400 to 1000 lbs) usually required large heat rates to increase ullage pressure. If propellant temperatures are allowed to increase (100 to 120 °F), two critical events can occur: 1.) Vapor pressure can increase to the level of MEOP and 2.) Engine performance can decrease at high temperatures. The

2

impacts of these areas can be addressed by analysis; however, hot and cold propellant temperature are recommended to be tested to address the interaction of propellant conditioning with engine combustion..

C. Propellant Feed Systems

Most satellites that are launched as a payload required dry feed systems during launch and require three mechanical inhibits to avoid a critical hazard event (i.e. propellants leakage). Because of this requirement, most feed systems are launch dry and have to demonstrate propellant filling operations within the feed system. Priming with normal operating tank pressures (200 to 350 psia) drives high feed system peak pressures. Although this design approach has been demonstrated on the GRO propulsion system (with anomalies) and Boeing 601 satellites, ambiguity may exist at engine(s) start. Therefore some testing at the component level or a development test can demonstrate quality priming.

Other areas of concern involve engine feedback interaction under severe engine duty cycles. This design area should be addressed by analysis and by tests to demonstrate sufficient pressure margins maintain engine inlet pressures above the frequency response between the propellant feed system and the normal periodic heat release of the reacting propellants. The concern between propellant feed system and engine pressure oscillations presents the interaction of the feed system response and combustion chamber Pressure Oscillations. If no engines are couple with the propellant feed system, pressure oscillations can occurred at a rocket engine feed pressures below the nominal design inlet pressures. The primary driving source of low frequency pressure oscillation in the combustion chamber is caused by the normal periodic heat release of the reacting propellants. When the pressure oscillations travel upstream through the injector and valves and couple with the feed system and amplify the chamber pressure oscillations, this phenomenon is known as feed system chugging, where chugging can occur at high, mid and low frequencies. In past tests, rocket engines have exhibit low frequency pressure oscillations at approximately 150 to 300 Hz.

A cold flow test with referee fluids can be used to demonstrate pressure margins are establish above the engine inlet design limits. System characteristics can be addressed for specific engine inlet conditions; however, engine pressure envelopes need to be well established. In Easy 5, a forcing function can be inputted as Engine pressure oscillations and the concern of operating within a dynamic resonance (e.g. 150 to 300 Hz) can be addressed to show frequency response is voided for specific inlet pressures. The exact mechanism cannot be model; however, by demonstrating sufficient pressure margins, low frequency pressure oscillations can be avoided. If ullage pressures are driven by design limits (e.g. weight and low MEOP), then Hot Fire testing is recommended to demonstrate that low frequency pressure oscillations are avoided and understood to establish operating requirements.

D. Engine Systems

Gas ingestion, thermal cycles, heavy pulse mode operations, total propellant through put, total thermal & pulse cycles need to be demonstrated by test and/or by accumulated information that has been provided by test results. Low inlet pressures and total system pressure loss assist in determining the tank operating pressure and answer the characteristic of engines turning off and on under the stringent cases of a mission duty cycle. Careful review of the mission duty cycles can be compared with previous engines to determine if system level test is needed. Inlet conditions (pressure, temperature and flowrates) need to be demonstrated to assure nominal and off nominal boundaries of a system are established. If combustion instability is not an issue under the nominal operating envelopes, development testing can answer the design inlet conditions. If combustion instability surfaces to be an issue, development testing is required to verify the various inlet conditions will not cause engine instability. If an ambiguity area of a design is revealed to be repeat, the repeatability is key in understanding the ambiguity area. Once repeat behavior is establish for the questionable conditions, system test boundaries and operating envelopes are define to establish nominal operating envelopes. Off nominal conditions should also be tested to define the operating limits.

E. System Conditions

The propulsion systems needs to be evaluated for unique operating conditions and environments which affect the performance of the integrated system. Existing test and similarity data of previous systems can be used to address the specific conditions. Examples of specific conditions include:

- Processing of propellant loading.
- Long Term Propellant Exposure to pressurization systems, affects of propellant vapor migration.
- Long Term Propellant Exposure to Materials and System Effects

Requirements can be defined for long term storage; however, testing duration (e.g. years) will not lend itself to address the qualification aspect of the requirements. Therefore, determining how much testing is sufficient to verify the requirements presents the dilemma of verifying the affects of long term exposure. Long Term Propellant exposure can be address by previous applications for Space Shuttle systems.

F. Test Considerations

What tests information will change the design? Test information critical to the design is defined by a pass-fail criterion and the defined operating constraints specific to the components. Instrumentation, flow metering, data acquisition, pictures, videos, answer the quest to understand system performance behavior. Once repeated behavior is accomplished for nominal and off nominal cases, the pass-fail criteria is used as a tool to assure the ambiguity areas have been addressed. The Pass-Fail criterion is the target and the road map to a successful design. Test(s) information and the criterion are used to assure the ambiguities will be answered.

What criteria should be applied to the verification process to assure requirements are met? A compliance method should be used to assure the verification processes always verifies that the system requirements have been demonstrated. By reviewing a standard verification process and by evaluating the compliance, a criteria definition for the type of verification process can be derive which assures requirements are demonstrated by analysis, inspection, demonstration, test or similarity. Consulting with experts that have designed and flown space systems assure lessons learned have been captured and assure key engineering personnel are prepared to accept or reject the verification process.

What is the Target Cost? A budget estimate or target cost is required to address the program affordability and to address the technical design issues. Once the issues are identified, cost of flight like hardware, propellant required, test facility and engineering staff required can be defined to assure the technical issues will be address with the target cost. System level tests and the fidelity of the Flight Like Hardware couple with simulated environments provide the avenue for addressing ambiguous concerns.

What type of test Schedule should be implemented? -Ideally, development tests should start at PDR time frame and be completed at or after Critical Design Review (CDR) to implement design changes prior to system production. Since ideal planning rarely prevails, identifying the risks and planning to retire the risks prior to CDR assist to avoid hardware changes. The remaining testing post CDR or Post MRR should be definition of operating limits rather than testing component limits,

4

III. Verification Testing

Prior to progressing to a verification approach, it is recommended that defined and undefined requirements be identified and determine the methodology required for verification. All the mission phases that are required and its associated system requirements need to be defined in a specification in order to flow down the test requirements. Once the requirements are identified, bench level testing and/or subassembly testing can be derived to satisfy the interaction between subassemblies (e.g. feed system and engine manifolds). If a development tests can address the quest for the unknown performance characteristics and capture requirements, the test objectives should address those areas of concern and define the limits of the requirements for acceptance. The next step should be to address the variance of the requirements that will affect system design within the Operational Phases, such as, Pre-Launch, Launch, On-Orbit or De-Orbit. The following are recommendations for addressing flight issues for the verification process:

A. Pre-Launch

An example of the X-37 vehicle, no new pre-launch process was implemented. Typical propellant loading techniques such as Shuttle were proposed. The feed systems will be launch wet and the Propellant Tankage system will be loaded to a 95% fill fraction of the total tank volume. During filling, the tank will be vented to a low pressure (1 to 5 psig) prior to filling the tank. A low helium pad pressure of 25 to 60 psia will top off the propellant tank. Because authors views this process as a heritage operations (i.e. no new technology or design concerns), no ambiguous area of concern is identify. These requirements can be verified by analysis couple with test data. For this application, the design team did not recommend any testing in the loading operation definition. During the design phase for defining the propellant tank PMD, Tank Loading techniques were defined to assure successful tank loading by consulting with NASA/KSC Florida Operations. As part of the Verification Process for both the Tank PMD and Vehicle, the tank and Vehicle can be loaded with propellants to demonstrate successful tank loading prior to launch without a test.

B. Mission- (Ascent, On-Orbit & De-Orbiter, Re-Entry/Landing)

For the X-37 Vehicle, the vehicle plan is to insert to a 150 nmi altitude via an Evolved Expendable Launch Vehicle (EELV). This will require the vehicle to perform stage separation maneuvers: On-Orbit Attitude Hold, Orbit Transfers, RCS maneuvers, De-Orbit, Null Burns and Earth Re-Entry. The following system issues are recommended to be addressed:

- Pressure Modulation: System Regulation and effects of avionics command and response. Address time dependent constraints.
- Helium Saturation gas effects on system operation and performance. This is tank pressure and feed system dependent. Address evolution of helium for low inlet pressures.
- If feed system is launched dry, testing is required to address feed system activation (Priming). Address MEOP/pressure spike on components.
- Address Dynamic feed system interactions and effects on thruster performance, life and stability.
- Address Long life propellant exposure issues. Propellant Vapor mitigation tend to generate iron nitrate problems with specific materials.

C. Post Flight Ground Operations

Consideration of Ground processing of propellant-contaminated systems (e.g. reusable systems) and the air interactions with water vapor affecting system life should be strongly considered. However, the verification process in terms of years may not lend itself for timeline verification. Applications from Space Shuttle Orbiter may provide technical data and/or test applications which address similar requirements. Examples of Propellant vapor migration are significant problems that actively affect pressurization systems (i.e. constant exposure to propellant vapor). Lessons Learn from materials and reaction of propellant vapor will support the verification process.

IV. Test Approach

The following are conditions that are complex for defining the verification approach for system tests:

Address System Issues that cannot be addressed by Analysis and Similarity:
- Engine Combustion interaction with feed system capacitances are unity and cannot be modeled. Subjects, such as, high & low frequency Pressure Oscillations and Feed System Capacitance with multiple Engines are difficult topics to resolve without testing. Therefore, if such topics are of concern, testing is recommended if engine inlet conditions are challenged outside the operating envelope. This is recommended to address the combustion issues at low inlet pressures.
- When Thermal environments are the sole affect on system performance, testing can be eliminated; however, when thermal environments impact other design issues (e.g. heat transfer between components), system testing will be required to simulated flight conditions. An alternative is to simulated environments by insulating the propellant Lines to simulate (e.g. zero convection).
- Effects of Helium saturation need to be assess on different inlet condition to eliminate the concern of engine instability.
- System contamination which effect soft goods or valve seats (i.e. N_2O4 reacting with materials or ambient conditions) are effects which cannot be modeled and require isolated testing to characterize component performance.
- Integrated Avionics, Software, Propulsion systems require interaction time delays and response with flight hardware.

D. Propulsion System Test Objectives

Determining the type of test for addressing Feed System and Engine performance involves the consideration of Hot Fire System and Engine test, a Hydraulic Water Flow (Cold Flow) test or an Avionic Integrated Control test, the identified test requirements driven from the system requirements define the test objectives which will drive the type and level of testing required. The following are the types of tests and the objectives that can be accomplished:

1. Engine System Hot Fire Test will demonstrate the following:
- Actual Mission Duty Cycles (MDC) will alllow anchoring of the math models to address system interactions and specifically requirements. Validation of the math model will provide certification process for addition MDCs .
- Demonstrate feed system, pneumatic system activation and surge pressure requirements. Prior to system test prepare a pass/fail criteria to establish verification of requirements.
- Verify Propellant Depletion and Safing Operations Requirements.
- Address long term propellant vapor effects, on propellant and pressurization systems. These affects can be continued after completion of all performance test and the test article can server as a path finder.
- Verify ground processing procedural Tests and requirements
- Verify Ground processing procedures/requirements.
- Address Sensitive areas were propellant-contaminated/air reaction effects Teflon soft goods, seals, mechanical propellant interfaces. This can be performed with the Test Article; however, it is recommended that coupon test samples get started at the onset of program initiation.
- Verify Engine(s) chamber pressure interactions with feed system capacitance (i.e. feed system geometry and volume). Verify Performance Requirements (e.g. engine inlet conditions).
- Verify Engine heat soak back effects or heat transfer to other engines. Define the Restart Requirements (e.g. if engines heat above operating limits, define the requirement for cool down prior to allow restart).

2. A cold flow test with simulated fluids (e.g. H_2O) will demonstrate the following:
- Anchoring of math model for MDC simulations at a hydraulic level (i.e. flow rate, pressure drops) and will provide limited insight into feed system interactions (i.e. Hydraulic effects) with engines. Delta Pressure of the engine valve and chamber back pressure need to be simulated to demonstrate requirements.
- Feed system, Pressurization system activation and Surge pressures requirements.
- Low Fidelity Propellant Dump/Safing Operations requirements.

6

Compare to a Hot Fire tests, the following are objectives which will not be realize with a cold flow test: (Assuming Simulated Fluids).

- Thruster chamber pressure feedback interaction with system cannot be verified. However, with the anchoring of the math model of the cold flow test, chamber pressure start and shut down transients can be evaluated and verify inlet and pressure drop requirements..
- Engine heat soak back effects can not simulated.
- Nozzle configurations and altitude affects can not be demonstrated or verified.
- Simulated Fluids do not have identical fluid properties (i.e. Model needs to address the variation of fluid property differences), therefore, corrections need to be made for verifying performance requirements with propellant properties.
- Helium Solubility effects with simulated fluids can be demonstrated so the evolution of helium compliance can be verified..
- Vapor Migration and environmental effects and reactions with materials can be demonstrated.
- Thruster/Engine heat soak back effects are not simulated; therefore, restart capability cannot be demonstrated.
- Ground Processing Tests/De-Contamination Tests will be different because of different fluid properties; therefore, the need to address the effects of contamination cannot be demonstrated.

If propellants are used with a Cold Flow test, the following test objectives can be realized:

- Anchoring of math models for MDC simulations, will provide analytical insight (limited) into feed system interactions. Flow and pressure drop requirements can be verified.
- Feed system and pneumatic system activation and surge pressures requirements can be demonstrated and verified..
- Low Fidelity Propellant Depletion and Safing Operations requirements can be established.
- Address long term propellant vapor effects can be demonstrated.
- Verify ground processing procedural requirements
- Address sensitive areas due to propellant contamination and air reaction effects.
- Address soft goods, seals, and propellant mechanical interfaces.

3. *An Integrated Pressurization System with Avionics/Software Test can demonstrate the following:*
- Verify the Time constraint requirements with the system controller and system valve(s) response Times.
- Mode of Operations Requirements can be established and verified

V.   Hot Fire Altitude Test

Engine performance verification is highly dependent on the need for Altitude Testing. Engine testing at vacuum conditions verify engine thermal response, thrust performance, and high/low frequency instability concerns. For new development engines were qualification has not been completed, altitude testing is necessary to evaluate engine combustion effects with system interaction. Altitude testing is typically used when backpressure and thermal requirements are critical to verification process, the following test objectives and requirements can be verified with Altitude Testing:

1. Engine thrust performance at vacuum conditions.
2. Engine thermal interaction with other engines. This can be eliminated if insulation techniques are used to suppress convective heat transfer.
3. Combustion instability concerns with Engine start-up transients.
4. Propulsive Operations, such as, Propellant Depletion for Safing Operations (Applicable if vacuum chamber can pull a low torr level below the freezing point of propellants).
5. Thruster performance for various nozzle configurations.
6. Thruster MIB and effects of vacuum.

7

If economical budget concerns influence the design, Ambient Testing at Sea Level conditions can address the majority of the altitude testing objectives. Typically this method is used where backpressure and Thermal Characteristics are not critical to the test objectives/verification process:

1. All Items under the Hot Fire Test Article can be achieved with Ambient Conditions, with the exception of the items 1 through 6 listed under Altitude test.
2. Feed system dynamic evaluation and max/min ullage pressure requirements can be established or verified.
3. Propellant and pressurization system performance with nominal and off nominal conditions can be verified.
4. Software and valve sequencing requirements can be verified.

There is a significant cost increase and schedule impact to build-up and test at a specific altitude. In some cases, the test objectives can be met without simulated altitude. The following critical areas are recommended areas of emphases for verification:

1. Demonstrate system-operating characteristics over predicted operating pressure range.
2. Demonstrate Nominal and off-nominal conditions (i.e. bound the operating limits). Define the operating requirements for Ullage pressures, MRs, flowrates and temperature requirements.
3. Demonstrate Pulse and steady-state engine duty cycles for specific mission duty cycles for multiple engines. Verify mission duty cycle requirements.
4. Investigate the effects of Helium saturation as a function of Tank Pressure for various engine duty cycles. Define and Verify the operating limits of the system.
5. Evaluate engine and propellant feed system dynamics under engine "chug" instability conditions. Verify the low inlet pressure requirements will not cause low frequency instability.
6. Verify engine/system stability under defined operating envelopes.
7. Evaluate system dynamic response when engine chug instability is present.
8. Avionics software verification
9. Address Long duration propellant exposure effects
10. Verify Ground processing requirements of a propellant contaminated system.

A. Engine Instability

If system/engine instability is encountered during testing, the next topics provide some background information and provide some recommendations for processing through the verification process. Two types of instabilities associated with liquid rocket engines can develop with storable systems. Low Frequency and High Frequency combustion instability are two areas of concerns that need to be retired before qualifying the system with the associated engines.

Low frequency less than 1000 Hz is referred to "chug". Characteristics of chugging concerns involve rough chamber pressure incidences were low inlet pressures or helium bubbles in propellants cause low frequency instability. This may be detrimental to engines (e.g. affect film cooling); however, it will also result in unpredictable propellant consumption and have mission short falls. This area usually does not influence engine start-up conditions; however, it will produce feed system oscillations if chug frequency couples with system natural frequency.

High frequency greater than 6000 Hz is referred to as combustion instability. If the engine is well defined and significant development testing has been captured, high frequency combustion instability is not a concern. However, helium ingested by the engines can induce erratic behavior. Random chamber pressure oscillations are indicative of high frequency instability. These conditions occur at start-up transients and typically are capture at development or qualification engine testing. High Frequency can develop were a new system configuration causes gaseous helium to evolve as solution. This can result were an engine has not be tested, particularly were gaseous helium is significantly ingested beyond engine level stability envelopes.

VI.   Test Options

A test program should define the required objectives needed to relax the technical concerns. The following were X-37 test options that were critical to the success of the program.

1. Verify System Dynamics during initial system priming.
2. Verify operating requirements of key fluid components, during normal and failure mode operating conditions
3. Verify acceptable fluid dynamics during simulated normal and worst-case engine duty cycles.
4. Generate flow calibration data to used during system assembly and for cold flow calibration test.
5. Address Long duration pneumatic system vapor exposure effects
6. Address response times for an integrated pressurization system with avionics and software interaction.
7. Verify Feed system steady state and dynamic pressure interactions for the operating range of thruster/engine MDCs.
8. Address Propellant depletion requirements
9. Address Long term propellant interactions (iron nitrate)
10. Address ground environment of propellant-contaminated system (iron nitrate/leakge evals)
11. Verify Procedures for processing of propellant contaminated propulsion system

Testing at ambient conditions is recommended if sufficient qualification testing of the engines is available. For the X-37 program, ambient testing is an acceptable method for verification because feed system dynamics will not be affected by altitude effects, i.e. Delta-P, Flowrates conditions can be demonstrated by various tank pressures. Engine operating envelopes can be demonstrated and verify off nominal requirements are addressed for any chugging concerns. With this test setup, propellant saturation effects can still be evaluated.

As a minimum, the test article should implement the following physical characteristics:

*   Tubing bents and 90 degree fittings are recommended. Long runs of tubing coiled to minimize space is acceptable.
*   Mounting characteristics (i.e. Simulate stiffness of flight structure where possible).
*   Flow Characteristics (Match Flow impedance of propulsion system).

When high or low frequency instability is encountered, repeatability is key to assure specific pressures, temperatures and flowrates are identified that cause instability. With the data capture, develop an operating envelope to avoid the instability. By evaluating the envelope, hardware changes can be realized to avoid the instability domains. Example of this phenomenon is to avoid low inlet pressures, minimize delta-pressures by changing filter delta pressures, minimize sharp bents that could trap helium evolution, consider re-orifice of the system to avoid large delta pressures. These recommendations need to be considered against the program objectives to sacrifice the proper system requirements.

VII.   Summary

This paper provides an outline for reviewing a propulsion system requirements and defining the type of test required to address the necessary test objectives for verification. It is assumed that the structure of deriving and defining requirements is allocated to system and component specifications for further development. It is not necessary that fully mature requirements be established; but, identified (i.e. requirements) to derive a suitable test article to mature the requirements during demonstration.   What is essential for selecting the types of test for verification are:

1. Fluid system Hot Fire or Cold Flow Test Article.
2. Test matrix that address the requirements of the system and component specification.
3. A test plan that addresses the questionable design areas and verifies the requirements

Balancing this scope will require the allowed budget and schedule to assure successful completion. Therefore, considering trade between a hot and cold test will guide a design team to the proper choice for verification. Considering the following will aid the selection between hot or cold flow testing.

When engine performance has been demonstrated, a cold flow test can be recommended to demonstrate the following (assuming simulated fluids):

- Anchoring of math model for MDC simulations, provides limited insight into feed system interactions
- Feed system, pneumatic system activation and surge pressures requirements can be verified.
- Low Fidelity Propellant Depletion can be verified.
- Safing Operation Requirements can be verified.
- Control of the pressurization with Avionics/Software
- Interaction (i.e. evaluate system controller and system response).

A. Items than **cannot be demonstrated** with a cold flow test (Assuming Simulated Fluids):

- Thruster chamber pressure feedback interaction with system.
- Simulated Fluids do not have identical fluid properties (i.e. Model needs to address the variation of fluid property differences).
- Helium Solubility effects with simulated fluids.
- Vapor Migration effects and environmental effects/reactions with materials.
- Thruster/Engine heat soak back effects are not simulated.
- Processing Tests/De-Contamination Tests will be different, need to address the effects of contamination.

B. Cold Flow Test with Propellants can demonstrate the following:

- Verify the Anchoring of model for MDC simulations, insight (limited) into feed system interactions
- Verify feed system and pneumatic system activation and surge pressures requirements.
- Verify Low Fidelity Propellant Depletion requirements
- Verify Safing Operations requirements.
- Verify long term propellant vapor effects,
- Verify ground processing procedural Tests
- Development, insight into ground processing requirements
- Address sensitive areas due to propellant-contaminated/air reaction effects Address soft goods, seals, mechanical propellant interfaces.

Assuming Actual Propellants: Issues that cannot be achieved with a cold flow test:

- Thruster chamber pressure feedback interaction with system.
- Thruster/Engine heat soak back effects are not simulated.

C. Items that cannot be addressed by Analysis and Simularity:

- Combustion/Thruster interaction with the feed system capacitance and associated environments (High & Low Frequency Combustion Pressure Oscillations and Feed System Capacitance interaction with multiple Engines).
- Thermal environments (i.e. no convection in space). System can be simulated to achieve simulated environments by insulating the propellant Lines.
- Helium saturation, contamination, life degradation (e.g. aging of soft goods exposed to propellants & repeated fatigue of ground environments), reusability of hardware with ground environments (i.e. N2O4 reacting with ambient conditions), Propellant Vapor Transport and other effects not modeled *(either)* due to engineering *(judgement or failure to identify potential for effects on performance)*.
- Integrated Avionics/Software/Propulsion interaction time delays, response with flight hardware.
- Ground Processing of actual flight configuration *(and development of associated procedures)*.
- Assumptions and Unknown Issues are valid for the experience data based.

VIII. Conclusions

Three types of test article can be selected to resolve the technical issues and provide a means for certifying a propulsion system. Careful identification of design issues and requirements is required to identify the type of test

10

needed. The authors have provided the trade exercise accomplished on previous programs and have consult with Space Shuttle and NASA JPL propulsion engineers to arrive at the recommendations provided. Included are lessons learned from the Space Shuttle programs and NASA JPL Cassini Program.

Acknowledgments

The authors would like to thank the NASA JPL, MSFC agencies for their extensive experience in accumulated information from Space Shuttle, JPL long term Space Vehicles and MSFC Propulsion Systems.

References

1. Non-Toxic System Architecture for Space Shuttle Applications, Boeing Reusable Space System, AIAA-98-3821, July 12-15, 1998.
2. Non-Toxic Cryogenic Storage for OMS/RCS Shuttle Upgrade, Boeing Reusable Space System, AIAA-98-3821, July 12-15, 1998
3. Boeing Supportability and Obsolescence Study, Boeing Internal Study/Henry Rodriguez, 2001.
4. Main Propulsion System Maintainability Issues for the Future Shuttle, Boeing Reusable Space Systems, AIAA-02-3756, July 7-10, 2002.