Design Processes and Criteria for the X-51A Flight Vehicle Airframe

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ABSTRACT

Flight vehicle airframes in today's advanced flight systems are required to optimally integrate a variety of multi-functional requirements to maximize effectiveness with acceptable risk. The X-51A airframe design process and criteria draw upon decades of successful design of both manned and unmanned flight vehicles for production and experimental intent. This paper summarizes the X-51A vehicle mission requirements, system design, design processes used for airframe synthesis, design safety factors, success criteria and issues facing the incorporation of advanced optimization techniques in the development of airframes for vehicles such as the X-51A.

1.0 INTRODUCTION

The X-51A program is a jointly funded project sponsored by two US government agencies: the Air Force Research Laboratory (AFRL) and the Defense Advanced Research Projects Agency (DARPA) with AFRL as the lead project office [1]. The fundamental objective of the X-51A flight test program is to flight demonstrate the USAF Hypersonic Technology (HyTech) scramjet engine being developed by Pratt & Whitney Rocketdyne under contract to the AFRL (Figure 1). The scramjet engine is based on a hydrocarbon fuel that ignites and operates in both acceleration and cruise modes in the Mach 4.5 to 6.5 range. The engine flowpath is cooled using fuel to both maintain tolerable flowpath temperatures as well as "crack" the fuel to facilitate ignition once it is injected into the combustion region of the scramjet engine. The external vehicle configuration utilizes a waverider-type aerodynamic mold line to maximize hypersonic lift to drag (L/D) ratios. The hypersonic cruise duration is expected to occur for greater than 5 minutes with the first of four planned missions to occur by the end of 2008. The ultimate goal of the entire X-51 program is to demonstrate the HyTech scramjet engine thrust and specific impulse performance characteristics over the specific Mach number range at specific fuel ratios, dynamic pressures and angles of attack through analysis, ground test and flight test. The near term application is for a fast-reaction long range air-to-surface system with a Mach 6+ cruise capability and a flight time of several minutes, with a carriage capability on a multitude of flight platforms. The engine and airframe technologies advanced in the X-51A system are expected to enhance future systems capabilities in both 1) time critical, long range standoff response, 2) hypersonic reach/reconnaissance vehicles and 3) reusable on-demand access to space systems.

This paper describes the hypersonic vehicle design development and engine integration underway to flight test the HyTech engine. Specific discussion is provided on the rationale of the approach in the overall X-vehicle

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airframe technology selection, design process and design criteria. Of special note are the process, rationale, test plan and analysis that were involved in selection of the factors of safety to be used for airframe thermal-structural integrity analysis.

- Joint AFRL-DARPA flight demo
- HC (JP-7) fueled cooled scramjet
- Wave-rider airframe
- Scramjet take-over at Mach 4.5
- Accelerate to Mach 6.5 to 7.0
- 5 minute-plus flight duration
- Four to eight flights (FY09 1st flight)

Near Term: Affordable Fast Reaction Standoff Weapon
    Time critical targets: rapid response, long range standoff (600 NM in 10 min)
Far Term: Affordable On-demand Access to Space

Figure 1. X-51A Project Overview

2.0 BACKGROUND

The United States is developing scramjet engine technology that is expected to be needed by the next generation of high speed air breathing vehicles [2]. The scramjet engine can be combined with rockets and/or high speed turbine engines to provide efficient propulsion over a broad range of Mach numbers (Figure 1). NASA, through the X-43A program, is developing hydrogen fueled scramjet engines and has demonstrated Mach number of approximately 7 to Mach 10 operation with the focus on establishing a technology base for access to space systems. Under the Hypersonic Technology (HyTech) Program, the Air Force Research Laboratory's Propulsion Directorate has defined a technology thrust for liquid hydrocarbon fueled hypersonic propulsion systems. This program is demonstrating the operability, performance, and structural durability of an expendable liquid hydrocarbon scramjet propulsion system that operates from Mach number of approximately 4 to 7.

In order to mature engine technology to the point of readiness for consideration in an operational vehicle, it is required that flight testing be performed to validate the technology developed in the required environment. Design/hardware details, performance analysis, ground test data, propulsion/vehicle aero interactions, flight control and overall performance and operability must be demonstrated/validated to properly reduce the risk in transition to an operational system. Ground test facilities and analytical methods can only encompass a limited amount of the relevant environments. Geometric scale, pressure, temperature, Mach number, Reynolds number, chemistry effects, time and all of their interactions typically require a compromise in order to properly simulate any given subset of desired environmental conditions when using ground test facilities. In addition, many of the most applicable wind tunnel facilities are 'blow down' in nature and significantly compromise the ability of the system to come to thermal equilibrium before the time-dependent tunnel resources are exhausted. Once the full extent of ground testing and analysis models have been explored; the next logical step is flight testing where all of the proper environmental levels and the appropriate interactions can be fully explored and previous databases can be validated.

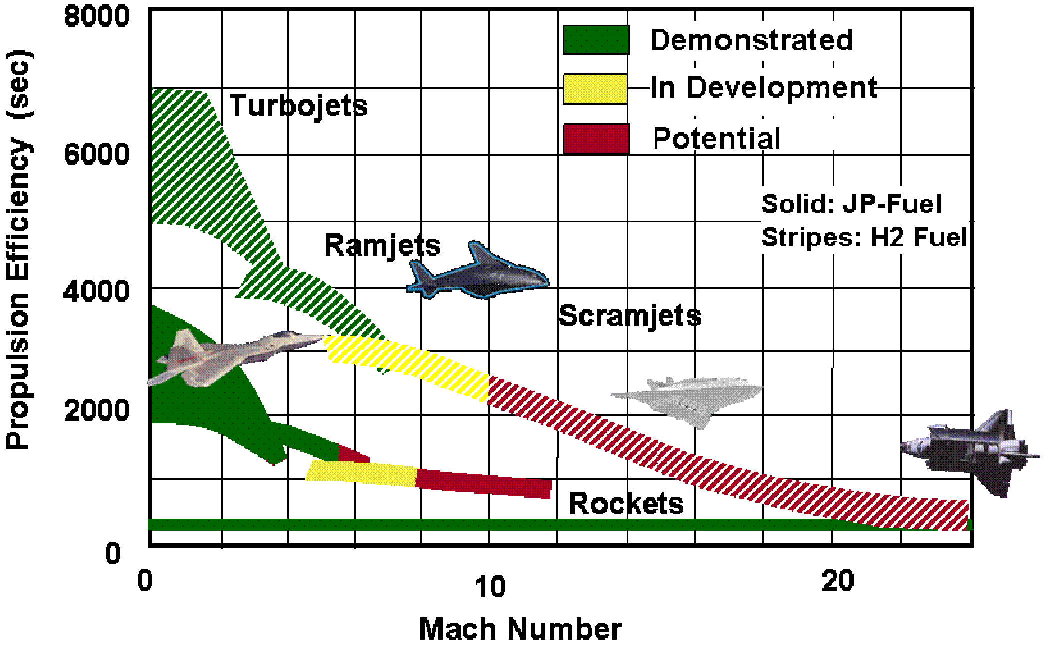

Figure 2. – Airbreathing Engines Offer Efficient Thrust for High Speed Aircraft or Space Access Vehicles

3.0 SYSTEM OVERVIEW

The X-51A flight demonstrator is composed of two major flight elements; the scramjet air vehicle demonstrator (AVD) and a B-52 captive-carry system. The AVD is approximately 25 ft long and 2 feet in diameter and is composed of three primary elements or structural assemblies as shown in Figure 3. These three primary structural assemblies are; 1) the booster, 2) the cruiser and the 3) interstage. The booster is an existing Army Tactical Missile System (ATACMS) booster that is slightly modified to accommodate the required forward structural integration, two horizontal fins to enhance the AVD pitch stability and an expanded nozzle to enhance high altitude booster performance. The cruiser is the hypersonic boost/cruise vehicle that is composed of main propulsion and vehicle systems that are configured to meet the requirements of the hypersonic portion of the demonstration mission. The main propulsion system is composed of the scramjet engine to be flight tested with the supporting engine controller and fuel pump. The vehicle subsystems include the primary/secondary structural elements, thermal protection system (TPS), pressurization and fuel delivery subsystems, vehicle controller, inertial measurement system, guidance computer, power, telemetry and flight termination components. The structural arrangement and components have been packaged with an aerodynamic mold-line that provides the required hypersonic trim conditions with maximum lift to drag ratio. The cruiser is equipped with an array of sensors to characterize the flight experiment. The third major structural element is the interstage. The interstage provides three important functions. These include providing 1) the primary structural transfer between the booster and the cruiser, 2) the structural attachment and electrical interface to the B-52 captive carry vehicle and 3) a flowpath for the air entering the scramjet engine to support cruiser engine preheating while the AVD is mated together during the boost phase.

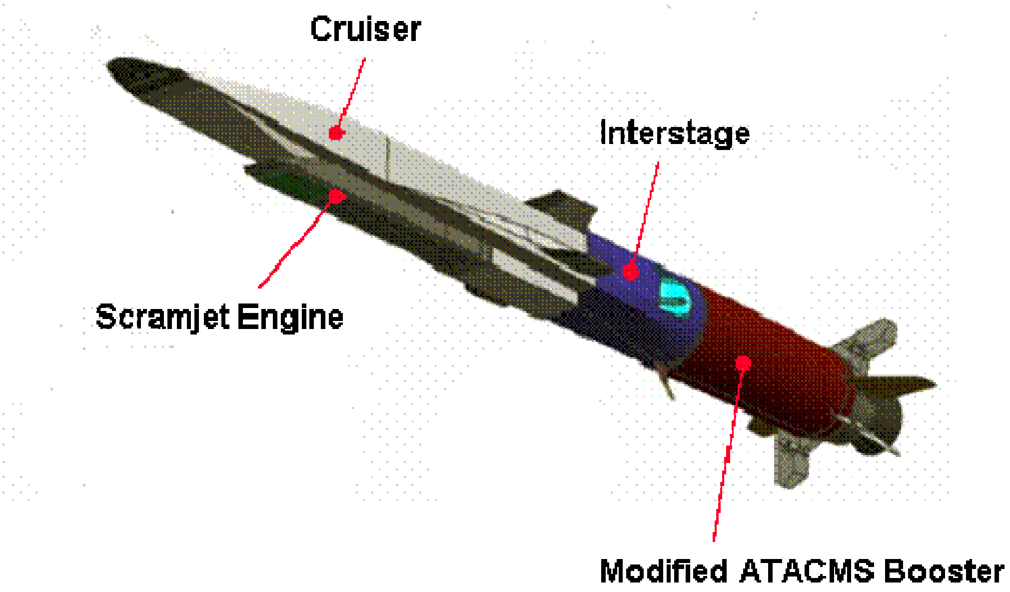

Figure 3. X-51A Air Vehicle Demonstrator Overview

The concept of flight test operation is illustrated in Figure 4 where the X-51A AVD is carried aloft by a B-52 to its staging altitude of approximately 45,000 ft at a Mach number of approximately 0.8. After successful completion of system health checks, the AVD is released from the B-52 and allowed to clear a safety sphere before the booster is ignited. The booster accelerates the stack upwards to an altitude of approximately 70,000 ft at a Mach number of 4 to 5. After the booster thrust begins to tail off to a prescribed level, the system is separated at a plane between the cruiser and interstage. During the boost phase, the engine flowpath has been preheated and is conditioned for scramjet engine start. The engine start sequence begins and the cruiser then accelerates to Mach 6 to 7 and climbs to approximately 90,000 ft. The scramjet engine operates for approximately 5 minutes and then is shutdown upon fuel depletion. The vehicle then performs specific aerodynamic maneuvers to acquire hypersonic aerodynamic characteristics. After completion of these maneuvers, the cruiser then completes its mission with a hypersonic/supersonic glide and a water entry.

4.0 THE DEMONSTRATION CHALLENGE

In developing the airframe design for the X-51A flight demonstrator, it was important to establish some overall guidelines in its development that is consistent with the program philosophy. The flight demonstration is fundamentally a propulsion test that must have minimum risks in other vehicle systems in order to maximize the ability to setup the required conditions for the engine experiment. Therefore, it was required that the airframe structural integrity be a low risk element of the overall flight vehicle system. However, at the same time the resulting airframe design criteria is required to not be overly conservative as to be detrimental to the performance of the flight test vehicle due to unnecessary weight to the overall flight system and without adversely affecting development cost/schedule. Therefore, a proper balance of airframe analysis methods, materials technology selection, test demonstrations/validations and factors of safety is required. Design criteria is required to consider 1) overall risk tolerance of Boeing and the project customer, 2) standard practices for aerospace vehicles, 3) standard practices by the Boeing - Huntington Beach engineering development site and its heritage of advanced flight vehicle development programs and 3) the human interactions during the fabrication, assembly, checkout and flight test operations.

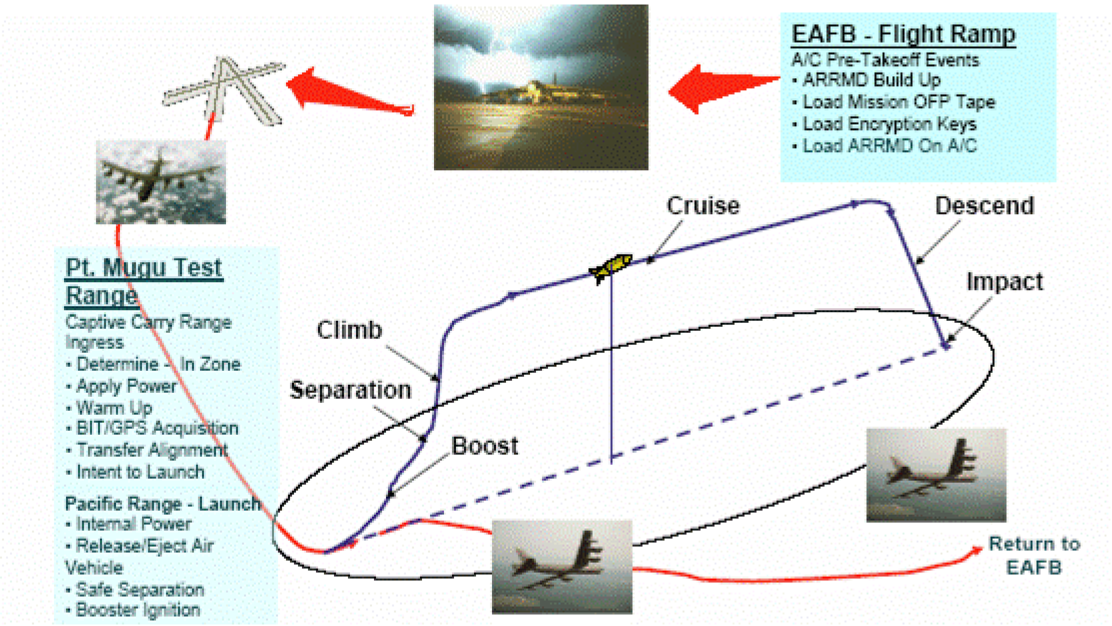

Figure 4. X-51A Flight Test Operation Overview

5.0 VEHICLE AIRFRAME MATERIAL TECHOLOGY SELECTIONS

The primary airframe material technology selected for the X-51A can be classified as a conventional built-up metallic structural design approach with a parasitic TPS for structural temperature control. Alloys of various thermal capabilities were chosen based on strength properties at temperature for the various sizes and product forms required and local environments that they are subjected to. However, to facilitate specific high temperature, external shape critical regions of the external aerodynamic surface, refractory elements were chosen. These regions include the control fin leading edges and the nosecap. Composite hot structure (CHS) is utilized for the leading edges due to its high specific strength and stiffness at high temperature. A refractory metallic was chosen for the nosecap due to its high temperature capability and synergy with the ballast required to support flying qualities. Both materials are coated to control oxidation. The appropriate material characteristics and design features were incorporated into the global finite element model shown in Figure 5.

The external vehicle skin and exhaust nozzle are subjected to temperatures that range from ~1500 Deg F to ~3500 Deg F. The external TPS and nozzle liner are a combination of ablative thermal protection materials and third generation reusable surface insulation (RSI) more commonly referred to as 'Shuttle-tile' material. The ablative materials utilize various formulations of the Boeing Lightweight Ablator (BLA) that have been developed for the HyFly and Delta IV programs. The BLA class of materials can be combined with fillers, reinforcements and under-layments to maximize the benefits of insulative, ablative and weight performance. The RSI material is applied in regions where shape stability is required or expulsion of ablative products can not be tolerated. These regions included the scramjet inlet ramp and the chine/windward areas of the cruiser. The BLA class of TPS materials was chosen to minimize raw material and installation costs in areas of complex surface geometry where charring and limited mass removal can be tolerated. These regions include the leeward side of the cruiser and the exhaust nozzle. Thermal protection systems are all designed to limit structural materials for the design reference missions to maximum operating temperatures that do not exceed creep thresholds for metallic members. Creep thresholds are generally defined as temperatures that are half the melting point of the material. This threshold also typically coincides with the significant drop-off in design allowables with temperature.

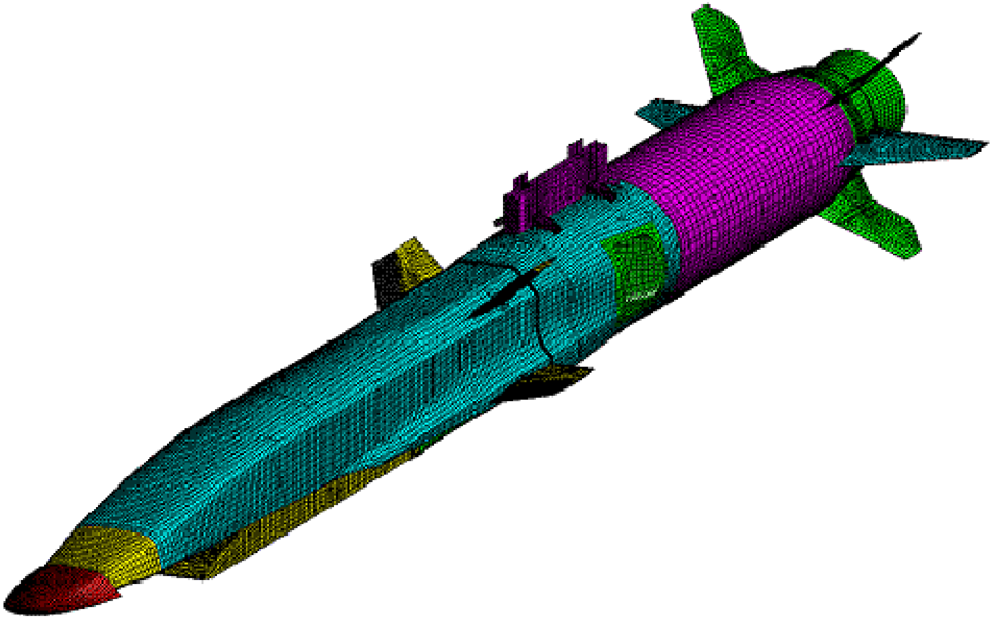

Figure 5. AVD Global FEM Including the MAU-12 Ejector

6.0 THE DESIGN PROCESS AND CRITERIA

Upon initiation of the design process, key terms were defined that are considered important in the X-51A design integrity process. Key element definitions included the classification of vehicle airframe elements as structure (primary or secondary), thermal protection and tubing/ducts. Key criteria definitions included limit mechanical load conditions, limit thermal environment conditions as well as the application of acceptance test factors and ultimate design factors on these predicted conditions. In addition, a process was also defined to address anomalous events or ‘subsystem failures’ and the appropriate design factors to apply.

Primary structure is defined as having either one or both of the following properties: 1) flight vehicle structural elements that either carry core body loads, trim/maneuver loads or system pressurization loads and/or 2) a structural element in which its single failure would guarantee a flight failure condition. Secondary structure is defined as all other structural elements that are not classified as primary structure which may include structural elements that attach subsystems to primary structure and/or elements that provide closeout of subsystems or structural assemblies. Tubing and ducts that transfer fluid systems (gas or liquid) under pressure from one subsystem element to another are also considered structural elements. Their classification as primary or secondary structure depends upon their flight critical nature. All structure that falls into the 'primary' category is required to be composed of a mature material system. Mature material systems are defined as having an associated "A or S-basis" design property database or having a design allowables database documented in a "peer reviewed" materials report, approved by Boeing materials and process engineering and traceable to a controlled material process specification. In general, all of the materials chosen have a proven flight history. TPS is defined as an element that provides passive protection of heat transfer to temperature sensitive elements. All elements classified as TPS do not carry primary loads nor trim/maneuver loads. Elements that carry primary loads and/or trim/maneuver loads and are subjected to extreme external thermal environments are typically called 'hot structure' and are treated as primary structure. In sizing and validating structure in light of manufacturing tolerances, local strength and stability analyses are based on the "minimum material condition" while global stability, safe life and temperature analyses are based on "nominal material condition".

The next step in the process was the development of mechanical and thermal limit loads. These were defined by examining the entire operational envelop of the AVD system which not only included flight test operations but also included all load events associated with the assembly, ground handling and captive carry phases of the AVD life. B-52 load factors, maximum dynamic pressure, aerodynamic heating, angle of attack, sideslip angle and AVD maneuver accelerations were defined to enable full, robust exploration of the required engine flight test envelope while also providing a weight efficient airframe. In addition, design trade studies were conducted with flight controls to assure that trim and maneuver conditions could be implemented through the control surfaces while minimizing the design limit load condition. As a result, maximum angle of attack, dynamic pressure and fin deflection envelopes were pre-defined to facilitate separate, but concurrent development of flight control and airframe design. Environmental conditions were selected that enabled 95 percentile operability under weather conditions at the planned operations site. Structural design allowables are all based on either time consistent temperature conditions or a given maximum operating temperature limit for the specific structural material under consideration. The X-51A loads database concluded with the definition of thousands of unique load cases for consideration with over 10% of these databases being critical in defining the design condition for a given airframe structural part.

One of the major airframe trade issues studied during the preliminary design process was the strong interplay between the heat load created during flight and engine operation and the design requirements for the thermal protection system. Minimum thickness/weight TPS designs favor high acceleration to the cruise Mach number and low angle of attack/low dynamic pressure flight profiles with high operating temperatures for primary structure. However, structural temperatures needed to be maintained in order to 1) minimize the degradation of material allowables with temperature, 2) reduce the effects of stresses due to thermal gradients/expansion and 3) avoid creep effects. In addition, specific structural temperature limits were set in order for the structural design process and thermal protection design process to proceed into detailed design in an efficient manner. An important design consideration was the significant time planned in the mission at the cruise Mach number which creates a significant thermal soak through the heatshield and engine interface components into the airframe structure and components. To manage this heat load for the duration of the flight required either a thicker TPS or a limit on the mission duration. A compromise was reached in which an 'assured mission duration' timeframe was established to derive thermal conditions for full vehicle structural integrity analysis. This 'assured mission duration' (AMD) was defined to coincide with all vehicle ground and flight operations thru the end of scramjet engine operation. Scramjet engine operation concludes at the point where all of the fuel is depleted and the cruiser becomes a glider.

Another major trade issue studied during the preliminary design phase was the definition of the protocol for handling anomalous events. It was desired that structural integrity be maintained under specific unplanned or anomalous events. The two principle cases considered were 1) a scramjet engine unstart and 2) an error driven flight condition outside the specification derived flight envelope. Under these conditions a positive margin of safety was desired under a limit rather than an ultimate design condition.

Skins, structural stiffening and interface features of all major weight bearing structural elements were continually optimized throughout the preliminary and detailed design phase to provide a minimum weight airframe that was compliant with the requirements of the integrity process. All thermal and structural design margins of safety are required to be zero or positive throughout all events associated with the manufacturing, acceptance test, transportation and flight test operations through scramjet engine operation or AMD.

7.0 FACTORS OF SAFETY

In order to initiate the structural and TPS sizing process and complete the design validation process, factors of safety to be applied in conjunction with limit load conditions to define the ultimate and yield design load conditions needed to be defined. The values derived also needed to be responsive to the intended techniques applied for validation. Design validation techniques generally fall into 5 categories: analysis, test, inspection, demonstration and similarity [3]. In addition, factors of safety used for applied mechanical loads can be significantly different if an applicable full scale ground validation test is performed. If ground test is used for validation, then it is required that the test article survive test while loaded in a manner to produce an equivalent or less margin of safety compared to that predicted in operation. Design factors of safety are also defined to encompass all of the indirect environmental conditions required to size or assess a structural element's integrity. Table 1 identifies those unique design conditions in which factors of safety were defined.

Table 1. Design Conditions in Which Unique Factors of Safety Are Defined

Analytical or Empirically Predicted Condition
Aerodynamic Heating
Flutter Velocity
Random Vibration
Shock
Thermal Load
Mechanical Applied Load
Differential Pressure
Mechanical Relieving Load
Safe Life
Acceptance Test Load

However, it should be noted that any of these factors may be modified on a case-by-case basis depending on the degree to which relevant test data may be available for a particular design load condition or load component in the build-up of a design load condition. In addition, specific components related to flight test termination have different factors of safety applied to them depending on their criticality to range safety requirements.

In addition to the ultimate design factors, some of these load conditions affect yield design criteria for metallic parts where an additional set of design factors and margins of safety are defined and considered. However, those factors are typically derived based on the ultimate factors used and are therefore not discussed explicitly here. Pressurized systems are proofed to the acceptance test load factor. These systems are designed to the maximum number of expected test checkout and operational cycles or a minimum, predefined number of cycles plus the proof cycle, whichever is larger. A safe-life is validated using linear elastic fracture mechanics in conjunction with a ‘leak before burst’ design requirement. Effects of friction are also considered, however, it is never used as a primary load path. Frictional loads are considered in cases where an element design load may be increased as a result of its existence.

One of the key issues debated early in the program was developing an agreement on the factors of safety used in the design of the X-51A for applied mechanical and pressure loads. Boeing proposed a program that included a structural element validation by analysis to avoid the costs and schedule impacts associated with a dedicated full scale static structural ground test. The proposed design factor to be used for applied ultimate mechanical and pressure loads in an unmanned vehicle was 2.0 which is also commonly referred to as a ‘no-test’ factor of safety. This factor is based on a heritage of applications in the development of aerospace vehicles at Boeing-HB. This level of ‘no-test’ factor has been used successfully in programs that included 1) elements of production hardware, such as the Delta II, III & IV space launch vehicles and GPS Block IIF satellites, 2) demonstrator hardware such as the Orbital Express, and 3) on experimental vehicles such as the Delta Clipper Experimental (DC-X). AFRL project support engineering, however, preferred a factor of safety of 2.35 based on their heritage use of ‘no-test’ factors. A compromise was reached in which an ultimate design factor of safety of 2.0 is used and supported by a static structural ground test. The ground test concept was streamlined, however, to facilitate a level of structural testing to validate the load transfer modeling throughout the vehicle while not risking it to test levels that may create conditions where yielding would occur. A test level of 115% of limit load was selected for a test configuration that would simulate a critical load event and configuration. The test setup is shown in Figure 6. As a precaution to reduce the influence of test risk on the flight vehicle, load cases were developed that simulated the test configuration and folded into the design load cases for validation analysis to ensure that a factor of 2.0 was maintained including the non-optimum effects of the test load conditions. This was felt to be important as the test configuration represents discrete load points to create a shear and moment envelope while the actual flight loads are more distributed being a result of continuously distributed inertial and aerodynamic load components. The planned structural test success criteria are as follows:

1. Strain and deflection gage data can be correlated to within a 10% fractional uncertainty when compared to the AVD global FEA data
2. No significant hysteresis is noted as a result of loading and unloading
3. No permanent geometric deflections are noted

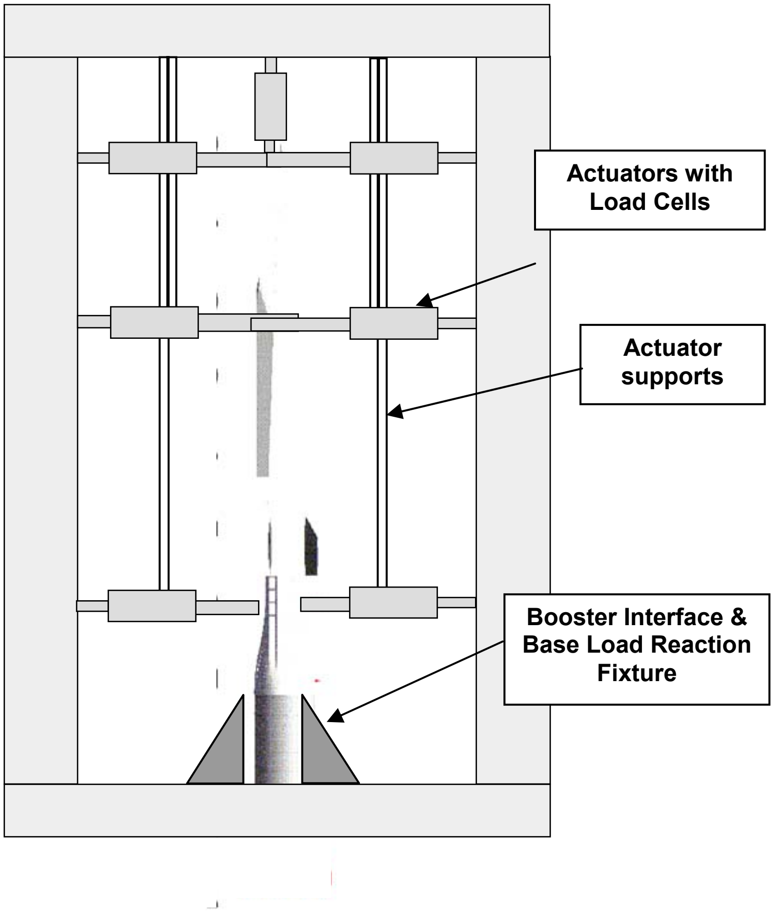

Figure 6. Test Setup Concept for Static Loads Test

The ultimate goal of both the X-51A project office and contractor is to achieve similar, high levels of reliability whether a lower factor of safety (~1.25) is used in conjunction with analysis and a full-up ground test program or whether a higher factor of safety (~2.0) is used in conjunction with analysis only. The optimum method remains a subject dominated by heritage, judgment and experience.

In order to shed some light on the subject however, a past trade study at Boeing-HB was resurrected to address the issue. The purpose of this previous study was to address the use of probabilistic methods as a means of advancing optimization techniques to increase air vehicle performance by reducing structural design factors and thus reducing structural weight. However, it was concluded at the time that full implementation of probabilistic design integrity analysis remains unreachable simply due to the shear computational volume required in a Monte Carlo analysis to have confidence in fully assessing all of the associated and interrelated parameters. However, in this past analysis some insight was gained to illustrate and obtain a level of confidence in the 'no-test' factor approach. A limited, simplified reliability analysis was performed on an air vehicle structural part to determine the effects of principle uncertainties involved in the structural integrity process. The factors considered and their estimated uncertainties were combined in a probabilistic manner to estimate the effect of factor of safety on the component reliability [4]. Factors and uncertainties considered in the process included the 1) vehicle flight performance level effects of dynamic pressure, angle of attack, distributed aerodynamic coefficients, 2) vehicle mass properties, dimensional characteristics as well as the effects of modeling and material properties. For each one of these parameters a nominal and a 3-sigma fractional uncertainty value was defined as shown in Figure 7. Although nominal values are available through direct analytical or empirical models, expert opinions were solicited to define the fractional uncertainties for those parameters where limited data existed. Each parameter variation was assumed to be normally distributed and mutually exclusive with the other parameter variations. The parameters were mathematically combined to define an allowable load and its uncertainty and compare it with the applied load and its uncertainty [5]. The probabilistic tails were combined to define an overlap region to represent the probability of failure or one minus the probability of failure to represent the reliability. The end result was a model that could be exercised to relate the factor of safety used (i.e. relationship of the nominal load to the nominal allowable) and the resulting reliability. As can be seen in Figure 7 an important factor that tends to dominate the results is the effect of modeling uncertainty depending on whether full scale static test data is available. The fractional uncertainty of model validation remains a highly subjective point as experience remains as the best gage of this relationship. Figure 8 represents the resulting relationships of reliability and factors of safety depending on whether modeling uncertainty is reduced as a result of a structural test. There are two important results of this analysis. First, it appears that a similar reliability can be attainted using the ‘test’ and ‘no test’ factor of safety approach proposed. For instance, the component reliability for a design factor of safety of 1.25 with full structural test validation is similar to a ‘no-test’ factor of safety of 2 to 2.25. Secondly, reliability grows at a much faster rate using a ‘test’ approach as opposed to a ‘no-test’ approach which strongly suggests that some level of structural test validation is of value if affordable.

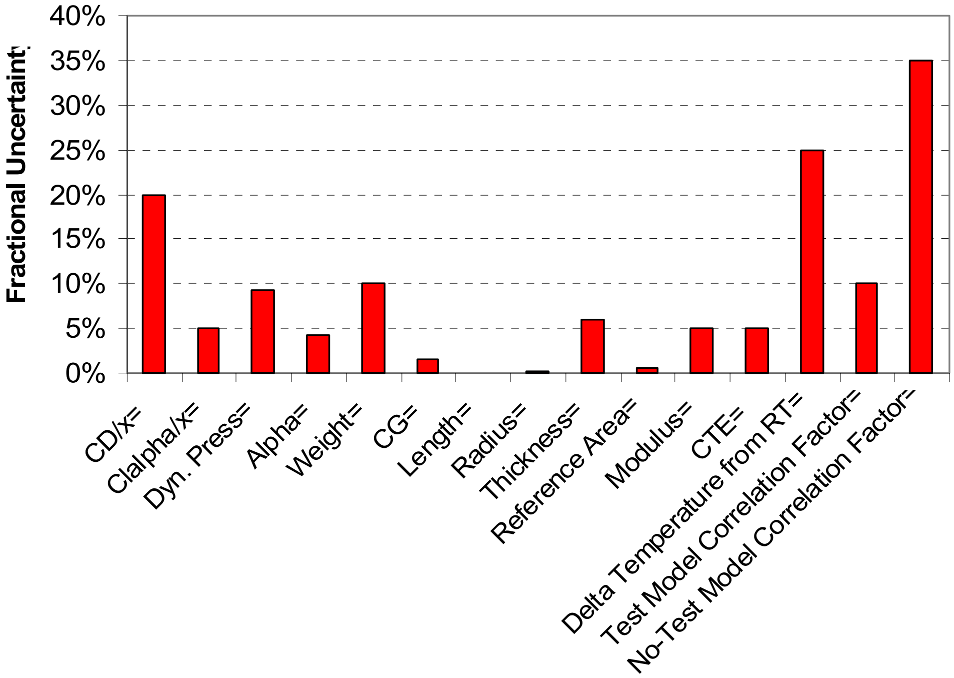

Figure 7. Fractional Uncertainties Considered in Reliability Analysis

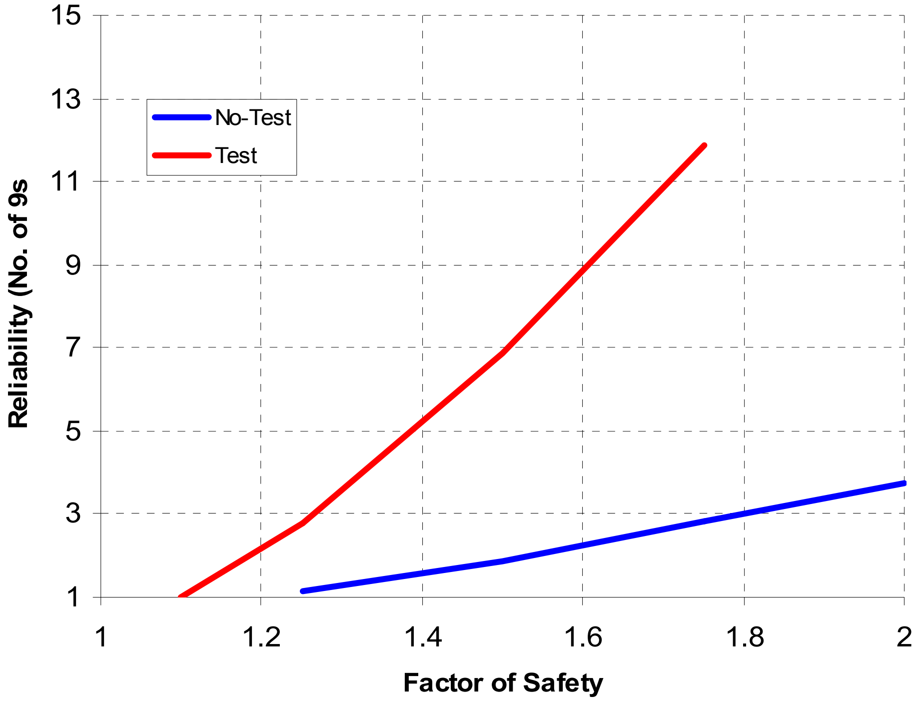

Figure 8. Component Reliability versus Factor of Safety

8.0 SUMMARY

The following points can be made to summarize the preceding discussion.

1. Flight test is the natural and logical next step in the evolution of scramjet engine development.
2. The X-51A flight demonstrator meets the requirements associated with the requirements of scramjet engine flight testing.
3. A concise, well structured airframe design synthesis and evaluation process has been defined that meets the requirements of the X-51A program.
4. Airframe structural validation by using test or 'no-test' factors of safety are valid means to achieving high levels of airframe reliability.

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