STRUCTURAL INTEGRITY CHALLENGES

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The past success of the U.S. Air Force Structural Integrity Program is illustrated by the reduction in the number of catastrophic structural failures over the past thirty years. However, there are still many challenges that face the structures engineer. Several challenges are discussed that appear to be the most dominant for current aircraft as well as for future aircraft. There are aging aircraft issues, aircraft exposed to buffet environments, hypersonic vehicles structures, "smart" technology and affordability. Some current activities are described to illustrate progress toward solutions to these challenges.

INTRODUCTION

The Aircraft Structural Integrity Program (ASIP) has served the USAF well. It is a cradle to grave philosophy with sufficient flexibility to permit continued upgrading as new technology and new ideas emerge. As we look to the future, several areas appear to be particularly challenging. These are the aging aircraft issue and buffeting effects on current aircraft, hypersonic structures technology, "smart" technology for vehicles as well as structures, and affordability. The implications of these areas on aeronautical fatigue will also be discussed.

Aircraft Structural Integrity Program

Prior to 1958, aircraft design was based upon static strength requirements. A deficiency in this design philosophy was that it did not account for material and structural degradation which often occurred due to repeated (fatigue) loadings.

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Consequently, numerous structural cracking problems occurred which were attributed to structural fatigue. To alleviate these cracking problems, the United States Air Force developed and implemented the original Aircraft Structural Integrity Program (ASIP) in 1958. ASIP was first based on a fatigue-crack-initiation approach and was moderately successful. However, some fatigue cracking problems continued to occur which detrimentally affected aircraft structural safety. In the early 70's, it became evident that a limitation of the fatigue-crack-initiation approach was that it did not account for flaws and defects that often exist in aircraft structure as it comes off the production line. Such imperfections can be inherent to the material or introduced during manufacturing and assembly of the airframe. In order to account for these imperfections during the design process, the ASIP philosophy was changed in 1975 (Ref 1) from a fatigue-crack-initiation approach to a fracture-mechanics (fatigue-crack-growth) approach. This new ASIP philosophy which incorporates "Damage Tolerance" includes the assumption that imperfections are present in an airframe as soon as it enters service. Airframe contractors are now required to analytically and experimentally demonstrate that the assumed initial fatigue cracks will not grow to critical sizes and cause failure of the airframe during its design service life. The fracture mechanics based methods required to implement the current ASIP are a product of the Wright Laboratory's Flight Dynamics Directorate's technology program. (Figure 1)

The Flight Dynamics Directorate developed much of the technology currently used in the very successful Air Force Aircraft Structural Integrity Program (ASIP). The current ASIP design philosophy, based on a fracture-mechanics (fatigue-crack-growth) approach, has provided dramatic improvements in aircraft structural safety as compared to that obtained using a prior ASIP philosophy based on fatigue-crack-initiation. During the 15-year time period between 1960 and 1975, when the prior ASIP philosophy was in effect, there were a total of seventeen Class A structural failure mishaps for Air Force aircraft (involved a fatality, $1 million or more in property damage, or aircraft damage beyond economic repair or total destruction). For the following 15-year interval 1975-1990, with the current ASIP philosophy in effect, the total number of Class A failures was five. Furthermore, it should be noted that two of the five failures that occurred between 1975 and 1990 involved older aircraft that had not been certified using the current ASIP philosophy. Taking this into account, the current ASIP design philosophy actually reduced Class A structural failures by 84 percent. It is readily apparent that the current ASIP is extremely effective in ensuring the structural safety of Air Force aircraft. This enormous success resulted in ASIP being used as a model for formulating similar integrity programs for engines (ENSIP), avionics (AVIP) and mechanical subsystems (MECSIP). In addition, ASIP philosophy for ensuring structural safety is gradually being adopted by numerous agencies, both military and commercial, throughout the world. (Figure 2)

The current ASIP philosophy (fracture-mechanics approach) represents a significant improvement over the prior philosophy (fatigue-crack-initiation approach) for ensuring the structural safety of Air Force aircraft. Today's aircraft are designed for increased structural safety which translates into increased operational readiness.

Risk Analysis of Aging Aircraft

Eighty percent of the USAF aircraft inventory in the year 2000 is currently flying, and some of these aircraft have exceeded or are approaching twenty five years of age.

TABLE 1 - Inventory of Aging Aircraft

Aircraft	Total Number	Average Age
B-52	262	29
C/KC-135	735	28
T-37	608	27
T-38	808	23
C-141	271	23
T-41	100	22
C-130	728	21
OV-10	78	20
F-4	1569	20
F/FB-111	392	18
A-7	369	16
C-5	116	13

Because of the excessive costs associated with designing and procuring new aircraft, these operational aircraft are often required to perform considerably beyond their design service lives. Degradation in the structural integrity of these aircraft can increase with time, resulting in higher probabilities of failure and increased maintenance and repair costs. This is illustrated by recent structural problems encountered by aging commercial aircraft. The best example of this is the recent Aloha Airlines incident (Figure 3). Research is needed to determine the impact on the structural integrity of these aircraft due to material property changes, corrosion, fatigue cracking, changes with mission usage, frequency of inspection, etc. and an extensive program is underway sponsored by the U.S. Department of Transportation. A procedure is required for determining the residual strength, remaining structural life, and associated confidence levels or risks for these aging aircraft as a function of time. One approach to accomplish the above is a probabilistic fracture mechanics approach that includes the effects of corrosion and multiple-site damage. Burns, et. al., describe such a procedure (Ref 2). Experimental data are needed to evaluate the accuracy of this approach to predict the degradation in structural integrity of the aircraft. If this research is successful, a capability will exist to accurately predict the current state of damage of aging aircraft and the risks involved in keeping these aircraft in service beyond their design service lives versus replacing them with new aircraft.

Buffeted Aircraft

Lee and Brown, Ref 3, state that modern combat aircraft must be capable of flying under conditions of separated flows in order to achieve high manoeuvrability. Aircraft structures under such conditions are subject to random aerodynamic loads arising from pressure fluctuations due to flow separations and/or impact of vortical flows on the structures. An example of this type of severe random aerodynamic loading is found in the F/A-18 vertical tail buffeting when the highly turbulent flows, resulting from bursting of the leading edge extension (LEX) vortices, impact the vertical fins (Figure 4). The effect of buffet loads on structural integrity of the vertical fins is currently a major concern.

While this phenomena is usually associated with twin tailed aircraft, recent experience illustrates that buffeting can be very severe on single vertical tail aircraft such as the X-29. Harter, Ref 4, describes vertical tail buffet conditions experienced during X-29 flights at angles of attack between 20 and 35 degrees. The procedures followed to protect the structural integrity included measuring local in-flight strains and conducting crack growth analysis on a day-to-day basis.

Ground testing of structures exposed to maneuver as well as dynamic loads can lead to complex set-ups as described by Graham and Watters (Ref 5). The Australian Aeronautical Research Laboratory (ARL) is preparing for a full scale fatigue test of the F/A-18 aft fuselage and empennage in collaboration with Canada who will test the center fuselage and wing. These tests will provide durability and damage tolerance data for the Royal Australian Air Force and Canadian Forces to enable economic and safe management of their F/A-18 fleets.

ARL has developed techniques using airsprings and hydraulic shakers to apply combined maneuvers and dynamic loads to the four tail surfaces of the test article. The test article is shown in Figure 5 and the loading scheme is shown in Figure 6.

The USAF has undertaken a program to apply passive damping technology to extend the lifetime of the upper outer wingskins on the F-15 aircraft. These wingskins developed skin cracks due to fatigue from exposure to the turbulent flow. Various methods of applying passive damping were studied and the results showed that the lifetime of the skins could be greatly extended, depending on the method.

This program has included field measurements of dynamic response, laboratory testing under dynamic inputs, testing of the results of various damping treatments under load and with various temperatures, and will involve the confirmation of the suitability of the damping treatment selected.

Figure 7 shows a typical damping treatment configuration on the interior F-15 wing. The dynamic response before and after treatment indicates that the lifetime will be increased significantly.

Hypersonic Structures Technology

Hypervelocity vehicles encounter extreme-hostile environments with high temperatures exceeding 3000°F and low temperatures reaching 423°F below zero. Such environments, when combined with aerodynamic loads at high mach numbers, greatly affect the structural integrity of aerospace vehicles.

The assurance of the structural integrity of structures subjected to extreme temperatures requires experimental approaches to determine the thermal-mechanical load effects on damage and damage growth resistance of advanced materials, such as aluminum, titanium, titanium aluminides and organic/inorganic composites. Also analytic approaches must be pursued to assess the structural life under simulated flight loads and temperatures.

It is necessary for modern hypersonic vehicles to fly for sustained periods of time at high dynamic pressures in order to achieve the necessary level of propulsion system performance. The resulting trajectories will be subject to extreme thermal, aerodynamic pressure and acoustic environments. Typical hypersonic vehicle "acreage" structural design environments resulting from these envelopes are shown in Figure 8 and Figure 9. (Ref 6)

While for the majority of the vehicle it is possible to utilize hot structure or thermally protected structure, all areas of the vehicle that experience heat fluxes over approximately 50 BTU/ft^2/sec will require active cooling. Hypersonic engine leading edges may experience heat fluxes up to three orders of magnitude higher than the peak heat flux on the space shuttle nose during reentry. The airframe leading edges are also extreme when compared to the space shuttle ranging from approximately 900 BTU/ft^2/sec. The combination of these design environments and the desire for lightweight structures has created one of the most difficult design challenges ever faced by aircraft designers.

Harmon and Saff (Ref 7) developed a fracture mechanics based life prediction procedure for hypersonic airframe subjected to combined mechanical and thermal load profiles (Figure 10). The analysis models crack growth behavior in metals and accounts for the effects of temperature on yield strength, fracture toughness, environmental effects and sustained load at elevated temperatures on crack growth rate.

Figure 11 represents an advanced fighter mission with a peak temperature of 800°F. The load spectrum is characterized by high temperatures and moderate loads during supersonic cruise and dash. The large, infrequent overloads typical of combat fighter aircraft were assumed to occur at lower temperatures in the subsonic and transonic regimes.

To develop this spectrum, a mission profile was created for a Mach 3.0-3.5 fighter. This profile was divided into seven mission segments which include take-off/climb, initial cruise, track/intercept, weapon delivery, maximum acceleration/ dash, return cruise, and approach/landing.

The aerospace vehicle load and temperature spectrum was developed using a procedure similar to that used in developing the advanced fighter spectrum. The load-time history for the aerospace vehicle was used under constant temperature in the model development tests. The combined load and temperature profiles were used in the verification tests. (Figure 12)

The aerospace vehicle spectrum consists of two 30 minute missions per flight hour. The load spectrum for each mission contains only the portion of the mission within the atmosphere. One thermal cycle is applied for each exit or entry of the atmosphere.

The first mission contains an orbital plane change, known as a synergetic turn in which the vehicle leaves then re-enters the atmosphere twice during the mission. The second mission represents a cruise mission with high altitude maneuvers. The vehicle does not leave the atmosphere in this mission. The combination of these two missions provided a rigorous load-temperature-time profile for testing.

A total of twenty-four verification tests were completed. The test results and the final predictions are listed in Figure 13. The test life and the predicted life represent the number of flight hours required to achieve the crack length specified in the column marked "c_f." They are not lives to failure. A comparison of life to failure can be misleading because it does not indicate the accuracy of the crack growth rate prediction.

In general, the methods used predict the effects of temperature and environment on crack growth rate fairly accurately. Figure 14 summarizes the number of predicted crack growth lives that were within 20 percent of the test data.

The structural efficiency of advanced materials for systems experiencing high temperatures is illustrated in Figure 15 (Ref 8). Figure 16 correlates the materials with Mach number and altitudes. The introduction of these advanced materials into systems can lead to new failure modes that must be investigated. The cracking patterns of metal matrix composite, shown in Figure 17 for room temperature fatigue and elevated temperature fatigue, illustrate the changes that can occur.

Experimental techniques are vital to the development of aerospace vehicles experiencing extreme environments. Actively cooled nose cap concepts such as illustrated in Figure 18 (Ref 9) have been tested under radiant heating using the Vortek heating system (Figure 19). The nose cap has withstood heating rates of 1200 BTU/ft^2-sec. The Vortek Arc heating system concentrates heat (approximately 1000 BTU/ft^2/sec) over a relatively small area (approximately 1" x 4") for a single arc lamp.

Figure 20 illustrates an integral liquid hydrogen tank component. It is a flight weight design of welded and brazed Rene 41 honeycomb construction approximately 30" by 80". The tests have been conducted to simulate the load and temperatures experienced during re-entry (Figure 21). Exit testing will demonstrate liquid hydrogen containment that will be accomplished in the Figure 22 facility. In this facility, structures of the size illustrated in Figure 20 will be tested with liquid hydrogen, under load and temperatures up to 2500°F.

Combined environmental test techniques are required for many locations on a typical hypersonic vehicle where mechanical loads, extreme temperatures and high acoustic levels are expected. The development of a prototype facility with test panel capability of approximately 10" x 10" is underway at Wright

Laboratory. The goal is to obtain an overall sound pressure level of 180 dB over the frequency range of 50-1500 Hz with temperatures to 2500°F (Figure 23). A much larger facility is in the design phase with the goals as stated in Figure 24. Similar work is underway at IABG, Ottobrun, Germany (Ref 10).

For prototype or X-designated aircraft, flight certification is frequently accomplished by a proof test to design limit load. Flights are then restricted to 80 percent of design limit load. Certification for production aircraft requires full scale tests for static and fatigue certification. Certification for hypersonic vehicles can be expected to follow a similar procedure. However, when consideration is given to full scale testing for vehicles that use cryogens for propulsion, the complexity and cost of full size and complete vehicle testing may be prohibitive. Such a facility, could be expected to cost in the order of 1/2 billion dollars (Ref 11). Alternate ways need to be explored for ground certification of hypersonic vehicle.

"Smart" Technology

Smart Technology is being developed for each subsystem and each discipline used on aircraft. Potential applications include structural health monitoring, threat detection, damage detection, process control during manufacture, embedded antennas, thermal management, signature control, fault detection, flight controls reconfiguration, flight vehicle management, etc. See Figure 25. Structural health monitoring and the analysis of data on board the aircraft for the ASIP individual airplane tracking and the loads/environmental spectra survey is a very attractive application of smart technology. It is anticipated that the percentage of valid data recorded and the timeliness of the results would be greatly improved. Some centralized collection and processing of results would still be necessary for determining overall force wide trends of damage accumulation and for future aircraft design considerations.

Perhaps more important is the integration of "smart" structures technology into a "smart" vehicle where data common to the various subsystems of the aircraft may be shared. Further, direct integration of the technologies could lead to increased performance, lighter weight and less maintenance. For example, structural sensing could be integrated with the flight control system. As maneuvers are accomplished, structural sensing at critical locations could influence the flight controls so that structural limits not be exceeded. This would permit full usage, if desired, of the allowable strength of the structure. Possible reductions in the time honored structural margins might be possible that would lead to further efficiencies in the structure.

Affordability

Acquisition cost is becoming a major consideration in weapon system procurement. One only has to observe the publicity received in the US concerning the cost of the A-12, B-2, ATF and C-17 for example. The affordability of an aircraft system is influenced by such factors as operations and maintenance (including the personnel required), fuel efficiency as well as the acquisition cost. It is doubtful that cost will be the primary consideration for military aircraft, but it is obvious that it has become a major consideration along with performance and supportability. While cost should not be an inhibitor to exploring research ideas, the researcher must be prepared to address the cost issue when transition of the technology to aircraft in development is advocated.

CONCLUSION

Four major structural integrity challenges for the future have been identified. Suitable solutions for these challenges will lead to improved structures for aircraft that will be more efficient and more affordable.

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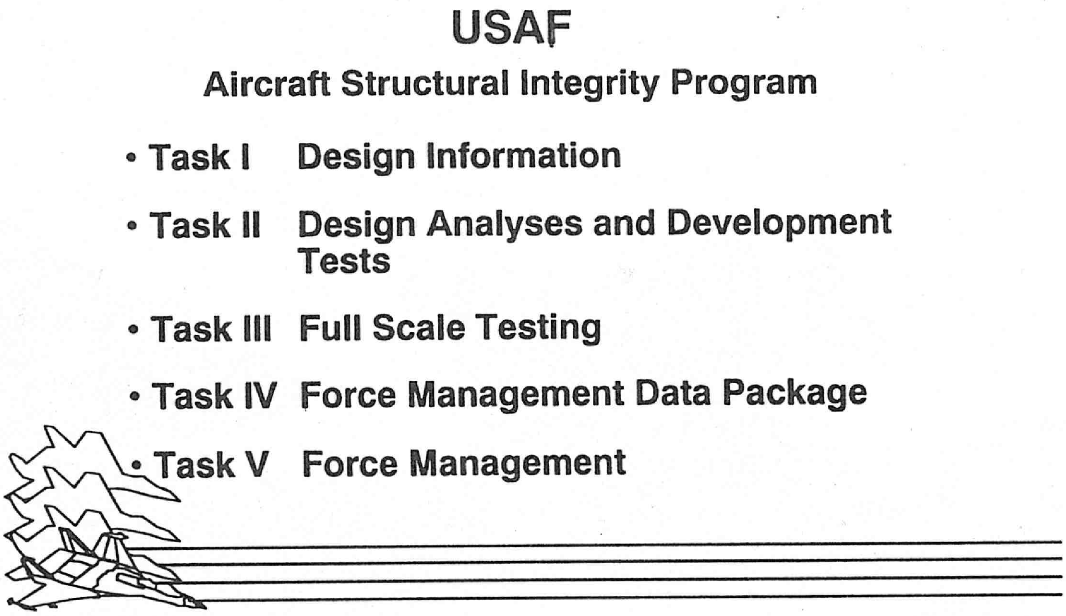


Figure 1 Aircraft Structural Integrity Program

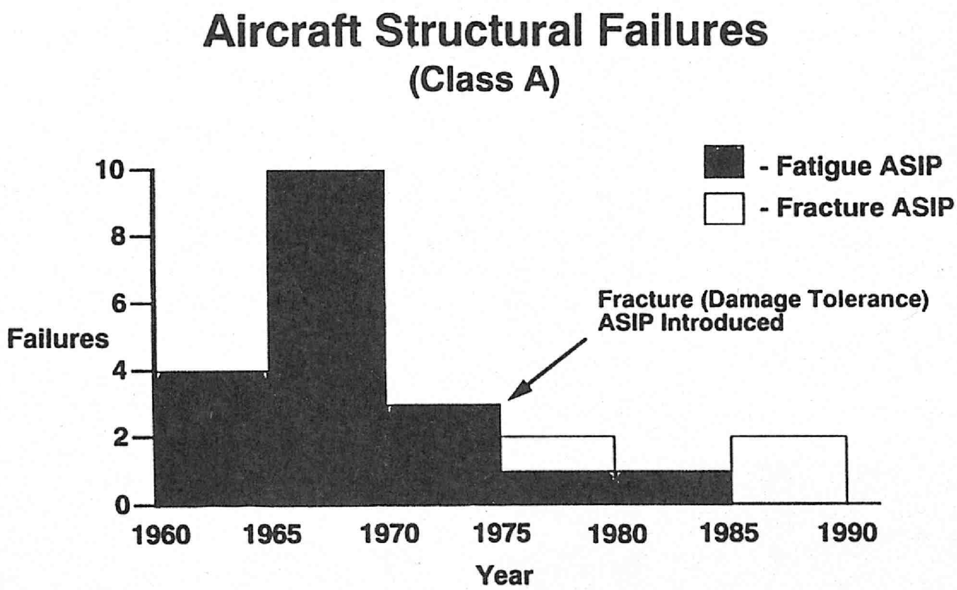
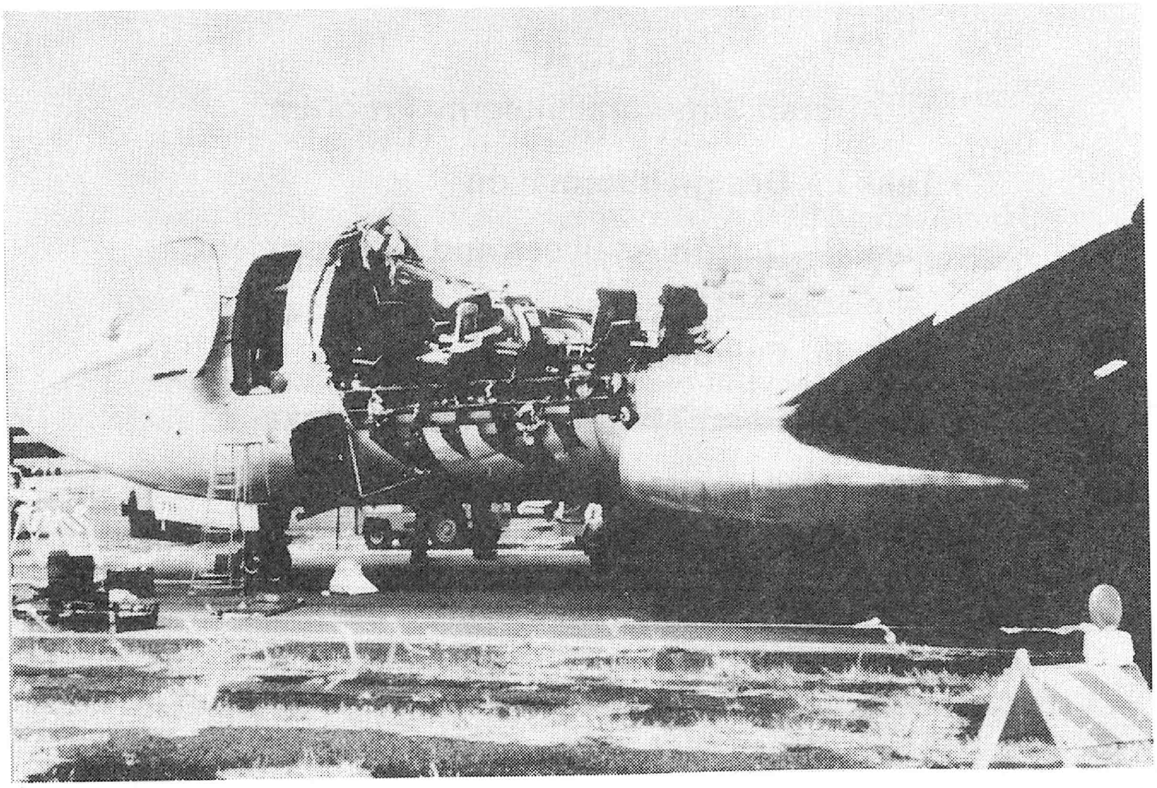


Figure 2 Aircraft Structural Failures



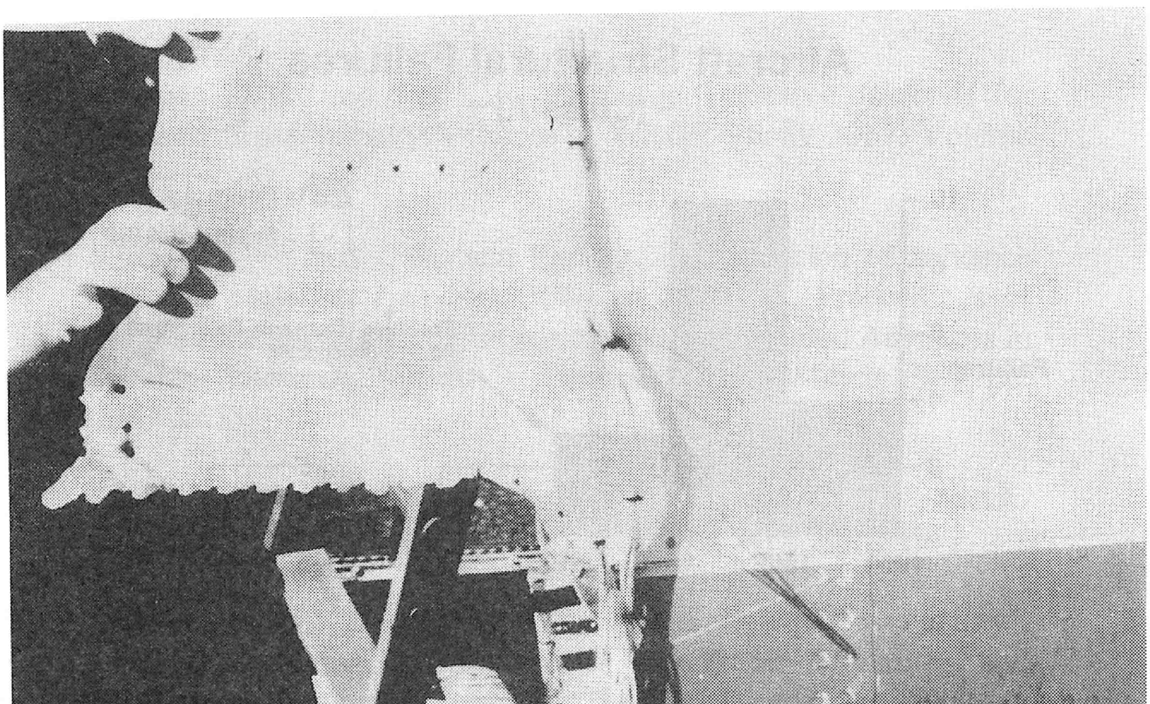


Figure 3 Risk Analysis for
Aging Aircraft

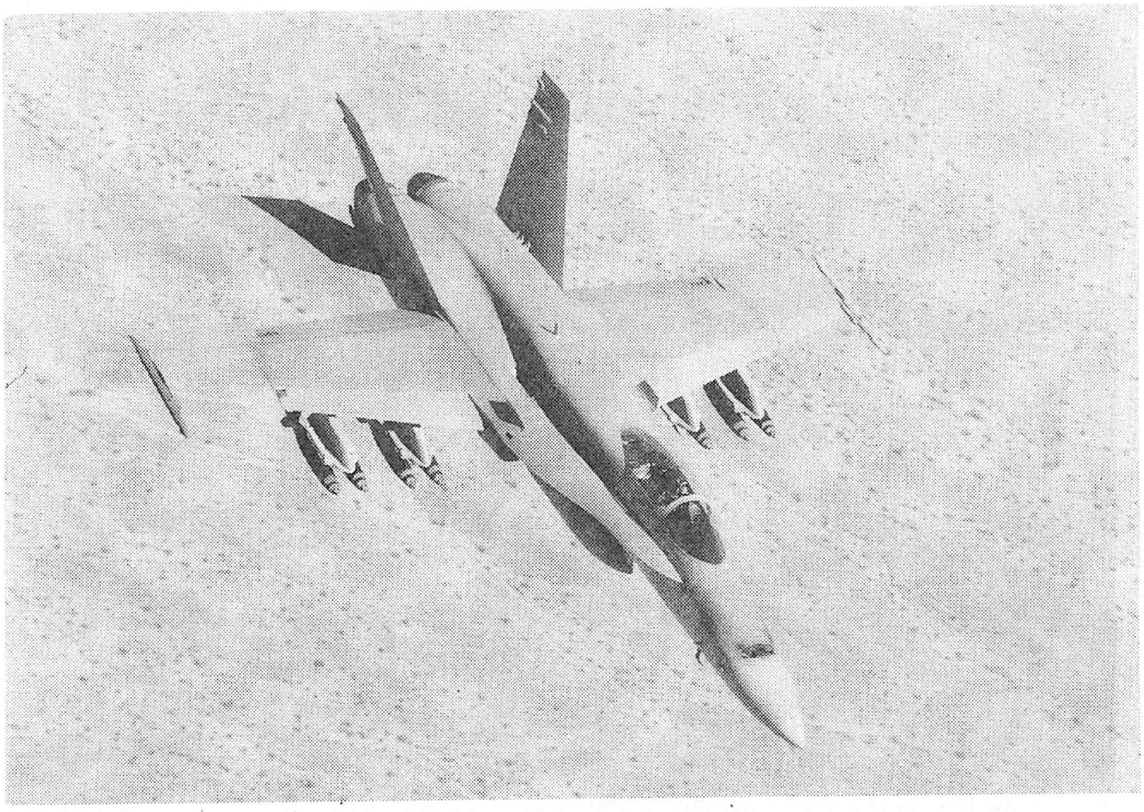


Figure 4 Twin Vertical Tail Buffet

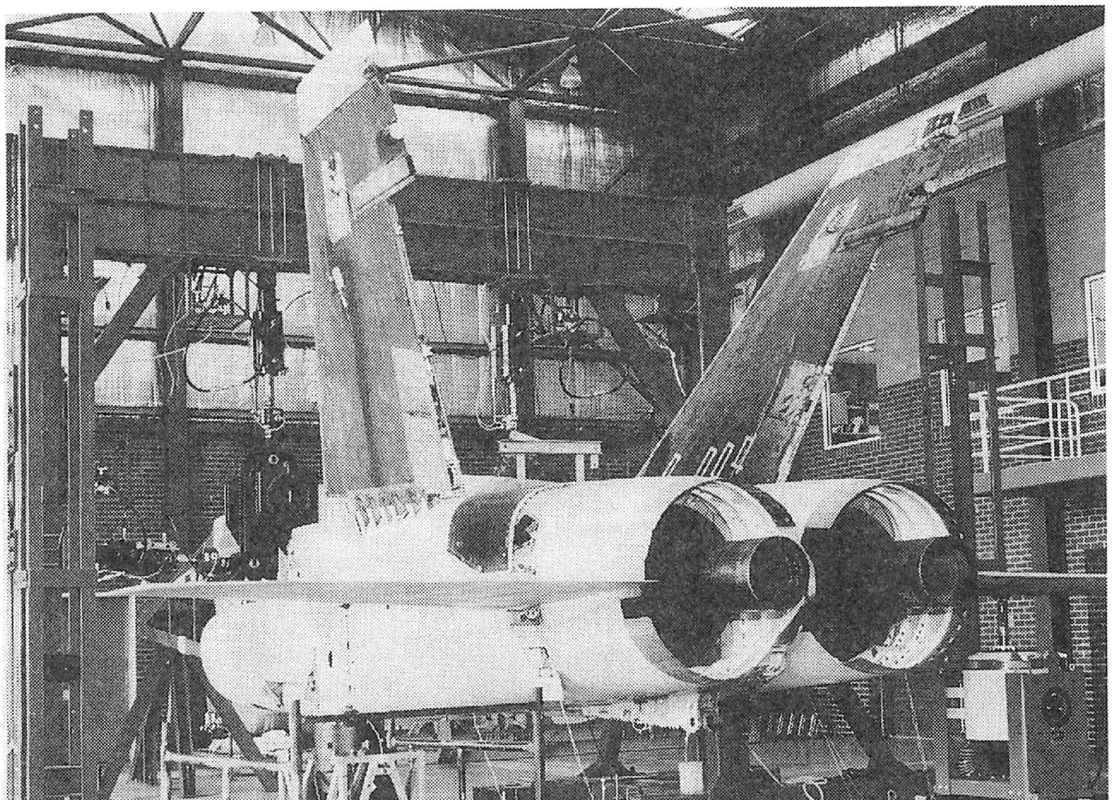


Figure 5 F-18 Test Article

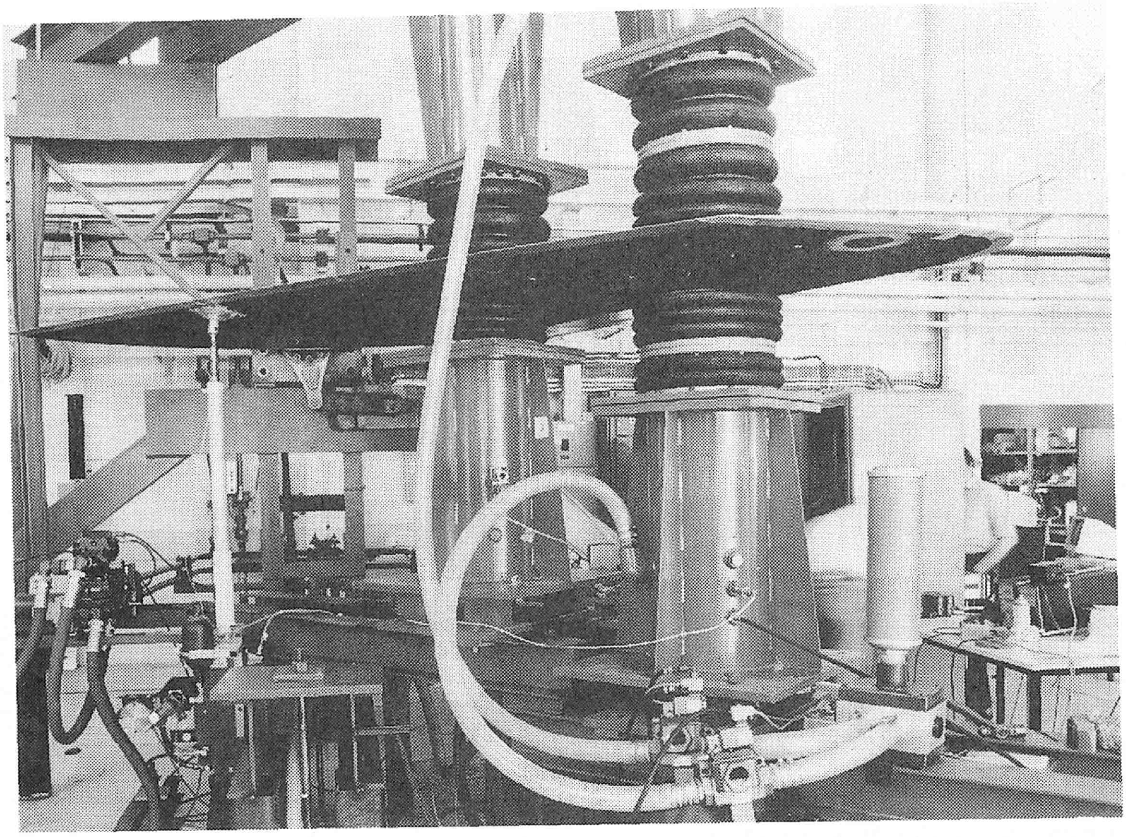


Figure 6 Combined Loading Scheme

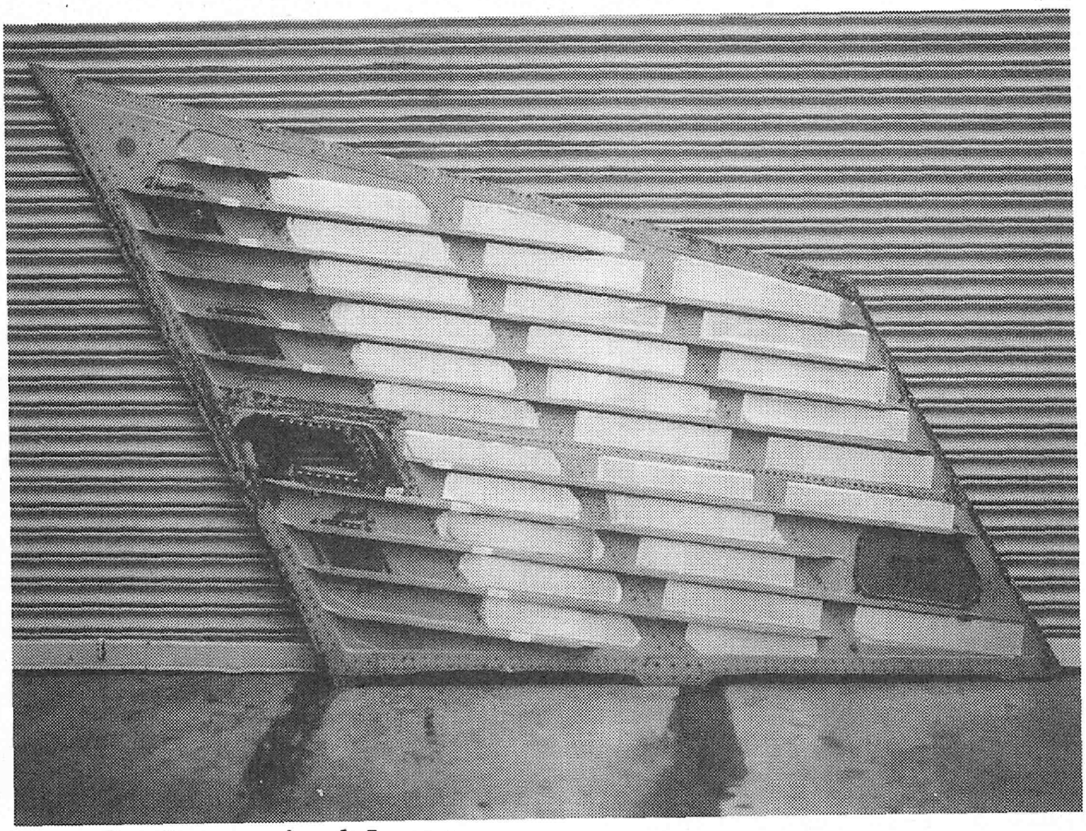
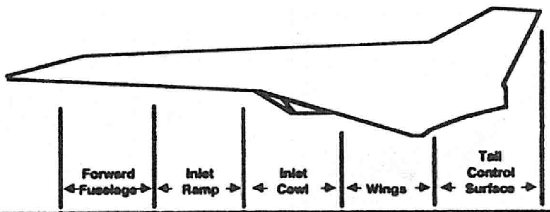


Figure 7 Constrained Layer Damping Treatment

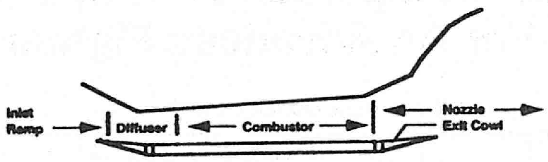
Hypersonic Design Environments



Requirements		Forward Fuselage	Inlet Ramp	Inlet Cowl (External)	Wings	Tail Control Surface
Peak Heat Flux (BTU / Ft^2 Sec)	Ascent	11 to 35	80 to 220	20 to 40	8 to 40	7 to 35
	Descent	8 to 16	6 to 12	8 to 16	8 to 30	5 to 25
Max Aero Pressure (PSF)		70 to 140	150 to 300	250 to 500	250 to 500	500 to 1400
Max Acoustic Pressure (dB)		150 to 160	157 to 165	157 to 165	160 to 178	160 to 178
Max In-Plane Loads (Lb / In.)						
• Longitudinal		200 to 600	-1500 to -2500	25 to 125	900 to 1300	-3000 to -7000
• Transverse		-100 to 300	500 to 1500	-25 to 25	-300 to 300	-1500 to -2500
Design Life						
• Load Cycles		1440	1440	1440	1440	1440
• Operational Life (Hr)		300	300	300	300	300

Figure 8 Hypersonic Design Environments

Hypersonic Design Environments



Requirements		Engine			
		Diffuser	Combustor	Exit Cowl (Internal)	Nozzle
Peak Heat Flux (BTU / Ft^2 Sec)	Ascent	400 to 600	1100 to 1500	300 to 350	150 to 300
	Descent	N/A	N/A	N/A	N/A
Max Aero Pressure (PSF)		1000 to 4000	10800 to 23000	1000 to 1400	1000 to 1400
Max Acoustic Pressure (dB)		160 to 176	16 to 176	160 to 176	160 to 176
Max In-Plane Loads (Lb / In.)					
• Longitudinal		50 to 150	50 to 150	-200 to -800	-200 to -800
• Transverse		50 to 150	50 to 150	-200 to -800	-200 to -800
Design Life					
• Load Cycles		1440	1440	1440	1440
• Operational Life (Hr)		300	300	300	300

Figure 9 Hypersonic Design Environments

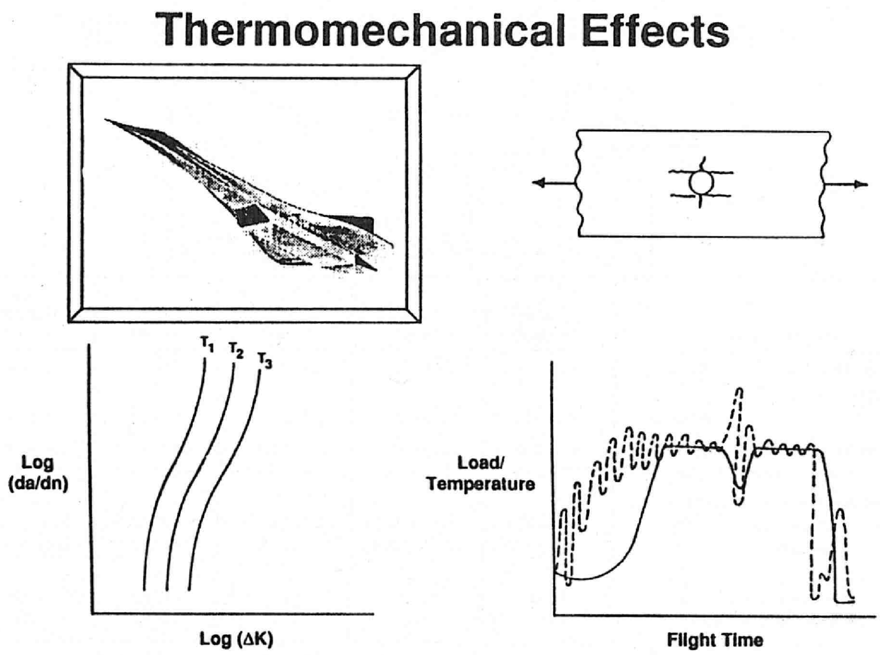


Figure 10 Thermomechanical Effects

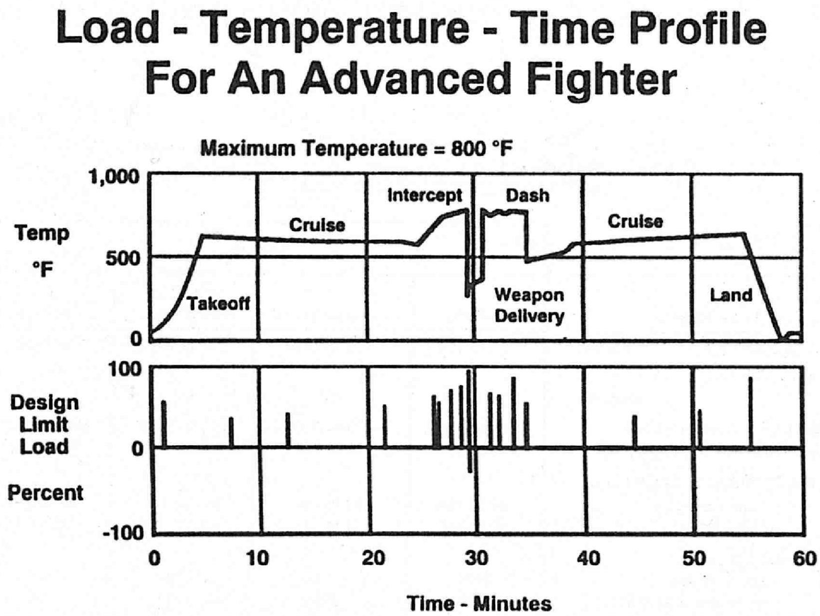


Figure 11 Advanced Fighter Profile

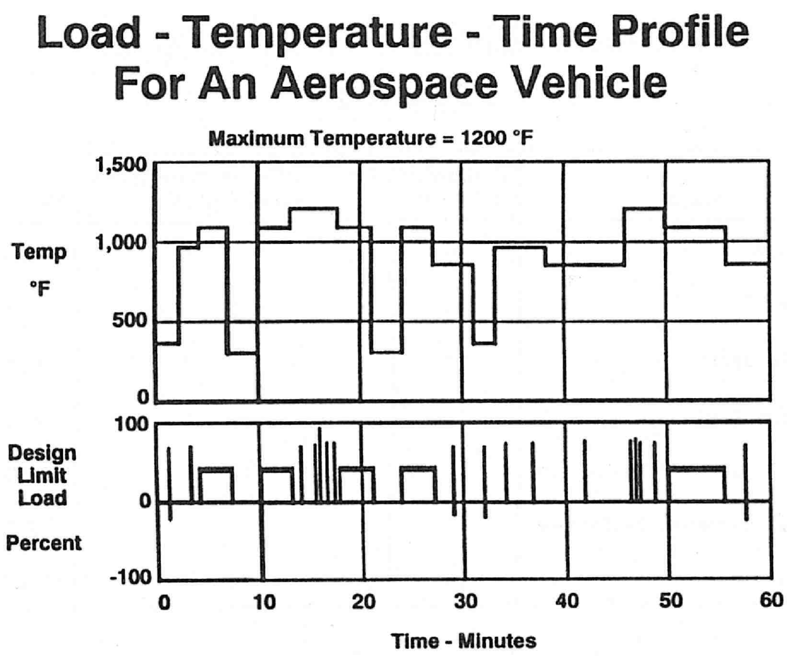


Figure 12 Aerospace Vehicle Profile

Specimen ID	Spectrum	Specimen Type	Stress (ksi)	C_{in} (in.)	C_f (in.)	Predicted Flight Hours	Test Flight Hours	Percent Difference
				6Al-2Sn-4Zr-2Mo Titanium				
Ti-30	AF-C100	CCT	28.0	0.300	0.837	3,052.0	3,400.0	10.2
Ti-31	AF-C100	CCT	28.0	0.300	0.837	3,052.0	3,400.0	10.2
Ti-32	AF-C10	CCT	30.0	0.610	0.817	285.0	425.0	32.9
Ti-36	AF-C100	OHT	29.0	0.350	0.734	1,050.0	1,125.0	6.7
Ti-38	AF-C100	OHT	29.0	0.350	0.734	1,050.0	1,125.0	6.7
Ti-37	AF-C10	OHT	30.0	0.480	0.779	425.0	725.0	41.4
Ti-33	AV-C100	CCT	40.0	0.300	0.894	1,867.0	2,200.0	15.1
Ti-34	AV-C100	CCT	40.0	0.300	0.814	1,820.0	2,778.0	34.5
Ti-35	AV-C10	CCT	40.0	0.470	0.843	803.0	450.0	78.4
Ti-39	AV-C100	OHT	40.0	0.230	0.566	2,900.0**	3,400.0*	14.7**
Ti-40	AV-C100	OHT	40.0	0.230	0.645	3,300.0	3,300.0	0
Ti-41	AV-C10	OHT	40.0	0.450	0.949	2,150.0	1,070.0	100.9
				IN 718				
In-30	AF-C100	CCT	50.0	0.350	0.885	3,053.0	3,400.0	10.2
In-31	AF-C100	CCT	55.0	0.350	0.816	2,055.0	2,125.0	3.3
In-32	AF-C100	CCT	55.0	0.350	0.815	2,055.0	1,750.0	17.4
In-40	AF-C100	OHT	54.0	0.400	0.785	1,050.0	925.0	13.5
In-41	AF-C100	OHT	54.0	0.400	0.785	1,050.0	1,025.0	2.4
In-39	AF-C10	OHT	56.0	0.620	0.777	238.0	170.0	38.8
In-33	AV-C100	CCT	65.0	0.350	0.873	2,233.0	3,550.0	37.1
In-34	AV-C100	CCT	65.0	0.350	0.873	2,233.0	4,000.0	44.2
In-35	AV-C10	CCT	65.0	0.520	0.871	1,053.0	1,025.0	2.7
In-36	AV-C100	OHT	65.0	0.200	0.800	2,733.0	3,000.0	8.9
In-37	AV-C100	OHT	65.0	0.200	0.800	2,733.0	3,350.0	18.4
In-38	AV-C10	OHT	65.0	0.420	0.697	930.0	840.0	10.7

AF - Advanced Fighter Spectrum (1 mission per flight hour)
AF-C10 - Advanced Fighter Spectrum (10 missions per flight hour)
AF-C100 - Advanced Fighter Spectrum (100 missions per flight hour)
AV - Aerospace Vehicle Spectrum (2 missions per flight hour)
AV-C10 - Aerospace Vehicle Spectrum (20 missions per flight hour)
AV-C100 - Aerospace Vehicle Spectrum (200 missions per flight hour
R = 0.90 load cycles removed)

Figure 13 Verification Test Results

Predicted Lives Within 20% Of Test Lives

Category	Number of Specimens	Number of Predictions Within 20% of Test Life	Percent
6-2-4-2 Ti	12	7	58.3
IN 718	12	9	75.0
CCT Specimen	12	7	58.3
OHT Specimen	12	9	75.0
Time Compression Factor = 100	17	14	82.3
Time Compression Factor = 10	7	2	28.5
Overall	24	16	66.7

Figure 14 Accuracy of Predictions

Structural Efficiency Versus Operating Temperature For Several Candidate Materials

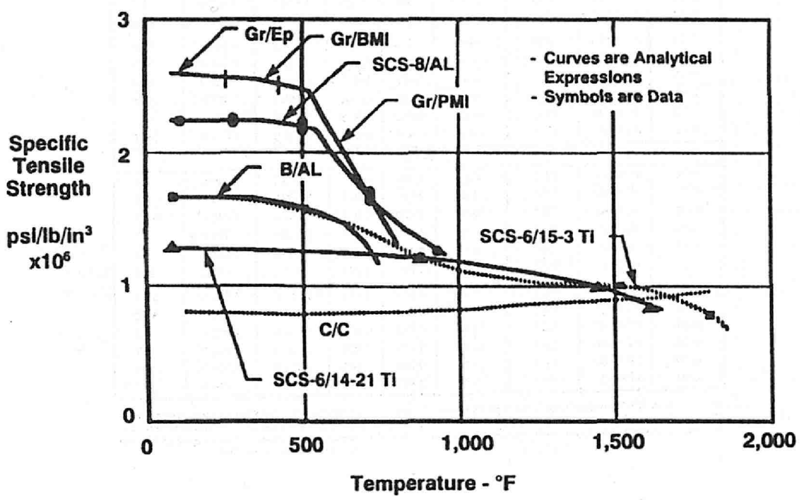


Figure 15 Structural Efficiency of Materials

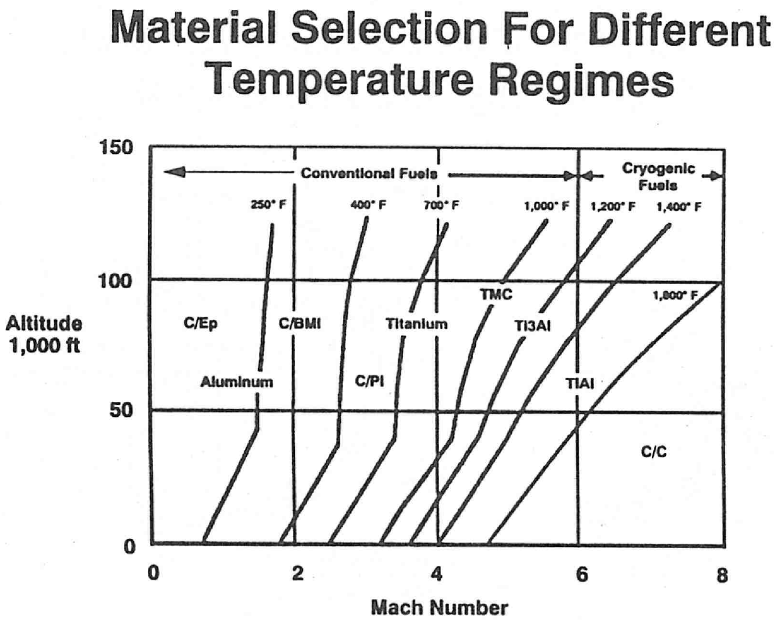


Figure 16 Material Selection

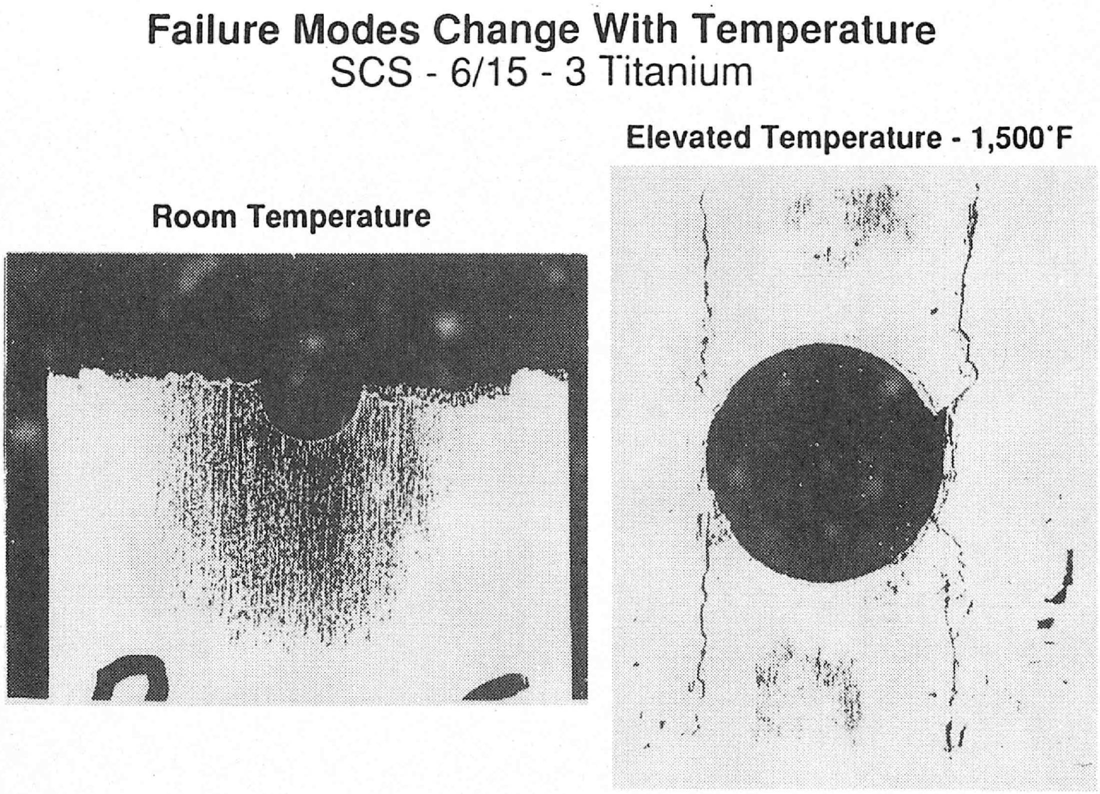


Figure 17 Failure Modes

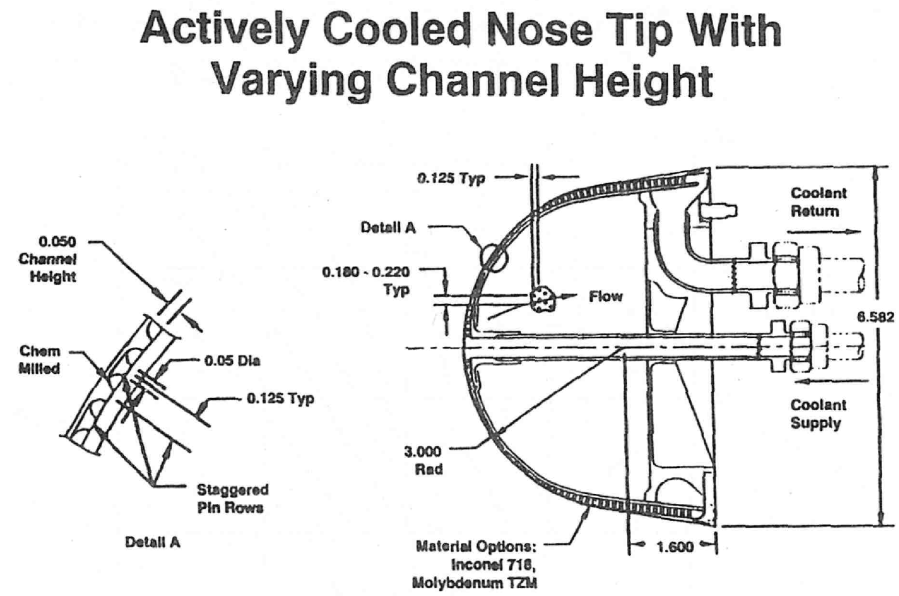


Figure 18 Actively Cooled
Nose Tip

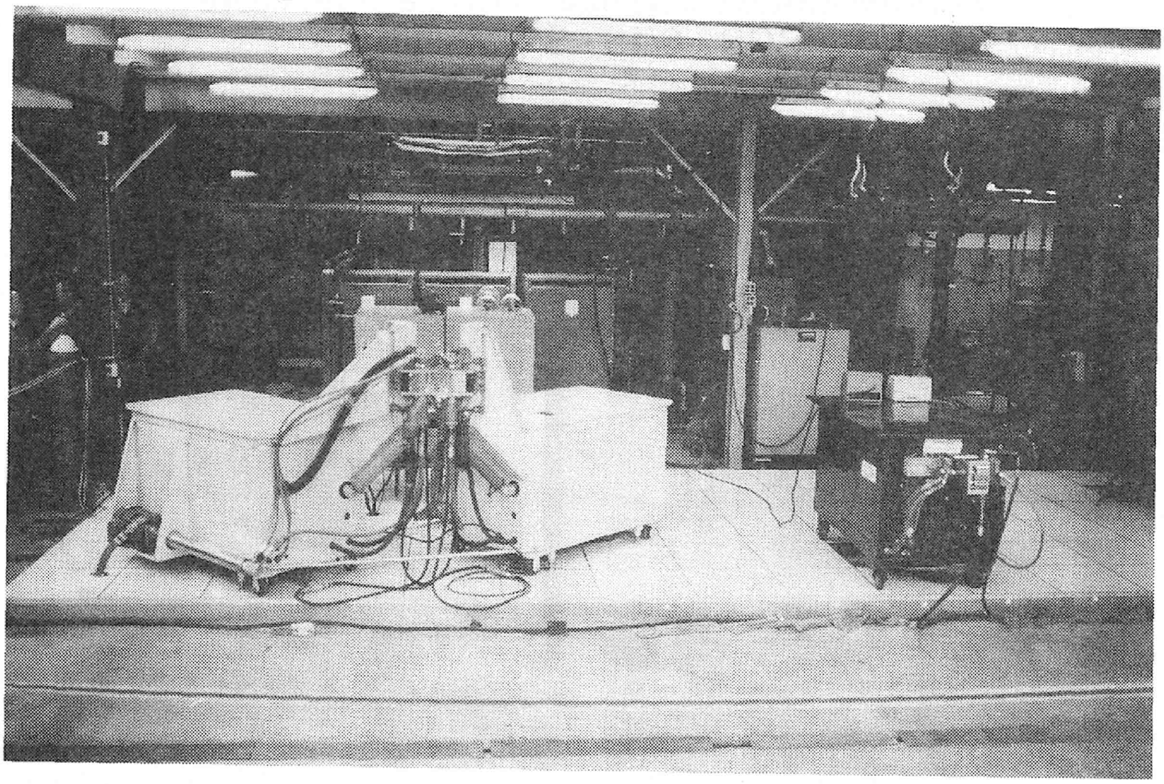


Figure 19 Vortek Heating
System

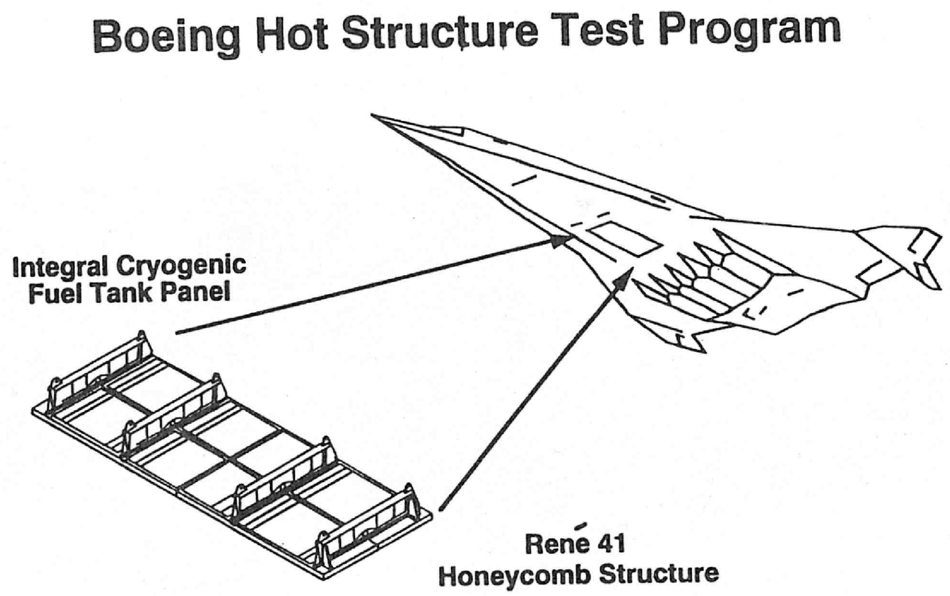


Figure 20 Boeing Hot Structure

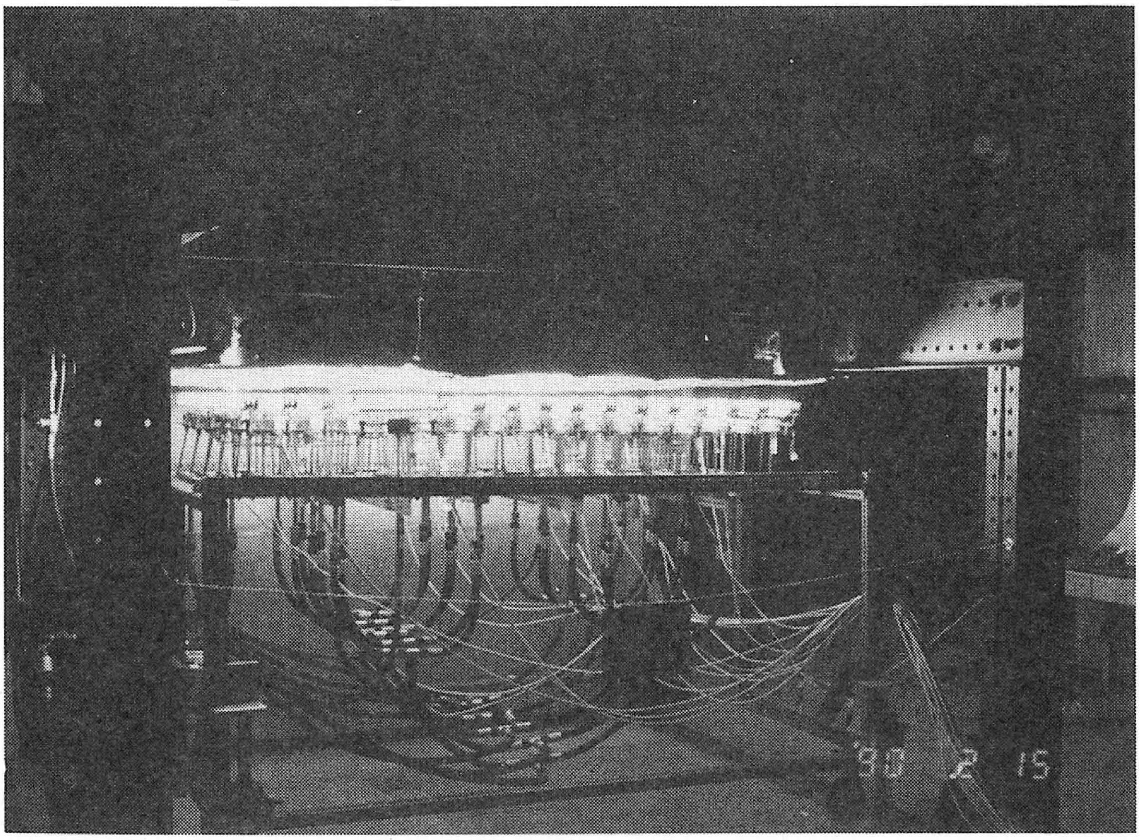


Figure 21 Re-entry Heat & Load Test

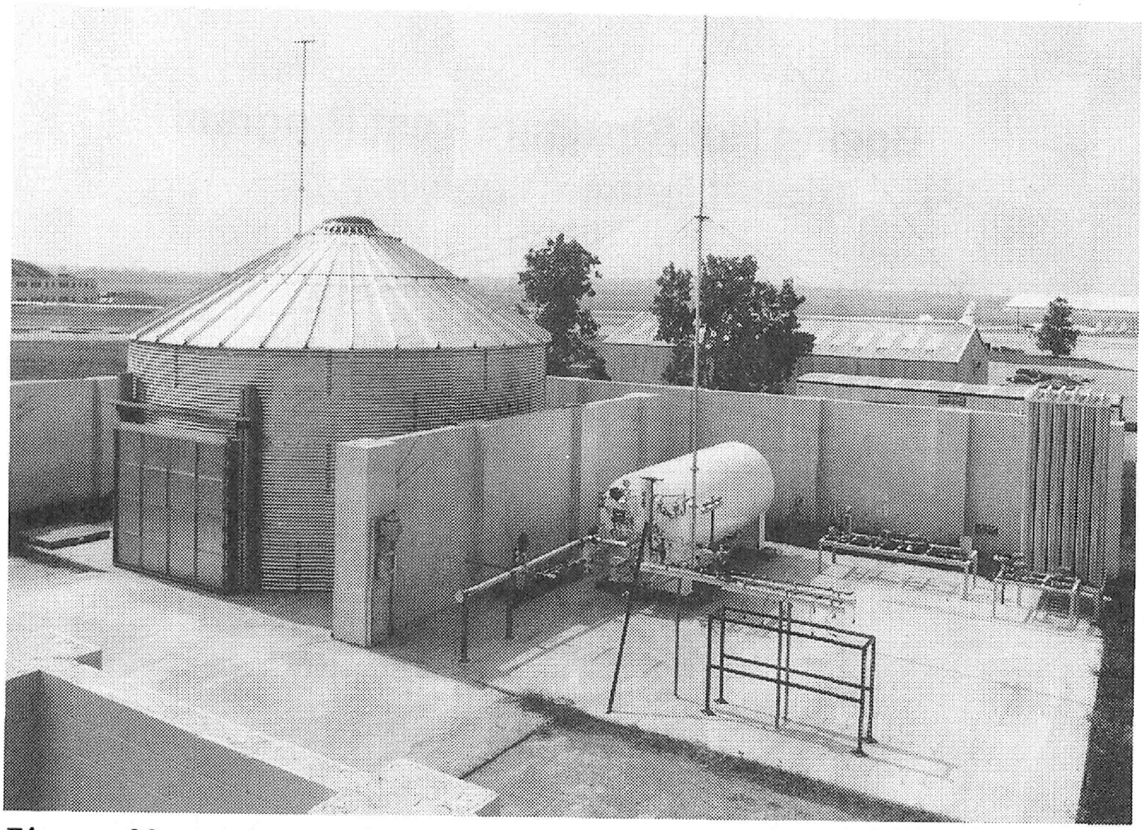


Figure 22 Liquid H_2 Structural Test Facility

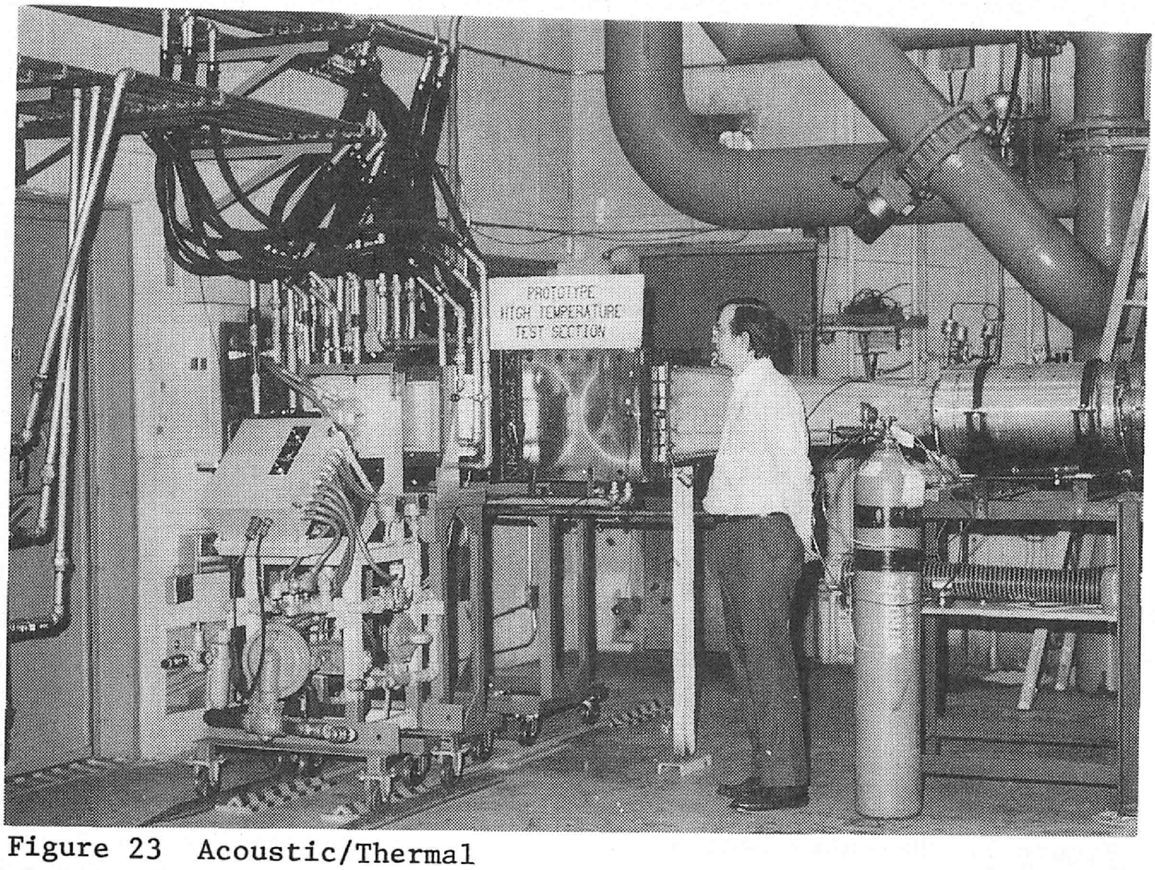


Figure 23 Acoustic/Thermal Test Facility

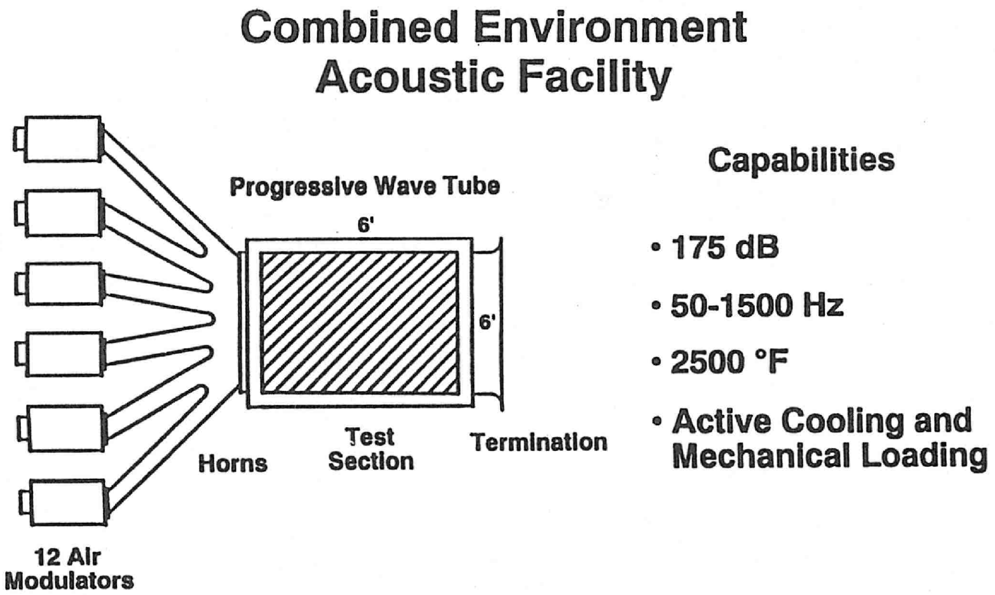


Figure 24 Combined Environment Facility

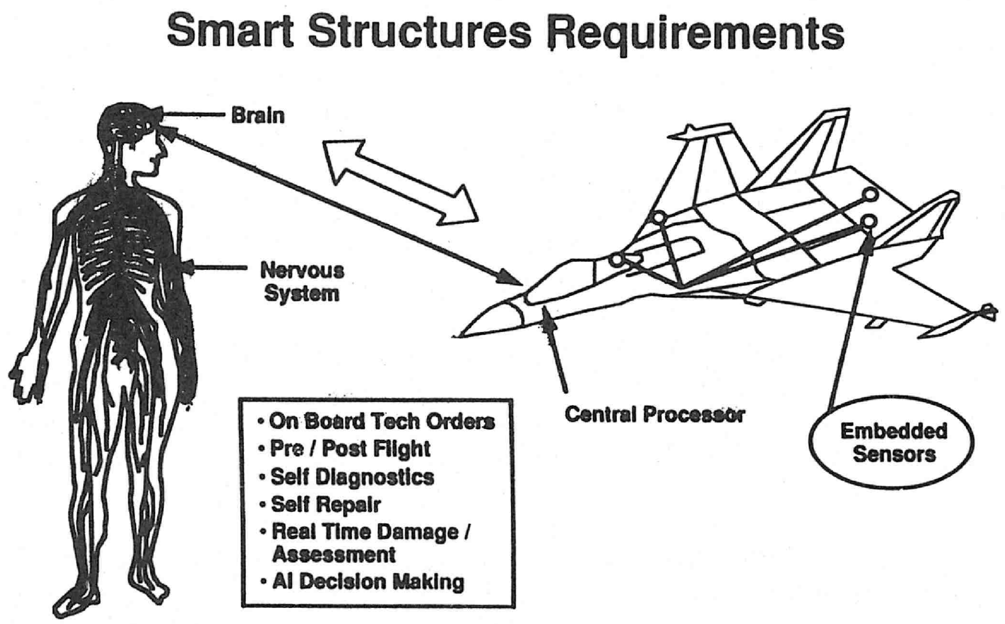


Figure 25 "Smart" Technology