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Consolidation and Analysis of Loading Data in Firefighting Operations

Analysis of Existing Data and Definition of Preliminary Air Tanker and Lead Aircraft Spectra

October 2005

Final Report

U.S. Department of Transportation
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16. Abstract

This report contains documentation and analysis of existing loads spectra data, obtained from fixed-wing aircraft involved in the aerial firefighting role and operating as both air tankers and lead aircraft. Where appropriate, spectra from aircraft in other low-level roles, such as agricultural spraying, are included to demonstrate the relative severity of air tanker operations. Based on the analysis of the usage data and a relative damage criterion, preliminary spectra for different categories of air tanker operations are proposed. Every attempt was made to err on the side of conservatism; however, the inherent variation associated with air tanker operations may result in occasional occurrences outside the proposed spectra. Therefore, until more data becomes available, it is recommended that the proposed spectra be used in conjunction with structural health monitoring programs to ensure that the associated assumptions are not violated. Finally, it should be noted that most of the data and the spectra themselves are based on center-of-gravity acceleration data and, therefore, are applicable to structure contained within the center wing and fuselage of an aircraft.

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PREFACE

This report proposes normal acceleration spectra for airplanes used in firefighting and lead roles. Spectra for heavy, medium, and light airplanes are provided and compared. These spectra were based exclusively on data, which were obtained a number of years ago. There are, however, a number of issues regarding the use of the spectra contained in this report, which need to be addressed, explained, and considered.

The report suggests that a severity factor for firefighting operations can be derived. Although this is true, such a factor assumes that the internal stress levels in the structure do not change as a result of the addition of tank(s) filled with fire-retardant chemicals. Although this report does not attempt to address the load redistribution to the aircraft structure due to the addition of the tank(s), regulatory authorities are well aware that this issue is recognized to be an important consideration for the continued safe operation of these airplanes. For example, during the analysis of the conversion of the DeHavilland DASH-8 for firefighting operations, a load case became critical (was not originally) such that the aircraft would not be able to meet the certification requirements. When similar circumstances exist for other aircraft modified for firefighting operations, the operator must ensure that the stress cycles associated with the new configuration are computed and not ignored. Without adequate knowledge of the new load distribution, the increase in stress would go unnoticed and the use of a simple severity factor would be inappropriate. This report does, however, adequately describe the extent to which the number of load occurrences in the firefighting role can be directly measured and subsequently compared to a normal acceleration spectrum of these aircraft during prior service.

In the past, the severity factor was generally applied to a Supplemental Inspection Document without any investigation of additional locations that may have now become more severe. One of the suggestions made in this report is for continuous loads monitoring to be done for the life of the aircraft equipped with strain gauges sufficient to estimate stress for all major aircraft components. Should an applicant be required to monitor his aircraft continuously, the cost may be prohibitive; should a large number of strain gauges be required, their long-term reliability will come into question. Thus, the argument of economic burden would play a large role in the use of such a process. Alternatives to this approach need to be investigated and researched and cost-effective measures implemented.

As newer airplane models such as the Boeing 747 are converted for firefighting roles, regulatory agencies have to be concerned with not only fatigue but also damage tolerance issues. Since the geometry and design methodology of current modern aircraft has changed, the publication of this report does not imply that regulatory agencies agree to use a simple severity factor based on stresses derived from Engineering Sciences Data Unit Wings and Empennage.

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The many insights and suggestions obtained through personal discussions with Mr. Philip Newman have proved to be invaluable and are gratefully acknowledged. Additional helpful comments and input provided by Mr. Joseph F. Braun, President of Systems & Electronics Inc., SEI staff, and Mr. John Miner of Celeris Aerospace Canada Inc., have also been appreciated.

Finally, it would be remiss of the author not to acknowledge the considerable insight, skill, and expertise of the men and women who operate and maintain the aircraft used in the aerial firefighting role. Their ongoing professionalism and dedication to providing a safe and reliable public service in a very challenging environment is highly commendable.

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LIST OF ACRONYMS

AGL	Above ground level
ASW	Anti-Submarine Warfare
c.g.	Center of gravity
FAA	Federal Aviation Administration
IAT	Individual Aircraft Tracking
ILS	Instrument Landing System
MEAT	Multiengine air tanker
MTOW	Maximum takeoff weight
NRCC	National Research Council of Canada
Nz_{cg}	Vertical acceleration at an aircraft's center of gravity
SEAT	Single-engine air tanker
SHM	Structural Health Management
USDA/FS	United States Department of Agriculture Forestry Service
VOR	VHF Omnidirectional Range (Beacon)

EXECUTIVE SUMMARY

Recent catastrophic structural failures of operational aerial firefighting aircraft have once again put emphasis on understanding the low-altitude operating environment to which these aircraft are subjected. Furthermore, as most of the aircraft operating continuously in this environment were not originally designed for use in the aerial firefighting role and are flying outside their original design intent, the ongoing structural integrity of these aircraft needs to be re-evaluated.

While all aircraft operating in a low-level environment will be subjected to a more severe cyclic loading environment than similar aircraft operating at higher altitudes, aircraft operating in the aerial firefighting role are subjected to one of the most severe of all fatigue loading spectra. In addition to the increased gust and maneuver frequencies associated with general low-level usage, these aircraft must cope with the turbulent conditions in and around the fire zone.

This report consolidates the limited repeated-load flight data that has been gathered from air tanker, lead aircraft, and other aircraft operating in similar low-altitude missions over the past 30 years. Much of this data is limited to vertical accelerations measured at the center of gravity (Nz_{cg}) with no data being available to correlate the recorded accelerations with the weight at which they occurred. Based on an analysis of this data, design spectra are proposed for various classification of aircraft employed in the role. The limited quantity and quality of the data available leads naturally to the development design loading spectra that are believed to be conservative. As more data becomes available, these spectra may be reviewed and updated as appropriate.

The report also discusses methods that may be used to establish the relative damage accrual rates under differing loading spectra and suggests the future development and application of structural health monitoring programs on individual airplanes or airplane fleets.

1. INTRODUCTION.

1.1 PURPOSE.

The overall aim of this research was to develop preliminary baseline spectra for aircraft operating in the low-level (below 2500 ft above ground level (AGL)) aerial firefighting role. These preliminary spectra will be generated from the limited amount of available data recorded by aircraft operating in low-level roles, in general, and the aerial firefighting role, in particular. This report presents the analysis of the existing aerial firefighting data and the subsequent development of conservative loads spectra that can be used for the preliminary evaluation of aircraft involved in the air tanker and lead aircraft roles.

1.2 BACKGROUND.

In the summer of 2002, two air tankers operating in the aerial firefighting role suffered catastrophic operational failures in their wing structure. These failures highlighted the need to obtain a better understanding of the loads that special mission public use aircraft, operating in roles for which they were not originally designed, are subjected. Subsequent to the accidents, the Federal Aviation Administration (FAA) and the United States Department of Agriculture Forestry Service (USDA/FS) have established a number of structural health monitoring programs. The aim of these programs is to characterize the loads experienced by aircraft operating in the aerial firefighting role. Unfortunately, due to the relatively low annual utilization of these aircraft (250-350 flying hours per year) and the varied environments in which they operate, it will be some time before comprehensive and statistically valid aerial firefighting loads spectra can be defined. In the interim, it is necessary to define spectra that can provide a conservative design basis for new or modified aircraft that will ensure the continuing airworthiness of aircraft operating in aerial firefighting roles.

The majority of published and unpublished data pertinent to the aerial firefighting aircraft is primarily comprised of vertical acceleration at an aircraft's center of gravity (c.g.) (Nz_{cg}) exceedance data. Such data can only be used to generate stress spectra at critical locations bounded by the center wing and center fuselage of an aircraft. As these areas tend to be the most sensitive to low-level role fatigue-induced failures, a preliminary spectra generated from this data should provide a reasonable basis for ensuring the ongoing structural integrity of aerial firefighting aircraft until validated operational spectra can be generated.

From a fixed-wing perspective, there are two types of aircraft involved in the aerial firefighting role; namely, air tankers and lead aircraft. Air tankers drop retardant materials or water on the fire and are subject to sudden and abrupt changes in weight during their flight profile. Lead aircraft initially survey the immediate fire vicinity by ascertaining the best approach and exit routes from which the air tankers can execute their attack on a fire. Subsequently, they coordinate the attack on the fire by leading the air tankers, indicating the exact location where retardant should be dropped and assessing the accuracy of each drop. While these aircraft do not execute drops themselves, they appear to be subjected to at least as severe, if not a more severe spectrum than the air tankers themselves.

This report attempts to consolidate data obtained from test programs that have gathered data from air tanker and lead aircraft over the past 30 years. Much of the data currently available is limited to vertical accelerations recorded at the c.g. (Nz_{cg}), with no data being available to correlate the recorded accelerations with the weight at which they occurred. A number of recent Structural Health Monitoring (SHM) programs initiated by the FAA and the USDA/FS are currently underway and should provide better data upon which the characterization of the aerial firefighting role can be based. However, to date, the accumulated amount of validated data was insufficient to be included in this study.

In the interim, the present study has focused on evaluating aerial firefighting spectra and using a relative damage methodology to define preliminary operational loads spectra for aircraft operating in the air tanker and lead aircraft roles. Based on the low quality and quantity of data available, the spectra that are proposed are conservative and rely in part on operational data acquired in similarly demanding low-altitude missions, such as aerial survey work. Should additional data from SHM programs become available, the proposed spectra could be reviewed and updated as appropriate.

Based on the analysis completed to date, the following conclusions were derived:

- The majority of air tankers and lead aircraft were not originally designed for use in the aerial firefighting role. Air tankers and lead aircraft operating in the aerial firefighting role are subjected to a far more severe load spectra than are similar aircraft operating in their original design intent role. This increase in severity is associated with the consistent use of an aircraft in a low-level environment (typically less than 2500 ft AGL) and the rigors associated with the aerial firefighting role itself.

- It is neither feasible nor desirable at this time to attempt to isolate the individual contributions to fatigue damage arising from atmospheric turbulence and pilot-commanded maneuvering. Emphasis will, therefore, be placed on developing an overall loading spectrum considering the combined effects of both. It is known that turbulence is much more severe at low altitude, and that this could be further exacerbated by mountainous terrain or thermal activity in the fire zone, even though the overall effect might be offset to some extent by reduced operating speeds. Despite the increased severity of repeated gust loading, it still appears that the majority of very high load cycles are associated with maneuvering in the fire zone.

- There is evidence not only of increased fatigue damage rates, but also of numerous in-service exceedances of the airplane maximum g operating limitations. This may be particularly true if an air tanker is routinely operated in a high-lift configuration, where the design maneuver capability is less than with flaps retracted. It is not clear if such breaches of the design flight envelope also result in frequent exceedance of structural limit load, since the peak loads may be alleviated by simultaneous factors such as operation at less than maximum gross weight and maximum operating speed. There is, nevertheless, the concern that relatively frequent design load factor exceedances could be accompanied by static loads, which approach or exceed the limit design strength envelope.

- The effect of relatively large aircraft weight changes due to the release of retardant causes uncertainty to the assessment of ongoing structural integrity, since mission weights have not been routinely tracked. Preliminary evidence obtained from some recently instrumented aircraft suggests that the high g levels occur both at high gross weight prior to the retardant drop and at lesser gross weights after the retardant drop. The overall rate of damage accrual determined from measured acceleration data should account for representative changes of aircraft weight in a realistic or conservative manner.

- The limited data available suggests that lead aircraft may be subject to a far more severe loads environment than the air tankers. As these aircraft do not experience the significant and abrupt weight changes seen by the air tankers, it is likely that critical structural areas in these aircraft are subject to both a cyclic and static loads environment beyond their original design envelopes.

- Relative damage calculations indicate that there is significant variation in both the air tanker and lead aircraft loads environments. For air tankers, the cyclic (fatigue) loads that are responsible for the majority of the cumulative damage sustained by an aircraft structure appear to be related to aircraft size. Damage sustained by larger, heavier aircraft (in excess of 80,000 lb) is principally attributable to large numbers of relatively low-level loads. Conversely, the damage sustained by smaller, lighter aircraft (less than 30,000 lb) is primarily attributable to smaller numbers of relatively high load cycles. These factors have a number of implications for future SHM programs implemented on air tanker and lead aircraft. These include, but are not necessarily limited to:

  – Implementing individual aircraft tracking (IAT) programs on all air tanker and lead aircraft. While initial sampling programs can be used to establish preliminary spectra for air tankers and lead aircraft, significant variations in usage between aircraft operating in nominally the same role appear to exist. Consequently, it will be necessary to track individual aircraft to ascertain exactly how they are being operated and adjust their associated inspection and maintenance schedules accordingly.

  – Exercising considerable care when defining the resolution (granularity) of parameters such as Nz_{cg} and strains for use in SHM programs. Resolutions used to monitor aircraft in more conventional/design intent roles may result in load cycles that contribute a significant amount of cumulative damage to the structure being overlooked. This is particularly true for larger, heavier aircraft used in the air tanker role.

  – Segmentation of the various phases of the air tanker and lead aircraft roles through the use of discrete signals and markers to ascertain whether the variability in the data is primarily due to the loads experienced in the immediate vicinity of the fire. If this proves not to be the case, other factors such as crew training, pilot technique, and terrain should be investigated to establish whether or not the data variation that has been observed is inherent to the aerial firefighting role.

- While some data suggests that the operation of aircraft involved in the aerial firefighting role is primarily maneuver dominated, care has to be taken when coming to this conclusion. There is some evidence to suggest that traditional methods of separating gust and maneuver loads developed from data obtained from aircraft operating at higher altitudes may not be applicable for aircraft consistently operating in a low-level environment.

Based on these conclusions, recommendations pertaining to future work are as follows:

- The ongoing structural integrity of lead aircraft operating in the aerial firefighting role be urgently evaluated. While preliminary data suggest that the loads environment in which these aircraft operate is more severe than the loads environment experienced by the air tankers, little to no work has been done to assess the longer-term effects of the continued use of aircraft in this role.

- IAT of appropriate SHM parameters be implemented on all air tanker and lead aircraft involved in the aerial firefighting role. At a minimum, these programs should account for variations in aircraft weight over a mission and seek to quantify the implications of the aerial firefighting environment on the ongoing structural integrity of aircraft operating in this environment.

- A common structure/methodology for the implementation of SHM programs and the subsequent assessment of aircraft operating in the aerial firefighting environment be developed. This will facilitate an extensive and complete characterization of the aerial firefighting environment and the development/enhancement of realistic regulatory criteria for aircraft operating in this environment.

- A central repository be established for the collection of data related to aerial firefighting. The relatively small number of hours flown by aircraft operating in this role every year (250-300 hours) requires that every effort be made to ensure that the maximum benefit is derived from all data that is gathered.

- The applicability of methods traditionally used for the separation of maneuvers and gusts to aircraft that operate continuously in a low-level environment be examined in some detail. Preliminary analysis of recent data obtained from aerial firefighting aircraft suggests that rules developed for aircraft operating at higher altitudes may not be applicable to aircraft operating at lower altitudes.

1.3 PRIMARY REFERENCE DOCUMENTS.

Potential documents that were identified for review in this report were summarized in reference 1. Since the generation of reference 1, other documents of interest were identified and reviewed, and where appropriate, these are cited in section 10. However, with regards to aerial firefighting usage, most of the available data has been collated into the two following reference documents that have been used as the basis for much of the analysis that was undertaken.

- "General Aviation Aircraft – Normal Acceleration Data, Analysis and Collection Project," DOT/FAA/CT-91/20

- "The Impact of Low-Level Roles on Aircraft Structural Integrity With Particular Reference to Firebombers," NRCC/CR-2002-0258

These documents are designated references 2 and 3, respectively.

It should be noted that both references 2 and 3 and a number of the other references cited in this report are primarily based on c.g. acceleration data, which is 20-30 years old. Documentation pertaining to much of the source data is, at worst, unavailable and, at best, very limited. This fact combined with the accidents that occurred in 2002 demonstrate that there is an urgent need to establish ongoing and robust SHM programs to track the operational loads experienced by air tankers and lead aircraft operating in the aerial firefighting environment. In light of the accidents that occurred in 2002, attempts to acquire more recent and extensive data have commenced [4, 5, 6, 7, 8, and 9]. To ensure the ongoing structural integrity of aircraft operating in the aerial firefighting role, it is essential that these data acquisition programs be both supported and expanded by the aerial firefighting community as a whole.

A summary of the content and scope of the reports identified in reference 1 is contained in appendix A.

2. AN OVERVIEW OF FIREFIGHTING MISSIONS.

While the focus of this project is on aerial firefighting spectra, it has been shown that the continuous operation of any aircraft in a low-level role, defined as less than 2500 ft AGL, will have a detrimental effect on the fatigue life of an aircraft [3]. Continuous use of aircraft in low-level roles, such as aerial firefighting, geophysical survey, pipeline survey, and Instrument Landing System/VHF omnidirectional range (beacon) (ILS/VOR) calibration are not well-suited to analysis using data extracted from standard loads spectra such as in reference 10.

2.1 AIRCRAFT CLASSIFICATIONS.

For the purposes of this report, the following aerial firefighting aircraft classifications are used:

- Large Air Tankers: These aircraft fall into the multiengine air tanker (MEAT) category and have the capability to carry anywhere from 2000-3000 U.S. gallons of retardant. Current examples of heavy air tankers include P-3A, C-130A, DC-4/6/7, and P2-V.

- Standard Air Tankers: These aircraft also predominantly fall in the MEAT classification. They typically carry between 800 and 1400 U.S. gallons of retardant and, in some instances, water (primarily amphibious-scooping aircraft). Current examples of standard air tankers include the CL-215, CL-415, and DC-3.

- Small Air Tankers: These aircraft predominantly fall into the single-engine air tanker (SEAT) classification and carry up to 800 gallons of retardant or water. The majority of these aircraft are either derivatives of or multirole variants of small agricultural crop-dusting aircraft. Current examples of these aircraft include the Air Tractor 800 and M-18 Dromader.

- Lead Aircraft: Lead aircraft are either twin- or single-engine light aircraft that survey a fire zone to initially establish appropriate approach and exit routes for the air tankers. Subsequently, they lead the air tankers into the drop zone to indicate exactly where the retardant is to be dropped and then position themselves so that the onboard forestry officer (typically positioned in the right-hand seat) can evaluate both the accuracy and effectiveness of each air tanker drop. Current examples of lead aircraft include the Beech 58 Baron, Beech King Air, and Beech Queen Air.

2.2 THE AERIAL FIREFIGHTING ROLE.

A summary pertaining to some of the tactics and mission profiles associated with the aerial firefighting role can be found in reference 11. From a structural perspective, the most pertinent details with regard to the aerial firefighting profile are as follows:

a. Aircraft generally operate from bases in relatively close proximity to the fire such that a typical operational sortie will be between 50 minutes to 1 hour.

b. It is usually not the case that aircraft will transit to the fire zone at design cruise altitude. To avoid excessive transit time, most aircraft will transit to the fire at lower altitudes. Often 2500 ft AGL or less.

c. Once in the immediate vicinity of the fire, the aircraft will usually join a racetrack circuit until they commence their retardant drop run. The circuit will be typically 1000-1500 ft AGL.

d. When requested by the lead aircraft (or at the pilot's discretion if he or she is lead attack qualified), the pilot will commence a retardant drop run. The need to ensure the retardant properly coats the foliage, thereby generating an effective fire barrier, requires that the following altitude and airspeed and flight conditions be used:

1. Altitude of 150 ft AGL parallel to the terrain on which the retardant is to be dropped. On level terrain, this results in an altitude of approximately 150 ft AGL. On mountainous terrain, this will result in a varying altitude as the pilot attempts to maintain an altitude of approximately 150 ft parallel to the terrain. To facilitate maximum control and exit options when dropping retardant on mountainous terrain, the aircraft will always fly downhill.

2. Airspeed of approximately 110-140 knots equivalent airspeed.

3. Typically 50% and, on occasion, 100% flap with a high engine power setting. This results in pilots having immediate access to power to exit the drop zone upon retraction of their flaps without having to be concerned about potential time delays associated with engine spool-up. Such delays could be potentially catastrophic when attacking fires in mountainous regions. In this type of terrain, the natural geography or other ground obstructions (e.g., communications towers, power lines, etc.) require terrain avoidance procedures be implemented towards the end of, or immediately upon exiting, the drop zone.

4. Incremental retardant drops. Typically, most of the large and standard tankers will drop their load in 50% increments, thereby resulting in two drop runs per sortie. Occasionally, they will be requested to undertake 100% drops. Small air tankers will invariably drop their full load in one pass. The length and number of drops performed during an individual sortie depend on both the aircraft capacity and the coverage level requested by on-site fire management personnel. Coverage levels are equivalent to specifying the concentration (distribution) of retardant within the fire zone. The higher the coverage level, the greater the concentration and, for a given level of retardant, the shorter the length over which it can be distributed. Originally, coverage level was controlled by the sequencing of multiple tank release doors. In latter years, the multiple door tanks are gradually being replaced by constant-flow systems. The majority of constant-flow systems control retardant drop concentration by varying the aperture of a single set of doors.

2.3 THE LEAD AIRCRAFT ROLE.

Lead aircraft primarily coordinate the aerial attack on a fire. In this role, they perform three primary functions.

- Liaise with ground-based firefighters to support their activities with respect to the fighting and subduing of a fire.

- Evaluate the drop zone and surrounding vicinity to determine appropriate entry and exit routes for air tankers.

- Precede each air tanker into the drop zone to indicate exactly where a drop should be made and to subsequently evaluate the accuracy and effectiveness of each drop.

Lead aircraft may stay on station for 3 to 4 hours at a time. Depending on the severity of the fire, this may result in them accumulating 6 to 8 passes per hour over the fire zone. Over time, this will result in them making significantly more passes over the fire zone and being subjected to the most intense segments of the aerial firefighting load environment far more frequently than the air tankers. Additionally, a common maneuver carried out by these aircraft once they have indicated where retardant needs to be dropped is that of undertaking a sharp 90-degree roll to the right and reversing their previous direction. This allows the forestry service officer, who is generally in the right seat, to observe the placement and effectiveness of each air tanker drop. Hence, although they are not subjected to the drop loads or the associated significant and rapid change in weight, the lead aircraft are subjected to at least as severe and in all likelihood a more severe load environment than the air tankers themselves.

2.4 RELATIVE COMPARISONS WITH OTHER ROLES.

Many of the aircraft operating in aerial firefighting and other low-level roles, such as ILS/VOR calibration, pipeline-survey and, in some instance, agricultural crop spraying, were originally designed to operate at much higher altitudes in more conventional cargo/transport roles. It has been demonstrated on a number of occasions that from a cyclic load (fatigue) perspective, the structural damage accumulated by any aircraft operating in a low-level role will be greater than that sustained by a similar aircraft operating in the higher-level role for which it was originally designed [3 and 12]. In reference 3, it was shown that for larger transport aircraft operating in low-level roles, the aerial firefighting role was by far the most severe. This was primarily attributed to the inordinately large number of relatively low-level load cycles (with maximum Nz_{cg} cyclic values ranging between 1.1 and 1.7 g's, where 1.0 g is equivalent to straight and level flight) sustained by aircraft operating in this role. This finding is discussed in greater detail in section 2.5.

2.5 OBSERVATIONS ON THE DIFFERENCE BETWEEN ORIGINAL DESIGN AND AERIAL FIREFIGHTING ROLES.

For many years, the basis for converting or using aircraft in the aerial firefighting role has primarily been based on performance and, in the case of the air tankers, retardant carrying capability. While these factors will continue to remain important selection criteria, the accidents that occurred in 2002 [13] illustrate that there is also a need to evaluate the long-term structural integrity of aircraft operating in the aerial firefighting role using appropriate data. As discussed in reference 3, much of the low-level design data that is used to evaluate the impact of continuous low-level usage on an aircraft's structural integrity, for example references 14 and 15, has been generated from data that was gathered as aircraft climbed to altitude. Generally, this data does not adequately characterize the loads environment to which aircraft continuously operating in a low-level loads environment, such as aerial firefighting, will be subjected. Therefore, when evaluating the suitability of an aircraft designed for another role for use in the aerial firefighting role, it is important to remember that while an established and reputable service history in its original design role is a necessary condition, it may not be a sufficient condition to ensure the ongoing structural integrity of an aircraft in the aerial firefighting role.

A common source of confusion when considering the suitability of an aircraft to operate in a low-level role, such as aerial firefighting, is the difference between ultimate (static) loads and cyclic (fatigue loads). The ultimate load is more often euphemistically termed the breaking load. Typically, in aircraft design, ultimate load cases are equal to 1.5 times the limit design load cases. Limit design load cases are defined as the maximum load cases the aircraft is expected to experience once in its lifetime. Conversely, cyclic loads relate to the wearing out (or fatiguing) of structural components due to the damage sustained from the continual application of many different load cycles. The magnitude of these cyclic loads may be small relative to an aircraft's limit load capability. Typically, failure of aircraft structure occurs as a result of cracks, initiated at structural details containing design deficiencies or manufacturing flaws, growing undetected and starting to weaken the remaining (or residual) strength of a structure. Eventually, the crack(s) grow to a point where the structure has been weakened so much it can no longer sustain normal operational loads and failure occurs. A more detailed discussion of these concepts can be found in references 16 and 17.

Unfortunately, when a failure occurs, there is a natural tendency to focus solely on characterizing the larger loads that might have failed the structure rather than on also characterizing the cyclic loads that often precipitated the failure. Furthermore, as it is far easier to characterize and gather data related to maximum/minimum load excursions than it is to gather and characterize cyclic load data, the emphasis of any data gathering and analysis programs is often placed on defining larger loads. Consequently there is a tendency of reports, such as references 18 and 19, to place significant emphasis on the periodic occurrence of large load excursions to the detriment of considering the cumulative damaging effect of lower load occurrences; even though in all likelihood it is the lower load occurrences that precipitated the failure of the structure [3].

A good example of how not assigning appropriate significance to the continuous loads encountered by aircraft operating in a low-level environment was demonstrated in a preliminary analysis of data obtained from an S-2 Tracker aircraft. Data was available for the S-2 aircraft being operated in both its original design role of Anti-Submarine Warfare (ASW) and as an air tanker [20]. The Air tanker role was found to be approximately twice as damaging as the ASW role, even though, in this specific instance, the ASW spectrum contained larger and more frequent maximum g-level load excursions. (Although note that, in general, the air tanker role will be found to be more severe at all levels of normal acceleration.)

3. PROPOSED APPROACH.

3.1 FUNDAMENTAL QUESTIONS TO BE ADDRESSED.

To assess the structural impact of operating an aircraft in any environment, it is necessary to resolve two fundamental questions:

- How is the aircraft being used? This involves characterizing the nature and severity of the loads that are applied to the aircraft in its actual operating environment.

- What are the structural implications of using an aircraft in its operational environment? This involves assessing critical structural locations throughout the aircraft and requires not only evaluating the environment itself but also considering the configuration and manner in which the aircraft is operated (e.g., airspeeds, altitudes, control positions, impact of high-lift devices, weight, etc.).

3.1.1 Aircraft Usage.

During its operational life, an aircraft may encounter many different load conditions. Consequently, a statistical approach is usually applied to characterize the anticipated loads environment to which it will be subjected. Over time, if a full range of representative conditions are encountered, measured, and correctly characterized, a realistic loads spectrum for the role(s) in which an aircraft operates can be developed. For aircraft operating in the cargo/passenger role, large quantities of data have been accumulated over many years and incorporated into design specifications such as references 14 and 15. Unfortunately, the same is not true for aircraft operating in low-level roles such as aerial firefighting. There are a number of reasons for this that include, but are not necessarily limited to, the following.

- Only a limited number of aerial firefighting aircraft have been equipped with SHM equipment to record the loads to which they are subjected while operating in this environment.

- A small number of aircraft are engaged in aerial firefighting operations each year. During a heavy fire season, each aircraft accumulates somewhere between 250 and 350 flying hours per year. This results in representative data being accumulated at a relatively slow rate.

- Isolating the loads associated with a typical aerial firefighting environment from the recorded data is not straightforward. Aerial firefighting aircraft operate in a variety of terrains ranging from fairly flat, undulating terrain to extremely mountainous terrain. The low-level gust and maneuver environment in these different terrains can vary considerably. Furthermore, the fires themselves are not uniform and their impact on the surrounding air circulations will vary from location to location and from year to year. Aerial firefighting aircraft are often based at one geographic location and flown by the same crews for years at a time. Therefore, data measured on individual aircraft may not be representative of typical aerial firefighting usage but rather contain a snapshot of aerial firefighting operations relative to a specific crew and location. Ultimately, this may result in the need to characterize the use of aerial firefighting aircraft through the application of an ongoing IAT program, as opposed to a limited sampling program based, for example, on aircraft type.

3.1.2 Structural Implications.

Evaluating structural implications of a given operating environment involves assessing how critical structural details for each aircraft type respond to the loads that are applied to them. While two different aircraft types operating in the same environment can sensibly be assumed to experience the same loads, the resultant stresses (load per unit area) that these loads generate in each structure is influenced by the geometry of the structures and the materials from which they are constructed.

An illustration of this concept can be obtained by considering two circular bars made from different materials that are suspended from a beam. The cross-sectional area of the first bar, which is assumed to be manufactured from stainless steel, is half the cross-sectional area of the second bar, which is assumed to be manufactured from aluminum. Both bars have a 10,000 lb weight (load) suspended from them. While both bars have the same load applied, the intensity of load per unit area (stress) is a function of geometry and is, therefore, twice as great for the stainless steel bar as for the aluminum bar. Notwithstanding that the stainless steel bar is subjected to twice the stress of the aluminum bar. Before an assessment of whether one of the bars will fail can be made, it is necessary to ascertain the capabilities of the materials (material characteristic) from which the bars are manufactured to withstand the stress that is applied to them.

Given that the structural response of different aircraft to the same environment will vary according to both the structural geometry and materials used in the construction of the aircraft, quantifying the significance and severity of the aerial firefighting loads environment recorded by different aircraft at different locations can prove to be challenging. The method of comparison used in this report will be an adaptation of the relative damage concept developed by the National Research Council of Canada (NRCC) and is described in reference 21. The application of the NRCC-adapted method, as applied to the data analyzed in this report, is summarized in section 3.4. A more detailed discussion of the method can be found in reference 22.

3.2 CHARACTERIZING THE LOADS ENVIRONMENT TO WHICH AN AIRCRAFT IS SUBJECTED.

From a structural standpoint, the main purposes of characterizing the load environment to which an aircraft is subjected are as follows:

a. To determine whether limit and or ultimate load conditions are being exceeded.

b. To evaluate the long-term accumulated damage sustained by the aircraft due to the constant and repetitive application of load excursions of various magnitudes. There are two phases associated with any such evaluation.

1. The calculation of when the damage sustained at local areas of geometric stress concentration (geometry) or material flaw will coalesce into a detectable crack and begin to propagate through the structure. This is usually termed fatigue analysis.

2. The characterization of how a crack (or cracks) will propagate through the structure such that an assessment can be made as to how long it (they) will take to propagate to a critical length whereupon catastrophic failure will occur. Once the crack growth characteristics of critical location(s) have been established, appropriate inspection and maintenance intervals have to be established to ensure that any damage is identified and addressed prior to it becoming critical. Of necessity, the scope of such assessments has been expanded to address not only single cracks but also multiple-site damage and widespread fatigue damage [23].

A realistic structural assessment of airframe components requires that representative stress spectra be generated for each critical location. This implies that the relationships between the parameters being measured and the stresses at critical locations of interest have to be developed. The relationship between the measured parameters and the stresses at critical locations, termed transfer functions, range from relatively simple to quite complex relationships; each of which may be comprised of one or more parameters. It is important to note that although the parameters themselves are often referred to and used to define operating limitations, from a structural perspective, they are acting as a proxy for a stress limitation that is applicable to one or more critical locations. For example, an operating limit of 2 g's with flaps down, being placed on an aircraft is another way of saying that if 2 g's is exceeded, the allowable or design limit load at some critical location(s) (in this instance the wing) will be exceeded. However, there is an additional subtlety associated with this type of statement. The g term pertains to the acceleration due to gravity. As part of the process of converting g to stress, the weight of the object in question (in this instance the aircraft) will need to be factored into the equation. The structural implications of an operational g-level exceedance for an aircraft cannot be assessed without knowing the mass that was associated with the derivation of the limitation. Normally, aircraft designers conservatively assume that when a limiting g-level occurs, the aircraft is at its maximum operating weight. For an aircraft operating in its original design/transport role where dramatic changes in weight do not generally occur, such an assumption, while conservative, is not overly conservative. Conversely, for large air tankers that can instantaneously loose 20,000-30,000 lb of weight (approximately 2000-3000 gallons of retardant or approximately 25%-30% of their operational weight) when they drop their retardant, the high g/high weight assumption may be overly conservative. The resultant stresses at critical locations in the wing and other locations corresponding to a g-level that occurs after the retardant has been dropped will be significantly less than those that would be incurred if the aircraft was fully loaded. Consequently, in addition to measuring parameters of interest, such as Nz_{cg}, an accurate and realistic understanding of the data can only be obtained by the measurement of additional parameters that provide the context needed to correctly interpret the significance of the data recorded. Such parameters include, but are not necessarily limited to, aircraft weight, control positions, airspeed, altitude, etc. [24].

3.3 CHARATERIZING USAGE—THE CUMULATIVE Nz_{cg} EXCEEDANCE SPECTRUM.

It has frequently been common practice for aircraft loading spectra to be defined only with reference to normal load factor excursions at the aircraft c.g. (Nz_{cg}). This one parameter alone is insufficient to determine the local stress levels throughout the structure, although it is usually a reasonable proxy for the stresses in major wing and fuselage components. Whenever stress transfer functions are to be developed for a particular structure, due regard must be taken of expected loading actions and whether or not normal acceleration can be considered the principal determinant. For example, it would not be appropriate to base the fatigue loading of control surfaces or high-lift devices on maneuver load factor exceedances, since the loads on these are determined mainly by other flight parameters (in this case speed and surface position). Even though this data is limited in scope, it has proved useful for aircraft operating in low-level roles, as the wing and fuselage tend to be among the most important for fatigue failure [12].

Originally, cumulative exceedance diagrams were primarily generated due to the limitations of the recording technology and data storage capacity. For many years they formed the basis for cyclic load stress analysis and were widely used throughout the aerospace industry [16 and 17]. While advances in data recording, storage technology, and structural analysis generally mean they are no longer used for this purpose, they still provide an excellent medium for comparing the relative severity of different operational environments and detecting time-related trends in overall operational usage.

The general format of a cumulative exceedance diagram is shown in figure 3-1. Absolute values of g-level are plotted along the horizontal axis, whereas the cumulative number of exceedances of a given g-level per hour are plotted on the vertical axis (note: the vertical axis is traditionally plotted on a log scale so that a relatively small vertical displacement indicates a significant change in the number of cumulative exceedances per hour). As absolute g-levels are being plotted, the vertical axis intersects the horizontal axis at 1.0 g. A cumulative exceedance plot is comprised of two components, namely, a positive spectrum and a negative spectrum (note: a positive g-level exceedance will cause passengers in an aircraft to be pressed down into their seats, whereas a negative g-level exceedance, which is moving the passengers towards weightlessness (0.0 g), will cause them to be lifted from their seats).

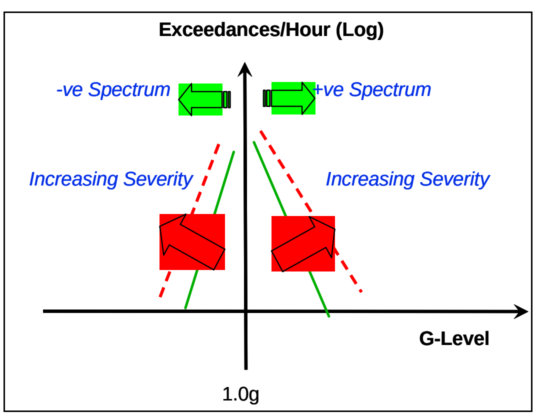

FIGURE 3-1. SCHEMATIC ILLUSTRATION OF A CUMULATIVE EXCEEDANCE DIAGRAM

As positive and negative sets of curves migrate outwards from the origin (which in this instance corresponds to 1.0 g not 0.0 g) the severity of the spectrum increases, i.e., at a given g-level, the aircraft is experiencing a greater number of cumulative exceedances per hour.

The rationale behind the use of cumulative exceedances per hour merits some explanation. The first recorders used to record variations in Nz_{cg} were electromechanical recorders that counted the number of times certain preset g-levels were exceeded. This is best illustrated by the example shown in table 3-1.

TABLE 3-1. CUMULATIVE EXCEEDANCE EXAMPLE

g-Level Attained	Cumulative Counts—Negative Spectrum			Cumulative Counts—Positive Spectrum				
	-0.50 g	0.00 g	0.50 g	1.25 g's	1.50 g's	2.00 g's	3.00 g's	4.00 g's
1.30	0	0	0	1	0	0	0	0
1.75	0	0	0	1	1	0	0	0
3.50	0	0	0	1	1	1	1	0
0.25	0	0	1	0	0	0	0	0
-0.25	0	1	1	0	0	0	0	0
Totals	0	1	2	3	2	1	1	0

Consider an electromechanical Nz_{cg} excursion recording device with eight registers set to record g-level excursions. Assume that three registers were assigned to record negative Nz_{cg} excursions using settings of 0.50, 0.00, and -0.50 g, respectively. Similarly, assume that five registers were assigned to record positive Nz_{cg} excursions using settings of 1.25, 1.50, 2.00, 3.00, and 4.00 g's, respectively. Samples of how various g-levels would be recorded are shown in table 3-1 together with the total cumulative exceedances that would be registered by the recorder. For example, consider an Nz_{cg} value of 1.75 g's. An Nz_{cg} value of 1.75 g's is a positive spectrum exceedance (relative to 1.00 g) and, hence, would only be recorded in the positive registers. The registers at 1.25 and 1.50 g's would be incremented by one count as 1.75 g's exceeds these values. Conversely, the registers at 2.00, 3.00, and 4.00 g's would not be incremented by one count as 1.75 g's is less than these values. Hence, the simplicity of the recording device limited its resolution to being the difference in counts between two adjacent registers. The values obtained indicate the number of Nz_{cg} excursions that exceeded the lower level but did attain the higher level, the exact value of excursion being unknown. Therefore, when plotting the data, the number of exceedances are generally plotted at the mid-range of two registers, i.e., in the case of the example above, positive spectrum values would be plotted at 1.125, 1.375, 1.75, 2.50, and 3.50 g's.

Cumulative exceedances per hour provide a convenient format for comparing data obtained from flights of different durations by normalizing them with respect to time. They are obtained by dividing the number of cumulative exceedances at different Nz_{cg} values by the total flight time over which they were gathered.

3.3.1 Gust and Maneuver Load Separation.

Ideally, it is desirable to separate the loads experienced by aircraft in the aerial firefighting role into gust and maneuver spectra to facilitate the development of appropriate transfer functions (section 3.1.2). However, in some instances, the source data for the exceedance curves were lost and it may not be practical to separate the data using conventional methods. For aircraft operating in the cargo/transport role, approximate techniques to synthesize gust and maneuver spectra from a combined spectrum may be employed [25 and 26]. However, as noted in reference 25, it is questionable whether techniques developed for aircraft operating at higher altitudes can be applied to data obtained from aircraft that are continuously being operated in a low-level role.

3.3.2 Limitations of c.g. Spectrum.

While aircraft recording and data storage limitations resulted in Nz_{cg} being a convenient parameter to use, this data in and of itself has a number of limitations:

- The data obtained can only be used to reliably generate stresses at critical structural locations in the immediate vicinity of the center wing and center fuselage, providing asymmetric loading is not an issue. These are the only areas that can sensibly be considered rigid relative to the c.g., thereby allowing straightforward and repeatable relationships (transfer functions) to be established between the recorded values of Nz_{cg} and the stresses at critical locations. A combination of structural flexibility and associated time delays (phase differences) between the occurrence of maximum/minimum values of Nz_{cg} and stresses at locations in the outer wing and empennage generally make it impractical to establish straightforward and repeatable transfer functions at critical structural locations in these areas. If the stress history at critical structural locations other than the center wing and fuselage need to be determined, additional sensors such as strain gauges or other accelerometers have to be positioned at appropriate locations. This allows the required stresses to be measured directly or calculated via appropriately derived transfer functions.

- An accurate assessment of the stresses at critical locations can only be made if reasonable estimates of the aircraft's weight at the time of a specific g-level occurrence are known. In the absence of any other information on aircraft operating weight, it might be possible to obtain a reasonable estimate based on knowledge of the associated takeoff and landing weights and an assumed fuel burn rate, providing no sudden and drastic in-flight changes in weight occur. For roles such as aerial firefighting where sudden and drastic weight changes do occur in flight, it is necessary to maintain a more detailed awareness of the weight of an aircraft throughout an entire flight.

3.3.3 Evaluation of Single-Load Spectrum for Aircraft Groups.

It is sometimes necessary to combine the load spectra for a group of individual aircraft in a given family, e.g., same role/same maximum takeoff weight (MTOW), into a single-load spectrum. This is accomplished using the following expression to give cumulative exceedance per hour:

$$CuEx / hr_{TOTAL} = \Sigma \, (CuEx / hr * Hours)_{A/C} \, / \, \Sigma \, Hours_{A/C}$$

where

> *CuEx/hr* is the cumulative exceedance per hour for an individual aircraft
> *Hours* are the hours of data recorded for an individual aircraft
> $\Sigma\ Hours_{A/C}$ are the total hours of recorded data for all aircraft in the group

3.4 DAMAGE METRICS—THE STRUCTURAL IMPLICATIONS OF AIRCRAFT LOAD ENVIRONMENT.

To evaluate the significance of a loads spectrum for a given aircraft structure, it is necessary to have some mechanism for developing a stress spectrum at each critical location. The stress spectra are used to calculate damage metrics that evaluate the impact of a given segment of flying on the structural health of the aircraft. Typical metrics that are used within the aerospace industry are fatigue damage (sometimes expressed in terms of a fatigue index or a fatigue life expended) or crack growth rates [16 and 17]. Generally speaking, fatigue damage is related to the time to crack initiation, and crack growth rates relate to the time for a crack to propagate from a reliably detectable crack size to a critical crack length, whereupon failure occurs.

As noted in sections 3.1.2 and 3.3, the impact of a spectrum on aircraft structure requires knowledge of specific structural details pertaining to that aircraft type and variant. Given that structural details vary from aircraft to aircraft, it becomes extremely challenging to compare the relative severity of load environments unless the aircraft operating in each load environment have identical structural details. In the case of aerial firefighting and many other roles, a variety of aircraft types are used and, hence, the question arises: Is there a basis for comparing the relative severity of load environments derived from data recorded by different aircraft?

The basis for comparing the relative severity of spectrum for similar roles recorded by different aircraft at different locations used in this report is based on work undertaken by a number of different researchers at the NRCC during the 1970-1990 time period [21, 27, and 28]. For clarity, a summary of the method will be provided in the following sections. Detailed discussions as to how these methods have been adapted can be found in references 22 and 29.

3.4.1 Required Elements for Relative Damage Evaluation.

If it is the case that a reliable component stress transfer function can be found, which relate available usage data to local stresses, the relative damage evaluation can be approximated based on a fatigue evaluation undertaken using a simple Miner's Law analysis. In its simplest form, Miner's Law states that structural damage becomes evident when the cumulative damage incurred by a structure reaches a finite value equal to 1. This is commonly expressed as

$$Damage = \sum \frac{n}{N} = 1$$

where

> n is the number of cycles sustained at a given stress level.
>
> N is the number of cycles it would take for damage to become evident if only cycles at a specific stress level were applied.

In its expanded form, Miner's Law becomes

$$Damage = \frac{n_1}{N_1} + \frac{n_2}{N_2} + ... + \frac{n_n}{N_n} = 1$$

In essence, these equations state that damage will become evident (occur) as a result of the cumulative application of relatively small load cycles, relatively large load cycles, or any combination in between [16 and 17].

The small *n* cycles are determined from measuring the actual number of times that cycles of a given stress level occur, whereas the large *N* at a given stress level is a combined material and geometry (stress concentration) characteristic determined from appropriate stress versus number of cycles (S-N) curves.

Therefore, to undertake a damage calculation, it is necessary to obtain

- a measured spectrum that defines the number of occurrences of different cyclic load levels. A cumulative g-level exceedance curve is one example of such a spectrum;

- a way of converting the measured spectrum to a stress spectrum that is applied to each critical area of interest; and

- representative S-N curves that can be used to calculate the value of N for each value of n isolated in the measured spectrum.

Discussions pertaining to how each of these items will be obtained for the purposes of relative damage evaluation are summarized in sections 3.4.2 to 3.4.4.

3.4.2 Measured Spectrum.

Most of the data available for analysis (section 1.3) provides the data in the form of a cumulative g-level (Nz_{cg}) diagram (section 3.3). For the purpose of comparing the data obtained from differing aircraft operating at a variety of locations, the spectrum has to be processed in two phases, namely

- the g-level range over which the damage due to the applied loads will be calculated has to be made the same for each spectrum to be analyzed; and

- the resulting spectrum has to be subdivided into component cycles together with their corresponding number of exceedances.

3.4.2.1 Equalization of the g-Level Ranges.

Inspection of the data analyzed in this report (section 4), primarily obtained from references 2 and 3, shows that both the ranges and recording intervals of the data obtained vary from aircraft to aircraft. Therefore, to provide a range over which data from differing aircraft can be compared and trends identified, it was necessary to both curve fit and extrapolate the data. The method used for curve fitting the data and extrapolating the data is similar to that described in reference 27 with the exceptions that

- the method described in reference 27 was based on the interpolation and extrapolation of the positive spectrum fitted with a quadratic curve fit and a negative spectrum fitted with a linear curve fit. As discussed in reference 29, to accommodate the data that was analyzed, it was necessary to expand this capability to accommodate cubic curve fits for both the positive and negative spectrum.

- the extrapolations from the curve fits were based on matching the slopes between the extrapolated parts of the curve and the slope obtained from a linear fit of a user-specified number of points at either end of the curve. Engineering considerations also provide the additional constraints that the positive spectrum should be asymptotic to 1.0 g and Gp_{ult} (figure 3-2) and that the negative spectrum should be asymptotic to 1.0 g and Gn_{ult}. Based on some initial assessments of the data, whenever practicable, the linear fit used for slope matching was based on the last three points at either end of the curve. Further details pertaining to the use of this technique can be found in reference 29.

The fitting and extrapolation of the data is shown in figure 3-2.

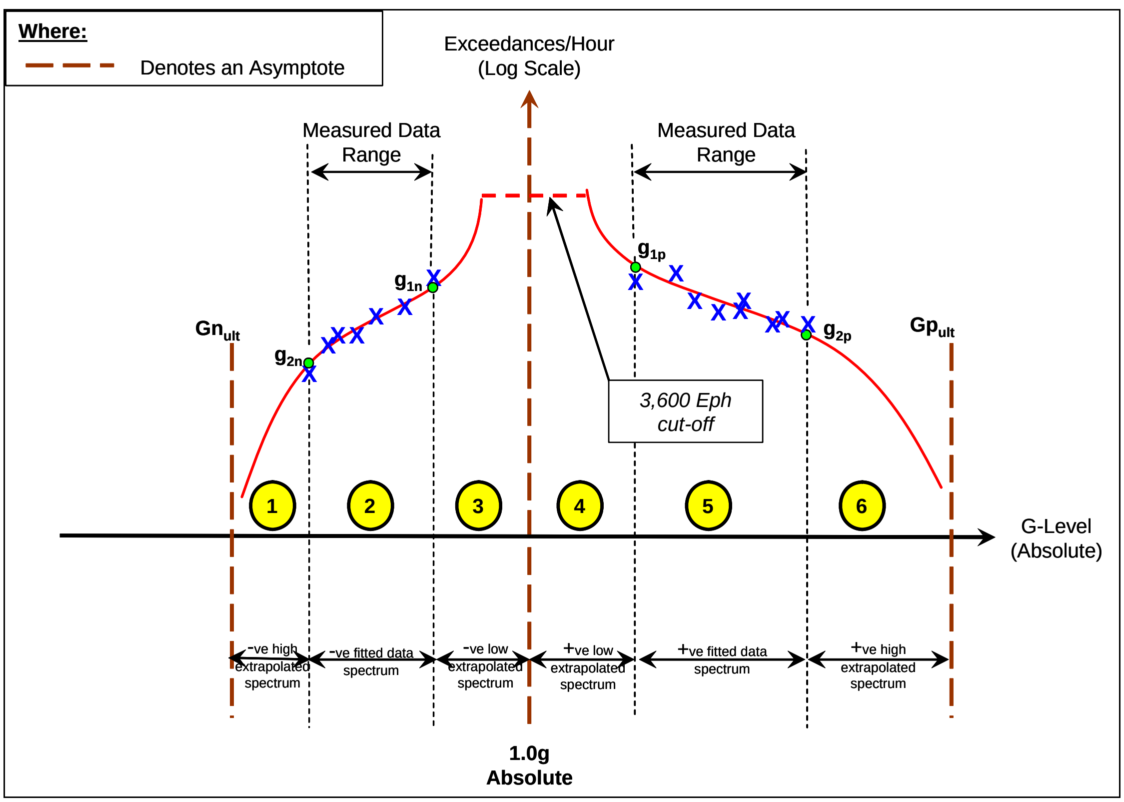

FIGURE 3-2. CURVE FITTING AND EXTRAPOLATION OF g-LEVEL EXCEEDANCE SPECTRA

The final exceedance curves were subdivided into six regions. Regions 2 and 5 encompass the actual data and were fitted using the following generalized polynomial equation:

$$Log_e(eph(g)) = c_0 + c_1 * g + c_2 * g^2 + c_3 * g^3$$

implying that

$$eph(g) = e^{(c_0 + c_1 * g + c_2 * g^2 + c_3 * g^3)}$$

where

c_0, c_1, c_2, and c_3 are constants determined via regression analysis.
eph(*g*) is the exceedance value for each g increment.

As previously mentioned, the majority of the data was fitted using a cubic fit, but in some instances, too few data points were available and quadratic or linear fits were used. In such instances, the constants associated with the cubic term were set to zero.

Regions 1, 6, 2, and 4 were designated the high and low extrapolation regions, respectively. In accordance with the guidelines provided in reference 27, the high extrapolation region was made asymptotic to the positive and negative ultimate load ranges. Conversely, the low extrapolation region was made asymptotic to 1.0 g with the added caveat that the number of exceedances per hour was cutoff at 3600 eph, as a greater number of occurrences than this was deemed to be beyond the physical response capability of most aircraft.

Data for the high extrapolation regions (regions 1 and 6) were generated using the equation

$$eph(g) = ephg_2 \times \left[\frac{G_{ult} - g_2}{G_{ult} - g} \right]^{S \times \left(\frac{G_{ult} - g_2}{\log_{10} e} \right)}$$

Whereas data for the low extrapolation regions was generated using the equation

$$eph(g) = ephg_1 \times \left[\frac{g - 1.0}{g_1 - 1.0} \right]^{S \times \left(\frac{g_1 - 1.0}{\log_{10} e} \right)}$$

where, with the exception of the term *S*, the definitions of all terms used are defined in figure 3-2, and *S* is the slope obtained from a linear data fit of the last three fitted data points at the appropriate ends of the fitted curve.

3.4.2.2 Division of the Spectrum Into Constituent Cycles.

Once a spectrum is established, it is split into its component cycles by

- selecting an absolute acceleration increment for which values of *n* are to be determined,
- determining the cumulative number of exceedances per hour that corresponds to each g increment that falls within the positive spectrum (g >1.0), and
- determining the negative g-level (g<1.0) to be matched with the positive g-level based on the matching of identical numbers of cumulative exceedances per hour.

This process is shown in figure 3-3.

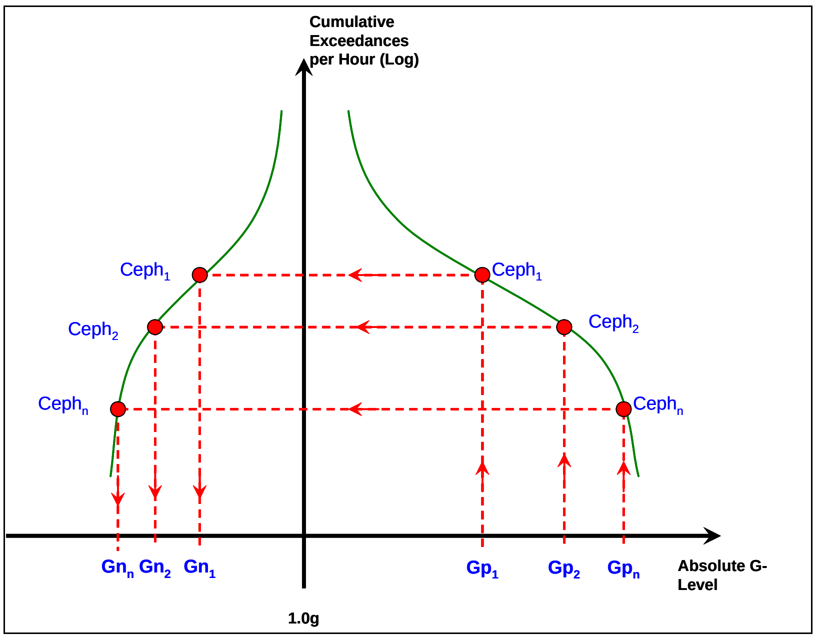

FIGURE 3-3. SPLITTING A SPECTRUM INTO ITS COMPONENT CYCLES

Once each positive g value has been matched with its corresponding negative g value, the maximum, minimum, and alternating g-levels can be defined as follows for each cycle:

$$G_{\max} = Gp_n \qquad G_{\min} = Gn_n$$

$$G_{mean} = \frac{G_{\max} + G_{\min}}{2}$$

$$G_{alt} = G_{\max} - G_{mean}$$

where

G_{alt} is alternating g increment
Gp_n is positive g increment
Gn_n is negative g increment

4. USAGE DATA ANALYSIS.

While the main focus of this report is intended to look at air tankers (i.e., aircraft that deliver retardant or water on a fire), it is beneficial to compare the available air tanker data with data obtained from other roles. This helps provide a better context from which the significance of the operational usage of air tankers can be evaluated. In particular, where data is available, aircraft operating in the following roles have been considered:

- Lead aircraft: These aircraft first check the fire zone to establish safe approach and exit routes and then precede the air tankers on each drop to indicate where the retardant should be placed. They then reverse their course and rotate 90 degrees so that the onboard forestry service officer can assess the accuracy and effectiveness of the drop. Data obtained from lead aircraft give insight into the aerial firefighting environment decoupled from the effects of the loads imposed by the drop itself.

- Agricultural aircraft: Large and small agricultural aircraft also operate continuously in a low-level environment at similar altitudes to the aerial firefighting aircraft. Examination of data from these aircraft may provide insight into the low-level operational environment when it is decoupled from the fire environment. Of particular interest is data from smaller agricultural spray aircraft, which are being considered for dual use in both the agricultural and aerial firefighting roles.

- Aircraft operating in their design intent roles: Many air tankers are aircraft that were converted from their original cargo/passenger design intent role. Design or operational data pertaining to the original design intent of the current air tankers can provide insight with regard to how severe the aerial firefighting role is relative to the role for which they were originally designed.

4.1 PRELIMINARY DATA REVIEW.

A preliminary review of the data in references 2 and 3 was undertaken to assess how best to group the data for analysis.

4.1.1 Grouping by Role.

The first grouping of available data related to parsing the aircraft into the roles of interest, as defined in section 4, in the following manner (note the aircraft identification nomenclature used corresponds with the identification nomenclature used in references 2 and 3).

a. Aerial firefighting and commercial survey operations: Comprises multiengined, propeller-driven aircraft employed in firefighting operations, fire support operations, or in other low-altitude operations assumed to be generally representative of the air tanker mission.

   1. Air tankers

      - Aircraft 19, 19^1, 20, 20^1, 21, 22, 24, 24^1, 24^2, 24^3, 24^{4,} 24^5 [2]
      - S-2 Tracker and F-27 [3]

2. Lead aircraft (27, 41, 25) [2]

b. Agricultural aircraft

1. Small agricultural aircraft [2]

- 29, 291, 30, 301, 302, 30A, 31, 32, 322, 33, 331, 33A, 33A1, 33A2, 34, 341, 342, 343, 35, 351, 352, 36, 36A, 37, 371

2. Large agricultural aircraft [3]

- DC-6B (budworm spraying)

c. Original design intent role:

1. DC-6 [3]

4.1.2 Role Subgroups.

Subsequently, role-related subgroups were developed based on an initial evaluation of some of the exceedance data extracted from reference 2. This process is shown in figure 4-1.

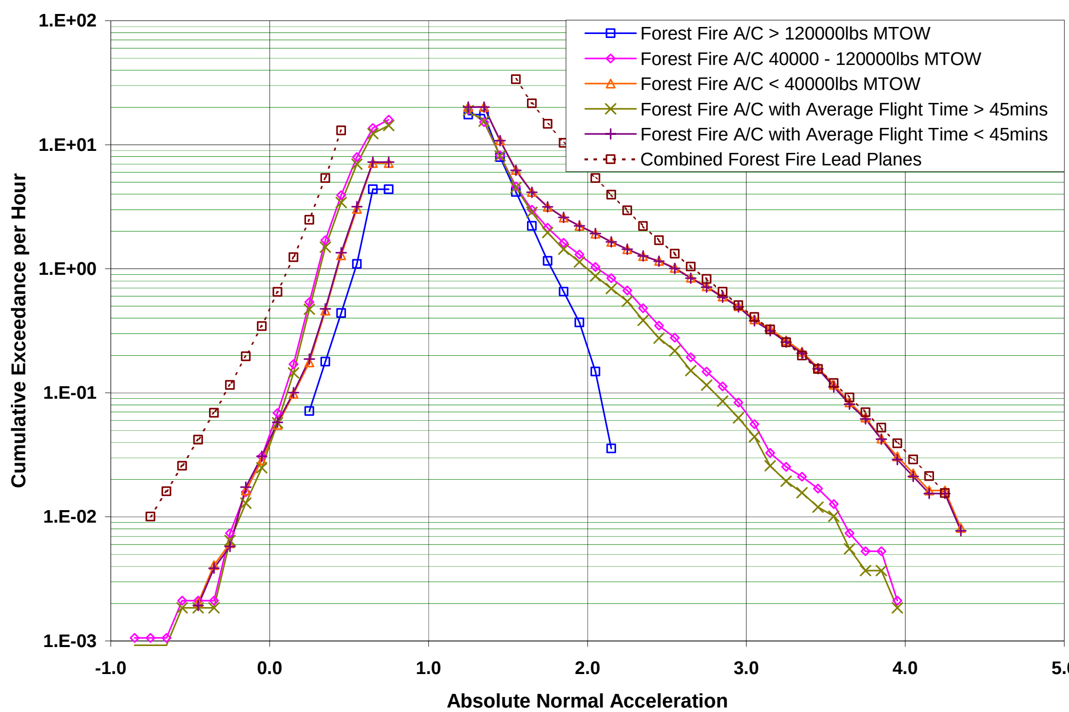

FIGURE 4-1. INITIAL EXCEEDANCE PLOT OF REFERENCE 2, FIREBOMBERS, AND LEAD AIRCRAFT DATA

As shown in figure 4-1, the cumulative exceedance plots indicated that within the overall firefighting roles data, there were a number of distinct subsets or groupings of data that merited further exploration, namely

- Aircraft weight, as categorized by MTOW: Figure 4-1 shows an increase in load spectrum severity with decrease in aircraft MTOW.

- Aircraft time: Figure 4-1 shows an increase in load spectrum severity with decrease in flight time (note the number of minutes quoted for each aircraft is assumed to be directly related to aircraft flight time. It is possible that the quoted time relates to time at the fire site and not the en route segments to and from the fire zone).

- Aircraft operational role: Of the two roles shown on figure 4-1, the lead aircraft spectrum is considerably different than the aircraft in the air tanker role for both the positive and negative spectrum.

The resultant groups and subgroups that were subsequently used for data analysis are summarized in table 4-1.

TABLE 4-1. AIRCRAFT GROUPINGS USED FOR ANALYSIS

Group		Aircraft Type	Aircraft ID	Operational Role	MTOW (lb)	No. of Flights	Recorded Data (hours)
No.	Description						
1	Lightweight firebomb—aircraft 24 (short flight)		24	Firefighting	26,300	248	78
2	Lightweight firebomb—aircraft 24		24[1], 24[2], 24[3], 24[4], 24[5]			168, 126, 120, 171, 155	92, 67, 67, 101, 85
3	Mediumweight firebomb—aircraft 22		22		64,000	61	29
4	Mediumweight firebomb—aircraft 21		21		80,000	304	305
5	Heavyweight firebomb—aircraft 20		20, 20[1]		106,000	343, 391	285, 328
6	Heavyweight firebomb—aircraft 19		19, 19[1]		126,000	163, 28	143, 24
7	Fire lead, aircraft 27		27	Firefighting—lead plane	2,950		253
8	Fire lead, aircraft 4		4[1]		4,830		134
9	Fire lead, aircraft 25		25		5,400		246

TABLE 4-1. AIRCRAFT GROUPINGS USED FOR ANALYSIS (Continued)

Group No.	Group Description	Aircraft Type	Aircraft ID	Operational Role	MTOW (lb)	No. of Flights	Recorded Data (hours)
10	Lightweight crop spray—all aircraft		37, 37^{1}	Aerial applications—crop spraying	2,900	829, 488	175, 342
			36A		3,800	180	72
			36		4,000	1195	208
			35, 35^{1}, 35^{2}		4,200	1300, 652, 342	357/392/137
			34, 34^{1}, 34^{2}, 34^{3}		4,400	156/337/347/731	31/203/187/322
			30A		6,000	2873	782
			32, 32^{2}, 33, 33^{1}, 33A, $33A^{1}$, $33A^{2}$		6,075	760/1446/594/467/247/230/107	100/198/351/124/45/23/13
			30, 30^{1}, 30^{2}, 31		6,900	605/58/546/507	127/47/140/174
			29, 29^{1}		8,200	1164/424	339/298
11	Lightweight firebomb—aircraft CF-OPV	Grumman (S-2) Tracker	CF-OPV	Aerial Firefighting	29,150	44	26.8
12	Lightweight firebomb—aircraft C-GHQY	Grumman (S-2) Tracker	C-GHQY	Aerial Firefighting		69	50.6
13a	Mediumweight firebomb—aircraft C-GFST	Fokker F-27	C-GSFST	Aerial Firefighting	45,000		69.7
13b							58.9
14	Heavyweight budworm spray	Douglas DC-6B		Budworm spraying		43	68.0
15	Heavyweight budworm spray—all aircraft	Douglas DC-6B		Budworm spraying	106,900	242	316.2
16	Heavyweight domestic	Douglas DC-6		Domestic	106,900	N/A	N/A

4.2 IMPACT OF POTENTIALLY SIGNIFICANT PARAMETERS.

Significant parameters that might impact the analysis or presentation of the data were also evaluated on a preliminary basis prior to undertaking the final analysis of the data. These are discussed further in sections 4.2.1 to 4.2.3.

4.2.1 Separation Into Gust and Maneuver Spectrum.

The analysis conducted in reference 2 presents the load spectra for both the gust and the maneuver spectra. To assess the significance of these two elements on the total airborne spectra, the gust and the maneuver spectra for three individual aircraft were reviewed.

The aircraft selected, 24[2], 21, and 19 [2], are typical of the aircraft operating in the air tanker role and represent the light, medium, and heavy MTOW categories. The spectra for these aircraft are shown in figures 4-2, 4-3, and 4-4, respectively.

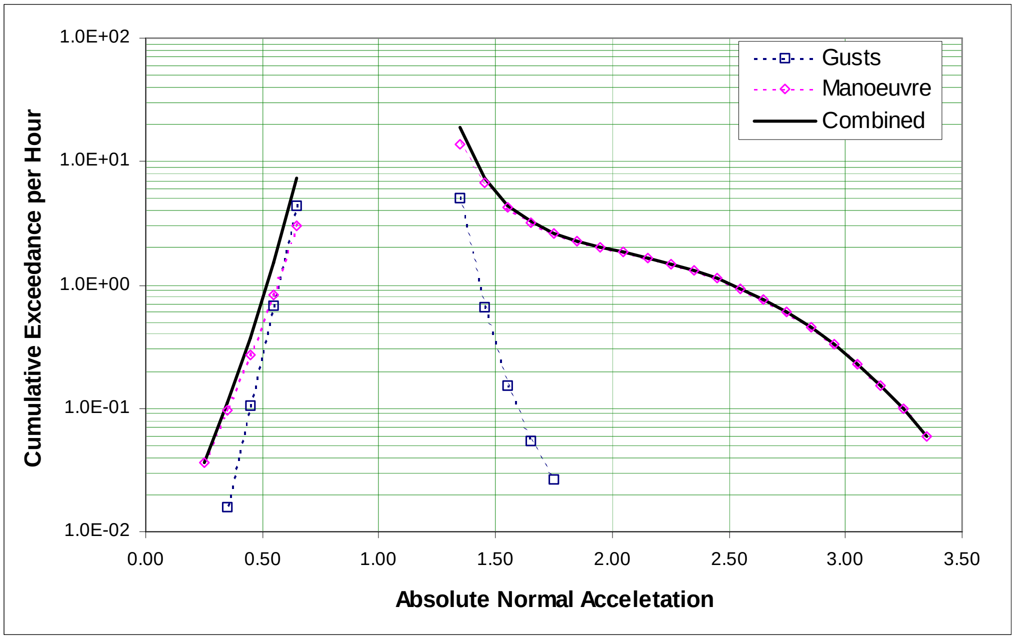

FIGURE 4-2. GUST, MANEUVER, AND COMBINED LOAD SPECTRA FOR AIRCRAFT 24[2]

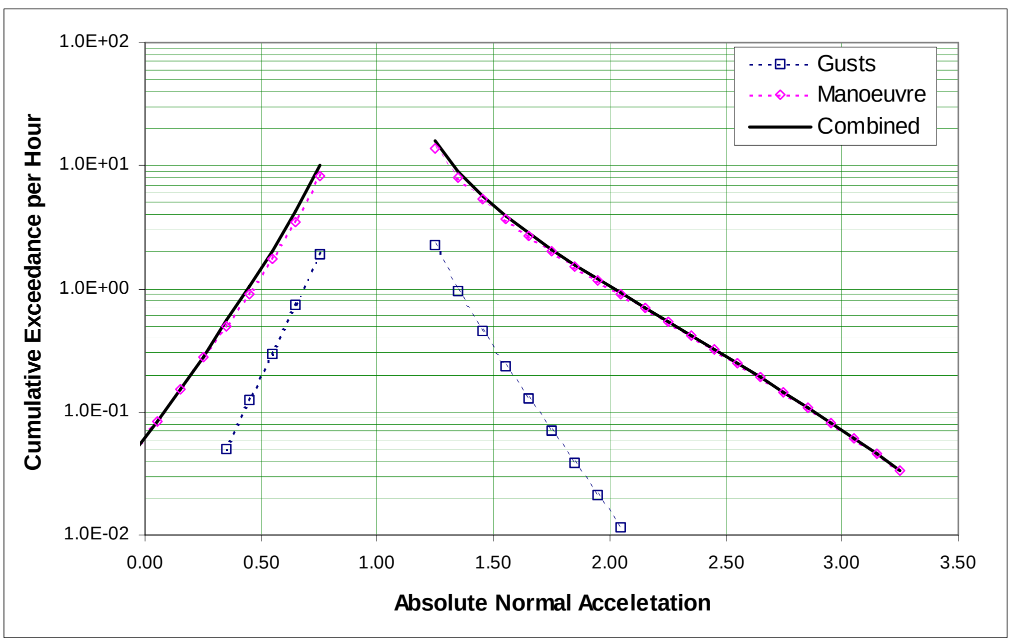

FIGURE 4-3. GUST, MANEUVER, AND COMBINED LOAD SPECTRA FOR AIRCRAFT 21

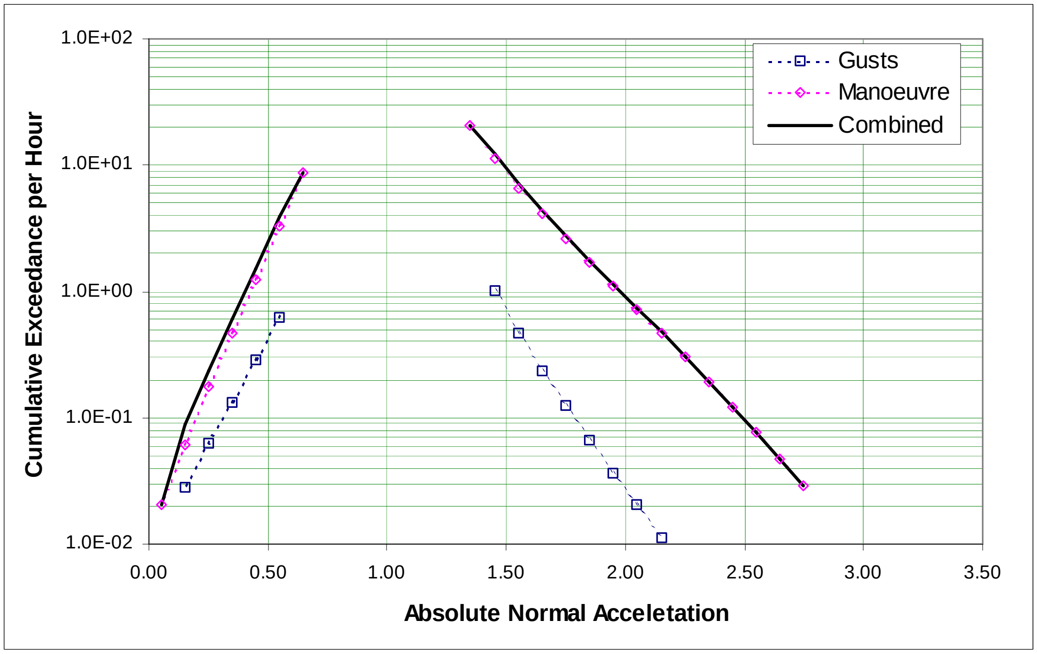

FIGURE 4-4. GUST, MANEUVER, AND COMBINED LOAD SPECTRA FOR AIRCRAFT 19

These three examples cover the full range of MTOWs for aircraft in the air tanker role. In each case, the maneuver cumulative exceedances per hour curve are almost coincident with the total (maneuver and gust) exceedance per hour curve over most of the data range. This suggests that the spectra for the air tankers is predominantly maneuver-dominated and implies that in addition to abrupt terrain avoidance maneuvers, there is a considerable amount of control input required to keep the aircraft relatively straight and level at lower altitudes. However, this conclusion assumes that the traditional methods adopted in reference 2 for separating exceedances into maneuvers and gusts at higher altitudes also applies to aircraft operating in close proximity to the ground. The traditional methods applied to data obtained from higher altitudes are based on the premise that airflows at these altitudes can be sensibly assumed to be circulatory. As discussed in reference 25 and section 3.3.1, this may not necessarily be the case for aircraft operating at low altitudes in flat or mountainous terrain.

4.2.2 Effect of MTOW on Load Spectrum Severity.

An initial review of some of the available air tanker spectra suggested that the severity of the spectra experienced might be dependent on the weight of the aircraft (i.e., generally speaking, lighter aircraft are more maneuverable than heavier aircraft and more responsive to gusts). Unfortunately, for the majority of the data available, the weight of the aircraft at the time a given exceedance was incurred was not available. Therefore, to assess the impact of aircraft weight on spectrum severity, an attempt was made to ascertain whether aircraft MTOW could be correlated with severity of spectrum. The results are shown in figure 4-5.

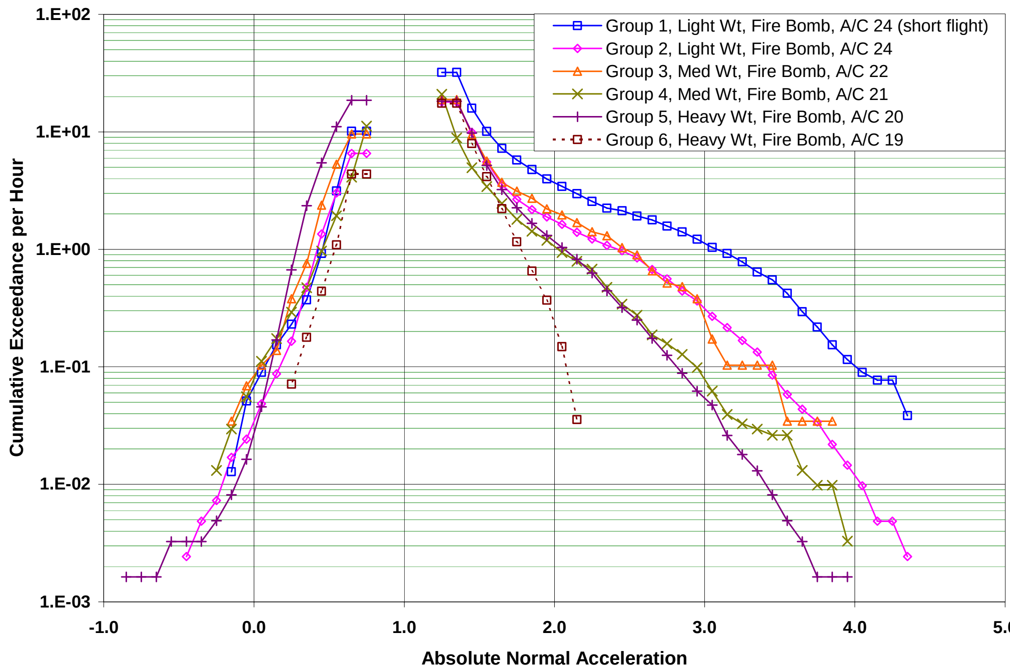

FIGURE 4-5. EXCEEDANCE PLOT FOR DIFFERENT MTOW CATEGORIES, FIREBOMBER DATA

Figure 4-5 shows the load spectra for five different MTOW categories of firebombers. Groups 1 and 2 have a MTOW of 26,300 lb. For the reasons discussed in section 4.2.3, even though the aircraft in groups 1 and 2 have the same MTOW, their data is kept separate due to distinct differences in flight times. Groups 3 through 6 have MTOWs of 64,000, 80,000, 106,000, and 126,000 lb, respectively. There is one aircraft in the 80,000 MTOW category and one in the 64,000 MTOW category. For the other MTOWs, the data from multiple numbers of the same aircraft type are combined to give single cumulative exceedance per hour spectra using the method outlined in section 3.3.3.

While there appears to be a trend that might support the hypothesis that the severity of the usage spectrum is related to aircraft weight, there are two areas in figure 4-5 that suggest that such an inference cannot be drawn without further information. The MTOW for groups 1 and 2 is 26,300 lb. However, rather than their exceedance curves being coincidental, their exceedance curves are quite distinct. Similarly, while groups 5 and 6 contain aircraft in a similar weight category (MTOWs of 106,000 and 126,000 lb, respectively) their exceedance curves are also quite distinct. Before a relationship between MTOW and severity of spectrum can be established, it will be necessary to determine the weight of each aircraft at the time a given exceedance occurs.

<u>4.2.3 Effect of Flight Time on Load Spectrum Severity</u>.

An alternative approach to understanding the spread observed in the load spectra was to consider the different average flight times. For example, the average flight times for groups 1 through 6 shown in figure 4-5 are 19, 33, 30, 60, 50, and 50 minutes, respectively. With the exception of group 6, for the portion of the load spectra containing normal accelerations greater than 1 g, the plot shows that the data for groups 2 and 3 (33 and 30 minutes) and for groups 4 and 5 (60 and 50 minutes) collapse closely together at the lower levels. This suggests that any variation in load spectra was more likely attributable to flight time than MTOW. However, at higher acceleration levels, there was significantly more scatter. The single aircraft, defined by group 1 (19 minutes), follows the same trend of increasing severity with shorter flight times. One potentially influential factor that was not possible to extract from the data is the capability of the heavier aircraft to conduct multiple bombing runs during a single sortie. This capability can result in significant changes in the weight of an aircraft several times during its mission.

The reason for this observed trend, at least in part, is that the most damaging segment of the firebombing role will be the segment associated with the dropping of fire retardant or water over the fire. Recording longer periods of flying to and from the fire only tends to dilute the severity of the load spectra per hour of recorded data. If the reason for the shorter flight times having more severe load spectra is because they result in more firebombing events per hour of operation, then converting the load spectra to cumulative exceedance per flight should better collapse the data.

As an example, aircraft 24 averages 18.9 minutes per flight (based on 78 hours of data being obtained from 248 flights). Whether the assumed average flight time is accurate does not matter, provided that each flight contains the accelerations associated with the firebombing activity. Plots of absolute normal acceleration versus cumulative exceedance per flight for groups 1 to 6 are presented in figure 4-6.

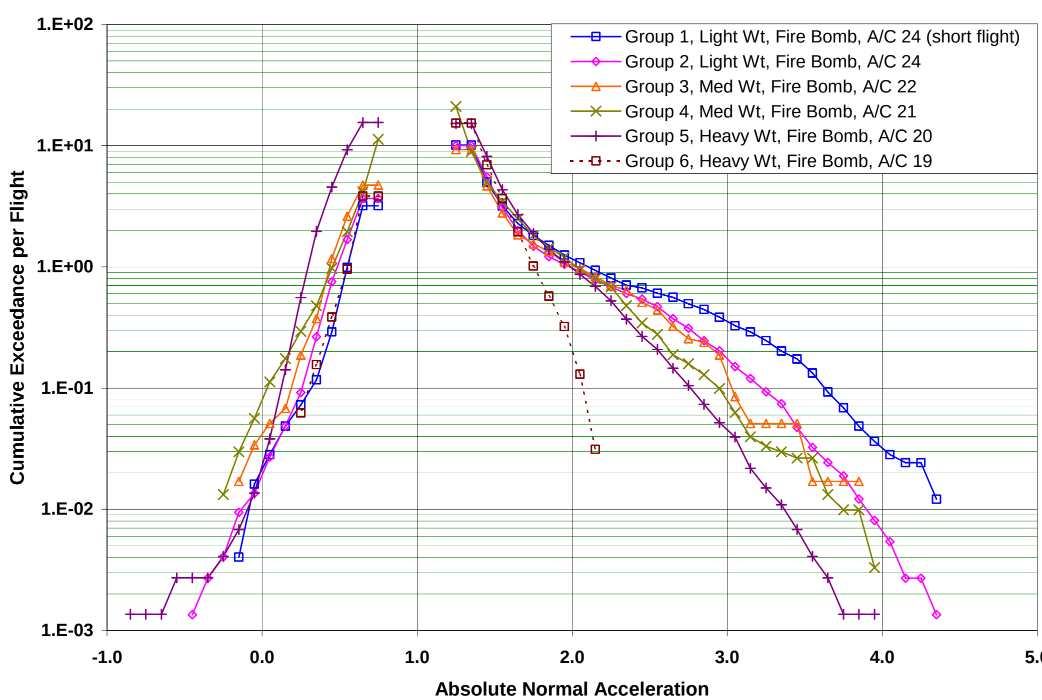

FIGURE 4-6. CUMULATIVE EXCEEDANCE PER FLIGHT FOR GROUPS 1 TO 6, FIREBOMBER DATA

This method of presenting the firebombing data does reduce the scatter relative to exceedance per hour plots. For data between -1.0 and +1.0 g, the scatter is similar to that observed in figure 4-5. With the exception of aircraft 19, the data for the other aircraft shows improved correlation between +1.0 g and approximately 2.2 g's relative to the data presented in figure 4-5. The remainder of the data shows similar, although perhaps marginally less, scatter than the data plotted in figure 4-5.

4.3 REVIEW OF DIFFERENT OPERATIONAL ROLES.

Having looked at parameters that might influence overall data trends in section 4.2, it is appropriate to review data based on aircraft used in similar roles.

4.3.1 Firefighting—Air Tankers.

Figure 4-7 compares all air tanker data, grouped by weight, obtained from both references 2 and 3. A review of this data shows that there is significant scatter in the data obtained.

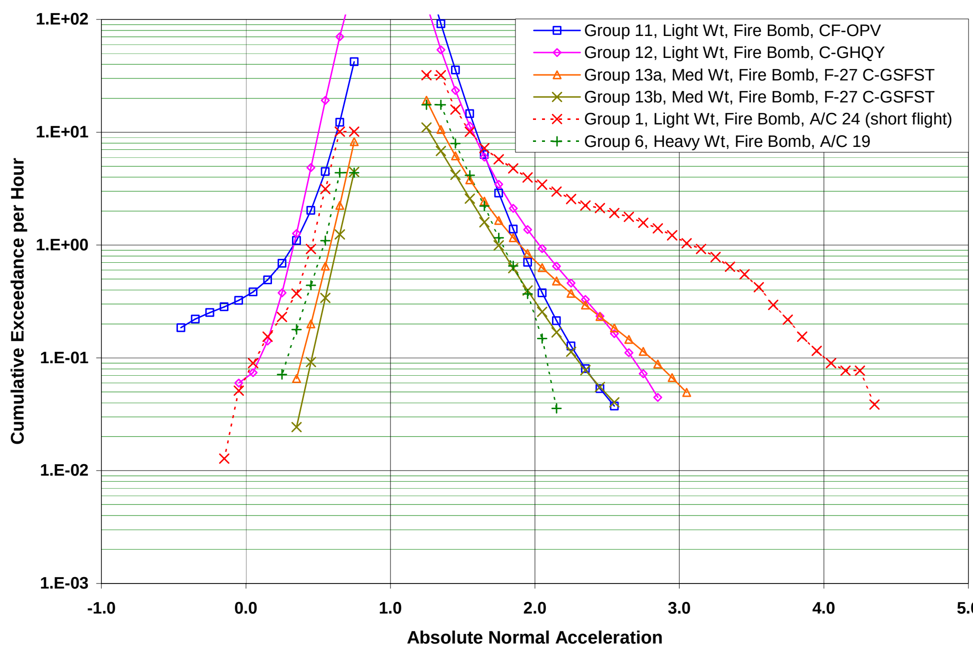

FIGURE 4-7. EXCEEDANCE PLOT FOR OTHER FIREBOMBERS [3], FIREBOMBER DATA

Some of the scatter exhibited in figure 4-7 may be attributable to significant factors that were not possible to extract from the data. For example, the source data does not discriminate whether or not the aircraft were being used to fight fires in mountainous or undulating terrain. Preliminary data obtained from recent programs suggests that this needs to be accounted for, as the spectrums that are obtained can be quite different. Notwithstanding this limitation, there are some interesting trends in figure 4-7 that are worthy of comment.

The medium and heavy aircraft groups (MTOW 45,000 lb and up, groups 13 and 6) tend to experience less severe spectrum than the lighter weight aircraft (groups 1, 11, and 12). On the positive side of the spectrum (greater than 1 g) up to approximately 2.0 g's, they exhibit fairly similar exceedance curves. Above 2.0 g's, these curves start to diverge. This would be consistent with the aircraft seeing and responding to similar gust environments, but being subjected to the different maneuver environments as a result of the terrain over which they were operating and the control inputs required for terrain or object (buildings, power lines, etc.) avoidance. On the negative spectrum side, their spectrums appear to be consistent and reasonably comparable.

With the exception of the aircraft included in group 1, the lighter weight air tankers appear to experience a similar but slightly more severe spectrum than the medium and heavy air tankers. Once again, there is some divergence at higher g-levels that could be consistent with their use over different types of terrain or requirements related to terrain or object avoidance.

It would appear that the lightweight air tankers in group 1 are being used in a very different manner than all the other aircraft involved in this role. Depending on the weight of the aircraft at the time of the exceedances, the large number of exceedances per hour recorded at the higher g-levels could prove to be very detrimental from a fatigue standpoint.

4.3.2 Firefighting—Lead Aircraft.

The load spectra for the three different lead aircraft included in reference 2 are shown in figure 4-8. For reference, the envelope cases for the air tanker role (groups 1 and 6) are also presented.

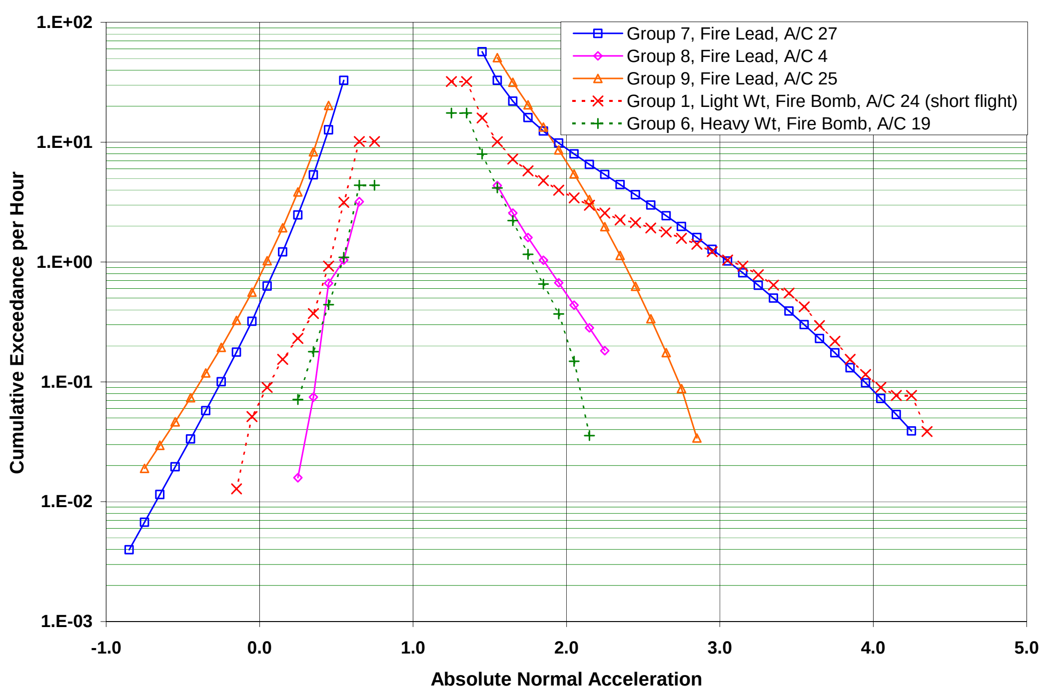

FIGURE 4-8. EXCEEDANCE PLOT, AERIAL FIREFIGHTING LEAD AIRCRAFT DATA

The spectra for the lead aircraft shows that the group 7 aircraft spectrum differs significantly from the spectra recorded by aircraft in the other two lead aircraft groups (groups 8 and 9). In fact, the spectrum experienced by the group 7 lead aircraft closely matches the heavy air tanker group (group 6). The lead aircraft in groups 8 and 9 have load spectra that are far more severe than the most severe air tanker spectrum.

As seen from table 4-2, the weight of the aircraft is certainly a factor with the lightest aircraft having by far the most severe spectrum. However, the fact that the heaviest aircraft does not have the least severe spectrum indicates that there are other factors influencing the data that need to be investigated.

TABLE 4-2. WEIGHTS OF LEAD AIRCRAFT

Group	Aircraft in Group	Weight (lb)	Hours of Data
7	27	2950	253
8	4[1]	4830	134
9	25	5400	246

The difference in data recorded by these aircraft suggests that within the lead aircraft role there are a number of significant subroles. Depending on which subrole is being flown, the loads environment to which these aircraft are subjected will vary drastically.

Of more concern is that, at best, the loads spectrum experienced by lead aircraft is at least as severe as loads spectrum experienced by an air tanker and, at worst, far more severe. Unlike the air tankers, the lead aircraft do not experience drastic changes in their in-flight weight and, therefore, the corresponding stress levels at critical locations in their structure may well be significantly higher than was anticipated during their original design. This preliminary analysis suggests that there is an urgent need to review and quantify the lead aircraft loads environment and assess the impact of this environment on the ongoing structural integrity of these aircraft.

4.3.3 Agricultural Aircraft.

The in-flight failure of the wings of two large air tankers in 2002 [13 and 19] resulted in the majority of the large air tankers not having their contracts renewed for the 2004 fire season [30]. To address the loss of capacity, a large number of SEATs were contracted to provide air tanker support. The majority of these aircraft were converted to small agricultural aircraft. Therefore, it is useful to review data obtained from agricultural aircraft to compare the loads experienced in their normal operating environment against those experienced in the fire environment.

A single load spectrum for all the different crop spraying aircraft (aerial applications) contained in reference 2 is shown in figure 4-9 together with the spectrum obtained from a heavy aircraft involved in budworm spraying obtained from reference 3. For the reference 2 data, the aerial application data is combined to give single cumulative exceedance per hour spectrum using the method outlined section 3.3.3. Envelope cases for the air tankers (groups 1 and 6) are also presented for reference.

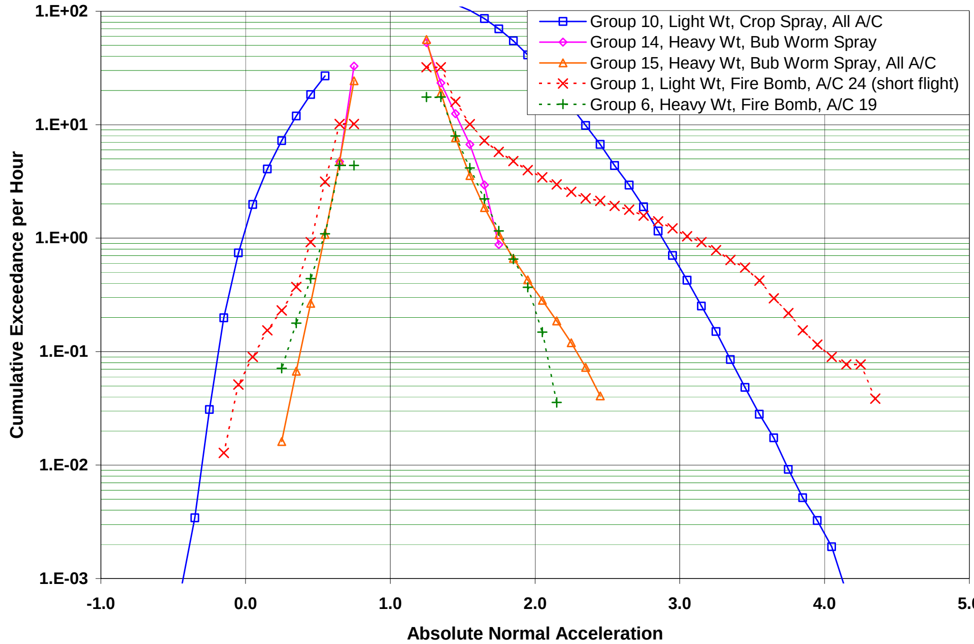

FIGURE 4-9. EXCEEDANCE PLOT, AGRICULTURAL AIRCRAFT DATA

The spectrum for the lightweight crop spraying aircraft (group 10) was much more severe than the most severe load spectrum for the air tanker at lower g-levels. At around 3 g's, the air tanker spectrum becomes more severe than the agricultural aircraft. The agricultural spectrum was gathered from aircraft with MTOWs ranging from approximately 3000 to 8000 lb. An aircraft with a MTOW of 26,300 lb recorded the most severe air tanker spectrum.

It is also worth noting that there is a significant difference between the agricultural spectrum recorded by the lightweight agricultural aircraft and the spectrum recorded by a heavy agricultural aircraft with a MTOW of the order of 80,000 to 90,000 lb. The load spectra for the heavier aircraft used for budworm spraying aligns closely with the spectrum obtained for the heavier air tankers of a similar weight.

4.3.4 Normal Operations.

A question that often arises is, How much more severe is the low-level loads environment with respect to the higher-level environment for which many low-level aircraft were originally designed? While this can be difficult to quantify precisely, some estimate of the relative severity can be obtained from figure 4-10, which shows data obtained from a DC-6 in domestic operations, plotted against the two extremities of the air tanker envelope presented in figure 4-7.

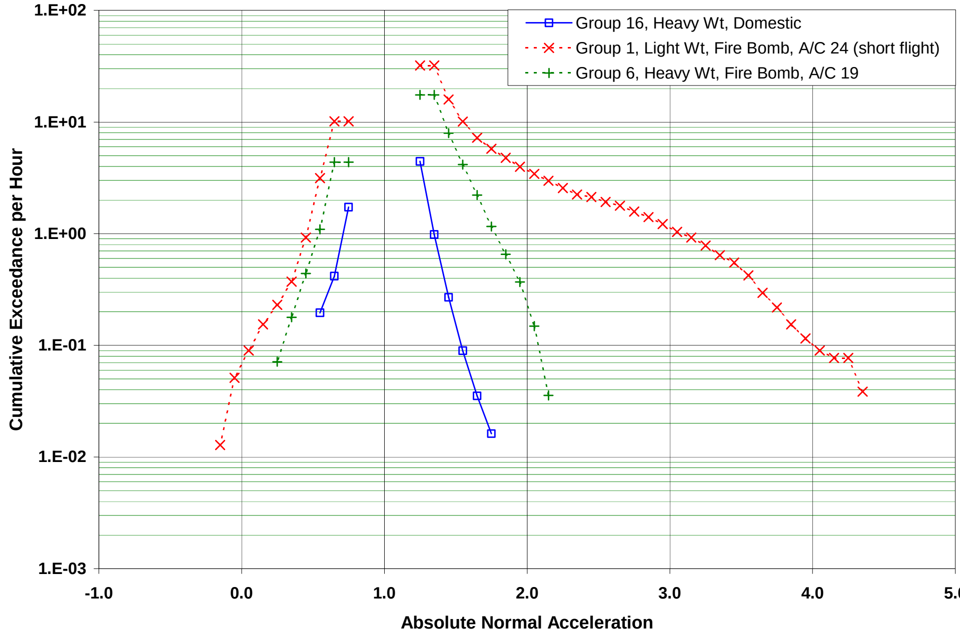

FIGURE 4-10. EXCEEDANCE PLOT, DOMESTIC OPERATIONS

As would be expected, the load spectrum for the aircraft engaged in nonfirefighting roles (approximately MTOW of 106,900 lb) is well within even the least severe firebombing load spectrum. This does, however, illustrate that careful attention needs to be paid to establishing structural inspection programs for aircraft engaged in aerial firefighting operations. As can be seen in figure 4-10, even the least severe load spectrum for the aerial firefighting role is at least an order of magnitude greater than the load spectrum for nonfirefighting operations for similar model types.

5. ANALYSIS OF STRUCTURAL IMPLICATIONS OF THE USAGE DATA.

A rigorous quantitative analysis of the structural implications of a given loads environment on an aircraft requires the generation of a detailed stress spectrum for each critical structural location for each aircraft type. However, as described in section 3.4, a qualitative evaluation of the data can be undertaken to assess the relative significance of the different usage. Using the techniques described in section 3.4, a relative assessment of the data that was extracted from references 2 and 3 was completed. The results of this assessment are presented in sections 5.1 and 5.2.

5.1 CURVE FITTING AND DATA INTERPOLATION/EXTRAPOLATION.

The first stage in the relative evaluation of the data was to ensure that all the data used in the analysis had a comparable range. Given that the data included in references 2 and 3 were gathered from a variety of sources for a number of different aircraft, the g-level range over which exceedance data was obtained varies significantly. Therefore, for the purpose of this analysis, the curve fit and extrapolation techniques described in section 3.4.2 will be used to equalize the g-level ranges.

5.1.1 Selected Data Range.

As shown in figure 3-2, the ultimate positive and negative load factors of an aircraft are used to define the extreme positive and negative asymptotes used for the overall curve fit. Limit load factors for both lighter and heavier weight transport category aircraft are specified in Title 14 Code of Federal Regulations (CFR) Parts 23 and 25, respectively. These can be converted to ultimate maneuver load factors (limit load times 1.5). However, inspection of the data obtained from reference 2 indicated that to encapsulate all the recorded data, the positive and negative limits should be set at +4.5 and -1.0 g's, respectively. Consequently, for the purpose of analyzing the recorded data, these limits were used, even though in some instances such values exceed those prescribed by 14 CFR Parts 23 and 25.

It should be emphasized that when generating a curve for analysis purposes, the limits of prescribed 14 CFR Parts 23 and 25 should be followed.

5.1.2 Equalization of g Exceedance Curves for All Aircraft.

Using the equations specified in section 3.4.2.1, the g-level exceedance curves for all measured data were equalized over the range specified in section 5.1.1. A sample of the resulting fit, relative to the original data, for one of the heavy air tankers (aircraft 20, group 5, table 4-1) is shown in figure 5-1. Plots for all the data examined, plus the associated curve fit values, are summarized in appendix B.

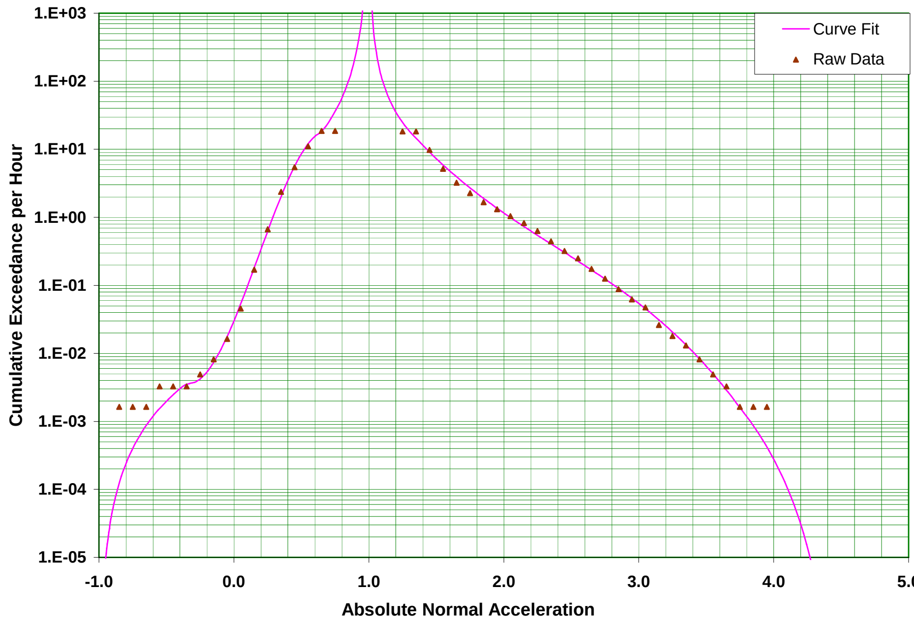

FIGURE 5-1. EXTRAPOLATED LOAD SPECTRA, HEAVY AIR TANKER, AIRCRAFT 20

While the selection of the asymptote values of -1.0 and +4.5 g's may seem somewhat arbitrary, these values are much less significant than the required asymptotic value of +1.0 g. As will be demonstrated in section 5.2, this portion of the load spectra together with the fitted raw data are the regions to which the majority of the accumulated damage can be attributed.

5.2 ESTIMATES OF RELATIVE DAMAGE RATES.

To gain insight into damage rates occurring in firefighting operations, certain assumptions are made in this section concerning the stress levels and appropriate S-N curves for typical built-up wing structures. In particular, the likely fatigue rates of typical inboard wing structure will be selected for evaluation. It is emphasized that this is done only to provide an indication of probable general trends and will not necessarily constitute the expected behavior in all cases.

The assumptions made are as follows:

- The typical average inboard wing stress levels may be assumed to be of order 10 ksi per g.
- Stress levels are a function only of normal acceleration.
- S-N characteristics of built-up wing structure can be based on typical characteristics developed by the Royal Aeronautical Society [28].

Note that while the S-N curves used here were originally generated from the constant-amplitude fatigue testing of a variety of complete and partial aircraft following cessation of hostilities in the Second World War, they were found to correlate well with data obtained from full-scale fatigue tests. The original typical wings and tails curves were subsequently reviewed and analyzed by the NRCC [28] who proposed a number of modifications to further improve their predictive accuracy. It is these latter curves that were incorporated into the relative damage calculations used in this report. In particular, the Sewell definition of the curves were used to calculate the *N* values corresponding to the values of *n* that were identified in accordance with the procedure described in section 3.4.2.2.

5.2.1 Calculation of Relative Percentage Cumulative Damage.

A plot of relative percentage cumulative damage versus maximum g-level is used to identify the parts of a cyclic loads spectrum that contribute the most damage to an aircraft. A schematic diagram of relative percentage cumulative damage is shown in figure 5-2.

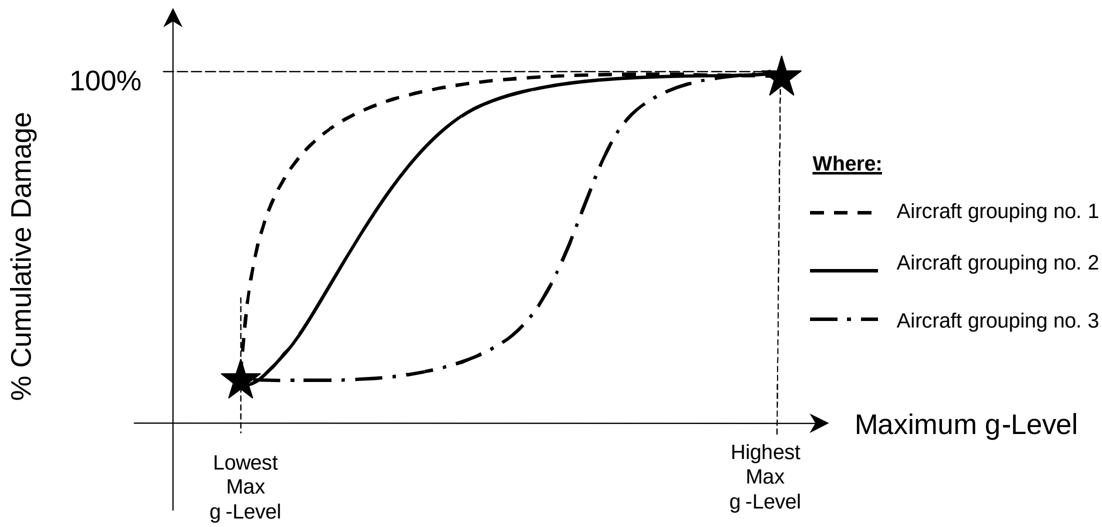

FIGURE 5-2. RELATIVE PERCENTAGE CUMULATIVE DAMAGE

The relative cumulative damage clearly shows the contribution to the overall cyclic damage sustained by a structure for cycles with different maximum g-levels. The leftmost curve in the figure indicates a situation where the majority of the damage is incurred by relatively low-magnitude cycles. The center curve indicates a situation where the overall damage accumulation is contributed fairly evenly by cycles of all magnitudes. Finally, the rightmost curve illustrates a situation where the majority of the cyclic damage sustained can be attributed to relatively high-magnitude cycles.

Percentage relative cumulative damage is calculated by

- dividing the positive spectrum of each fitted/extrapolated curve into a series of finite g-ranges and determining the associated cumulative number of exceedances per hour and the corresponding negative g-level, as described in section 3.4.2.2.

- translating each pair of positive and negative g-levels into corresponding stress levels using the unit transfer function and calculating the associated mean and alternating stress levels.

- calculating the actual number of occurrences per hour for each pair of positive and negative g-levels by successive subtraction of the cumulative number of exceedances per hour for each adjacent finite g range (this provides *n*).

- using the mean and alternating stress levels associated with each finite g-range to calculate the number of cycles when the damage will become evident (initiate) if a structure were subjected to a constant mean and alternating stress level equal to the mean and alternating stress level of the current cycle being considered (this provides *N*).

- calculating the damage contribution associated with each finite g-range assuming Miner's hypothesis holds true (i.e., n/N).

- summing the cumulative damage from each successive cycle and dividing it by the total damage for all cycles. This result is converted to relative percentage cumulative damage by multiplying by 100.

The methodology and a sample calculation are in accordance with the description and sample calculation provided in reference 22. The results presented in this section are based on the calculation of cumulative damage ($\Sigma\ (n/N)$) between n = 1.1 g's through to n = 4.4 g's. The incremental and cumulative damage values are normalized using the calculated total damage to give a total damage of 1.0 for all cases. A typical result for a heavyweight air tanker is shown in figure 5-3 (aircraft 20). Plots obtained for all other individual aircraft are contained in appendix C. Cumulative plots comparing the relative damage for different aircraft are presented in section 5.2.2.

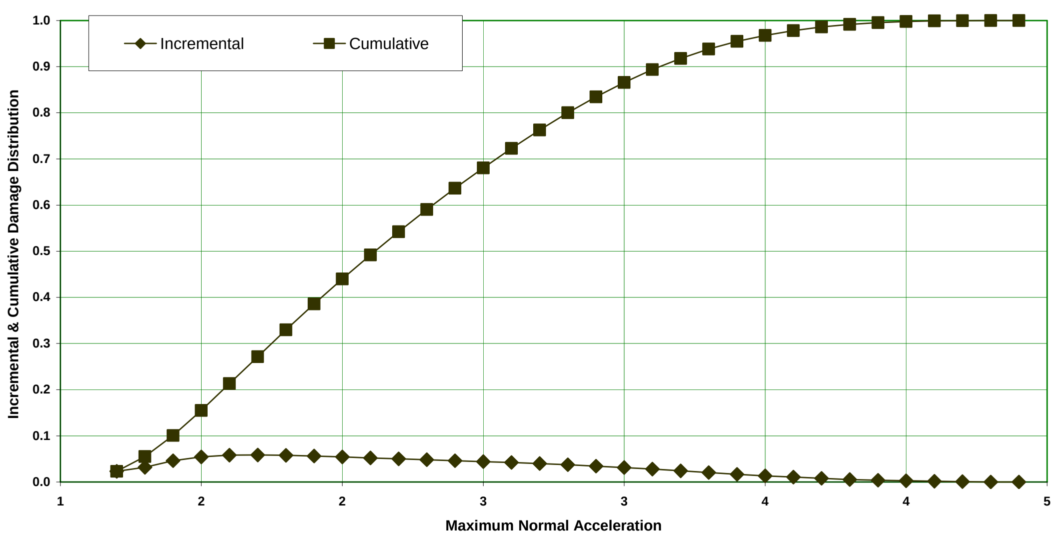

FIGURE 5-3. INCREMENTAL AND CUMULATIVE DAMAGE FOR AIRCRAFT 20

The cumulative curve in figure 5-3 indicates that approximately 50% of the accumulated damage comes from g-level excursions with a maximum g-level of 2.5 g's or less. The incremental curve indicates that the maximum amount of damage is attributable to g-level excursions with maximum g-levels in the 2.0- to 2.25-g range.

5.2.2 Relative Percentage Cumulative Damage vs Acceleration.

The relative percentage cumulative damage for the aircraft groups listed in table 3-2 are presented in figures 5-4 to 5-6 inclusive. The figures depict the accumulation of damage as the maximum acceleration levels of the measured cycles increase.

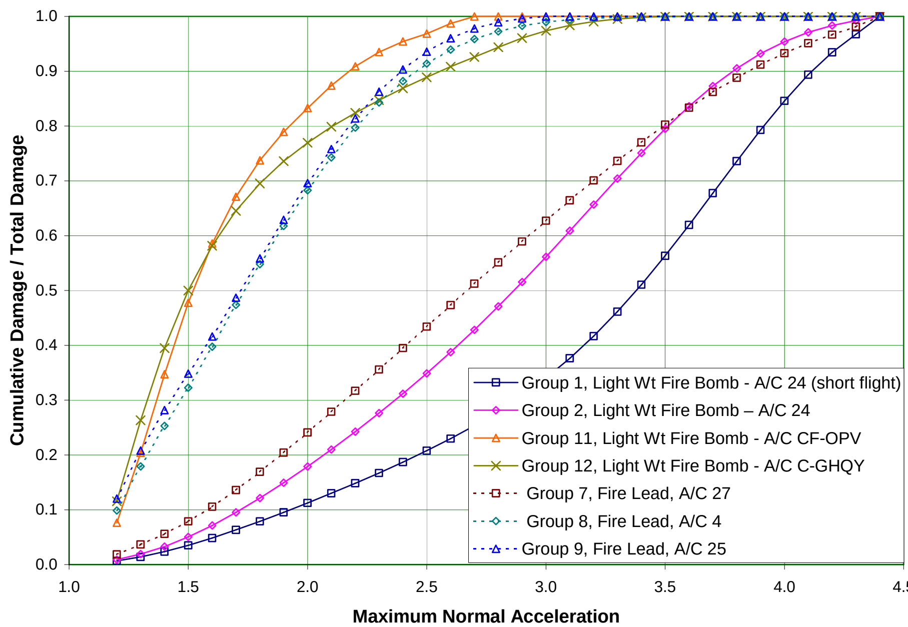

FIGURE 5-4. CUMULATIVE DAMAGE, LIGHTWEIGHT AIR TANKERS AND LEAD AIRCRAFT

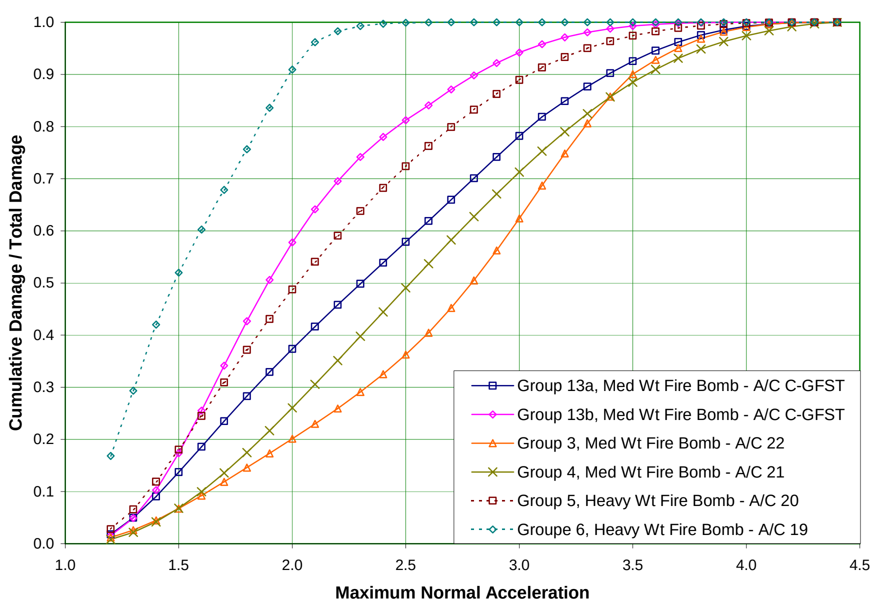

FIGURE 5-5. CUMULATIVE DAMAGE, MEDIUM- AND HEAVYWEIGHT AIR TANKERS

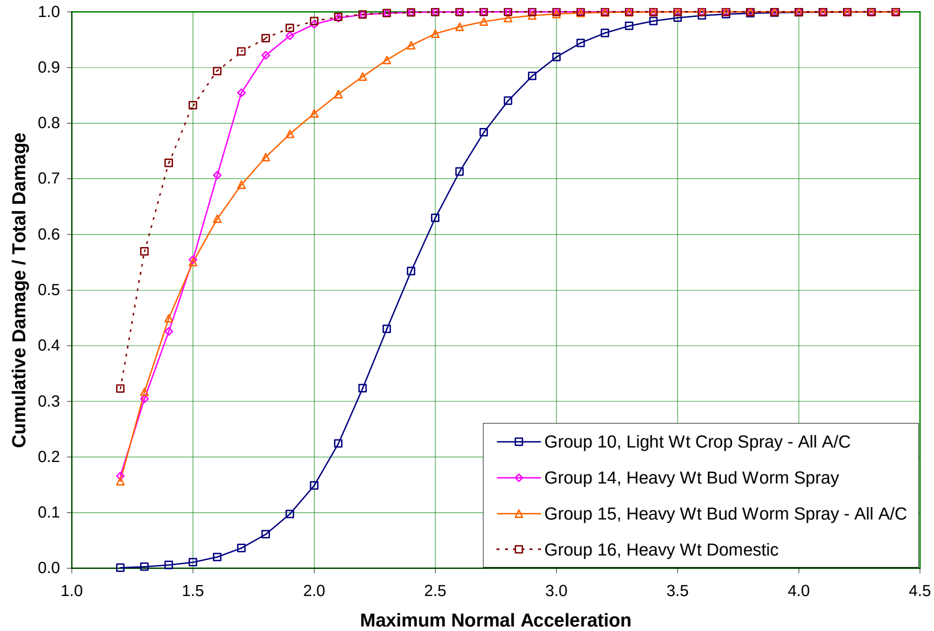

FIGURE 5-6. CUMULATIVE DAMAGE, CROP SPRAYING AIRCRAFT

Figure 5-4 shows damage plots for the lighter weight air tankers and the lead aircraft. Data obtained from two of the lighter weight air tankers and two of the lead aircraft (groups 11, 12, 8, and 9, respectively) indicate that the majority of the damage sustained by these aircraft can be attributed to relatively large numbers of smaller cycles. For example, cycles with a maximum g-level of 2.0 g's or less account for anywhere from 70% to 82% of the accumulated damage. Conversely, data for one of the lead aircraft and one lightweight air tanker indicates that the majority of the damage can be attributed to a lesser number of larger cycles (approximately 2.5 g's and higher). It is interesting to note that for those air tankers where the majority of damage can be attributed to a lesser number of larger cycles, there is a significant difference in the damage distribution for similar types of aircraft involved in short and longer duration flights (section 4.2.3). This may be a result of the apparent reduction of the severity of spectrum due to the spectrum over the fire being combined with different lengths of more benign operations that are experienced during transit to and from the fire zone [31].

Another observation of interest is that air tankers with the majority of damage attributable to larger numbers of lower-level cycles were operated in both undulating and mountainous terrain in Canada [3], whereas air tankers with the majority of damage attributable to smaller numbers of higher-level cycles were operated in undefined terrain in the United States [2]. This suggests that other factors, such as operational technique and crew, may have a significant impact on severity of loading to which the aircraft is subjected. Unfortunately, the data that is available does not allow the impact of such factors to be evaluated.

Data for the medium- and heavyweight air tankers are depicted in figure 5-5. Once again, it appears that the aircraft being evaluated are experiencing quite different load spectra and, hence, subjected to varied usage. Although the influence of whether the data was obtained from aircraft operating in Canada [2] or the United States [3] seems not to be as significant as it was for the lighter weight air tankers and lead aircraft (figure 5-4). There is one interesting trend that was observed. If the data for groups 13a and 13b are removed from the data, the position of the cumulative damage curves is ordered by aircraft MTOW. For example, the MTOW of the leftmost curve (group 6) is 126,000 lb. Moving from left to right, the MTOW of the remaining aircraft groupings are 106,000 lb (group 5), 80,000 lb (group 4), and 64,000 lb (group 3). There are two observations that can be drawn from this analysis.

- The Canadian and U.S flying once again appears to be different. It is interesting to note that the Canadian data obtained from the same aircraft on two different occasions was also significantly different. The source data is not detailed enough to allow a determination of whether this is due to differences in operational procedures, pilot techniques, terrain, or a combination of all three.

- The damage accumulated by the heavier air tankers is primarily attributable to large numbers of lower cycles, whereas the damage accumulated by lighter air tankers is primarily attributable to lesser numbers of larger cycles. This finding is consistent with the findings of reference 2 for heavier aircraft and suggests that great care is required when specifying the ranges and resolution of SHM instrumentation.

For comparative purposes and because some of the smaller agricultural aircraft are being considered for aerial firefighting applications, data for light- and heavyweight agriculture aircraft are shown in figure 5-6 together with some data recorded by similar heavyweight aircraft operating in their original design intent role. This graph once again reinforces the trends observed in figures 5-4 and 5-5, namely, that for larger, heavier aircraft in low-level roles, the majority of the structural damage that is sustained is attributable to a large number of relatively small load cycles. Conversely, for lighter, more maneuverable aircraft, the majority of the damage that is sustained is attributable to lesser numbers of large load cycles.

5.2.3 The Influence of Aircraft Size on Cumulative Damage Distribution Damage.

In an attempt to gain some further insight into the influence of aircraft size (as expressed by MTOW) on cumulative damage distribution, the maximum g-level values at which 50% of the cumulative damage occurred are shown in figure 5-7 for a variety of aircraft.

As can be observed from figure 5-7, the National Aeronautics and Space Administration data for the larger aircraft embodied in reference 3 does suggest that there is a size effect (as defined by MTOW) related to the load cycles that will contribute the most structural damage to aircraft operating in low-level roles. The quality and, in some cases, quantity of all other available data is such that a similar trend cannot be identified for other aircraft. A plausible explanation for this might be the lower gust response and maneuverability characteristics of the larger, higher weight aircraft relative to smaller, more agile aircraft. Further exploration of this relationship is certainly required as, if valid, it will impact the design of SHM programs aimed at evaluating the effects of continued low-level operation on air tankers, lead, and other low-level aircraft.

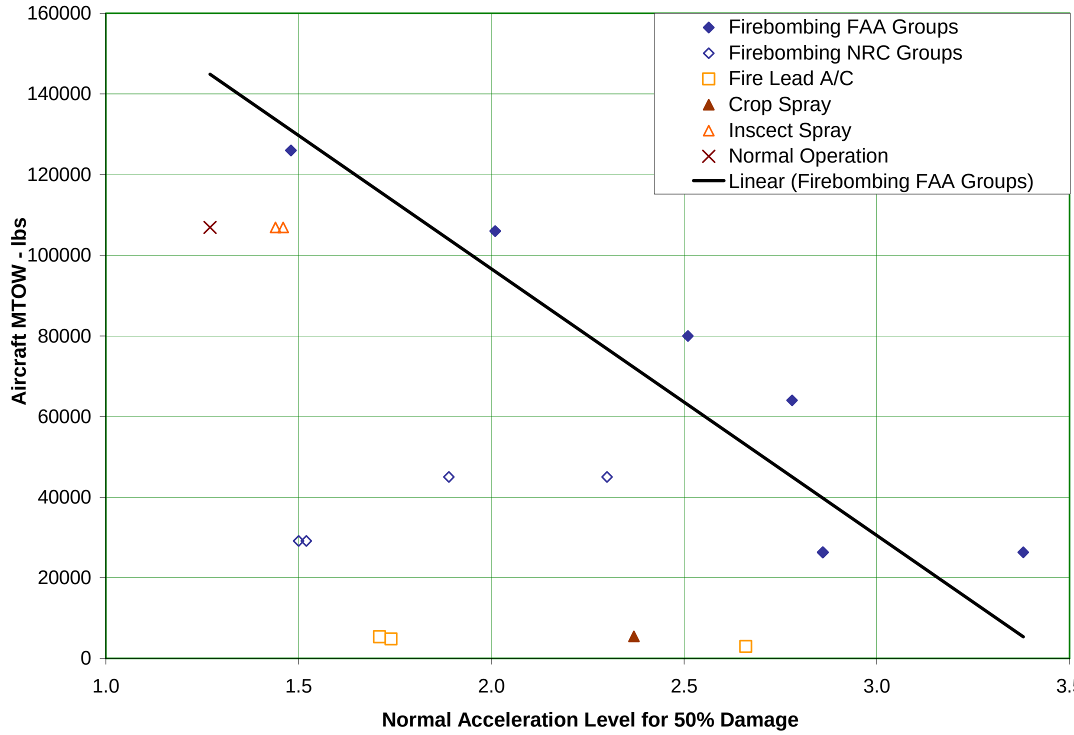

FIGURE 5-7. NORMAL ACCELERATION AT WHICH 50% DAMAGE OCCURS

The relative damage for the airborne segment of flight for aircraft in different roles is shown in figure 5-8. The selected datum is group 1 (aircraft 24) that contains the air tanker with the most severe load spectrum. Values have been calculated for assumed stress transfer functions of 7 ksi and 10 ksi per g.

The two different stress levels show that the relative damage is essentially invariant to the stress levels that could be expected for these types of aircraft. At some of the lower relative damage values, the ranking of aircraft severity is modified slightly, depending on whether 7 ksi per g or 10 ksi per g is used for a transfer function. Further investigation as to why there should be minor changes in the relative ranking at lower relative damage rates suggests that the change in ranking occurs in areas where extensive data interpolation was required due to lack of valid data. The solution to this problem would appear to be a finer resolution of recorded data in these areas. Therefore, while the trends identified through this relative damage analysis are not changed substantively, the absolute values of relative damage that were derived in this report should not be used to infer the actual severity of damage sustained by aircraft being used in identical roles to those that have been investigated.

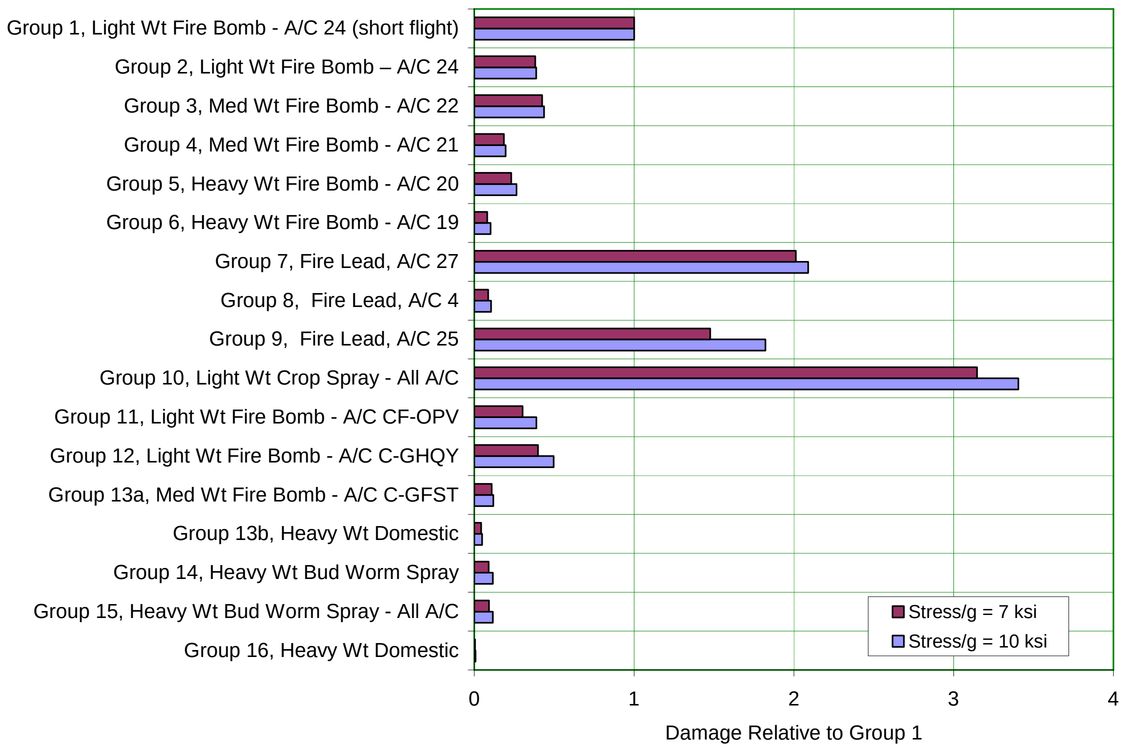

FIGURE 5-8. DAMAGE OF DIFFERENT ROLES RELATIVE TO AIRCRAFT 24

6. PRELIMINARY LOADS SPECTRA FOR AERIAL FIREFIGHTING ROLES.

The aerial firefighting role of primary interest was the air tanker role. However, the severity of the load spectra experienced by some of the lead aircraft was also of some concern. Based on the preceding analysis, preliminary Nz_{cg} spectra were proposed for both air tankers and lead aircraft. Note that such spectra can only be used to derive stress spectra at critical locations in the center wing and center fuselage of the aircraft. Factors such as structural flexibility and phase differences between Nz_{cg} and the strains at critical locations will invariably require the measurement of additional parameters before stress spectra for critical outer wing and empennage locations can be generated.

6.1 AIR TANKERS.

The preliminary analysis of both the exceedance and damage data presented in sections 4.3 and 5.2 indicates that the spectrum and resultant damage distributions were influenced by aircraft size, as defined by MTOW, and differ significantly. Consequently, it would be inappropriate to define a single spectrum that encompasses all air tanker usage.

Until a significant, statistical amount of valid data that takes into account variations in aircraft operational weight has been gathered, it was proposed to provide three conservative spectra for preliminary design and analysis purposes based on data presented in figure 4-6. These spectra will be classified as spectrum for heavy-, medium-, and lightweight air tankers, respectively. Based on the analysis of the data used in this report and the associated data trends, the definition of a heavy, medium, and light air tanker is summarized in table 6-1.

TABLE 6-1. HEAVY, MEDIUM, AND LIGHT AIR TANKER CLASSIFICATIONS

Classification	MTOW (lb)	Spectrum Developed From Aircraft
Heavy	> 80,000	Group 5
Medium	> 30,000 to 80,000	Groups 3 and 4
Light	<30,000	Group 1

Coefficients for generating the spectra in accordance with the equations defined in section 3.4.2.1 are summarized in tables 6-2 and 6-3 and illustrated figure 6-1 for assumed values of Gp_{ult} and Gn_{ult} of 4.5 and -1.0 g's respectively (section 5.1.1).

TABLE 6-2. PROPOSED PRELIMINARY AIR TANKER SPECTRA

Classification	Spectrum Type	Fitted Spectrum						Extrapolated Spectrum			
		Range of Applicability		Data Coefficients				Low		High	
		Low (g)	High (g)	c_0	c_1	c_2	c_3	eph_{g1}	s	eph_{g2}	s
Heavy	Positive	1.35	3.75	14.13521	-13.21072	4.30715	-0.59942	14.52261	-1.9573	0.00159	-2.48937
	Negative	0.65	-0.35	-3.50900	10.99281	8.59656	-15.92618	18.07718	2.53487	0.00362	1.54136
Medium	Positive	1.25	3.95	11.27347	-9.97511	2.94909	-0.37712	14.52646	-1.77116	0.00472	-1.75477
	Negative	0.75	-0.25	-2.57117	6.09986	-3.06234	5.13474	11.55797	3.76900	0.01268	3.22095
Light	Positive	1.35	4.35	12.41651	-11.0069	3.64397	-0.45004	22.00056	-1.42557	0.0286	-1.84675
	Negative	0.65	-0.15	-2.7495	7.45909	-13.61021	22.17563	11.45678	5.57374	0.01427	3.99906

TABLE 6-3. PROPOSED PRELIMINARY LEAD AIRCRAFT SPECTRUM

Classification	Spectrum Type	Fitted Spectrum						Extrapolated Spectrum			
		Range of Applicability		Data Coefficients				Low		High	
		Low (g)	High (g)	c_0	c_1	c_2	c_3	eph_{g1}	s	eph_{g2}	s
Lead	Positive	1.45	4.25	11.4069	-7.72269	2.07904	-0.25363	45.01254	-1.34991	0.03571	-1.55213
	Negative	0.55	-0.85	-0.81713	6.37461	1.93925	1.15191	32.04601	3.83536	0.00392	2.35435

Notes (Applicable to tables 6-2 and table 6-3):

1. The extrapolated spectrum should only be generated when the desired range of values is outside the fitted spectrum range of applicability.

2. Maximum exceedances per hour should not exceed 3600 (i.e., a cutoff should be applied), as this is outside a reasonable response frequency for the wing and center fuselage (references 27 and 29).

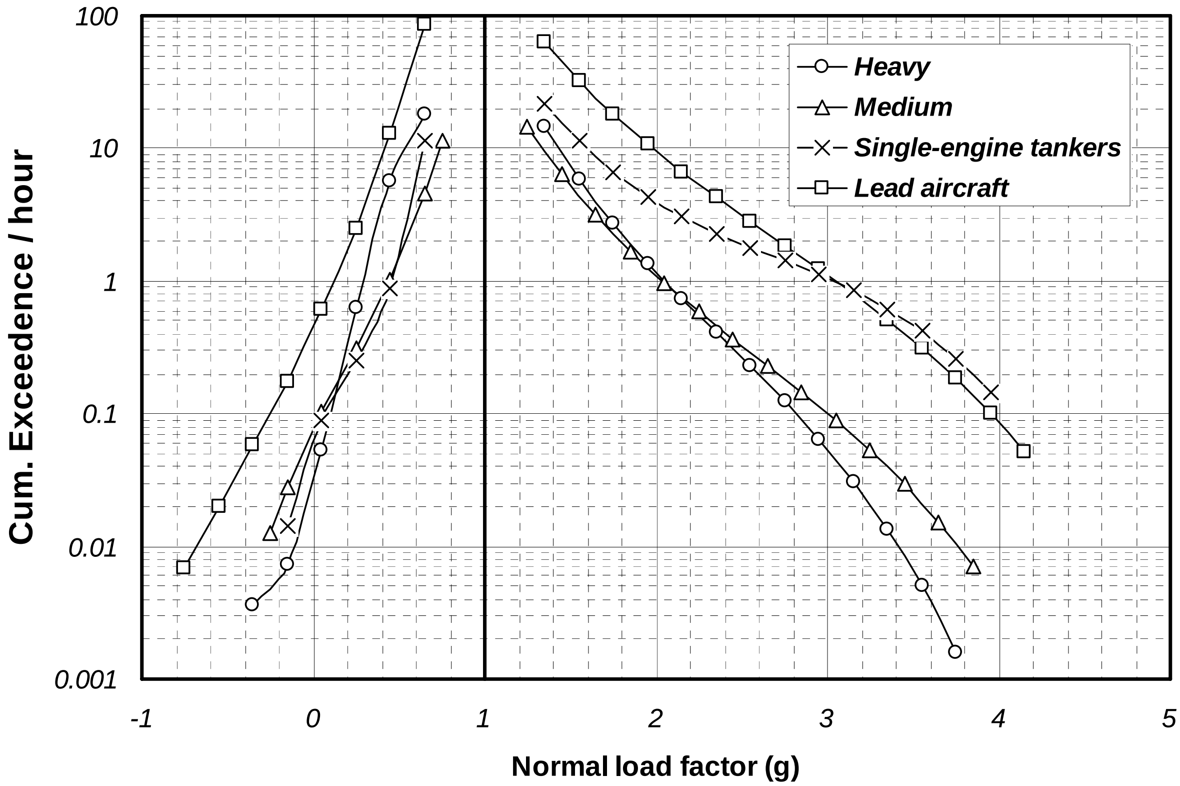

FIGURE 6-1. PROPOSED PRELIMINARY SPECTRUM FOR AIR TANKERS AND LEAD AIRCRAFT

6.2 LEAD AIRCRAFT.

In the absence of more comprehensive data that would help to better define load spectra for lead aircraft, it was proposed that the load spectra be conservatively based on the spectra presented in figure 4-8 for group 7. Coefficients for generating the spectra in accordance with the equations defined in section 3.4.2.1 are summarized in table 6-3 and illustrated figure 6-1 for assumed values of Gp_{ult} and Gn_{ult} of 4.5 and -1.0 g's respectively (section 5.1.1).

Note that the negative spectrum on the heavy air tanker in figure 6-1 exhibits some saddle points not seen in the curves for the other categories of aircraft. Further investigation of this data showed that the saddle points were evident in the source maneuver and gust data obtained from reference 2. Consequently, attempts were not made to eliminate any points that, although resulting in a smoother curve, would detract from actual trends that were evident in the measured data. Unfortunately, reference 2 does not contain enough source data to allow the cause of these phenomena to be investigated further.

6.3 SPECTRUM ADJUSTMENTS.

6.3.1 Truncation.

The proposed spectra presented in table 6-3 and figure 6-1 are smooth analytic curve fits of available data, and as such, they are extrapolable to higher normal acceleration levels than are contained in the basic data records. It does appear to be the case that while in the drop zone many operational high-load exceedances occur with the airplane maneuvering at close to maximum aerodynamic lifting capability, but some caution should be exercised in the extrapolation of the proposed curves to high g-levels, since there are no circumstances where the stall load factor will be exceeded.

Maximum attainable normal acceleration is primarily a function of airspeed, and since airspeed will generally be reduced in operations around the fire zone (for spray pattern control, traffic pattern hold, or other reasons), the maximum load factor is often also limited. In transit to and from the fire zone, the airspeed might be higher, and yet there is no indication of excessive maneuvering in the transit phases. The majority of high load exceedances will be found to occur in the fire zone, particularly the entry to and egress from the retardant drop itself, and it was, therefore, recommended that the load factor corresponding to maximum aerodynamic lifting capability be evaluated for the typical or worst-case operating conditions (aircraft weight and airspeed) in the drop zone, and that the load factor spectra be truncated at that point.

The resultant spectra will then be of different form to that normally seen, where there now could be numerous occurrences of loading at close to stall load factor, and none above.

6.3.2 Effects of Gross Weight.

The proposed spectra of table 6-3 and figure 6-1 were developed from measured data at unknown airplane weights. However, it is reasonable to assume that the airplane weight at the time of the data measurement was, on average, the mean of the representative weights of the airplane arriving at, and departing from, the drop zone. If this average representative weight in the drop zone is W_{mean}, then the equivalent load factor spectra referenced to design MTOW are such that

$$\Delta N_Z \; at \; MTOW = (\Delta N_Z)_{proposed} \times W_{mean} / MTOW$$

When it is anticipated that the operational weight in the drop zone will be significantly less than MTOW, then the proposed load factor spectra may be applied at this expected operational weight, or alternatively, the load factor spectrum may be adjusted to smaller values to be applied at MTOW, per the equation above.

7. IMPLICATIONS OF THE DATA ANALYSIS.

Based on the analysis of the data presented in sections 4 and 5, there are some immediate implications related to both the monitoring and evaluation of data gathered from aircraft operating in the firefighting role. These implications are discussed in sections 7.1 and 7.2.

7.1 STRUCTURAL HEALTH MONITORING PROGRAMS.

The cyclic load region in which the majority of the damage is accumulated differs for different aircraft. The majority of the damage accumulated to the larger, heavier (less maneuverable) aircraft is principally attributable to large numbers of relatively small load cycles, whereas the majority of the damage accumulated by the smaller, lighter aircraft is principally attributable to smaller numbers of relatively large load cycles. This will impact the parameter resolution and the need to determine absolute strain values.

7.1.1 Parameter Resolution.

For the heavier (larger) aircraft, the resolution of any recorded Nz_{cg} or strain data, as defined by deadband and rise-fall criteria [32] should be relatively fine at the lower levels. Elimination of relatively low-level cycles to minimize data storage requirements may result in a significant underestimate of the damage that was being sustained by the structure. For lighter, smaller aircraft, the resolution specified for Nz_{cg} or strain data appeared not to be as critical. However, until additional data has been gathered, it was recommended that relatively fine resolutions be used. Based on the preliminary analysis of data obtained from larger, heavier aircraft [32], it was proposed that the values for the deadband and rise-fall criteria be set to provide a resolution corresponding to changes in stress levels of approximately ±500 and 500 psi, respectively. Using these guidelines, deadband and rise-fall values for Nz_{cg} and strain measurements on a large transport aircraft converted to an air tanker [5] were determined to be as specified in table 7-1.

TABLE 7-1. EXAMPLE OF SHM SYSTEM DEADBAND AND RISE-FALL CRITERIA FOR A LARGE AIR TANKER

Parameter	Deadband	Rise-Fall
Nz_{cg}	±0.05 g	0.05 g
Strain	±50 με	50 με

It should be emphasized, that the values of deadband and rise-fall criteria of ±500 and 500 psi, respectively, and their corresponding application, as specified in table 7-1, are meant to provide guidelines that can be used during the initial specification of a SHM program. The actual values used may need to be adjusted for individual aircraft types. They should only be implemented following a review of proposed fatigue and crack growth data curves that will be used in any subsequent stress analysis [32] and a review of the initial recorded data that is obtained.

7.1.2 Use of Absolute Strain Data.

When strain gauges are applied to an existing aircraft structure, such as an aircraft wing, they are not applied at zero strain. The wings are actually strained due to their own weight plus the weight of any external attachments such as engines. From the perspective of the strain gauge, its datum was the strain at which the gauge was applied. Consequently, any strain gauge that is applied will only read the change in strain relative to the value of strain existing in the structure when it was applied. To convert the strain readings recorded by a gauge to absolute strain readings, it is necessary to determine the value of strain (offset) that existed when the gauge was applied. This can be done in one of two ways.

- Comparing the recorded strain with the absolute value of strain for known flight or ground conditions, as determined from test or analysis.

- Ascertaining the strain when the structure being monitored is unloaded, this automatically provides the appropriate offset.

For many of the aircraft operating in the aerial firefighting role, test or analysis data is often unavailable. Therefore, the following techniques may be used to determine the appropriate strain offset value.

- Aircraft wings: A Roller-Coaster Maneuver is flown. As the aircraft bunts over, it approaches zero g, which can sensibly be considered to correspond with the wing being unloaded. By plotting the strain versus g relationship for each wing gauge and extrapolating the data back to zero g, the offset value of each gauge can be determined.

- Aircraft empennage structure: Unlike the wing structure, the empennage structure cannot be considered to be sensibly unloaded at zero g. Fortunately, the structure of horizontal and vertical stabilizers is generally less complex than that of the wing. Therefore, the required offsets can often be determined from simple mass-balance calculations using strain data from ground-based conditions.

Note that such pseudo-calibration techniques are only valid when the stress being measured is a linear function of normal acceleration. In some instances, the gauge offset value is neglected, and relative, as opposed to absolute, strain is determined. The premise of proceeding in this manner is that the error that is introduced will not significantly impact any fatigue or crack growth calculations. Not accounting for a strain offset results in an error in mean strain level being introduced. When dealing with relatively low-level load cycles, such errors can result in a significant error in either the predicted number of cycles to failure or estimates related to crack growth threshold levels. As it appears to be the lower-load levels that are the primary contributor to cumulative damage in the larger, heavier aircraft, considerable caution should be exercised before deciding whether or not to neglect strain offsets on the wing and empennage structure.

7.2 SOME COMMENTS ON THE USE OF MISSION SEVERITY FACTORS.

A common method of establishing inspection and maintenance intervals for aircraft operating in special mission, low-level roles for which they were not originally designed is to base the inspection/maintenance intervals on equivalent hours, where equivalent hours are defined as

$$Equivalent\ Hours = Hours\ in\ Design\ Mission + (Hours\ in\ Special\ Mission \times Mission\ Severity\ Factor)$$

Calculating the mission severity factor requires the undertaking of fatigue or damage tolerance analyses at critical locations using both the original design spectrum and the special mission spectrum. The mission severity factor is obtained by taking the ratio of the values of the lives obtained from the two calculations, i.e.,

$$Mission\ Severity\ Factor = \frac{Calculated\ Life\ in\ Design\ Role}{Calculated\ Life\ in\ Special\ Misson\ Role}$$

For a special mission aircraft such as an air tanker, there are four distinct phases associated with a flight:

- Transit to the fire from an operational base: This is often undertaken at altitudes below 2500 ft AGL and, hence, the aircraft is subject to the unique characteristics of the low-level environment, which from a cyclic loading perspective is invariably more severe than that anticipated during the aircraft's original design.

- Loiter in the vicinity of the fire: This phase usually involves circling the fire at anywhere from approximately 1,000 to 25,000 ft AGL until a retardant drop is requested or authorized. From a cyclic loading perspective, the loads experienced by an aircraft will be more severe than those experienced during the transit to and from the fire.

- Retardant drop runs: During this phase, the air tanker will descend to approximately 150 ft AGL, or in mountainous terrain 150 ft above and parallel to the terrain, and drop a quantity of retardant. Depending on the nature of the fire and the air tanker size and capacity, one or more drops may be made in a single flight. Additional loiter times may or may not occur between successive drops. From a cyclic loading perspective, this will be the most severe phase of the flight. The implications of these loads for the structure of the aircraft are not easily determined, as during this phase the aircraft is subject to significant and abrupt changes in weight.

- Transit from the fire to an operational base: Once again, this is often undertaken at altitudes below 2500 ft AGL, and hence, the aircraft is subject to the unique characteristics of the low-level environment. From a cyclic loading perspective, this environment is invariably more severe than that anticipated during the aircraft's original design.

If the recorded data could be appropriately segmented, one could actually calculate a mission severity factor for each phase of the flight. The equivalent hours calculation could then be revised to

$$Equivalent\ Hours = Hours\ in\ Design\ Mission + \sum_{n=1}^{n=4}(Hours\ in\ Phase\ n \times Mission\ Severity\ Factor_{Phase\ n})$$

Unfortunately, it is not always straightforward to define each phase of the flight such that the data can be consistently segmented. Consequently, an aerial firefighting flight has traditionally been defined as the time from weight-off-wheels to weight-on-wheels. The cumulative exceedances per hour spectrum has then be derived by taking the total number of cumulative exceedances that occur during the flight and dividing them by the total time of the flight (wheels-up to wheels-down). This is the basis for the spectra proposed in tables 6-2 and 6-3.

When using any of the spectra proposed in tables 6-2 and 6-3 to determine a mission severity factor, the resultant value has to be applied to the total number of hours accumulated during aerial firefighting operations from wheels-up to wheels-down. As noted in reference 31, a consistent approach to the application of mission severity factors has to be applied. A factor derived from a wheels-up to wheels-down spectrum cannot be applied to just part of a flight, as this will significantly underestimate the severity of usage experienced by the aircraft. Similarly, if applied to a whole flight (wheels-up to wheels-down), a mission severity factor calculated purely based on the spectrum that occurs during an actual retardant drop and divided by the associated retardant drop time will significantly overestimate the severity of usage experienced by the aircraft. A more detailed discussion of the use of mission severity factors can be found in reference 31.

8. CONCLUSIONS.

An analysis of available data for air tankers and lead aircraft operating in the aerial firefighting role was undertaken. The data examined has primarily been based on the vertical acceleration at an aircraft's center of gravity (Nz_{cg}) data. Unfortunately, it has not been possible to account for the significant weight changes experienced by the air tankers. Relative damage calculations were used to provide some insight into the load excursions that are responsible for the cyclic (fatigue) damage incurred by the aerial firefighting role. Based on the analysis undertaken, the following conclusions were drawn:

a. The majority of air tankers and lead aircraft were not originally designed for use in the aerial firefighting role. Air tankers and lead aircraft operating in the aerial firefighting role are subjected to a far more severe load spectra than similar aircraft operating in their original design intent role. This increase in severity is associated with the consistent use of an aircraft in a low-level environment (less than 2500 ft above ground level) and the rigors associated with the aerial firefighting role itself.

b. While the loads environment to which air tankers are subjected is severe, the implications of this load environment on ongoing integrity of the structure is hard to ascertain as a result of the significant changes in weight that occur during the dropping of retardant. Preliminary evidence obtained from some recently instrumented aircraft suggests that the high g-levels recorded by these aircraft occur immediately prior to or following the completion of a retardant drop. Consequently, assessing the ongoing structural integrity of these aircraft based on a high g/high weight assumption is overly conservative. Similarly, the identification and need for harsh usage inspections, for example over-g, based solely on g-level alone, might need to be reviewed. Depending on the weight of the aircraft at the time of the occurrence, the stresses at critical structural locations may be nowhere near as high as previously assumed.

c. The limited data available suggests that lead aircraft may be subject to a far more severe loads environment than the air tankers. Because these aircraft do not experience the significant and abrupt weight changes seen by the air tankers, it is likely that critical structural areas in these aircraft are subject to both a cyclic and static loads environment beyond their original design envelopes.

d. Relative damage calculations indicated that there is significant variation in both the air tanker and lead aircraft loads environments. For air tankers, the cyclic (fatigue) loads that are responsible for the majority of the cumulative damage sustained by an aircraft structure appear to be related to aircraft size. Damage sustained by larger, heavier aircraft (in excess of 80,000 lb) is principally attributable to large numbers of relatively low-level loads. Conversely, the damage sustained by smaller, lighter aircraft (less than 30,000 lb) is primarily attributable to smaller numbers of relatively high load cycles. These factors have a number of implications for future Structural Health Monitoring (SHM) programs implemented on air tanker and lead aircraft. These include, but are not necessarily limited to, the following:

1. Implementing Individual Aircraft Tracking (IAT) programs on all air tanker and lead aircraft. While initial sampling programs can be used to establish preliminary spectra for air tankers and lead aircraft, significant variations in usage between aircraft operating in nominally the same role appear to exist. Consequently, it will be necessary to track individual aircraft to ascertain exactly how they are being operated and adjust their associated inspection and maintenance schedules accordingly.

2. Exercising considerable care when defining the resolution (granularity) of parameters such as Nz_{cg} and strains for use in SHM programs. Resolutions used to monitor aircraft in more conventional/design intent roles may result in load cycles that contribute a significant amount of cumulative damage to the structure being overlooked. This is particularly true for larger, heavier aircraft used in the air tanker role.

3. Segmentation of the various phases of the air tanker and lead aircraft roles through the use of discrete signals/markers to ascertain whether the variability in the data is primarily due to the loads experienced in the immediate vicinity of the fire. If this proves not to be the case, other factors such as crew training, pilot technique, and terrain should be investigated to establish whether or not the data variation that has been observed is inherent to the aerial firefighting role.

e. While some data suggests that the operation of aircraft involved in the aerial firefighting role was primarily maneuver-dominated, care has to be taken when coming to this conclusion. There was some evidence to suggest that traditional methods of separating gust and maneuver loads developed from data obtained from aircraft operating at higher altitudes may not be applicable for aircraft consistently operating in a low-level environment.

9. RECOMMENDATIONS FOR FUTURE WORK.

Based on the results of the analysis contained within this report and the associated conclusions, the following recommendations are proposed.

- Evaluate the ongoing structural integrity of lead aircraft operating in the aerial firefighting role. While preliminary data suggest that the loads environment in which these aircraft operate is more severe than the loads environment experienced by the air tankers, little to no work has been done to assess the longer-term effects of the continued use of aircraft in this role.

- IAT of appropriate SHM parameters be implemented on all air tankers and lead aircraft involved in the aerial firefighting role. At a minimum, these programs should account for variations in aircraft weight over a mission and seek to quantify the implications of the aerial firefighting environment on the ongoing structural integrity of aircraft operating in this environment.

- A common structure/methodology for the implementation of SHM programs and the subsequent assessment of aircraft operating in the aerial firefighting environment be developed. This will facilitate an extensive and complete characterization of the aerial firefighting environment and the development/enhancement of realistic regulatory criteria for aircraft operating in this environment.

- A central repository be established for the collection of data related to aerial firefighting. The relatively small number of hours flown by aircraft operating in this role every year (250-300 hours) requires that every effort be made to ensure that the maximum benefit is derived from all data that is gathered.

- The applicability of methods traditionally used for the separation of maneuvers and gusts to aircraft that operate continuously in a low-level environment be examined in some detail. Preliminary analysis of recent data obtained from aerial firefighting aircraft suggests that rules developed for aircraft operating at higher altitudes may not be applicable to aircraft operating at lower altitudes.

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APPENDIX A—SUMMARY OF AIRCRAFT DATA REFERENCES REVIEWED IN DETAIL

TABLE A-1. SOURCES OF HISTORICAL USAGE DATA

No.	Report	Title	Date	Authors	Data Format Recorded and Data Source	Aircraft Usage	Aircraft of Interest	Second Source of Data	Comment
1	DOT/FAA/CT-91/20	General Aviation Aircraft - Normal Acceleration Data Analysis and Collection Project	Feb 93	Locke, Smith, Gabriel, DeFiore	Data from 77 Aircraft in NASA "VGH General Aviation Program" and 98 Aircraft load spectra from NASA VGH database Data in Appendix C Plotted and tabulated data for cumulative number of occurrences / nautical mile vs incremental load/incremental limit load Separate manoeuvre and gust plots and data	1A - Single engine, basic flight instruction (10 airplanes), pB3.			
						1B - Single engine, business/personal (24 airplanes), pB3.	No 28 fish spotting No 41 floatplane.		
						2 - Single engine, special usage (4 airplanes), pB4.	No 6A & 17 pipeline patrol No 9B forest fire patrol and transport No 27 forest fire lead plane.		
						3 - Single engine, aerial application (25 airplanes) ,pB5.	Nos. 29 - 37 ???	Raw data in CT91-20_Air tanker_Exceed_01.xls	
						4 - Twin engine, general usage (8 airplanes), pB6.			
						5 - Twin engine special usage (3 airplanes), pB6.	No 4 and 25 forest fire lead plane No 26 pipeline patrol.		
						6 - Single and Twin engine, pressurized, general usage (3 airplanes), pB7.			
						7 - Twin engine, executive jet (3 airplane), p B7.			
						8 - Large airplanes, special usage (6 airplanes), pB7	Nos. 19 - 24 forest firefighting.	Raw data in CT91-20_Air tanker_Exceed_01.xls	
						9 - Aerobatic airplanes			

TABLE A-1. SOURCES OF HISTORICAL USAGE DATA (Continued)

No.	Report	Title	Date	Authors	Data Format Recorded and Data Source	Aircraft Usage	Aircraft of Interest	Second Source of Data	Comment
2	NASA TM X-72622	Operating Experiences of Retardant Bombers During Firefighting Operations	Nov 74	Jewel, Morris, Avery	2 DC-6B aircraft in firefighting operations. VGH (sensor mounted 3 ft to right of fuselage centerline). Tabular load factor frequency distribution on table III.	Firefighting operations			Source of data re: details of firebombing, e.g., duration of sortie, No. of drops, time to fire, .. NOTE - max and min "g" only recorded once per drop
3	KU-FRL-689-5	Forest Fire Tankers Tabulated Data Report	Jul 86	Reyner	VGH				The majority of the data is duplicated data, i.e., selected data from DOT/FAA/CT-91/20 Does include nonoperational hours for selected Aircraft (p E i) Graphs same as DOT/FAA/CT-91/20, except noncurve fitted
4	TP 11574	Analysis of Fatigue Loads Data Obtained from TC Challenger & Dash-8 Aircraft Engaged in Low Level Flying Operations	Nov 92	David, Plante, Peck	Data from 2 CL601 and 2 Dash8 Data in appendix F Tabulated g level vs EPH	CL601 engaged in Low-level flying.	ILS and VOR from Oct 85 - Sept 91		
						Dash 8 engaged in Low-level flying.	ILS and VOR from June 86 - Sept 91		
5	58E792	Safe Life Prediction of the Model 58P (Beech Aircraft Corporation)	Mar 83	Anders, Tomlinson		Aircraft S/N TJ 177			
						Aircraft S/N TJ 247			
						Aircraft S/N TJ 290			
						Aircraft S/N TJ 370			

TABLE A-1. SOURCES OF HISTORICAL USAGE DATA (Continued)

No.	Report	Title	Date	Authors	Data Format Recorded and Data Source	Aircraft Usage	Aircraft of Interest	Second Source of Data	Comment
6		Small Airplane Fatigue Loads Program: A Study of the Expanded NASA VGH Data Base and Revision of Fatigue Spectra in FAA Report AFS-120-73-2	May 87	Gabriel	Plotted and tabulated data for cumulative num occurrence/nautical mile vs incremental load/incremental limit load, selected data from DOT/FAA/CT-91/20.	Operations specified - fighting forest fires lead [planes and retardant bombers, flight to check magnitude and turbulence in and near the fires, flights to mark drop sites, smoke jumper for fire fighters, personnel carrier, cargo carrier Aircraft Nos. 4 and 25 - lead/spotter flights, not used as retardant bombers Aircraft No. 26 only - pipeline patrol over level and mountainous terrain.	Small airplanes - No 4, 25, 26 Large airplanes - No 19 thru 24		Duplicated data i.e. selected data from DOT/FAA/CT-91/20
7	LTR-ST-733	Flight Loads on Large Aircraft Engaged in 1974 Budworm Spraying Program	Sept 74	Campbell	Tabulated data in CT91-20_Airtanker_ Exceed_01.xls Acceleration level counter (see p3).	1974 budworm spraying, DC-6 and Super Constellation			
8	LTR-ST-815	Flight Loads on DC-6 Aircraft Engaged in 1975 Budworm Spraying Program	Dec 75	Campbell	Tabulated data in CT91-20_Airtanker_ Exceed_01.xls Acceleration level counter (see p3).	1975 budworm spraying, DC-6			
9	CR-SMPL-2002-0258	The Impact of Low Level Roles on Aircraft Structural Integrity with Particular Reference to Firebombers	Nov 02	Hall	Tabulated data in CT91-20_Airtanker_ Exceed_01.xls				Summary of existing data from different sources

TABLE A-1. SOURCES OF HISTORICAL USAGE DATA (Continued)

No.	Report	Title	Date	Authors	Data Format Recorded and Data Source	Aircraft Usage	Aircraft of Interest	Second Source of Data	Comment
10		An aircraft structural integrity program - FAA flight inspection Beech 300 fleet	Nov 93	Gould	Data from Beech 300's Figure 6-1, one plot (could be scaled from graph) exceed per hour vs absolute load factor, data recorded include strain (32 Hz) and n (16Hz), data stored as peaks and valleys in a time sequence format.	Beech 300's flown in flight inspection/airways calibration role, 67% of the time operated at or below 2000 ft.	Low-level flying		
11	DOT/FAA/AR-01/44	Statistical loads data for Cessna172 aircraft using the aircraft cumulative fatigue system (ACFS)	Aug 01	Cicero, Feiter, Mohammadi	Appendices A, B, and C All results presented graphically for various altitude bands (could be scaled from graphs), various axes used including cum occ per 1000 hr vs inc load factor.				Data for flight at low-level (below 2000 ft) presented graphically

APPENDIX B—EXCEEDANCE CURVE FITS—ALL AIRCRAFT

TABLE B 1. SUMMARY OF EXCEEDANCE PLOTS—ALL AIRCRAFT

Figure	Aircraft	Title
B-1	Aircraft 20/20[1], 106000 MTOW, 50/50 min.	Group 5—Air Tanker—Heavyweight, Aircraft 20
B-2	Aircraft 21, 80000 MTOW, 60 min.	Group 4—Air Tanker—Mediumweight, Aircraft 21
B-3	Aircraft 22, 64000 MTOW, 29 min.	Group 3—Air Tanker—Mediumweight, Aircraft 22
B-4	Aircraft 24[1]/24[2]/24[3]/24[4]/24[5], 26300 MTOW, 33/32/34/35/33 min.	Group 2—Air Tanker—Lightweight, Aircraft 24
B-5	Aircraft 24, 26300 MTOW, 19 min.	Group 1—Air Tanker—Lightweight, Aircraft 24 (Short Flight)
B-6	Aircraft 19/19[1], 126000 MTOW, 50/50 min.	Group 6—Air Tanker—Heavyweight, Aircraft 19
B-7	Aircraft 27	Group 7—Lead Aircraft, Aircraft 27
B-8	Aircraft 4[1]	Group 8—Lead Aircraft, Aircraft 4
B-9	Aircraft 25	Group 9—Lead Aircraft, Aircraft 25
B-10	All Aerial Application Aircraft	Group 10—Crop Spray—Lightweight, All Aircraft
B-11	CF-OPV Tracker Firebomb 1975	Group 11—Air Tanker—Lightweight, Aircraft CF-OPV
B-12	C-GHQY Tracker Firebomber	Group 12—Air Tanker—Lightweight, Aircraft C-GHQY
B-13	F-27_.003_Total	Group 13a—Air Tanker—Mediumweight, Aircraft C-GFST
B-14	F-27_.004_Total	Group 13b—Air Tanker—Mediumweight, Aircraft C-GFST
B-15	DC-6 Budworm 1974	Group 14—Budworm Spray—Heavyweight
B-16	All DC-6B_Bud_Spray 1975	Group 15—Budworm Spray—Heavyweight, All Aircraft
B-17	DC-6B_Domestic	Group 16—Heavyweight Domestic

MTOW = Maximum takeoff weight

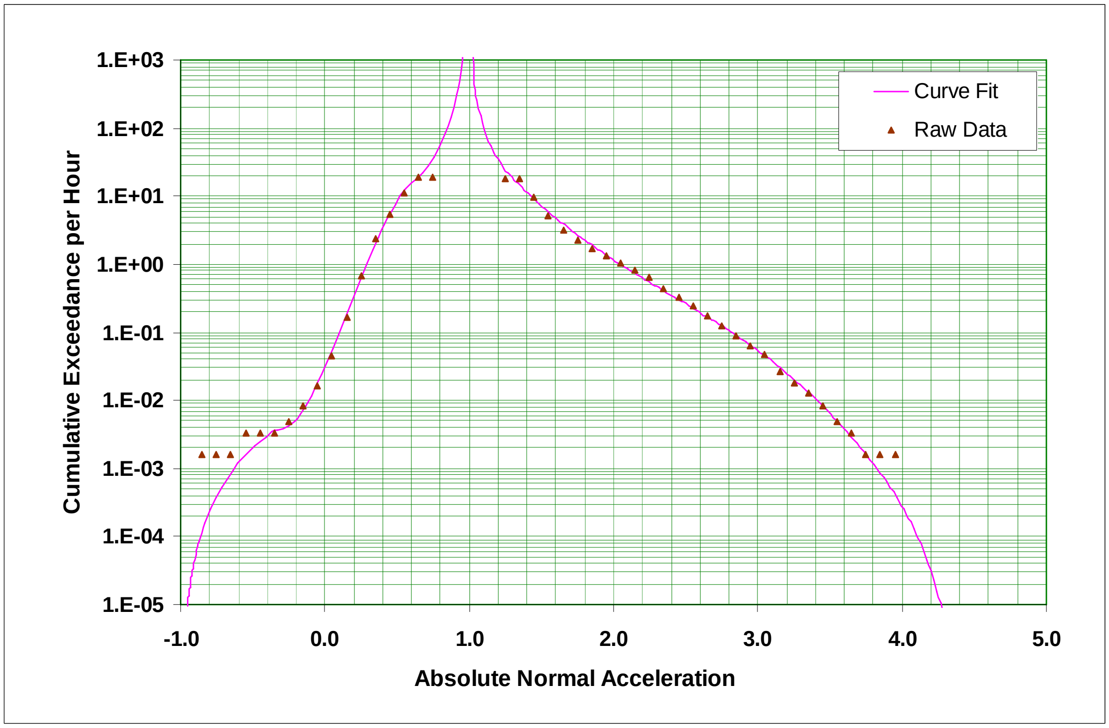

FIGURE B-1. GROUP 5—AIR TANKER—HEAVYWEIGHT, AIRCRAFT 20

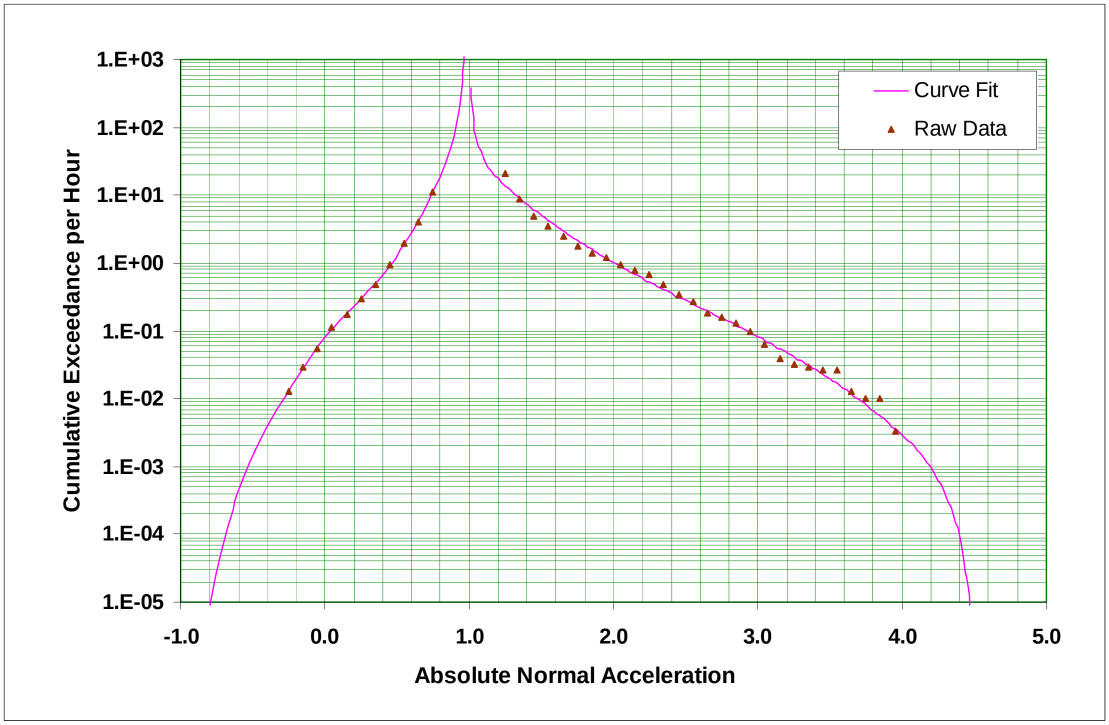

FIGURE B-2. GROUP 4—AIR TANKER—MEDIUMWEIGHT, AIRCRAFT 21

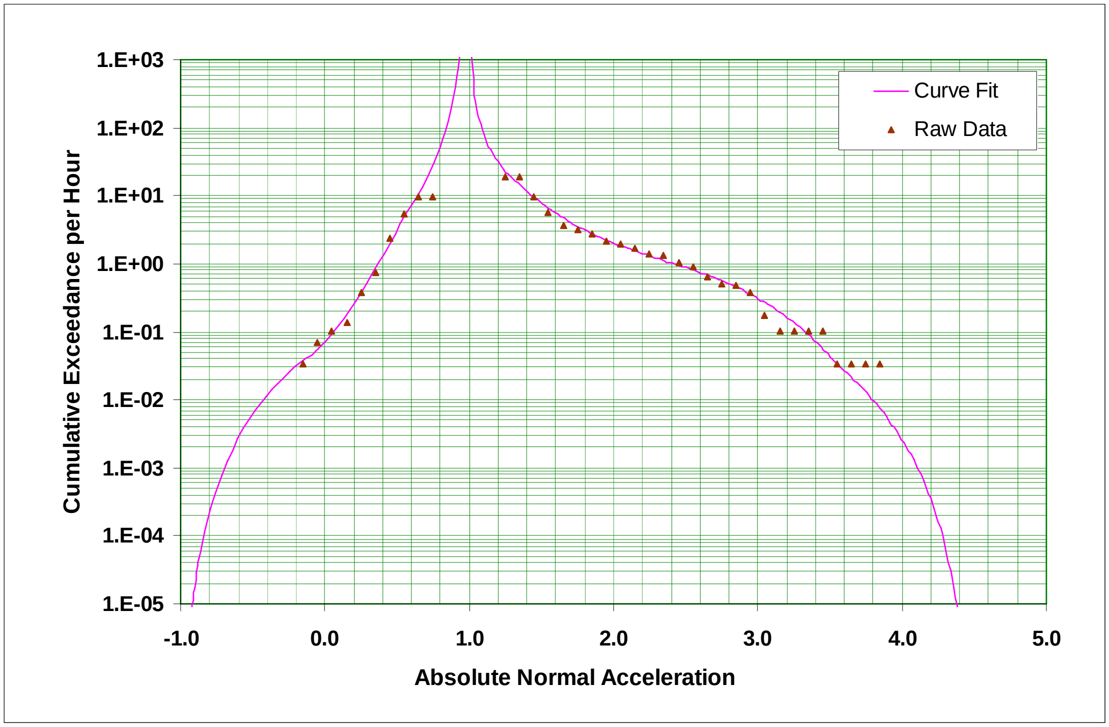

FIGURE B-3. GROUP 3—AIR TANKER—MEDIUMWEIGHT, AIRCRAFT 22

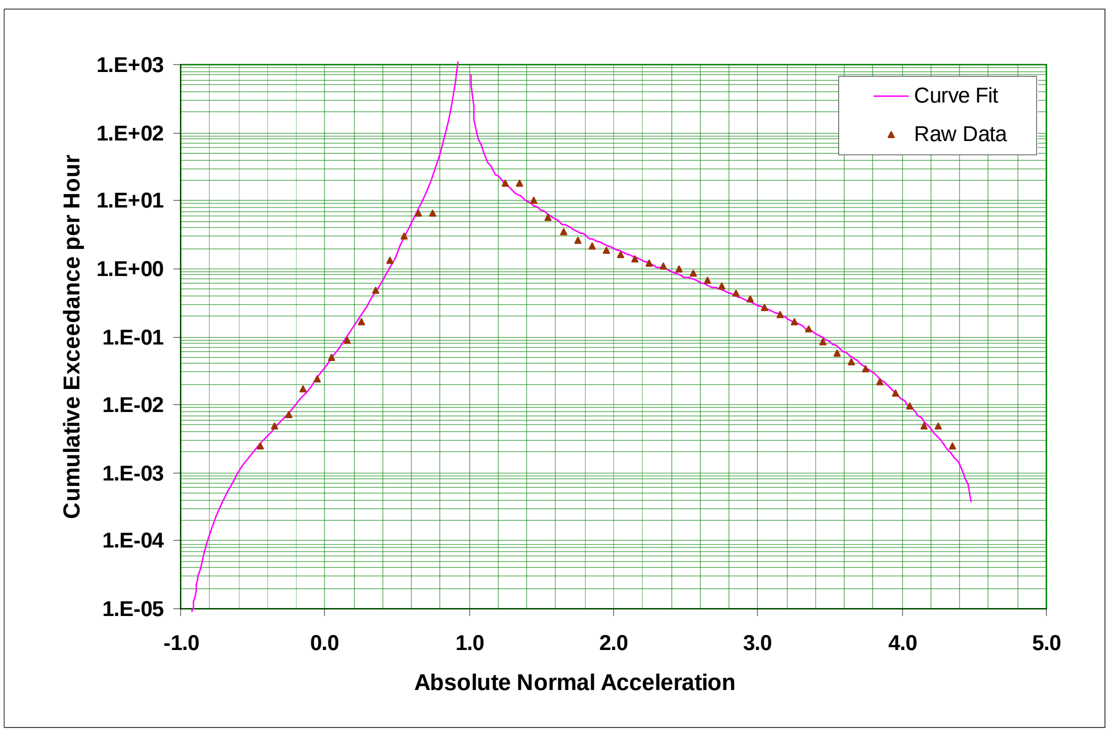

FIGURE B-4. GROUP 2—AIR TANKER—LIGHTWEIGHT, AIRCRAFT 24

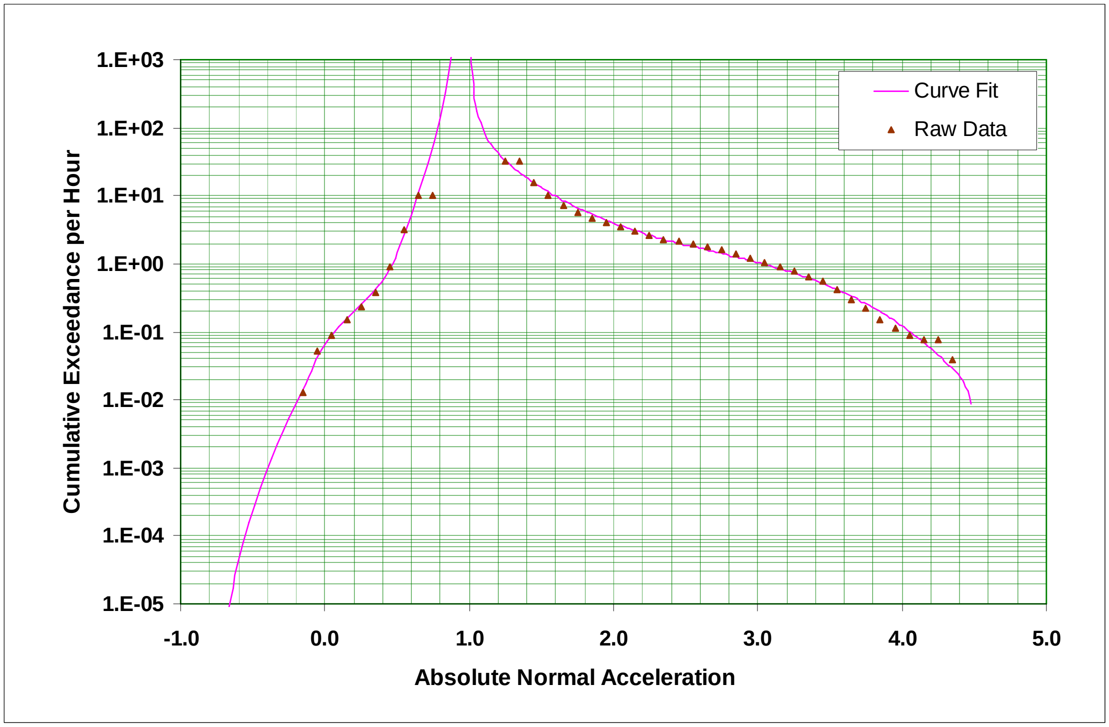

FIGURE B-5. GROUP 1—AIR TANKER—LIGHTWEIGHT, AIRCRAFT 24 (SHORT FLIGHT)

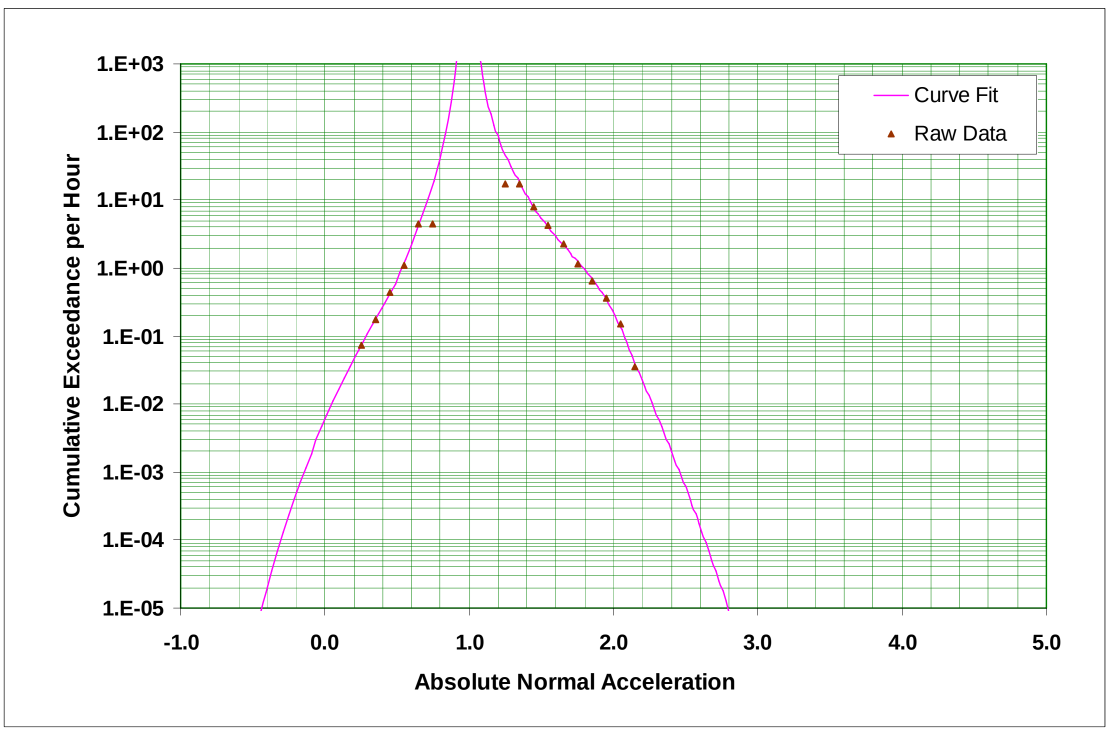

FIGURE B-6. GROUP 6—AIR TANKER—HEAVYWEIGHT, AIRCRAFT 19

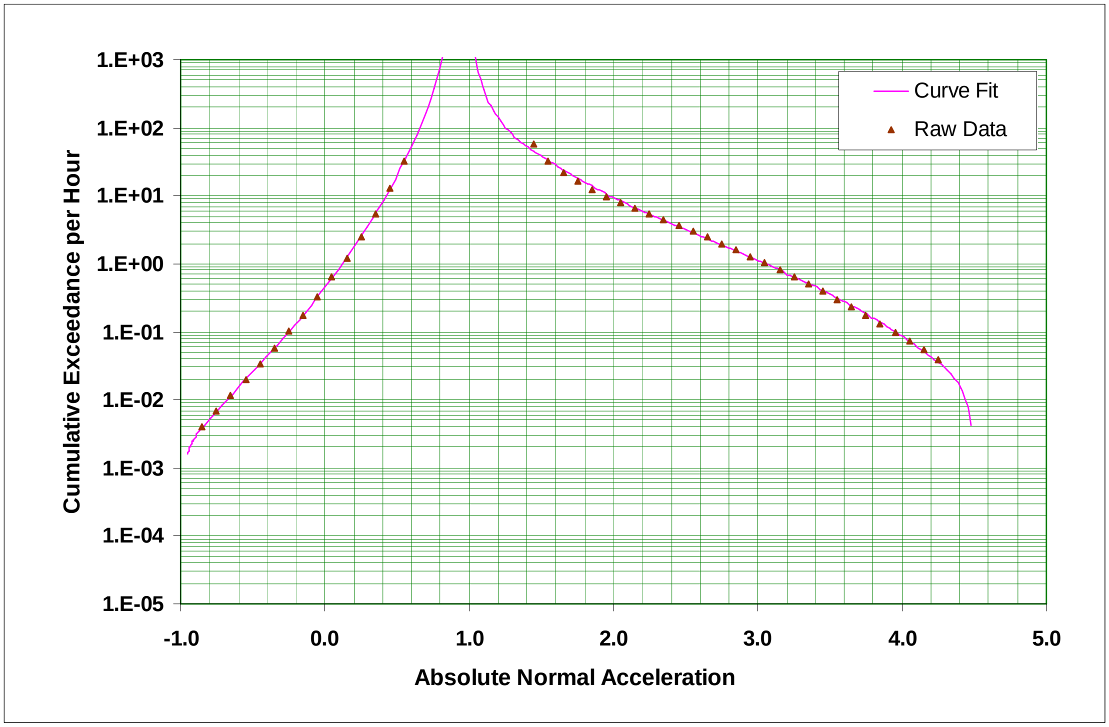

FIGURE B-7. GROUP 7—LEAD AIRCRAFT, AIRCRAFT 27

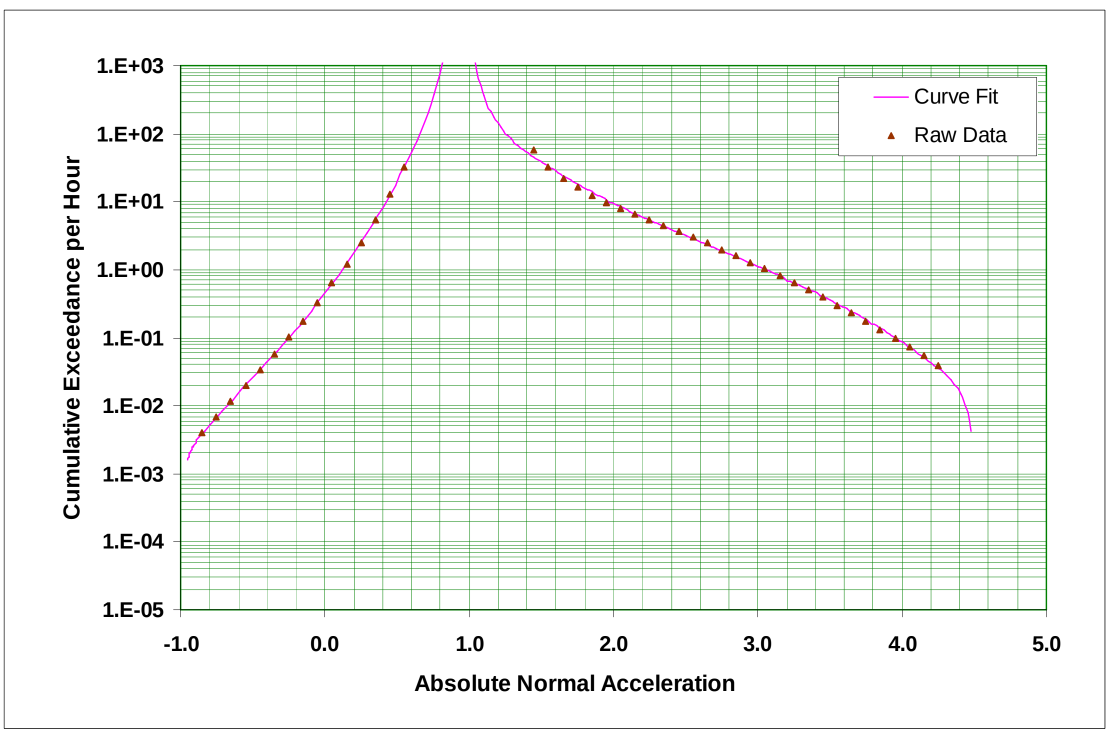

FIGURE B-8. GROUP 8—LEAD AIRCRAFT, AIRCRAFT 4

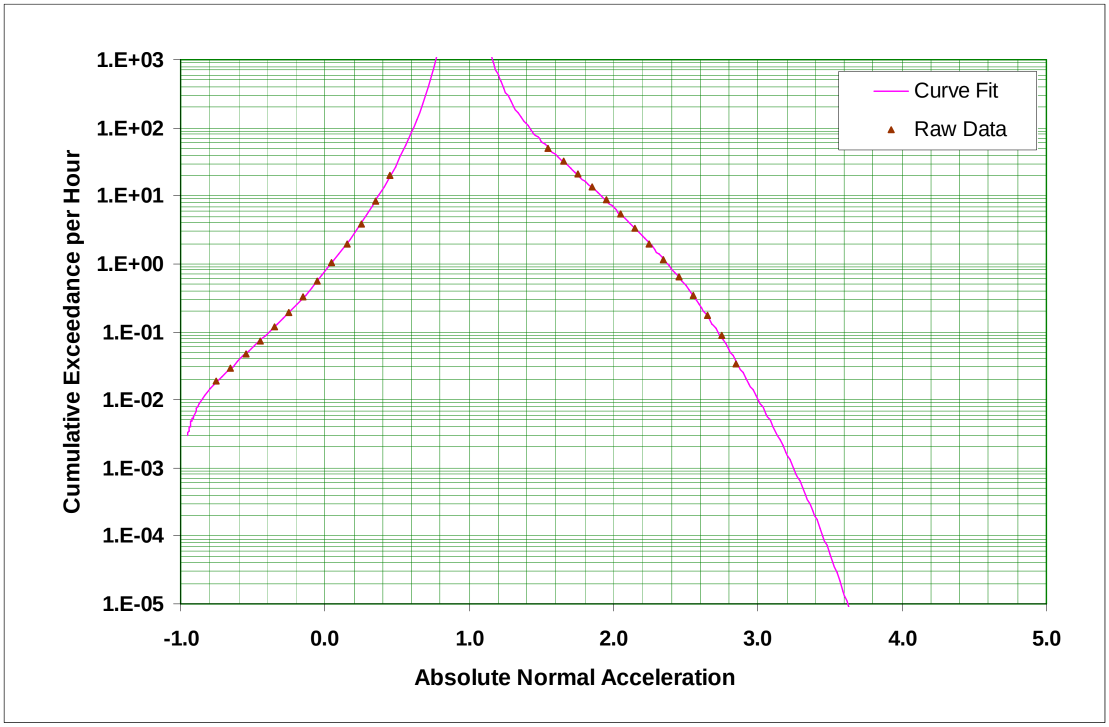

FIGURE B-9. GROUP 9—LEAD AIRCRAFT, AIRCRAFT 25

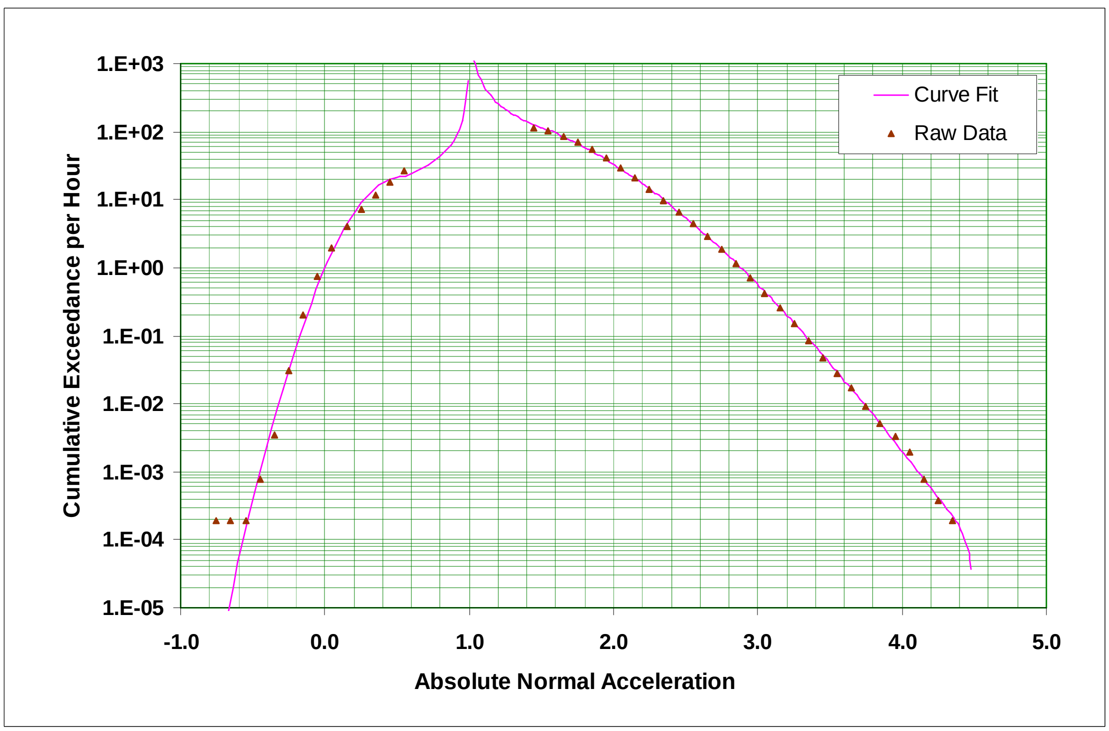

FIGURE B-10. GROUP 10—CROP SPRAY—LIGHTWEIGHT, ALL AIRCRAFT

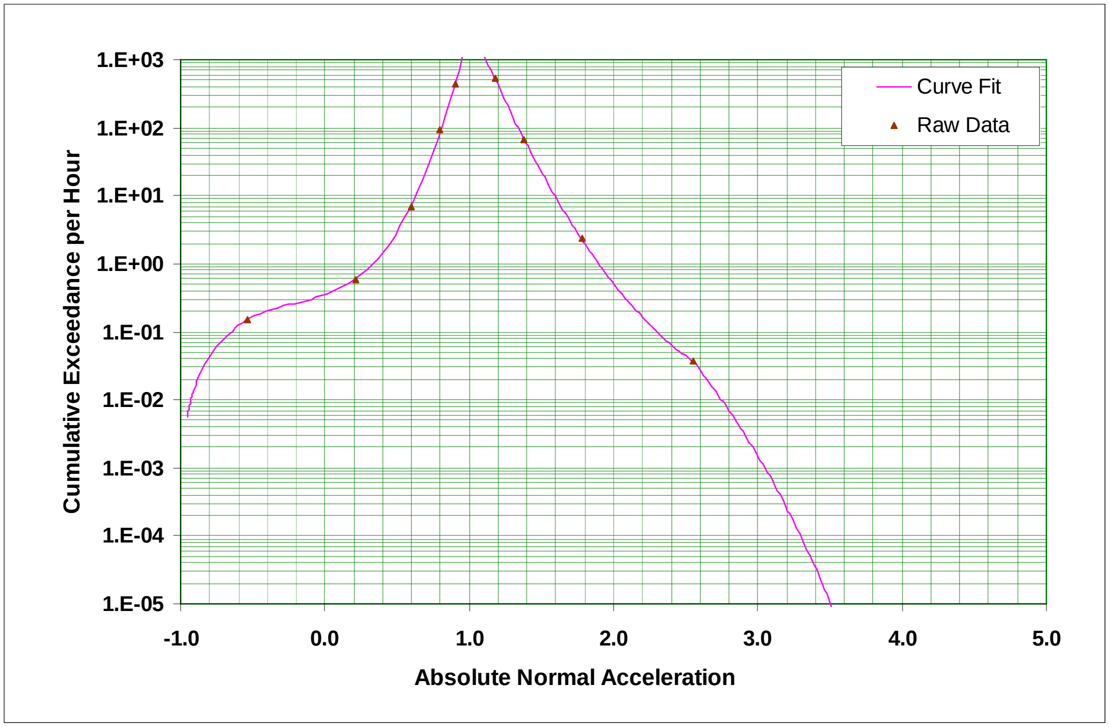

FIGURE B-11. GROUP 11—AIR TANKER—LIGHTWEIGHT, AIRCRAFT CF-OPV

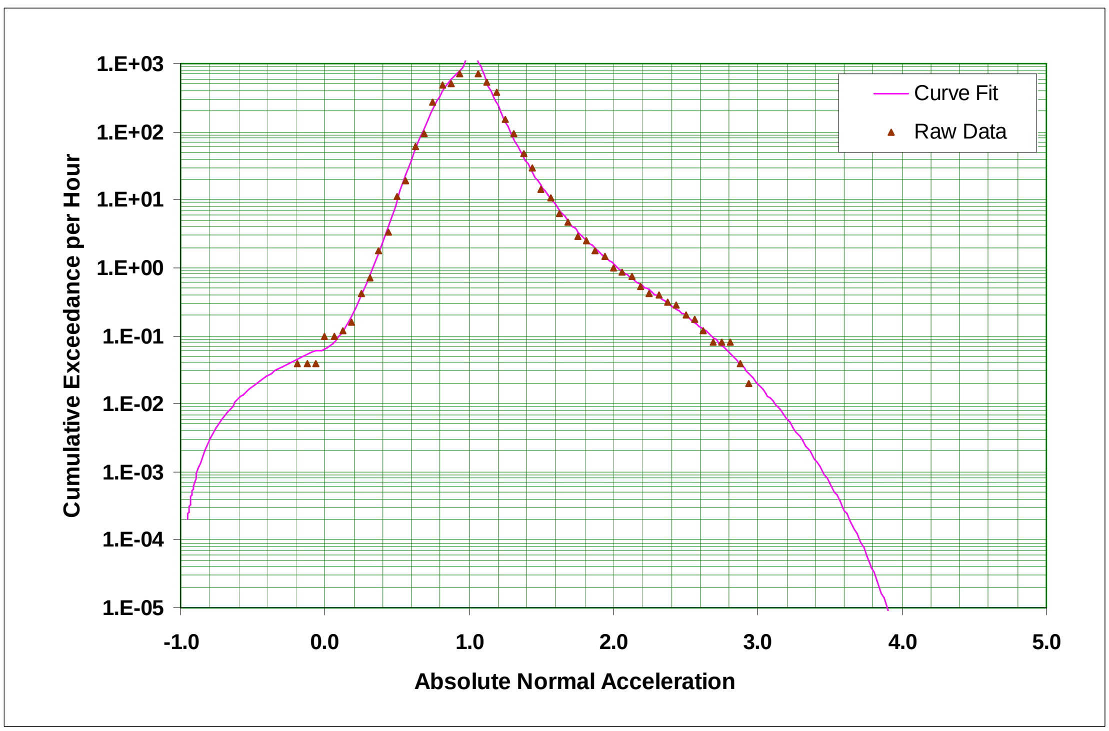

FIGURE B-12. GROUP 12—AIR TANKER—LIGHTWEIGHT, AIRCRAFT C-GHQY

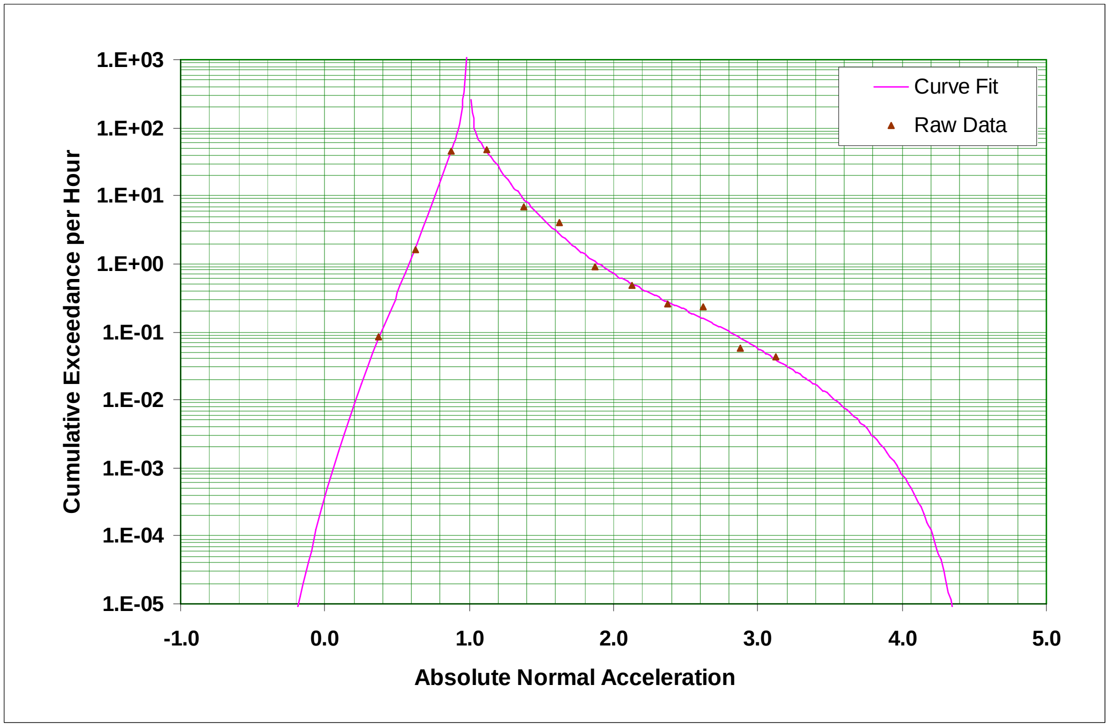

FIGURE B-13. GROUP 13a—AIR TANKER—MEDIUMWEIGHT, AIRCRAFT C-GFST

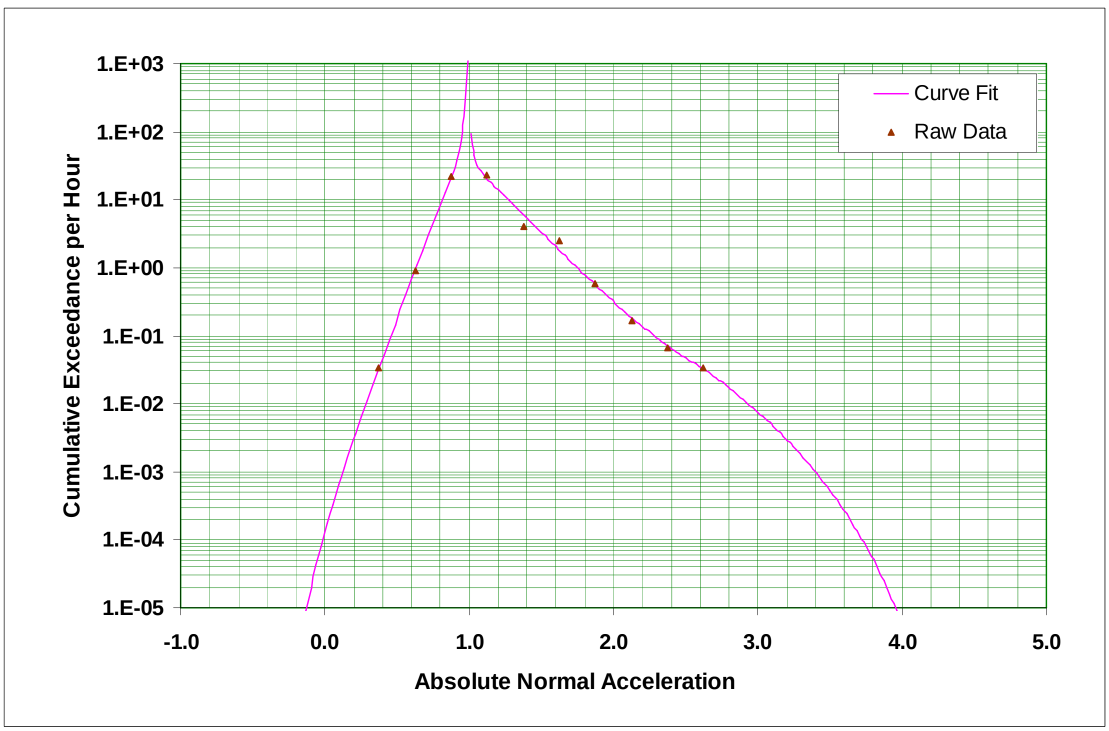

FIGURE B-14. GROUP 13b—AIR TANKER—MEDIUMWEIGHT, AIRCRAFT C-GFST

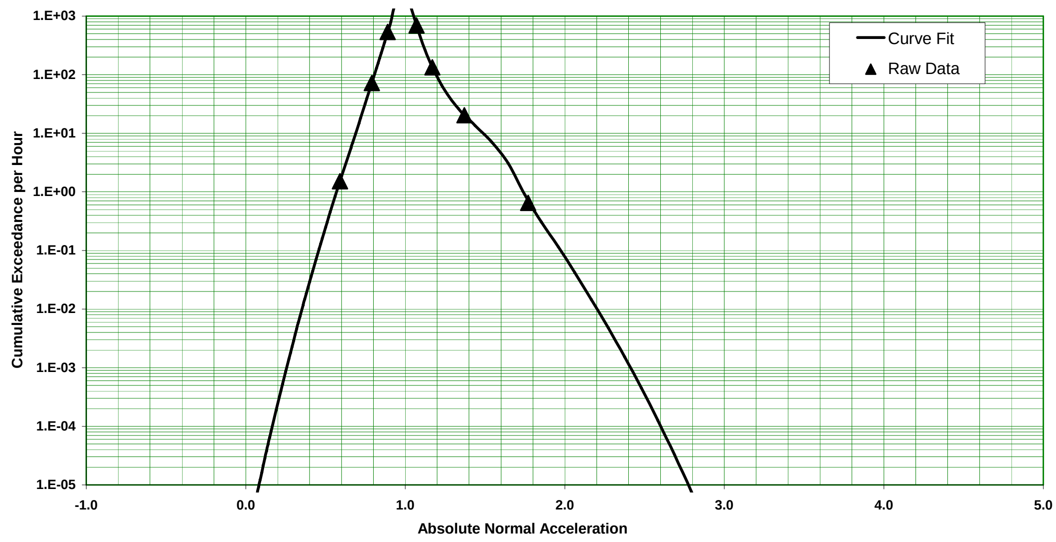

FIGURE B-15. GROUP 14—BUDWORM SPRAY—HEAVYWEIGHT

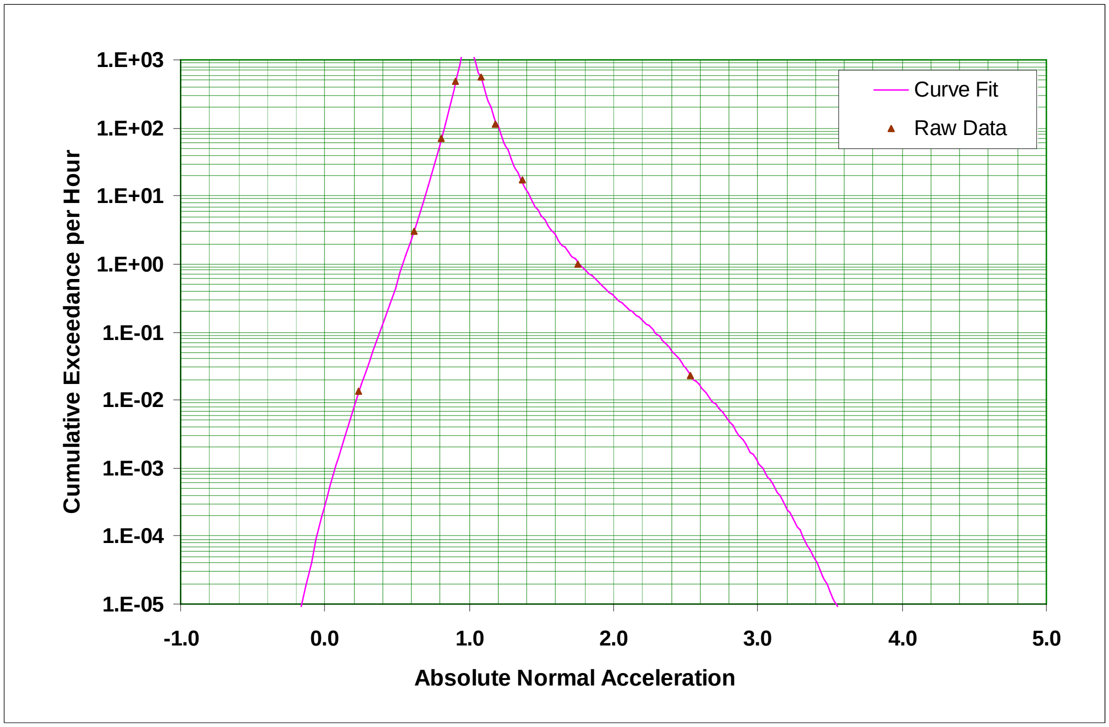

FIGURE B-16. GROUP 15—BUDWORM SPRAY—HEAVYWEIGHT, ALL AIRCRAFT

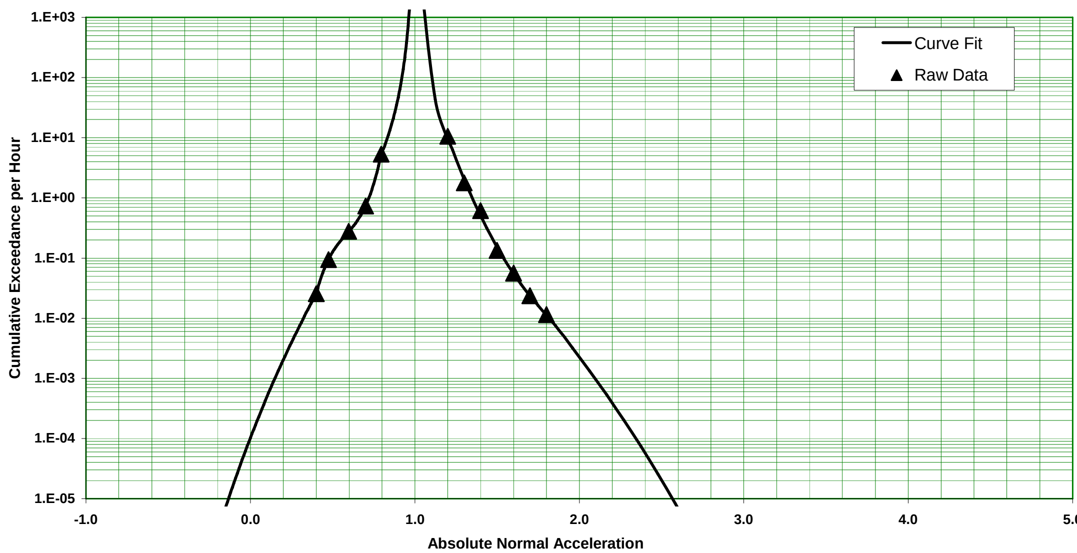

FIGURE B-17. GROUP 16—HEAVYWEIGHT DOMESTIC

APPENDIX C—RELATIVE DAMAGE PLOTS—ALL AIRCRAFT

TABLE C 1. SUMMARY OF RELATIVE DAMAGE PLOTS—ALL AIRCRAFT

Figure	Aircraft	Title 2
C-1	Aircraft 20/20[1], 106000 MTOW, 50/50 min.	Air Tanker—Heavyweight, aircraft 20
C-2	Aircraft 21, 80000 MTOW, 60 min.	Air Tanker—Mediumweight, aircraft 21
C-3	Aircraft 22, 64000 MTOW, 29 min.	Air Tanker—Mediumweight, aircraft 22
C-4	Aircraft 24[1]/24[2]/24[3]/24[4]/24[5], 26300 MTOW, 33/32/34/35/33 min.	Air Tanker—Lightweight, aircraft 24
C-5	Aircraft 24, 26300 MTOW, 19 min.	Air Tanker—Lightweight, aircraft 24 (short flight)
C-6	Aircraft 19/19[1], 126000 MTOW, 50/50 min.	Air Tanker—Heavyweight, aircraft 19
C-7	Aircraft 27	Lead Aircraft, Aircraft 27
C-8	Aircraft 4[1]	Lead Aircraft, Aircraft 4
C-9	Aircraft 25	Lead Aircraft, Aircraft 25
C-10	All Aerial Application Aircraft	Crop Spray—Lightweight, all aircraft
C-11	CF-OPV Tracker Firebomb 1975	Air Tanker—Lightweight, aircraft CF-OPV
C-12	C-GHQY Tracker Firebomber	Air Tanker—Lightweight, aircraft C-GHQY
C-13	F-27_.003_Total	Air Tanker—Mediumweight, aircraft C-GFST
C-14	F-27_.004_Total	Air Tanker—Mediumweight, aircraft C-GFST
C-15	DC-6 Budworm 1974	Budworm Spray—Heavyweight
C-16	All DC-6B_Bud_Spray 1975	Budworm Spray—Heavyweight, all aircraft

MTOW = Maximum takeoff weight

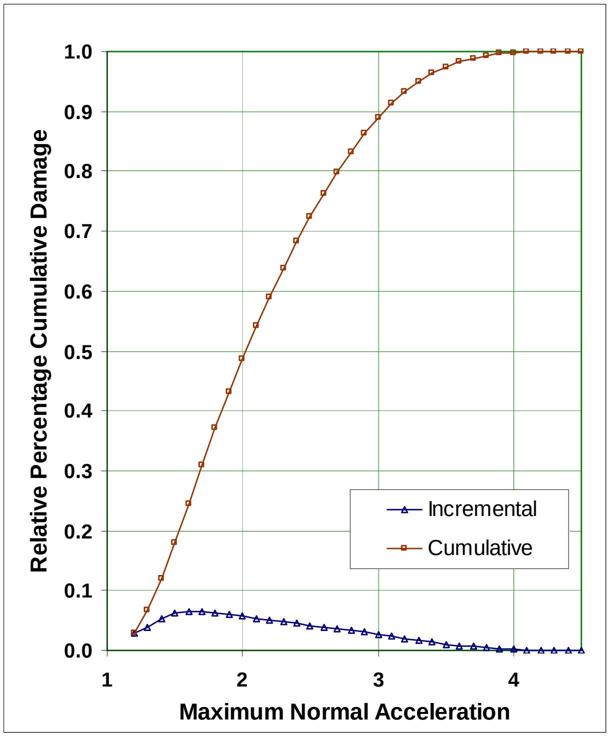

FIGURE C-1. AIR TANKER—HEAVYWEIGHT, AIRCRAFT 20

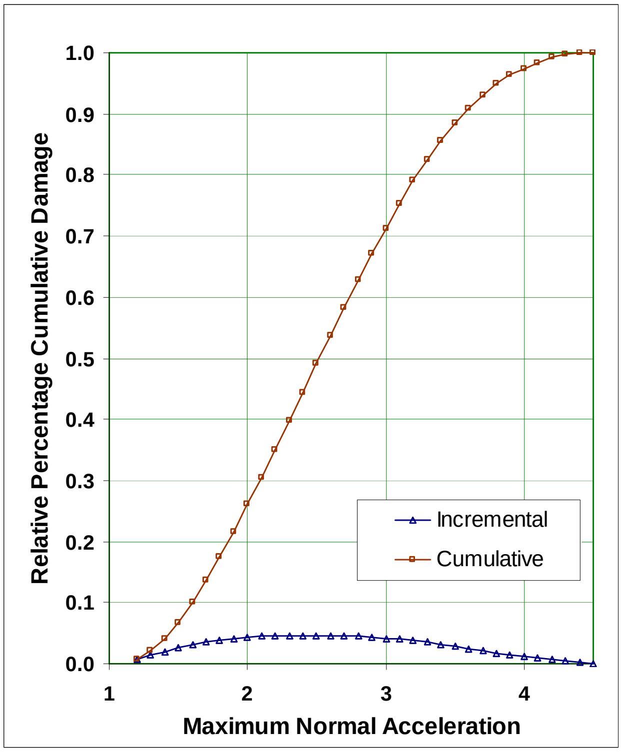

FIGURE C-2. AIR TANKER—MEDIUMWEIGHT, AIRCRAFT 21

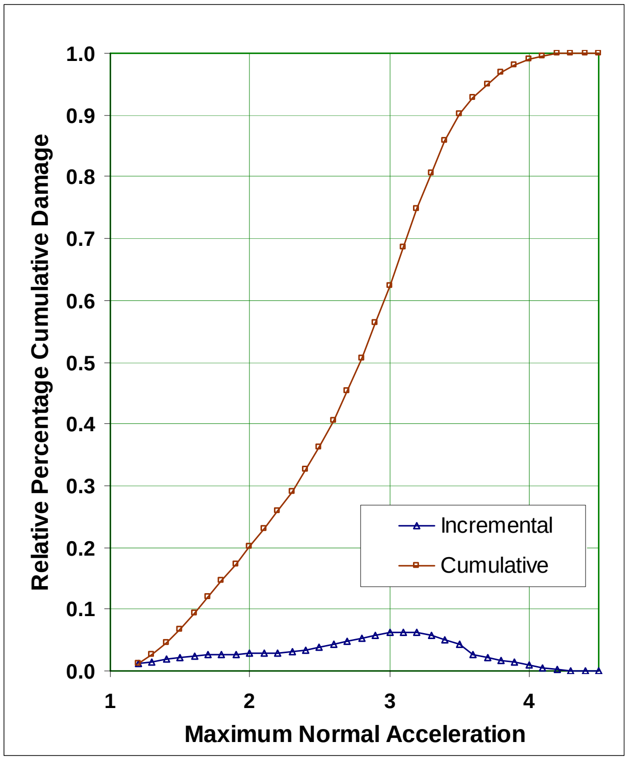

FIGURE C-3. AIR TANKER—MEDIUMWEIGHT, AIRCRAFT 22

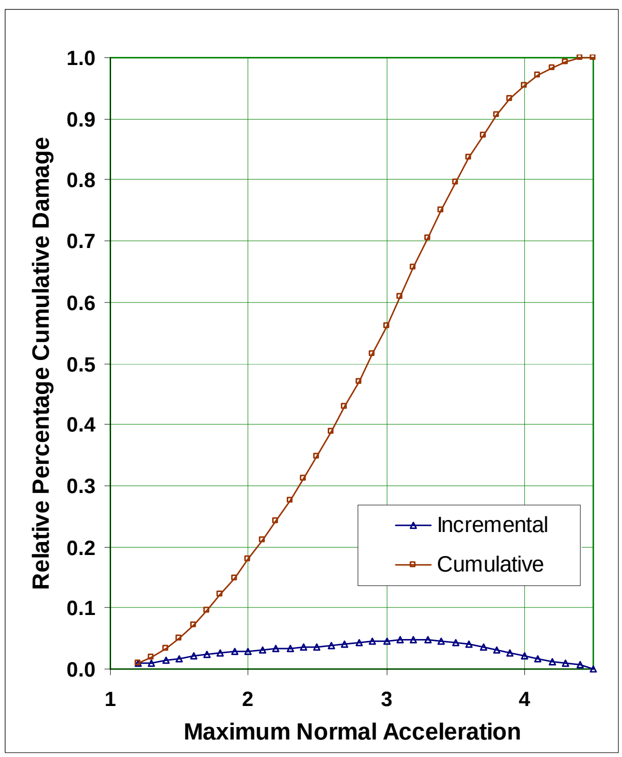

FIGURE C-4. AIR TANKER—LIGHTWEIGHT, AIRCRAFT 24

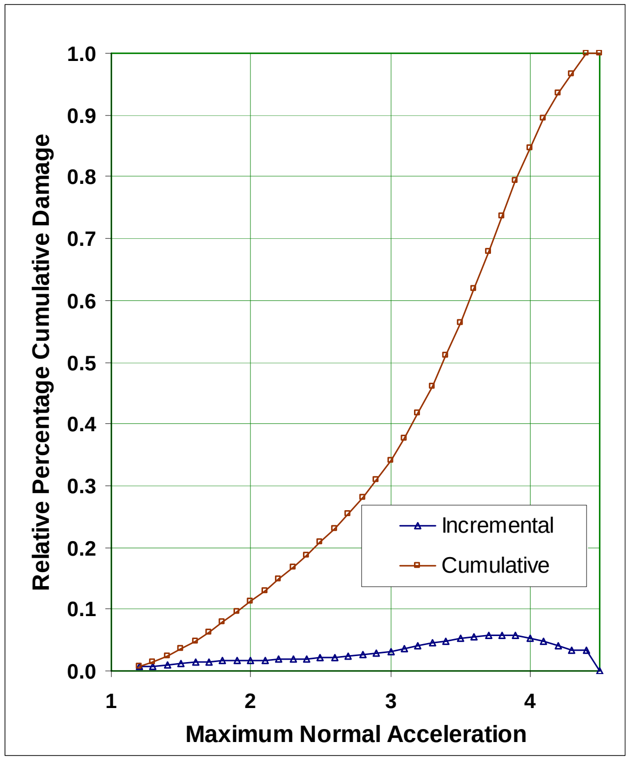

FIGURE C-5. AIR TANKER—LIGHTWEIGHT, AIRCRAFT 24 (SHORT FLIGHT)

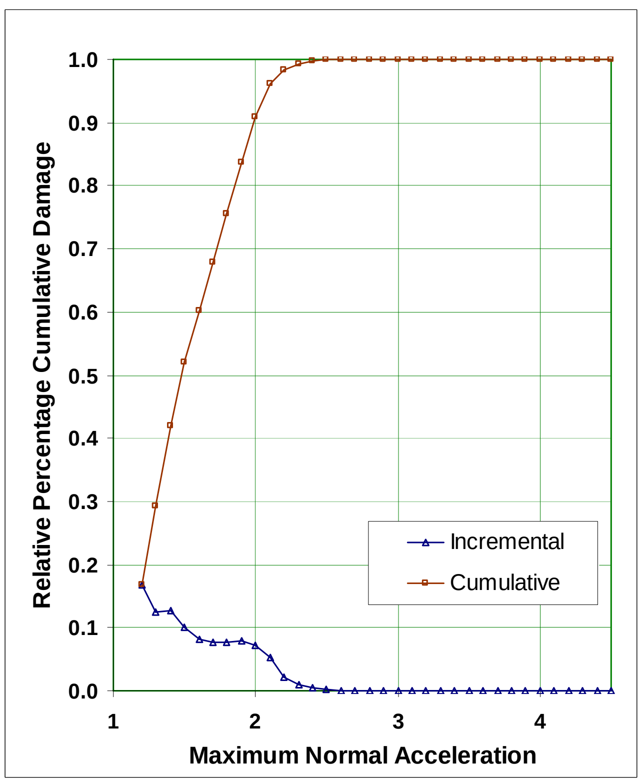

FIGURE C-6. AIR TANKER—HEAVYWEIGHT, AIRCRAFT 19

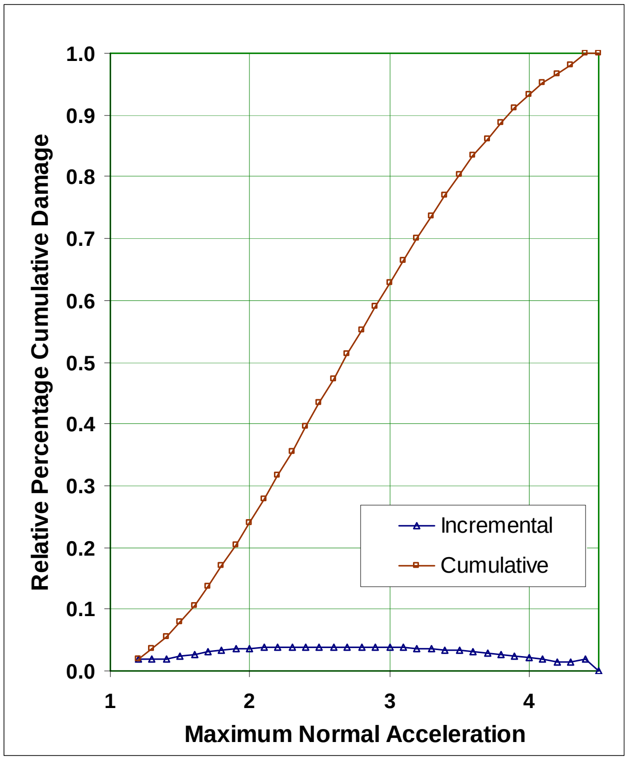

FIGURE C-7. LEAD AIRCRAFT, AIRCRAFT 27

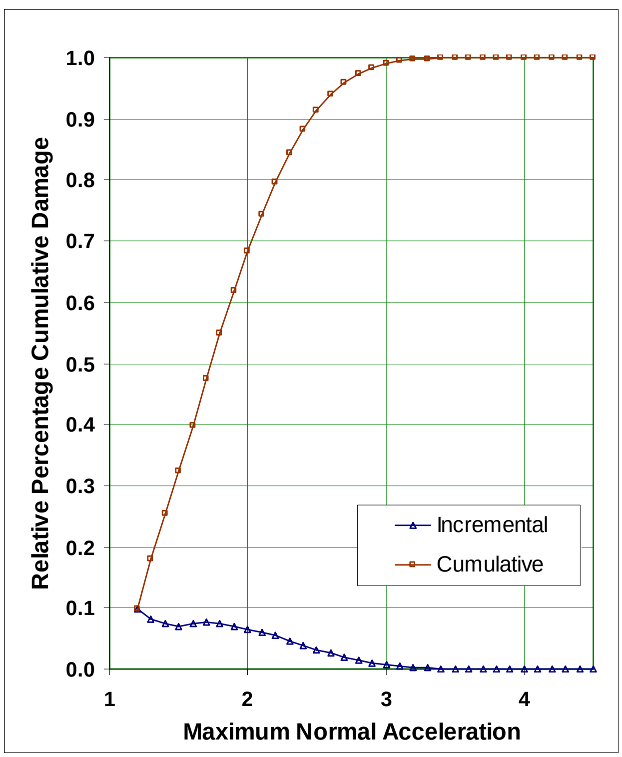

FIGURE C-8. LEAD AIRCRAFT, AIRCRAFT 4

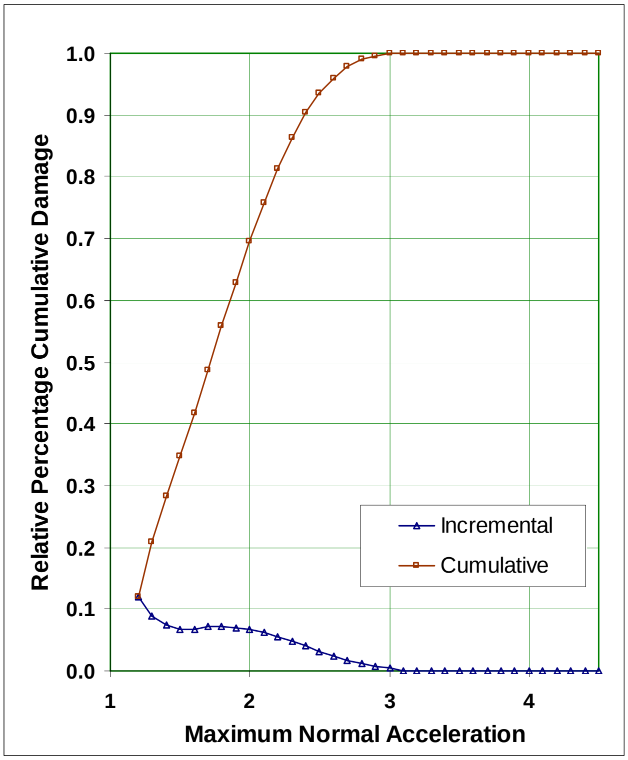

FIGURE C-9. LEAD AIRCRAFT, AIRCRAFT 25

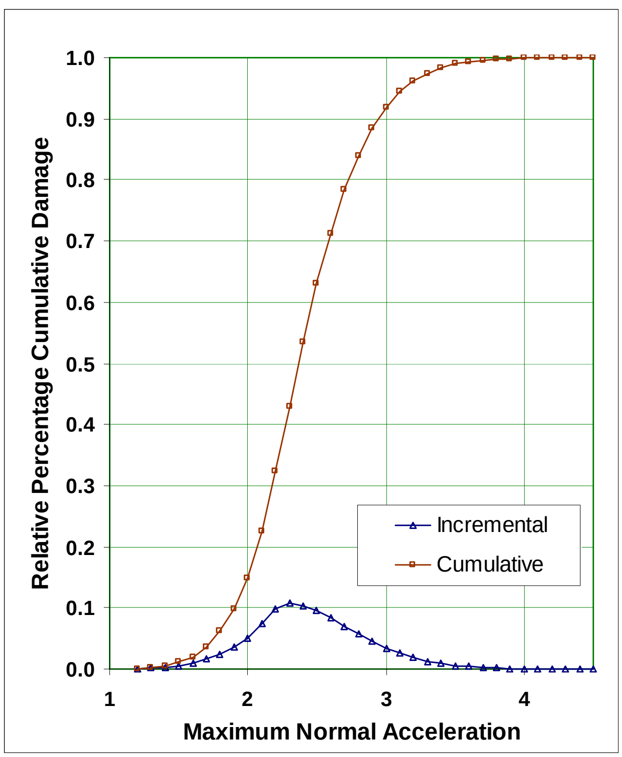

FIGURE C-10. CROP SPRAY—LIGHTWEIGHT, ALL AIRCRAFT

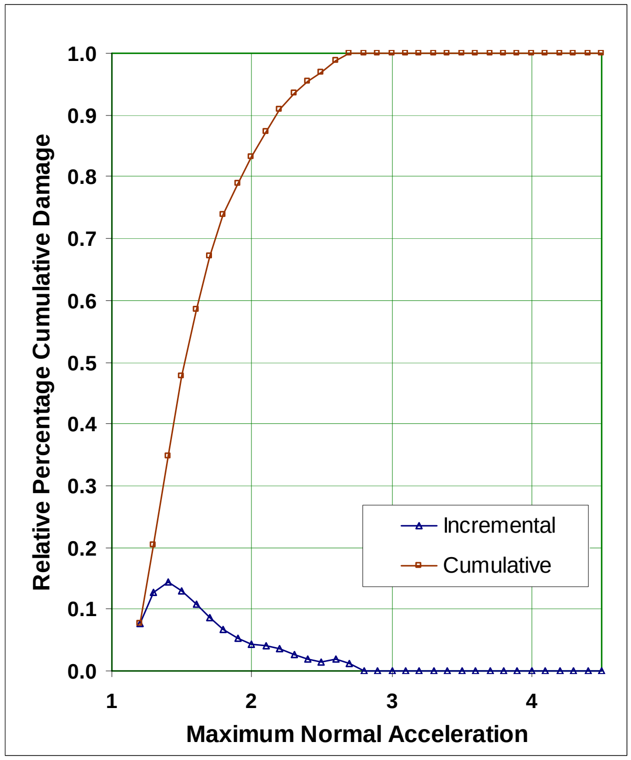

FIGURE C-11. AIR TANKER—LIGHTWEIGHT, AIRCRAFT CF-OPV

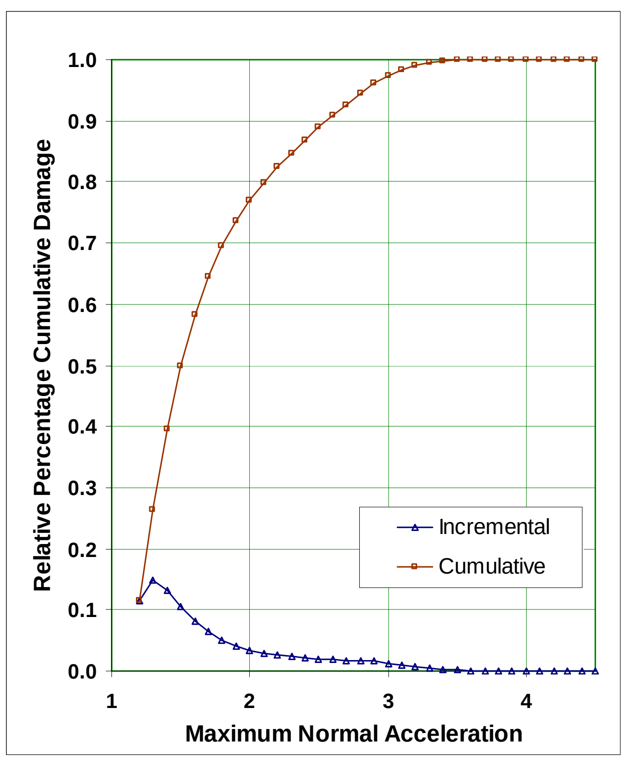

FIGURE C-12. AIR TANKER—LIGHTWEIGHT, AIRCRAFT C-GHQY

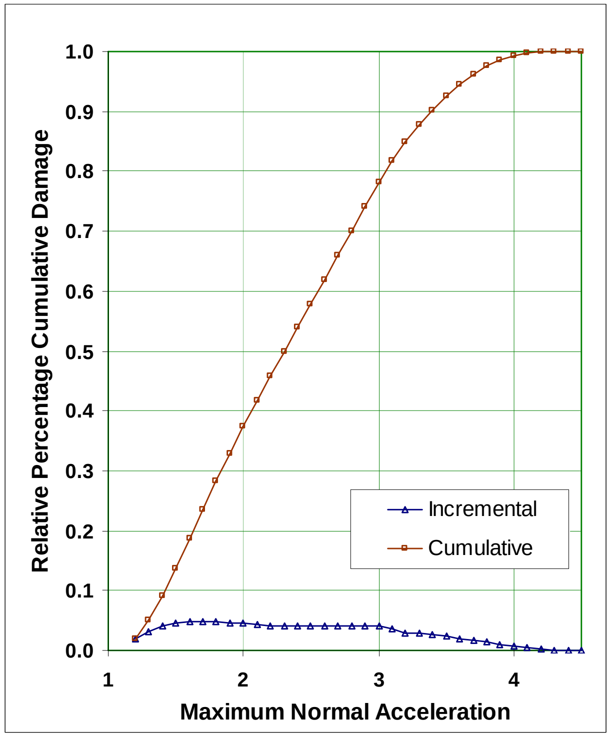

FIGURE C-13. AIR TANKER—MEDIUMWEIGHT, AIRCRAFT C-GFST

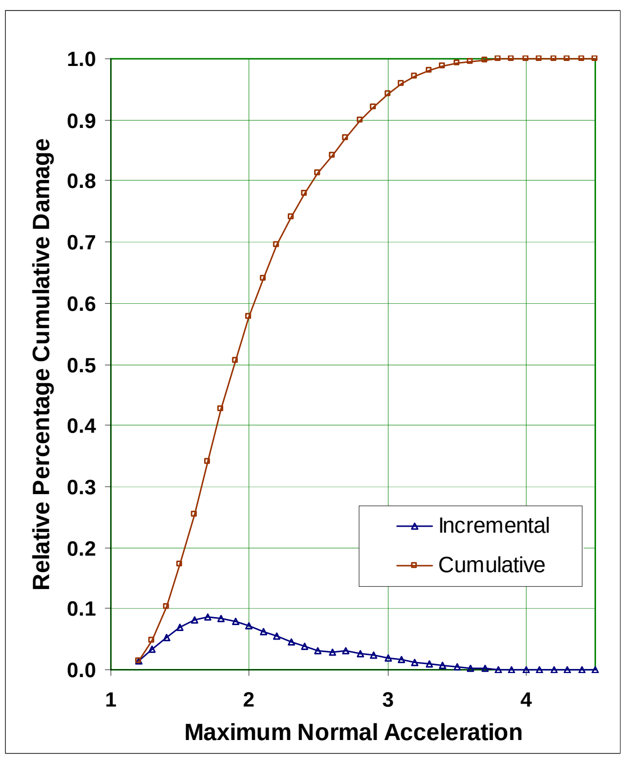

FIGURE C-14. AIR TANKER—MEDIUMWEIGHT, AIRCRAFT C-GFST

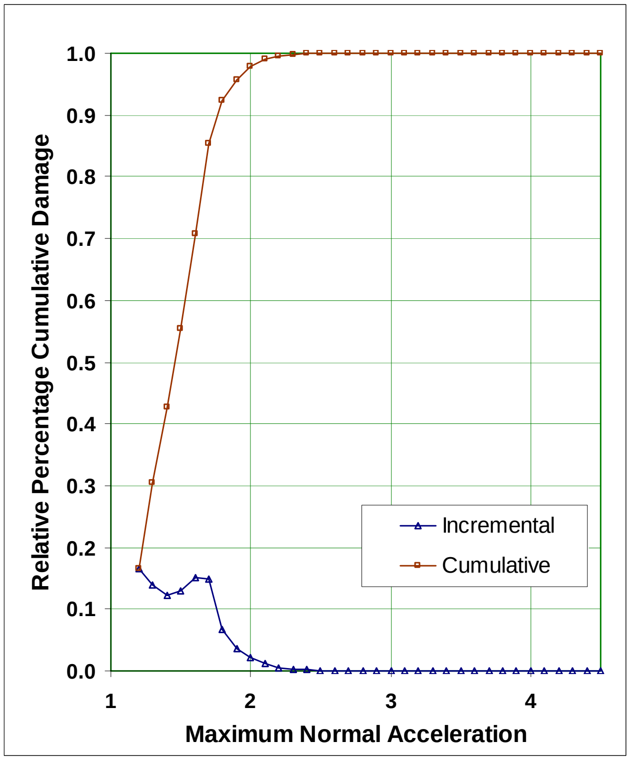

FIGURE C-15. BUDWORM SPRAY—HEAVYWEIGHT

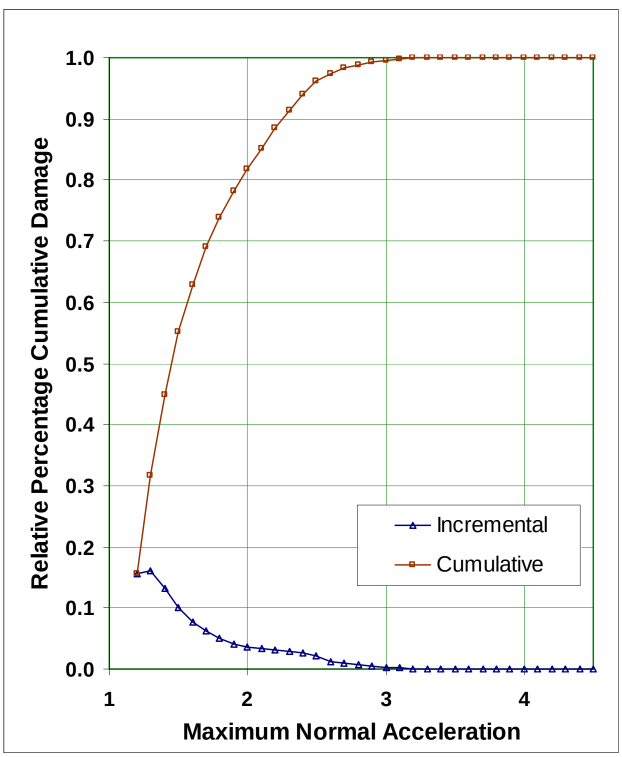

FIGURE C-16. BUDWORM SPRAY—HEAVYWEIGHT, ALL AIRCRAFT