T-45 Structural Fatigue Life Tracking System

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Abstract

The United States Navy's T-45 Training System is the world's premier aviator training system designed for carrier operations. The T-45 airframe is designed to reliably withstand the rigors of naval aviation training. The training system includes a comprehensive Structural Fatigue Life Tracking (SFLT) effort to determine ongoing fatigue damage for each of the 200+ aircraft in the fleet. The Airborne Data Recorder tallies 38 flight parameters and 6 strain gage readings as a function of time. Onboard aircraft data is recorded using rise-fall criteria to minimize data quantity without diluting its technical content. The data files are collected regularly and transmitted via internet to a ground processing facility. The sensors suite can provide loads information for the fuselage and interchangeable components of the wing, empennage, nose landing gear, main landing gear, and arresting gear. SFLT software, which runs on a PC platform, simultaneously assesses sensor health and computes accumulated damage at 68 fatigue-critical structural locations. Accumulated damage at each location is contrasted against full scale airframe fatigue test results to compute a Fatigue Life Expended (FLE) statistic. FLE values are recorded to a database for quality assessment, retrieval, and reporting. This system has been diligently maintained resulting in a sustained data capture rate in excess of 90% of total fleet flight time with 100% accuracy of component assignment. The SFLT allows the retirement of structural components to be based on FLE predictions rather than the certification life (half the life demonstrated in the full-scale airframe test). Accurate FLE predictions show that actual usage is less severe than the design criteria, resulting in increased service life and inspection intervals. Thus, the dual benefits of the T-45 SFLT program are high confidence in structural integrity predictions with commensurate safety, and quantified increased economy of the fleet of aviator training assets.

Introduction

Based on the earlier British Aerospace Hawk, the two-seat T-45 Goshawk was designed for intermediate and advanced portions of the Naval and Marine Corps student aviator program, built specifically for carrier based operations and tactical strike missions training. Figure 1 illustrates the airframe configuration. The 200+ jets are distributed among training squadrons at two training bases. Detachments to an available aircraft carrier serve as the final exam. A small group of jets is also assigned for flight testing at any given time. A T-45 is designed to withstand 1,020 catapults and traps, 56,210 landings, and 14,400 flight hours of service. A full scale fatigue test successfully validated the structure per the design loads. As with any aircraft, the design requirements are derived from past experience of previous vehicles with similar missions. Feedback is necessary to assess the new structure's ability to withstand the actual usage. Feedback also helps the fleet in its assessments of significant events, which could require unscheduled inspections with commensurate repercussions. Accuracy of feedback is of supreme importance in making informed economic and safety decisions for the fleet of jets and its inventory of spare components.

Figure 1: T-45 Airframe and Undercarriage Are Designed for Carrier Operations

T-45 Structural Fatigue Life Tracking System

The T-45 Structural Fatigue Life Tracking System is a reliable, cost effective, comprehensive program to assess usage and the ongoing structural fatigue damage for each individual aircraft in the Navy's fleet of advanced trainer jets. The Fatigue Life Expended (FLE) statistic (Figure 2) is derived from the number and severity of recorded flight events, full scale fatigue test results, plus pilot and maintenance reported events. 68 fatigue critical locations on the fracture critical structural components that make up an airframe are monitored.

$$\text{FLE} = \frac{\text{Accumulated Damage per Recorded Events}}{\text{Test Demonstrated Damage} \times \frac{1}{2}} \times \frac{\text{Pilot Events}}{\text{Recorded Events}} \times 100\%$$

Figure 2: Fatigue Life Expended Balances Usage and Verification

T-45's Fatigue Tracking System is comprised of three major components: onboard hardware and software, data collection and transmittal, and ground-based software and processing. Data quality assurance is performed within each component and all downstream processes. Figure 3 illustrates the three components, with subtle emphasis on the dozens of T-45s on the tarmac ready to fly, providing ample opportunity for data collection.

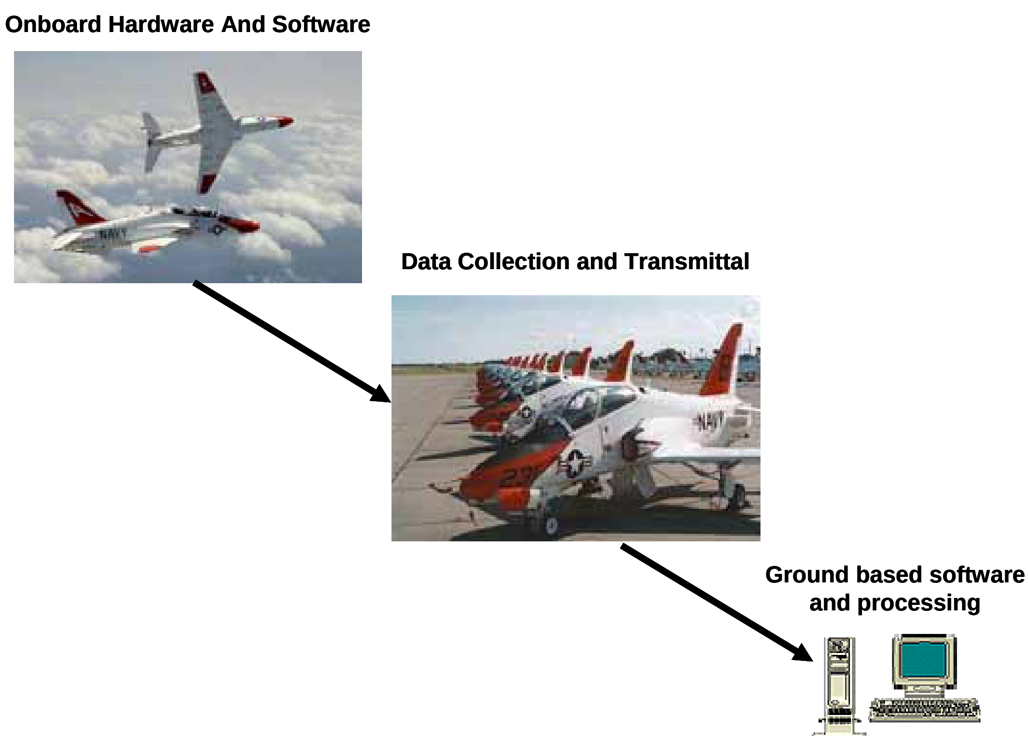

Figure 3: Components of the T-45 Structural Fatigue Life Tracking System

The onboard Aircraft Data Recorder (ADR) allows reconstruction of the airframe loading history by recording time sequenced response from strain sensors, trajectory measurements, and aircraft configuration. 45 aircraft parameters are measured at frequencies ranging from 1 to 32 Hz. 27 of the parameters cause data to be recorded when the parameter peaks or valleys pursuant to pre-established rise-fall and dead band criteria. A landing is identified by a Weight on Wheels event (WOW). WOW causes all parameters to be recorded at maximum frequency for one second prior to, one second during, and one second subsequent to WOW indication. Supplementary Mach/Altitude/AoA is also categorized and recorded once per second without reference to time sequence. Rate and range checks are applied to all parameters. Failing measurements are tallied per sensor but not recorded. Non-signaling sensors are identified and recorded to the download file. The data suite consists of 6 strain gages readings (located in the left and right wings, fore and aft fuselages, vertical and horizontal tails), 16 configuration discretes (gear up, hook down, etc), 21 trajectory parameters (time, linear accelerations, angular velocities, roll acceleration, control surface positions, etc.) and 2 ADR accounting parameters. A display panel in the nose wheel well indicates severe flight or landing exceedances, requiring inspection. Figure 4 itemizes the ADR measurands. Figure 5 illustrates the overall path of data flow and types of refinement.

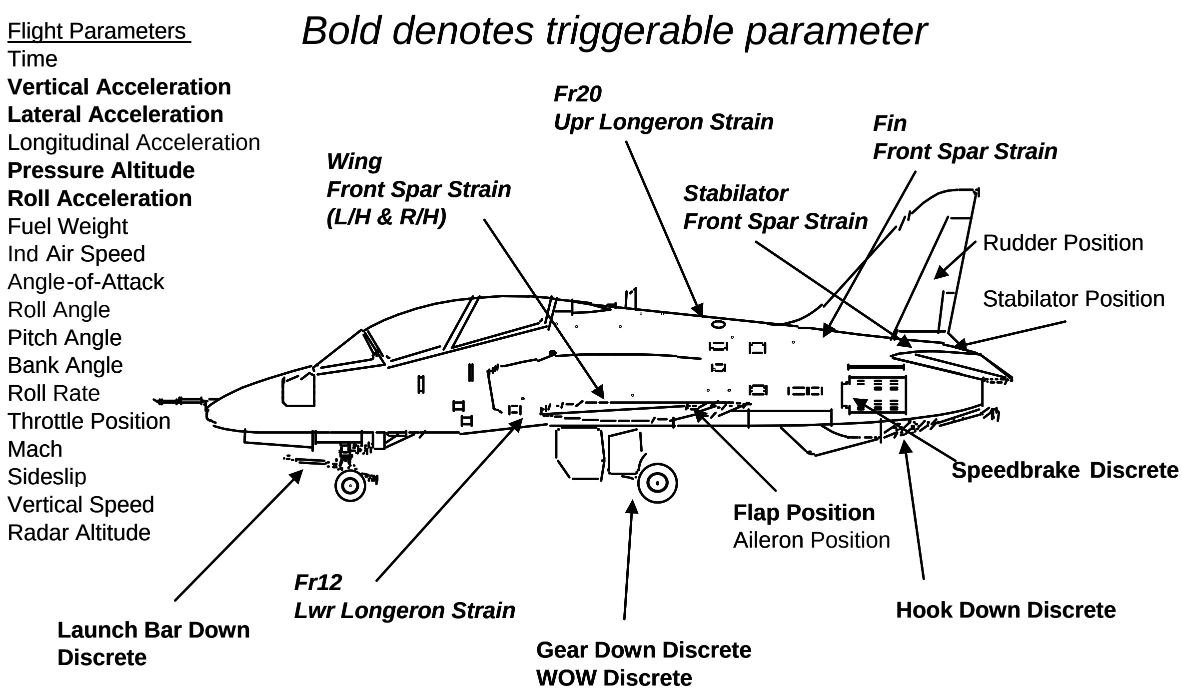

Figure 4: T-45 Structural Fatigue Life Tracking ADR Parameters

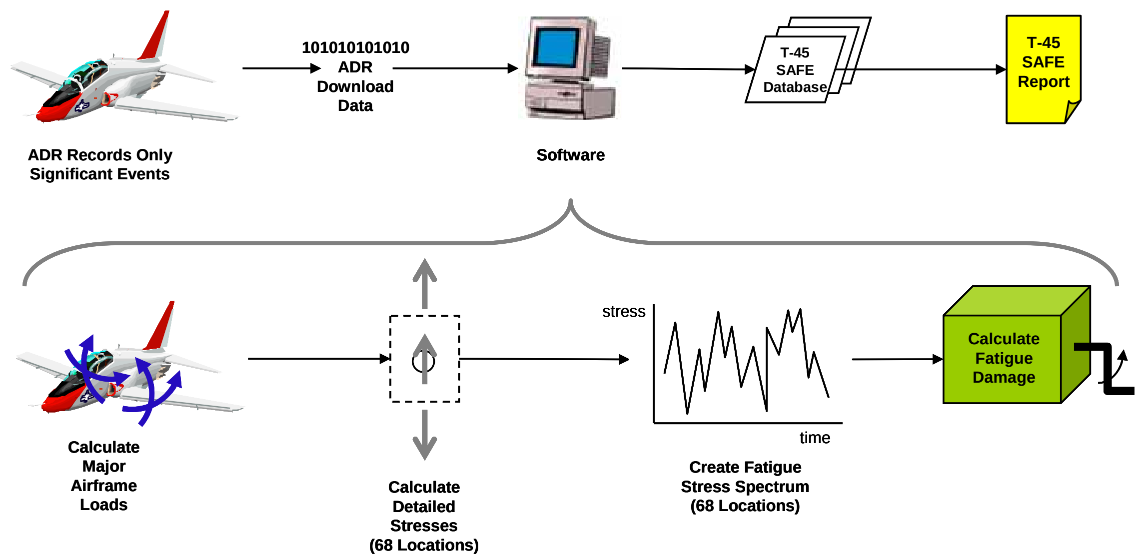

Figure 5: Data Processing Summary

Base ground support personnel harvest all data. ADR data is regularly downloaded from the aircraft by plane handling personnel. ADR files are matched with pilot reported flight information collected from Logs & Records to assess completeness of both the ADR file inventory and the pilot reported inventory. The matching exercise has proven to be very effective at identifying, locating, and remedying unaccounted data, corrupted ADRs, plus feedback on fidelity to the task of collecting ADR data in general. The result is an extremely high percentage of flight hours are recorded in the data. New assignments of removable structural components are provided by Maintenance to Logs & Records. The pilot reported events, all ADR files, the matching exercise, and new component assignments are transmitted to the ground-based data processing facility.

The ground-based data processing facility collects and warehouses all data, performs several data checks, performs FLE analyses, and publishes the Structural Appraisal of Fatigue Effects (SAFE) report. All data is posted to a timeline database using PC mounted software.

When a new jet is manufactured, its component serial numbers and aircraft empty weight are collected and entered into a database. Serial numbers are checked for uniqueness. (Subsequent weight changes due to structural modifications require updates to the software tables to account dates, significant weight increases, and changes to location stress transfer functions.)

The pilot reported data is checked for accuracy. All jets are tallied. Current month deltas plus prior month totals must equal current month totals for flight hours, catapults, landing types, and flights. Landing counts by type must add up to monthly landing total. Arrestment counts by type must add up to the reported monthly arrestment total. Ship arrests must equal ship catapults unless informed otherwise by the fleet due to a rare downing aboard ship.

Discrepancies are reported back to Logs & Records who rectify the discrepancy and communicate the correction back to the data processing facility.

Component assignment changes are entered from aircraft Inventory Records and component "passport" records. A component must be available from its previous assignment in the database per the component "passport." When discrepancies exist, the user contacts the base Logs and Records personnel for clarification such as previously unreported assignments or corrections to errant prior assignments.

On rare occasions, ADR data will be submitted with issues. It is possible that the ADR data will be accidentally not cleared from a jet after a download. The un-cleared data is re-submitted in the subsequent download at which point the duplication is identified. Upon identification, the earlier file is removed to prevent duplication in subsequent analyses. The ADR box itself is often transferred between jets and the new assignment must be programmed correctly. When the ADR is downloaded, the downloader assigns the jet name as part of the ADR file naming convention while the ADR writes its assigned jet within the file. If those two jet indications disagree, ground support personnel are called to diagnose and correct the problem, detailing the findings to the ground-based processing facility which repairs the discrepant file accordingly.

ADR data is inventoried with files allocated to aircraft folders and summary information posted to a database table. Files with excessive errors are deemed corrupt and removed from further analysis. Repeat offenders are identified and remedied.

On a monthly basis, ADR files are assessed for accuracy of information in excess of ADR check capabilities. A check of accelerations is performed when the jet is stationary to assure that readings have not drifted. If trajectory information is acceptable, a trajectory-computed structural load can be used to validate wing and stabilator strain readings against full-scale strain survey results. Figure 6 illustrates a typical correlation for an acceptable wing strain gage. Malfunctioning strain gages are flagged in the timeline database. Non-signaling sensors recorded by the ADR are noted as well. Sensor gripes are issued to the bases for all detected sensor malfunctions. Ground support personnel are responsive to sensor gripes and perform repairs within the economic constraints of the day. Ground support personnel are also empowered to self-diagnose several of the operationally restricting sensor problems (fuel weight, poor vertical acceleration readings causing false over-G indications, etc.) without waiting for the monthly sensor gripe report. Malfunction of critical sensors or combinations of other sensors can prevent a damage accumulation in the FLE analysis. For the past 10 years, less than 5% of all possible data has been unsuitable for FLE computations due to sensor malfunction.

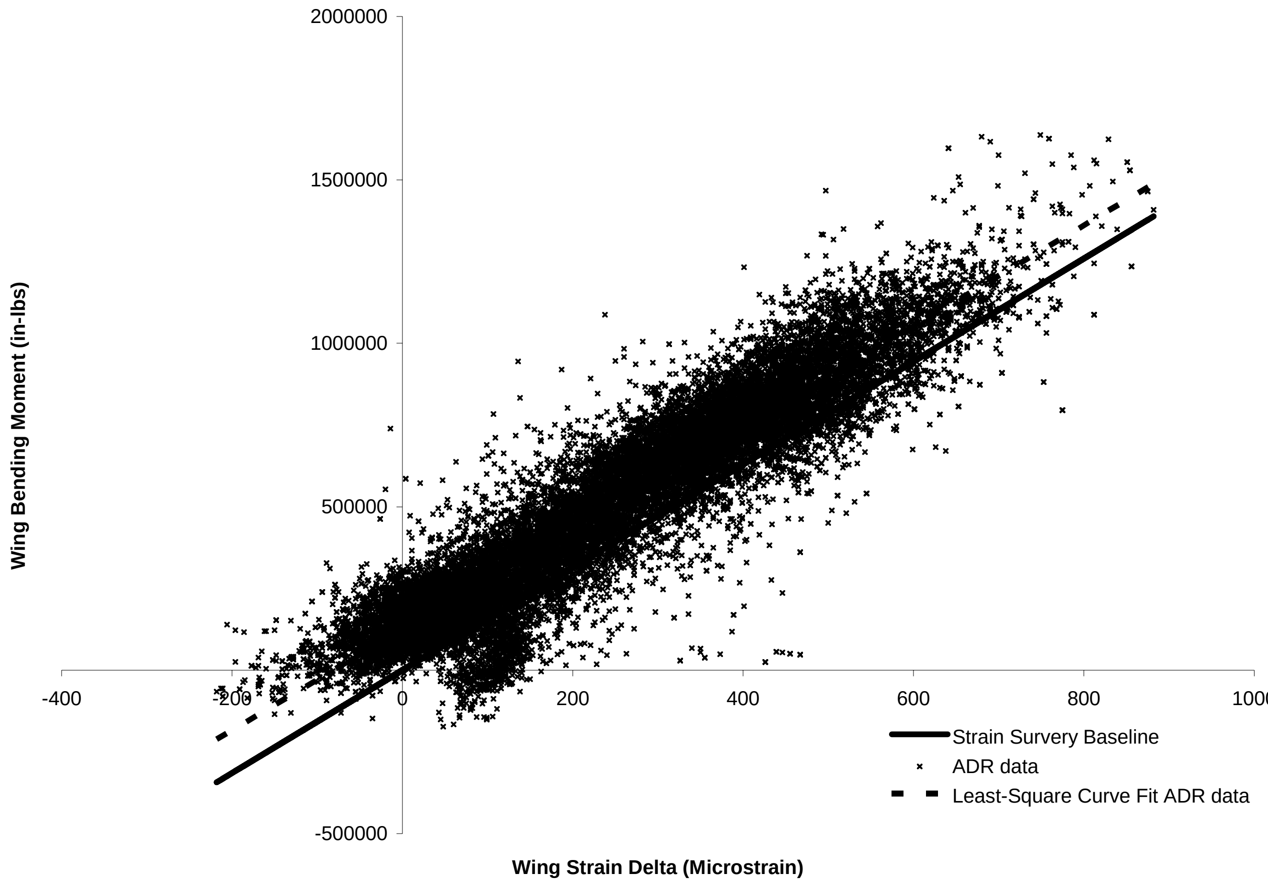

Figure 6: Example of Acceptable Wing Strain Gage Assessment

Once all data has been rectified the FLE analysis can begin. Aircraft empty weight is recalled from current configuration information. The aircraft's analysis timeline is extended per the reporting period, typically 3 months. A guardrail in the software prevents prior ADR information from being re-analyzed or previous results overwritten in the database. Pilot reported information is accessed on a per aircraft basis for each month. The month's total of pilot reported events are incremented for all parts in the jet's configuration on day 1 of the month. Pertinent ADR files are accessed for the time period. ADR time slice data contains a fuel weight reading, and crew weight is conservatively assumed to compute aircraft weight as a function of time during flight. External stores are rare occurrences with negligible weight on T-45 and are not accounted. A flight trajectory model is input with ADR time slice trajectory parameters. The trajectory model computes internal airframe loads. When valid strain sensor measurements are available, strain readings are used instead of trajectory model computed loads. During ground events, ADR acceleration data recorded at maximum frequency is assessed to recognize the maneuver. Depending on the recognized maneuver, available predetermined load sets are accessed to determine airframe loads. Available maneuvers are flared landings, catapults, arrestments, and free-flight engagements. Each maneuver has realistic ranges of severity available. 44 internal loads are tabulated across the airframe and undercarriage. Once the load histories are calculated, component location stress histories are computed, filtered, and cycle counted. Hysteresis effects from previous loadings serve as the initial conditions for a crack initiation analysis to increment location damages. All data processing results are posted to the timeline database. If a component assignment change is evident in the aircraft's analysis timeline, the ADR timeslice analysis is suspended at the appropriate date, the component assignment change is made, and analysis resumes. Ground support is instructed to harvest ADR files prior to performing a component change. This instruction allows FLE analysis to be halted in between files, mitigating the need for a mid-file analysis suspension. Such instruction also prevents ADR data from remaining uncollected aboard a hangar queen whose parts are being cannibalized. The FLE computations and SAFE report appendix information are generated using a query module. Commercially available word processing and data plotting packages are used to present the summary information. Figure 7 diagrams the flow of data.

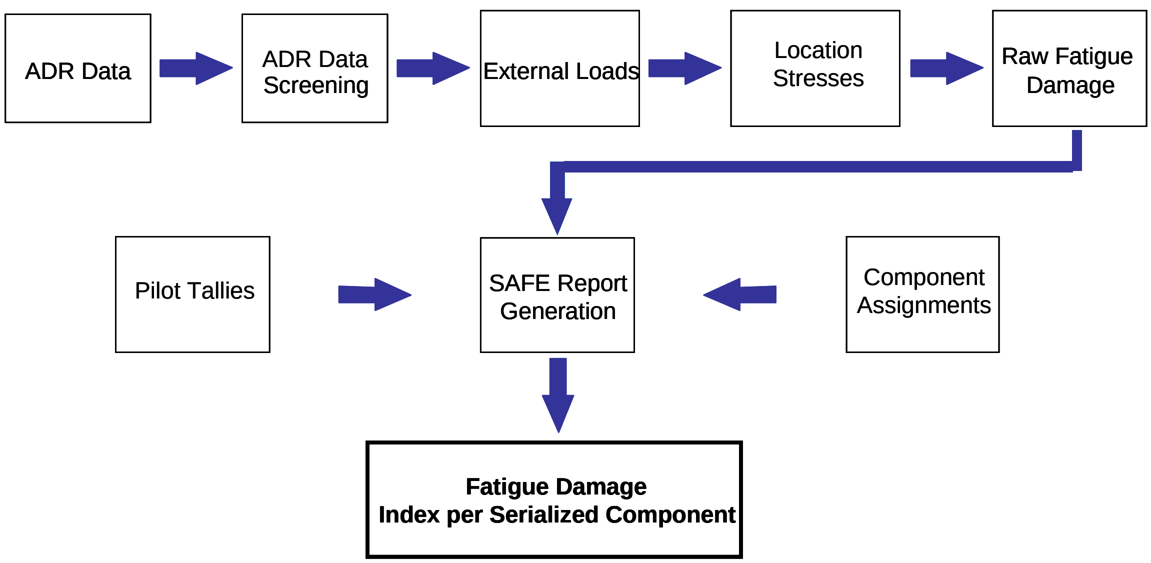

Figure 7: Details of FLE Computations

Data processing facility personnel periodically perform audits of component assignment information. This is accomplished by collecting all component assignment information from the bases for comparison against database entries reflecting reported component assignment changes. Discrepancies are rectified by requesting component "passport" cards and entering the missing transaction, reprocessing ADR as necessary. Collection of component assignments to support audits has evolved and devolved over the years. Data processing personnel have visited bases in part to photocopy aircraft Inventory Records. Most recently, base personnel photocopied the Inventory Records for mailing to the data processing facility.

Results

The result of all T-45 Structural Fatigue Tracking System effort is high fidelity information about the structural health of the fleet and the ways the fleet is used. Figure 8 shows the historical results of data capture efforts. The vast majority of reported flight hours are validly captured, above 90% since 2nd Quarter 1999. Memory overflow and contaminated data have been consistently low, a testament to the good performance of the base personnel to collect the data and maintain the sensors. Data loss in transmission has been non-existent, due primarily to use of the internet to transmit data, rather than physical transport. The definition of flight hours in Figure 8 also benefits from the measured non-flying time reported by pilots. Non-flying time is excluded from the definition of flight hours in Figure 8. Data capture and accuracy is the key to having confidence in the Structural Fatigue Life Tracking results.

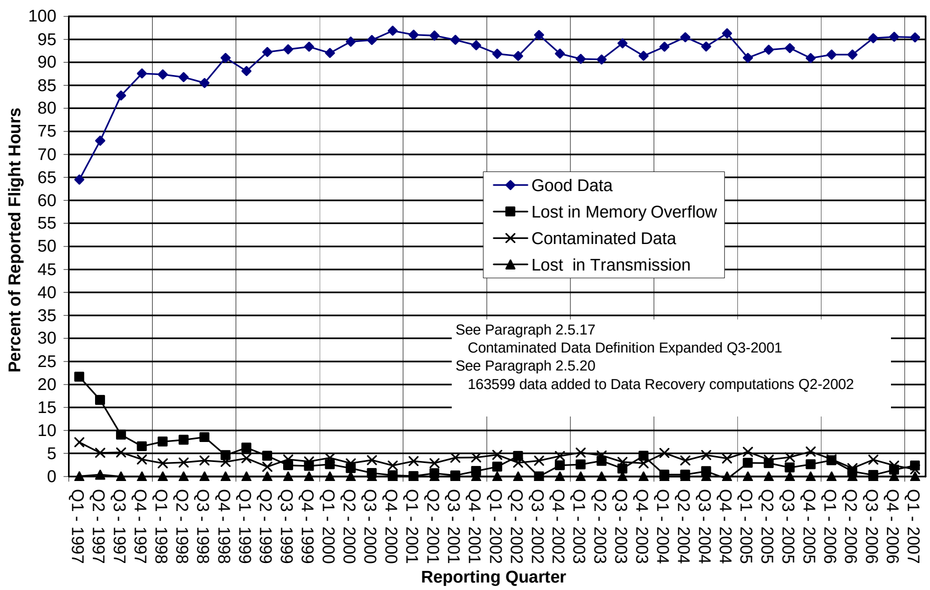

Figure 8: T-45 Structural Fatigue Life Tracking System Data Capture Quantifications

Figure 9 illustrates how T-45s landing usage compares to the design criteria, one of many examples of the high fidelity usage information tabulated by the data processing facility.

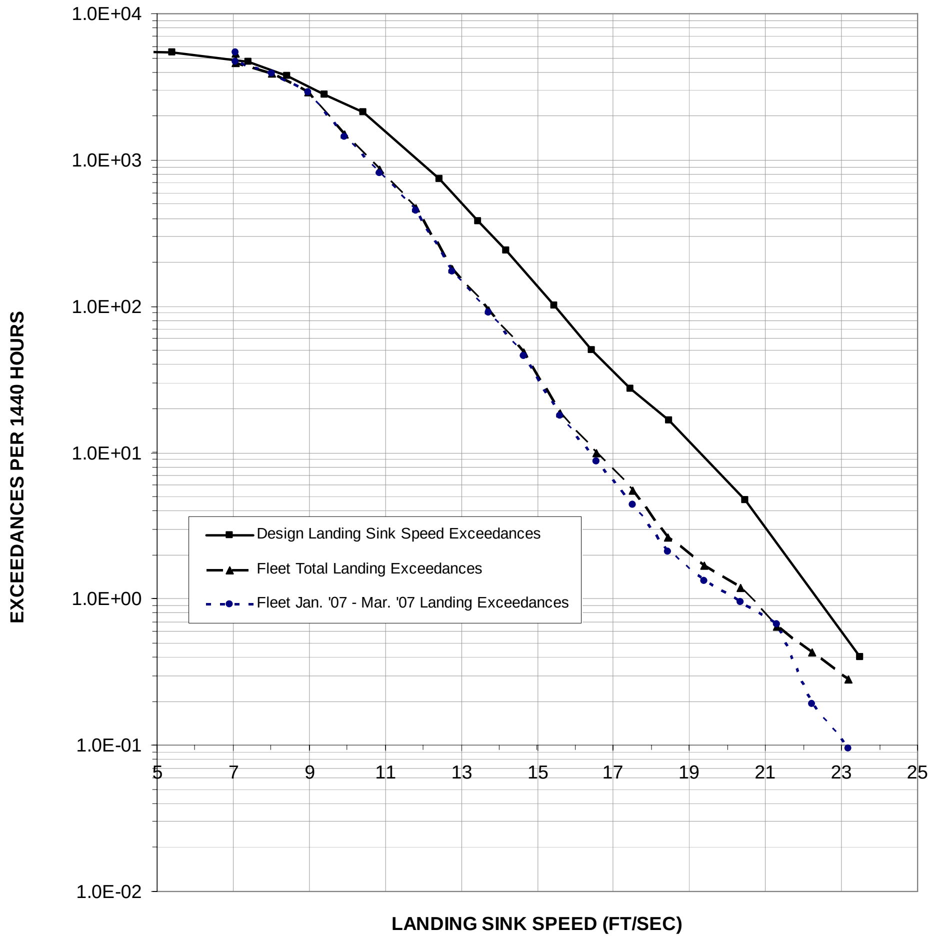

Figure 9: T-45 Structural Fatigue Life Tracking System Measures Usage

Payoffs

The payoffs of the T-45 Structural Fatigue Life Tracking System have proven to be well worth the investment. High fidelity usage feedback can be confidently used to make decisions about component and/or airframe usage, repairs, structural modifications, and retirements. Figure 10 shows the T-45 tracked locations ranked on the basis of projected life.

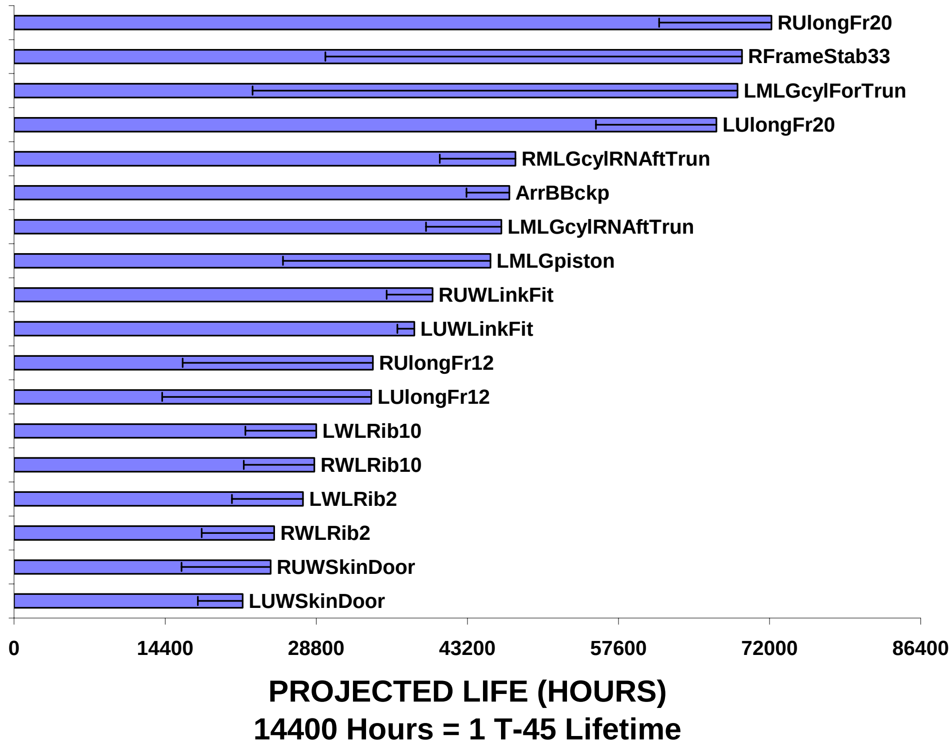

Figure 10: T-45 Structural Fatigue Life Tracking System Results Project Component Life

Numerous operational incidents have been accurately reconstructed. These successes help confirm or refute pilot reports and determine necessary structural inspections before returning the jet to service. In the most severe or recurring cases, modifications to flight or maintenance procedures, cockpit displays, or flight controls have been developed with the first step being assessment of pertinent ADR data. The usage information collected for the T-45 Service Life Assessment Program can be used with high confidence. T-45 Service Life Assessment is expected to yield a 1.5X life extension in accordance with the results of the Tracking System to date. Production quality assurance and aircraft deliveries have benefited from ADR data to assess anomalies evident during acceptance test flights. In the event of findings during a structural inspection, similarly affected components can be quickly located because component location is accurately catalogued. As the fleet approaches retirement, structural safety concerns can be mitigated economically by accurate retirement and replacement of components whose lives have been expended. No mishaps to date have occurred due to structural failure. The fleet has been able to maintain its required sortie rate.

All of these successes have been supported by feedback information provided by an excellent Structural Fatigue Life Tracking system.