Tactical Aircraft Engine Usage—A Statistical Study

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The use of realistic engine usage prediction for creation of the structural design criteria for advanced propulsion systems is being encouraged by the Air Force and Navy. Inclusion of realistic structural design criteria early in the conceptual design phase will help minimize the system life cycle cost by reducing costly usage related structural deficiencies. To this end, several engine usage prediction models are currently under development by industry. Unfortunately, little continuously recorded operational engine usage data exist for the purpose of building and verifying these models. Under the Engine Usage Data Acquisition Program, the Aero Propulsion Laboratory obtained about 240 h of this type data from A-10, F-15, and F-5E aircraft during Tactical Air Force Red Flag exercises and home base training flights. A statistical and subjective analysis of these data was performed. The results show that 1) tactical aircraft engines spend a considerable amount of time in ground operation; 2) the three systems have usage containing a large number of small amplitude throttle cycles; 3) aircraft thrust to weight and mission type greatly influence mission throttle cycle content and time at temperature; 4) combat flying can be more engine damaging than peacetime training; and 5) pilot-to-pilot variation dramatically influences engine damage accumulation. The authors urge that the American engine manufacturing community enlarge the continuously recorded engine usage data base to include a broad range of aircraft and missions and to use these data to develop and validate engine usage prediction models.

Introduction

ONE of the primary considerations in the design and development of the next generation of Air Force and Navy weapon systems is to establish designs which will minimize the overall cost of ownership for that aircraft. Since the engine operating and support costs are a major contributor to the system's life cycle cost, engine designs which stress reliability and durability with minimum impact on performance will be a necessity in the future. To achieve this goal the engine's operating environment must be well understood so that realistic structural design criteria can be established early in the conceptual design process.

Past engines have been designed to requirements based on the sizing, steady-state combat mission definition. Unfortunately, recent experience has shown that peacetime usage implies an entirely different set of design criteria. The well-documented case of the F100 structural design not accounting for idle-to-intermediate throttle movements, which resulted in a rash of low-cycle fatigue induced failures, points out the importance of understanding exactly how the engine is to be used and designing for it.

The joint Navy/Air Force Advanced Technology Engine Study is an excellent example of the importance the Armed Services are placing on predicting engine usage early in the design process. This program is a study effort to identify the critical engine technologies that must be developed to assure their availability for weapon systems through the year 2010. The study, which includes five engine manufacturers and ten airframers, is investigating 16 different systems, using minimum system life cycle cost as the primary figure of merit. One of the initial tasks for each company was to define detailed usage scenarios for each peacetime mission and the appropriate mission mix for each system in the study. These duty cycles were carefully reviewed by the Services and further work by the contractor could not continue until they were approved as realistic and representative. This information was then used by the engine manufacturers to establish structural design criteria to be used in the various technology evaluations and trades. The requirement for predicting usage will continue to be an important task in all future conceptual design studies.

The basis for projecting engine usage for future systems must be an adequate understanding of the usage of current systems. A data base of current system usage is also necessary for development and verification of models which attempt to predict the engine usage of future weapon systems. This paper makes use of 240 h of continuously recorded engine usage data from an A10, F5E, and F15 (Ref. 1) to identify and quantify some of the important influences which will have to be considered when attempting to model and predict the engine usage for an advanced weapon system.

Background

Several recent studies have shown that the most advantageous time to influence the life cycle cost of a system is in conceptual design. It is during this phase of development that the decisions are made that ultimately determine 75-80% of the system's total life cycle cost. Recognizing the importance of the conceptual design phase and noting the usage related engine structural problems in recent high performance weapon systems, the Aero Propulsion Laboratory sponsored a program with industry called Life Utilization Criteria Identification in Design (LUCID). LUCID developed the methodology to facilitate engine performance and life trades in conceptual design.[2,3] Pratt & Whitney Aircraft and Detroit Diesel Allison were the prime contractors. A key piece of the LUCID concept is the ability to accurately and systematically predict engine usage for advanced weapon systems. McDonnell Douglas and Boeing were subcontractors in the LUCID effort, developing the usage prediction procedures. McDonnell's model is analytical in nature and uses digital flight simulation models to define engine throttle usage for a variety of different missions.[4] The Boeing model, on the other hand, is empirically based, relying on a limited amount of continuously recorded data from several current systems to predict time-dependent throttle histories for advanced weapon systems.[5]

A survey of possible sources indicated that only a limited amount of continuously recorded engine usage data was available for use in developing and validating these models. Some recent engines have been equipped with "level-crossing"-type engine monitors which count events of a certain type [e.g., the events history recorder (EHR) on the

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F100 engine]. This information is useful for validating the overall model; however, continuous data are necessary to insure accurate simulation of maneuvers performed during various individual mission segments. In addition, usage recorders such as the EHR give no information on the number of less damaging partial cycles that are part of the engine's usage. As new materials and advanced design techniques are employed, these partial cycles, which are now neglected, may become important and should be accurately reflected in the usage prediction models.

The Aero Propulsion Laboratory initiated an in-house Engine Usage Data Acquisition Program (EUDA) with the objective of obtaining continuously recorded engine parameters for tactical weapon systems in a simulated combat environment. The approach was to modify one operational A10, F5E, and F15 and record engine data at Red Flag exercises and normal home base flying. Red Flag is a combat training exercise held several times annually at Nellis Air Force Base, Nevada, and simulates the realistic combat threat environment. The systems were selected to give a range of system design variables (i.e., thrust-to-weight) and design mission (air-to-air and air-to-ground).

The parameters that were recorded are shown schematically in Fig. 1. Altitude, airspeed, and load factor were already available on the recorder for the three systems. The F15 modification included the ability to record power lever angle (PLA), fan rotor speed (N_{fan}), and core rotor speed (N_{core}) from the F100 engine. The J85 engine parameters recorded on the F5E were compressor rotor speed (N_{core}), exhaust gas temperature (EGT), and power lever angle. Unfortunately, the F5E power lever angle transducer was defective and no useful PLA data was obtained. Fan rotor speed, core rotor speed, interturbine temperature (ITT), and power lever angle were the parameters recorded from the TF34 in the A10. Some of the engine parameters had different sampling rates due to recorder operation. The minimum sampling rate was once per second and the maximum 15 times per second. However, the analysis of the engine data was performed using a sampling rate of once per second for every parameter.

The types of analyses performed included average altitude and flight profile distributions, average power setting distributions, rainflow cycle counting, level crossing cycle counting, and average "g" loading distributions.

The A-10 used in the EUDA program was home based at Myrtle Beach AFB, S.C. It was a participant in Red Flag 80-4. Thirty-one Red Flag ground support sorties were recorded providing 43 h of combat simulation data; 22 home base training flights provided 33 h of training usage data.

The F5E was a member of the Nellis aggressor forces; it participated in Red Flag 80-4 and 81-2. Twenty-one Red Flag missions were recorded providing 17 h of combat air patrol data. No training flight data were recorded for the F5E. Data return on the F5E was poor owing to recorded and transducer failures.

The F-15 was home based at Holloman AFB, N.M. It was a participant in Red Flag 81-2. Twenty-two combat air patrol sorties, eight range familiarization and ferry flights, and seven home base training flights were recorded for a total of 67 hours of F-15 engine usage data.

Personnel from the Aero Propulsion Laboratory were on site during the Red Flag exercises to conduct pilot debriefs for all sorties flown by the instrumented aircraft. These interviews detailed routes to and from the target, a description of the combat engagements, and the other significant maneuvers and events of the flight. Also, written Red Flag evaluation sheets were obtained. These forms are completed by the pilots for each sortie and they detail threats, maneuvers, targets, and mission effectiveness. With this information, significant maneuvers and flight events in the recorded data can be identified.

Data Analysis

Engine usage is a complicated phenomena which is difficult to predict and model. A large number of factors influence usage and the following discussion identifies and quantifies some of the more important. In several instances F15 composite usage will be employed for comparison purposes. These are field data acquired by Pratt & Whitney and are the average usages for all F100's in F15's from all bases.

System Design Impacts

Low-cycle fatigue (LCF) is one of the major consumers of engine parts life. The most damaging cycle from an LCF standpoint is the off-to-intermediate-(maximum rpm)-to-off cycle. One of these cycles is accumulated during each mission and thus the number accumulated per engine flying hour is directly related to the mission length. Figure 2 presents the number of 0-max-0 cycles per engine flying hour for the F5E, the A10 at Myrtle Beach and at Indian Springs during Red Flag, and the F15 at Nellis during Red Flag and F15 composite usage. F5E accumulates more of these cycles than the other systems because of its very short range. The A10 Red Flag flights were shorter than the training flights at Myrtle Beach and hence the accumulation of 0-max-0 cycles was about 35% higher. The F15 data from Nellis show that the accumulation rate was just slightly higher than an average F15.

The direct dependence of 0-max-0 cycles on mission length requires an accurate representation of ground operations. The ratio of total engine operating time per engine flying hour is also shown for the three systems in Fig. 2. Surprisingly, a significant amount of engine run time is spent in ground operation ranging from about 30 min of ground time per engine flying hour for the F15 to about 8 min per flying hour for the A10 at Myrtle Beach. Normal design mission calculation procedures allow only 5-6 min of preflight ground time per mission. Obviously, field usage is considerably different.

Ground operations are usually spent at low power settings

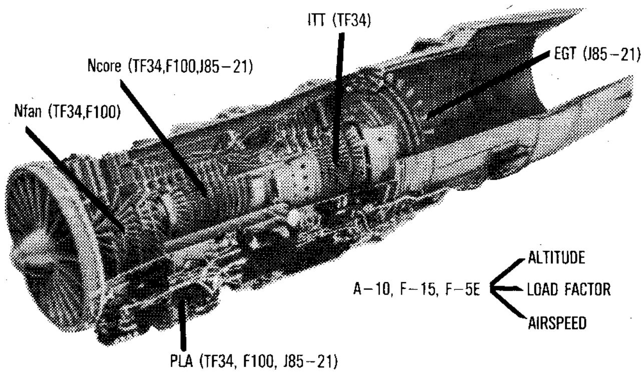

Fig. 1 Recorded parameters.

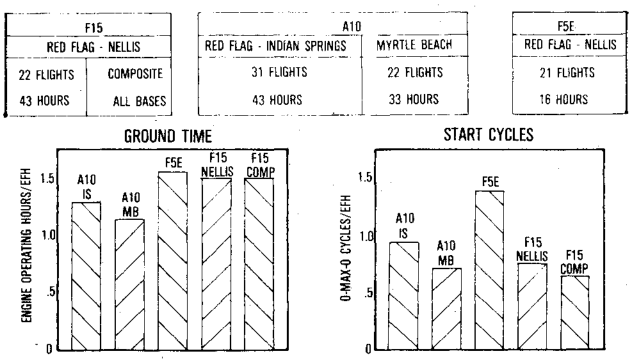

Fig. 2 Engine starts and ground operation.

and are generally not damaging to the rotating machinery. However, it is important to usage because the long ground operations consume significant amounts of fuel, which limits the flight length. In addition to impacting the 0-max-0 cycles, it also effects the accumulation of other types of damaging events that are encountered owing to the shorter (or longer) flight lengths. The ground time is usually used for avionics warmup, pre- and postflight maintenance and inspections, arming/disarming and safing of external stores and weapons, and time spent waiting for takeoff clearance. As the data in Fig. 2 indicates, the system, the configuration, and the base are all significant influences.

In addition to the 0-max-0 cycles, low-cycle fatigue life consumption is directly related to the number and magnitude of the rotating component speed changes. A number of cycle counting techniques are available to count the various speed excursions seen in the time history traces. Based on the work of Dowling,[6] a "rainflow" cycle counting technique was employed because "rainflow" was found superior to the other techniques when applied to complicated time histories. The rainflow method defines cycles as closed hysteresis loops and hence corresponds closely to the cyclic response of metals. The rainflow algorithm developed by Richards, LaPointe, and Wetzel[7] was employed in this study.

The rainflow cycle counting was applied to the time histories of high pressure compressor rotor speed for every flight and then arithmetically averaged for each system. The data were first filtered to eliminate speed changes of less than 1%. The cycle counting algorithm requires the amplitude of the time history to be divided into a number of bands. The larger the number of bands, the more accurate the cycle count. In this analysis, 49 bands were selected as a good compromise between accuracy and computer storage and executive time requirements. Reference 7 estimates this introduces a possible error of 4% in the cycle count.

Using rainflow procedures, all cycles of at least 2% magnitude were counted and the average results are shown in

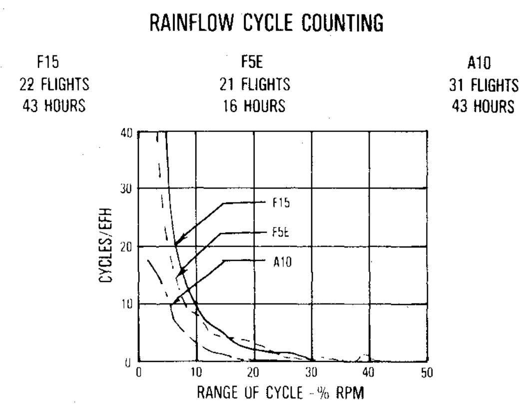

Fig. 3 Cyclic usage distribution—Red Flag usage.

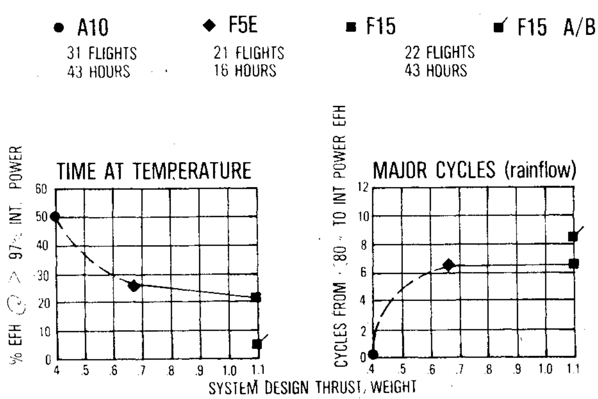

Fig. 4 Summary of damaging events—Red Flag usage.

Fig. 3. The number of each type of cycle per engine flying hour is plotted against the range of that cycle in percentage of rpm for the A10, F5E, and F15 Red Flag missions. The data show that for all three systems, as the range of the cycle decreases, the number of these types of cycles per engine flying hour increases dramatically. It is also apparent that the high thrust loaded systems (F5E, F15) accumulate more of each type of cycle than the lower thrust loaded system (A10).

One of the most important criteria in hot section design, because of its dramatic impact on stress rupture, creep, oxidation, and erosion life, is the engine operating time spent at near maximum temperature conditions. For this analysis, time spent at power settings greater than 97% of intermediate was considered damaging. For low-cycle and thermal fatigue life limited parts, the major damaging events are large speed excursions which in this analysis were defined as cycles from less than 80% to intermediate power. Throughout this paper, 0-max-0 cycles are counted separately and are not included in the summaries of damaging cyclic events. A summary of the average occurrence of these damaging events per engine flying hour at Red Flag is presented in Fig. 4 as a function of the system design thrust-to-weight ratio. Despite the fact that the results are plotted vs thrust-to-weight, it is unclear whether the major influence affecting the difference in usage between the A10 and F5E/F15 is system thrust-to-weight or design mission (air-to-air vs air-to-ground). Hence the A10 data point is connected with the other data points using a dashed line.

The data in Fig. 4 show that, on the average, the A10 spends over 50% of its time within 97% of intermediate power during a Red Flag ground attack mission. This is significantly higher than the F5E (25%) or the F15 (20%). The data also show that time at temperature is only a weak function of system thrust-to-weight for relatively highly thrust loaded air-to-air fighters.

The flagged symbol represents the average amount of afterburner operating time for the F15. It is a relatively low 5% of the mission. Comparable data for the F5E were not available owing to the power lever angle transducer failure.

The average A10 Red Flag usage included less than one major cycle per flying hour, while both the F5E and F15 usage included nearly 6.5 of these damaging cycles per flying hour. Cyclic usage appears to be nearly independent of system thrust-to-weight for highly loaded air-to-air fighters.

Again, the flagged symbol represents the number of augmentor transients for the F15. The augmentor is used an average of 8.5 times per flying hour during a typical F15 Red Flag combat air patrol mission.

Figure 4 indicates that the F5E and F15 are flown in a similar manner for combat air patrol missions. This was confirmed by analyzing their respective average flight profile and power setting distribution for Red Flag missions. The detailed results are presented in Ref. 1. Basically, both systems spent most of their mission in the 10,000 to 15,000 ft (MSL) altitude range and a majority of the time between 0.6 and 0.8 Mach number. Both systems showed two predominate power settings in terms of dwell time, a part power cruise setting and intermediate power and above.

Environment

The normal procedure for conceptual design studies is to assume that peacetime training flying is more damaging to the engine than the design (or combat) mission. Hence peacetime usage establishes the structural design criteria for the engine. One of the objectives of the Engine Usage Data Acquisition Program was to verify this assumption. Red Flag data were recorded because this was as close to realistic combat as possible. These data could then be compared with data recorded from home base training for the A10 and the Pratt & Whitney composite data for the F15 to identify any significant differences in the accumulation of damaging events.

Figure 5 compares the average flight profile distributions for the A10 flying Red Flag missions from Indian Springs Auxiliary Air Field with training sorties from the home base, Myrtle Beach Air Force Base. These plots were generated by defining ten equal altitude and velocity intervals and summing the amount of flying time spent in each interval. The data were averaged and then plotted at the midpoint of each interval.

The A10 was flown differently during Red Flag than at Myrtle Beach. Over 78% of the Red Flag mission was spent in the 3000-6000-ft-altitude region. Noting that the Indian Springs field elevation is over 3000 ft and the range elevation varied between 3000 and 8000 ft, it is apparent that the Red Flag ground attack missions were flown almost entirely "on the deck," i.e., at altitudes below 500 ft above the ground. This was confirmed from the pilot interviews. On the other hand, Myrtle Beach missions (field elevation at Myrtle Beach is 26 ft) averaged only 40% of the flight at altitudes less than 3000 ft MSL and spent the remaining flight time at much higher altitudes than seen at Red Flag.

The velocity profile shows a similar story. A majority of the flight time for average Myrtle Beach missions is spent between 200 and 250 knots calibrated airspeed while at Red Flag the predominant airspeed is on the average between 250 and 300 knots. Seventy percent of the mission is flown in this airspeed range while only 60% of the average Myrtle Beach mission was flown at its dominant air speed. In other words, the average A10 Red Flag mission was flown much faster and at lower altitudes than the average Myrtle Beach mission.

In terms of damaging events to the engine, the differences are equally as striking as shown in Fig. 6. The average Red Flag flight contains less than one major throttle cycle (less than 80% to intermediate) per engine flying hour but nearly 50% of the sortie is spent at or near intermediate power. On the other hand, the normal training flights contain a much higher cyclic content, about 2.8 cycles per EFH, but only 17% of the mission is spent at or near intermediate power.

A similar comparison is presented in Fig. 7 for the F15. Engine damaging events from average Red Flag combat air patrol missions are compared with the composite F15 usage. In this case the Red Flag flying appears to be more damaging in both time at temperature and cyclic content. The average F15 mission contains about 15% time at intermediate power and above and about 4.5 type III cycles (idle to intermediate) per flying hour. The Red Flag data recorded on the EUDA modified aircraft show an average of about 18.8% time at intermediate power and above and almost 6.5 type III cycles per flying hour (based on EHR reading and not continuous data to be consistent with composite usage averages). While the sample size for the Red Flag data is relatively small, the results are very similar to those reported for Red Flag flying in Ref. 4.

The results presented in the preceding two figures indicate that combat usage may indeed be more damaging to the engine than peacetime training. At the very least it shows that there is a significant difference in usage depending on the base and the type of flying being done. However, this analysis indicates a need to investigate the design combat mission for future systems to check the damage content and assess its impact on the structural design criteria.

Mission-to-Mission Variation

Even within a given set of system characteristics the individual mission and the elements and maneuvers that make up the mission can have a significant impact on usage and the damage content to the engine. While at Nellis, the F15 flew a number of different types of missions. These included six flights of dissimilar air combat training (DACT) (10 h), seven flights of combat air patrol (CAP) (11 h), nine flights of combat air patrol with air-to-air refueling (CAP/AAR) (22 h), and seven ferry and range familiarization flights (ferry/fam) (14 h).

The differences in average damage content per flying hour for each of these types of sorties are shown in Fig. 8. As

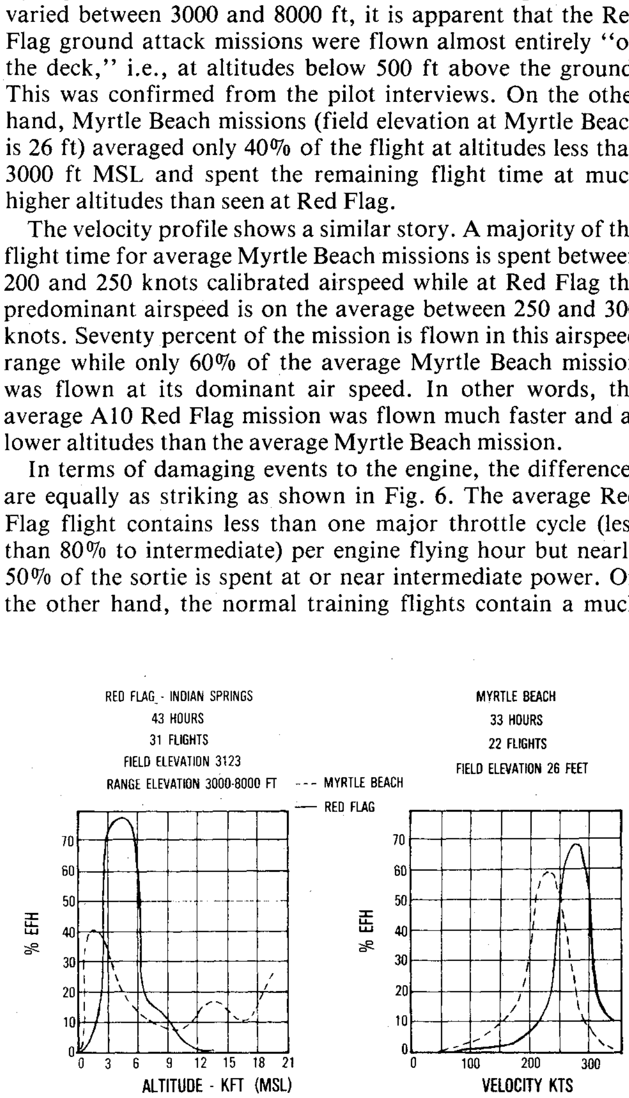

Fig. 5 A10 flight profile distribution—Red Flag and Myrtle Beach.

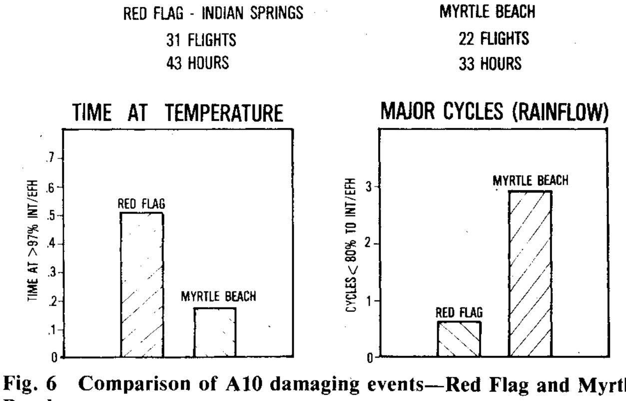

Fig. 6 Comparison of A10 damaging events—Red Flag and Myrtle Beach.

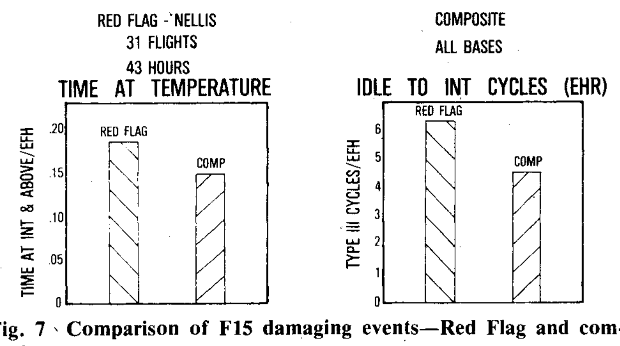

Fig. 7 Comparison of F15 damaging events—Red Flag and composite usage.

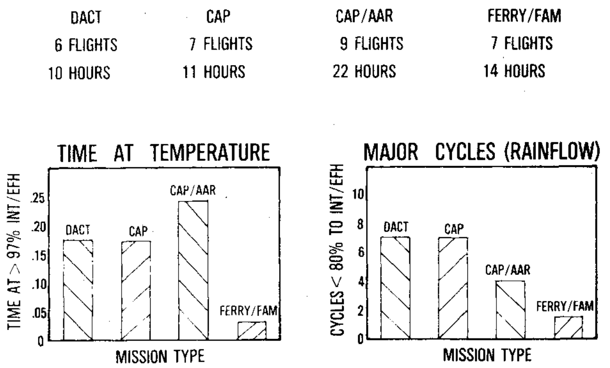

Fig. 8 F15 mission-to-mission impact on damaging events.

expected, the ferry and range familiarization flights were least damaging, with less than 5% flying time near intermediate and above and only 1 major throttle cycle from less than 80% to intermediate. The dissimilar air combat training and combat air patrol missions are very similar, spending about 17% time at temperature and encountering over 7 damaging throttle cycles per flying hour. Surprisingly though, the combat air patrol sorties with air-to-air refueling contained marked differences in damage content. These flights contained nearly 25% time at greater than 97% intermediate but only 4 cycles per flying hour from less than 80% to intermediate. In other words, air-to-air refueling reduces the damage content of an average combat air patrol mission by over 40% in cyclic content but increased by 45% the time at temperature. In addition to the data in Fig. 8, the average mission length varied from just under 1 h to almost 2 h, which as mentioned previously, is the determining factor in the accumulation of the damaging off-max-off cycles. From these results is is apparent that an accurate definition of usage will require an accurate understanding of the individual missions and the corresponding mission mix.

Pilot-to-Pilot Variation

Since a number of different pilots flew the aircraft instrumented for the EUDA program, the data from similar missions provide an excellent opportunity to quantify differences in usage caused by pilot techniques.

The first example compares two A10 Red Flag ground attack missions. Both missions were roughly the same length, approximately 75 min. Both pilots were lead in two ship formations. The missions were flown entirely at low level using terrain following/terrain masking techniques. The targets were located in the same general area of the Nellis Range. The aircraft carried identical fuel and weapons loads, both missions were flown out of Indian Springs Auxiliary Air Field, and atmospheric conditions were comparable. During these sorties, neither pilot encountered any air threat but had to use ground threat evasion tactics at several points in the mission. The ingress and egress routes to the target were similar and approximately five passes were made on the target.

Figure 9 presents the flight profile traces for these two missions. The altitude (feet, MSL) traces are very similar. The velocity traces (knots, calibrated air speed) are roughly the same, although pilot A seemed to fly at a slightly higher air speed at different parts in the mission. Figure 10 compares the throttle movements that each pilot made to carry out these very similar missions. (PLA of 100 is intermediate and PLA of 16 is idle). The difference is amazing—pilot B made 347 throttle movements while pilot A made only 25. In terms of damaging cycles, comparisons are not quite so striking, but from a time at temperature standpoint, pilot A spent over 65% at near intermediate power and pilot B spent only 34%. Pilot B had many more flying hours but had less experience in A10's than pilot A.

A similar example of wide differences in pilot technique can be found in the F15 data base by comparing two similar combat air patrol missions flown by different pilots. Both missions in this comparison were the same length, approximately 1 h. Both pilots were wing man in two ship formations and both sorties were flown with the same fuel and weapons load. Both missions were flown out of Nellis

	PILOT A	PILOT B
THROTTLE MOVEMENTS	25	347
MAJOR CYCLES < 80% TO INT	0	1
TIME AT > 97% INT	65.4%	34.0%

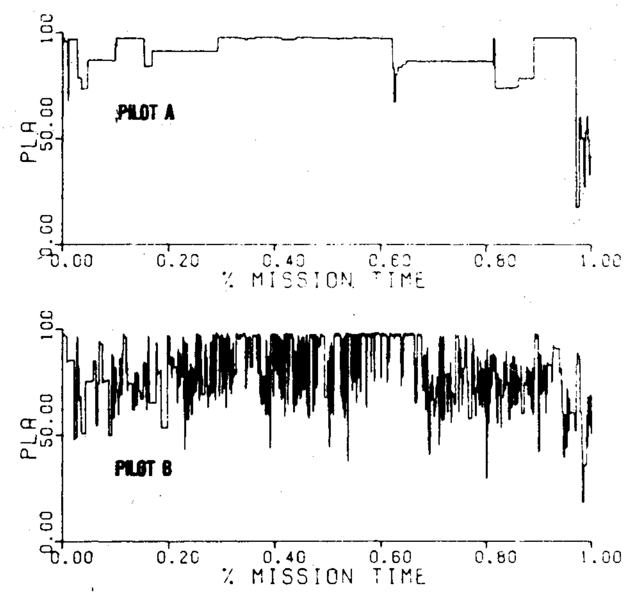

Fig. 10 A10 pilot-to-pilot variation—power lever angle.

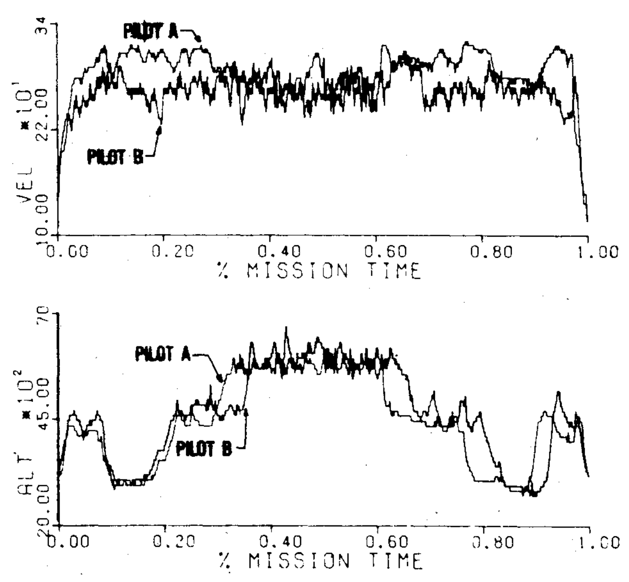

Fig. 9 A10 pilot-to-pilot variation—altitude and velocity.

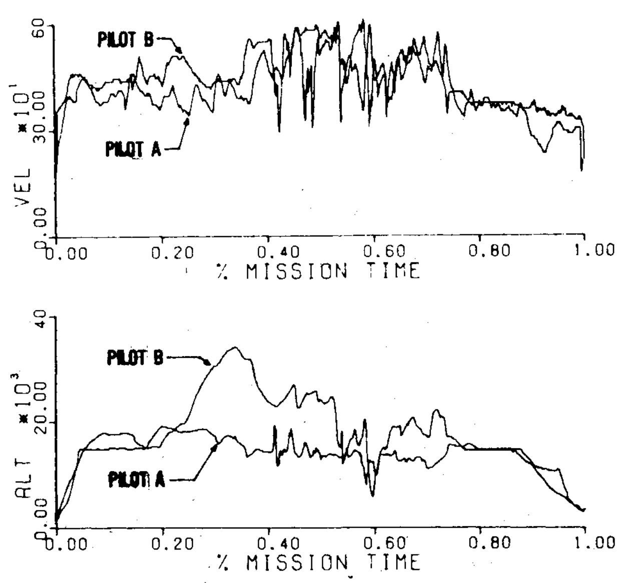

Fig. 11 F15 pilot-to-pilot variation—altitude and velocity.

	PILOT A	PILOT B
MAJOR CYCLES < 80% TO INT.	2	14
EHR CYCLES	3	15
TIME AT > 97% INT	12.1%	20%
A/B TIME	3.4%	5.4%

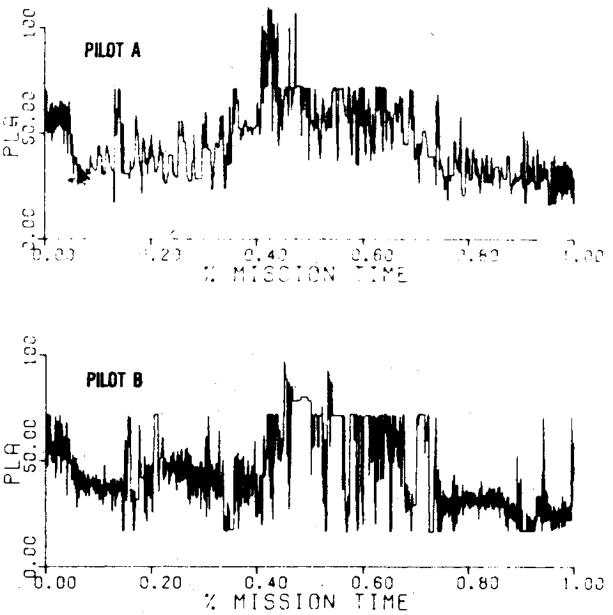

Fig. 12 F15 pilot-to-pilot variation—power lever angle.

AFB over roughly the same area of the Nellis Range, and atmospheric conditions were comparable. The combat portion of the missions were approximately the same duration. Pilot A's combat consisted of approximately five engagements, 2V2 with F5E's. Pilot B's combat was five engagements, 2V2 with F4J's.

The flight profiles for the two missions are compared in Fig. 11. The velocity traces (knots, calibrated air speed) are very similar. The altitude traces show some differences, with pilot B spending more of his flight at higher altitudes. The power lever angle traces that go along with these missions are presented in Fig. 12. (PLA of 100 is maximum afterburning, 73 is intermediate, and 16 is idle.) At first glance both pilots seem to make a very large number of throttle excursions. However, a close inspection reveals a definite difference in pilot technique. When pilot A retards the throttle from intermediate, he generally stops at a PLA about 40 rather than going all the way to idle as is the tendency with pilot B. The difference in damage to the engine due to this different technique is drastic, as is shown in the table comparison in Fig. 11. The engines from pilot B's flight accumulates 15 type III cycles from the EHR count or 14 cycles from less than 80% to intermediate using the rainflow analysis of the continuous high-pressure rotor speed trace. On the other hand, pilot A's flight is much less severe, accumulating only three type III's by EHR count and 2 cycles by rainflow count. In addition, pilot A spends only 12.1% at greater than 97% intermediate power while pilot B's flight contained 20% of the time at these damaging conditions. Both pilot A and pilot B had similar flying experience levels.

While these two examples may represent extremes, it does point out that there can be significant differences in damaging event accumulations for seemingly identical sorties. Whether it is truly caused by pilot technique or some other factor is immaterial. As a measure of the amount of dispersion in the data, the standard deviation was calculated for all the significant usage parameters from the Red Flag flights of all three systems. The results are presented in Table 1. The standard deviations are all quite large, indicating a significant dispersion about the mean.

It is reasonable to expect that over an extended period of time, each engine will see "average" usage. However, there are other important implications associated with the large variations in the usage data. As was previously mentioned, engine usage prediction models are being developed in industry. Some of these are empirical and directly use the limited amount of continuous data as a basis for the model. Other analytical models are using the continuous data to verify the models and make adjustments where necessary. The large standard deviation associated with the EUDA data indicates that great care should be exercised in using the data for modeling purposes and interpreting results.

In the recent past, attempts have been made to define the usage for current systems by instrumenting one aircraft, and having one pilot fly specified missions. Again the EUDA data indicate this could cause misleading results depending on how representative of average field usage the pilot and the specified missions were. The odds do not appear favorable. In addition, the impact of pilot technique dictates that usage data be recorded from aircraft with operational pilots and not flight-test pilots because flight-test-oriented handling techniques are different and may give erroneous results when extrapolating the damage content of a flight to the operational environment. One of the primary requirements of the EUDA program was to generate usage data for operational aircraft flying operational missions (not simulated) with operational pilots.

An interesting implication can be drawn from the widely varying engine damage content associated with nearly identical missions. Based on the F15 example in Fig. 12, the potential appears to exist to teach pilots some type of throttle management without sacrificing operational effectiveness. This could translate into significant reductions in engine operating and support cost.

Finally, the rather large standard deviations for the important usage parameters can have a significant impact on future engine designs. Normal design practice calls for structural design criteria which represent the average usage plus two standard deviations. It is important, therefore, to obtain a large enough sample size to verify (or reduce) the magnitude of the deviations.

Table 1 Mean and standard deviations for important usage parameters

	A10		F15		F5E	
	$\bar{x}$	$\bar{\sigma}$	$\bar{x}$	$\bar{\sigma}$	$\bar{x}$	$\bar{\sigma}$
Percentage of time at > 97% intermediate power	50.1	17.9	20.2	7.6	25.6	9.1
< 80% N2→100% cycles	0.64	0.95	6.5	4.0	6.4	4.7
A/B time	...	...	0.05	0.02	...	...
A/B transients	...	...	8.3	5.6	...	...
EOT/EFH	1.31	0.12	1.559	0.239	1.585	0.241
0-max-0 cycles	0.99	0.312	0.847	0.284	1.4	0.191

Summary/Conclusion/Recommendation

Increased attention toward developing weapon system designs which minimize life cycle cost requires that the environment in which the engine must operate be characterized accurately early in the design process. To provide a data base of engine usage data and to identify important drivers and assist in usage model development and verification, the Aero Propulsion Laboratory instrumented and recorded engine usage data from an A10, F5E, and F15. A total of nearly 240 h of edited data were recorded during Red Flag combat training and home base flying.

The results of the analysis of the data from the A10, F5E, and F15 are summarized below.

1) All three systems spend considerable amounts of engine run time in ground operations.

2) All three systems have usage which includes a large number of small amplitude throttle cycles.

3) F15 and F5E combat usage (Red Flag) is very similar for combat air patrol missions in terms of flight profile, number of major cycles, and time at maximum temperature conditions.

4) The low thrust-to-weight, air-to-ground system's (A10) combat (Red Flag) usage includes very few major throttle cycles (F1/EFH) but a large amount of time at maximum temperature conditions (50% EFH).

5) The high thrust-to-weight, air-to-air system's (F5E/F15) combat (Red Flag) usage includes many major throttle cycles (6-7/EFH) but reached time at maximum temperature conditions (20-25%).

6) Combat flying can be more damaging to the engine than normal peacetime training.

7) Mission variations can have a significant impact on damage content.

8) Pilot-to-pilot variation has a dramatic impact on the damage content of a mission on a given system.

The results of the analysis of the rather limited data base presented in this paper show that engine usage is a complex phenomena which is affected by a large number of factors. The complexity of the problem demands a much larger data base to include other systems and cover the entire operational environment. Not every engine in the fleet needs a sophisticated recording system. However, a certain amount of continuously recorded data would be very useful for monitoring usage trends in current systems as well as providing the basis for usage prediction for future systems. The ASIP recorder is already in place on a large number of systems, will be included in future systems, and can be easily adapted to record engine data. The data processing procedures are also well established. The British currently have such a continuously recorded engine usage monitoring system.[8] The American engine community should follow the example of their airframe counterparts and the British engine community to provide the necessary data base to avoid serious use related structural deficiencies in future systems and the resulting high operating and support costs.

References

[1] May, R.J. Jr. et al., "Analysis of Engine Usage Data for Tactical Systems," AIAA Paper 81-1370, July 1981.

[2] Blevins, G., Osmen, J.D., and Novotng, R., "Engine Life Methodologies for Conceptual Design," AIAA/SAE/ASME 17th Joint Propulsion Conference, Colorado Springs, Colo., July 1981.

[3] Holmes, J.E. and Reitz, M.D., "Methodology for Engine/Aircraft Selection with Life and Utilization Consideration," AIAA/SAE/ASME 17th Joint Propulsion Conference, Colorado Springs, Colo., July 1981.

[4] Dietrick, C.C. and Schuppan, K.L., "Engine Usage Prediction for Advanced Fighter Aircraft," AIAA Paper 81-1367, July 1981.

[5] Kyle, S.G., "Preliminary Design Method for Prediction of Engine Utilization for Tactical Aircraft," AIAA Paper 81-1369, July 1981.

[6] Dowling, N.E., "Fatigue Failure Predictions for Complicated Stress-Strain Histories," *Journal of Materials*, Vol. 7, No. 1, March 1972.

[7] Richards, F.D., LaPointe, N.R., and Wetzel, R.M., "A Cycle Counting Algorithm for Fatigue Damage Analysis," SAE Automotive Engineering Congress, Feb. 1974.

[8] Hurry, M.F. and Hedgecock, R.B.G., "Engine in Flight Data Collection and Analysis in United Kingdom Aircraft," U.K. Ministry of Defence.