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T700 Turboshaft Engine Operating Cost Computer Modeling

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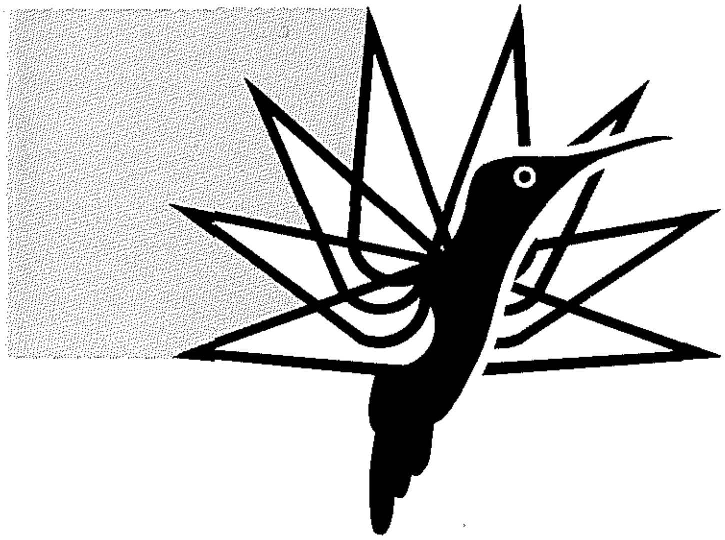


Abstract

General Electric has developed a T700 Turboshaft Engine Reliability and Maintainability computer model used for sophisticated predictions of engine operating cost in various helicopter systems and with a variety of user support concepts. Description of the considerations and the results of this reliability and maintainability model are described in this publication.

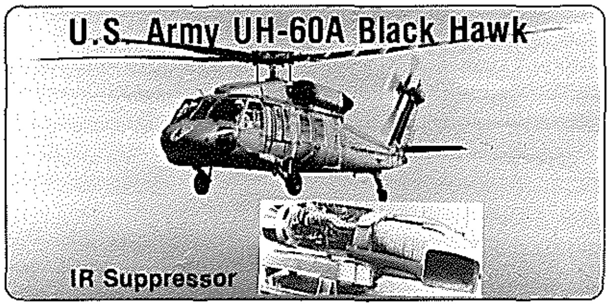
For the purposes of this study, the engine is broken down into 78 major sub-assemblies. Interrelationships of sub-assembly failures (primary and secondary) are defined by Failure Modes, Effects and Criticality Analyses (FMECA), originally developed for the U.S. Army. Failure rates are also divided into Quality, Durability, Environment and Human Error categories.

Sub-assembly model input also includes individual parts cost and the maintenance man-hours necessary to troubleshoot, remove, replace and verify each malfunctioning item.

A typical T700 operating cost analysis has been included to illustrate the relationship of various cost elements with total operating and support costs.

T700 Applications on Contract

T700-GE-700 turboshaft engines and infrared suppressors are currently in production for the U.S. Army Black Hawk program and the identical engine model is undergoing maturity flight testing for the Advanced Attack Helicopter. GE anticipates producing several thousand engines for these U.S. Army programs. GE is also developing the T700-GE-401 Navalized derivative for the U.S. Navy LAMPS program and will eventually build several hundred engines for this program.


U.S. Army UH-60A Black Hawk

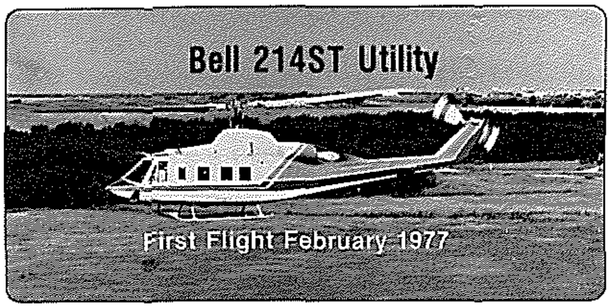

U.S. Army AH-64 Advanced Attack


U.S. Navy LAMPS
Mark III Multi-Purpose

Demonstrator Programs Underway

The Bell 214ST utility helicopter has been conducting demonstration flights since early 1977 and has recently initiated formal FAA certification testing. GE and Bell are jointly investing funds to demonstrate an improved altitude hot day version of the AH-1T Cobra gunship. First flight is scheduled for early 1980 and a follow-on flight test program will help the U.S. Marine Corps evaluate the mid-1980's production potential for this AH-1T "plus" helicopter.

The British Ministry of Defence has recently awarded GE a contract for nine T700 engines and associated installation support for the WG. 34A concept demonstrator program. This three-engined Dynamic Test Vehicle will fly by April 1981, paving the way for operational ASW aircraft by the late 1980's.


Bell 214ST Utility

First Flight February 1977


Bell AH-1T "Plus" Gunship

First Flight February 1980


Westland WG. 34 ASW

Tri-Engine T700 — First Flight April 1981

T700 Program Status

Developing advanced technology engines that meet today's requirements for durable, low-cost operation requires many years of development and maturity testing, as well as associated financial support several times greater than the classic development programs, which culminate in a 150-hour Model Qualification Test.

From the very beginning, the T700 has been designed for complete, on-condition maintenance. In order to achieve this ambitious goal, the engine must combine improved reliability and durability designs with at least 5,000 hours' aircraft mission life. In addition, the engine must concurrently withstand the thousands of thermal fatigue cycles which are encountered during helicopter operation. Already the T700's combination of basic design capability, rapid maturity and "remaining life" monitoring via an integral history recorder has allowed it to avoid scheduled maintenance.

- **14 Years, $260 Million Investment**
- **In Production For Black Hawk**
  - 100+ Engines Delivered
  - 20 Engines/Month Rate
- **5,000-Hour Mission Life**
- **15,000 Low Cycle Thermal Fatigue Life**
- **Full "On-Condition" Maintenance**

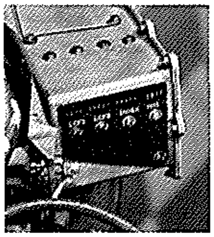
T700 History Recorder

The integral engine history recorder is a feature which allows long-term engine on-condition maintenance. Actual helicopter flight usage is converted into three key parameters used for computing remaining engine life. These measurements are displayed on the face of the recorder unit and include the following:

- The time-temperature index, which exponentially increases counts per minute with increasing turbine temperature, is based on the stress rupture life characteristics of gas generator turbine blades.
- LCF #1 moniters the thermal fatigue effects of startup/high power-shutdown cycles encountered during engine operation.
- LCF #2 is a partial thermal fatigue cycle which can be an important factor in nap-of-the-earth operation or in long ASW missions requiring multiple dipping sonar passes.

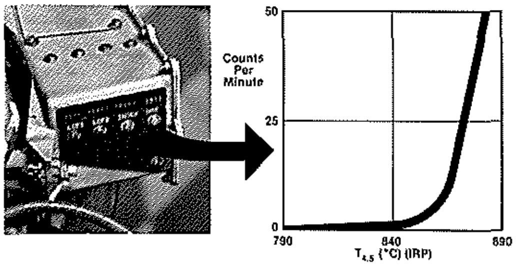
The unique aspects of T700 design and the elimination of time-based maintenance are significant factors in minimizing life cycle cost.

T700 History Recorder

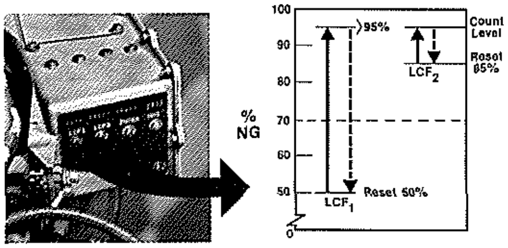


- **Integral With Engine**
- **Numerical Count Record**
  - Total Run Time
  - Engine Life Consumed

Time-Temperature Index



Low Cycle Thermal Fatigue Counters



Engine Life Cycle Costs

Estimation of life cycle costs can include a wide span of associated costs, both direct and indirect. However, the principal direct costs fall in three general areas: Development, Acquisition, and Operating and Support Costs.

Development costs include those necessary for design evolution, investigative testing and corrective improvements necessary to mature the engine for production and to bring it to complete operational readiness. Component Improvement (CIP) is also included for further maturity during the first years of field deployment.

Acquisition covers the costs necessary to procure installed engines, fill the spare engines and modules "pipeline" and set up support facilities at all maintenance levels.

Operation and Support cost includes maintenance and repair labor at all levels, replacement components, consumables, fuel and various indirect support elements such as maintenance training.

This computer model is used primarily to evaluate and analyze operating and support costs. Not only does this category often involve the largest cost item of the three areas (in some cases 50% or more of the total), but it is also the area where changes and improvements can have the largest impact.

Engine Life Cycle Costs

- **Development**
  - Maturity
  - Component Improvement Program (CIP)
- **Acquisition**
  - Engines
  - Spares
  - Tooling
- **Operating and Support**
  - Fuel
  - Spares Inventory
  - Spares Consumption
  - Maintenance Labor

Computer Modeling

Operating Cost Computer Model

This model is based upon a U.S. Air Force logistics support model, originally developed as a generalized aircraft system logistics support cost tool. GE has developed a model derivative specifically suited to engine studies: based on deterministic software, it provides rapid, inexpensive analytical assistance. The T700 model accepts and uses 160 general support system parameters which have impact on logistics costs, e.g., the number of major repair facilities, which in turn impacts tooling and transportation costs.

It also incorporates a detailed T700 representation using 1900 different inputs, each derived through a methodical analysis of individual engine components. By varying these inputs it is possible to study the effects of design changes and both positive and negative variations in engine component reliability, as well as to evaluate the results of various operational support systems. The model is used in various trade-off studies which are done in the early stages of possible design change investigation. As the design evolves, the model also provides a means of evaluating the final benefits that are an integral part of Engineering Change Proposals. This gives quantitative justification and verification of the need for the change.

Operating Cost Computer Model

- **Based On U.S. Air Force Logistics Support Cost Model**
- **Modified By GE For Aircraft Engine Studies**
- **Model Uses Detailed Component Build-up**
  - T700 Engine: 1,900 Inputs
  - Total Life Cycle Cost: 160 Support System Parameters
- **Model Evaluates Logistics Impact**
  - Engine Design Changes
  - Component Reliability
  - Operational Philosophy

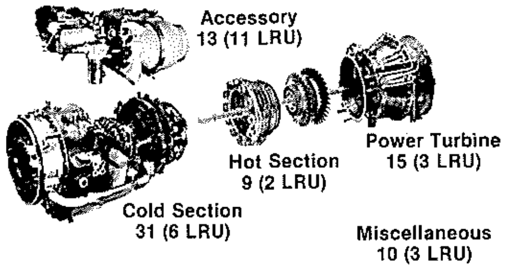
78 Sub-Assemblies Defined

The T700 has been divided into 78 components/sub-assemblies. Detailed quantitative inputs provided for each one are listed in Appendices A & B.

In addition to the primary failure rate (in which the component was the primary cause of the maintenance action), an estimate is also provided for maintenance action on the component which is incidental to other maintenance (secondary failure rate). Note that this includes additional items discovered during the course of investigating and/or repairing another failure.

The model also includes consideration for failures which are the result of the primary failure. For example, a combustor malfunction could cause downstream damage to the Gas Generator and Power Turbines. Another estimate provided by the model is access time for items which can be repaired while the engine is still installed in the aircraft. This is added to the remove and replace time, which is based on having clear, unobstructed access.

78 Sub-Assemblies Defined
Grouped By Modules



25 Elements Defined For Each Sub-Assembly

- Primary And Secondary Failure Rate
- Percent Failures Repairable
- Parts Cost
- Access Time
- Remove/Replace Time
- Repair Time
- Intermediate And Depot Turnaround Time

Three-Level Support System

The sample helicopter fleet analysis in this paper assumes a three-level support system. The model is readily adaptable to other maintenance support philosophies, as are the individual input items.

The T700's only scheduled maintenance is performed at the flight line level. A borescope inspection is required every 500 hours and primarily checks the engine's compressor, combustor and high pressure turbine. Pre- and post-flight servicing includes oil topping, history recorder log check and fuel and oil filter checks. Unscheduled flight line maintenance, when necessary, involves removing and/or replacing any of 25 engine components (with the engine still installed), or replacing the engine itself. For the purpose of this paper, extremely limited intermediate level capability has been assumed. Repair capability is limited to the ability to remove and/or replace individual modules and to perform a simple performance verification.

Flight Line

- **Borescope Inspection (2.7 Hours Every 500 Hours)**
- **Servicing (12 Minutes/10 Hours)**
- **Flight Line Replaceable Unit (25) Remove/Replace**
- **Engine Remove/Replace**

Intermediate Level

- **Module Remove/Replace**
- **Performance Verification**
- **No Repair Capability**

The depot level includes labor and parts cost associated with all 78 sub-assemblies. Depot maintenance can accomplish complete engine repair, including repair and calibration of modules, assemblies, components and individual parts. Depot overhead factors are also evaluated, including mechanic training (providing for personnel turnover) and periodic update of technical manuals.

Depot Level
(All 78 Sub-Assemblies)

- **Replacement Components (All Levels)**
- **Component Repair**
- **Engine Assembly**
- **Engine And Component Calibration**
- **Inventory Management**
- **Mechanic Training**
- **Technical Manuals**

Computer Model Reliability Methodology

Engine failures are broadly categorized into those directly controllable by the engine manufacturer and those over which General Electric exercises no control. Engine-caused inputs to the model include estimates for the frequency of manufacturing defects, for design problems (random with age) and for the failure/removal of components due to eventual wear out.

The model also considers the relative impact of the various non-engine caused failures. Although not within the control of the engine manufacturer, much can be done to minimize the impact of these factors and the model is a useful tool for evaluating various trade-offs when studying possible alternative actions.

An example of this use is the integral inlet particle separator. Although there are weight and performance penalties associated with this component, it provides a significant reduction in the costs resulting from adverse environmental factors such as foreign object damage and sand erosion.

Although at least in part a function of specific aircraft installation and operating environment, a representative value for non-engine caused events is approximately equal to that for the engine caused events quantity. This is an overall figure — individual components may vary considerably from this value. For example, because external accessories are easy to remove and replace, there is a strong tendency to practice "trial and error" troubleshooting. The result is a high percentage of unnecessary and erroneous maintenance.

Computer Model
Reliability Methodology

Engine Caused Failures	Non-Engine Caused Failures
• Quality	• Environment
• Random Faults	• Operational Factors
• Durability	• Human Error — Improper Maintenance — Pilot Error

Engine Caused/Non-Engine Caused = ≈ 1

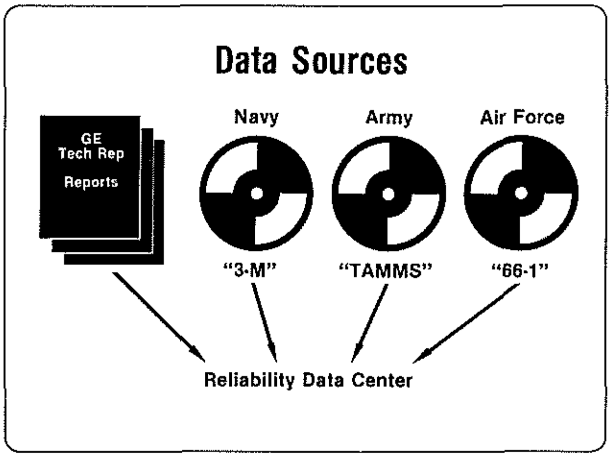
Data Sources/Processed Data

Two major sources provide the background reliability material which forms much of the standard against which the T700 has been evaluated: GE technical representative reports and U.S. military data systems.

GE's own technical representatives, on site at various test and operational bases, provide reports on events involving engines and engine components. These reports are extremely detailed and provide precise and comprehensive information on cause and effect of each problem reported.

The quantity of these reports is limited, however, and the information provided does not cover all activity at all locations. To supplement these reports, computer tapes with engine information are routinely provided by the U.S. Military and are translated into computer codes compatible with the General Electric data system. The information contained in the various military data systems is valuable in estimating total removals and other maintenance actions.

Once stored both the General Electric and military system data are available through a number of flexible selection criteria to form the background for various reliability analyses.



Failure Modes, Effects and Criticality Analysis (FMECA)

A fundamental part of GE's FMECA philosophy is to utilize the most qualified individuals available for the analysis of any given component. The reliability engineer provides background information from the data system and traces component effects through to the engine level, while the designer provides knowledge of the physical and functional design aspects of each component and related engine sub-systems.

The FMECA goes to the detailed individual piece part and considers each possible failure cause for each element, identifying possible failure modes and then carefully tracing each to assess its impact at each sub-system level.

In this process, the reliability and design engineers compare each component characteristic against the anticipated mission and environment, using existing computer-compiled experience as a standard.

For the entire T700 engine almost a thousand pages of FMECA's form the documented results of thousands of man-hours of detailed studies.

Failure Modes, Effects And Criticality Analysis (FMECA)

- Joint Effort — Design And Reliability Engineers
- Qualitative Analysis At Piece Part Level
  - Failure Causes
  - Failure Modes
  - Consequential Impact
    - Secondary Part Damage
    - Sub-System Operation
    - Engine Operation
- Quantitative Analysis: Assessment Versus Historical Data
  - Consider Mission And Environmental Effects

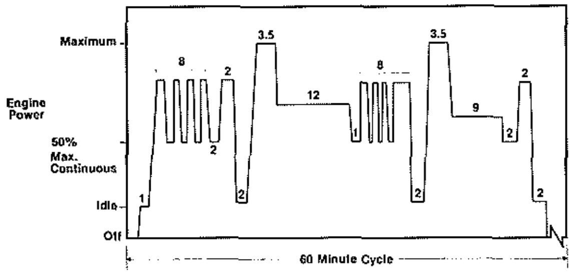
Mission Impact on Reliability Baseline

Different helicopter missions can affect the baseline FMECA reliability predictions, primarily in the engine's combustor and gas generator turbine.

The composite Black Hawk mission subjects the engine to 12 major power transients per hour and a large percentage of operating time at high power. Changes to the baseline power levels or transients will impact calculated component life expectancy for stress rupture (primarily Stage 1 turbine blades) and for low cycle thermal fatigue. The FMECA process assesses the impact of increased or decreased life on component reliability, and allows computer model inputs to be adjusted as required.

Mission Impact on Reliability Baseline

Composite Black Hawk Mission "Test Cycle"



FMECA Report: Lube and Scavenge Pump

A sample FMECA for the lube and scavenge pump is included in Appendix C. It is divided into two complimentary sections, Sheets A and B. Sheet A is intended for use by design engineers in primary design analysis. It reviews all individual piece parts of the design and ascertains the build-up of effects which those parts can have on the operation of "downstream" sub-assemblies and, eventually, on the entire engine. Sheet B, which is prepared by reliability engineers as a continuation of Sheet A, records an assessment of the part and component failure effects upon the complete engine as installed in an aircraft. Sheet B also contains the reliability classification and failure rate assessments.

The principal content of Sheet A is in the first six columns of the form. In the first column, the designer is required to identify the probable failure modes of each part; that is, if the part can be expected to bend, break, or jam, each of these possibilities must be analyzed separately. The "LOCATION" column is used to specify the exact location of the failure, such as "at the pivot pin," or "on the bearing surface." In the calculation of mechanical stress, for example, the location is selected in the area of worst loading or maximum unit stress.

The principal causes of each failure mode are listed in the next column, while the primary effects of each part's failure mode are listed in the fourth column. The latter are the immediate effects of failure and may or may not be discernible during operation. The secondary effects are those which occur as a result of the primary effects and may result from what happens to the engine as a whole, or to any subsystem in the engine.

Sheet A: Design Analysis

- **Probable Failure Modes: Causes And Subsequent Effects**
- **Operational Interrelationships Of All Parts**
- **Design Margins And Redundancies**

The sixth column, entitled "Design Approach/Criteria for Each Failure Cause," is a key element of the FMECA, in which the designer is expected to document what provisions have been made in the design to prevent or minimize the probability that the particular failure will occur. The designer states stress or performance margins; tells what levels of essential parameters he has incorporated; points out redundancies of parts; describes materials, hardnesses and finishes used; and summarizes past experience with similar designs. His objective is to completely tell how the failure causes have been prevented, or how the effects have been minimized.

Sheet B: Reliability Assessment

- **Classify Each Failure Effect**
  - Reliability: I = Catastrophe To V = Minor
  - Hazard: I = Minor To IV = Catastrophe
  - Kill: Immediate, 5 Minutes Or 30 Minutes
- **Assign Failure Rates For Each Mode**
  - Total Lube And Scavenge Pump: 76 Failures/10^6 Engine Hours (Engine Caused Only)
  - Primary Failures: 153/10^6 · All Causes
  - Secondary Failures: 187/10^6

The last three columns (Design Action, Special Tests, and Action Date), are used occasionally to highlight proposed design follow-up to be done, special tests which may be necessary for qualification or for acceptance of production parts, and the dates when these follow-up actions would be completed.

Sheet B is a tool for reliability assessment of the design and the derivation of its general qualitative and quantitative characteristics. The classification of each failure effect by its influence on aircraft and engine operation allows a standardized set of criteria for setting failure priorities. Such priorities may be applied to operating instructions, maintenance techniques, proposed design changes and any other field of inquiry which could affect reliability and safety. The reliability classification is concerned primarily with the degree of abnormality of the engine, while the hazard classification is concerned with serious damage to crewmen and to hardware. The kill classification is used to indicate a general level of performance available from the engine in the event of any specified failure mode.

Failure rate estimates are also presented for each piece part and its failure modes. The rates are based on a selection of experience data available from both factory testing and field operations on a variety of General Electric gas turbine engines. In every case the selection of a failure rate is heavily influenced by the quality of the data source, the quantity basis for the data, the similarity of the hardware and usage being analyzed to those of the data sources, and the test of overall reasonableness in relation to other engine lines. The resulting failure rates are segregated by part and by maintenance level (flight line, intermediate, or depot), so they may be used directly in the operating cost computer program as unscheduled maintenance frequencies.

For example, a summary of all twelve lube and scavenge pump failure modes predicts 76 failures per million engine hours for the primary engine-caused only rate. Non-engine caused failures increase the primary rate to 153 failures per million hours. Secondary failures (those caused by another component's primary failure or failures discovered while repairing other components) add another 187 events. Thus, the operating cost computer model uses a predicted 340 lube and scavenge pump failures per million engine operating hours.

T700 Reliability for Operating Cost Model

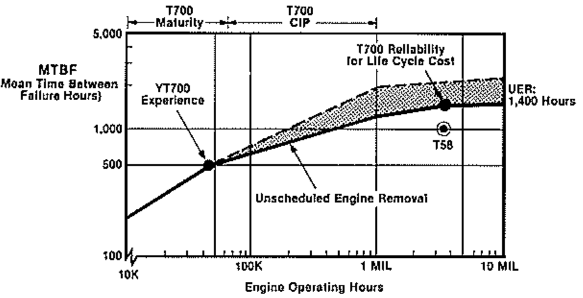
The integration of the 1,000 pages of individual part FMECA studies predicts that the mature T700 engine will have a Mean Time Between Unscheduled Engine Removal (there are *no* scheduled removals!) of at least 1,400 hours (engine-caused only).

GE's T58 and T64 experience shows that engine reliability will continue to grow at a moderate rate as a result of active Component Improvement Programs. Beyond one million engine hours (1985 for T700), CIP funding is greatly reduced and engine reliability growth slows down and eventually stops altogether. Reliability growth extrapolation from YT700 UTTAS/AAH experience predicts a "mature" T700 MTBUER range of 1,400 - 2,500 hours.

As a reference, the current U.S. Navy T58 MTBUER is 1,000 hours. It is interesting to note that this engine has scheduled hot section inspections every 1,000 hours and a complete overhaul at 2,400 hours.

The operating cost model has combined FMECA and reliability growth trend predictions and uses the bottom end of the MTBUER range to ensure a conservative orientation for T700 Cost Forecasts.

T700 Reliability for Operating Cost Model



T700 Reliability For Operating Cost Model

	Mean Time Between Failure
• Unscheduled Engine Removal Engine Caused Only	1400 Hours
• Unscheduled Engine Removal All Causes	670 Hours
• Failures Discovered At All Levels All Causes	90 Hours

Three-Level Task Times

Reliability characteristics have been projected from an existing data base following historical growth trends. On the other hand, maintainability data has already been repeatedly demonstrated by U.S. Army mechanics for all levels of maintenance. These results have been directly inputed into the operating cost computer model. Original design emphasis on ease of maintenance has resulted in dramatic remove/replace time improvements over the current U.S. Army T53 engine.

Three-Level Task Times

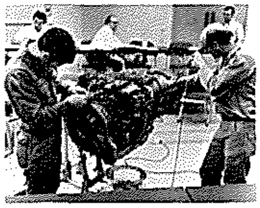
(Remove/Replace—Man-Minutes)

	U.S. Army T53	T700
• Flight Line		
— Fuel Control	115	8
— Fuel Manifold	157	14
• Intermediate Level		
— Power Turbine	144	64
— Combustor	310	96
• Depot Level		
— 1st Stage Turbine Wheel	360	72

Designed for Easy Maintenance

Ten simple tools (compared to more than 150 tools for the T53) are the only ones required for all flight line and intermediate level maintenance. These ten tools can be used to remove and replace all 25 engine flight line accessories in less than 2½ hours. The maximum time for any of the 25 accessories is 15 minutes and, in all cases, the engine is ready to fly — no ground run or adjustments are required. These same 10 tools are used at the intermediate level for module remove/replace: maximum time to remove and replace a cold section module is 79 minutes. Also, the T700 combustor can be removed and replaced in no more than 55 minutes.

Maintainability

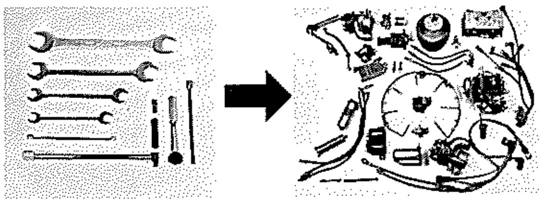


- Maintainability Characteristics Required By The Development Contract
- Demonstrated By U.S. Army Mechanics In 1976

Designed For Easy Flight Line Maintenance

Only 10 Simple Tools

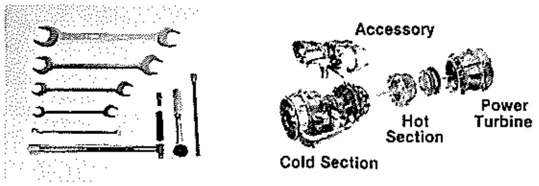
Flight Line Accessories



Designed For Easy Modular Maintenance

Ten Tools

Modules

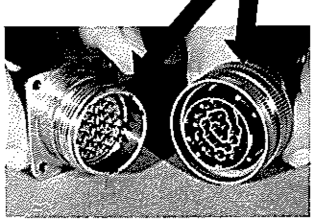


- Complete Module Interchangeability
- No Critical Dimension/Calibration Checks

Details Are Important

Army and GE experience shows that more than 60% of current engine maintenance is spent on external "accessory" engine items — lockwiring casing bolts, replacing oil lines and electrical harnesses, etc. Therefore, very careful attention was aimed at eliminating these troublesome and time-consuming maintenance activities. The T700 has *no lockwire* and requires no adjustment or ground running after components or modules have been replaced.

Details Are Important



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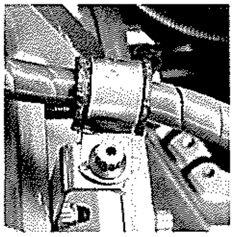
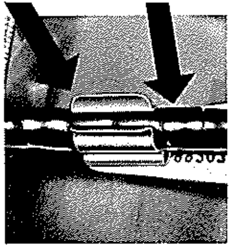




- No Lockwire
- No Field Adjustments

Model Maintainability Inputs

Although the Army mechanic demonstrations have been repeated a number of times with very consistent results, the T700 operating cost computer model uses a 400% margin over demonstrated times to account for the inefficiencies of flight line and intermediate maintenance. The mechanic must first acquire access to the engine by opening nacelle cowling and, in a few cases, by removing airframe-mounted components. He must also consult a technical manual for troubleshooting advice and general guidance and, finally, must pick up replacement parts from the spares storage room. All of these activities tremendously increase the maintenance times that can be demonstrated on a bare engine.

Although Sikorsky and Hughes have demonstrated very rapid engine replacement times (15 - 20 minutes), the T700 computer model assigns 6.8 man-hours per engine removal. This is to account for the 4:1 factor and assumes that spare engines have to be built up with the airframe Quick Change Assembly.

Model Maintainability Inputs

- Remove/Replace Time:
  Computer Model = 4 x T700 Demonstrated
  (Flight Line And Intermediate)
  - Installation Accessibility
  - Troubleshooting
  - Replacement Part Delivery

EXAMPLE:

Fuel Control
Demonstrated . . . 8 Man-Min.
LCC Model . . . . . 32 Man-Min.

- Engine Remove/Replace: 6.8 Man-Hours/Event
  (Flight Line)
- Fault And Performance Verification
  (Depot)
  - Post-Repair Engine Run
  - Components Bench Checked, Performance Calibration At Vendor

Another significant maintainability consideration is the fault and performance verification required at the depot level. This varies from checking component functions on a test bench to running a complete engine after it has been repaired and rebuilt. Detailed component performance calibration is assumed to be performed by outside vendors, so calibration costs are assigned to hardware repair costs, not depot level labor.

Typical Helicopter Fleet Analysis

A sample analysis has been included to illustrate the typical inputs and results obtained from the T700 operating cost computer model. Rapidly escalating fuel costs mean that today most military aircraft fly no more than 30 aircraft hours per month; thus in this example, 100 three-engined aircraft will accumulate slightly less than one million engine hours over 15 years. This example uses a fairly typical distribution of operating support sites and aircraft density (11 aircraft per site). The transportation times assumed are consistent with European rail or truck transportation and *include some allowance for ship transportation* to the depot.

Typical Helicopter Fleet Analysis

- **Fleet Definition**
  - 100 Aircraft At 9 Sites
  - 3 Engines Per Aircraft
  - 2.5 Engine Hours/Aircraft Hour (1 Shutdown During Cruise)
  - 30 Aircraft Hours/Month

15 Year Total = 975,000 Engine Hours

Support System

- **9 Flight Line Sites**
- **3 Intermediate Sites:**
  - 0.5 Month Turnaround
  - 0.5 Month Transportation
- **One Depot:**
  - 2 Month Turnaround
  - 1 Month Transportation

Operational Costs

The relationship between direct labor rates and indirect labor costs varies tremendously between military organizations. Thus, results of this study are presented in both man-hour/engine hour and dollar per hour format to assist comparison with non-U.S. Navy support systems.

A significant item sometimes overlooked by cost analyses is the miscellaneous "consumables" that can significantly add to labor overhead.

This study ensures that spare parts for all three maintenance levels are purchased in large quantities from an existing production line. Therefore, the additional overhead costs to procure a new spare part are limited to an average 22% more than the cost of the same part used in a complete engine.

All parts are initially processed through the Depot and the computer model assigns their costs to this level. Additional overhead costs for packaging and transportation to Intermediate or Flight line sites are not included.

Operational Costs

- **Labor Rates***

– Flight Line	$15.95/Man-Hour
– Intermediate	15.95/Man-Hour
– Depot	23.50/Man-Hour

*(Based On U.S. Navy LAMPS)

Operational Costs

- **Consumables**
  - Oil
  - "O" Rings
  - Cleaning Fluid, Etc.

Intermediate Level:	$2.30/Man-Hour
Depot Level:	$6.70/Man-Hour

Operational Costs

- **Replacement Parts: 122% Equivalent New Engine Part Cost**
  - All Parts Cost At Depot Level
  - Does Not Include Packing And Transportation For Intermediate Or Flight Line

15-Year T700 Cost Summary

Combining all of the previously discussed input and assumptions, the T700 Life Cycle Cost computer model has been run and the following items relating to operating cost have been individually highlighted.

Spares "Pipeline" — A combination of enhanced engine reliability and complete on-condition maintenance means that the T700 requires far fewer spare engines and modules than current engines. The sample analysis predicts a need for only 15% spare engines versus the typical 30 - 40% required for medium-sized European helicopter programs. The U.S. Army is currently buying approximately 20% spares for the Black Hawk Program, versus their normal practice of almost 50%. Spare parts are also minimized because of the high concentration of engines (33) at relatively few operating sites.

Spares "Pipeline"

- **Spare Engines/Modules . . . . 44 Equiv. Engines** (15% Of Installed)
- **Spare Components . . 3.3 Equiv. Engines**

Operating and Support Costs — In order to simplify output format, various categories of maintenance support have been combined into meaningful groups. For example, Intermediate level labor and consumed parts are almost negligible under the three-level maintenance system; therefore, these have been integrated into the Depot level. The computer model centralizes repair and replacement parts costs for all three levels at the Depot.

Operating and Support Costs

- **Flight Line Maintenance — Labor** **$1.3 Million ($1.35/Hour)**
- **Intermediate And Depot Maintenance**
  - **Labor . . . . $3.4 Million ($3.50/Hour)**
  - **Consumed/Repaired Parts . . . . . . 22 Equiv. Engines**

Indirect Support Costs — It is interesting to note that indirect support costs can become a very significant percentage of operating cost for a modern, on-condition engine. In this sample analysis, the indirect support cost of approximately $3/engine hour is about 25% of total engine operating cost.

Technical manual development cost has not been included because complete manual series have already been generated for the U.S. Military (manuals for a new engine can cost up to several million dollars).

Indirect Support Costs (Depot Level)

• **Consumables**	**$0.96 Million**
• ***Inventory Management***	**$0.95**
• **Mechanic Training**	**$0.30**
• **Tech Manual Updates**	**$0.63**
Total	**$2.84 Million** ($2.90/Hour)

High Value Consumed Parts — The computer software has been structured to rank the 78 sub-assemblies in order of total lifetime operating cost for any given helicopter fleet analysis. For this particular example, the Hydromechanical Fuel Control is the highest total cost sub-assembly. As expected, engine hot section components closely follow the control, but it is somewhat surprising to see that high frequency of replacement makes fuel and oil filters among the highest cost components on the entire engine.

High Value Consumed Components

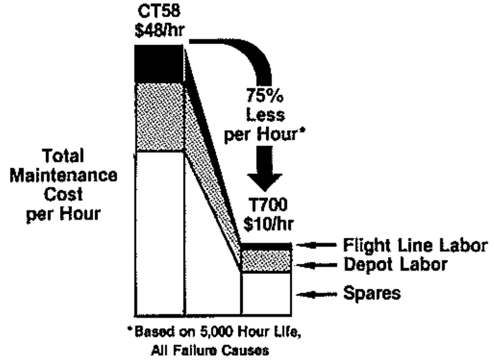
	(Ranked By Total Cost)
• Hydromechanical Fuel Control	68 Units (8% of Total O&S Cost)
• G.G. Turbine Stage 1 Nozzles	253 Sets
• G.G. Turbine Stage 1 Buckets	147 Sets
• Fuel Filter	1,960 Units
• Electronic Fuel Control	79 Units
• Oil Filter	5,050 Units

T700 Reduced Support Costs

Comparing the results of this operational cost study with the current 1979 commercial operating forecast for the CT58 engine, the T700 is predicted to be more than 75% cheaper than its GE predecessor: $5.40/engine hour for spare parts; .15 man-hours per engine hour for immediate and depot level labor; and .09 man-hours per engine hour for flight line labor.

Comparing the design and operational philosophy of the T700 versus CT58 quickly illuminates the credibility of such a significant cost differential. The T700 has no scheduled periodic or overhaul inspection intervals. It has a much more rugged and damage-tolerant design (Integral Inlet Particle Separator, rugged compressor blades, etc.) and its extensive development and maturity programs give it enhanced reliability compared to its earlier generation predecessor.

T700 . . . Reduced Support Costs



*Based on 5,000 Hour Life, All Failure Causes

T700 Computer Modeling Summary

The sample analysis showed that the very detailed reliability and maintainability sub-assembly build-up in the T700 computer model will produce a realistic and useful prediction of the entire logistics support system required for a potential T700 fleet operator. However, this model can also be used to identify critical parameters of the logistics support system by varying particular inputs through multiple computer runs. It can also identify marginal areas where additional "beefing up" should be considered.

Overall, realistic operating cost projections are only possible by building a detailed engine model from the ground up. The combination of exhaustive FMECA studies and vast historical data from GE's computerized data file has made possible the creation of valid T700 operating cost forecasts.

T700 Computer Model Summary

- **Evaluates Logistics Support System**
- **Defines Spare Parts "Pipeline"**
- **Determines Total Manpower Loading**
- **Provides Parametric Analysis Of Critical Engine Sub-Assemblies**

Realistic Definition Of Total T700 Operating Cost!

APPENDIX

A. 78 Engine Sub-Assemblies

B. Inputs for Each Sub-Assembly

C. Lube and Scavenge Pump FMECA

APPENDIX A

78 Engine Sub-Assemblies

Swirl-Vane Frame	CS1
Front Frame	CS2
Inlet Guide Vanes	CS3
Main Frame	CS4
Compressor Case	CS5
Diffuser	CS6
Midframe	CS7
Output Shaft	CS8
PTO Drive	CS9
VG Vane Linkage	CS10
Stage 1 Vanes	CS11
Stage 2 Vanes	CS12
Stage 3/4/5 Vanes	CS13
Compr. Rotor Assy.	CS14
Stage 1 Blisk	CS15
Stage 2 Blisk	CS16
Stage 3/4 Blisk	CS17
Stage 5 Blisk	CS18
Impeller	CS19
No. 1 Bearing	CS20
No. 1 Bearing Seal	CS21
No. 2 Bearing	CS22
No. 3 Bearing	CS23
No. 4 Bearing	CS24
Fuel Injectors	CS25
Anti-Ice/Bleed Valve	CS26
ECU	CS27
Harnesses-(6)	CS28
Exciter	CS29
Ignition Leads	CS30
History Recorder	CS31
Combustion Liner	HS1
Primer Nozzles	HS2
Igniter Plugs	HS3
Stage 1 Nozzles	HS4
Stage 1 Blades	HS5
Stage 1 Disk	HS6
Stage 2 Nozzles	HS7
Stage 2 Blades	HS8
Stage 2 Disk	HS9
Turbine Casing	PT1
Exhaust Frame	PT2
PT Shaft	PT3
Stage 3 Nozzle	PT4
Stage 3 Blades	PT5
Stage 3 Disk	PT6
Stage 4 Nozzle	PT7
Stage 4 Blades	PT8
Stage 4 Disk	PT9
No. 5 Bearing	PT10
No. 5 Bearing Seal	PT11
No. 6 Bearing	PT12
Thermocouple Harness	PT13
Torque-Sensor	PT14
Speed Sensor	PT15
Radial Drive Shaft	A1
AGB	A2
Separator Blower	A3
HMU	A4
Alternator Stator	A5
Lube/Scavenge Pump	A6
Oil Filter Assy.	A7
Oil Cooler	A8
Oil Filter Bypass SE	A9
Chip Detector	A10
Fuel Boost Pump	A11
Fuel Filter Assy.	A12
Sequence Valve	A13
Air Line	EA1
Fuel Lines	EA2
Oil Lines	EA3
EMI Filter Box	EA4
Fuel Pressure Transmitter	EA5
Oil Pressure Transmitter	EA6
Oil Temperature Transmitter	EA7
Fuel Filter Element	EA8
Oil Filter Element	EA9
Igniter (Wearout)	EA10

APPENDIX B

Inputs for Each Sub-Assembly

AMH_i	Maintenance man-hours to access component "i" at the Flight Line
CMPSIN_i	Component Significant Item Number (S.I.N.) component "i"
COMPC_i	Component Cost ($)
DRTAT_i	Average elapsed time required for repair of a component at depot (months)
ESN_i	Number of previously existing National Stock Number parts in component "i"
FLRMH_i	Maintenance man-hours for Flight Line repair action on component "i"
FSN_i	Number of new National Stock Number parts in component "i"
FVMH_i	Man-hours for fault verification in component "i"
IRTAT_i	Average elapsed time required for repair of a component at Intermediate (months)
K_i	Number of pieces of Ground Support equipment required for component "i"
LRUV_i	Line replaceable unit - 1 replaceable, 0 not replaceable
PCOND_i	Proportion of unscheduled maintenance actions, component "i" where component is condemned and scrapped.
PRD_i	Proportion of component "i" repairs performed at Depot
PRI_i	Proportion of component "i" repairs performed at Intermediate
PRRMH_i	Primary Man-minutes to remove and replace component "i"
PUMARI_i	Primary Unscheduled Maintenance Action Rate for component "i" (events per 10^6 hours)
PWO_i	Proportion of engine operating time when component "i" is operational
QCMP_i	Quantity of component type "i" in each engine
RCD_i	Repair cost at Depot of component "i", as a fraction of component cost
RCI_i	Repair cost at Intermediate of component "i", as a fraction of component cost
RDMH_i	Manhours to repair component "i" at Depot
RFL_i	Proportion of unscheduled maintenance actions on component "i"
RIMH_i	Man hours to repair component "i" at Intermediate
SRRMH_i	Secondary Man-Minutes to remove and replace component "i"
SUMAR_i	Secondary Unscheduled Maintenance Action rate for component "i" (Events per 10^6 hours)
W_i	Unpackaged weight of component "i" (lbs)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS — SHEET "A"

Page 1 of 1

NOMENCLATURE: Lube & Scavenge Pump/(Lube System)
(PART/SUBSYSTEM)
PREPARED BY: O.D. Taylor DATE: 3/6/78

DWG. NO.: 5043T73P02
REVISION NO.:

FUNCTION: Pumps oil from tank to sumps and return

Failure Mode	Location	Possible Failure Cause(s)	Primary Effect	Secondary Effect	Design Approach/Criteria For Each Failure Cause	Design Action or Trade-Off	Special Tests	Action Date
1 Worn supply pump	Gerotor pumping surfaces & port plates	a) Contaminated oil b) Inadequate clearances or misalignment c) Inadequate material hardness	Low oil supply	Bearing or gear damage	a) 3 Micron Filtration System. Tank pickup above bottom. Pumps sized with flow margin to tolerate some deterioration. b) Tolerancing and quality control to be maximized within limits of producibility c) Material choice and heat treatment specifications as proven on successful pumps			
2. Worn B-sump Scav. Pump	Same	Same	Sump Flooding	High oil Consumption	Scavenge inlet screens filter contaminants.			
3. Worn AGB-Sump Scav Pump	Same	Same	Same	None	Gravity drainage to tank prevents extreme flooding.			
4. Worn A-Sump/ C-Sump Scav. Pump	Same	Same	Same	Sump Flooding	Dual pumps in A & C sumps prevent extreme flooding.			
5. Sheared Shaft	Shear-area	a) Contaminants in pumping elements from tank or sumps b) Seized pump bearing	No oil supply	Limited engine life on emergency oil system	5a & b) Coarse screens on all pump inlets. Cockpit chip indicator. Emergency air/oil mist oil system is provided to give a minimum of one minute operation after lube pump shaft is sheared.			
6. Worn Spline (Excessive)	Pump drive spline	a) Lack of lubrication b) Misalignment c) Overloaded	No oil supply	Same as 5	6a) Oil supply to spline is bled through hollow pump shaft from supply pump discharge 6b) Tight dimensional control between pump socket & drive gear Spline L/D approximately 1:1 6c) Spline sized per proven design practices			
7. Seized pump bearing	3 pump journal bearings	a) Lack of lubrication b) Contamination	No oil supply or scavenge	Same as 5	7a) Positive oil supply to each bearing from relatively clean bleed point 7b) 3 Micron system filtration			
8. Unseated snap ring (primary)	Aft end of cartridge (Clamps portplates)	a) Extreme vibration b) Excess load	None	None	a) Retained by secondary retaining ring which is unloaded b) Same			
9. Interelement Leakage	• Supply to Scav. • Scav. to Scav.	a) Excessive clearances b) Porosity in partplates c) Unclamped partplates	• Poor oil supply performance • Sump Flooding	• None • High oil Consumption	a) Proven tolerancing and use of wear materials. b) Quality inspection and pump acceptance testing. c) Belleville spring assures clamping			
10. Broken	Belleville spring	a) Nicked or notched b) Brittle (heat treat)	Sames as 1	None	a & b) Pump cover limits degree of unclamping to a few mil inches. Pumping element is pressure loaded without spring. Spring is also trapped in place.			
11. Unseated retaining ring (secondary)	Aft end of cartridge (clamps, snap ring)	a) Not fully engaged at assembly b) Extreme vibration	Wear particles generated	Lube sys debris	a) Retaining ring installed by pump vendor, easily installed. Dimensional check for clamped height. b) Double wrap (spriralox) snap ring resists vibration disengagement.			
12. Stripped	Jacking screw threads	Overtorque	Unable to disassemble	Incomplete overhaul	Use of self-locking steel threaded inserts and steel screws in cooler will minimize chance of stripping. Inserts are also replaceable if necessary.			

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS — SHEET "B"

Sheet "B"
Page 1 of 2

NOMENCLATURE: LUBE & SCAV. PUMP PREPARED BY: J.L. Leblanc / L.A. Schafer DATE: 10/5/72 REVISED (DATE) 3/9/78	DWG. NO.: 5043T73P02 REVISION NO.:	FUNCTION: Pumps oil from tank to sumps

		Failure Effect			Classification						Oper. Experience		
	Failure Mode	Component	Engine	Secondary	Reli-ability	Hazard	Kill	Unsched. Maint. Type	Failure Rate per 10^6 EFH	Possible Adverse Environment/FMECA Cross-References	No. of Test Failures	No. of Test Hours	Comments
1	worn supply pump	low oil supply flow	low oil pressure	See Sheet A	V	I	NK	Comp R/R	15.				
2.	worn B-sump scav. pump	low B-sump scav. flow	leakage into drain - low oil level	"	V	"	"	"	15.				
3.	worn AGB sump scav. pump	low AGB scav. flow	high sump scav. temp. - partially flooded sump	"	V	"	"	"	10.				
4.a)	worn A-sump scav. pump	low A-sump scav flow	exhaust smoke - low oil level - oil leakage out tail pipe	"	"	"	"	"	10.				
4.b)	worn C-sump scav. pump	low C-sump scav. flow	exhaust smoke - low oil level - oil leakage out tail pipe	"	"	"	"	"	10				
5	sheared shaft	pumping stops	no oil pressure manual shutdown	"	II	II	B kill	Engine R/R	Neg				
6	spline wear	"	no oil pressure engine shutdown	"	II	II	B kill	"	Neg				
7	seized pump bearing	pumping stops - pump shaft shears	"	"	II	II	B kill	"	Neg				
8	unseated snap ring (primary)	none	none	"	V	I	NK	Comp R/R	5.				
9.	interelement leakage • supply to scav. • scav. to scav.	low flow	• low oil pressure • sump flooding	"	V	I	"	"	3.				

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS — SHEET "B"

Sheet "B"
Page 2 of 2

NOMENCLATURE: LUBE & SCAV. PUMP
PREPARED BY: J.L. Leblanc / L.A. Schafer
DATE: 10/5/72 REVISED (DATE) 3/9/78

DWG. NO.: 5043T73P02
REVISION NO.:

FUNCTION: Pumps oil from tank to sumps

		Failure Effect			Classification						Oper. Experience		
	Failure Mode	Component	Engine	Secondary	Reliability	Hazard	Kill	Unsched. Maint. Type	Failure Rate per 10^6 EFH	Possible Adverse Environment/FMECA Cross-References	No. of Test Failures	No. of Test Hours	Comments
10.	broken - belleville spring	slight low flow	none	See Sheet A	V	I	NK	Comp R/R	3				
11.	unseated retaining ring (secondary)	wear particles generated	lube system contamination	"	V	I	NK	"	5				
12.	stripped - jacking screw threads -	disassembly problem	none	"	"	"	"	"	·				
									$\sum = 76$				