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service news

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A Service Publication of Lockheed Aeronautical Systems Company

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Cover: A new C-130H recently delivered to the 914th Airlift Group of the New York Air Force Reserve overflies the spectacular cataract of Niagara Falls.

Back Panel: Celebrating 40 years in continuous production, the world's most versatile airlifter looks forward to a high-tech future as the C-l 30J takes shape.

Cover and photographs on pages 3, 16, 18. and 19 by John Rossino.

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Focal Point

Ben Methvin

Forty to the Future!

There has never been a program like that of the Hercules. Forty years of continuous production is unprecedented. The wonderful Gooney Bird was in production for less than 11 years-although 10,629 C-47/DC-3s were constructed. The C-133 was in production 9 years (50 were built), the Belfast 4 years (IO), the C-160 Transall 13 years (213), and the Antonov 12 for 16 years **(145.0).**

There are good reasons for the success of the Hercules. Foremost, it is a sound design which has been continuously improved. It fits a broad operational spectrum. Like the basic design of the pickup truck, the Hercules fits a world need for just this size air vehicle. It carries varied loads just the right distance and puts them in just the right places. It is a safe machine with no bad habits. Aircrews around the world test these capabilities daily, and it consistently brings them home safe and sound.

The closed loop of continuous improvement and resulting longevity of production seem to imply that the Hercules program will continue to flourish for a long time. Each succeeding model was changed. The "A" (231 built) was a "hot-rod" with its short takeoff and quick response, the "B" (230) had longer range, and the "E" (488) had both payload and range increases. The "H" (950+) took the experience of the preceding models and was given more power and many structural and maintenance improvements. Range and payload had been found to be near optimum and were not significantly changed.

Changes in a successful product are not made lightly. The C-13OJ. now entering production, was recently referred to as "the son of Hercules" by one prestigious English magazine. The "J" takes the best from all four ancestors, plus those state-of-the-art improvements which make it significantly more cost-effective in doing what it does best.

Would-be competitors have designs to replace the Hercules. It's been tried before. The planned FLA will carry "more and bigger," as will the Antonov 77T. But "more and bigger" is not consistent with the niche presently filled by the Hercules. Furthermore, neither will be able to achieve the price-to-value ratio of the Hercules.

I have been associated with the Hercules since the first flight of the prototype, and take great pride in working with the people who build it, support it, fly it, maintain it, and utilize its capabilities. I no longer even try to predict how long this marvelous airplane will be in production, but I do know that only a Hercules can replace a Hercules.

Sincerely,
Ben Methvin

Ben Methvin'
Regional Director
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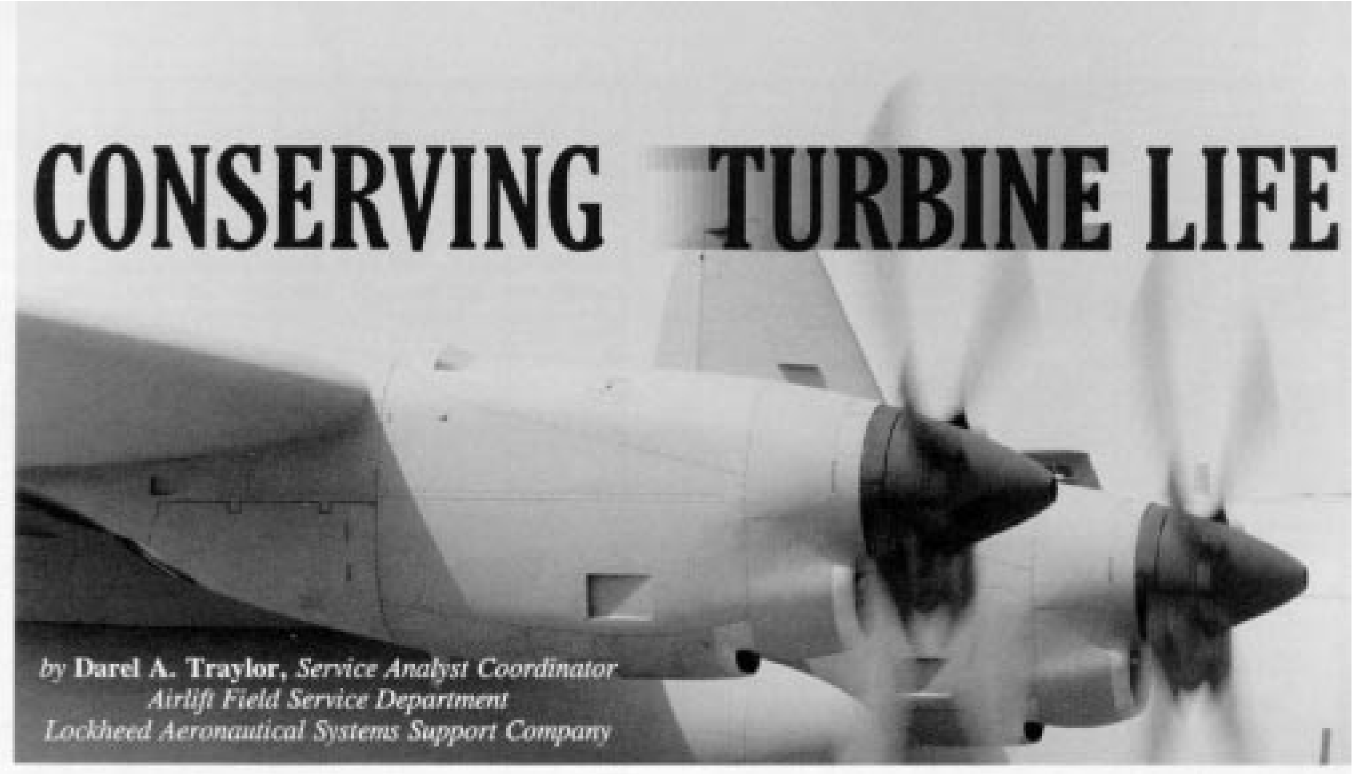

CONSERVING TURBINE LIFE

by **Darel A. Traylor**, *Service Analyst Coordinator*
Airlift Field Service Department
Lockheed Aeronautical Systems Support Company

The single most important cause of degraded performance and premature failure in gas turbine engines is exposure to excessive heat. It makes little difference from the standpoint of the effect on the engine what the cause of the overtemperature condition might be. What is important is only the degree of the overheating and how long it continues. Each and every exposure to excessive operating temperatures takes its toll on engine life, decreasing operational efficiency and increasing maintenance costs.

The important role that is played by the practices of individual Hercules aircraft operators and their maintenance organizations in determining engine service life is not always fully appreciated. The fuel system of the Allison 501/T56 engine that powers the Hercules aircraft is provided with effective, automatic controls that keep engine temperatures within safe limits over a wide variety of operating conditions.

As good as this system is, however, it was not designed to work alone. It cannot take the place of careful and conscientious management of the overall operational environment. This is something only the human side of the equation can provide.

Life Cycle Factors

The normal maximum time between overhauls for a particular model of the Allison 50l/T56 engine is established on the basis of engineering considerations, user experience, and a careful evaluation of any safety factors involved. Within that time period, however, an engine's individual maintenance requirements are largely determined by the effect of the operating environment upon major engine components.

For example, in areas subject to blowing sand or heavy burdens of dust in the atmosphere, the compressor section may be seriously eroded long before other parts of the engine require attention. More typically, the repair intervals will be determined by the condition of the turbine, combustion liners, and inlet guide vanes of the "hot" section.

The turbine section components are made of metal alloys designed to be as durable as possible in a high-temperature operating environment. The service life is nevertheless rather dramatically affected by the temperatures to which they are subjected. Metals do not "forget" incidents of exposure to overtemperature conditions. Repeated exposure to high temperatures will eventually result in changes in their physical characteristics that can lead to material failure. Let us look at some of the effects of high-temperature engine operation on turbine vanes and blades in more detail.

Sulfidation

Turbine blades and vanes are subject to gradual deterioration as engine operating hours accumulate. The process is commonly referred to as sulfidation. Turbine sulfidation is caused by the accelerated oxidation of metals in the presence of sulfur ions, in particular sulfides and sulfates. The oxidized metal goes out the tailpipe, leaving eroded blade and vane surfaces behind.

To help prevent such damage to the metal surfaces and extend the service life of the turbine section components most often affected by sulfidation, diffused coatings of aluminum or aluminum and chromium (often referred to as Alpak and AEP, respectively) are applied to new turbine blade and vane surfaces.

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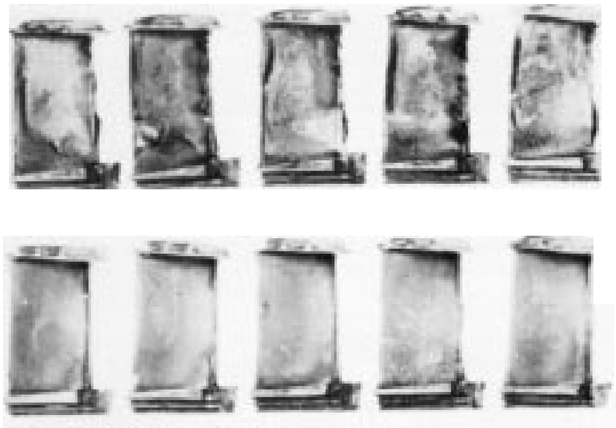

First stage turbine blades after a service test.
Top row: uncoated alloy.
Bottom row: the same alloy protected with Alpak.

These coatings are effective while in place, but they are eventually eroded away by the hot gases and abrasive particles passing through the turbine section. This means that sooner or later the base metal of turbine components will become exposed to the damaging effects of sulfur ions.

Controlling Sulfidation

The sulfur ions responsible for sulfidation come from a variety of sources and are not entirely avoidable. They may come from the sulfates in sea water, sulfur in jet fuel, the sodium sulfate in aircraft cleaning solutions, hydrogen sulfide and sulfur dioxide in the air, or sulfur-bearing particulates injected into the atmosphere by industrial processes.

While sulfidation is by far the most common and most pervasive of the destructive processes affecting turbine components, it is also in some ways the most controllable. The key to reducing the damaging effects of sulfidation lies in understanding the factors involved in the process. The rate at which sulfidation occurs in the engines is dependent on three factors:

- Hours of operation.
- Concentration of sulfur ions.
- Temperature of the metal components.

There are limits to what can be done about some of these influences. It is obviously impractical to reduce aircraft operating hours just to avoid the sulfidation problem. It is also impossible to avoid encountering the sulfur ions in the atmosphere totally, although it is wise to avoid areas of heavy industrial pollution and unnecessary low-altitude exposure to sea air.

For all practical purposes, the first two of these factors can be regarded as constants, more or less beyond the operator's control. The situation is quite different, however, in the case of the third factor.

How rapidly protective coatings like Alpak and AEP are worn away, and how rapidly sulfidation proceeds thereafter, is strongly affected by the operating temperature. Sulfidation is fundamentally a chemical reaction and, like most chemical reactions, it proceeds more rapidly at higher temperatures. It is no coincidence that this destructive process is often called simply "hot corrosion."

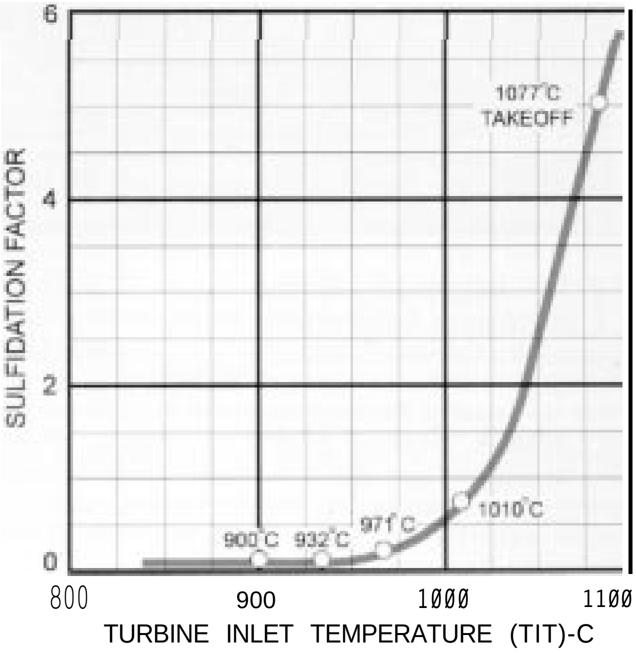

Figure 1. Effect of temperature on sulfidation.

Sulfidation rates tend to be exponentially related to the temperature of the metal, as shown in the chart in Figure 1. It is important to remember, however, that turbine temperature is not a constant. The temperature at which the turbine of the 501/T56 engine operates is a variable which is largely within the control of the operator.

Reducing Sulfidation Effects

There are three principal ways in which flight crews and maintenance specialists can help in reducing the temperatures that turbine section components are exposed to, and thereby retard the sulfidation process.

- Fly at reduced cruise TIT whenever possible.
- Pay careful attention to starting temperatures.
- Ensure that the TIT sensing and indicating system is properly 'maintained.

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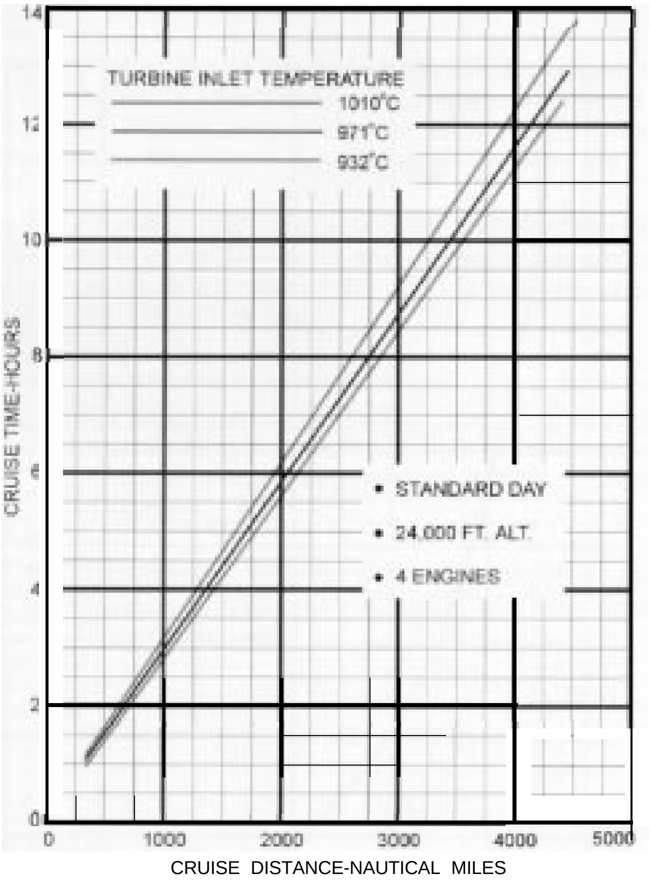

Figure 2. **Cruise time versus distance.**

Cruise Conservation

Consider a mission where all parameters are fixed except for cruise TIT. A reduction of only 30 or 40 degrees metal temperature will reduce the sulfidation factor by almost one-half. Even further increases in turbine life may be realized with further reductions in cruise TIT. When operation of the aircraft can be accomplished with a lower TIT, the life of the turbine section is greatly increased.

Furthermore, the sacrifice in terms of airspeed that will result from a modest reduction in TIT is really quite small. Figures 2 and 3 provide a comparison of power settings and their effect on cruise time or fuel consumption over a given distance. These charts help point up the relatively minor time advantage that can be expected from exposing the turbine sections of an aircraft's engines to high cruise TIT.

For 501-D22A, T56-A-15, T56-A-16, and T56-A-423 engines, decreasing power from 1010°C to 971 'C increases block time only 3.8 minutes per hour of block time, while a further reduction to 932°C increases block time by just 6 minutes per hour. Moreover, it is possible to achieve fuel savings of approximately 3 percent with a TIT reduction from 1010°C to 971 "C. Approximately 5 percent total fuel savings may be realized by reducing engine power from 1010°C to 932°C.

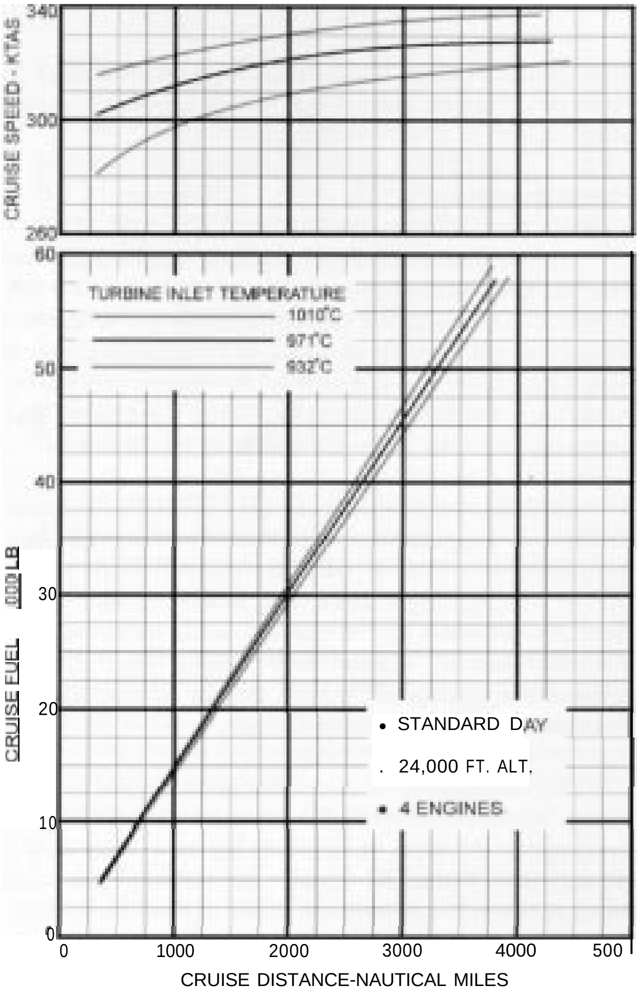

Figure 3. Cruise fuel versus distance.

This points up two of the reasons why Lockheed recommends that climbout TIT for this series of engines be set no higher than 971 'C whenever possible, and cruise temperature be set no higher than 932°C whenever possible. Relatively little extra speed will be gained from the use of high TIT settings, and these higher settings are also wasteful of fuel. But most important, lower power settings will contribute greatly to a longer turbine life.

The same conservation philosophy can also be applied to 501-D22, T56-A-9, and T56-A-7 engines with good effect, although in these cases the temperature settings will be lower. A number of operators of Hercules aircraft equipped with these engines have found that keeping continuous cruise TIT at 900°C or below yields excellent results.

The nature of aircraft operations requires that aircraft engines be subjected to high power outputs and high temperatures on many occasions during their time in service. However, experienced operators have discovered that conservative engine temperature settings in cruise and at other times when safety and operational

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considerations allow it will yield worthwhile benefits in terms ofturbine section reliability and reduced operating costs.

Stress Rupture

Another heat-related factor which must be taken into consideration in realizing maximum engine service life is stress rupture. Stress rupture is breakage of turbine blades as a result ofphysical stress. The characteristic is time-dependent and a result of the stress applied by centrifugal force (turbine rpm), sonic resonance, and temperature in the turbine's operating environment.

Of these, only the temperature (TIT) can be readily controlled. Turbine blades are more flexible when they are hot, and therefore they are more subject to the effects of centrifugal force and sonic vibration when they are exposed to excessively high temperatures. Keeping turbine blades well within their normal operating temperature range is the key to reducing the possibility of stress rupture damage.

The relationship between temperature and turbine blade "stress rupture life," a measure of resistance to breakage of this type, is shown in Figure 4. Note how a 30-degree C increase above the normal operating temperature will decrease the stress rupture life by two-thirds. On the other hand, 30-degree decrease in blade metal temperature can double stress rupture life.

Relatively few instances of actual turbine blade breakage due to stress rupture have been recorded for the Allison 501/T56 engine. In the majority of these cases, however, inspection of the affected parts has revealed previous exposures to overtemperature conditions.

A Good Start on Conservation

Starting the engines is always a minor moment of truth for an aircraft mission; the start can also be something of a moment of truth as far as the engine turbines are concerned. To obtain good starts with consistency, be sure to comply with the checklist procedures closely. Pay particular attention to the following:

- The throttle must be in the GROUND IDLE (military aircraft) or GROUND START (commercial aircraft) position.
- The propeller should be at minimum torque blade angle.
- Aircraft boost pumps should be ON for the start to ensure a good fuel supply to the engine fuel systems.

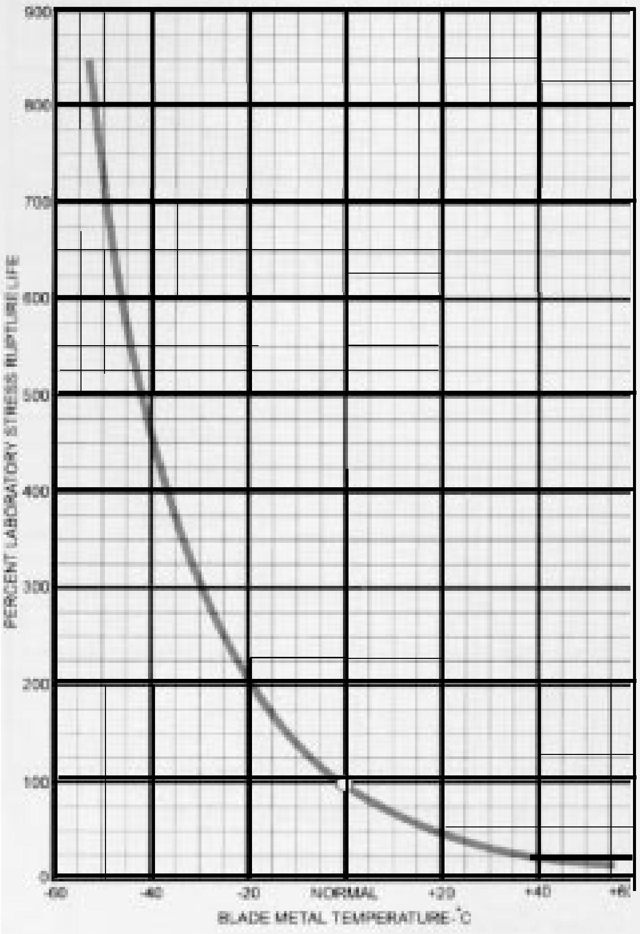

Figure 4. Effect of temperature on turbine blade materials

- Be sure that the residual TIT in the engine is less than 200°C before initiating a start.
- The GTC or APU should be operating properly and at maximum output. Always check for a minimum bleed air manifold pressure of at least 35 psi before the start is initiated, and a minimum of 22 psi during the start itself.
- Air conditioning must be off during engine start, and in those aircraft so equipped, the ATM should be off unless absolutely needed. In cases where the ATM must be on for some reason, be sure to monitor the bleed air pressure very closely while starting the first engine.
- On manually controlled starter systems, be sure that the engine reaches 60% rpm before releasing the starter switch or button; then release it promptly to ensure maximum starter life.
- Observe engine acceleration rate and the start time specified in the applicable technical manual and operator handbook.

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- Do not use enrichment on normal ground starts unless the engine will not start without it; however, all in-flight starts should be accomplished using enrichment.

- Closely monitor engine instruments throughout the start cycle. TIT is the most important parameter during starting. Watch this gage continuously while the start is in progress.

- Check for the first rpm indication, which indicates that the start cycle has begun. Lightoff ordinarily occurs between 16% and 24% rpm, and acceleration should be continuous until the engine is on speed.

- If enrichment is used, check for fuel flow and immediate cutback after 16% rpm. Disregard it for the rest of the start.

- The secondary fuel pump pressure light should be steadily illuminated by the time the engine reaches 65 % rpm. It should go out above 65 % rpm.

While the start cycle usually occurs without difficulty, each start must be closely monitored so that it may be discontinued in case an unexpected problem arises. The start should be aborted for any of the following reasons:

- TIT exceeds temperature limits cited in the applicable manuals.

- Bleed air manifold pressure falls below the minimum acceptable value of 22 psi.

- Hesitating or stagnating rpm.

- Fuel is observed pouring from the nacelle drain.

- Torching-visible burning of fuel in and aft of the tailpipe-is observed. Note that a momentary burst of flame, an “enrichment burst,” is normal if enrichment is selected.

- Excessive smoke is seen from the exhaust.

- Compressor surging or stalling occurs.

- Abnormal vibration is noted.

- Permissible start time is exceeded.

- The engine does not light off (no increase in TIT) by 35 % or maximum engine rpm attainable with the starter, whichever occurs first.

Problem Starts

The most desirable engine start is of relatively short duration (less than 60 seconds), with peak TIT between 780°C and 810°C. Note that starting temperatures cooler than 780°C are not necessarily better ones.

Temperatures on the cool side may result in acceleration rates inadequate to complete the start within the prescribed time limit. Low starting temperatures may be evidence of a lean TD null orifice valve setting or a lean fuel control acceleration schedule, or improper fuel nozzle flow patterns.

Improper fuel nozzle flow patterns can result in such problems as downstream burning of fuel, excessive blade/vane heat soak temperatures, and a high incidence of aborted starts.

On the other hand, starts with turbine inlet temperatures on the high side apply a great deal of thermal stress to the turbine section of the engine. The rapid expansion forced upon turbine vanes, blades, and other critical components by the sudden application of extreme heat can cause the parts to crack.

Such “hot starts” can do a lot of damage in a short period of time and must be avoided. Remember that the TD system can only reduce high starting temperatures after they have been detected; it cannot prevent the initial high readings from occurring. High temperatures at start can often be corrected by making null orifice adjustments. If this does not solve the problem, further troubleshooting will be required. The following are the start overtemperature limitations and the required action if exceeded.

Over 830 Degrees C

TIT over 83O'C, but less than 85O'C, and excluding the peak normally occurring at 94% rpm, requires the flight crew to record the extent of the overtemperature condition and call for maintenance at the next layover where maintenance is available.

The action by maintenance personnel will be to check the TD valve null setting and adjust it toward decrease. If it is found on the subsequent engine start that the previous adjustment did not reduce the starting temperature to within limits, it will be necessary for maintenance to perform the starting overtemperatnre check described in the applicable maintenance manual.

Over 850 Degrees C

If the TIT exceeds 85O'C, excluding the peak occurring at 94 % rpm, the flight crew should proceed as follows:

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1. Shut the engine down by moving the condition lever to the GROUND STOP position (not FEATHER), and record the maximum TIT.

2. Allow the engine to cool to below 200°C TIT before attempting to restart. The engine may be motored with the starter to cool it more rapidly, if necessary. When the engine has been cooled in this manner, wait one minute to make sure that the temperature has stabilized before initiating another start. Remember not to exceed the starter duty cycle.

3. If 850°C is exceeded on the second start, shut down the engine and record the temperature, then call maintenance. Making another attempt to start the engine is not recommended.

Maintenance action will be to perform the starting overtemperature checks listed in the appropriate maintenance manual.

Over 965 Degrees C

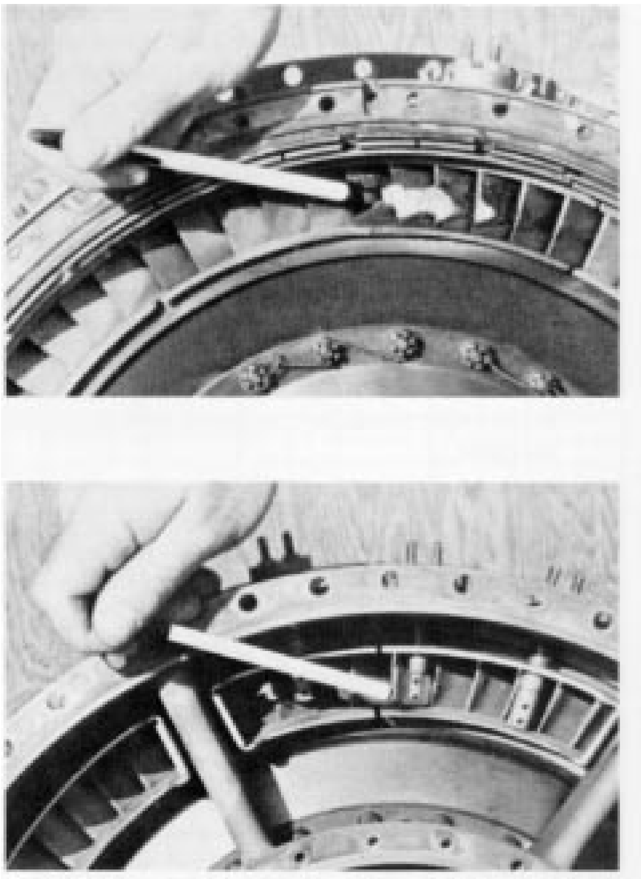
If TIT exceeds 965 'C during a start, shut down the engine, record the peak temperature and call for maintenance. Make no attempt to restart the engine. Maintenance action will be to perform an overtemperature inspection, consisting of a borescope visual inspection of the turbine section components.

If no damage is found in the course of these inspection procedures, all thermocouples must be removed, visually inspected, and electrically tested. If this inspection reveals no damage, maintenance can perform the starting overtemperature checks listed in the appropriate maintenance manual as required to correct the condition.

Thermocouples

The proper operation of the TIT indicating system has a critical bearing on the overall operation and service life of the 501/T56 engine. Malfunctioning or damaged thermocouples, or installed thermocouples of the wrong type, can lead to increased operating temperatures within the turbine and materially reduce engine life.

It is important not to become complacent about the accuracy of the TIT indicating system. It is possible to exceed the maximum allowable takeoff TIT limitation without knowing it if the engine has several deteriorated thermocouples. Under such circumstances, the operator would experience significantly reduced engine service life while mistakenly believing that the engine has been operating properly or has even begun developing more power at the same throttle settings.



This turbine wane burn-through was caused by the use of thermocouples of the incorrect type.

The engine TIT is measured by 18 thermocouples installed in the turbine inlet casing. Each thermocouple has two separate junctions that act as sensing elements. One junction of each of the 18 thermocouples is connected in parallel to provide an averaged signal to the TD amplifier.

The TD amplifier uses this signal to determine the actual TIT of the engine. The other junction of each thermocouple is also connected in parallel. Its signal becomes part of the averaged signal representing TIT that is displayed on the TIT indicator mounted on the engine instrument panel. Although unusual, it is possible for only one of the junctions to fail, causing incorrect temperature sensing if the side connected to the TD amplifier fails, or a low instrument panel reading if the indicator side is affected.

The Allison 501/T56 engine incorporates a system of multiple combustion chambers, which causes the temperatures measured at the turbine inlet to be somewhat nonuniform. A system of multiple thermocouples is used to compensate for these differences in temperature by sampling both the hotter and cooler areas and supplying an average temperature signal.

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Since the temperature signal represents a value obtained by averaging the input from 18 different locations around the turbine inlet, it is very important that all of the thermocouples be functioning properly at all times. If any of the thermocouples fail, the signal being sent to the TD amplifier and the TIT indicator will be affected.

Thermocouples fail for a variety of reasons, including high resistance, open circuits, and probe tip damage. The failure of the thermocouple is an event that can initiate a whole series of further events, all of them bad.

The basic problem is too much heat. Where one or more of the thermocouples around the turbine area are damaged or inoperative, the temperature signals being received by the TD amplifier and the TIT indicator will no longer represent the true TIT values. The reason has to do with the design characteristics of the TIT indicator and the TD amplifier.

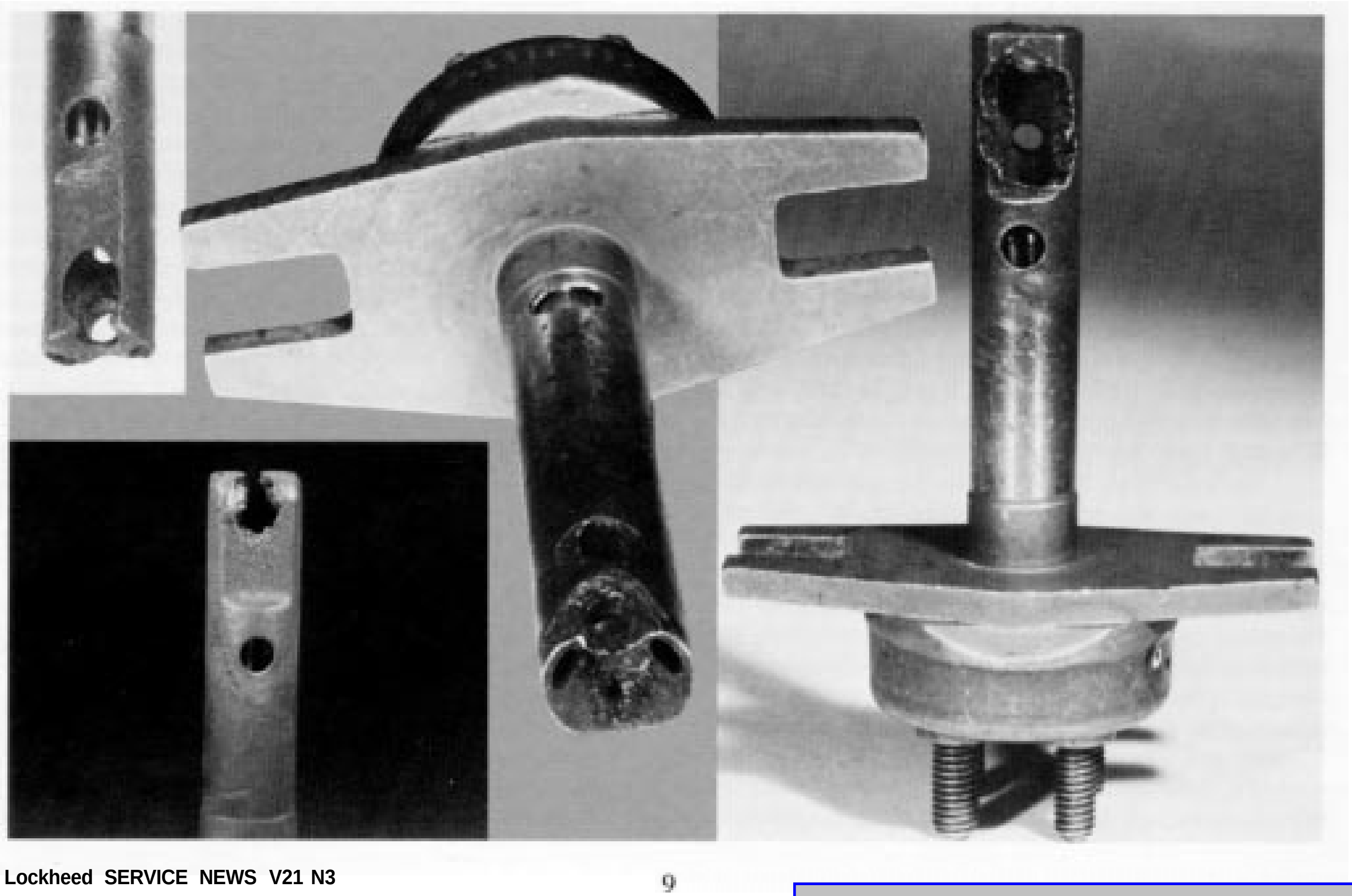
These devices respond to variations in the minute voltages generated by the thermocouples as the TIT rises and falls during changes in engine power. But the voltages will reflect the actual temperatures involved only as long as normal operating conditions prevail in the TD control system. The electrical resistance loads in the system circuitry are designed to yield accurate results with 18 fully functional thermocouples. The loss of any of the thermocouples will be accompanied by a reduction in current flow that affects the voltage values from which the temperature data are derived.

As a practical matter, this means that if the current flow is reduced by the failure of one or more thermocouples in the circuit, the voltage “seen” by the TIT indicator and the TD amplifier will also be reduced. Since lower voltage will be interpreted by the engine temperature control system as lower TIT, the control system increases the fuel flow to compensate. The additional fuel burns to produce more heat, which sets the stage for overtemperature problems.

An important consequence of this effect is that over time, thermocouple problems tend to be progressive and cumulative. A single thermocouple failure can begin a snowballing chain of events in which the increased fuel flow-and resulting higher temperatures-cause a second thermocouple to fail, and then another, and so on until the engine is severely overheating.

Eroded or defective thermocouples that are still producing current can also cause temperature control errors, although for a different reason. In fact, the temperature error in these cases can be even more severe than when a thermocouple has dropped completely off line. One thermocouple with the aft wall of the probe tip eroded, for example, can cause the true operating TIT to increase by as much as 7.5'C.

All of these thermocouples were damaged by exposure to overtemperature conditions.



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A sequence of failures involving five thermocouples with probe tip aft wall erosion can therefore raise the actual operating temperature of the engine by over 35 °C at every power setting above crossover. Such exposure to excessive operating temperatures is very destructive to engine components and will result in significantly shortened engine life.

Thermocouple Maintenance

Since properly functioning thermocouples play such a vital role in the engine control system, it is clear that a well-designed and conscientiously followed thermocouple maintenance program is of utmost importance. All thermocouples should be regularly removed, inspected, and tested as described in T. 0. 1C-130B-6 or SMP 515C, and the applicable Allison manual.

One of the most important things to remember about thermocouple inspections is to do it often enough. Finding more than three defective thermocouples in one engine at inspection time is a good indication that the period between inspections needs to be shortened.

When thermocouples are removed for examination, be sure to tag them as they are removed and keep a record of the positions where they were located. The condition of individual thermocouples often provides valuable clues about underlying problems involving other components. For example, thermocouples with badly burned probe tips or unusual carbon deposits suggest malfunctioning fuel nozzles or defective combustion liners, as does repeated thermocouple failures at the same location.

Inadequate maintenance of fuel nozzles can considerably shorten engine life. Allison recommends that all fuel nozzles be regularly removed, inspected, and functionally tested as part of an ongoing fuel nozzle maintenance program. An inspection interval of 1200 hours is useful as a starting point for operators initiating such a program, but this should be modified as necessary to satisfy prevailing conditions. Many operators using JP-8 fuel, for example, have reduced the fuel nozzle inspection interval to every 600 hours.

For operators not equipped to accomplish fuel nozzle inspection at the operating facility, the most practical approach will be to remove the nozzles and replace them with a set known to be serviceable every 600 - 1200 hours (depending on your conditions). The removed units can then be sent to a properly equipped repair facility. Those that meet specifications after inspection, testing, and any necessary repairs can be returned to service in the next cycle.

Also, don’t overlook bad fuel as a possible source of thermocouple problems. Fuel contamination by dirt or microorganisms can lead to thermocouple trouble by clogging fuel nozzles and altering fuel spray patterns.

Preventing Overtemperature Damage

Beyond strict adherence to the thermocouple maintenance and inspection procedures set forth in the authorized manuals, the best insurance against overtemperature damage brought on by malfunctioning thermocouples is vigilance on the part of the flight crew. Higher than normal fuel flow and torque above crossover for a given TIT are possible signs of malfunctioning thermocouples.

Another is higher than normal torque for a given TIT. Since fuel flow and torque are closely interrelated, an increase in fuel flow to raise the average TIT signal will also cause an engine’s torque output to increase. Careful attention to the fuel flow and torque indicators can pay substantial dividends in terms of timely detection of overtemperature conditions.

We have already seen that the TIT indicator will often not be a reliable guide to the actual TIT when thermocouple trouble is present. Usually the indicated TIT will be lower, sometimes much lower, than the true value. You can make use of this fact to perform a simple test when problems in the thermocouple system are suspected. With all engines running and above crossover, and bleed air turned off, position the throttle levers so that torque and fuel flow for each are about equal. An engine with thermocouple damage will show a noticeably lower TIT than the other three.

Finally, an important thing to remember is that turbine engines never get better with age. They can only deteriorate as the combined effects of heat, erosion, sulfidation, corrosion, and wear gradually reduce their efficiency. A 501/T56 engine that seems to be improving with age-producing more torque at the same indicated TIT, for example-should immediately attract your attention. Some things are too good to be true, and this is one of them. It is very likely that there are problems in the TIT indicating system in this engine and prompt action is needed to prevent overtemperature damage.

The author and *Service News* wish to express special thanks Wayne Shiver for his valuable assistance with the preparation of the thermocouple section of this article.

Dare1 Traylor can be reached at 404-431-6567 (voice) or 404-431-6556 (fax).

“Conserving Turbine Life” first appeared in Service News, *Vl4N1, and proved so popular that the issue is now out of print. To help ensure that this important information remains accessible to Hercules operators, we are pleased to present an updated version of the same article in this issue.* *- Ed.*

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Providing MIL-STD-704E Quality Power in Older C-130 Aircraft

C-130 Electrical System Upgrade

by **Susan H. Berk**, *Senior Staff Engineer"*
ESU Design Team
Lockheed Aircraft Service Company

The electrical power system of the C- 130 Hercules airlifter has served well over the years, but as with other aircraft electrical systems of older design, it has sometimes been subject to AC power system dropouts, spikes, and generator switchover anomalies. In the past, the aircraft's analog electrical equipment tolerated these problems reasonably well and serious power fluctuation-induced failures were uncommon.

However, most current and next-generation digital avionics components are considerably more sensitive to spikes and dropouts than the older equipment. This can lead to system malfunctions which result in erroneous readings and a variety of other problems. The advent of more advanced avionics equipment clearly mandates "cleaner" electrical power.

New Hercules airplanes coming off the assembly line at Lockheed's production facility in Marietta, Georgia, now contain updated electrical systems designed to meet many of these requirements. C-130 aircraft Lockheed serial number 53 10 and up built for the U.S. military, and all Hercules airlifters serial number 5358 and up, are equipped with electrical systems that feature bus switching units, solid-state inverters, and new generator control units. These updated systems offer improved AC power suitable for use with most types of modern avionics equipment.

Updating the Fleet

The factory-installed upgrades provide new production Hercules aircraft with cleaner power for the AC avionics buses, but the U.S. Air Force recognized the need for a solution to the AC electrical power problems in older C-130s as well. The result was a competitive procurement for improvements to the electrical systems of existing C-130s that would address these issues, and in particular meet the high quality standards of MIL-STD-704E power. In response to this requirement, Lockheed Aircraft Service developed an electrical system upgrade (ESU) modification package that has been accepted by the Air Force for installation in most of the older C-130 Hercules aircraft in the USAF inventory.

The main components of the ESU modification package for existing C-130 aircraft are shown in Figure 1. The new system offers the following performance enhancements:

- 10 KVA avionics AC buses that meet the power quality requirements of MIL-STD-704E.
- Uninterruptable AC power for a period of up to 70 milliseconds.
- Avionics AC buses with both a primary and a secondary source of power.
- New generator control units, solid-state inverters, a BIT status panel, and a modified overhead control panel.

This article describes Lockheed's ESU approach, and provides additional information on the new capabilities these improvements provide.

Bus-Switching System Components

Lockheed's solution to the problem of designing a practical and affordable C- 130 ESU modification package for existing Hercules aircraft is somewhat different from the approach used in new-production aircraft, but it achieves many of the same results while offering MIL-STD-704E quality power. The design is based on a proven frequency converter which is presently used in a USAF Special Operations Forces

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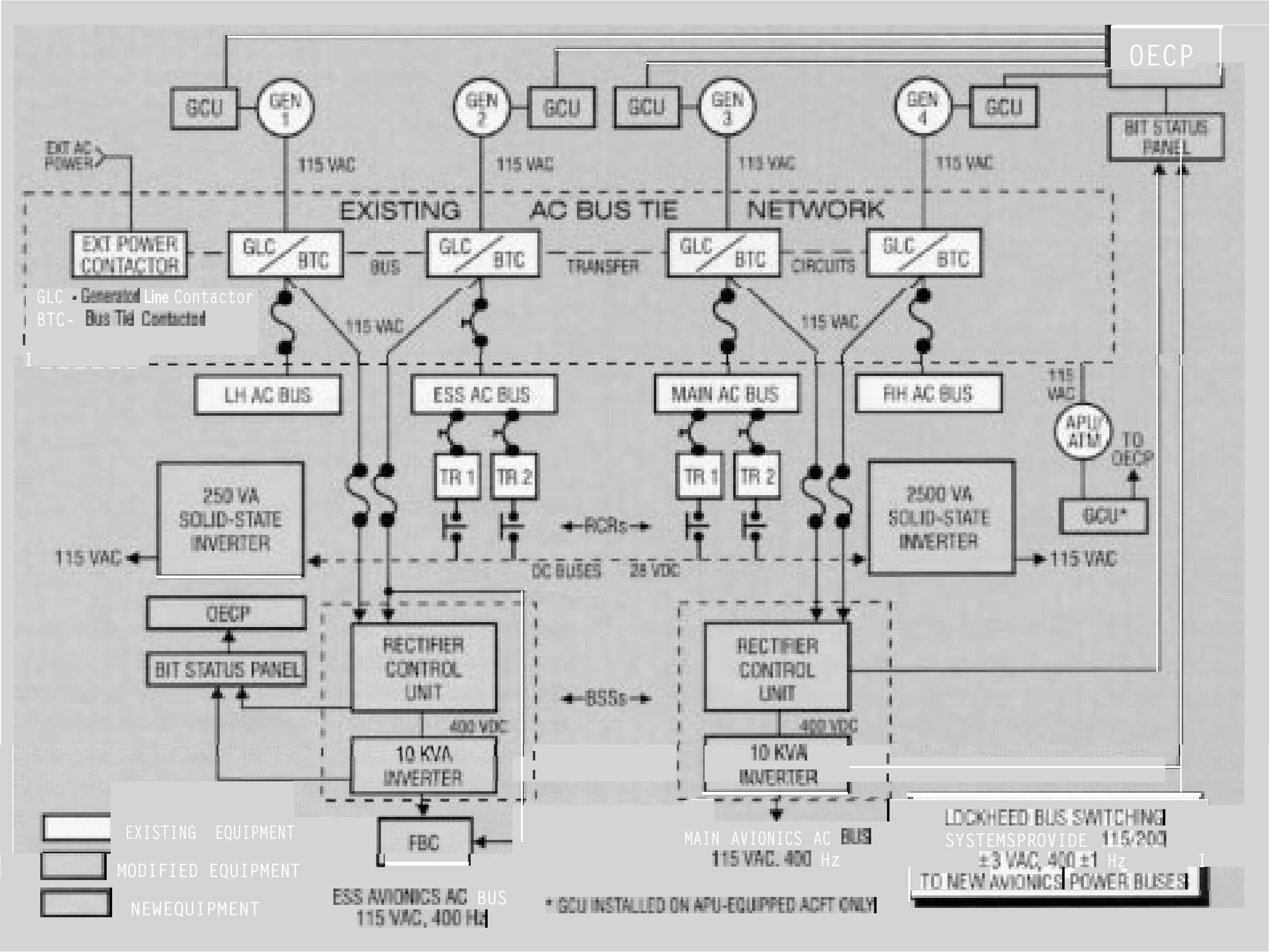

figure 1. Electrical system upgrade (ESU) block diagram – one phase shown.

program. That system employs a versatile bus switching system (BSS) to provide clean power under a wide variety of operating conditions. The Lockheed ESU employs a similar design philosophy and includes the following subsystems in the BSS portion of its circuitry:

- Rectifier control units
- 10 KVA inverters

Rectifier Control Units

Two rectifier control units (RCUs) provide the 400 VDC input required by the associated 10 KVA inverters (Figure 2). Input to the two RCUs is aircraft 1 15/200 VAC, 400 Hz, three-phase power. Each of the RCUs has two inputs, each from separate AC buses. The design of the RCUs provides a nonswitching selection of the AC input source. The RCUs feature a dual-redundant design that uses separate circuitry to develop the required DC output. If the primary DC/DC boost converter portion of an RCU fails to supply the 400 VDC output, the unit switches to the secondary input source and the secondary boost converter DC output.

The primary boost converter is set to regulate the output at 400 VDC. The secondary boost converter is set to regulate at 390 VDC. Whenever the primary circuit no longer provides the 400 VDC output required, the load is automatically picked up by the secondary circuit. If a loss of both input power sources occurs, the capacitive power storage built into the system can maintain the specified DC power output for a minimum of 70 milliseconds.

10 KVA Inverters

The RCUs provide 400 VDC input to the 10 KVA inverters. These solid-state 10 KVA inverters reconstruct the DC to clean, uninterruptable, regulated 115/200 VAC, 400Hz power, which is then supplied to the avionics AC buses (Figure 3). The power input to the 10 KVA inverters-can drop as low as 220 VDC and they will continue to operate and provide 115/200 VAC, 400 Hz output power.

Should conditions arise in which one of the 10 KVA inverters can no longer provide MIL-STD-704E power, the power output of the inverter drops to zero volts. This

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design feature ensures that avionics AC bus equipment is not damaged due to voltage degradation.

When the 10 KVA inverter senses that the input has dropped below 220 VDC, an orderly shutdown of the inverter is initiated and the circuits in the RCU are reset. When the DC voltage from the RCU to the affected 10 KVA inverter increases to a minimum of 220 VDC, the inverter restarts and is again able to generate a stabilized 115/200 VAC, 400 Hz output.

Fail-Safe Bypass Contactor

The Lockheed ESU design approach incorporates an important safety feature, the fail-safe bypass contactor (FBC). The BSS includes an FBC at the essential avionics 10 KVA inverter output to help eliminate single-point failure and ensure safety of flight. The FBC also provides automatic emergency bypass power to the essential avionics AC equipment if the essential BSS fails.

Additional Electrical System Enhancements

In addition to the BSS, the Lockheed ESU incorporates several other important new electrical system enhancements, including:

- New generator control units.
- Solid-state inverters.
- Modified overhead electrical control panels.
- BIT status panels.

Generator Control Units

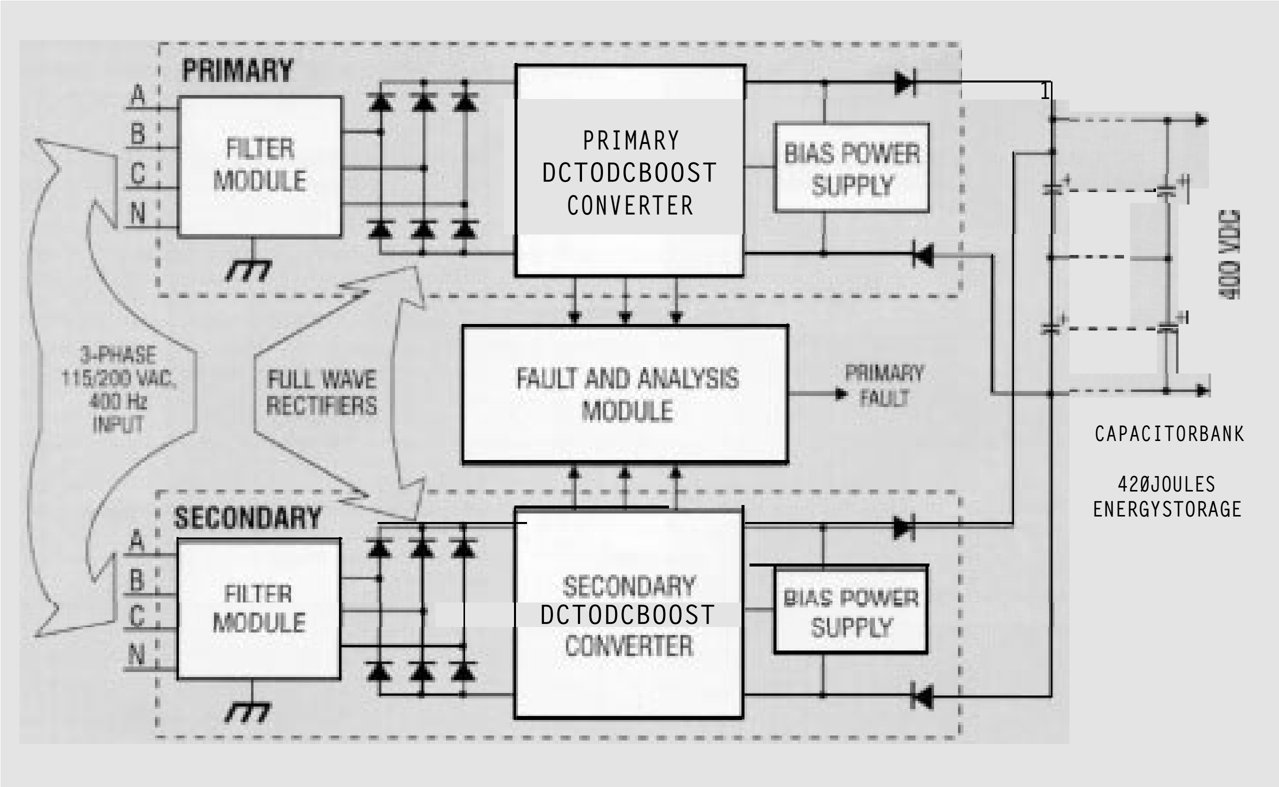
The new generator control units (GCUs) are off-the-shelf units that have been modified to provide remote built-in-test (BIT) status. Essentially the same model GCU is now being installed on new Hercules aircraft.

The GCU upgrade offers improved control of all generator output functions, and works with either Bendix or Leland (GE) generators. The new GCUs automatically detect which generator is present and select the appropriate internal voltage regulation functions. The GCUs also provide system AC bus protection by sensing when the electrical operating parameters are out of limits or serious conditions such as feeder faults are present.

For example, the GCUs automatically sense when frequency exceeds or falls below specified limits. If such a situation arises, the affected line contactor is opened, the OUT light on the overhead electrical control panel (OECP) is illuminated, and the appropriate BIT code is displayed. If voltage is sensed to be outside the allowable limits, the system responds in the same way, except that the generator is also deenergized.

When frequency returns to within limits, the line contactor automatically resets and the OUT light on the

Figure 2. Rectifier control unit (RCU).



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OECP extinguishes. In cases where a voltage failure has been detected, however, the crew must reset the generator with the control switches on the OECP. Note that if a feeder fault is present, the GCU will “latch” the affected generator system out, and it cannot be reset with the engine running. More detailed information about the operation of the new GCUs will be found in *Service News* issues Vol. 19, No. 2 and Vol. 20, No.3.

Solid-State **Inverters**

Two new solid-state inverters replace the C-130’s two existing rotary inverters. One new inverter replaces the AC instruments and engine fuel control inverter; the other replaces the copilot’s AC instrument inverter. The solid-state inverters use the same mounting and cabling as the existing equipment. The new inverters accept as input the nominal 28 VDC off the DC buses and supply MIL-STD-704E continuous 115/200 VAC output.

Overhead Electrical Control Panel

The modified OECP allows the crew to manage the electrical power system during both normal and emergency operations. Minor wiring changes allow the new GCU switches to be installed, providing complete control of the new GCUs. The panel overlay has been replaced to reflect the new controls, and other changes have been included to afford Night-Vision Imaging System (NVIS)compatibility.

Three positions are provided on the GCU switches, an “on” position labeled to identify the associated generator (Figure 4), OFF/RESET, and TEST. The “on” position enables generator operation. Selecting the OFF/RESET disables the generator and resets the GCU. The TEST position enables the generator in order to allow monitoring of AC voltage and frequency but leaves the generator line contactor deenergized.

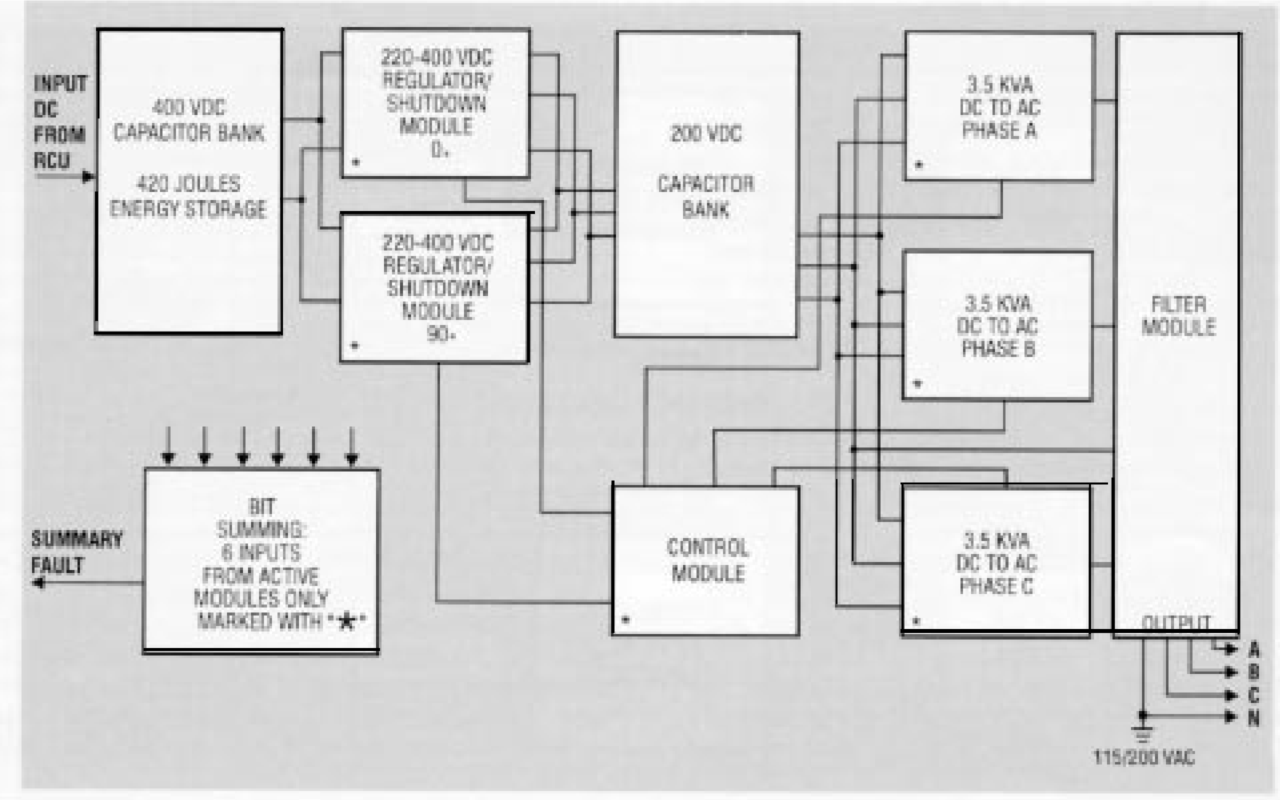
BIT Status Panel

The OECP modification also includes adding a new BIT status panel. This panel provides unit failure annunciation for the ESU line replaceable units. The BIT status panel provides rapid identification of a GCU, RCU, or 10 KVA inverter failure.

Other Kit Equipment

All electrical and mechanical equipment necessary for installation are included as part of the Lockheed ESU kits. The electrical components include cable assemblies and miscellaneous wiring bundles. The mechanical components include mounting angles, nameplates, brackets, shelves, and hardware for installing the various components. The ESU was designed to minimize impact on the overall aircraft as a whole, and as a result, the requirements for miscellaneous fittings, adapters, etc., are minimal.

Figure 3. 10KVA inverter.



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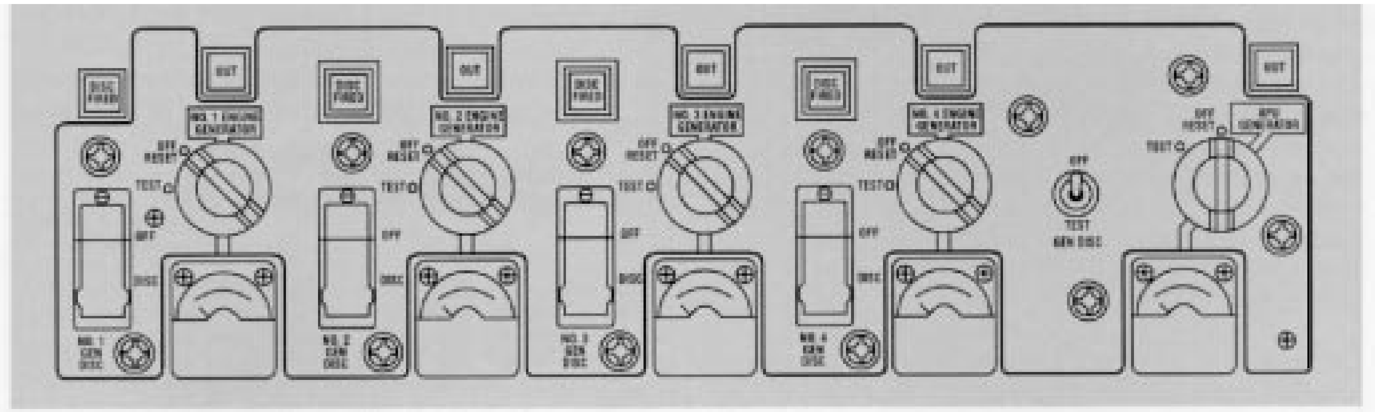

Figure 4. Modified overhead electrical control panel **(OECP) with APU –** typical.

Equipment Changes

The ESU modification addresses three major systems: the BSS supplying uninterruptable power to the two avionics AC buses, the GCU upgrade, and the solid-state inverter upgrade.

Installing the BSS equipment requires no equipment removals. Presently, the aircraft essential and main DC buses are each fed by two transformer-rectifier units, and these units are supplied power from the essential and main AC buses. The addition of the BSS does not alter this bus arrangement. The existing bus-tie network, supplying the input power to the RCU, remains unchanged.

The GCU upgrade requires the removal of the existing voltage regulators and generator control panels, from the electrical control and supply racks, and the frequency-sensitive relays from the lower main AC distribution panel. The new GCUs that replace all of these units require half the space of the old equipment and provide a weight savings of 52 pounds.

Replacement of the rotary inverters involves removing the 250 VA and 2500 VA inverters from the forward right-hand underdeck area. They are replaced by new 250 VA and 2500 VA solid-state inverters. The new solid-state inverters provide the same control and status as the old rotary inverters. In addition, the new solid-state inverters use the existing mounting and connectors.

A new color-coded legend is provided for the circuit breaker panel. This permits ready identification of the equipment powered by the new, clean avionics AC buses.

Summary

The new BSS with its RCUs and 10 KVA inverters offers significantly improved C-130 avionics AC bus power. The BSS provides MIL-STD-704E quality power with +/-1Hz frequency control and +/-3 VAC voltage control, exceeding the specification requirements. The BSS also ensures uninterruptable power for input AC power losses of up to 70 milliseconds. The BSS requires no AC bus tie network alterations to existing aircraft. The ESU includes new GCUs, solid-state inverters, and modification of the OECP to incorporate all GCU and BSS functions.

The Lockheed ESU provides older C- 130 Hercules aircraft with a practical and affordable solution to the requirement for improved AC power to operate today's digital avionics equipment.

The author and *Service News* would like to extend special thanks to Steve Rice, chief systems engineer on the ESU project, without whom this article would not have been possible. Grateful acknowledgement is also due to Norm Stevens and Bob Parker for their helpful comments and suggestions during review.

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Fin Stall It's Not!

In Search of Fin Stall

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Flight Control Department

The term "fin stall," as it applies to the Hercules aircraft, is often misunderstood. There is a small group of C-130 aircrew members who are convinced that almost any sideslip excursion brings on fin stall. Others believe that any fairly rapid yawing motion beyond that expected of the typical student pilot can cause the laws of physics and aerodynamics to be repealed and control of flight to be lost-all under the banner of fin stall.

The truth of the matter is that the Hercules aircraft is *not* susceptible to fin stall under these circumstances, and the term fin stall itself is inaccurate when applied to the Hercules in such situations.

Flight Control System Design

So what is really going on? The large power effects created by the propeller slipstream that make the Hercules such a great short-field tactical transport also mandate a large vertical stabilizer (fin) for directional stability, with a large rudder for low-speed control of asymmetric power from the engines. These features also had to be considered when it came to engineering the flight control system.

At the time of the C-130's design in the early 1950s a propeller-powered transport aircraft did not justify the cost and complexity of the fully powered, irreversible flight controls that are used on many aircraft today. A more conventional reversible system was selected instead. Each control surface was sized to provide the control power required, and a hydraulic booster was added to assist the pilot in situations where the forces needed to move the controls were too heavy for manual power alone.

One characteristic of this type of system is that the pilot enjoys excellent feedback from the flight controls. He is directly connected to the main control surfaces and

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can feel each surface's position and the force necessary to hold it or move it. Another characteristic is that in the absence of inputs from the pilot, the rudder will "float" to an angle where the aerodynamic loads on the rudder are zero.

Sideslip Basics

During straight flight, these same aerodynamic loads cause the rudder to float at the neutral position, and the pilot must apply pedal force to push the rudder out to a given deflection. All other things being equal (equal power on all engines, etc.), the airplane nose will move in the same direction as the rudder when the rudder pedal is depressed. A small sideslip angle will then develop, which pulls the opposite wing up and results in a turn.

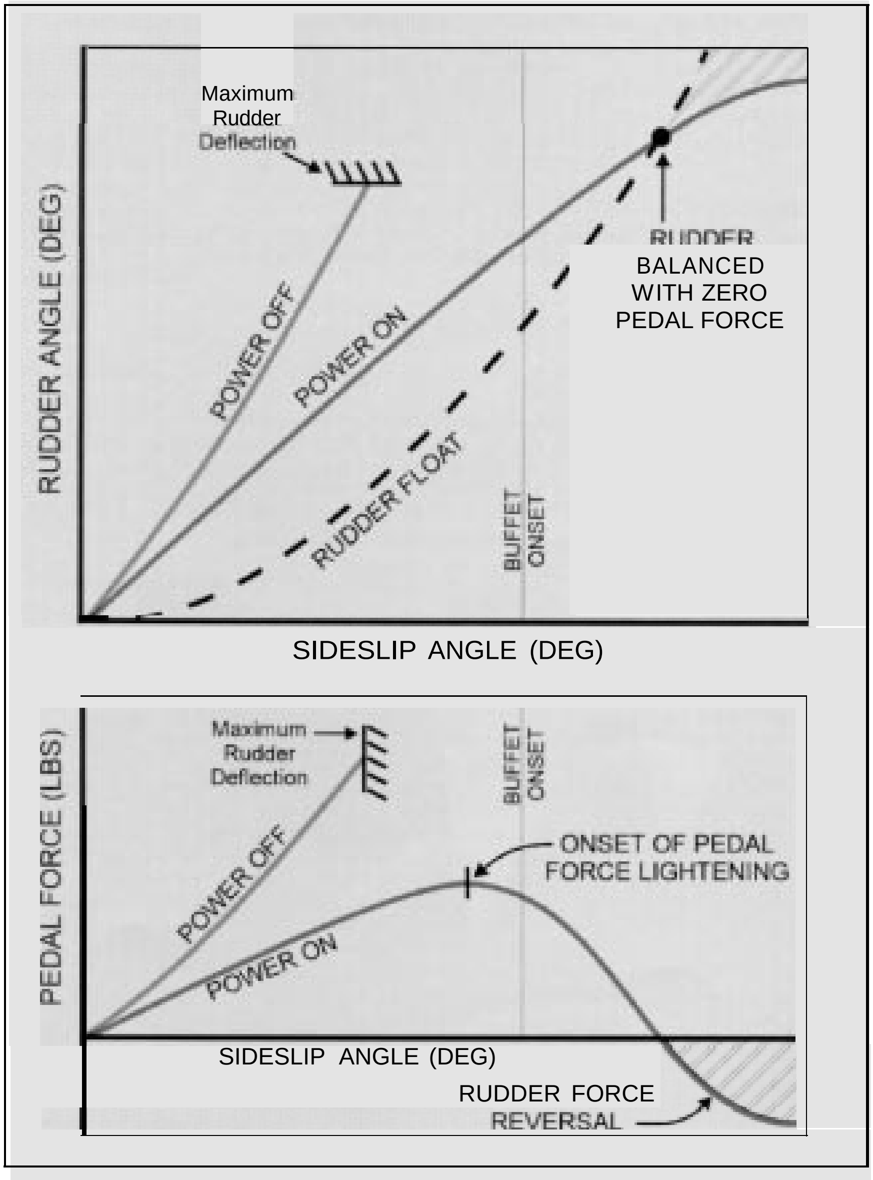

Figure 1. A graphical representation of the relationship between rudder angle and pedal force during sideslip manuevers in the Hercules aircraft.

If, instead, the pilot lowers the wing to bank in the direction opposite the turn, a steady-heading sideslip will result. The airflow now hits the vertical fin from the side opposite the rudder. This off-centerline flow acts to reduce the rudder force that the pilot had to overcome initially, and the difference in rudder pedal force can actually be felt by the pilot. Engineers call these forces "hinge moments" because they really are moments trying to rotate the rudder surface about its hinge line. Pilots prefer just "forces" because that is what they apply to the pedal.

If the rudder angle required to maintain a given sideslip angle is greater than the float angle for that amount of sideslip, then pedal forces must be applied to keep the rudder from returning toward neutral. As sideslip angles increase toward the higher angles, there is a tendency for the rudder to float out more rapidly and less pedal force is required to-hold the rudder deflection.

A point is finally reached where the rudder angle required to hold the sideslip angle and the rudder float position are identical. At this point the rudder stays where it is with no pilot force on the pedals. In effect, the rudder is balanced with zero pedal force (Figure 1). The term "rudder lock" is sometimes applied to this point, but this is misleading because the rudder is not actually locked. It does require force on the opposite pedal to return to a normal flight attitude, but the rudder will readily respond to that restoring pedal force.

Rudder Force Reversal

Beyond this point, the pilot must apply opposite pedal force to restrain the rudder from floating further out. This is rudder force reversal, also called rudder overbalance. It is not fin stall, because the airplane remains directionally stable and will return to straight flight if the rudder is returned to neutral and the wings are leveled.

Getting into rudder force reversal requires abnormally high sideslip angles, which are prohibited by the flight manual. Rudder force reversal is preceded by heavy, unmistakable buffet on the vertical tail (but not fin stall) that usually begins between 16 and 24 degrees of sideslip. A noticeable reduction in rudder pedal force starts at about 17 degrees of sideslip.

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Further increases in sideslip produce large yawing transients and a reversal of pedal forces. If the pilot lets the rudder float and does not reduce the sideslip, the aircraft will yaw out to a sideslip angle of 40 to 45 degrees. The nose-up pitching tendency that occurs simultaneously can cause one wing to stall. The airplane is now in very serious trouble! Both lateral and directional stability have been lost and recovery is problematic at best.

Susceptibility to encountering rudder force reversal is greatest at low speed and high power (usually 75% power or greater) with flaps extended. It has never been reported in a power-off condition. Power effects on the wing and fuselage of the C-130 reduce the directional stability level sufficiently so that rudder force reversal occurs before fin stall.

Recovery from a rudder force reversal condition requires returning the rudder to neutral and can be assisted by rolling wings-level, pushing the nose down to decrease angle of attack, and reducing power; but only if altitude permits.

Understanding Fin Stall

So does fin stall really exist? Theoretically, yes. Any lifting surface will stall if given enough angle of attack. The vertical fin is a lifting surface, and sideslip is just angle of attack viewed from overhead. What happens in true fin stall is complete separation of the airflow over the fin and rudder. Just like a wing stall, complete airflow separation over the fin removes its horizontal "lift," or side force. Directional stability is then lost because the restoring tail moment, which is totally dependent on that side force, disappears.

However, getting fin stall to occur on a Hercules requires sideslips far beyond the flight manual limits and much hard work on the part of the pilot, all in the wrong direction, of course. Extensive wind-tunnel testing and much flight testing have shown that the Here's vertical tail does not stall, even out to sideslips as high as 30 degrees.

But don't go out and try to verify this! Fin stall is outside the flight manual limits. You will get into rudder force reversal well before getting that high a sideslip angle, and you risk loss of the airplane if improper flight control inputs are made. Also, you have no real way of measuring sidelip angle with the instruments provided on your instrument panel, and the indicated airspeed becomes unreliable at large sideslip angles. Any line pilot who intentionally investigates this condition should seriously consider another line of employment.

Slip-Ball Savvy

It must be kept in mind that the turn and slip indicator, the "slip ball" on the instrument panel, is not a sideslip gauge. The slip ball, or slip-skid ball if you prefer, reacts only to one thing: lateral acceleration, whether that acceleration comes from aerodynamic forces, inertia forces, gravitational forces (due to bank angle), or any combination of these. In particular, the slip ball should not be considered a primary reference during engine-out flight.

When the Hercules is being flown correctly under engine-inoperative conditions, the ball may be slightly displaced from the center toward the good engines; but the amount of displacement varies with airspeed, bank angle, altitude, air temperature, and aircraft gross weight. DO NOT use the ball as an attitude reference during asymmetric thrust situations.

"Fin-Stall" Scenarios

Now consider the following scenario: You are exiting the drop zone on a formation drop and hit the wake of the Hercules that has crossed in front of you. The airplane rolls and yaws pretty violently and you feel the rudder try to go hard over all by itself. You push the rudder back to center with strong pressure on the opposite pedal – and recover to wings level.

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Was it fin stall? No, because you did not lose directional control. Was it rudder force reversal? Perhaps, but only for the brief time you were passing through the wake. As soon as you cleared the wake, the *rudder would have returned to neutral on its own. Yes,* it was scary, but should you have also pushed the nose over and reduced power? Not at that low altitude. The situation would have returned to normal once you exited the wake, given enough time, altitude, and speed. But it is better to know what was going on and react accordingly.

Here is another scenario: A training flight is being conducted to give the student pilot experience flying the C-130 with an engine inoperative. Under the guidance of an instructor pilot, the student is performing a series of approach and go-around maneuvers with the No. 1 engine simulated inoperative. He is being careful to keep his speed above the charted air minimum control speed.

Following the go-around, the flight crew begins an air traffic control-directed left turn at 1,700 feet above actual ground level. The student pilot relaxes the right rudder in a misguided attempt to keep the mm coordinated and the ball centered. The aircraft yaws rapidly to the left, pitches over, and begins a steep decent. In just 25 seconds the aircraft hits the ground, before control can be regained and recovery from the dive completed.

Was this loss of control caused by fin stall or rudder force reversal? Neither one! We have already seen that the fin does not stall at small yaw angles. In this engine-out scenario, the asymmetric power condition produces a left yaw which is being controlled by right rudder. *Rudder force reversal does not occur when the rudder control input is opposing the yaw.*

Improper use of the rudder, combined with improper bank angle, produced this loss of control. Maintaining air minimum control speed (Vmca) ensures only that the airplane can be controlled in steady flight at the prescribed conditions of maximum rudder (or pedal force), favorable bank angle, etc. It does *not* ensure additional yaw control for maneuvering, recovering from further upsets, or relaxing favorable bank angle or rudder deflection.

With No. 1 engine inoperative, turns should be made to the right to avoid the large increase in Vmca caused by the adverse bank angle. Remember that you, not the air traffic controller, are flying the airplane. The controller most likely does not know or comprehend the importance of maintaining a favorable bank angle during engine-out operation at low speeds. Make sure that you communicate your problem (simulated or real) to air traffic control and tell them what you plan to do.

Controllability Guidelines

To prevent departures from contr
especially during engine-out situations, the following guidelines are suggested:

- Maintain airspeed control. Do not let the airspeed drop below minimum control speed.
- Use smooth and coordinated flight control inputs. Control inputs should be slow enough so that any resulting roll rates or yaw rates, intentional or unintentional, can be stopped at any time.
- Make asymmetric throttle changes at a rate no faster than can be controlled, or balanced, by opposing rudder and aileron.
- Never turn into the inoperative engine(s),

While the probability of encountering rudder force reversal in flight is very remote, it is important that you know about this flight characteristic, know how to avoid it, and know how to recover from it. Even more important is that you fully understand the aircraft's handling qualities with an engine inoperative.

The low-speed limits specified by the air minimum control speeds and stall speeds are intended to prevent operation at airspeeds where any sudden loss of engine power or reduction in control capability would cause loss of control of the aircraft. The effects of bank angle on minimum control speed and on stall speed are significant and must be respected. ☐

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The Hercules Airlifter —

40 Years of Getting Better...

1954: The C-130A

...and Better!

1994: The Advanced (H3) C-130H

Tomorrow: The C-130J

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