September through December 1958
Vol. 5, Nos. 2 and 3

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field service digest

LOCKHEED field service digest

This publication is a digest of the most important technical information currently available and is intended to assist our customers in the service, maintenance, and operation of their Lockheed transport aircraft.

CONTENTS

Vol. 5, Nos. 2 and 3
September through
December 1958

THE ELECTRA

PART I GENERAL CHARACTERISTICS

PART II POWER PLANT, AIRFRAME AND SYSTEMS

COVER PICTURE Eastern Air Lines makes its entry into the jet flight age with the first of its 40-plane order of the 400-plus mph ***Electra Propjet***.

EDITOR
Terence B. Donahue

LOCKHEED AIRCRAFT CORPORATION • CALIFORNIA DIVISION

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Editor's note

When we were casting around for someone to write an introductory article on the Electra we immediately thought of John McDonald as a likely candidate because of his close association with the airplane's development coupled with his airline background. Commenting upon the length of the article which resulted, he observed to me ". . . and it's such an extremely interesting airplane that I didn't know where to stop!" Although future issues of the Digest will continue to include the usual types of articles on the Constellation and Starliner Series aircraft, we have decided to make this a special issue and include the whole article rather than divide it into two issues, because we believe that it will have greater value as a complete entity.

This article is intended to provide something of interest for everyone concerned with the maintenance — and to some extent the operation — of the Electra. It is aimed at the mechanic and the airline engineer while at the same time keeping in mind the executive who normally has little time available for detailed study of a new type airplane. While appreciating the fact that each particular specialist on systems, structure or power plant in the airline will find the notes applicable to his own field somewhat general and incomplete, the principal aim is to show how the whole flying machine "ties together." Subsequent articles of a more specific nature written by experts in their field will appear from time to time in future issues; meantime we hope that this will enable you to gather a good general impression of our new airplane — the second generation Electra.

T. B. D.

THE ELECTRA

PART ONE GENERAL CHARACTERISTICS

by JOHN F. McDONALD
Division Engineer
Service Engineering Division

1. INTRODUCTION

IT IS RARE that an opportunity is afforded in this magazine to write about a completely new airplane, but the advent of the Electra — and the kind invitation from the Editor to write an introductory article — provide me with a unique chance to present to you some of the thoughts and design background leading to the present arrangement of this very interesting turbo-prop — or, as is commercially preferred today, "prop-jet." This article will describe the airplane structures and systems fairly thoroughly, but in order to present a general picture at the outset these notes will more nearly correspond to a technical paper type presentation.

Externally the Electra looks very similar to contemporary transports, probably the only obviously different features being the shape of the engine nacelles and the wide chord four-bladed propellers. Internally, however, the airplane is indeed quite different, particularly from the viewpoint of the design of the functional systems employed. We are sure that you will pardon our enthusiasm if we appear to do a little quiet boasting about some of the airplane's characteristics since it is this writer's opinion that the Electra is, in many respects, probably the most advanced of any of the turbine era transports today, irrespective of size and shape. This is specifically true with regard to the detailed attention which has been given to the all important subject of designing towards superior maintenance characteristics from the earliest pencil lines on the preliminary design drawing board.

This article is divided into two parts: Part One discusses the development history of the airplane and then, after a survey of its characteristics, compares it with an earlier Lockheed transport in an attempt to gauge the extent of the overall design advancement. Following this will be a brief review of the flight station design and then we will discuss the philosophies employed in ramp handling and maintenance characteristics. Part Two will review the differences between the Electra and contemporary transports in some detail, starting with the power plant since it is, after all, the most significantly new aspect of the airplane. The airframe structure is dealt with next, followed by descriptions of those functional systems which incorporate interesting new design concepts. The article will finish by setting the stage for the content of subsequent articles.

2. DESIGN DEVELOPMENT AND HISTORY

Briefly today's Electra is a medium sized airplane intended primarily for short-medium range work but having, in addition, the capability for fairly long range tasks. The power plants are the Allison 501-D13 engines producing 3,750 ESHP for take-off and driving the Aeroproducts type 606 propellers. The aircraft's outstanding characteristics are low operating cost, excellent airport performance characteristics, low noise levels, and fast block-to-block speeds supplemented by designing for minimum time on the ground.

Perhaps a few words about the development of the Electra might be of interest at this point. In the autumn of 1954 design studies were made for a fairly small four-engined prop-jet in a high wing configuration using, among other engines, the Rolls-Royce Dart and the Napier Eland. This airplane was known by the California Division's preliminary design designation of CL-303, and the work was initially undertaken in response to an American Airlines specification which called for a range of 750 statute miles at a minimum cruise speed of 350 mph. Further evaluation of the designs proposed showed the airplane to be economically too small, and there were also some objections to the high wing arrangement because of doubt about its safety in belly landing type accidents or sea ditching.

Another larger model known as the CL-310 was proposed to meet new specifications by both Eastern Air Lines and American Airlines, this time of a low wing configuration and having the basic Allison military T-56 turbo-prop engine — an engine with which Lockheed was already very familiar through the development of such airplanes as the C-130 Hercules military transport. The principal design objectives for this airplane were: must cruise at more than 400 mph and have a range of 1,850 statute miles with an 18,000 lb. payload against a 50 knot wind with adequate fuel reserves. Through the influence of Eastern Air Lines the passenger capacity and range of this airplane were still further increased, accompanied by corresponding increases in the gross weight and wing area, until it eventually became the configuration which is in production today and now known as the Model 188. It was named Electra in honor of the very successful pre-war Lockheed transport of the same name and in the summer of 1955, having received firm orders from both operators, a production design project group was created and work was started in earnest.

The first production airplane was rolled out in November 1957, a month ahead of schedule and the same airplane flew on the 6th of December. CAA certification was completed as programmed on August 22nd of this year. The first delivery will be to Eastern Air Lines in October, and it is expected that Christmas 1958 will see approximately 14 airplanes delivered, several of which should be in passenger service. Today's order book stands at more than 160 airplanes to be delivered to 7 U. S. carriers and to 8 foreign carriers and the total value exceeds $340,000,000.

3. THE ELECTRA TODAY

General. Let us take a broad look at the airplane after all of the design refinement — in which task we were aided immeasurably by the major operators — had materialized. Although turbine powered the Electra is not necessarily a high altitude airplane under normal operating conditions. A basic characteristic of the pure jet airplane is its dependence upon gaining high altitude for acceptable fuel economy and by contrast it is for this reason, perhaps more than any other, that the propeller driven airplane is likely to remain supreme in the short-medium range role. However, before we discuss these aspects further, it would appear to be well to review the size and configuration of today's vehicle.

Size and configuration. With a wing span of only 99 ft. and a length of 104½ ft. it is actually a considerably smaller airplane than the Model 1049 Constellation series, and a good impression of its relative size can be gained from the superimposed profiles of the two airplanes in Figure 1. The basic Model 188A airplane take-off weight is 113,000 lb. and with its wing area of 1,300 sq. ft. the normal wing loading is 86.9 lb. per sq. ft. — a value which is well within the range of contemporary transports. The wing aspect ratio is 7.5 and it has a chord-thickness ratio of 14% at the wing root and 12% at the wing tip. It is interesting to note that the famous Lockheed F-80 Shooting Star jet fighter had a wing thickness of 13%, which is the same as the average thickness of the Electra wing. These characteristics were of course largely determined by the size of the fuselage, which in turn was established by the requirements for passenger carrying capacities. Let us, therefore, now look at some of the interior arrangements available.

Interiors. Initially two basic interior arrangements were designed for the airplane: one, a custom arrangement of 66 passengers seated 4-abreast on a 38″ spacing with a 26″ wide aisle and 20″ wide seats; and two, a standard arrangement for 85 passengers 5-abreast on similar spacing with a 17″ aisle and 18″ seats, in addition to which 6 passengers can be seated in the aft lounge in each version. Figure 2 illustrates these interiors. Large cargo compartments are provided in the belly, and carry-on baggage space is provided in the cabin on each side of the aisle. A great deal of consideration was given to the fuselage diameter to permit maximum flexibility of seating arrangement and the final choice was the unusually large value of 136″, which per-

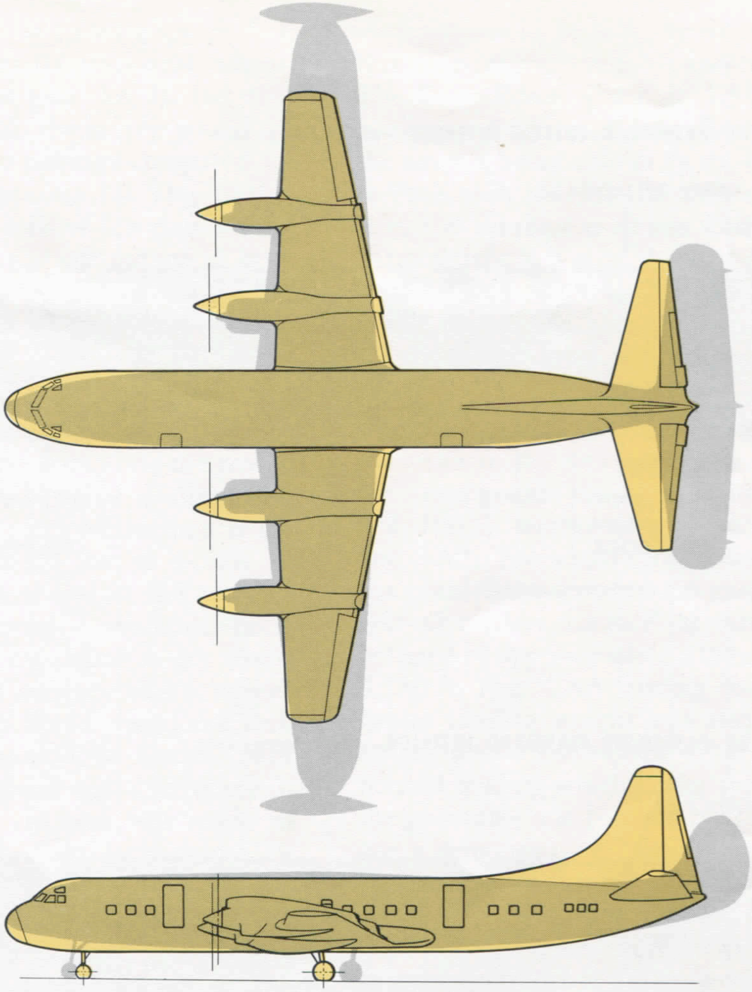


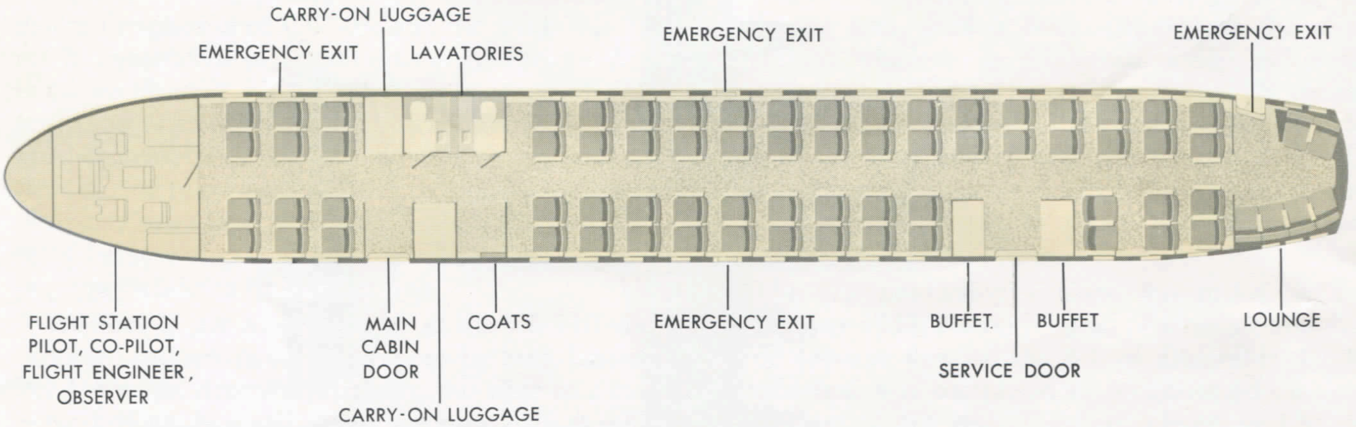
Figure 1
Size Comparison
of the Electra and
the Model 1049 Constellation

mits varying schemes from 4-abreast in luxury versions up to 6-abreast in "thrift" or "economy" class arrangements. Some layouts have been made in the latter category providing accommodation for as many as 120 passengers. An International interior version of the airplane is in production, which differs principally from the other two arrangements in that it has toilets at the rear of the airplane in addition to the amidships location and has a navigator's position in the flight station. This interior is also illustrated in Figure 2. Provision is made in this version for 83 passengers, but since a seat track arrangement is available the airline operator can easily and rapidly re-arrange the interior to suit a particular route condition, up to a maximum of 99 passengers.

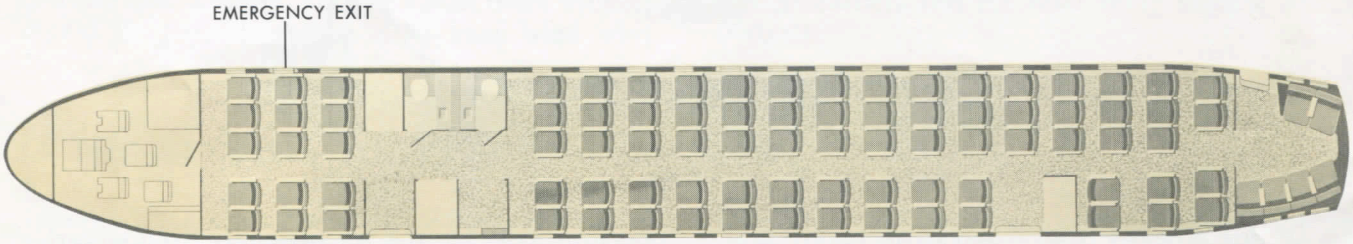
Operating cost. The large seating capacity is responsible for an extremely low passenger seat/mile cost which, of course, is one of the airplane's most important features. The direct operating cost varies little with altitude primarily because the main thrust producing device is a propeller. For example, the cruise altitude can be varied from 16,000 to 26,000 ft. with only 1% variation in operating cost. This permits short stage routes to be flown at economical altitudes. Using the 1955 ATA formula the direct operating cost for the 85 passenger version varies typically from 1.4 cents per seat/mile at around 2,000 miles range up to 2.0 cents at short ranges of approximately 200 miles. A recent Lockheed study of world seat/mile statistics showed that more passengers are buying tickets for the 150-400 mile range flight than any other.

Airport performance. The high landing and take-off frequency inherent in the Electra's mission has accentuated the need for superlative airport performance, both in terms of short landing and take-off distance, and maximum flexibility in the air traffic control pattern. The airplane was basically designed for operation within the limitations imposed by 5,000 ft. runways and since a marketing review shows that some 50 per cent of the world's scheduled airports have main runways of this length or more, the aircraft can serve a large proportion of the community. Originally the airplane was fitted with fuselage-mounted speed brakes to provide adequate descent control characteristics, but flight test work has shown that the very high drag available from the propellers alone makes it possible to easily meet the specification requirements and consequently the speed brakes have been removed. The airplane can fly in

66-PASSENGER CUSTOM INTERIOR *—plus 6 lounge seats*



85-PASSENGER STANDARD INTERIOR—*plus 6 lounge seats*



83-PASSENGER INTERNATIONAL INTERIOR *—mixed class arrangement*

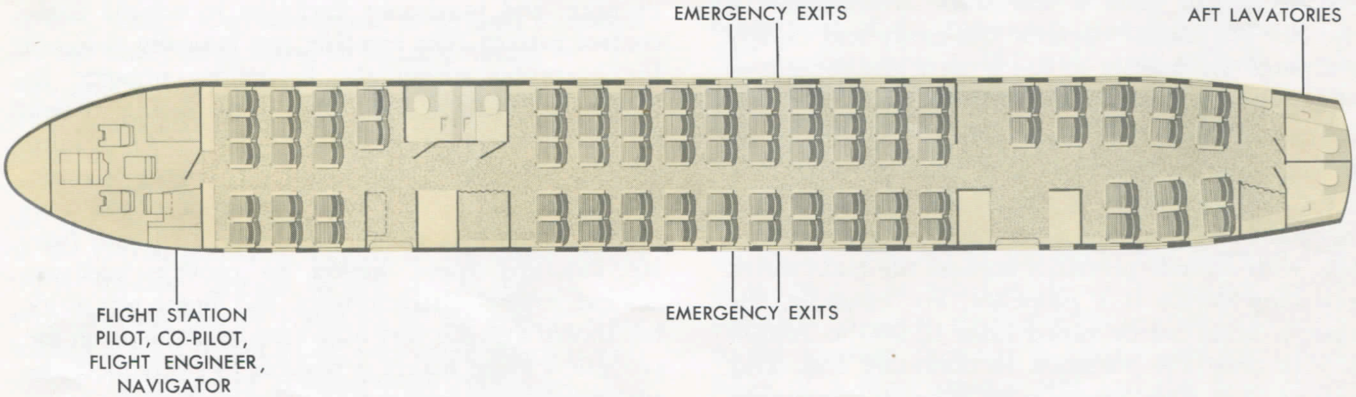


Figure 2 Interior Arrangements

existing airport traffic patterns at existing speeds and does not require the preferential treatment which may have to be accorded the pure jet. In fact the Electra shows 2.5 to 3 pounds thrust per pound of fuel consumed under these conditions compared to a typical pure-jet value of just over 1.0. Due to the high propeller drag, landing rolls of less than 1,000 feet have been accomplished without the use of propeller reverse pitch and only the minimum use of wheel brakes at the latter end of the roll.

The baulked-landing climb capability of this airplane is unique and is largely due to the fact that the propeller slipstream covers most of the wing area. The propeller is a good high lift device and the power response of the constant speed engine is almost instantaneous since no engine acceleration time is involved. Thrust can be developed just as rapidly as the propeller can change pitch, and in this case an angular rate of 15° per second is available. Such immediate thrust producing capability is not available with the large pure jet airplane and a typical comparison showed that with similar speed and sink rates in the approach configuration the Electra could reach a satisfactory flying speed again in approximately 2½ seconds after a decision was made to accept the wave-off, while the pure jet required 19 seconds to reach the same conditions.

Speed. As a propeller driven aircraft it is very fast, having an average cruise speed of well over 400 mph and a critical dive Mach number of .711. Its speed advantages are in the region of 100 mph over contemporary piston-engined transports and its overall block speeds on recurrent short sector type operations will be appreciably higher because of the minimum ground time features such as carry-on baggage, minimum ground equipment, integral engine starting, etc. Exceptional rates of climb of the order of 2,200-2,500 ft/min. for average conditions at sea level are possible because of the large climb powers available with the prop-jet engine. The airplane will climb at more than 1,100 ft/min. on any three engines at maximum gross weight and will maintain a positive rate of climb on two engines — at sea level standard day conditions, of course.

Range. The maximum range is up to 2,650 st. miles, under still air conditions, but the design zero fuel and landing weights are high in relation to the take-off weight, so that operation at ranges of 150 miles or less is entirely practical economically. After a flight from Chicago to Albuquerque (1,123 st. miles) for example, it is still possible to fly on to Los Angeles (676 st. miles) against a 50 knot head-wind all the way without refueling carrying an 18,000 lb. payload and 2 hours reserve fuel. Another example would be a flight from Cairo to Paris via Rome under the same 50 knot headwind condition. The Cairo-Rome sector of 1,320 st. miles permits landing and taking off from Rome without refueling, the aircraft being able to fly the remaining 697 miles to Paris with roughly the same reserves and payload as in the previous example. This is a very important characteristic of a good short-medium range transport since it permits great flexibility in a route pattern where alternating short and medium stage lengths are encountered such as in U. S. and European routes.

Flight Testing. The CAA certification of the airplane conforms to the new regulation SR-422 which calls for, among other things, a 35 foot obstacle clearance and 100% temperature accountability for take-off and climb. The actual certification testing at Burbank has enabled the specification guarantee for the "CAA take-off runway distance" at maximum weight to be bettered by approximately 21%, the new figure being 4,730 ft. The "CAA landing distance" for maximum design landing weight was also improved by 10% resulting in a certificated value of 4,867 ft. At the normal landing weight point specified by the airlines the guarantee was bettered by 14% giving 4,280 ft., and a demonstration landing was accomplished after clearing an imaginary 50 ft. obstacle in 2,565 ft. total runway distance to a complete stop, with only the minimum use of reverse thrust. (This latter figure should not be confused with the landing roll mentioned in a previous paragraph under "Airport Performance.") The actual cruising speed performance is better than the specification requirement and the airplane empty weight is well below the guarantees. The fuel system capacity is substantially larger and the refueling rate much higher than the guarantees. In general the airplane has met or exceeded all of the requirements to which it was designed, in some cases by very handsome margins.

Airplane growth. Future growth in the Electra is made possible by the installation of the Allison 501-D15 engine of 4,050 ESHP, and the engine nacelle has been configured to accept the higher powered engine when it becomes available, with very minor changes. The existing Aeroproducts propeller is suitable for the new engine, and the existing propeller reduction gear box is also suitable for the increased power. The airplane has been designed both structurally and aerodynamically to take care of this power plant change. Optional changes are now available to increase the gross weight to 116,000 lb. and a long range version of the airplane is under study, all the additional fuel being contained internally within the wing.

Ramp handling. Because a short-medium range transport of this type must necessarily spend a high proportion of its time in transit through en-route stations, it is particularly important that its superior cruise speed and airport performance characteristics be matched by minimum lost time on the ground. For this reason the airplane was designed to operate with minimum ground equipment and the elimination of so-called "ramp clutter." Loading, replenishing and refueling as well as passenger embarkation and disembarkation were designed for accomplishment at main terminal turn-around stations in 20 minutes, and en-route stations can be cleared in as little as 12 minutes, since refueling in the latter case would not normally be required. The significance of these values is apparent when one considers that an increase of 5 minutes over the ground times quoted, at for example a stage length of 200 miles at 15,000 feet would effectively mean a loss of block speed of 20 mph, or in another example of a stage length of 700 miles at 20,000 feet, a loss of 12 mph. This subject of fast ramp handling will be discussed in more detail later in this article.

Functional systems. To carry the foregoing thoughts into effect the principle of "self-containment" of the airplane's systems, i.e., minimization of the need for ground equipment, was provided for by the use of a single ground power source, completely self-contained heating and cooling, optional integral engine starting provisions and fast single point pressure refueling. The extensive influence which these requirements have had upon the airplane's functional systems will be particularly evident in Part Two of this article, and perhaps if there is a single statement which could be made, it would be that we have made the utmost use of alternating current electrical power to achieve the objective.

Noise. That much discussed problem, noise, has received careful consideration in the Electra, both internally and externally. To reduce cabin noise the engines were placed well outboard providing a clearance of some 40" between the propeller tips and the fuselage, and the fuselage structure is stiffened in the propeller plane area. The linear tip speeds of the propellers are quite low (721 ft./sec.) and propellers are equipped with a *phase synchronizer system. Special acoustical treatment is used in the cabin walls and floor and acoustical damping tape is used on the inside of the fuselage skin. Rotating machinery within the fuselage is mounted on suspension systems designed to avoid transmission of noise into the fuselage shell and many units are enclosed in acoustically absorbent boxes. The guaranteed specification average upper frequency noise level of 70 decibels has been bettered — the actual measured value being 65 db while the low frequency guarantee of 95 db has been met with an actual of 87 db.

Externally, an acceptably low noise level at the passenger ramp is assured by the provision of a low ground idle engine speed which is also used for taxi purposes. Compressor whine — characteristic of certain centrifugal flow turbo-prop engines — is noticeably absent. Characteristically the take-off and climb noise level is very much lower than that of contemporary piston engined transports and the airplane should thus be able to secure good community acceptance. Recent measurement of the external noise level by an independent group on behalf of the Port of New York Authority has confirmed that the average level at 200 feet distance is only 92 db.

Structures. Structurally the airplane has been designed to have comprehensive "fail-safe" characteristics, combined with long fatigue life. The semi-monocoque fuselage is of conventional fabricated construction while the wings use further developments of the Lockheed integrally-stiffened type design. Exhaustive fail-safe testing and fatigue life spectrum analyses have been conducted, and since this is one of the areas in which the development of the Electra differs extensively from past practice it will be described in more detail later in these notes. It should be mentioned here, however, that all three landing gears retract forward and are arranged to fall free and lock down in the event of hydraulic failure. Provisions are also made for mechanical release of the gear from the up position if the normal uplock should be jammed.

Power plant. In all of the foregoing characteristics the significant effect of the new power plant can be seen: in weight, power, propeller control, structural design, and systems arrangements. The 501-D13 engine is approximately half the weight of a comparable reciprocating engine, say the C18-EA3 engine in the Model 1049G airplane and has a specific weight of only .467 lb/ESHP. The axial flow arrangement of the engine results in small frontal area as can be seen in Figure 3 and the cooling drag is extremely low. The high position of the engine air intake is most favorable from the viewpoint of avoiding the ingestion of foreign objects thrown up from taxi strips or run-up areas.

The single spool engine has its own peculiar starting characteristics and the constant speed operation in all take-off and flight regimes has had important

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**See Field Service Digest issue of January-February, 1958 describing the principle of this system on the Model 1649A Starliner.*

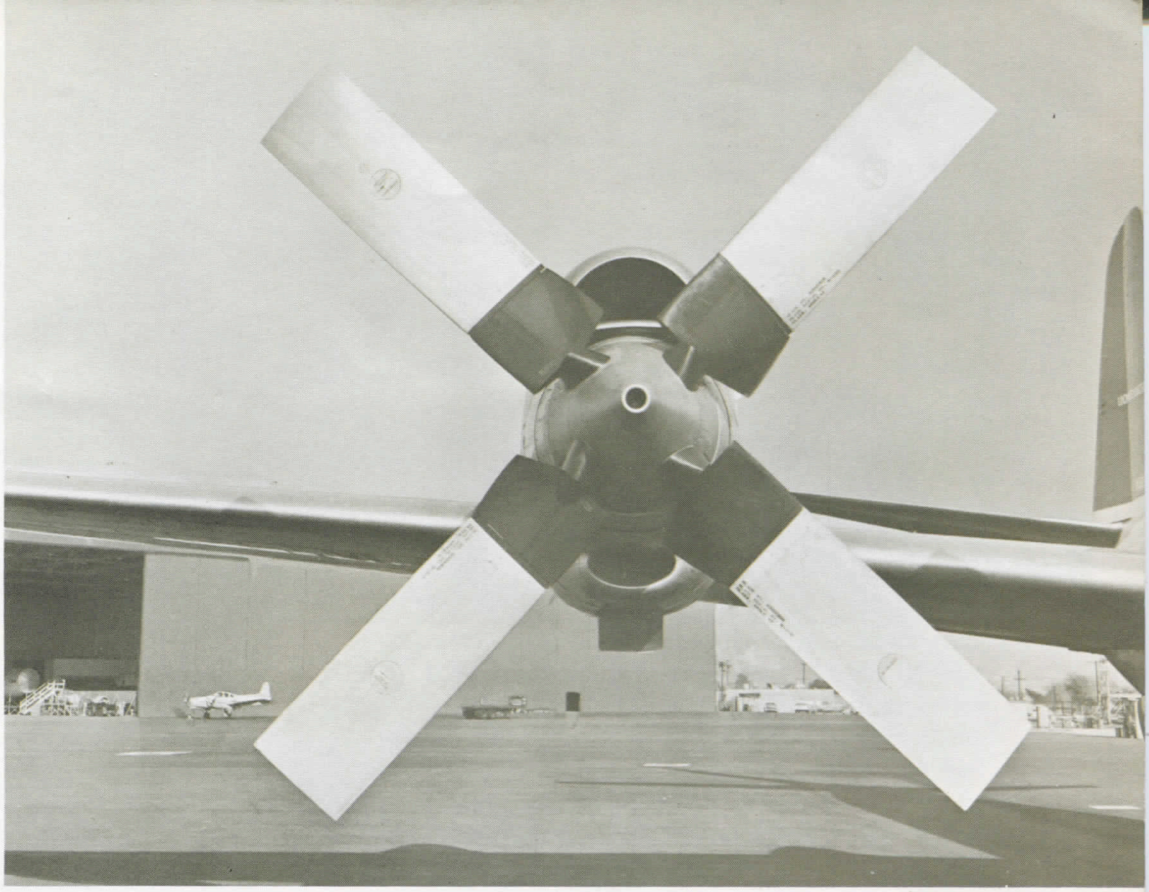

Figure 3
The Aeroproducts
Propeller

effect upon the design of functional systems in the airplane. It has been possible, for example, to completely eliminate the use of constant speed drive units for the electrical generators such as would usually be required for variable speed engines of the two spool or free turbine type. Similarly the cabin supercharger has become a much simpler unit thus reducing the weight and size sufficiently to enable it to be mounted directly on the engine accessory pad. The availability of hot air bled from the engine compressor has entirely changed the anti-icing system design among other things; however, it would be out of place to attempt to understand all the effects without first understanding the engine-propeller characteristics themselves. For this reason the power plant, its control and its safety devices will be dealt with at length in Part Two.

Equipment. Many new equipment installations are included in the Electra, some appearing in a delivered airplane for the first time. The RCA C-band weather radar is of particular interest in view of the large diameter reflector (30″) which provides a beam appreciably narrower than that obtainable with smaller reflectors, thus improving range and definition. The Eclipse-Pioneer PB-20E auto-pilot is provided with two new features: (a) "pre-select heading" which will automatically turn the airplane on to a pre-determined heading and hold it there and (b) "auto glide slope capture" which, as the name implies, provides automatic control on the ILS approach glide path. Several flush radio antennae are fitted, among them being VOR and VHF, both of which are installed in the vertical fin; DME—Tacan and ATC radar safety beacon (Airways Traffic Control) flush antennae mounted in the fuselage belly; a flush-mounted dual ADF antenna system to the latest AIRINC specifications installed in the fuselage belly below the wing center section and, last but not least, a Lockheed designed glide slope antenna mounted in the nose radome area providing a much better performance than the conventional type.

Two Eclipse-Pioneer Continental compass systems are installed which may be operated as either gyro-stabilized magnetic compasses or alternatively as free gyro compasses. The integrated flight instrument systems which are optionally available from Bendix, Collins or Sperry are of considerable interest. Essentially these systems receive inputs from radio navigational aids, compass systems and vertical gyro systems, the signals being fed into a computor and displayed on the pilot's flight instrument panel by a single instrument. Thus the pilot has only to fly to the single instrument instead of having to make complicated mental calculations, so that he, in effect, is simply providing the eye-to-muscle link to complete the servo system loop. Great care was taken to provide a good public address system which would be audible under all conditions and, to accomplish this, a speaker has been installed at each individual pair of seats on the under side of the hat rack.

1946 —
The Model 049 Constellation

1958 —
The Model 188A Electra

Figure 4

4. CONSTELLATION COMPARISON

Weights. Sometimes it is of considerable interest to evaluate the advances which have been made over the years, and many of you will remember the Model 049 Constellation, illustrated in Figure 4, when it was first delivered in 1946. This airplane was indeed a leader in its day and did a great deal to establish North Atlantic passenger service on sound commercial lines in the first post-war years. Comparing it to the Electra some twelve years later, let us look first of all at the significant advances in the weight field.

	049 CONSTELLATION	188 ELECTRA
Take-off weight	90,000 lb.	113,000 lb.
Landing weight	77,800	95,650
Maximum zero fuel weight	75,960	86,000
*Weight empty (approximate)	52,500	56,000
Fuel capacity	28,140 lb. gasoline (4,690 U.S. gals.)	36,984 lb. kerosene (5,520 U.S. gals.)
†Payload — maximum weight limit (approximate)	16,000	26,000

**"Manufacturers weight empty" including passenger seats, galley, radio, etc., but not including such items as blankets, pillowcases, galley supplies or crew with baggage.*

†*"Weight limit payload" is the maximum weight that can be carried irrespective of space limitations and will decrease considerably in practical airline operation according to range.*

You will see from this table that while the Electra's total structural, power plant and systems weight has increased by only 6½%, the fuel weight has increased nearly 32% and the take-off weight by more than 25%. Not all of this is direct gain, however, because the fuel is heavier and the specific consumption of a prop-jet is higher than a comparably-powered reciprocating engine thus using more fuel for a given range. The empty weight to take-off weight relationship has been reduced from 58% to approximately 49% — considered a major achievement in design engineering. If the increased gross weight value of 116,000 lb. is used (referred to in the ELECTRA TODAY section) the empty weight percentage is still further improved to approximately 48%.

The improvement of the design zero fuel weight relationship to take-off weight and landing weight is of considerable economic importance because of its effect upon the ability to perform alternating long and short hops on a given route carrying a large "through payload" without refueling. The last item in the table, however, is the most significant one of all, and it shows an increase in weight limit payload of approximately 63%.

Passenger capacity and environment. Passenger capacity is, of course, one of the most important comparisons which must be made, and the increases that have been made possible in the Electra stem very largely from the improvement in the weight situation outlined in the preceding table. In the typical comparison given below both provide First Class type accommodation.

	049 CONSTELLATION		188 ELECTRA	
Main cabin seats	43	4-abreast	66	4-abreast
Lounge seats	None		6	

It is interesting to note that seat spacing and average aisle width is actually considerably superior in the Electra to that provided in the early Constellation and, of course, the significant value of the lounge from the passenger appeal viewpoint will be readily appreciated. To make the comparison complete in this area we should also consider some of the environmental characteristics and facilities as follows:

	049 CONSTELLATION	188 ELECTRA
Fuselage pressurized volume	5,855 cu. ft.	7,785 cu. ft.
Cabin differential pressure	4.17 psi	6.55 psi
Total cargo/baggage volume	434 cu. ft.	636 cu. ft.

Of the foregoing comparisons the most significant is the increase in fuselage pressurized volume — actually some 33%. It is interesting to note that the Electra, while being in the overall sense a much smaller airplane than the later Model 1049G Constellation series has, in fact, an almost identical pressurized volume. The cabin pressurization improvement means a typical cabin altitude of 8,000 ft. at an airplane altitude of 30,000 ft. instead of 20,000 ft. The cargo space together with the carry-on baggage space in the cabin provides an increase in capacity of approximately 46%.

Speed and Power. No comparison would be complete without consideration of speed especially since it is, particularly in the case of a short-medium range airplane, one of the most important measures of the operational capability of doing work — in other words to fly a given route in less time and thus be available for further revenue flying. The values quoted below are typically those which an airline would actually use in practice and have no relation to the design structural speeds which are usually placarded in the cockpit.

	049 CONSTELLATION	188 ELECTRA
Maximum take-off power—total	8,800 BHP	15,000 ESHP
Maximum cruise power—total	4,400 BHP	9,720 ESHP
Cruise speed average	236 knots TAS	348 knots TAS

The increase in take-off power is, of course, very significant considering the relative take-off power loading of the airplanes. Of equal or perhaps even greater importance, however, is the much higher practical percentage of take-off horsepower which can be used for cruise purposes, this being a particularly advantageous characteristic of the turbine engine.

The large increase in cruise speed of 112 knots (129 mph) is, of course, due principally to the high cruise power. It should be noted that in the example above, 1,100 BHP per engine was used for the Model 049 case and 90% MRT (maximum rated temperature) for the Electra, both being taken at representative average weights and at the same altitude, namely 16,000 ft.

Summarizing, it is apparent that enormous advances have been made in structural weight, systems weight (which includes many new requirements), passenger capacity, payload and speed. Add to this the minimum ground time characteristics of the Electra together with airport flexibility and it can be fairly stated that substantial progress has been made.

5. FLIGHT STATION DESIGN

Upon entering the Electra flight station one is immediately impressed by the width and roominess as well as the excellent visibility. This is in part brought about by the rapid transition necessitated by the short fuselage nose section from the full diameter of the fuselage at the cockpit-to-cabin bulkhead, and permits the unusual arrangement of laterally sliding Captain and First Officer's seats to eliminate congestion. The two main windshield panels are probably the largest on any new transport and the short nose permits a 15° downward vision angle. The cockpit conforms basically to the SAE Type II, being arranged with the Flight Engineer's seat in the center between the two pilots and with an observer or check pilot's seat on the left behind the Captain. The arrangement is such that although designed for a three-man crew, the airplane could be flown by pilot and co-pilot in emergency ferrying operations. A general view of the flight station is given in Figure 5.

The cockpit width, permitting as it does this 3-abreast crew arrangement, also necessitates duplicated power lever controls for the pilots. An advantage stemming from the wide cockpit is the generous panel space provided for the Flight Engineer's instruments in the center group. Of these the most important instrument is now the turbine inlet temperature gauge (TIT) which corresponds very roughly to the function of the manifold pressure gauge in reciprocating engine practice. The other engine instrument of almost equal importance is the torquemeter which now, for the first time, is calibrated directly in horsepower. The flight instrument group gives pride of place to the weather radar scope and the panels are rigidly mounted — that is without shock mounts. Red, white or mixed lighting is provided and a large anti-glare shield is fitted to prevent instrument reflection on the windshield.

A special design team worked on the cockpit layout as a part of the preliminary design group right through to the production design stage and succeeded in making one of the most pleasing and yet truly functional flight stations in any of the new series of airplanes. For example, the crew seat design is attractive and clean with no exposed structure or mechanism, and all of the adjustment lever motions are in the correct sense of the travel desired. Even the name-plates on the panels have been the subject of special study for maximum readability under poor light or crew fatigue conditions. Attention has also been paid to the "crash worthiness" of the cockpit by the provision of non skull-piercing controls overhead, together with shoulder harness for the crew, etc. The sliding window panels were intentionally made large enough to serve as emergency escape exits.

Separate air temperature control is provided for the flight station when the cabin door is closed so that the long standing problem of widely varying comfort levels in crew and cabin areas is eliminated. The radio and electronic rack is partitioned off so that all the hot air is dumped overboard, air for cooling being independently supplied from the main air conditioning system. A fan provides cooling for this equipment when the airplane is on the ground. Individual outlets are provided for cooling air for the pilot's face and adjustable foot heating outlets are also installed. Windshield defogging is provided by a fan installed above the ceiling and the air flow can be adjusted to clear any particular local area. Transparent electrical heating film is used in the windshields, which are bird strike resistant.

6. RAMP HANDLING

The necessity for superior ramp handling characteristics and the adoption of "self-containment" design have been touched upon previously. The influence of these requirements upon the airplane is very significant and deserves further discussion. The need for minimum ground time from the economy viewpoint is but one aspect of the problem, and the other requirements of operation from smaller and sometimes poorly equipped airfields, or emergency alternates, have also received careful design consideration. The airplane was arranged so that not only would the need for a multiplicity of ground power sources be avoided, but also that the ramp equipment would be properly positioned to avoid confusion during a fast turn-around. Figure 6 shows a typical arrangement of equipment which could be expected at a terminal station. The airplane has been arranged so that all of the passenger embarkation functions can be accomplished from the left side of the airplane while refueling, cargo loading, water replenishing, toilet draining, and so forth can be accomplished from the right.

The basic airplane uses an external engine starting power source which involves an additional piece of

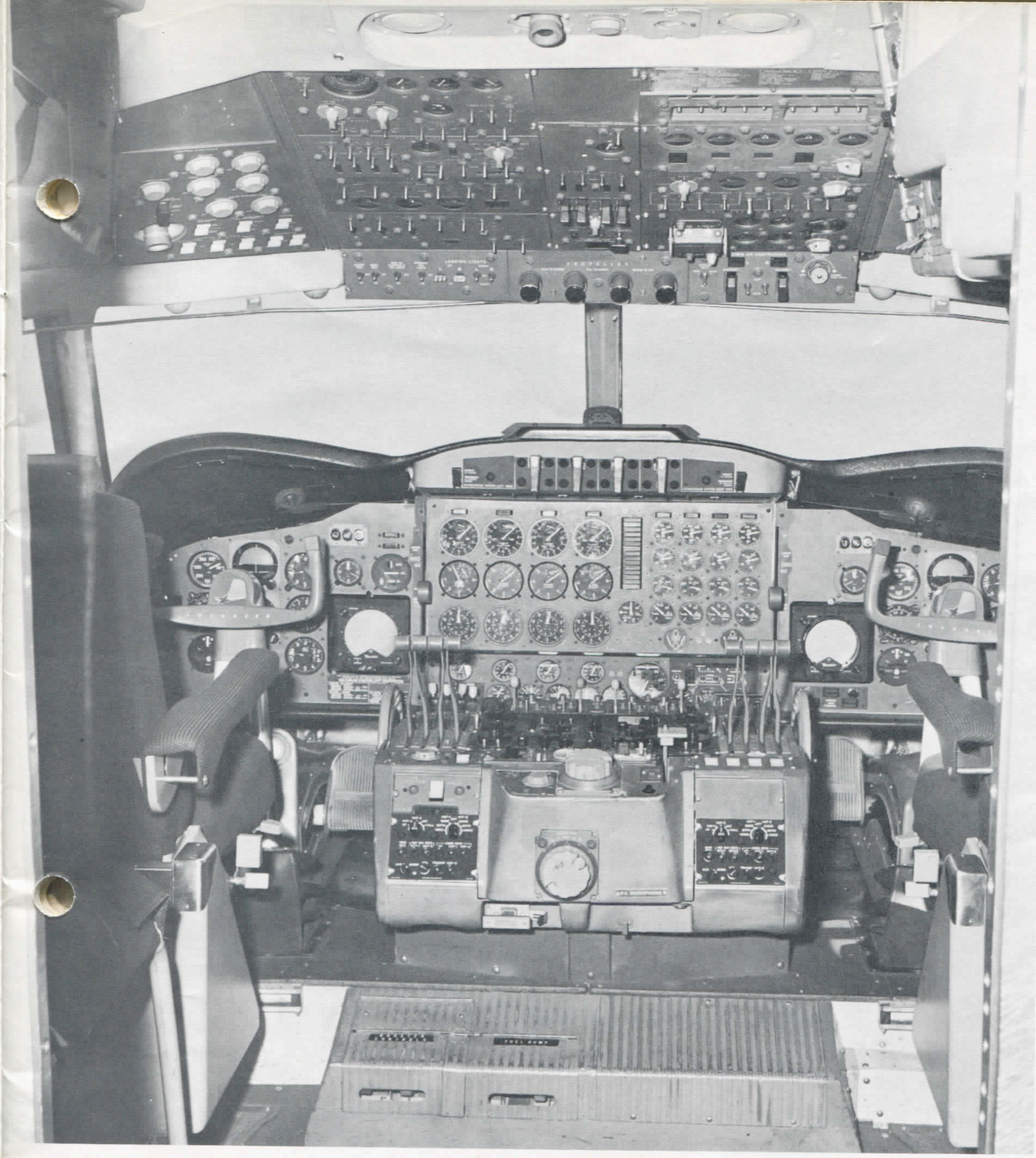

Figure 5
The Flight Station

ground equipment not shown in the illustration. To provide for the complete self-containment philosophy, however, an integral engine starting system is available and a number of operators have elected to use this. The starting sequence is such that the No. 4 engine is normally started first and conversely shut down last, the electrical system being arranged so that adequate power is available on the airplane for lighting and other purposes with only one engine running. All of the remaining engines can be started from No. 4 engine if desired by an interconnecting manifold; in fact any single engine will start the remainder in any combination. The No. 4 engine could be kept running during a fast transit operation where perhaps only two or three passengers are involved, thus saving several minutes in the shut-down and starting operation.

A large output alternating current electrical ground power cart (approximately 75-90 kva) is used in cases where all of the internal services are required, while at stations wherein the rapidity of transit obviates the necessity for heating or cooling facilities, a smaller ground unit can be employed (approximately 15-35 kva). For safety reasons the ground

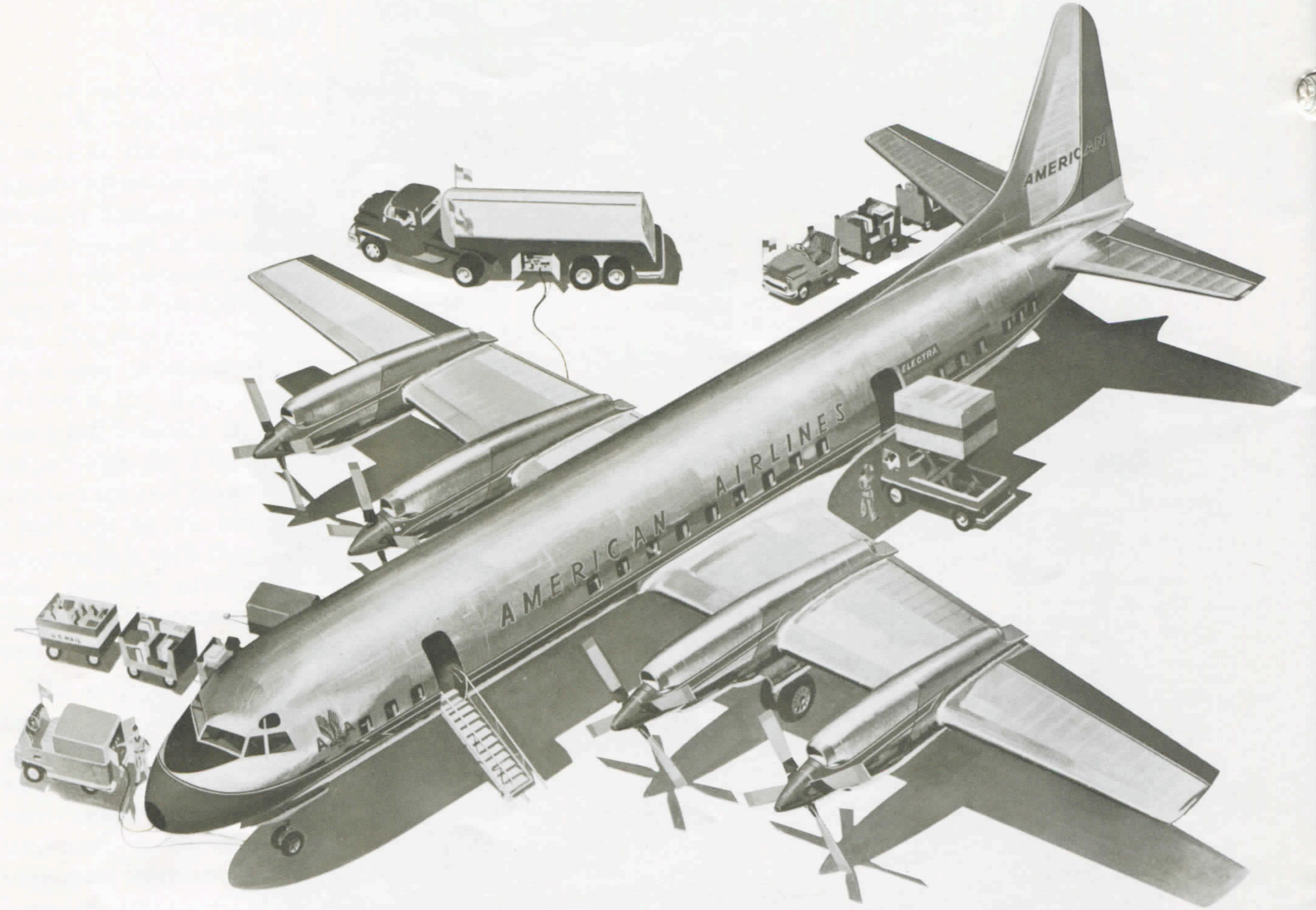

Figure 6 Ramp Handling at a Terminal Station

electrical power connection has been placed right up at the nose of the aircraft so that the crew can observe the position of ground trucks before taxiing away from the ramp. The ground electrical source will provide full cooling from the vapor cycle section of the air conditioning system, or conversely, full heating from the electric elements including fast warm up for extremely cold conditions. This entirely obviates the need for the usual external cooling or heating ground trucks and the system is part of the basic airplane design.

The hydraulic system, because of its electrically driven pumps, can be operated at normal working pressure on the ground thus making possible, for example, a complete check-out of the hydraulic surface control booster system without running the engines. Similarly, power is available for brake accumulator charging, integral passenger stairway operation, etc., either from the external a-c ground power source or, in emergency, from the d-c system powered by the aircraft's battery. It is this latter d-c function which makes it possible to operate an Electra equipped with the integral engine starting system out of an airfield with absolutely no ground equipment of any kind — a characteristic which we believe to be unique for a turbine-powered transport.

The fuel system uses a single point pressure connection, a control panel complete with tank gauges and a safety pre-check system all mounted in the No. 3 engine nacelle afterbody. This position makes hose connection an easy task without using step ladders or work stands and illumination is provided for night operation. The refueling rate is over 400 gpm and the average elapsed time for filling all four tanks from a typical minimum value to full is approximately 14 minutes. The improvement in refueling conditions brought about by such a system,

Figure 7 The Passenger Stairs

particularly for inclement weather and night operation, is most beneficial in reduction of the total refueling times, i.e., from the arrival of the fuel truck to its departure. Provision is also made for over-wing refueling at stations where pressure trucks are not available.

The cargo doors are exceptionally large (52″ x 42″) and are low enough that, in emergency, the compartment could be loaded or unloaded from the ground or by the use of an upturned box upon which a man could stand. The doors are so positioned that it should normally be possible to drive small ramp tractors and cargo trucks around in a circular movement rather than having to back into the loading position. The integral passenger stairs (see Figure 7) need little further comment here, except that they can be fitted to the aft cabin door as an alternative to the front position since the doors are basically interchangeable. It is impressive to watch the airplane arrive and park, the cabin door opening electrically and the stairs lowering hydraulically, followed almost immediately by the first disembarking passengers — some carrying their luggage — all in the space of some 30 seconds.

Taxiing and ground maneuvering is similar to current practice and, if anything, somewhat easier due to the large thrust which is available immediately on demand with the propeller control system employed. Airplane backing-up is permissible using the propeller reverse thrust. Engine cooling on the ground is excellent and, unlike reciprocating engines, is not critical in terms of airplane orientation into the direction of the wind. Tailpipe temperatures are quite low since the majority of heat energy, broadly speaking, is converted into shaft horsepower and the exhaust efflux is cooled by an ejector section which introduces ambient air between the engine and the forward end of the tailpipe.

7. MAINTENANCE CHARACTERISTICS

As was observed briefly in the introduction, the Electra was primarily intended to have superior maintenance, overhaul and servicing characteristics right from the earliest preliminary design days, if it was to complement its flight operation economics by the minimum mechanical delay rate and the lowest practicable overall maintenance cost. Many of our readers may not be aware that Lockheed employs a special group of ex-airline engineers whose efforts are devoted exclusively to the betterment of maintenance design characteristics. This was achieved by working closely in the earliest stages with the Preliminary Design group, in the intermediate stage with the Production Design project group and with the customer, and in the final stage by study of detailed airplane problems in service through liaison with the Field Service group. This degree of continuity of thought is afforded throughout the entire design stages which, we hope and believe, will make the Electra an outstanding airplane from the viewpoints of maintenance economy and convenience. We think you might be interested in some of the considerations which dictated the airplane layout finally adopted.

During the early design layout stages it became apparent that the requirement for a thin wing on the Electra would immediately predicate that many items of equipment similar to those which were formerly mounted within the leading or trailing edge areas of a thick wing like that employed on the Constellation, would now have to be mounted within the fuselage. For example, such things as air cycle cooling machine packages, wing life raft stowages and cabin combustion heaters could certainly not be contained in the Electra wing since the whole of the trailing edge was, in effect, filled with flaps and ailerons. Furthermore, to make the fuel tanks of the requisite capacity meant that the leading edge would not be very deep in the chordwise direction either.

The logical outcome of all of this was that we would have to put more equipment within the fuselage than ever before, but in the process it must be accessible and properly grouped from the viewpoint of specialized equipment and trades skills. This led us to adopt the service center concept shown in Figure 8 and the reasons underlying this particular arrangement are worth repeating here. As a first con-

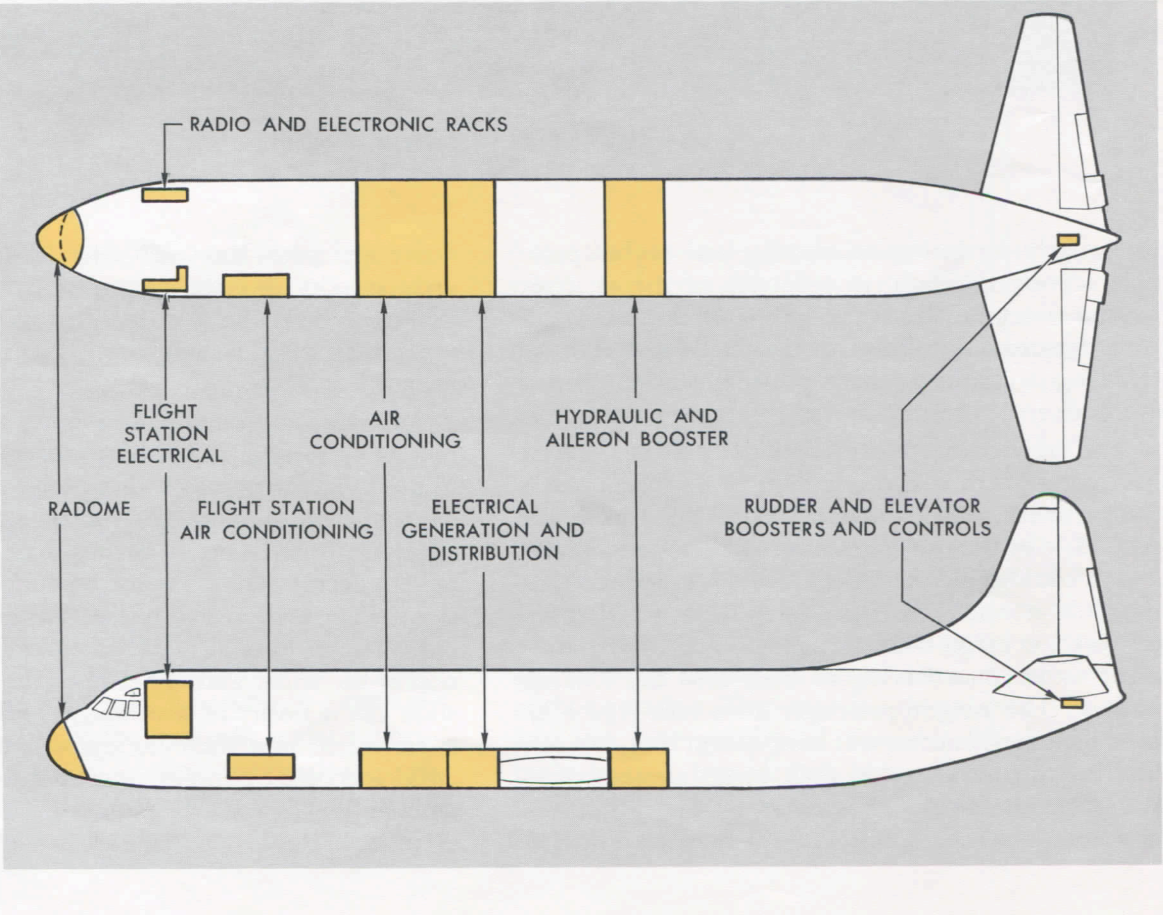

Figure 8
General Arrangement
of Service Centers

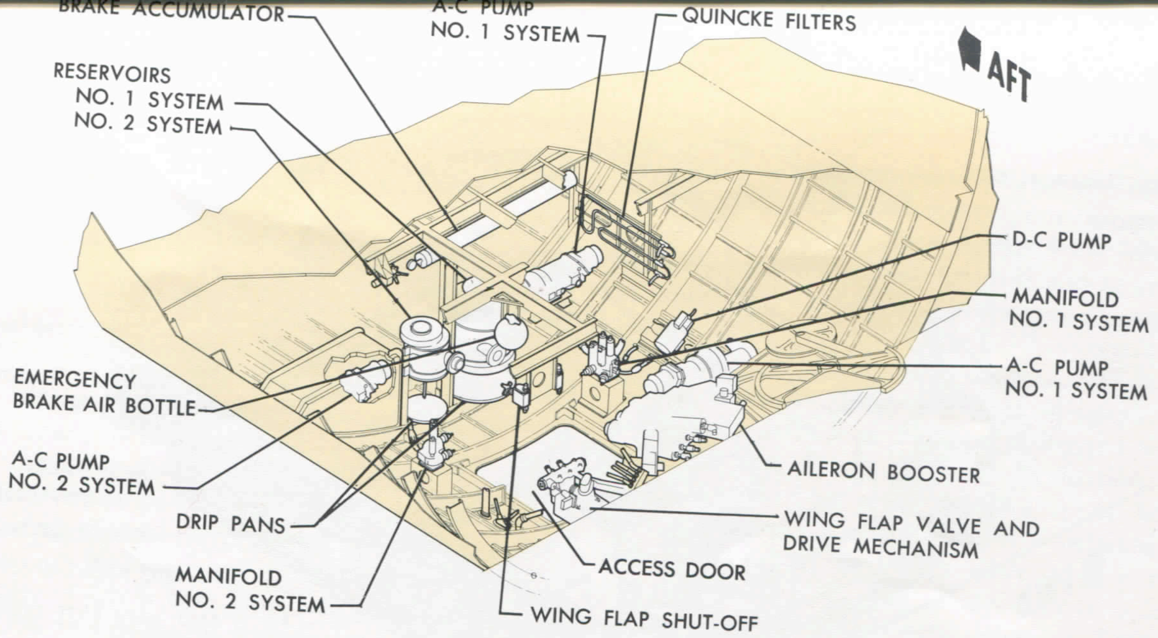

Figure 9 The Hydraulic Service Center

sideration we obviously could not be wasteful of space for the service centers since every cubic foot used for this purpose was to be taken out of potential cargo compartment capacity. At the same time we had already set ourselves the objective of avoiding, as far as reasonably possible, the necessity of entering the cargo compartment to accomplish work concerned with the aircraft's functional systems.

The first service center to be established was that containing the hydraulic components (see Figure 9) and, because of the existence of a single inboard surface control booster for the ailerons, this fell logically behind the rear face of the wing box beam. The decision to drive the hydraulic pumps electrically instead of placing them in the engine nacelles also lent support to this arrangement and provided a complete hydraulic power generation, control and distribution center. The next problem to be tackled was the design of the electrical component arrangement and, because of the convenience of running the main generator feeds from each of the four nacelles straight down the front face of the wing beam, it became logical to group these components forward of the wing box beam as illustrated in Figure 10. In addition to providing a group location for the main generation and distribution equipment, it also provided a good place for the future addition of central gyro type instruments or anything of this kind since it was fairly close to the airplane's center of gravity. Another important factor is that, in the case of a belly landing, the causes of fire ignition — principally electrical — are well separated from the combustibles, such as hydraulic fluid, by the very strong center section box beam structure.

It was realized almost from the outset that this airplane would have extensive electrical systems and that it would take full advantage of the gains to be derived from the use of alternating current prime generating systems. Consequently, if all of this electrical equipment was to be crammed into the one service center, it would produce bottlenecks in maintenance due to the limited number of people who could work in the area. Additionally, such an arrangement would also probably involve running numerous extra feeds to other areas such as the cockpit. To avoid these problems, an electrical sub-center was established in the left hand side of the cockpit (see Figure 8 again) and the nose wheel well was also used to house less vulnerable components such as transformer-rectifiers, inverter, and the airplane battery. By spreading out the electrical work areas in this way — and also in several other ways to be mentioned later — we have tried to avoid the traditional bottleneck which a poorly designed cockpit can cause, particularly in the overhaul task.

The last major group of components to be considered were those concerned with the air conditioning system. These are illustrated in Figure 11, which shows the service center. Because such a system must always employ large units like heat exchangers, condensers and large fans, it appeared logical to arrange these in a manner so that, while all maintenance work could be done from outside the airplane, access should also be available to remove

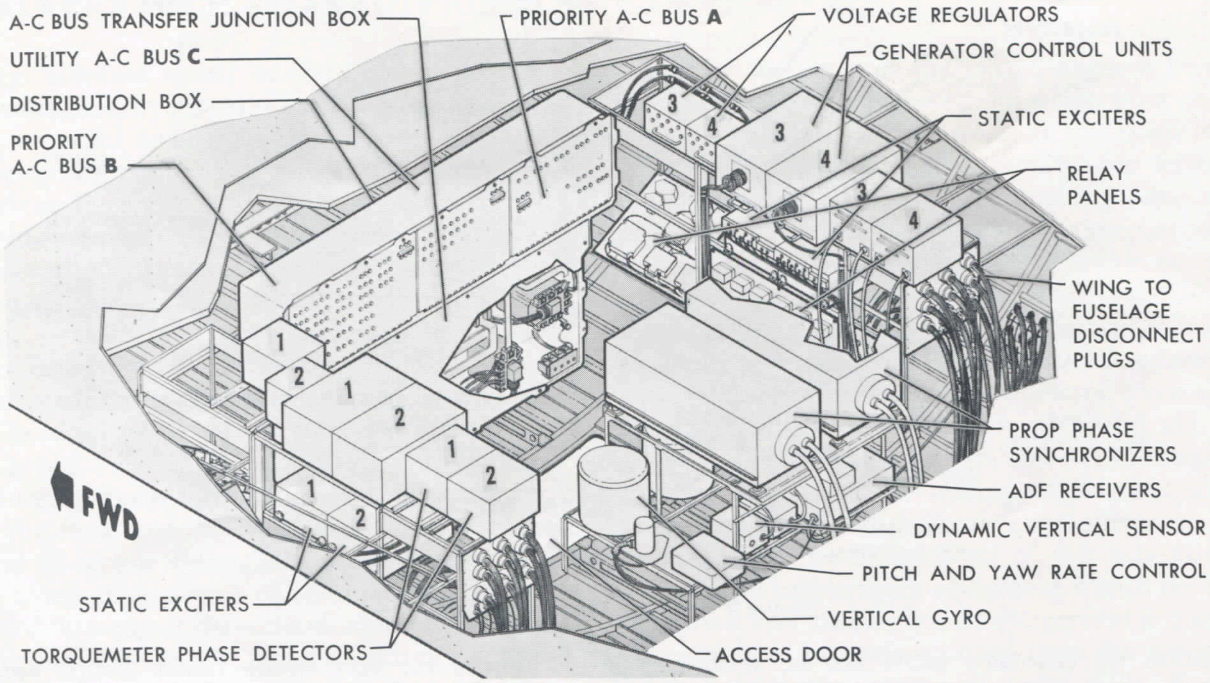

Figure 10 The Electrical Service Center

the larger components during overhaul from within the cargo compartment. This predisposed the location of the air conditioning service center to a point forward of the electrical center. With this arrangement, three or four men can work through the removable panels at the forward end of the cargo compartment simultaneously with the one or two men usually working through the external access door. Other than this arrangement, the installation of equipment behind cargo compartment walls has been specifically discouraged because of the length of time involved in clearing last minute mechanical delays occasioned by having to remove and reload all of the passenger baggage and cargo.

It is, in fact, a much more difficult task to make a smaller airplane like the Electra easily accessible and maintainable than is the case with larger airplanes of the transcontinental or transoceanic pure jet types, since there are roughly the same number of system components and considerably less than half the space available in which to mount them. Nevertheless, we established a criterion in this respect quite early in the Electra design program, namely that wherever possible, maintenance work should be capable of being performed from outside the airplane; in other words, to specifically avoid the need for mechanics to get inside the airplane often soiling or damaging the trim in the process.

A host of advantages, some minor and some major, become quickly apparent to the mechanics working on this airplane. For example the absence of windblast from the propeller coupled with the fact that most of the engine adjustments are accessible with only the side panels open mean comparative ease of making adjustments during ground running. A small step ladder is the only piece of equipment needed for most line maintenance work. Care has been taken in design to eliminate the need for safety wire and cotter pins in most cases — a small but very important detail to the mechanic who is in a hurry. For night operation lights have been fitted in each service center and wheel well and these areas are also painted white for maximum reflection and good "housekeeping." In fact, we have actually received compliments about the maintenance characteristics from some of our flight line mechanics — a most unusual concession, as most of you will agree!

In the engine installation design, criteria were set up to permit removing the turbine section with the remainder of the engine still in position. Similarly the propeller reduction gear section can be changed without removing the power plant. There is no physical connection between the engine and the tailpipe because of the ejector bell-mouth and thus engine change is facilitated and tailpipe life is enhanced. Two engines may be removed from the airplane without any ballast or tie down arrangements and all four may be removed with only 2,500 lb. nose weight. Structural attachment of the power plant is by only four bolts and it is arranged for fast replacement under practical field conditions. With regard to the engine itself the turbo-prop, as a type, has exhibited a significantly greater rate of increase in time between overhauls than reciprocating engines — a fact which gives cause for optimism in the important area of overhaul costs.

Special attention has been given to the functional systems design to permit easy trouble-shooting and, in some cases, there is a degree of deliberate redundancy to permit continuation of flight so that the correction may be made under the more suitable conditions which exist at the principal maintenance base. In many cases we have used an "on condition" design philosophy which is best illustrated by a typical example. The two hydraulic systems are each equipped with a filter which is of the porous metal re-usable type and equipped with a gauge measuring the pressure drop across it. In this way the older design practice of using paper filters and removing them at a given period is eliminated since the pressure drop will indicate the filter condition without the need for removal and the consequent risk of contamination of the system. This enables an "on condition" status to be assigned, thus minimizing the list of time-controlled components.

To ensure maximum ease in removing components, a list of all major and most minor components was established in the early design stage determining elapsed target times for removal and re-installation. Certain of the cases wherein there was doubt that we would achieve our self-stipulated objective were selected for demonstration on the actual airplane on the production line using relatively inexperienced mechanics to determine if design correction was necessary. Because of the thorough evaluation provided by this kind of program, the majority of the components are easily accessible and it is believed that we have eliminated any cases wherein it is necessary to remove a "high time" component in order to get at a "low time" component behind it. Extensive use has been made of "packaged" systems, that is, the grouping of components of a system into one unit or box so that rapid replacement can be made. Several system check-out boxes have also been developed so that the affected unit can be quickly located and replaced. Many of these characteristics will be apparent as this series of *Field Service Digest* articles proceeds into detailed description of the functional systems.

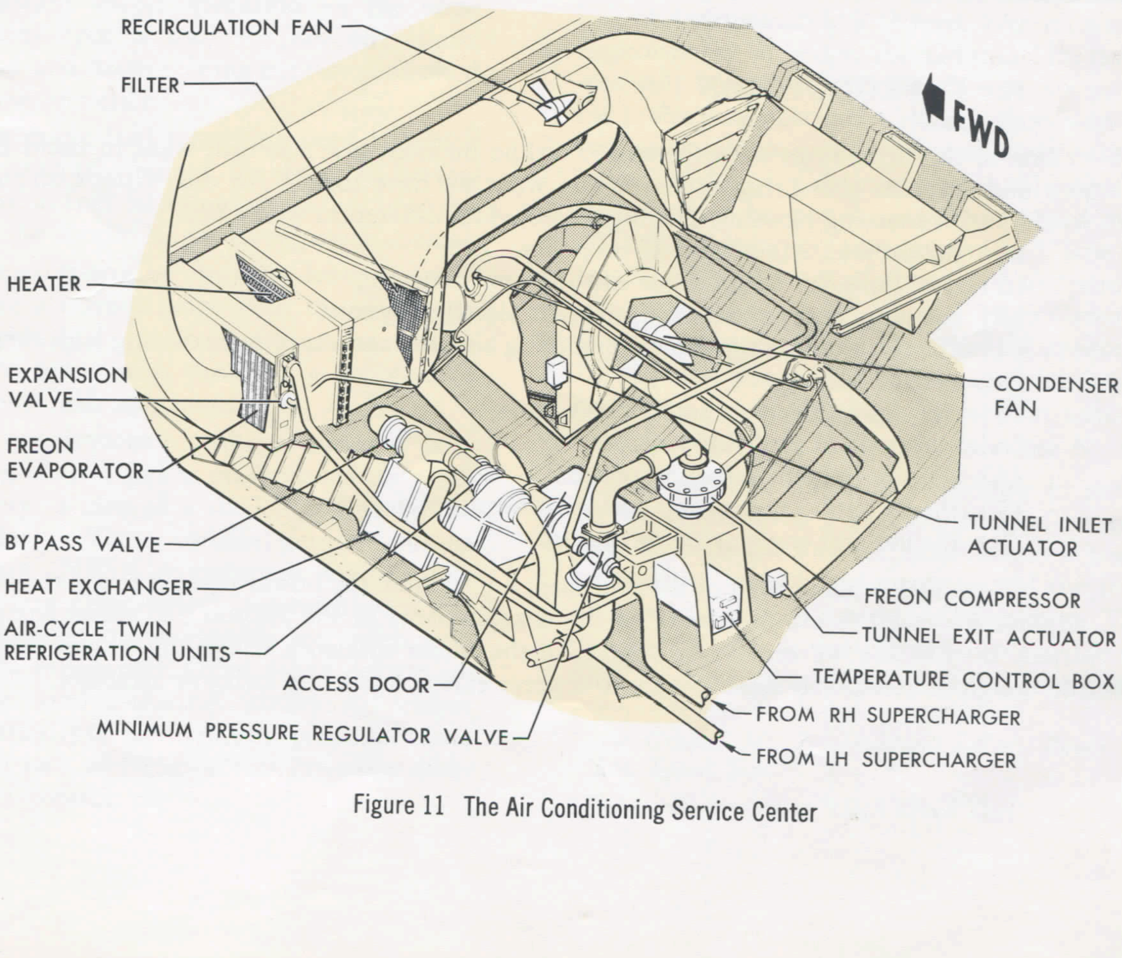

Figure 11 The Air Conditioning Service Center

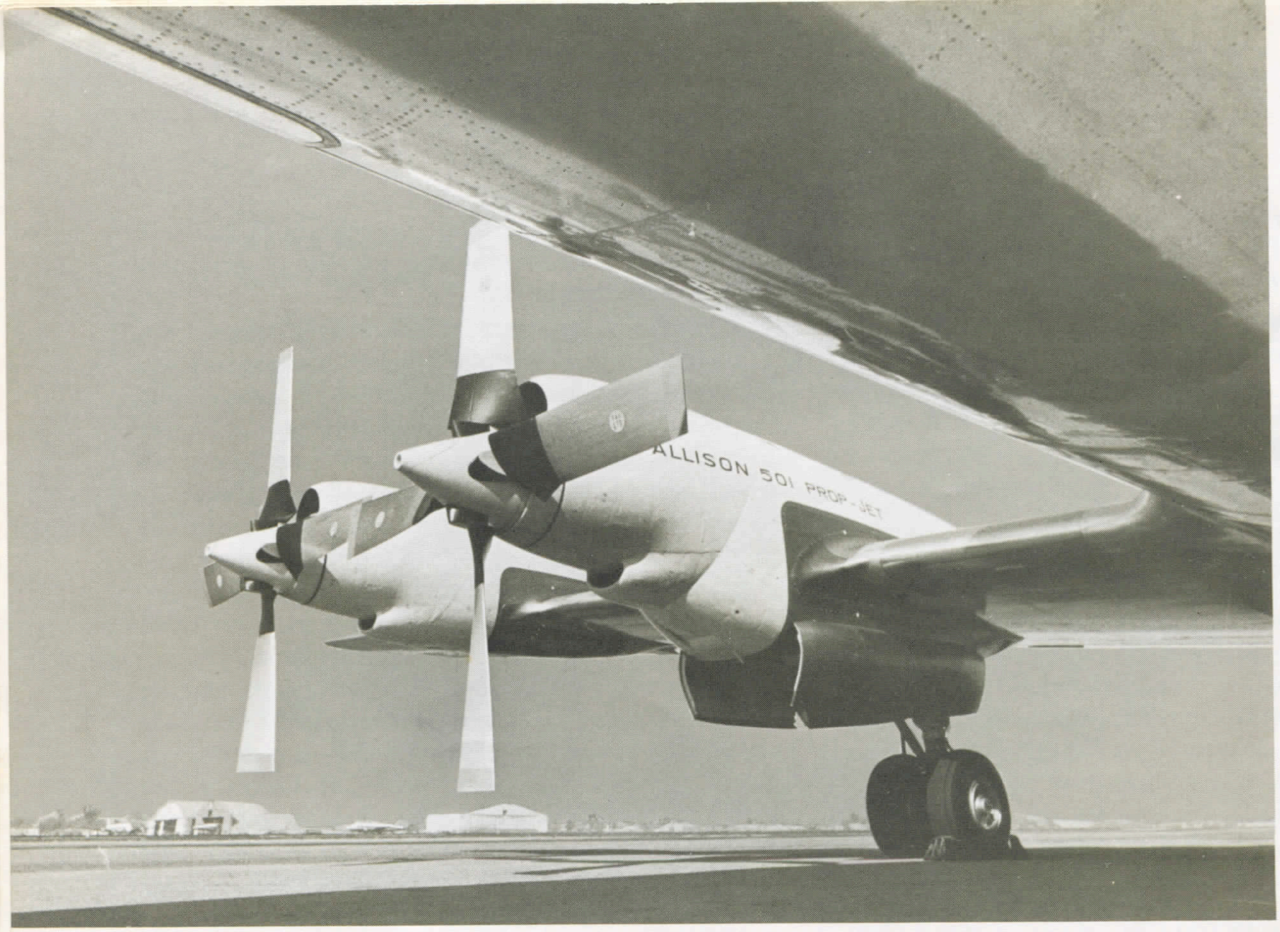

Figure 12
The Power Plant Installa
— General View

PART TWO POWER PLANT, AIRFRAME AND SYSTEMS

8. INTRODUCTION

One of the first things the experienced airline maintenance man will want to know is, "What's new and different about this airplane from what we have today?" In this writer's opinion the list would look something like this. The first and obvious differences would be:

(1) the prop-jet engine and its propeller,
(2) the "fail-safe" long fatigue life airframe structure,
(3) the large output alternating current electrical system,
(4) the air conditioning system combining air cycle and vapor cycle cooling with electrical radiant heating,
(5) the engine bleed air anti-icing systems.

A secondary list would probably include:

(6) the single point refueling system,
(7) the hydraulic system and surface control boosters,
(8) the integral engine starting system.

We will talk about each of these in turn, but because the power plant is really the heart of any airplane it is well to examine some of the characteristics of the Allison 501 series engine in some detail. In this way we can better appreciate the major influence which this engine has had upon the design of functional systems and, to a great extent, upon the airframe structure.

9. THE POWER PLANT

General. In the past the term "power plant" meant a reciprocating engine upon which was mounted a suitable propeller, these two principal components being — apart from suitable blade angle changes — largely independent of each other. This is not the case with the prop-jet of today since, while the reciprocating engine uses separate rpm and throttle levers, the prop-jet must necessarily combine both functions in a single control and it is well to understand this important fact thoroughly.

Taking the same approach as we did in the case of the overall airplane we might well ask, "What's new and different about this particular prop-jet?" Unlike the existing range of reciprocating engines there are relatively few design similarities among the prop-jet power plants currently in production throughout the world. The axial flow, single spool Allison 501 series engine together with its propeller is probably distinguished primarily by:

(a) **Arrangement of engine** with drive shaft and separate reduction gear permitting high ram recovery air intake and providing direct drive accessory section.

(b) **Constant speed operation** — the same turbine rpm is used for take-off, climb, cruise and descent, being entirely controlled by the propeller.

(c) **Automatic fuel trimming control** which electronically refines the basic hydro-mechanical fuel metering and makes practicable the simple single lever power control.

(d) **Propeller-engine power lever** control using a taxiing range with thrust directly proportional to lever movement, and a flight range with thrust as a function of turbine inlet temperature.

(e) **Safety devices** to enhance airplane handling control and to preserve structural integrity in case of a sudden engine failure in flight. These include negative torque system (NTS), an automatic engine safety coupling (Decoupler), a conventional low pitch stop, and a variable low pitch stop (Beta follow-up). Other safety devices include auto-feathering, ability to feather electrically or mechanically, propeller blade pitch lock and engine fuel governor overspeed control.

The following paragraphs will describe in more detail the principal characteristics noted above.

Engine development history. The Allison 501 commercial engine has quite a long family ancestry beginning with the military T-38 and T-40 turbo-prop engines and continuing through the T-56 which is currently in large scale production for C-130 series aircraft and others. When the engine was first considered for airline operation in the CL-310 (preliminary version of the Electra) it was apparent that certain changes would have to be made, none of them fortunately being of a very major character. The compressor and turbine characteristics were, however, unchanged so the constant turbine speed of 13,820 rpm was retained.

Principally there was the problem of high noise levels on the ground, since the military engine had a much higher propeller rotational speed of 1,106 rpm for take-off and 1,080 rpm — actually some 97% — for the Ground Idle case. The reduction gear ratio in the T-56 engine was 12.5:1 whereas the present 501-D13 commercial engine uses 13.54:1, thus giving a take-off value of 1,020 and a Ground Idle of approximately 992 rpm. This represented an improvement although the Ground Idle noise level was still not considered satisfactory for continuous use at the passenger ramp. Allison then went to work to produce a new very low Ground Idle position of a value consistent with minimum stable running and satisfactory operation speeds. This turned out to be 10,000 turbine rpm, now known as *"Low Ground Idle," and resulted in a propeller shaft speed of 738 rpm. Normal Ground Idle, or †"High Ground Idle" as it is now more frequently called, of approximately 13,450 rpm was retained and is used for fast taxiing or engine run-up purposes, in fact for anything requiring more thrust or more rpm.

Changes were made in the engine to permit the use of kerosene as a primary fuel or alternatively JP4. Most of the airlines have chosen kerosene because of its lower vapor pressure and the improved safety which is believed to result therefrom. The ignition system energy was increased to provide satisfactory air starting at high altitude when using low

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**Low Ground Idle is sometimes called "Ramp Idle" or "Low Speed Taxi."*

†This is also known as "High Speed Taxi."

volatility fuels such as kerosene. The engine oil specification was also changed to an extreme pressure additive synthetic turbo-prop lubricant for commercial use, providing longer engine overhaul life.

Engine safety devices previously developed for military application were incorporated together with some important additional features in conjunction with the Aeroproducts propeller. These will be described in detail later in these notes. There were also several changes during the "commercialization" of the T-56 effecting improvements in maintenance but they are not of primary significance for the purposes of this discussion.

The propeller. The Aeroproducts military propeller, too, came in for its share of adaptation to commercial practice and many changes were made to incorporate additional safety features and to improve the maintenance characteristics. The latter included such items as provision of a single point attachment spinner, readily removable governor and improved oil filling procedures. This propeller has a hydraulic blade angle changing mechanism which uses a rifle bore type helical splined sleeve and piston arrangement, all of the propeller oil being self-contained and completely separated from the engine functions. Operating power is generated by propeller rotation and it employs higher hydraulic pressures than most other designs. The hole in the spinner shown in Figure 12 provides cooling air which is directed through an annular space in the propeller hub. The only electrical signals used for control purposes are for synchronizing, phase synchronizing and auto-feathering — all other basic control functions such as governing, feathering, reverse pitch, negative torque signal (NTS), and taxi operation being mechanically operated from the flight station or the engine.

The spinner forward area is electrically anti-iced while the blade cuffs and aft area of the spinner are electrically de-iced, this being particularly important from the viewpoint of avoiding the buildup of ice which would seriously affect the air flow characteristics of the engine intake. The Napier "Spraymat" system is used and is the first application of its kind on American aircraft. No de-icing is provided on the propeller blades themselves apart from the cuffs. The blades are hollow steel of forged construction with a brazed-on camber sheet.

The propeller diameter of 13½ feet is small by today's standards although the thrust is very high — approximately 8,000 lb. for take-off. Surprisingly enough the 18½" wide blades have a high cruise efficiency of approximately 90% maximum, due mainly to the thinness of the blade, coupled with good blade twist/camber distribution. The cuff design and the cuff-to-spinner intersection also contribute materially to the high efficiency. The propeller weight complete with all control components is 1,017 lb. and is thus roughly equivalent to those in current use on high powered reciprocating engines. On the other hand, the saving represented by th engine dry weight of only 1,714 lb. means a tota power plant figure of 2,731 lb. which, when com pared to the Model 1049G Constellation, shows total weight saving per airplane of about 6,400 lb

An alternative propeller with solid dural blade is available, namely the Hamilton Standard typ 54H60-47, having a CAA-certified performanc which is substantially similar to that of the Aer products propeller. This propeller is illustrated Figure 13 and comparison of it with the Aeropro ucts propeller depicted earlier in Figures 3 and 1 shows the significant difference in blade plan for which is the principal distinguishing characteristic.

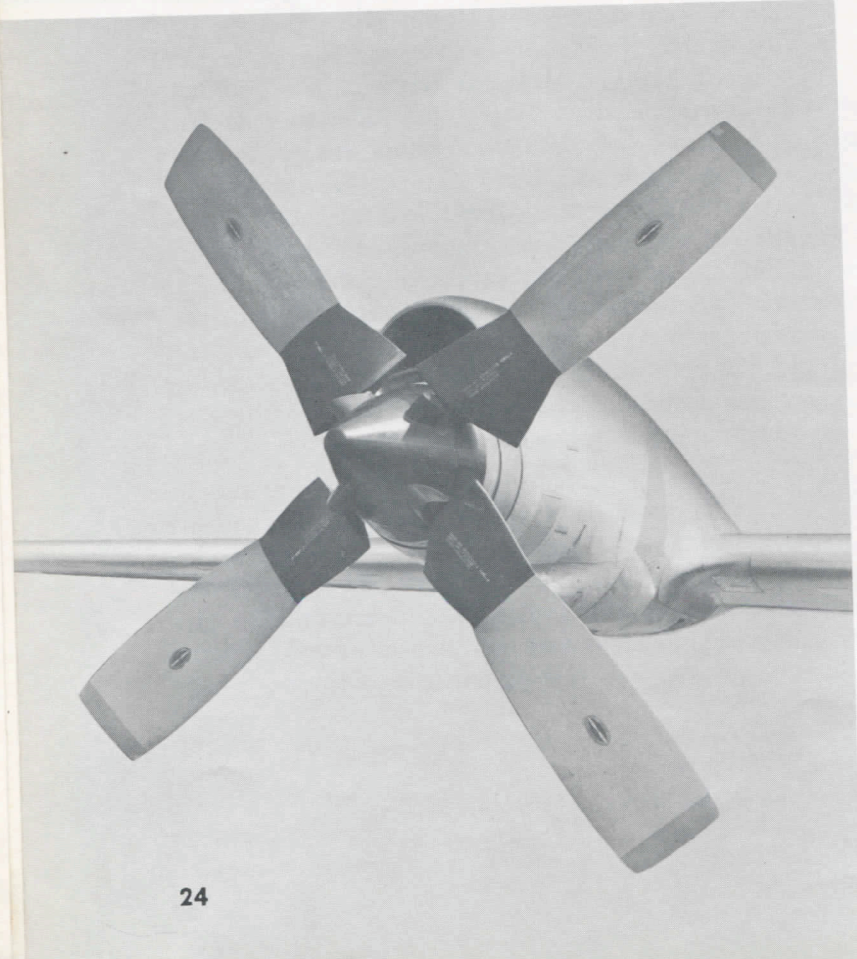

Figure 13
Hamilton Standard Propeller Installation

this propeller the cooling air enters through circumferential slots just aft of the blade cuffs and an externally applied electrical boot is used for ice protection. The hydraulic blade angle changing mechanism is basically similar to previous types of Hamilton Standard designs.

Engine description. Reference to Figure 17 showing a cutaway view of the engine reveals that it is made up of three main assemblies:

(a) Propeller reduction gear and engine drive shaft.

(b) Engine compressor together with engine fuel, oil and ignition accessories.

(c) Turbine section including the combustion section, turbine section and expansion area.

This latter assembly is often known as the "hot section." The engine configuration is unique and very flexible in that it can be obtained with the gearbox offset up for a high wing airplane, or offset down as in the case of the Electra installation for better layout in a low wing configuration. The propeller reduction gearing is in two stages, the first being a spur gear step down from the engine and the second a planetary gear set. Several of the engine safety devices are located in the reduction gear assembly. The forward end of the engine drive shaft contains the torquemeter which measures electrical phase difference signals resulting from twisting action of the drive shaft. Below the shaft drive connection on the rear face of the gearbox are mounted the engine driven accessories, such as pneumatic starter, cabin supercharger, a-c generator and tachometer generator. The reduction gear has its own dry sump oil system fed from the main engine oil tank.

Moving back toward the compressor air inlet, the inlet struts and guide vanes are hollow and are anti-iced with air bled from the compressor. The torquemeter shroud and drive shaft housing are similarly protected from icing. The compressor has 14 stages and operates at a compression ratio of 9.25:1. Annular bleed ports together with acceleration bleed valves are provided at the 5th and 10th compressor stages for unloading in the surge range, which is roughly 7,000 to 12,500 rpm. The acceleration bleed valves are an alternative method to the use of variable angle inlet vanes for compressor surge control purposes, and they are open at the 10,000 rpm "Low Ground Idle" position. At the 14th stage, bleed ports are provided for hot air to be used for airframe anti-icing and other purposes. Below the compressor case is an engine accessory drive section carrying the fuel control, fuel pumps, filters, oil pump, speed sensitive control, etc. Aft of this is the co-ordinator control which is mechanically linked to the power lever in the cockpit.

The air from the compressor enters the diffuser section which distributes it equally to the six burner cans in the combustion section, which is of the "can-annular" type. A large proportion of the air flows outside of the burner cans as secondary air and enters through slots to control the flame pattern. Each burner can is fed by a nozzle and two of the cans have ignitors, the flame being carried during starting to the other four cans by cross-over tubes. Moving aft, the hot gases from the burner cans combine in an annular area and feed through stator vanes into the four stage turbine assembly. It is at this position that the 18 dual thermocouples measuring turbine inlet temperature (TIT) are mounted. The measurement of temperature at the point of entry to the turbine provides much more accurate control than measuring the outlet, or exhaust gas temperatures, as in most other engines.

A relatively small amount of the energy from the last stage of the turbine leaves the tailpipe in the form of jet thrust. Actually the 3,750 ESHP* is made up of 3,460 SHP plus 726 lb. jet thrust. The jet thrust is factored by 2.5 to approximate ESHP so that 290 HP is added to the propeller shaft power to obtain the take-off power rating. The reason for using four turbine stages—unlike a turbo-jet engine which normally uses fewer — is that the maximum energy is extracted as shaft power for the propeller, rather than in the form of jet thrust. This is illustrated in Figure 15, which shows typical power, temperature, velocity and pressure relationships. In general terms some 10% of the total thrust comes from the jet pipe at the cruise condition.

Engine starting is accomplished by a pneumatic starter which in reality is a small high speed air turbine capable of very high power output. It is necessary to extend the cranking range of the starter to an engine speed of 8,000 rpm to avoid "hot starts" and to ensure positive engine acceleration. Several things happen automatically in the sequence of starting, including turning on fuel and ignition, controlling fuel pump output and operating the acceleration bleed valves. Most of these functions are controlled by the speed sensitive control unit. The ignitor plugs operate only during the starting sequence and cut off at stabilized speed, engine combustion being continuous thereafter.

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* *ESHP is the abbreviation for "equivalent shaft horsepower;" SHP is "shaft horsepower."*

The engines can, of course, be air started by windmilling after an in-flight engine shutdown. A propeller brake is provided to eliminate windmilling after feathering in flight and also to prevent engine rotation in a strong wind on the ground. It also assists in slowing down the engines at shutdown. The brake is mounted in the accessory section of the propeller reduction gearbox just behind the starter pad and is operated automatically by engine oil pressure. The propeller can be pulled by hand against the brake if necessary for maintenance purposes, but in one direction only since it prevents reverse rotation.

Automatic fuel trimming control. Since control of turbine inlet temperature (TIT) is really the clue to the simplicity of power lever operation for this engine, we should examine the mechanism more closely. The engine has a basic hydro-mechanical fuel regulator, or control, which is similar to that in many other turbine engines, the exact adjustment of fuel flow, however, being accomplished in a unique way. The fuel control actually feeds 120% of the amount required to operate the engine and a fuel trimming device consisting of a temperature datum valve — which is electronically controlled — either "puts" or "takes" a portion of the excess fuel delivered to it.

This temperature datum valve (TD Valve) maintains the selected TIT or limits it to a maximum value of 971°C. It is basically a temperature-density variation control operating by by-passing fuel and receives its signals from the electronic temperature datum control amplifier (TD Amplifier). This amplifier is really a comparator which measures the output of TIT thermocouples versus power lever angle provided by a potentiometer in the co-ordinator, and then sends the resultant signal to the TD valve to trim the fuel accordingly. The fuel is then fed through a flow divider to equalize the flow to the six fuel nozzles. It will be understood, therefore, that the automatic fuel trimming control — or TD System — is in reality a fuel heat-content sensitive device and is basically capable of adjusting itself to a range of different fuels from gasoline through JP4 to kerosene.

Should an electrical failure occur in the TD System it would mean that the TD Valve would return to the "NULL" position and the crew would revert to manual control of that particular engine by observation of the TIT gauges and manipulation of the power lever. A feature is included which permits "locking in" the last "put" or "take" adjustment for the engine and thus shutting off the action of the TD system, while still providing fairly accurate hydro-mechanical fuel control adjustment. This device is intended for landing purposes to provide uniform power lever angle versus thrust conditions for all four engines.

The power lever. The power lever (so called because it does really control power in the total sense and not merely open a throttle valve) has two basic ranges in its 90° quadrant (see Figure 14):

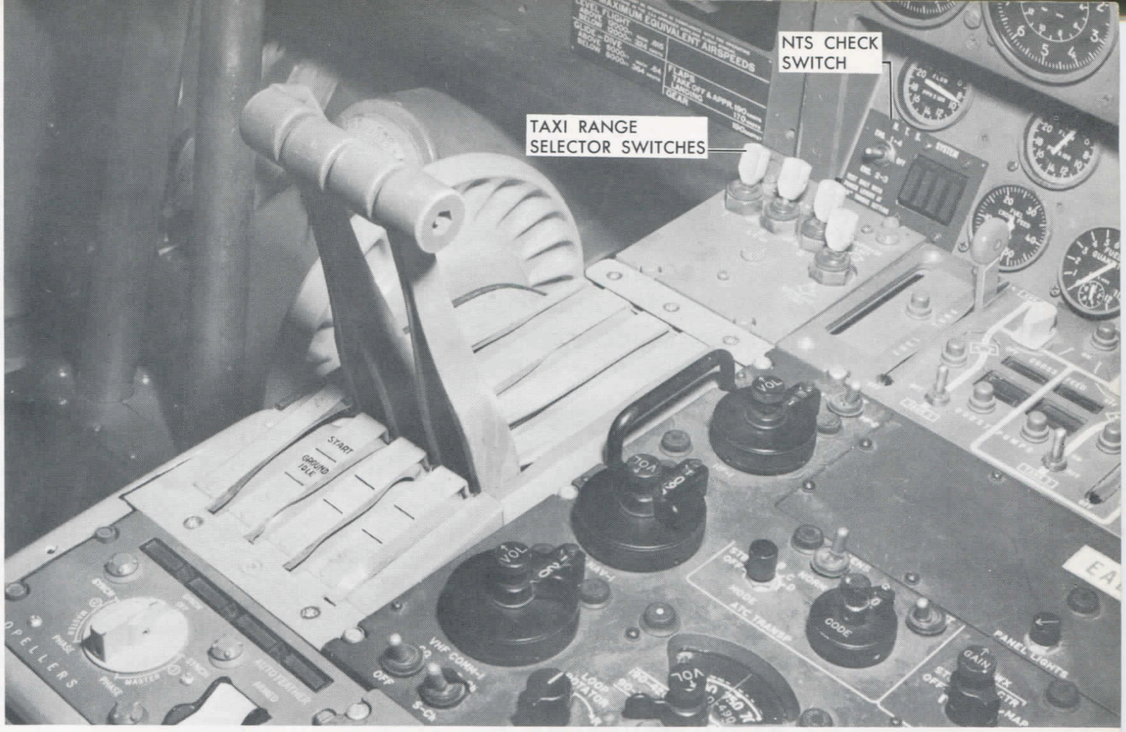
(*a*) TAXI RANGE or *"Beta Range" is used for all ground conditions and is aft of the 34° detent or Flight Idle position. In this range control of blade angle is directly related to the power lever position with the engine rpm at approximately 13,450 or below. *Thrust is proportional to blade angle.*

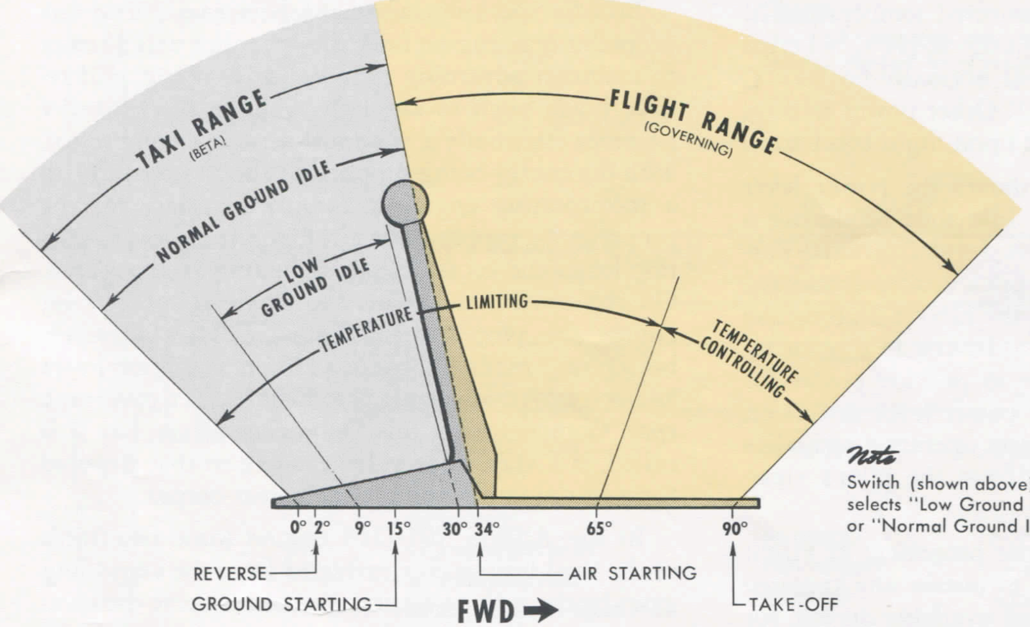
(*b*) FLIGHT RANGE or "Governing Range" is used for all flight conditions and is forward of the 34° travel position. In this range engine speed is governed by the propeller at 13,820 rpm. *Thrust is proportional to turbine inlet temperature (TIT).*

The power lever has to be lifted positively when pulling back from the FLIGHT RANGE to permit entering the TAXI RANGE or "Beta Range" and a device is included to prevent accidental entry while the airplane is in flight. This power lever lift motion is similar to the lift-to-reverse action provided on several current reciprocating engine transports for propeller reversing purposes. No separate lock release action is necessary in this case, however, apart from lifting the power levers since the safety device is actuated by the landing gear scissors switch. In case of malfunction the device can be over-ridden by the use of additional force on the power levers and is thus fail-safe. The connection between the propeller and the power lever is mechanical only and does not rely upon electrical functions.

It should be appreciated that the detent or "gate" is at the Flight Idle (34°) position in this prop-jet engine control system, unlike a reciprocating engine-propeller control which is normally at the point where the throttle levers enter reverse pitch. The reason for this important difference is principally concerned with the existence of jet thrust from the tail pipe. Whereas reciprocating engine-propeller controls modulate down to low thrust (fine pitch approach conditions) the next throttle movement is directly into reverse pitch by withdrawal of the low pitch propeller blade stop.

**The use of the word "Beta" comes from the aerodynami term for blade angle signified by the Greek letter β.*





Note
Switch (shown above)
selects "Low Ground Idle"
or "Normal Ground Idle"

Figure 14 The Power Lever

On the other hand, while the Flight Idle position in the prop-jet corresponds roughly to the low pitch stop position in the reciprocating engine, a fairly large component of forward thrust is added by the jet pipe. Consequently it would be difficult to slow down and control the airplane on the landing run if the next step was reverse pitch. For this reason a blade angle control was developed which permits modulation below the Flight Idle position and appropriately named the "Beta control" range. It will be understood, therefore, that the jet thrust makes lower blade angles necessary on the ground for the prop-jet than would be the case for a reciprocating engine at equivalent total thrust and, in fact, the blades are actually in reverse to a limited extent for static ground running purposes. It follows that there is no "gate" for reverse and further retarding of the power levers provides full reverse, if it should be required.

Looking again at the engine power lever in Figure 14 you will see that Reverse begins at 2° while maximum reverse is at 0°. A small detent is provided at 9° for Ground Idle. Engine starting is actually accomplished at 15° since this corresponds to the minimum torque requirement condition for the propeller and engine. "Low Ground Idle" at approximately 10,000 rpm is obtained by putting a taxi range selector switch in the "LOW" position. At this point the total thrust from the propeller is close to zero which means that the customary wind blast around the passenger ramp is noticeably absent. Sufficient thrust is available, however, for taxiing on four engines at this setting by advancing the power lever as required from 9° up to 30°. If more thrust is required the selector switch can be moved to the "NORMAL" ("High Ground Idle") position providing approximately 13,450 rpm, the fuel demands being satisfied automatically. This switch can be seen in the detail view in Figure 14.

Advancing the power lever through the 34° detent towards the Take-off position moves it out of the "temperature limiting" range wherein the engine is protected from overheating by a limiting device, into the "temperature controlling" range commencing at 65° in which the selected TIT value is controlled automatically by the TD System. At the 90° or take-off position the TIT is automatically controlled at the maximum value of 971°C (100% maximum rated temperature) or *3,750 ESHP. In the climb position the TIT will remain at the selected temperature of 895°C (94% MRT or *3,105 ESHP), whereas in the cruising position it will normally be 847°C (90% MRT or 2,700 ESHP). Other power settings are, of course, used depending upon flight conditions.

On touch-down the pilot moves the power lever from Flight Idle to Ground Idle thus producing a large amount of negative thrust for deceleration purposes. The use of full reverse pitch is only considered as an emergency condition on the Electra. Pulling the power lever back from the 9° Ground Idle point increases fuel flow, in this case to provide power for reverse pitch. To sum up the power lever discussion one only has to see the system in operation to realize how delightfully simple it is from the pilot's viewpoint — just watch the TIT!

The drag available from the propellers in Flight Idle makes it easily possible to obtain any required rates of descent and the control available during, for example, a typical ILS approach is almost uncanny. To the pilot, the airplane acceleration or deceleration appears to be directly linked to the power levers themselves. The absence of need for engine "clearing" at the end of the runway prior to take-off is another differing characteristic of the prop-jet and wheel-brake and tire life will be much improved because of the incremental propeller thrust control available during taxiing.

Safety devices. Because of certain conditions to be described very briefly herein, gas turbine engines have characteristics which differ markedly from reciprocating engine-propeller combinations. Early in 1953 Lockheed made extensive safety analysis investigations in relation to development of the prototype YC-130 military transport with the YT-56 engine and, using this research together with data derived from the Pratt & Whitney T-34 engines installed on the YC-121F and the R7V-2 (U. S. Air Force and Navy turbo-prop versions of the 1049 Constellation) developed concepts for protective devices. The test work included an extensive full scale T-56 engine program in the power plant wind tunnel at Ames Aeronautical Laboratory as well as flight testing in a Constellation flying test-bed airplane. The basic premise was that a turbine powered airplane must have an in-flight safety level which was at least equal to, or preferably better than, that of an equivalent reciprocating-powered transport.

Broadly speaking, when the power output of any propeller type engine fails, the propeller will attempt to maintain governing rpm and in so doing, will reduce blade pitch to an angle wherein the propeller becomes essentially a windmill driving a compressor, with the energy being supplied by the airstream. With a reciprocating engine it is only necessary for the propeller to supply power for pumping losses, friction losses and accessories to maintain governing rpm. On the other hand, with the single spool prop-jet engine the propeller must supply full compressor horsepower requirements in addition to friction losses and accessory requirements to maintain set governing rpm. Comparatively this "motoring power," as it is called, is a very large value relative to that required for a piston engine of similar power output.

In the Allison 501-D13 engine some two-thirds of the total horsepower extracted from the expanding gases by the turbine section are used to drive the compressor; in other words the compressor uses more than 6,000 shaft horsepower. Refer again to Figure 15 which shows the horsepower relationship graphically. From the previous paragraph it is apparent that the blade angle will depend upon the negative torque load required to motor the engine in the event of a sudden engine failure in flight. Study of the horsepower relationship diagram shows that such a failure could result in the absorption of enormous power from the airstream if protective devices were not included.

In general, two types of engine failure prescribe the maximum and minimum boundaries of necessary protection. The most simple case — and the most likely — would be flame-out due to fuel flow failure. Since, in this case, the engine is undamaged the tur-

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**Standard sea level static conditions—progressively less with altitude, of course, since the power behaves like an unsupercharged reciprocating engine and falls off proportionally with decrease in air density.*

bine wheels would continue to supply some useful energy to the compressor because the compressor discharge air is still expanding through the turbine blading — even though not a combustible mixture. The negative horsepower under this condition, in other words the power which could be absorbed from the air stream by the propeller at its governing speed of 1,020 rpm, would be about 1,800 SHP in order to motor an unprotected engine under typical conditions of about 300 knots at sea level.

The most severe case would result from failure of the turbine blades and in such a case the propeller, if in fairly low pitch, could absorb the full 6,000 plus shaft horsepower required to drive the compressor if no torque limiting devices were installed. Typical drag loads which could be caused by, say a failure of an unprotected outboard engine at the 300 knot sea level case would be around 4,000 lb. in the fuel flow failure example, whereas a complete turbine failure could approximate 15,000 lb. Adding the effect of the thrust from the remaining live engines would increase the total asymmetric drag values to some 7,500 lb. and 18,500 lb. respectively. Several devices have been built into both engine and propeller to completely protect against these occurrences and in addition structural strength is provided in the vertical

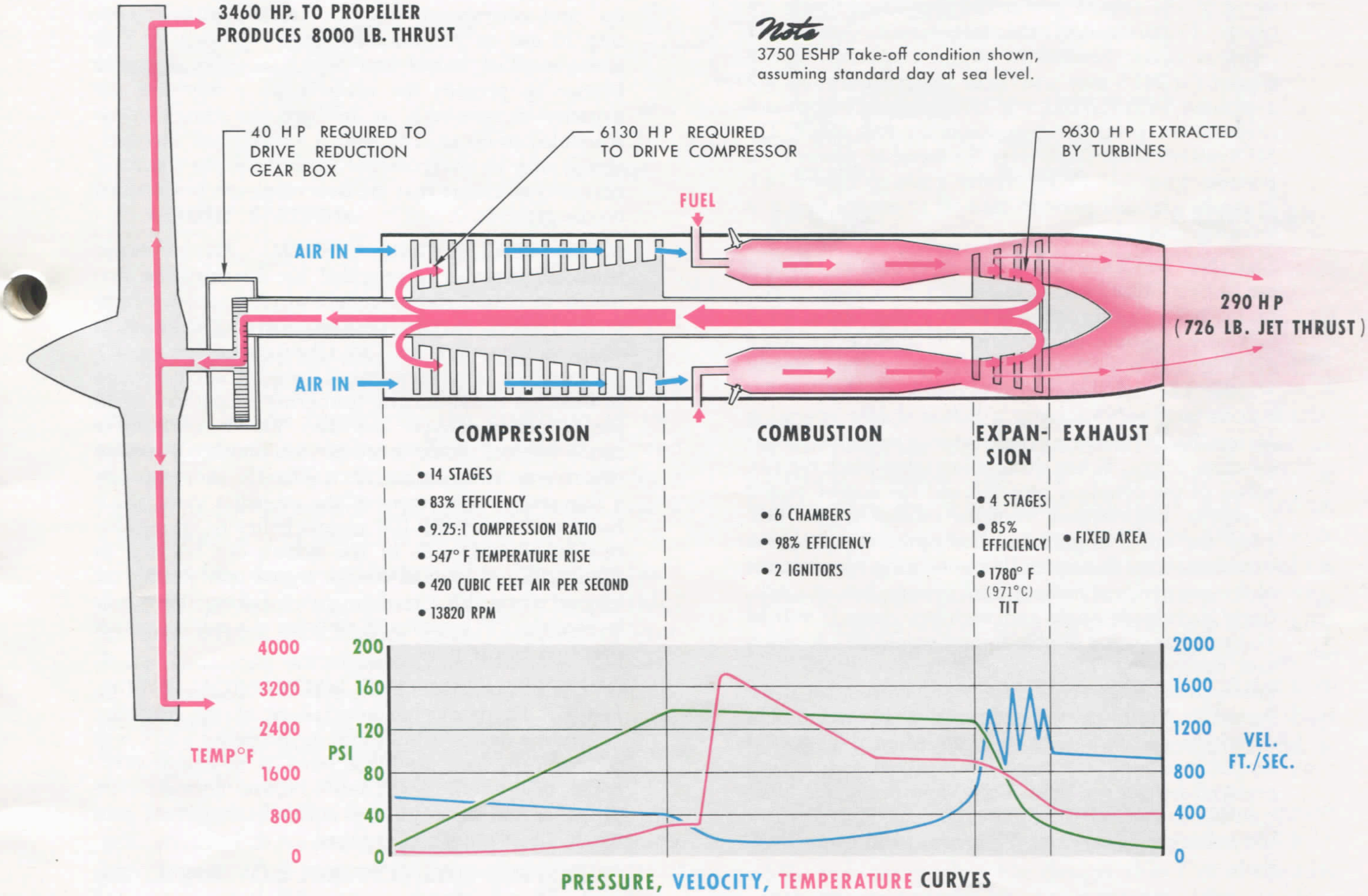


Figure 15 Allison 501 Engine — Basic Power Relationships

tail surfaces to take care of critical yawing loads coupled with forces which could arise from corrective action by the pilot.

NEGATIVE TORQUE SYSTEM (NTS). The propeller is prevented from absorbing large values of negative torque in the event of a fuel flow or turbine failure of the type previously discussed, by the provision of the negative torque signal system which is incorporated in the reduction gearbox. This system uses the output from the axial movement of a helical spline and coil spring assembly caused by the unloading effect of the propeller upon the planetary ring gear. It actuates the propeller in the increase-pitch direction to absorb more power from the engine (see detail in Figure 16). A small value of negative torque is permitted by the system to provide for a useful amount of propeller drag at Flight Idle which would be necessary at, for example, approach conditions. This device functions at approximately minus 375 horsepower and the crew would feel it working by a cyclic variation in thrust if the engine power did not immediately increase. Fluctuation of the torquemeters would, of course, also tell them of the engine condition. Operation of the NTS may also occur under conditions not associated with failures, e.g. during a steep approach or when the propeller encounters air gust loads. The NTS system is operative over the range of power lever position from 24° to 90° (refer again to Figure 14). It can be checked prior to take-off to ensure that it is working properly.

ENGINE DECOUPLER. This device is, in effect, a mechanical "fuse" and is essentially a back-up device for the NTS. Failure of the NTS to work at about −375 horsepower would be protected by this device when the negative horsepower magnitude reached around −1500. The decoupler works in a somewhat similar fashion to the NTS using a helical spline operating against Belleville spring washers as a negative torque sensitive device. When decoupling takes place the two halves of the coupling separate and the engine power section is disconnected from the reduction gear box. After the failed engine had decoupled the propeller would continue to windmill at governing rpm because of its independent hydraulic oil system, but at a relatively high blade angle and with low drag. It will be realized that such a double failure would be extremely rare, namely an NTS failure accompanied by a turbine failure, and in any case the airframe structure is designed to withstand such a critical combination. The decoupler will re-engage in flight when the negative torque is removed but must be inspected and possibly replaced before the next flight. The decoupler, illustrated schematically in Figure 16, is mounted within the reduction gear box at the forward end of the drive shaft.

VARIABLE HYDRAULIC LOW PITCH STOP. The "Beta follow-up"—which is the more usual name for this device—is provided to minimize asymmetric thrust should engine failure or propeller malfunction occur. It is a variable position low pitch stop which limits improper travel of the propeller blades much more suitably than a fixed mechanical low pitch stop could do. For example, in the event of fuel flow failure at take-off, primary protection is provided by the "Beta follow-up," while at high speed cruise conditions the protection is normally provided by the NTS system. Its operation is typically as follows: in case of failure of the NTS to signal for increased pitch the propeller governor would normally tend to decrease the blade angle toward the low pitch stop at 20°. With this device, however, the blades are stopped at, for example, about 31° for the take-off power condition and consequently the windmilling drag would be greatly reduced. The hydraulic low pitch stop position varies from 20° blade angle at 68° power lever position to 31° at the 90° position. Between the 68° and 34° Flight Idle power lever position the "Beta follow-up" acts as a fixed hydraulic low pitch stop ensuring a minimum blade angle of 20°. This device would operate before the engine decoupler was called upon to operate. The "Beta follow-up" is contained within the propeller but is not illustrated in this article.

MECHANICAL LOW PITCH STOP. This low pitch stop (18¼°) is a back-up device for the "Beta follow-up" and corresponds to the conventional low pitch stop in use on reciprocating engine propellers. This is the so-called "bar of iron" which serves as a positive barrier to prevent the blade from going into the negative range—such as in-flight reversing—unless scheduled to do so. The stop is so arranged, however, that it may be overpowered from the flight station if necessary to ensure that the Beta range can be obtained on the ground.

AUTO FEATHERING SYSTEM. An automatic feathering system is provided on this airplane primarily to obtain the maximum airplane gross weight under limiting airport performance conditions. It is actuated by a separate TSS (thrust sensitive signal) device which is independent of the other safety devices. In this case the automatic feathering is operated when the propeller delivers less than 500 lb. of positive thrust whereas the devices described previously require negative thrust to actuate them. The TSS is operated by a fore-and-aft movement of the propeller shaft which has a total travel of 0.10″ against Belleville springs for this purpose. Details of the system can be seen in Figure 16 and it is, of course, armed only during the take-off range by a switch operated from the power lever at the 75° position, in addition to a manual switch operated by the pilot.

OVERSPEED LIMITING MECHANICAL PITCH-LOCK. To protect against failure of the propeller governor a device is built into the propeller which will mechanically lock the blade pitch at an engine overspeed of 14,300 rpm (3½% above normal). The propeller can be feathered normally, however, even when the pitchlock is engaged.

OVERSPEED FUEL CONTROL GOVERNOR. The engine fuel control contains a flyball type overspeed governor operating at 14,450 rpm (4½% above normal). The only way that this condition could actually be realized in flight would be a double failure of the propeller governor and/or a mechanical drive failure between the engine and the reduction gear box. This overspeed governor is also known as the "topping governor."

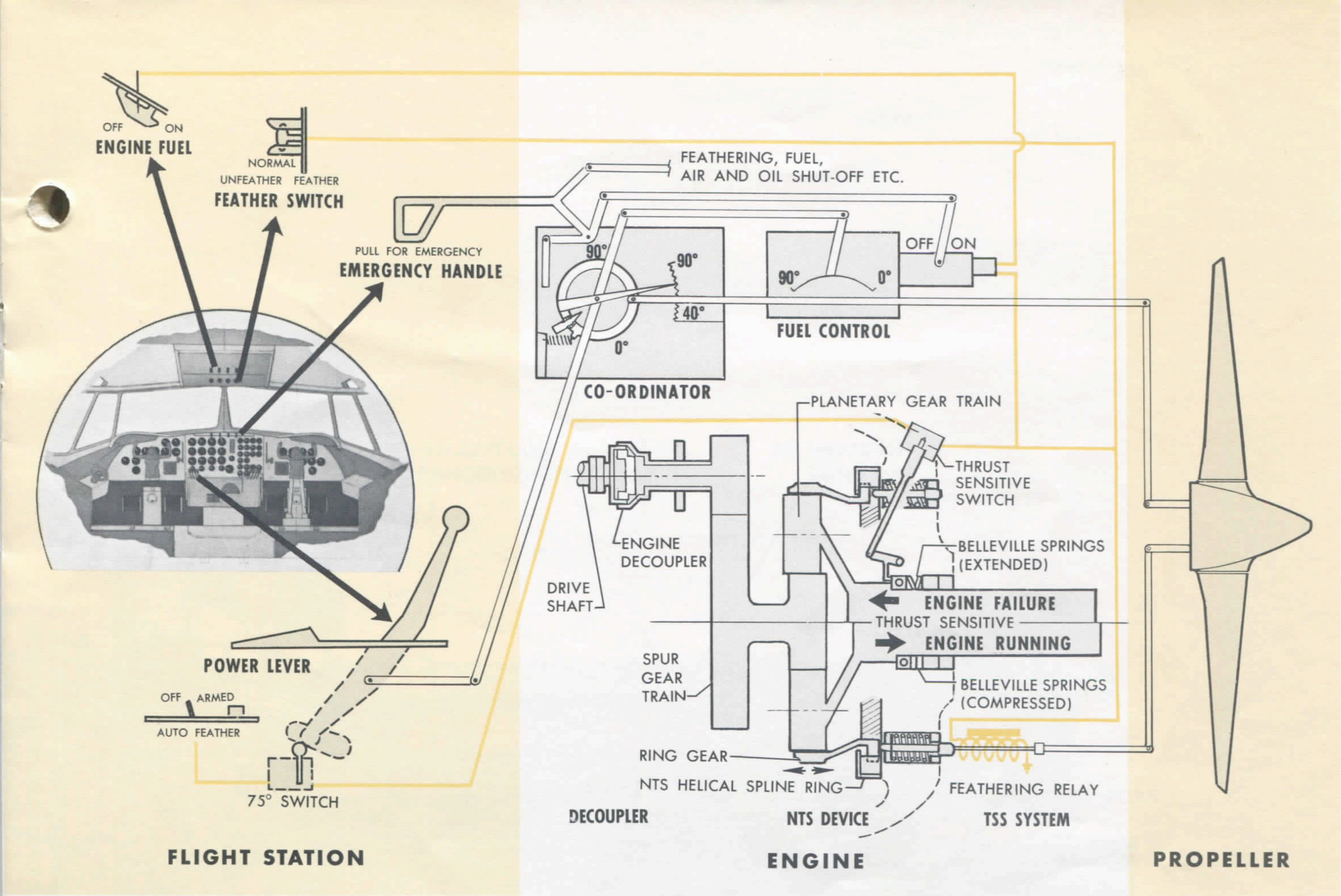


Figure 16 Engine/Propeller Control and Safety Devices

In addition the power plant includes normal and emergency feathering systems. Occasional loss of the ability to feather in reciprocating-engined aircraft is combatted in the Electra by the provision of two separate systems to the propeller; one electrical, and the other mechanical. Arrangements are made for a minimum feathering oil reserve in the latter case if a substantial loss of propeller oil has occurred.

One safety device concerned with the power plant deserves special mention here. A handle is provided for each engine which does several emergency shutdown functions simultaneously — mostly mechanically actuated. With a single movement the selected emergency handle will shut off fuel at the engine, feather the propeller, operate the fuel tank emergency shut-off valve, shut off generator cooling air, and so on, combining eight functions in all. Original development of this system came from the C-130 transport. Figure 16 illustrates this together with most of the other safety devices previously described.

Summarizing the power plant safety features discussion, it should be understood that the airframe has been designed so that it has adequate strength to survive the most improbable compounding of failures of the safety devices described under the most unfavorable operating conditions.

Power plant installation. Review of the engine and propeller would not be complete without briefly considering how they are installed in the airplane. The choice of the low wing airplane configuration dictated, for propeller tip clearance and landing gear installation reasons, that the engine centerline be higher than the wing. The reduction gear box on such an installation must necessarily be offset downwards to obtain, as nearly as possible, alignment of the propeller thrust line with the chord line of the wing. This configuration in turn, established the over-wing arrangement of the exhaust tailpipe as well as the high air intake position (see Figure 18). After consideration of the possible adverse drag effect of short tailpipes it was decided that they should extend to the trailing edge of the wing.

Whereas in earlier reciprocating engine intake design practice, ram pressure recovery values of 75 — 85% were acceptable, the design objective in the case of the Electra was 98% in order to meet the specification requirements for speed and range. Careful design was necessary to achieve this together with a good ram pressure ratio, the latter being an important measure of the overall engine inlet-outlet efficiency. In practice the design objectives have been exceeded and more than 100% total pressure ratio is available

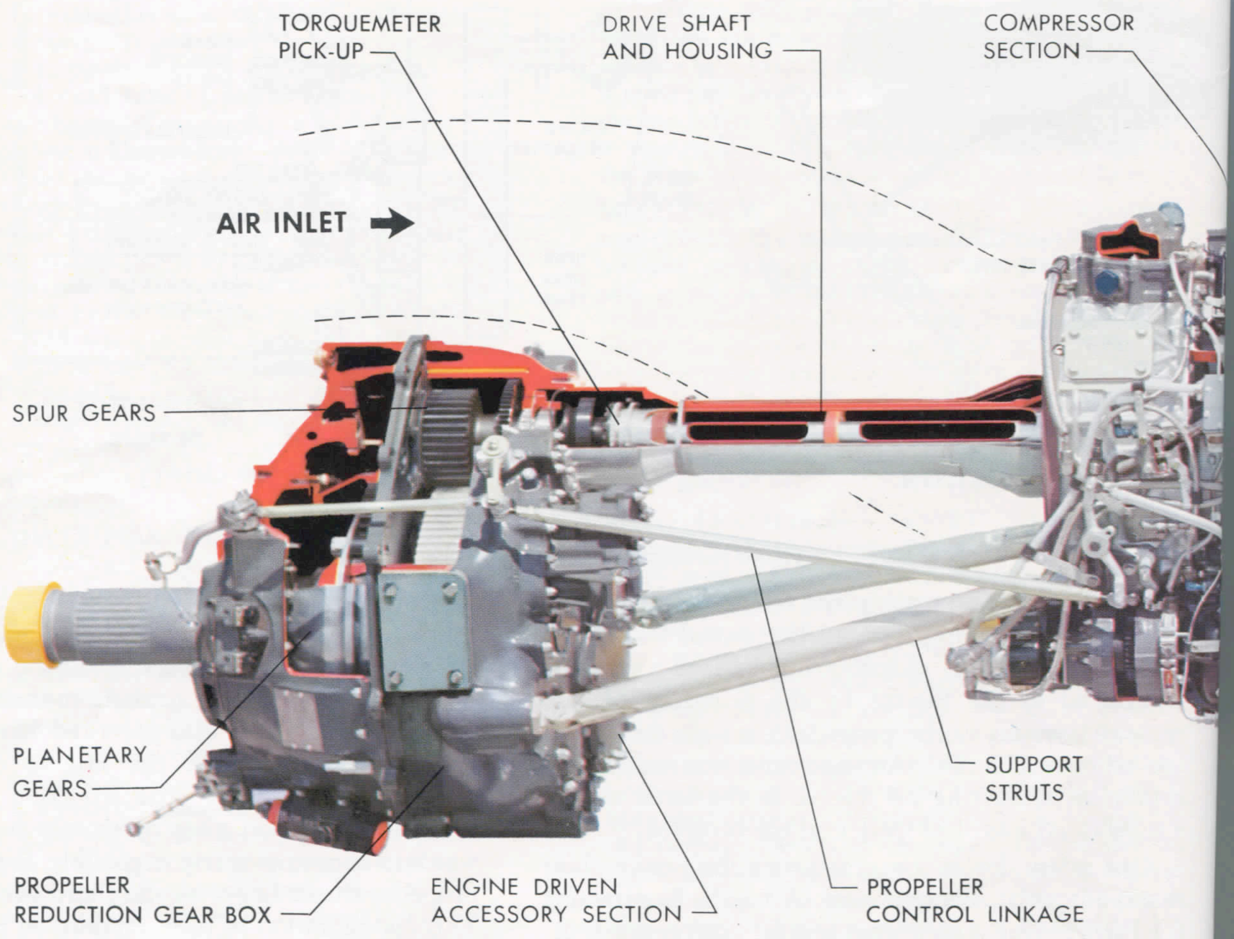
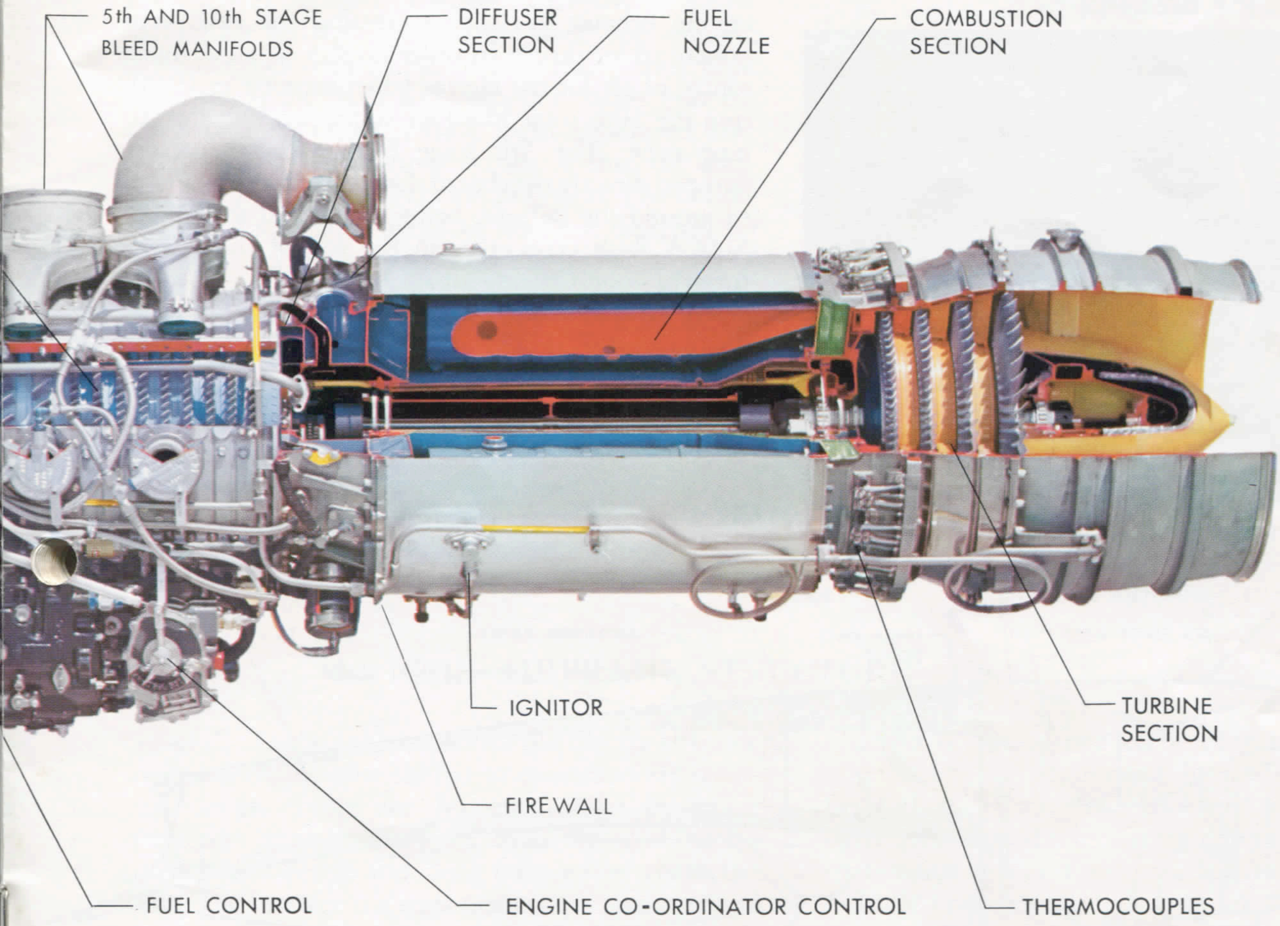


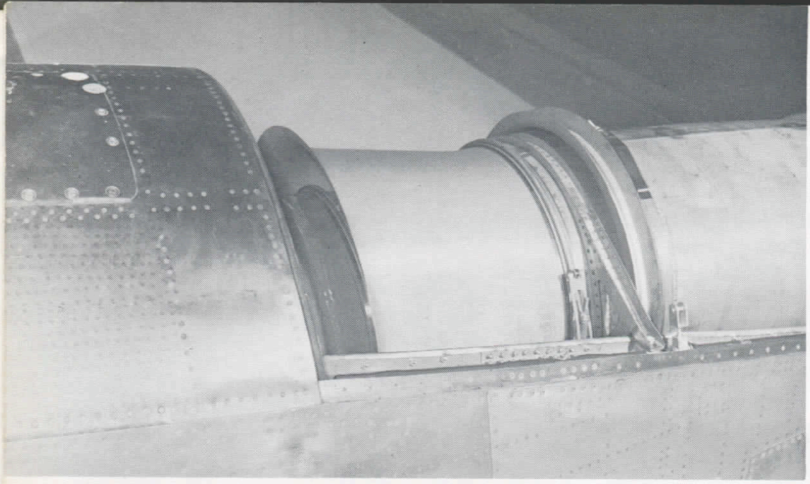
Figure 17 Cutaw



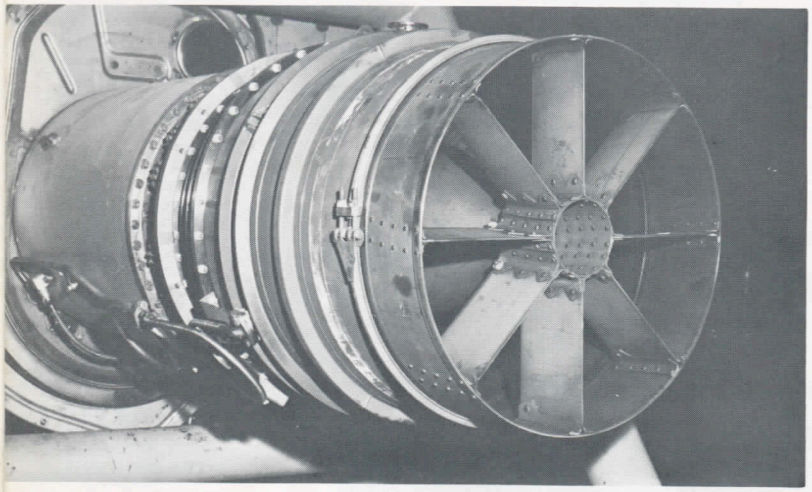
of Allison 501 Engine

at the cruise condition due to the pumping action of the propeller coupled with the suck-down effect of the exhaust ejector at the engine outlet. In practical terms this amounts to an increase in available power under cruise conditions of approximately 3% and for take-off, some 5% increase.

The exhaust ejector is illustrated at the top of Figure 18 and consists of a bell-mouthed section which induces air into the tailpipe, and forward of this are the anti-swirl vanes which straighten the engine exhaust gas thus increasing the axial component of jet thrust. In order to provide an adequate source of air for the ejector when running at 10,000 rpm the 10th stage bleed air is directed into the tailpipe zone. The 5th stage bleed air is separately dumped directly overboard. Cooling airflow is provided around the tailpipe, being introduced through an NACA flush type inlet on the top of the tailpipe forward door. Cooling air for the turbine zone is provided from a similar flush inlet together with flow distribution ducts. This inlet also serves as the second-



EJECTOR BELL-MOUTH



ANTI-SWIRL VANE INSTALLATION

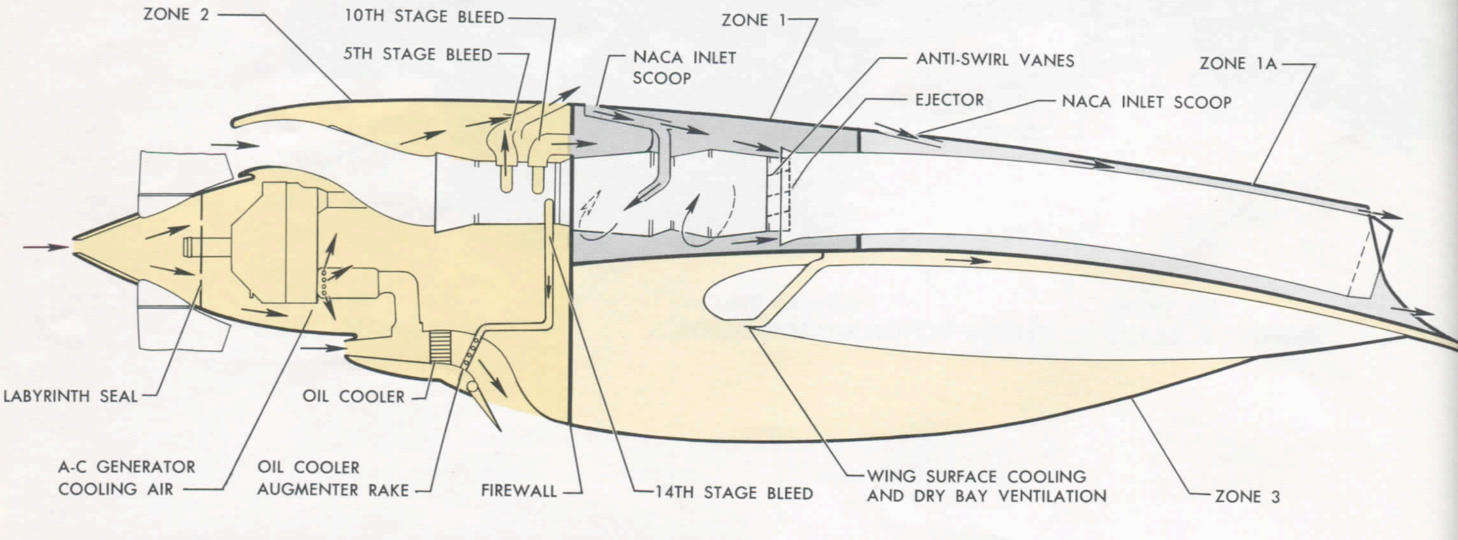
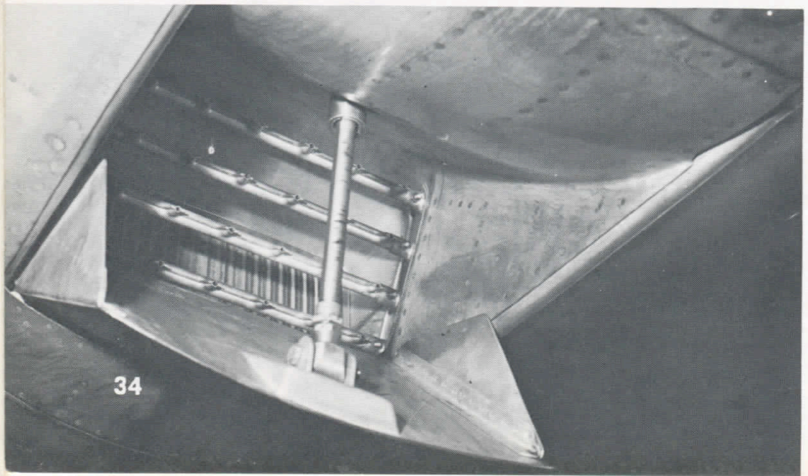


Figure 18 Installation — Inboard Engine



◀ OIL COOLER AIR-FLOW AUGMENTER RAKE

ary air source for the exhaust ejector. The wing upper surface is kept cool by a separate ram air system having inlets in the lower surface of the wing just outboard of each nacelle. The same air source is used to vent the wing dry bays in the inboard nacelles and, in the outboards, to cool the engine air starter bottle system components (when installed).

The propeller spinner contour, which is a modified conical form, was chosen because of its compatibility with the critical air intake flow requirements, and a labyrinth seal is used to prevent excessive propeller cooling air spillage between the fixed and rotating sections which would upset the boundary layer flow. The cooling air from the propeller passes into the accessory zone under normal flight conditions and, when propeller feathering occurs, is shut off automatically by a mechanical closure system. The boundary layer lip on the engine air intake is designed for optimum ram recovery even at the higher angles of attack common to take-off and initial climb out conditions. Both the intake lip and the top of the intake duct are anti-iced by air bled from the 14th stage of the compressor. The tailpipe diameter of 19″ was finally arrived at after a careful study to determine the optimum arrangement for the engine versus the lowest drag penalty from the aerodynamic viewpoint.

Several miscellaneous points are of interest in the power plant installation. For example, the engine ground running condition requires a propeller blade angle which is negative at the propeller tips in order to offset the static thrust of the jet efflux. This results in very low airflow over the oil cooler so an airflow inducer rake, or augmenter, is fitted on the aft side which uses bleed air exhausted through nozzles to draw cooling air over the matrix, thus providing adequate cooling irrespective of the airplane's orientation with respect to the wind. A detail view of this feature is shown in Figure 18. Another interesting point is the use of an oil-to-oil accessory heat exchanger in the engine oil cooler outlet line for cooling the cabin supercharger oil. This provides accessory cooling without the complexity and drag penalty which would be associated with a separate cooler mounted in the airstream while, at the same time, preserving the individual identity of main engine and accessory lubrication systems.

The most notable aspect of the overall power plant installation is that for the first time, to our knowledge, the engine provides more power when installed than when running at 100% performance on the manufacturer's dynamometer. The attention paid to the details of propeller and induction system design and exhaust system configuration have paid off in the dividends of power available to more than meet performance guarantees.

10. THE AIRFRAME STRUCTURE

General. To the casual observer the Electra airframe looks externally quite similar to contemporary transport design. There are, however, some important differences arising principally from the combination of "fail-safe" design and "long fatigue life" characteristics. The fuselage is a semi-monocoque structure and the wing is of the box beam type. The fuel tanks are of the integral type and the three landing gears are essentially conventional and retract forward. Extensive use has been made of large structural elements such as forgings and this practice, together with the well known Lockheed integrally-stiffened method, reduces "bits and pieces" construction to the very minimum. The importance of fail-safe and fatigue considerations is such that a brief description of the design philosophy and testing would not be out of place here. Although the two subjects are complementary in the overall sense they are nevertheless really two separate problems.

Fail-safe. The need for fail-safe design was principally established as a result of the widely-reported disasters involving two early jet transports in 1953 and became a requirement in the CAA structural design law in 1956. The Lockheed structural philosophy goes beyond these recent design certification requirements, however, since the legislation implies that fail-safe testing and analysis is an alternative to fatigue testing and analysis whereas in the case of the Electra we have accomplished both. Fail-safe affects not only the primary airframe structure but must also be present in windows, doors, flaps and flap actuators, and so on. The underlying philosophy of the fail-safe principle as it is applied to the Electra structure has been stated as follows: "Any single structural failure occurring in flight must not result in loss of the aircraft through structural collapse, loss of control, flutter, or unmanageable change in aerodynamic characteristics."

Failure of a single element in the wing structure, for example, should not reduce the remaining structural load-carrying capability to a value which would cause collapse; or in the case of the fuselage under cabin pressure and flight loads, the failure should be confined to a local point enabling the airplane to retain sufficient structural integrity to continue flight to an emergency landing airfield. In the case of wing design the integrally-stiffened structure method used in the later Model 1049 Constellation series lends itself well to this new requirement. The upper and lower surfaces of the Electra box beam structure are now divided up into a maximum of nine structural planks running spanwise (see Figure 19), each plank being of extruded and machined construction shot-peened to obtain the required curvature. Complete failure of any one of these planks or of the beam cap or shear beam web would not reduce the wing structural strength below limit load, and an extensive test program has demonstrated this. This fail-safe plank structure was developed on the Model 1649A Starliner, so that a great deal of experience is already available.

In the case of the fuselage the principal fail-safe problem is concerned with avoiding extensive rupture under full cabin pressure, and early work showed the need for using a skin material which had low crack propagation rates. Such a material would have to be ductile and have the best fatigue and tear resistance. For this reason 2024-T3 and T4 materials were used in the shell and the stringers are continuous with cutouts in the frames to permit them to pass through. This type of construction was found to be most suitable for the cabin differential pressure used (6.55 psi) and eliminates the risk of extensive longitudinal tears, confining them to the small panels formed by the stringer-frame combination. It was necessary to test this fail-safe concept thoroughly and a complete full scale non-flying fuselage — called "Serial No. 9999" — was set up to demonstrate this. This fuselage is illustrated in Figure 20 and the program included nineteen static sawcuts and nineteen dynamic spear cuts made under various combinations of full cabin pressure load together with flight maneuvering load, culminating in the simulation of major damage such as a very large hole in the side of the fuselage. In all of these cases fuselage rupture restricted itself to the local areas and the structure continued to carry the design load. In the final test for the large hole type damage, although as would be expected a rapid decompression resulted, the fuselage not only continued to carry full load but the load was subsequently increased to 125% to simulate mildly turbulent flight without failure or additional damage. The illustration shows how the test fuselage was supported as though by the wing, and the straps and hydraulic jacks for

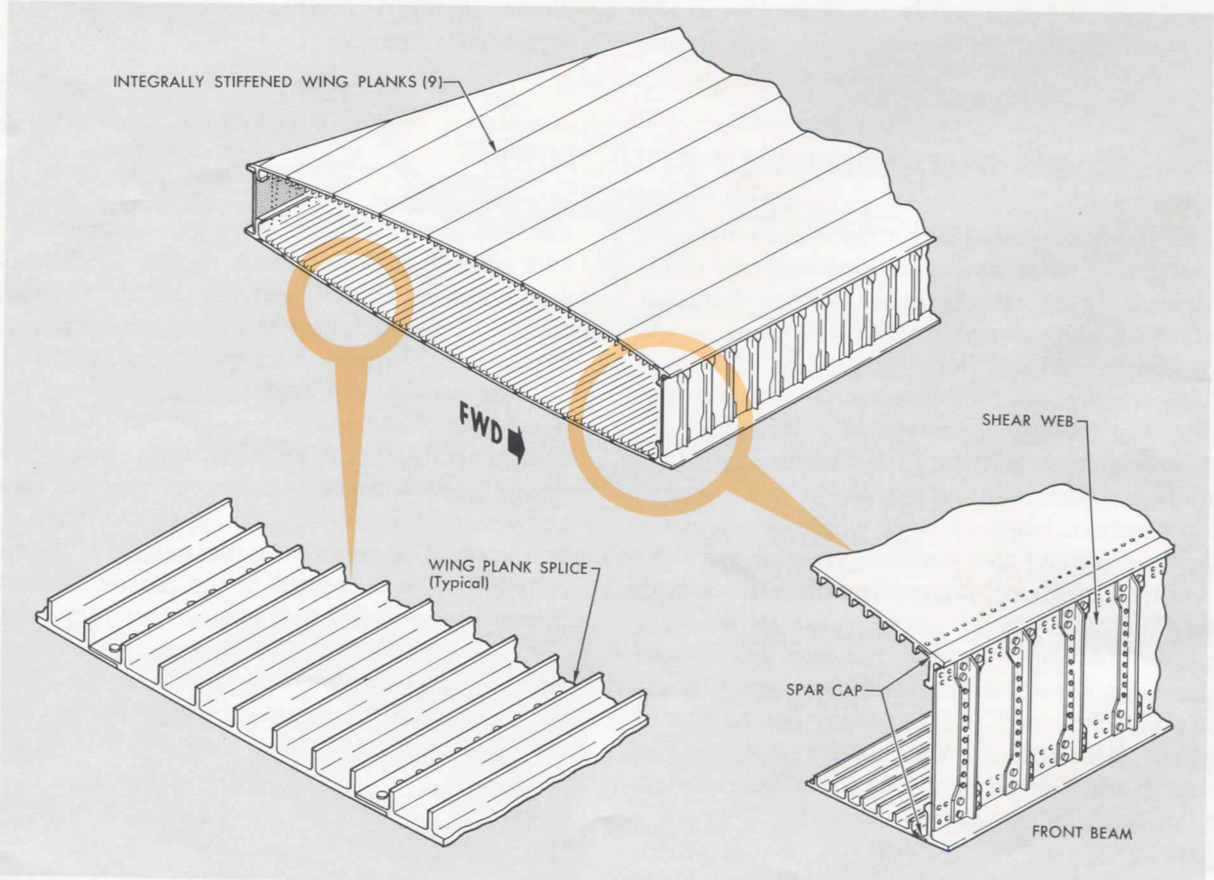
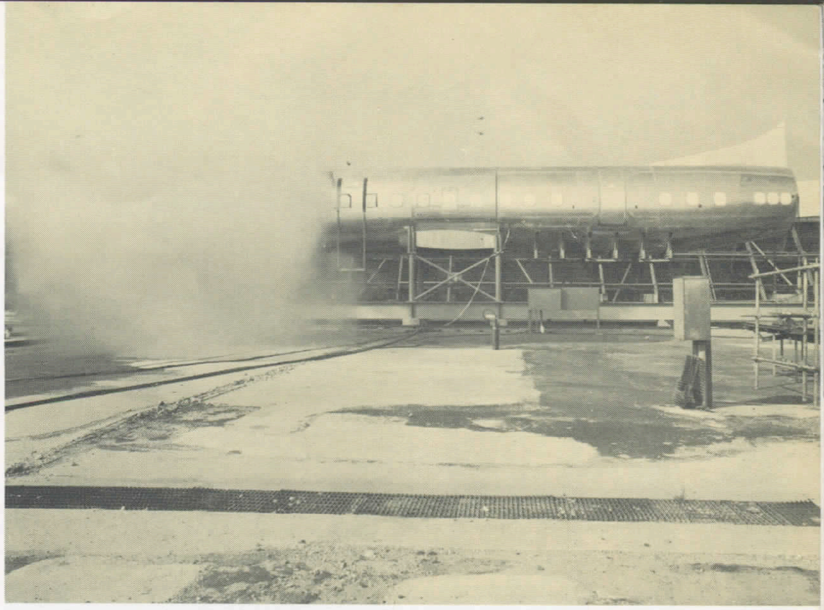


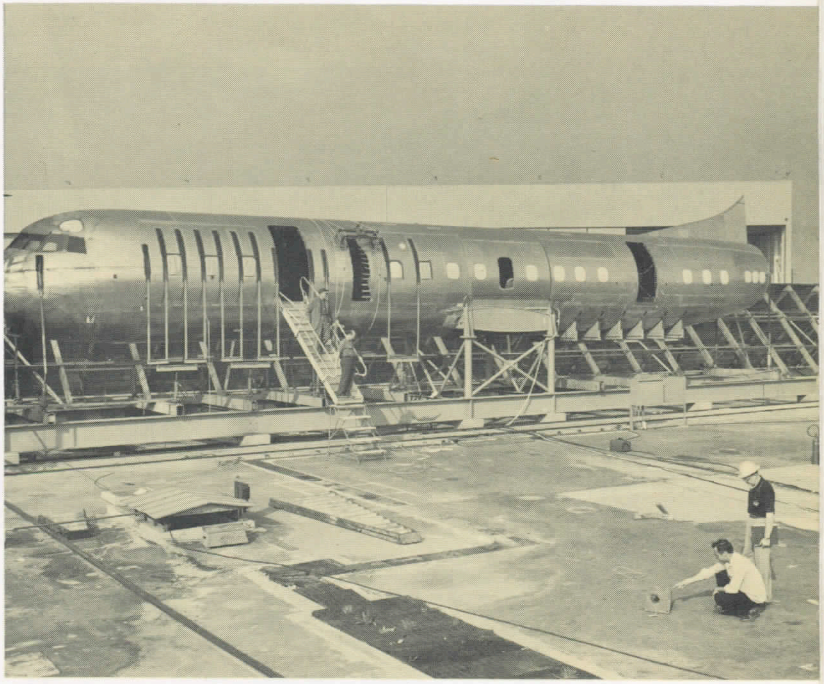
Figure 19 Wing Fail-Safe Details

applying bending and other loads can also be clearly seen. The entire program simulated cuts through fuselage frames, wing-fuselage main ring, windshield posts, between the closely spaced lounge windows, nose landing gear forgings, etc., as well as typical shell ruptures. Similar fail-safe tests were made with respect to the cockpit floor under pressure load in a separate program.

The wing fail-safe test program included a full-scale inboard section near the root which was used to demonstrate compliance with the requirements. Planks at mid-chord and adjacent to the spar caps were completely severed by sawcuts and, in addition, beam caps and complete shear webs were similarly treated. In every case the structure continued to support full limit load, which is about 25% greater than that specified by the CAA requirements. In no case did cracks propagate beyond the saw-cut areas and no significant change occurred in overall wing deflections as a result of severing any individual member. Typical examples of fail-safe tests of this type are shown in Figure 21. In addition to the wing and fuselage test programs, substantiation for fail-safe has been made for the empennage and its attachment to the fuselage, surface control hinges and tabs, flaps and flap actuators, and so forth — all with satisfactory results.



INSTANT OF FIRING SPEARS INTO PRESSURIZED FUSELAGE



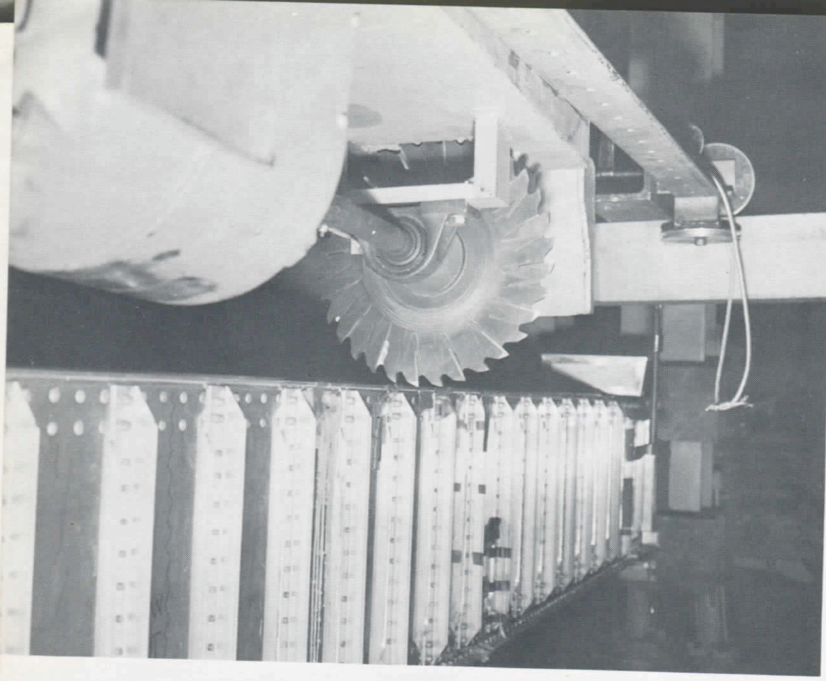
DAMAGE TO FUSELAGE SHOWING SPEAR ASSEMBLY IN FOREGROUND

DECOMPRESSION DAMAGE AS VIEWED FROM FUSELAGE INTERIOR

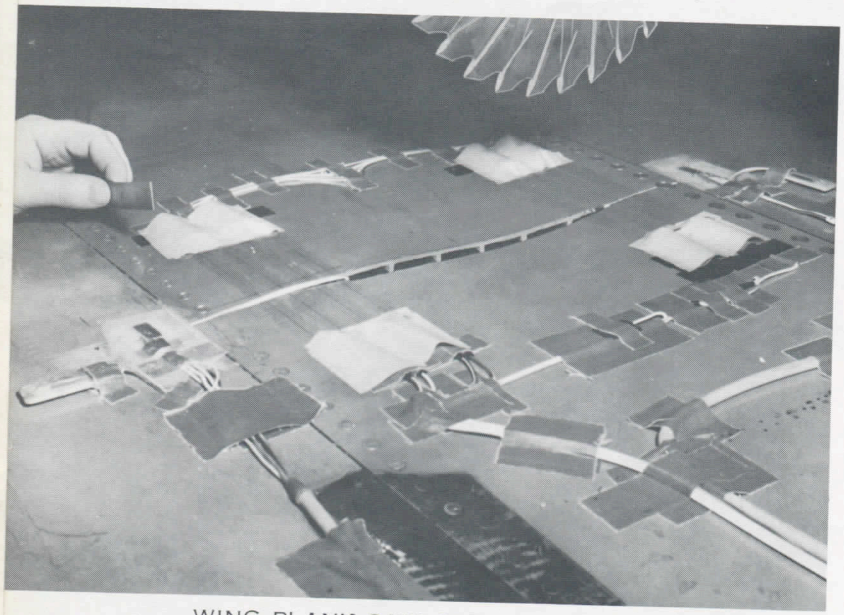
Figure 20 Fail-Safe Testing Sequences on Electra Fuselage

Fatigue Life. To be economically successful an airplane must have long life without structural fatigue problems. "Fail-safe" while protecting against the potentially catastrophic effects of most types of externally induced damage, also provides a high degree of protection against fatigue cracking. The fail-safe philosophy, however, should never be used as a means of accepting or condoning fatigue cracks and accordingly a comprehensive study was necessary on the Electra to see what was required for long structural life under practical operating conditions. These conditions vary widely between airlines and are related to the route structure, landing and take-off frequency, meteorological and gust conditions, etc. The Lockheed design philosophy is that the closest simulation of the actual operating conditions should be attempted by spectrum analysis and testing methods so that fatigue cracking is unlikely within the economically useful life of the airplane. Loading spectra were established and full scale components such as landing gear, fuselage joints, wing joints and empennage joints were exhaustively analyzed and tested. The main landing gear has been cycled to a simulated 270,000 flights and the nose gear to 160,000 flights, each "flight" including the effects of typical gear loads experienced from ramp to ramp such as taxiing, braking and landing, all with no significant difficulties. The tests have now been discontinued because they have exceeded an average landing gear life of many times that which could ever be expected in service — in fact, some 40 to 60 years!

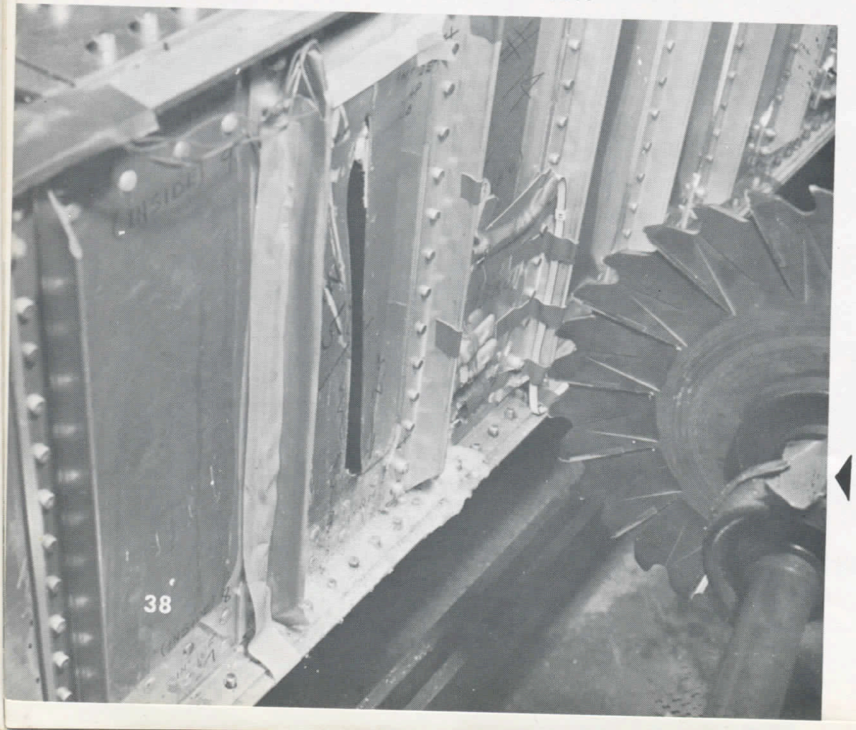
Reduced to its simplest terms the classic S-N curve (stress vs. number of load cycles) shows that the life of a material or structure is proportional to the working stress level — in other words the higher the working stress level the shorter the life. The Constellation has, generally speaking, achieved excellent results with its primary structure due in great measure to the relatively low working stress levels employed. The Electra continues this philosophy and the 2024-T3 fuselage skins, for example, have a maximum stress level of only 11,000 psi for hoop tension loads, under internal operating pressures. Door and other cutouts are reinforced so that the fatigue life is at least equal to the basic uncut fuselage shell, and considerable stiffening in the propeller plane area is provided to take care of the higher acoustic and aerodynamic vibratory loads.



SET-UP FOR SAWING BEAM CAP



WING PLANK SAW CUT, SHOWING STRAIN GAUGE INSTALLATION



◀ SAW CUT IN FRONT BEAM WEB

Figure 21 Typical Wing Fail-Safe Tests

In the wing structure design practice has been to eliminate fatigue-sensitive cutouts in the lower surface as far as possible, and for this reason the tension surface is uninterrupted by landing gear attachment structure as is the case in the Constellation. This results in a wholly externally stowed landing gear, a minor penalty for this excellent fatigue life characteristic being the small increase in the length of the inboard nacelles under the wing required to house the gear. The large fuel tank access doors are placed on the upper surface in the inner wing areas for the same reason, and in fact the only cutouts in the lower surface are those required for the fuel tank water drain valves and drip sticks since all tank components are mounted from the top or through the shear web (as described later under THE FUEL SYSTEM). In the outer wing areas the access doors are placed underneath due to the difficulty which would be occasioned from the maintenance viewpoint with upper doors in such a thin wing. There is no fatigue penalty, however, and although the tension stress levels are much lower in this region, the doors were designed and tested to the same fatigue requirement as the main wing joints. In fact the design stress levels employed are less than 60% of those available with the material used.

Integral tanks. The integral fuel tank design was adopted because it is by far the most efficient from the viewpoints of minimum weight, maximum capacity and simplicity of the fuel system. In the past the only defect has been that of fuel tightness and consequently major effort has been made in the Electra to eliminate this problem. The concept used is that the structure should not only be designed as a load carrying member but also as a tank and that it should be basically capable of containing fuel without the addition of sealing material. This is in contrast to the older practice of considering the wing almost solely from the structural viewpoint and then attempting to make a satisfactory tank by the addition of very large amounts of sealing compound.

Faying surface sealing is used at all joints between the mating surfaces, which are assembled while the sealing medium is wet. In addition to this, fillet sealing is used as a further insurance against leaks. The structure avoids the use of corrugations or closed spaces which tend to channel leaks, and the assembly of the fuel-carrying structure is largely made with interference type fasteners such as lock bolts. A minimum of loose-fitting fasteners such as screws is employed to guard against this source of leakage. The integrally stiffened structure affords the advantage of machined "sculpturing" to enable a flat surface contact to be designed for the fuel tank end ribs instead of the older built-up alternative of having to form and fit complicated pieces around continuous spanwise stringers and seal them heavily to obtain fuel tightness. Within the tanks the built-up wing ribs are attached to the integral stiffeners by tangs and "H clips" so that the wing outer surface is not penetrated by fasteners, thus eliminating any risk of leaks from this source. To avoid the old problem of leaks caused by the over-zealous re-torquing of bolts penetrating the tank structure, barrel nuts are employed in some cases, being assembled from outside the tank (see Figure 22). This practice also eliminates the need

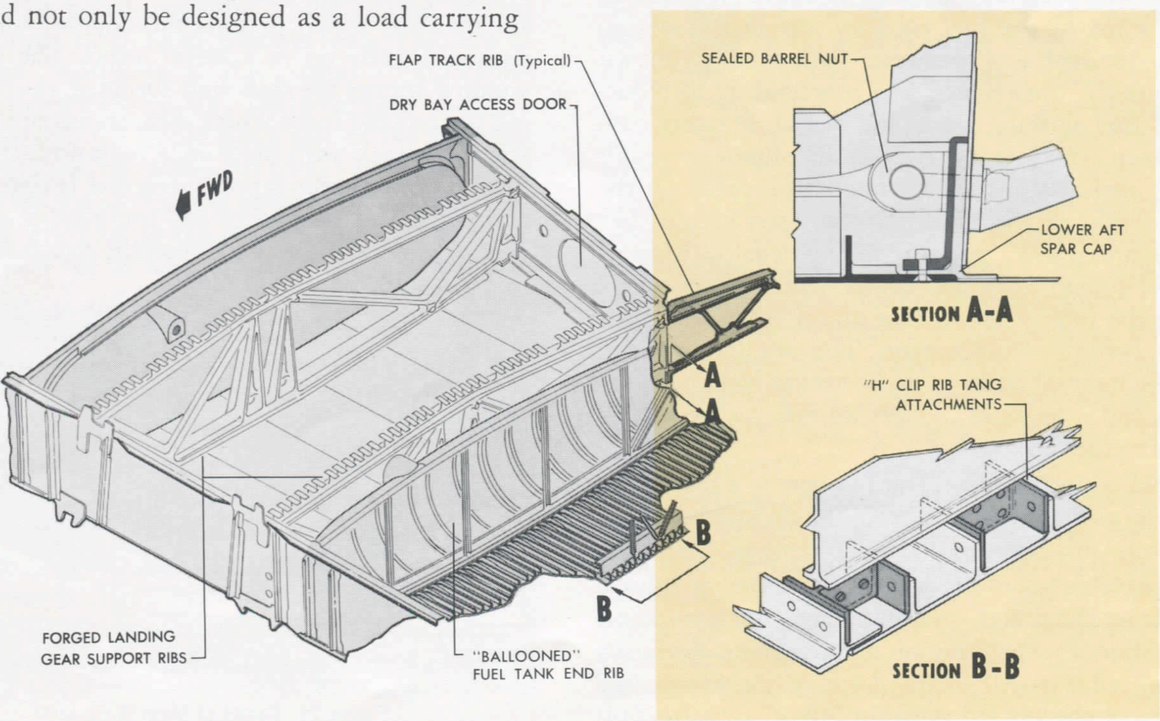


Figure 22 Wing Dry Bay Construction Details

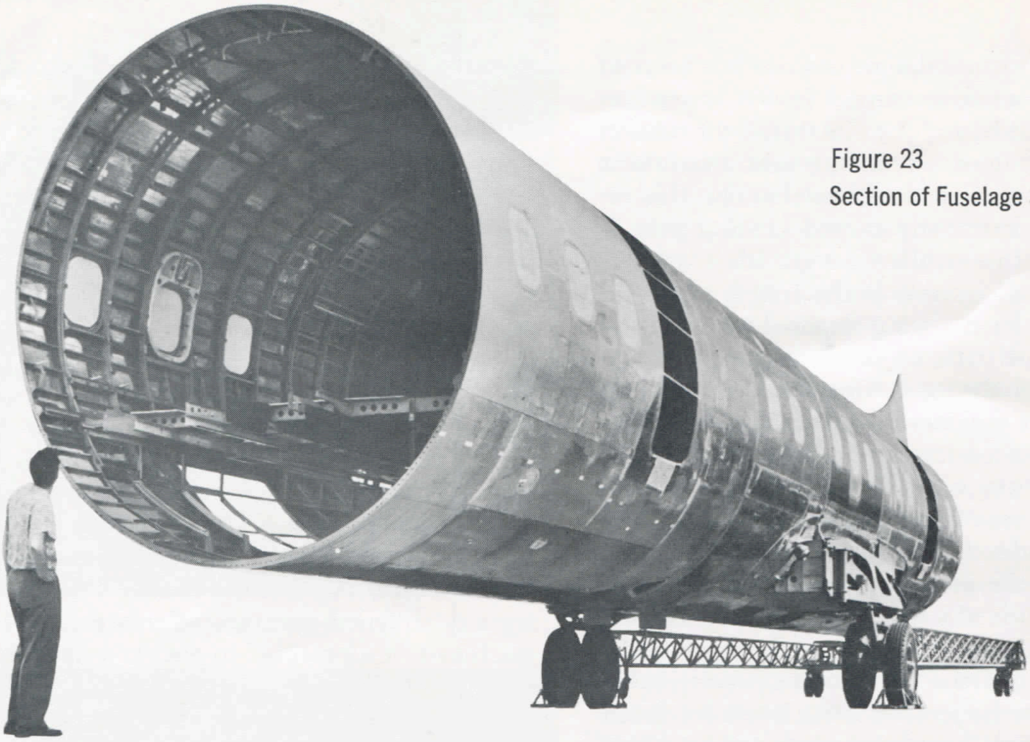


Figure 23
Section of Fuselage Structure

for personnel to enter the tank — a frequent source of fuel tank trouble in itself. Dome nuts are, of course, used in cases where there is no alternative to fastening by means of bolts or screws right through the tank structure.

A dry bay is provided over the landing gear area between the inboard and outboard tanks and the fuel tank end ribs are spaced away some 12″ from the landing gear support forgings so that a landing gear accident would not result in the gear being driven up through the fuel tank causing rupture. In order to regain some of the fuel capacity lost in this design feature, the tank end ribs were "ballooned" as shown in Figure 22, this change also contributing to reduction of fuel sloshing loads. For the same safety considerations, there is no fuel in the fuselage center section area and a drain channel is provided on the inboard side of the tank end rib (see Figure 24) to take care of leakage, if any should develop. Most of the fuel system lines and components are contained within the tank itself so that minor leaks from this source become unimportant. The results obtained with the integral tanks in flight testing have been excellent and it looks as though we really have a fuel-tight structure at last.

General construction. The fuselage is a true cylinder of large diameter right from the cockpit bulkhead to a point just forward of the aft lounge. There are many advantages to be derived from the cylindrical form from the design and manufacturing viewpoints in addition to the interior arrangement flexibility which it affords. All of the doors in the pressurized area are of the inward opening "plug" type for fail-safe reasons and the two main cabin doors — which are basically interchangeable — are neatly rolled around the inside circumference of the fuselage overhead thus avoiding any wasted floor space. One large 24″ x 48″ CAA type I emergency exit is provided in the aft lounge area and a 20″ x 40″ type III exit is provided over the wing on each side. A type IV exit 20″ x 30″ is provided in the forward cabin on the right side and the aft main cabin door is also classified as an emergency exit. The 16″ x 18″ windows are of bi-axially stretched Plexiglas — a new shatter resistant material which permits the double panels to be riveted directly on to a metal insert. The structural window frames are thin wall forgings, thus eliminating the racking loads which were transmitted into the window panels with older style built-up frame assemblies. The nose gear support structure is also a forging and is the largest used in any commercial aircraft to date. A general view of the fuselage structure is given in Figure 23.

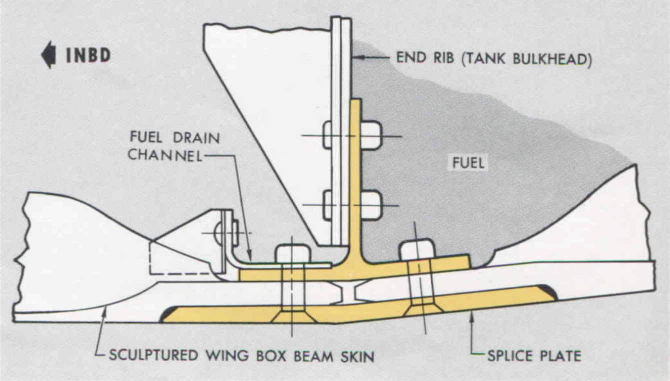


Figure 24 Detail of Main Wing Joint

The wing box beam plan form shows a "kink" in the rear shear beam, this being to permit the employment of simple constant chord one-piece flaps which are interchangeable from left to right. The flaps are of the Fowler type and the angular change which occurs with extension is provided by a simple ramp on the tracks instead of the link type assemblies used on the Constellation. The wing structure itself has been described in previous paragraphs and the lower surface is of 7075 material while the upper uses 7178 because of its superior compression characteristics. The box beam center section is assembled with the fuselage and the wing joints are outboard at wing station 65. The joints, shown in Figure 24, are of a very simple double shear type and so arranged that while not actually interchangeable, they are *replaceable* in the field in the event of major damage. The tension bolts at the upper and lower beam caps would serve as holding fixtures while the shear fasteners were being redrilled so the wing is essentially self jigging. The empennage is of conventional built-up construction using tapered skins of 7075 material which vary from .1″ at the root to .03″ at the tip.

The engine nacelle structure uses aluminum, titanium and stainless steel and differs from reciprocating engine practice principally because of the high torsional load design requirements coupled with the slender nacelle form. The maximum torsional reaction loads could be almost twice the normal engine output torque and are due, among other things, to the very high rate of propeller blade angle change and instantaneous power response of the engine. In this respect torque surge from possible turbine seizure or inadvertent feathering is the critical consideration from the design standpoint. The structural loads are carried through the upper fixed part of the structure over the engine, the lower oil cooler scoop area and a stressed section around the propeller reduction gearbox often irreverently referred to as the "horse collar," carrying the forward engine mounts. The power plant removal face was canted to provide power plant interchangeability between the inboard and outboard nacelles, and the diagonal side struts employed afford maximum accessibility to the sides of the engine. This can be seen in Figure 41.

From the fire protection viewpoint a vertical firewall of stainless steel is provided together with a flexible fire seal separating the accessory component zone from the turbine section zone. A stainless steel shroud extends aft to the wing trailing edge to prevent heat damage to the wing upper surface and is liquid tight to drain spilled fuel overboard. The fire protection concept employed is that a "lace-work" of high temperature resistant structural members should remain, capable of supporting load after the occurrence of a fire of maximum intensity.

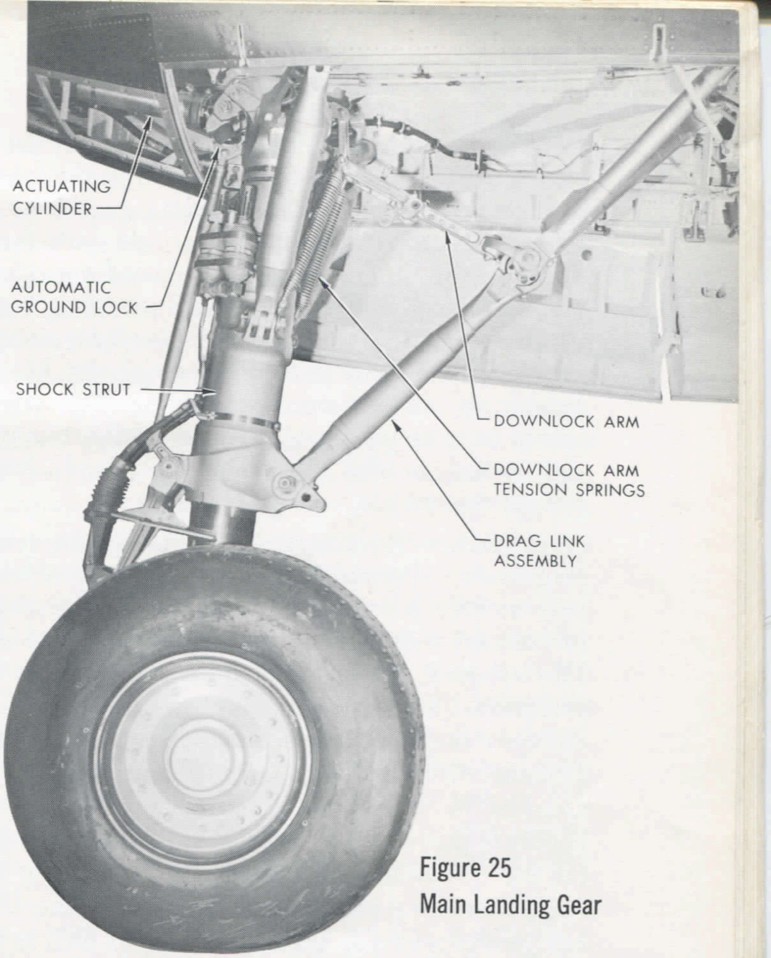


Figure 25
Main Landing Gear

Landing gear. The landing gear design, shown in Figure 25, is worthy of special attention because of its ingenious design and simple construction. One of the early design considerations was to make all three of the landing gears of the "free fall" type, that is to say they should be capable of being lowered and locked in an emergency without use of hydraulic power. This is made possible by air loads and gravity loads together with a simple tension spring arrangement which locks the gear in the down position. The hydraulic up latches are provided with mechanical overrides which are cable operated from the cockpit for all three landing gears, and sufficient mechanical leverage is available to break loose a jammed latch by virtue of large over-travel of the operating levers. In short, we have incorporated in this design just about everything we know to avoid the necessity of having to make belly landings because of failure of the gear to extend properly.

To avoid the need for ground safety pins the gear geometry is such that the main strut lies over center backward at a small angle, and similarly the down lock arm and drag strut are also well over-center, so that collapse of the gear would be physically impossible when the airplane weight is upon it. An additional related feature is the automatic ground lock which operates when the gear strut is compressed more than 4″ from the fully extended position and moves a "bar of iron" into the retracting cylinder linkage so that even if the landing gear lever was deliberately selected to the up position with the airplane on the ground, the system could not operate. The nose gear also contains an interesting feature which automatically releases the wheels for castering merely by the connection of a special tow bar thus permitting easy ground maneuvering. The tow bar cannot be removed until the nose wheels are centered and locked to the normal steering and shimmy damper mechanism.

Maintenance characteristics. Although the detailed maintenance characteristics will be apparent in the later articles, it would be inappropriate to complete this section without some general references to them. The structure was intended from the outset to have exceptional ease of inspection, and we believe that there are no blind or inaccessible areas in the entire airplane. Wing fillets, fairings and the like are attached by screws rather than rivets. Small local doors are provided for the wings and the access doors for the rear beam run almost the entire wing span. For store-room economy maximum interchangeability has been provided on major components such as landing gears, wing flaps, cabin doors and so on.

The characteristics of the line maintenance task — as distinct from the overhaul task — have been considered very carefully and one of the criteria used was that it should be possible to perform maintenance tasks with the aid of a screwdriver alone. For this reason generous use has been made of quick fasteners mostly of the Camloc type and the use of loose screws has been largely avoided. Major access areas, like the hinged wing leading edges which do in fact require the removal of a number of screws, are fitted with local quick fastening inspection doors for routine checks, and all doors of this type have the hinge line forward to eliminate inadvertent opening in flight if not securely fastened. As a general rule it has been the aim to match the access provisions to the task to be performed, i. e., servicing, inspection, maintenance or overhaul. The use of "plug" doors in the pressurized shell has also simplified latch mechanisms and rendered improper closing less hazardous. The use of magnesium for structural purposes, apart from accepted and satisfactory applications such as nose landing gear wheels, has been deliberately excluded because past practice has shown the difficulty of eliminating corrosion to be too great consistent with maintenance economy.

An incident occurred during flight testing which amply demonstrated the ruggedness of the airframe structure and is worth recording here. An extremely severe landing was accomplished with a vertical sinking speed of some 18 ft. per second, or approximately 180% of the design limit strength. The aircraft was flown to Burbank and inspection revealed a crack in one of the wing planks on the outboard side of No. 3 nacelle. Upon further examination the crack was found to be approximately 21″ long. The landing gear suffered no damage in this incident and there was no leakage from the fuel tanks.

11. THE ELECTRICAL SYSTEM

Discussion. Next to the power plant differences the most important consideration affecting the maintenance man is undoubtedly the electrical system. It was pointed out in the CONSTELLATION COMPARISON section that the empty weight of the Electra is extremely low. Power plant and structure have made major contributions to this low weight, but in the functional systems it is undoubtedly true that the extensive use of an alternating current primary electrical power system is the most important element. Weight relationships on a relatively small airplane are much more critical than those applying for example to the large pure jet transport, principally because overall systems requirements for the latter do not increase linearly with the large increase in gross weight.

The total auxiliary power requirement to be taken from the engines in one form or another in the Model 049 Constellation could, excluding de-icing, normally reach a maximum of approximately 200 hp, whereas in the case of the Electra it could be as high as 400 to 550 hp. It was, therefore, obvious that a proportional increase in systems weight to obtain the power required in the Electra would be quite prohibitive, to say nothing of the degree of flexibility demanded by improved passenger comfort facilities both on the ground and in flight. Preliminary design studies made it quite apparent early in the program that the only way to meet the power demand was by the use of an electrical system and fairly large requirements were envisaged depending upon the various systems configurations studied, varying all the way from 300 to 700 kva. These requirements included considerations of the "self containment" philosophy from the viewpoints of ground heating and cooling, electrical drive for the hydraulic system, electrical propeller de-icing and, at one stage, electrical anti-icing for the wing and tail surfaces.

Consideration of the older style 28 volt d-c primary generating systems was quickly eliminated because of the impracticability of driving the number of d-c machines which would be required, together with the attendant weight and space difficulties. There was no alternative, therefore, but to develop a new a-c system of the requisite capacity and the modern accepted standard 120/208 volt, 400 cycle, 3-phase power was selected. This choice is in common with most of the new turbine transport aircraft.

Some of the advantages stemming from the use of a-c electrical power are (a) flexibility in permitting the location of power devices around the airplane closest to the point of use — and therefore providing the lightest arrangement, (b) use of a single power source for all ground purposes including full heating, cooling, hydraulic and control system checks — all without engines running, (c) load transfer flexibility in the event of single or multiple engine failure and the ability to monitor selectively for non-essential functions, (d) large power output is possible with only a limited increase in weight of the prime generating system, (e) availability of reserve power for airplane type development — in other words ability to "stretch."

General arrangement of system. Two salient characteristics of the Electra system should be clearly stated first:

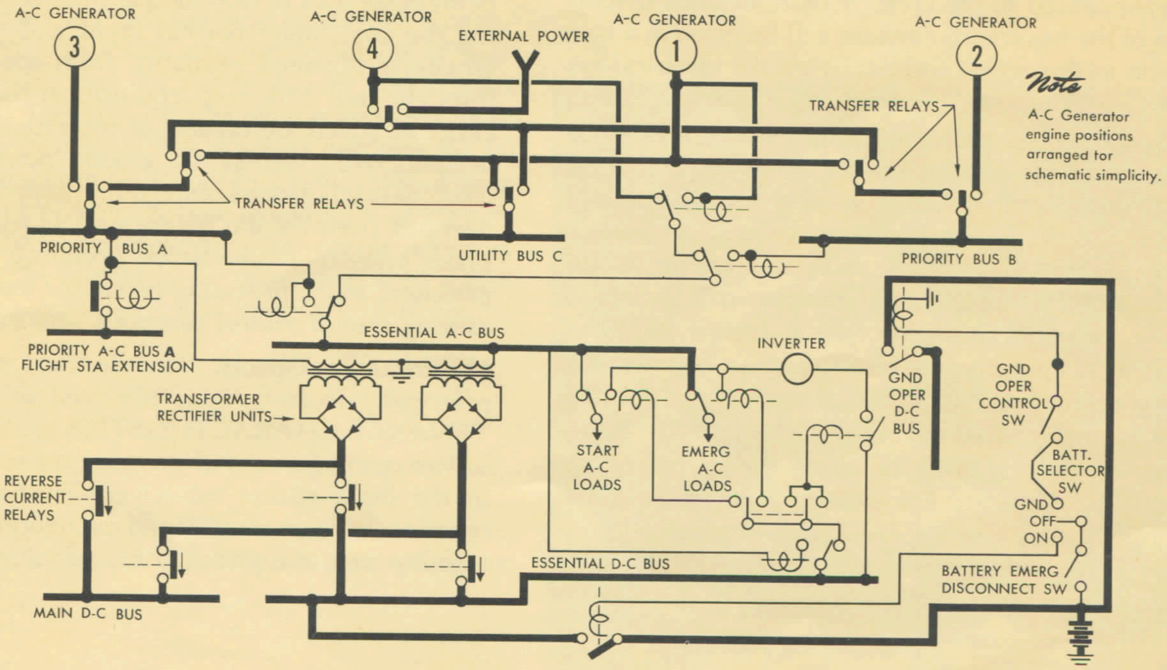
(1) The direct-driven generators made possible by the constant speed engine and,

(2) The non-paralleled system using three separate buses for power distribution.

Four 60 kva generators are installed, one being mounted directly on the accessory pad of each engine. It is to be particularly noted that there are no complicated "constant speed" hydraulic drive units with their attendant weight, space, maintenance and fire hazard problems. The generators are of a new design by General Electric developed for the Electra and use static excitation rather than the older rotating machine excitation with its inherent commutator problems. Although rated normally at 60 kva they were designed to be capable of 150% output with the cooling air available during normal cruising flight, in other words 90 kva. A continuous output of 60 kva is available on the ground without external cooling air. System capacity was influenced by the need for load growth allowance and also by the starting requirements for large motors. An item of interest is the provision of a generator bearing failure indicating device consisting of a rotor-stator interference signal. The generator weight is 98 lb. per machine and comparative studies show that no less than twenty 400 ampere, 28 volt generators, weighing approximately 55 lb. each would be necessary to supply equivalent power.

Although four machines are used it is actually a three-generator system, the fourth being used for ground purposes and on a standby basis during normal flight. The design load of the system is arranged so that it normally never exceeds the output of three machines — namely 180 kva. Three separate main buses are used (see Figure 26) and designated Priority Bus A, Priority Bus B and Utility Bus C in this decreasing order of load importance. The automatic

Figure 26 Electrical Power Distribution



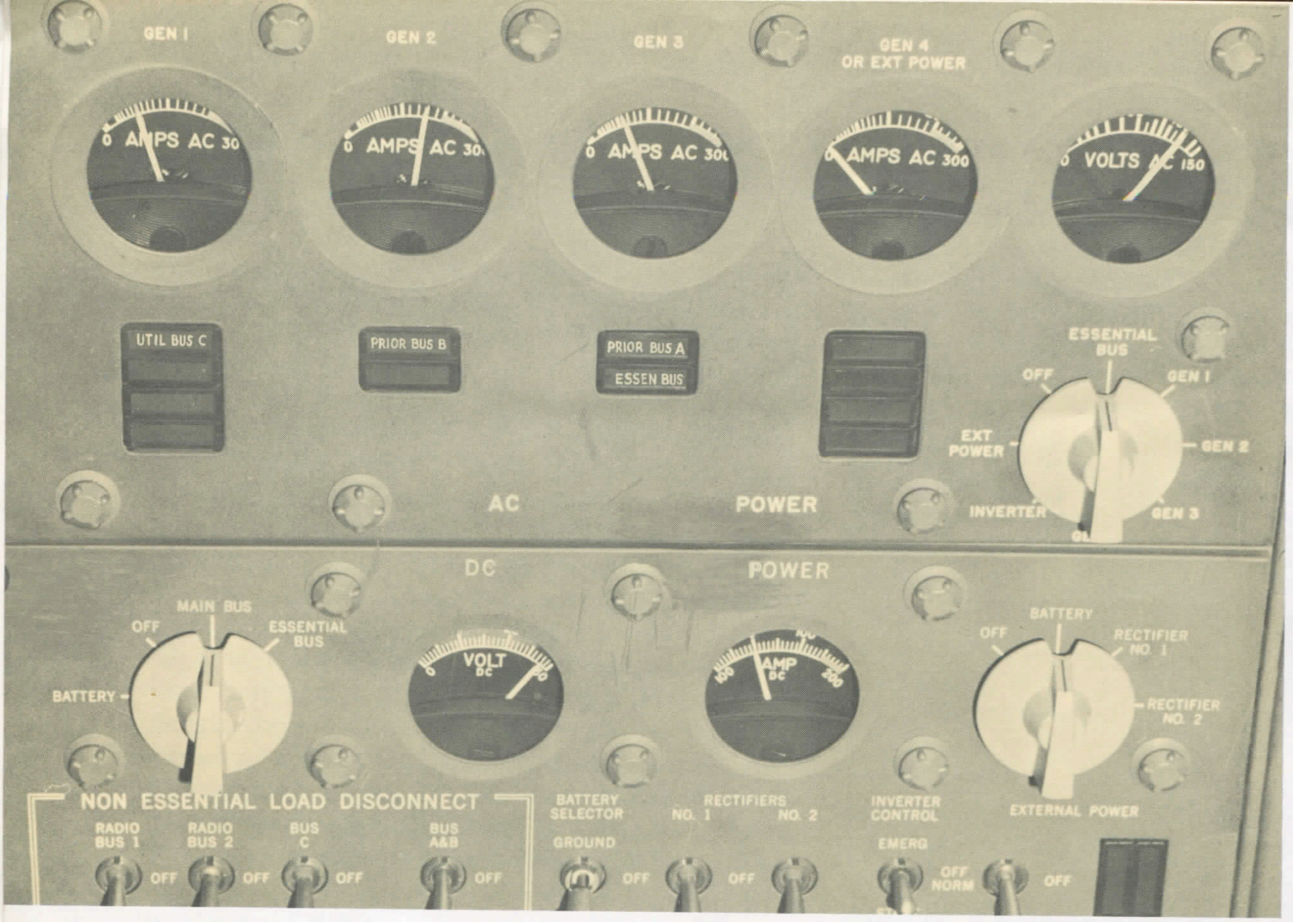


Figure 27
Overhead Electrical
Control Panel

transfer circuit is arranged so that three-generator reliability is provided for Buses A and B and two-generator reliability for the utility loads on Bus C. An automatic and independent transfer system provides four-generator reliability for loads connected to the Essential A-C Bus. In the flight station an overhead panel indicates the generator-to-bus connection at any instant by the illumination of small annunciator lights bearing the words "UTIL. BUS C," "PRIOR. BUS B," etc. below each of the four generator ammeters (see Figure 27). Automatic load transfer due to engine shut-down or other reasons is thus immediately indicated to the crew. A more detailed description of the bus transfer system will be given in a later article in this series, specifically on the electrical system.

System protection includes over-voltage and under-voltage as well as control of abnormal frequency. The design range of variation in frequency is 380-420 cycles and the system has been designed around the lower value instead of the more usual nominal 400 cycle value. The purpose of this was to take care of small variations in engine rpm and some additional weight was put into the electro-magnetic material in the generators to cope with this without overheating. For normal ground purposes with one engine running, or while starting or idling the remaining engines, the output of one generator is sufficient, and for this reason a two speed gear box is provided on Engine No. 4 only (see RAMP HANDLING section). A frequency sensitive system controls the two speed ratio selection so that when the engine is operating at Low Ground Idle (10,000 rpm) the generator output is within the normal frequency range. The installed generator together with the two-speed gear box is illustrated in Figure 28.

Extensive use is made of 28 volt d-c power for control functions and also for emergency flight use as well as emergency ground services. A 36 ampere-hour battery is installed together with a 250 va inverter, the latter providing critical flight instrument power in such an emergency as, for example, failure of all generators to feed the Essential A-C Bus. All of the d-c used under normal flight and ground conditions is obtained primarily from the a-c system through two 150 amp transformer-rectifier units, either of which are capable of meeting the complete demand. No external d-c ground power source is used. Several ground emergency functions can be operated from the d-c system such as recharging the brake pressure accumulators, operating the integral passenger stairs, providing power for integral engine starting system control functions, and so on.

Maintenance aspects. The electrical equipment is principally located — as described in the MAINTENANCE CHARACTERISTICS section — in the service center forward of the wing center-section, and in the flight station sub-center. The service center contains the main transfer and distribution assemblies together with the principal bus systems and contactors (refer back to Figure 10). Also installed in this area are the four generator static exciters, voltage regulators and control units. Generator feeder sizes look quite small to those more familiar with the large sizes common to d-c systems — actually they are No. 6 wires running continuously from the firewall into the electrical service center, with no disconnects through the fuselage skin. The flight station has its own transfer and distribution center together with a load center. This arrangement provides for cockpit control functions close to the Flight Station Priority Bus and eliminates a great deal of control system wiring which would otherwise go to the main service center.

From the maintenance trouble-shooting viewpoint many facilities have been incorporated to isolate trouble quickly, including the provision of a special test box for the check out of the main generator control units. The units are packaged and are rack-mounted for rapid replacement. Within the units themselves the chassis and components are arranged for maximum repairability and those which are unrepairable are purposely held to a low cost. Special attention has been given to minimizing the possibility of accidental reversal of phase connections by the use of color coding and, in some cases, clamping of wires to preclude cross-connecting at terminals.

Mechanically and electrically many a-c components are much simpler and more reliable in many ways than their d-c counterparts, typical examples being: elimination of brush gear on motors, elimination of limit switches on actuators by the use of stall-torque motors, and the use of lighter and smaller contactors. The use of current limiters has been kept to the minimum. For handling purposes the 60 kva generators can be hoisted by a removable sling in the power plant, and key-hole mounting slots are provided for rapid attachment to the engine accessory drive pad. The battery in the nose wheel well is provided with a built-in screw jack elevator platform.

Summary. Specifically, the electrical power in the Model 049 Constellation was provided by four 200 ampere, 28 volt d-c machines totaling approximately 24 kw. On the Electra the power available during normal cruise, discounting the large overload capacity, is 180 kva — or seven and a half times as much. The overall *generating* system weight, including generators, wiring and control components of the Model 049 system was approximately 294 lb. whereas in the Electra the same considerations show a figure of only 771 lb. — or to express it specifically a weight-power gain of nearly three times. If this were to be expressed on the continuous allowable overload basis of 270 kva it would show a gain of nearly four and a half times, or to be more specific, a weight of 2.85 lb/kva compared with the Model 049's 12.25 lb/kw.

It will be readily apparent that the provision of the large power output a-c system has had a far reaching effect upon the airplane's functional systems. The novel use of electrical radiant heating panels in the cabin — to be described in the next section — is only one example of the flexibility in design inherent in this form of electric power. The concept of a single ground power source for all purposes could have been satisfied in no other way. More comprehensive self-containment provisions have been made in the form of high capacity cabin heating and cooling than ever before and all — thanks to the use of a-c power — with an acceptable weight penalty.

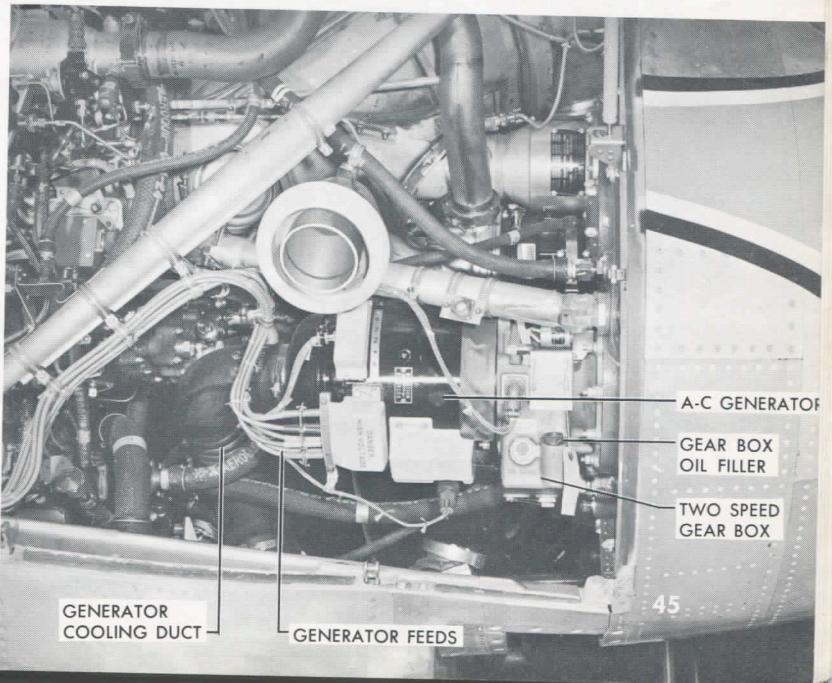


Figure 28 Side View of No. 4 Nacelle Showing Generator

12. THE AIR CONDITIONING SYSTEM

General. The air conditioning and pressurization system on the Electra is of unusual interest and merits a detailed description of the philosophies employed in its development. Several basic aims were established in the early design analyses, the most important of which were: (a) a higher passenger comfort level than previous airplanes — both on the ground and in flight, and for a wide range of passenger loads, (b) self-containment, i. e., no external ground trucks for cooling or heating and use of the simplest external ground power source, and (c) reasonably low power consumption, low system weight and minimum aerodynamic drag.

The system which finally evolved was a combination of several elements.

(1) Vapor cycle cooling.
(2) Air cycle cooling.
(3) Electrical radiant heating.
(4) Electrical duct heating.

The more important reasons for arranging the system in this manner will be reviewed later, but first let us consider the pressurization system.

Pressurization. Two engine driven superchargers are used for pressurizing the cabin at its normal maximum differential of 6.55 psi. Engine compressor bleed air was not used because of the risk of oil contamination and the relatively high engine power loss involved. The constant speed characteristics of the Allison 501 engine have made possible a light, high airflow capacity machine, one of which is mounted directly on the accessory drive case of each inboard engine. The superchargers are single stage centrifugal units having simple fixed ratio spur gear trains — a welcome departure from previous practice necessitating complicated variable speed hydraulic drives.

Control of supercharger output with altitude and load variations is accomplished by variable inlet preswirl vanes together with a spill valve and bypass system for surge control. It is now possible to mount the superchargers directly on the inboard engines instead of the earlier practice of mounting in the outboard nacelles with reciprocating engines. These early units were very large because of the need for variable speed control to obtain constant mass airflow against a wide range of engine rpm variation. Consequently they were too heavy for direct engine pad mounting and had to be shaft driven and installed in the outboard nacelles since the landing gear occupied most of the space in the inboards. In the Electra installation the air is tapped off the inside of the engine air intake thus avoiding the need for separate de-icing. The short, uninsulated ducts feeding from the supercharger to the pressure cabin mean less weight and pressure drop and fewer leaks. Rated cabin altitude can be obtained with either supercharger operating individually.

Control of cabin pressure is by a pneumatic system with the controller mounted in the cockpit and the outflow valve mounted aft of the rear pressure bulkhead at the end of an acoustic duct. The system is fairly similar to existing modern practice, apart from special design features to avoid cabin pressure "bump," and therefore does not warrant further description here. Let us, however, now return to the air conditioning part of the overall system since it is the major part of the problem.

Earlier designs. On the Model 649A Constellation, which was a most advanced airplane from the air conditioning system viewpoint, Lockheed pioneered the use of very large air cycle refrigeration capacity using this for both ground cooling and flight use. Full refrigeration of approximately 8.4 cooling tons was available by running the outboard engines at 1,200 rpm, but this practice was not universally approved by airline operators because of the long periods of ground engine running which were involved under high ambient temperature conditions in addition to which considerable wheel-brake wear was experienced. In these cases ground air truck sources — not cooled air — were used instead, employing the aircraft "bootstrap" air cycle system for the actual air cooling task. One of the important early teething problems was the generation of water fog and difficulties with water separators resulting in some cases of icing down-stream of the air cycle refrigeration unit.

Two other contemporary aircraft used vapor cycle systems but for differing reasons: one because the cabin was pressurized by exhaust driven turbo-supercharger bleed and insufficient air was available for large air cycle machines without excessive engine power penalty, while the other aircraft used vapor cycle as an additional system to provide only ground cooling due to the limitations of the existing small capacity air cycle machine when using a ground air source. In each of these cases commercial Freon refrigeration compressors of the reciprocating type were adapted and thus were heavy and inefficient. In all three of the transports considered, the heating was provided primarily by fuel burning combustion heaters.

System design considerations. Several differences in design requirements are present in the Electra today when compared with the Model 649A Constellation system. By far the most significant is the requirement for self-containment referred to frequently in previous pages. Among other considerations is the demand for separate flight station cooling and heating control, need for substantial improvement in tobacco smoke and buffet odor clearance, provision of no-draft ventilation and minimum temperature gradient and many others.

Cooling system. The whole cooling system consists of a vapor cycle (Freon) refrigerator system supplemented by two independent air cycle refrigerator systems, one in each cabin supercharger air supply duct. The question which immediately comes to mind is, "Why not use a large capacity air cycle system alone?" Several important reasons made this approach unattractive in the light of the large ground cooling requirements, namely 10 cooling tons,* which were part of the system design objective. Among these reasons were:

(a) For ground cooling without engines running a very large ground air source involving another expensive truck would be necessary contributing also to "ramp clutter."

(b) The large air flows required to operate the big air cycle machine would have increased cabin supercharger size, weight and accessory power demand to a prohibitive degree.

(c) In-flight cooling requirements are substantially increased by skin heating effects due to the higher speed, coupled with the considerable increase in heat given off by electrical and hydraulic equipment within the fuselage.

(d) Higher cabin pressure differentials mean increased back pressure — or a lower pressure ratio — which reduces the cooling capability of air cycle machines.

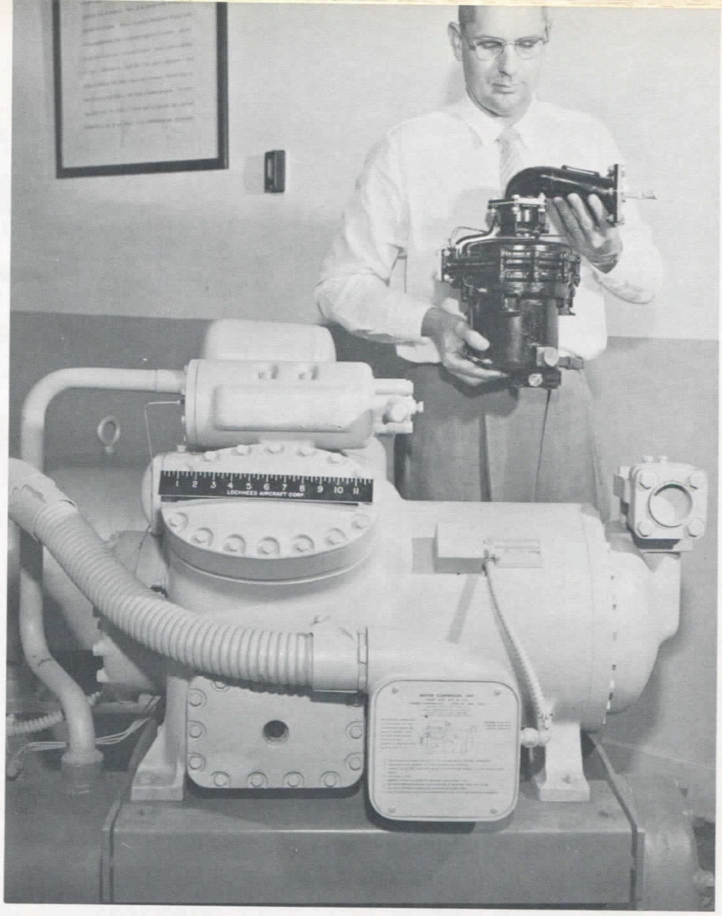


Figure 29 Comparison of Industrial and Electra Freon Compressors

These conditions led to renewed study of vapor cycle systems especially to try to meet the ground cooling case. Design requirements were drawn up for a light weight high efficiency Freon compressor, and after careful evaluation of positive displacement versus centrifugal machines the latter type was selected. The limited capacity (7.2 cooling tons) air cycle system showed great advantages when programmed with the vapor cycle system — at lower altitudes with the vapor cycle doing most of the cooling or operating in tandem with the air cycle system for maximum capacity. In general, at altitudes of above 15,000 feet the majority of the work is done by the air cycle machines only.

Vapor cycle system. The new compressor, which is a two-stage centrifugal machine of the "sealed unit" type, is considered a remarkable engineering accomplishment, weighing only 34 lb. compared to a modern industrial reciprocating machine of comparable output weighing 1,040 lb. (see Figure 29). It uses a 25 hp, two-pole, three-phase induction motor and the 400 cycle supply determined its relatively low speed which is approximately 23,300 rpm. The rotor assembly is entirely enclosed by the refrigerant and there are no external shaft seals. Freon 114 is used because of its compatibility with the centrifugal compressor design and, among other favorable characteristics, its relatively low operating pressure.

**A cooling ton is the amount of refrigeration required to convert a ton of water into ice at 32°F in 24 hours — or 288,000 BTU/24 hours.*

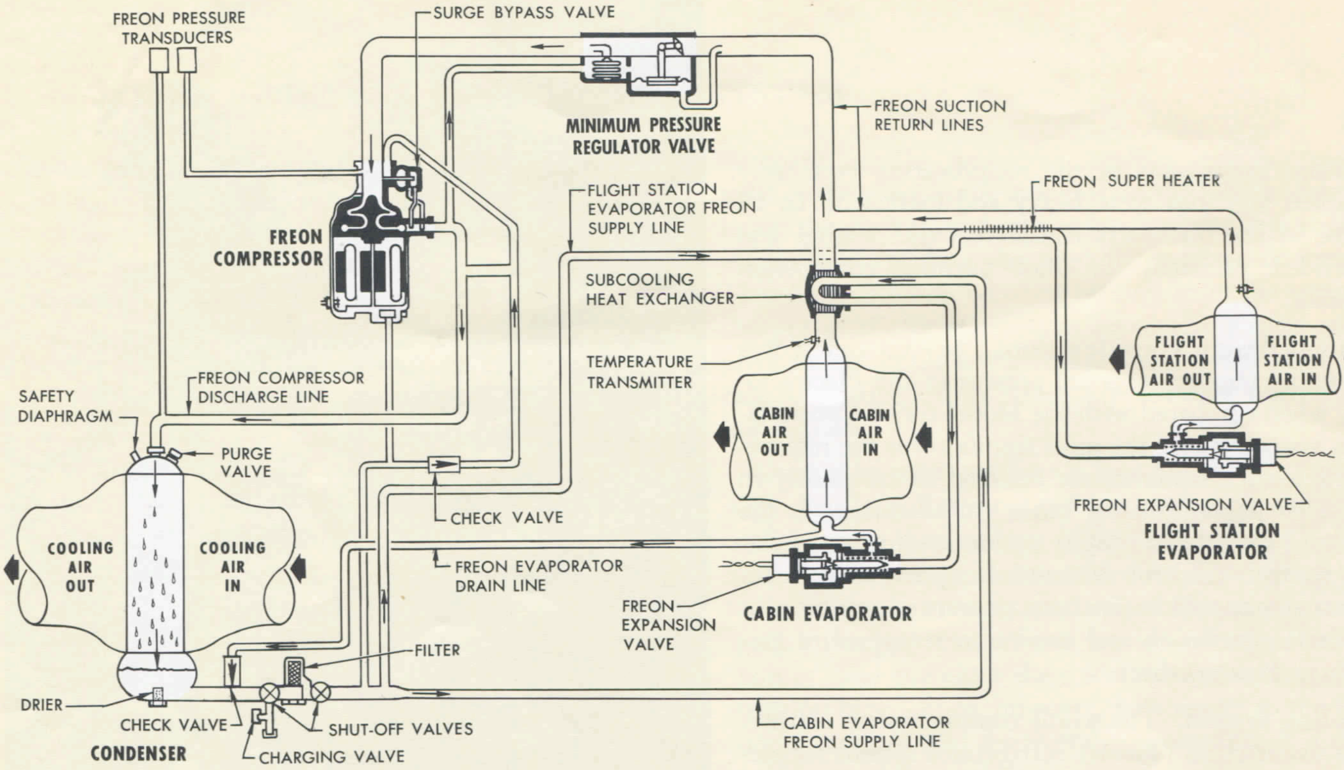


Figure 30 The Freon System

A large evaporator is used for the cabin cooling system and a smaller one for the flight station — a common condenser serving both. The condenser is mounted in a cooling air tunnel with controllable inlet and exit doors in the air conditioning service center (refer back to Figure 11), and a large electrically driven fan of 6,000 cfm capacity supplies cooling air on the ground. This fan is another example of light weight design made possible by the a-c electrical system, since its total weight is only 28 lb., including the 10 hp motor which, incidentally, together with the Freon compressor jointly constitute the largest single electrical load on the airplane.

The vapor cycle system provides cooling by the evaporation of the refrigerant within the heat exchanger (evaporator) over which the cabin air is circulated. The heat which is acquired by the evaporated refrigerant is ultimately rejected by condensation within the large air-cooled condenser. The receiver at the bottom of the condenser returns the condensate to the flight station and cabin evaporators via the respective electrically-positioned expansion valves which reduce the refrigerant pressure to permit evaporation at low temperature. Another line from the receiver passes liquid Freon back into the compressor to cool and lubricate it, since a small amount of oil is mixed with the refrigerant for this purpose. The amount of cooling provided by the system is established by the throttling control of the expansion valves which are modulated directly by the electrical signals from the temperature control system. This method of modulation is known as "variable superheat" since the superheat of the vapor at the evaporator exit is varied with load while maintaining a constant minimum evaporation pressure. A minimum back pressure regulator valve maintains the boiling temperature of the Freon in the evaporators to prevent sub-freezing temperatures, thus eliminating formation of frost. A simplified schematic diagram is shown in Figure 30.

Air cycle system. The two simple air cycle refrigeration units are fairly conventional and are mounted together with their respective turbine bypass valves on a single package dual heat exchanger. Each expansion cooling turbine is loaded by a fan which provides cooling air flow over the heat exchanger so that cooling is obtainable with this system on the ground with the inboard engines running to provide supercharger air. The ambient cooling air exit is controllable while the inlet is fixed, being of the NACA flush non-icing type. All of this equipment is mounted in the air conditioning service center and the joint output of cooled supercharger air feeds into the cabin and flight station distribution systems.

The significant difference in this air cycle system is that the discharge temperature is held to a value at, or slightly below, cabin temperature. This eliminates the need for a conventional water separator system and suits the purpose of the unique cabin air distribution described in a later paragraph. Generalizing it could be said that the principal task of the air cycle machines is to remove the heat of compression from the cabin superchargers. Conversely, of course, this heat is utilized when necessary to assist cabin requirements as programmed by the temperature control system. Separate air cycle machines were used rather than a single large unit since the efficiency of the large machine would fall off too sharply to provide useful cooling with the output of only one supercharger. With the separate machines either supercharger is independently capable of useful cooling output.

Vapor cycle and air cycle systems combined. The measure of overall design weight efficiency is, of course, the weight per cooling ton. The two contemporary aircraft referred to previously have vapor cycle system weights in the range of 125-150 lb. per ton while the Electra vapor cycle system is only 30-35 lb. per ton, or approximately one-fifth of the weight on a similar output basis. The maximum capacity of the combined air cycle and vapor cycle systems is 17.2 cooling tons at 100°F ambient, of which the vapor cycle contributes 10 tons, 1.5 tons for the flight station and 8.5 for the cabin. Very fast "pull down" is possible—that is, cooling of a heat soaked airplane on the ground — either with or without the engines running. The total cooling capacity is, in fact, almost double that of contemporary aircraft of similar size.

Heating system. Heating is provided entirely electrically in the form of radiant wall and floor panels in the cabin and lounge together with air heaters in the supply ducts. A brief review of the reasons for this unusual system is warranted here. Firstly, combustion heater methods were studied and eliminated for such reasons as unreliability at high altitudes when burning kerosene, excessive space requirements, the need for heavy and complicated fire protection equipment and so on. Other methods such as circulating glycol were studied but none came within reasonable range of meeting the requirements for superior heating comfort combined with a single ground power source and self-containment such as appeared to be possible with the electrical method. The flexibility afforded in terms of being able to place the heat source exactly where it is required in the cabin is obvious, and the capability for fast warm-up using large duct heaters is good and provides exceptional control.

Radiant panel heating. The cabin wall panels (see Figure 31) cover the area from the floor to the top of the windows, the lower two panels being approximately 12″ wide and of varying length from 2 to 8 feet long and the ones between the windows 15″ x 22″. The electrical input is approximately 20 watts

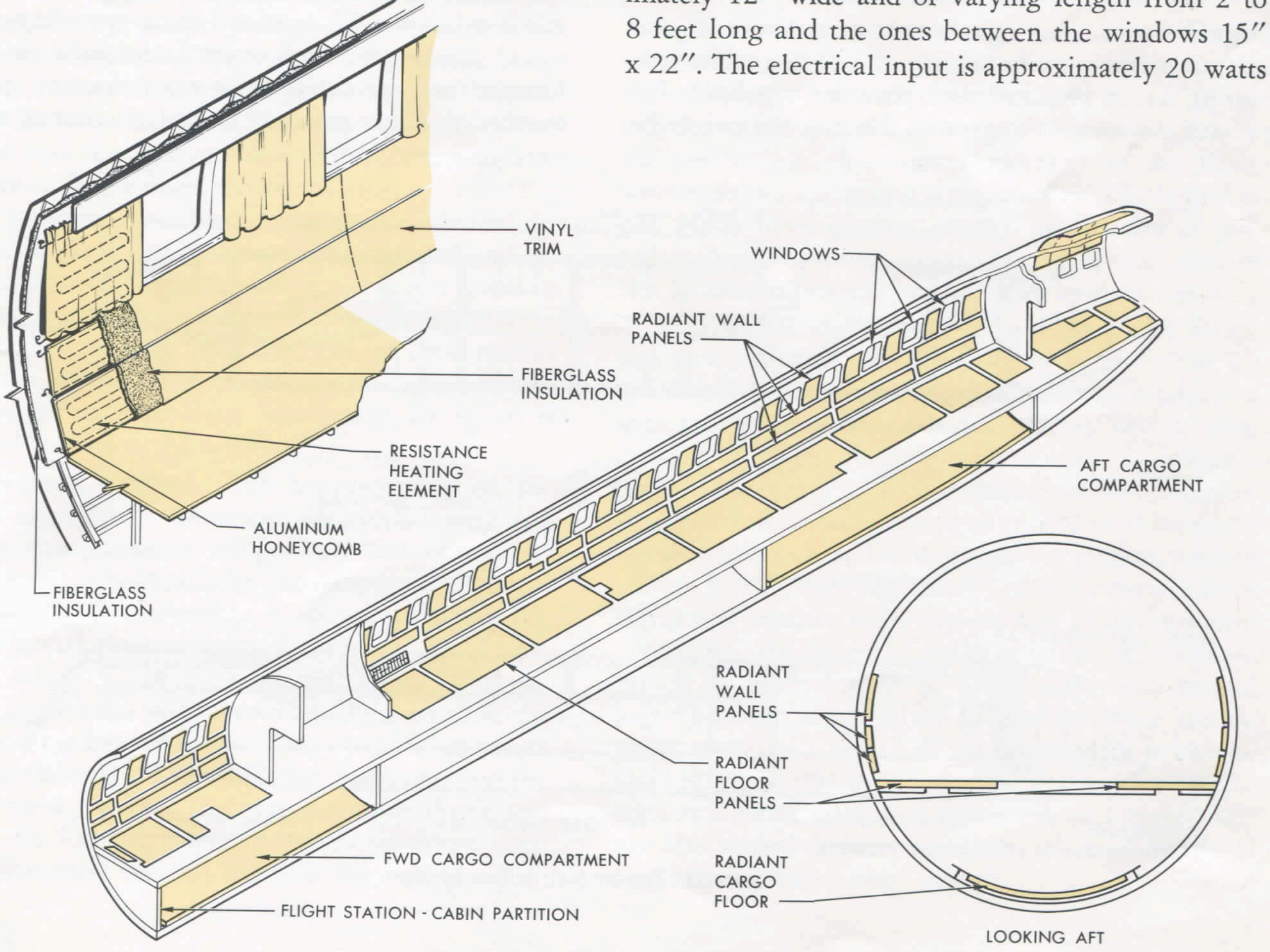


Figure 31 The Radiant Heating System

per sq. ft. and the normal temperature range is from 70° to 110°F maximum as determined by the temperature control system. This order of heat output is roughly similar to that of a domestic electric blanket and the panels are arranged electrically so that if one should fail it will not disrupt the remainder or the control system.

The floor panels are confined to the area below the seats being 36″ wide on the right and 30″ wide on the left. The aisle area is of plywood for long life and low replacement cost and, in any case, heat is not required in this area. The floor panel temperature range is 70° - 80°F and the power input is 20 watts per sq. ft. The heater elements are spirally wound to avoid breakage due to flexing and the panel structure is a honeycomb with the buried elements running back and forth to cover the area.

Both of the cargo compartments are heated by radiant panels spaced well below the floor to avoid damage. The requirement was that compartment temperature should not drop below 35°F and the radiant panel surface temperatures are approximately 75° - 85°F with a power input of 61 watts per sq. ft. Air is supplied in the forward compartment to provide a comfortable environment for the carriage of small pets.

Duct heaters. A large 18 kw duct heater of the sprayed ceramic resistance type heats the cabin ventilating air as required and provides capability for rapid warm-up on the ground. During normal flight operation in all but very cold conditions this heater is unlikely to be used much because of the heat rise available from the cabin superchargers. A similar duct heater is used for the flight station having an input of 10 kw but in this case supplies all additional heat since there are no radiant panels in this area.

Distribution system. The air distribution arrangements in the Electra were designed to overcome several major deficiencies of older systems among which were: (a) the practice of heating high velocity supply air to some 250-300°F and allowing it to be fed by lengthy ducts to the point of use resulting in poor distribution and drafts, (b) the thermal losses occasioned in the cooling case by such ducts, in some cases making a separate cold air duct system a necessity and (c) the lack of apparent air freshness and poor elimination of tobacco smoke and odors.

The new concept in this airplane is that substantial quantities of low velocity air at or below cabin temperature should be delivered close to the seated passenger's head level at all times (see Figure 32). This permits the radiant panels to provide additional heat as necessary to obtain excellent control and minimum temperature gradient in all directions. It is practicable to use the single main distribution duct system to feed the individual passenger air outlets. Air is exhausted by overhead ducts providing exceptional smoke and odor control especially since the forward and aft cabin areas are exhausted directly overboard. Cigar smoking in the aft lounge area is

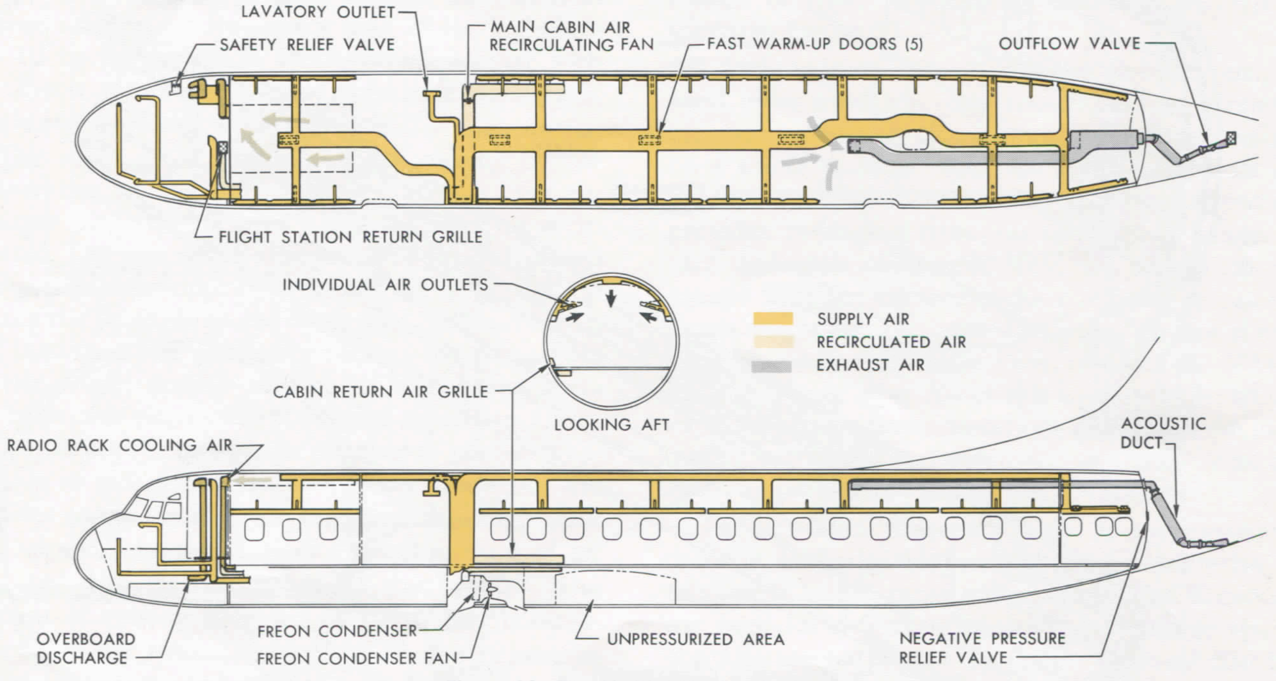


Figure 32 The Air Distribution System

not bothersome to non-smokers because the exhaust duct connects directly to the outflow valves ensuring a very high rate of air change in this zone.

Recirculation is used in the cabin to conserve heating or cooling requirements in the ratio of approximately two parts fresh to one part recirculated air. A large cabin recirculation fan of 2,000 cfm capacity is provided in the return air duct within the air conditioning service center for this purpose. The proportion of recirculated air varies between 35% in flight to 100% during cooling on the ground. The recirculation of air within the cabin is carefully controlled to avoid "short circuiting" of the fresh air being delivered, and a grille in the cabin wall is provided at foot level in the region of the service center to return air to the fan. The flight station has its own independent air supply which is not recirculated from the cabin. For the rapid warm-up case doors in the main overhead distribution duct open automatically to dump the higher temperature air directly into the cabin, thus bypassing the normal outlet system below the hat rack. Recirculation under these conditions is increased to 100% to conserve heat.

A large volume of exhaust air from the forward cabin is ducted to the radio and electronic equipment rack in the flight station for cooling purposes after which it is dumped overboard. A flow control fan operates on the ground or in flight to maintain a controlled discharge rate. The toilets have similar overboard air and flow control fan provisions to eliminate odors. The radio rack itself is totally enclosed so that the heat load does not interfere with proper temperature control in the flight station.

An auxiliary ventilation system is provided so that the airplane can be flown unpressurized and all of the electrical heating and vapor cycle cooling facilities are available under automatic control to provide good comfort standards. The air cycle system would not, of course, be operative under these conditions. A separate auxiliary ventilation air scoop is provided for the flight station.

Temperature control. The programming of the various elements of the entire air conditioning system for any particular temperature selection is accomplished automatically by the temperature control unit. The basic relationship is shown in Figure 33, but the actual programming for a given set of conditions will vary according to the demand. For example, the system will automatically determine the programming necessary with a very cold cabin before passenger boarding and will bring into operation the duct heaters, operate the fast warm-up doors and control the radiant panel system as necessary until the temperature reaches the selected value.

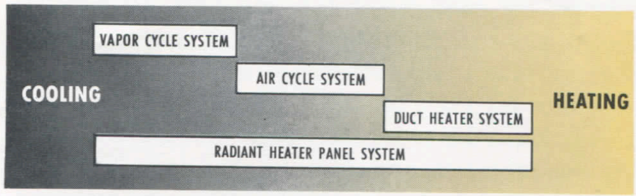


Figure 33 Temperature Control — Basic Programming

Another typical example would be that of cooling a heat-soaked airplane standing at the passenger ramp on a very hot summer day without the engines running. The recirculation mode of operation would first be selected and then the temperature control would automatically program full cooling from the cabin Freon system, full cooling from the flight station system and then modulate as the interior temperatures approach the selected value to avoid excessive overshoot. When the engines are operating and air cycle cooling is available, say during take-off and climb conditions, the Freon and air cycle would be automatically programmed to operate together if the cooling demand warranted, the Freon being gradually reduced by control modulation with increasing altitude until finally shut off. This might, for example, occur at 15,000 ft. or even higher and the air cycle system would then be doing all the work necessary with further increases in operating altitude.

Separate selectors are provided for cabin and flight station temperature control and the system is designed to regulate within plus or minus 1°F of the selected value with minimum overshoot when changing the setting. A program indicator in the flight station shows the actual program being followed at any given time. Manual control by switches is provided in the event of failure of any critical part of the automatic system or the need to override it.

The control unit is entirely contained in a standard rack-mounted case which is installed in the air conditioning service center. Cabin temperature sensors send signals via a bridge circuit which, after passing through an amplifier, operate a program motor. The program motor shaft operates a number of cams and potentiometers to modulate the control components such as Freon pressure regulator, radiant panels, etc. A "free dog clutch" on the program shaft integrates another shaft system and program motor controlling the air cycle and duct heater. The radiant panels in the cabin walls are divided into several zones and the temperature is modulated by cycling each zone "on" and "off" in accordance with the signals received from the sensors. Varying heat loads, such as a concentration of passengers in a given area, are also sensed and the zone heat adjusted locally as required by the control system.

Mechanically and electrically the control unit is designed for high reliability and uses no vacuum tubes or transistors. Plug-in magnetic amplifiers and program motor assemblies are employed and the entire unit is rigidly mounted, i.e., non shock-mounted. An external test box has been developed to simplify maintenance and trouble shooting. This test box replaces the actual control unit on the rack and thus checks the entire system wiring on the airplane in addition to establishing possible faults in the control unit itself. A basic concept in the system has been to arrange circuits in parallel so that loss of one component will only affect limited portions of the system and will result in minimum loss of performance pending repair. Repair can usually be effected at the main maintenance base at the next overnight service.

Summary. To summarize, the Electra air conditioning system provides high capacity with low weight and reasonable power consumption. Ventilation and distribution are excellent with minimum temperature gradient. The temperature control system is accurate and fully automatic under all conditions. The ground power requirements are simple and flexible serving at the same time all other necessary functions on the airplane. Few of these characteristics would have been possible but for the employment of a high output electrical system. Great credit is due to the AiResearch Manufacturing Company who designed the system components to Lockheed equipment specifications. Development and refinement of the system characteristics was then carried out by Lockheed on a full scale section of fuselage so equipped that the entire range of external temperature conditions could be simulated. In operation the comfort provided by the system is remarkable and the best compliment which can be paid to any air conditioning system applies, namely that it is unobtrusive and therefore somewhat ironically, largely unnoticed by average passengers in flight.

13. THE BLEED AIR ANTI-ICING SYSTEM

One of the more important differences in the Electra from any contemporary airplanes is the provision of an engine compressor bleed air anti-icing system for all flying surfaces — this practice, in fact, being common to certain other new turbine transports. The reason, of course, for the use of such a system is that relatively large amounts of very hot air can be tapped off the compressor at the last stage, providing a much more satisfactory source of anti-icing and deicing heat than would be conveniently available by other means, such as electrical heating. A maximum of 8% of the compressor output can be bled from two ports provided for this purpose at the 14th stage of the 501-D13 engine. The bleed air temperature is approximately 550°F at this point and the airflow and pressure vary with altitude, engine power and so on, a typical pressure range being 60-130 psia. This air is ducted out to the wing leading edges from a main manifold which runs along the front face of the wing beam and does double duty as the engine starting air manifold. The manifold is fed from each engine and a shut-off valve is provided in each power plant. Air for anti-icing the empennage is taken from the same manifold through a duct which runs beneath the cabin floor up into the tail cone and thence into the surfaces. The engine air intake ducts, together with the internal parts of the engine itself, are also protected by heat supplied from separate bleed ports on the 14th stage of each engine compressor.

Looking at the diagram in Figure 34 you will observe the peculiar shape of some of the ducts. This is brought about by the need to accommodate the relatively large deflections which come about when such a system is pressurized, due to both pressure and thermal growth. On earlier airplanes we originally used a series of stainless steel bellows (the ducts are of stainless steel because of the high temperature) and the growth resulted in a concertina-like distortion because of the extremely high end loads put into brackets and fittings. The answer was found in a reversion to old-fashioned steam engineering practice in which "Omega" loops were used having the property of being self-stabilizing under high temperature and pressure conditions. Such a system is then known as a "tension system" and is theoretically stable without the use of support brackets. These loops are, of course, very springy and are worked into the structure wherever space makes this possible in order to absorb the deflections transmitted into them. There are, however, some cases where space makes this impracticable and an ingenious compensating joint is then used which utilizes its own pressure to balance within itself and thus maintains tension in the basic duct system.

The air is distributed along the leading edges by tapered ducts and in the chordwise direction it flows through a passage at the inner face of the wing section as shown in the detail view in Figure 34. It is

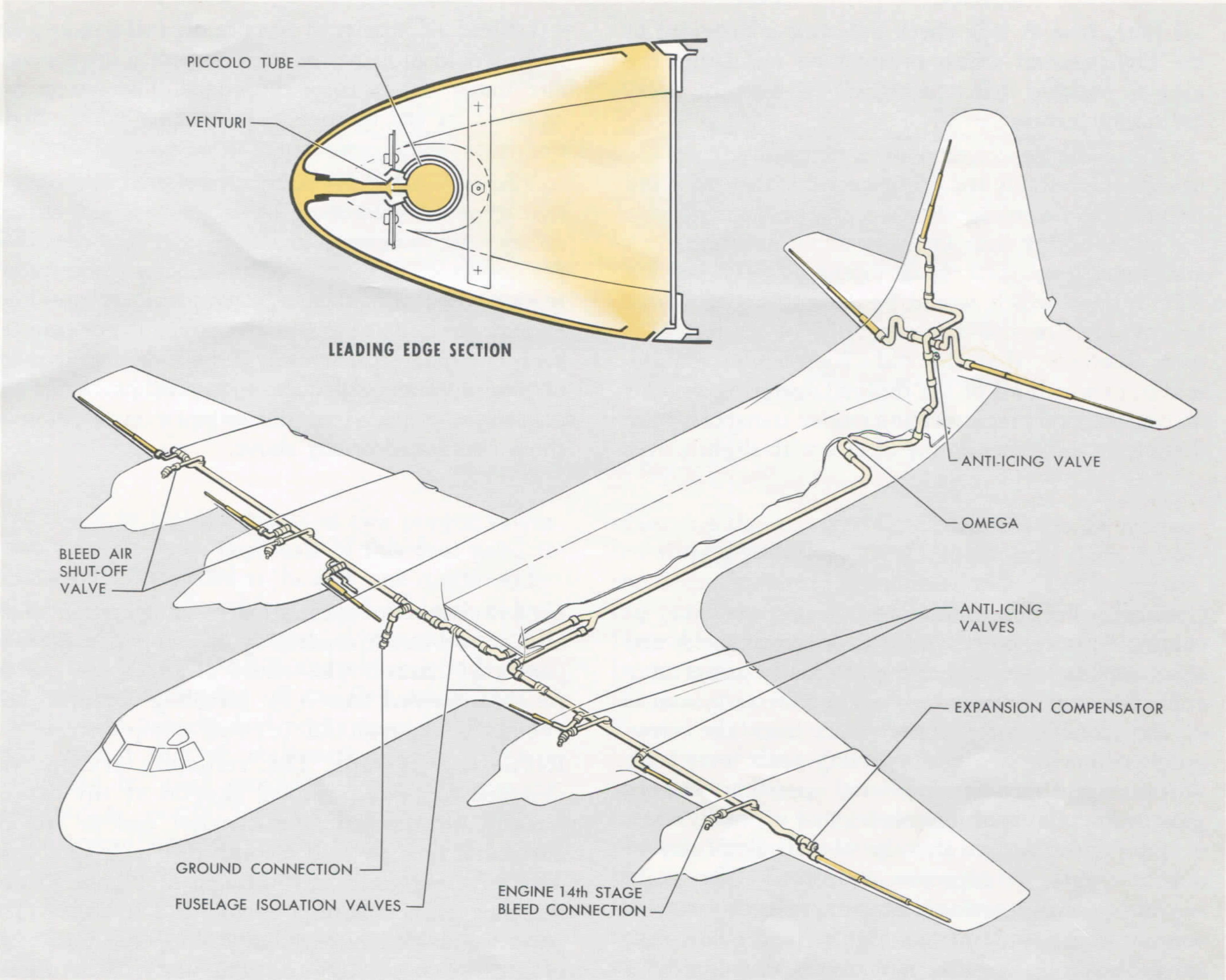


Figure 34 The Bleed Air Anti-icing System

directed into this passage by nozzles — nicknamed the "piccolo tube" — and a venturi throat at the entrance to the passage attracts a percentage of return air to provide mixing. Spent air from the ends of the anti-iced surfaces is exhausted overboard through the lower nacelle areas and in the case of the empennage through the lower side of the tail cone.

The wing system is controlled by anti-icing modulating valves between each piccolo tube system and the main manifold, and basically the operation of the system is continuous, that is to say it is fed at a fixed bleed rate and controlled at a given temperature. Because the engine power loss resulting from large quantities of bleed air is considerable, however, the system can be cycled manually by the pilot for *de-icing* purposes if desired, the "on" period being about 20 seconds and the "off" being about 5 minutes or more depending upon the rate of ice accretion. The icing rate is indicated to the pilot by an ice detector which has two probes in the air stream, one of which is allowed to ice, the other being continuously heated. A pressure differential between these two probes is caused by ice covering the bleed holes on the one which is allowed to ice up, thus actuating the detector system cyclically. The engine air intake and inlet guide vane anti-icing system is continuous —unlike the flying surfaces—and takes a maximum of about 3% bleed, which is allowed for in the engine design.

The pneumatically powered anti-icing valves modulate the air flow to maintain a constant exhaust temperature in order to control the leading edge temperature. The valves close pneumatically and open electrically for "fail-safe" reasons. Fuselage isolation valves are fitted and provisions are made in the system to avoid asymmetrical anti-icing. Overheat warning systems are provided and over-pressure relief doors are also incorporated. Ground checking of the system may be carried out at Low Ground Idle, at which rpm the bleed air temperature and pressure are fairly low. A leak check indicator is provided in the flight station which operates by measuring the rate of pressure decay in the ducts — a fast decay indicating leakage.

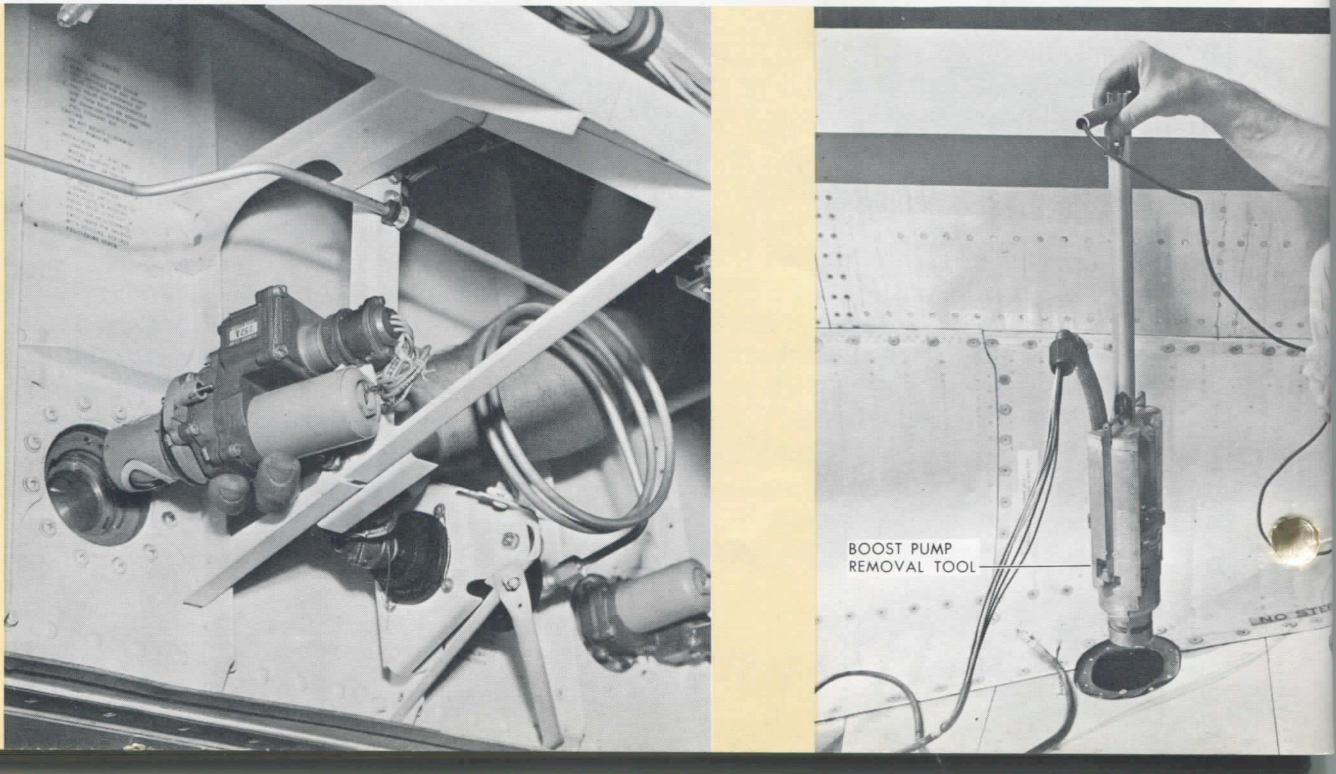
One of the important reasons necessitating the use of such an airframe anti-icing system is that the more recent CAA design certification requirements provide for much higher heat intensity at the leading edges and necessitate total heat inputs of 2-3 million BTU's/hour which would be almost impracticable by any other means. The capability of the system is such, however, that the old "light-icing" requirements, to which all of the thermal anti-icing systems on contemporary reciprocating engine transports were designed, can be met on the Electra with slightly over 4% bleed air supply. In practice the full 8% requirement would probably be used only very infrequently and under severe icing conditions. The system has equalled its specification requirements during flight test work and is considered to be very efficient.

The reason for discussing this system at length is that some understanding of its function and characteristics are necessary to ensure that due respect is paid to its maintenance, and especially toward elimination of leaks since the temperatures are high enough to do damage at some points if not detected early enough — particularly if the leaks are large and of long duration. Adequate means for check-out are, of course, provided in the airplane in addition to those mentioned briefly above.

14. THE FUEL SYSTEM

General. Pressure refueling systems are not, of course, entirely new to the commercial field and some contemporary aircraft are actually using moderate flow rate systems today. The Electra system is of considerable interest, however, from the viewpoints of having a single refueling point, very high flow rates and very simple ground operation. The engine fuel system is of interest because of the newness of component design and the overall simplicity of the four tank arrangement employed. The main reason for incorporating a pressure refueling system was not so much to obtain a high refueling flow rate, as to obtain the ground handling advantages of a single point as described under RAMP HANDLING. The main time saving accrues from the avoidance of need to clamber over the wing — an operation which also contributes considerably to wing damage and personnel hazard. The entire arrangement can be roughly divided into (a) refueling systems, (b) engine fuel system and (c) fuel dump system.

Refueling system. The refueling system was designed to permit manual shut-off at any desired quantity by the refueling operator and to provide automatic flow shut-off for the full tank condition. The refueling panel is illustrated in Figure 35 and the four gauges correspond to the four tanks. The panel is divided into roughly three functions (a) system pre-check, (b) refueling and (c) defueling. The fuel, fed from a single manifold running along the rear beam is controlled at each tank by a fueling


FUEL SHUT-OFF VALVE REMOVAL

BOOST PUMP REMOVAL

Figure 35
Fuel System
Maintenance and
Servicing Features

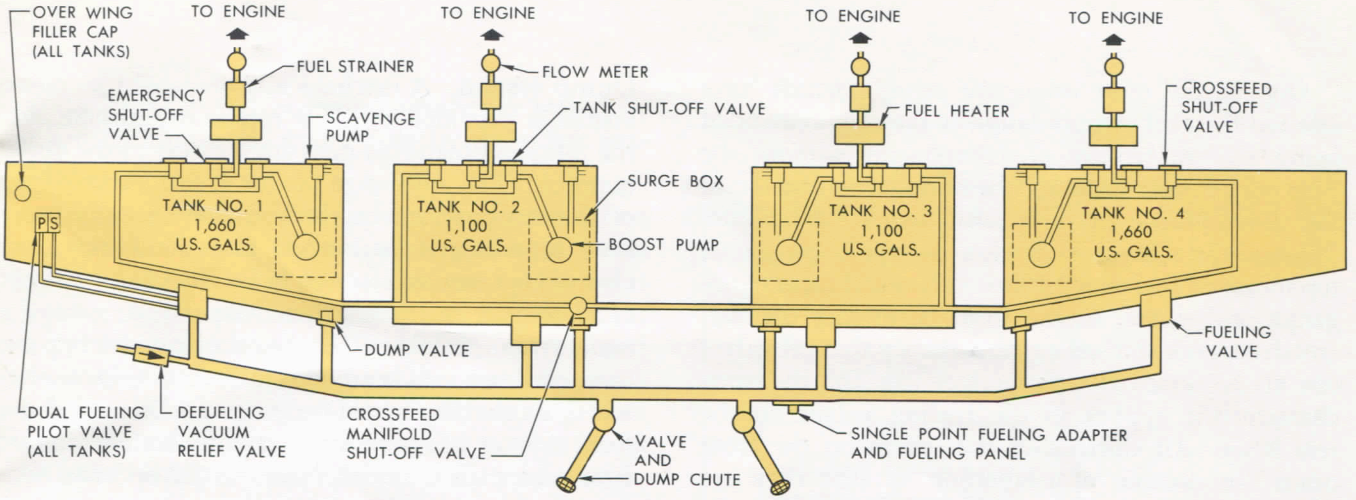
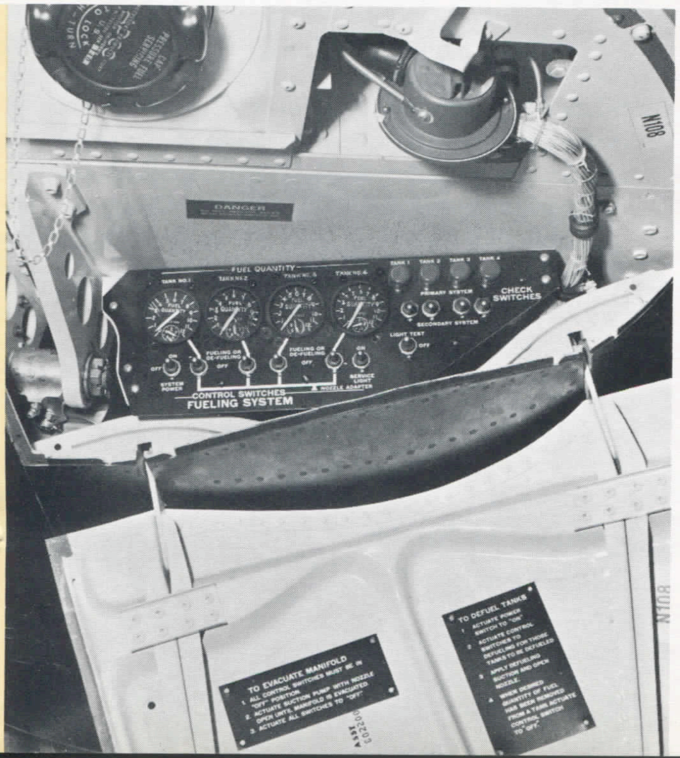


Figure 36 The Fuel System

valve which in reality consists of two poppet valves within a single body. Each half of this dual valve is automatically controlled at the full tank condition by the float shut-off pilot valves, which are also a dual assembly. This double system is designated PRIMARY and SECONDARY and either is independently capable of shutting off the fuel automatically. In addition to this, the fuel vent system is "sized" to accept limited shut-off malfunction without overpressurizing the tank structure. For safety reasons the operating "muscle" for the fueling valves is actually the hydraulic pressure in the fuel truck hose, thus eliminating reliance upon electrical signals for automatic shut-off purposes.

Operation from the panel is extremely simple and consists firstly, of connecting the ground truck fuel source, secondly, checking out the PRIMARY and SECONDARY systems by throwing the switches and observing the indicator lights, and thirdly, by operating the refueling switches and shutting them off at the desired quantity as indicated either by the refueling panel gauges or the refueling truck gauge. Defueling is accomplished from the same panel merely by reversing the fueling truck pumps and sucking the fuel out. The refueling manifold can also be drained in the same way after each manual refueling operation if desired from the safety viewpoint. The specification design refueling rate is 300 gpm at 35 psi, the pressure being held to a low value for safety reasons. The system has proved itself capable in practice of rates of 420 gpm when filling all four tanks simultaneously, and if the fueling pressure was to be raised to the military standard of 50 psi a rate of 500 gpm is obtainable. Over wing refueling is provided for use in cases where pressure equipment is not available and one 200 gpm filler well is provided for each tank. Underwing drip-sticks are provided for cases wherein very accurate manual fuel measurements are necessary — for example critical route sectors or accurate landing weight requirements.

REFUELING PANEL



Engine fuel system. The engine fuel system is very simple and follows closely the ideal arrangement which would be four tanks of identical capacity. The total capacity of 5,520 U.S. gallons is distributed with 1,100 gallons in each inboard tank and 1,660 gallons in each outboard tank so that only minimum crossfeeding is normally required except for ranges above approximately 1,800 to 2,000 miles. The natural affinity of turbine fuel for water entrainment constitutes a fuel system strainer or screen icing hazard and two system components are provided to take care of this: (a) an oil-to-fuel heat exchanger on each power plant and (b) a bypass check valve at each fuel tank booster pump to prevent feed blockage by icing. A schematic diagram of the entire system is given in Figure 36.

One of the most important criteria which have affected the fuel system design is the requirement of being able to remove all components without the need for entirely draining the tanks. This has led to the development of new components (see Figure 35) such as a bayonet attachment type boost pump, top-mounted fuel shut-off float valves and capacitance gauge probes, etc. In the front beam face the fuel crossfeed, tank shut-off and emergency shut-off valves can all be removed without fuel loss and the same characteristic applies to the fueling valves on the rear beam. All thirteen of the valves on the front beam are capable of adaptation so that they are directly interchangeable with each other. On the lower surface the drip sticks can be replaced as well as the water drain valves without defueling the tanks. The objective of all of this new design work was to convert what could have been, for example, a typical maintenance task of two or three hours to change a booster pump into perhaps a fifteen minute job only.

Dump system. A mechanically operated fuel dump system is provided and it is interesting to note that the refueling manifold does double duty as the dump manifold. The advantage of this is that the integrity of the dump system is checked automatically every time refueling is performed and the O-rings are always kept wet and free of leaks. This basic concept of having an emergency system operate as part of a main system, so that it is always being checked out in normal use, has been used in several systems elsewhere in the airplane. Dumping can be carried out from right or left wing independently but in each case from tank pairs only, i.e., Nos. 1 and 2 or 3 and 4.

There are, of course, many other components and parts of the fuel system which have not been mentioned in this section but, since many of them are not unusual in basic character, discussion of them was deemed out of place in this general article. The entire fuel system will be reviewed in a specialized article at a future date.

15. THE HYDRAULIC AND SURFACE CONTROL BOOSTER SYSTEMS

Hydraulic system. While we have not included the hydraulic system of the Electra under the primary "new and different" category, nevertheless it is of sufficient interest to merit a description in this article. Some of the techniques used in both the hydraulic system and the redesigned surface booster control system were worked out in the Lockheed C-130 Hercules and in the Constellation Model 1649A, so that there was a great deal of experience available from which to draw. For the moment, however, we will assume that most readers are familiar with the basic Constellation hydraulic system and attempt to describe how the Electra differs from the practice used in those airplanes. The Model 049 through 1049 series Constellation aircraft have four large hydraulic pumps, one mounted directly on each engine, and the system was divided by a crossover check valve into two parts: the primary system comprising pump Nos. 1 and 2 and the secondary system comprising pump Nos. 3 and 4. The boosters always had priority on the power supply from the primary system, while the secondary system normally fed the landing gear retracting cylinders, wheel brakes, etc., but would also divert its fluid into the primary system to feed the boosters in the event of a primary system failure. Certain disadvantages were apparent with this arrangement as extensive operational experience was gathered, and the complete redesign inherent in the Electra system overcomes these as well as providing several other basic improvements.

One of the basic disadvantages of the older system was that four very large pumps were in operation at all times because of the booster demand, yet in fact they had been "sized" for the maximum load which was landing gear retraction occurring for only a very short period. It was apparent that the booster demand could be supplied by much smaller pumps if some flexibility in controlling the pumps was available. The Electra arrangement of three electrically driven hydraulic pump packages overcomes this, since at least one pump could be shut down in cruising flight and the hydraulic system is rendered considerably less dependent upon failure of a critical engine because of the electrical load transfer arrangements which give priority, among other things, to the hydraulic system. In flight the shutdown of one, two or even three engines provides automatically for hydraulic load transfer through the electrical bus system with no action on the part of the pilot, and could indeed be an important factor under very critical emergency conditions. As an example, the rate of retraction of the landing gear would be substantially unaffected by the loss of an engine at take-off, say just beyond V2 (critical climb-out speed), because the hydraulic pump power requirements would be picked up almost instantaneously by the other generators.

Another important change from the Constellation was the provision of two entirely separate 3,000 psi hydraulic systems — so separate in fact that the fluids from one never mix with the other — their power output being combined at the surface control itself by a tandem actuating cylinder with a common piston rod. The significant advantage of this arrangement is that failure of either system could occur without the pilot having to take emergency manual change-over action, since the output of either cylinder provides enough surface control hinge moment to fly the airplane under all conditions except abnormal maneuvers. Additionally, the likelihood of losing fluid from *both* systems as a result of a component or line failure is extremely remote on the Electra, whereas the Constellation had suffered one or two incidents of this type. Manual control is provided for all three surfaces in the unlikely event of complete hydraulic failure. The systems are known as No. 1 and No. 2 and a block schematic diagram (Figure 37) shows the loads connected to each. It will be seen that the No. 2 system supplies power for one half of the boosters and wing flap motor loads only, while No. 1 feeds the other half together with landing gear, brakes, etc. The dual motor drive which this arrangement affords the flap system eliminates the need for a separate emergency system since either motor alone will operate the flaps.

There are, in fact, so many advantages inherent in the electrically driven hydraulic system that one frequently wonders why this had not been attempted in earlier designs. The removal of the pumps from the power plant where they would be in the general area of a hot compressor casing — perhaps as high as 450°F — is a valuable safety feature and eliminates (in this writer's opinion) the need for non-flammable hydraulic fluids. Another important safety characteristic from the performance viewpoint is the fact that any one of the pumps, if suspected to be failing, could be merely switched off whereas with an engine mounted pump an otherwise perfectly functioning engine has to be shut down perhaps necessitating a three engined landing. Whereas an electrically driven pump operates as a constant speed machine, it frequently happens that in older type systems an engine driven pump is called upon for higher flow output at the very time engine rpm is being reduced under some types of emergency condition.

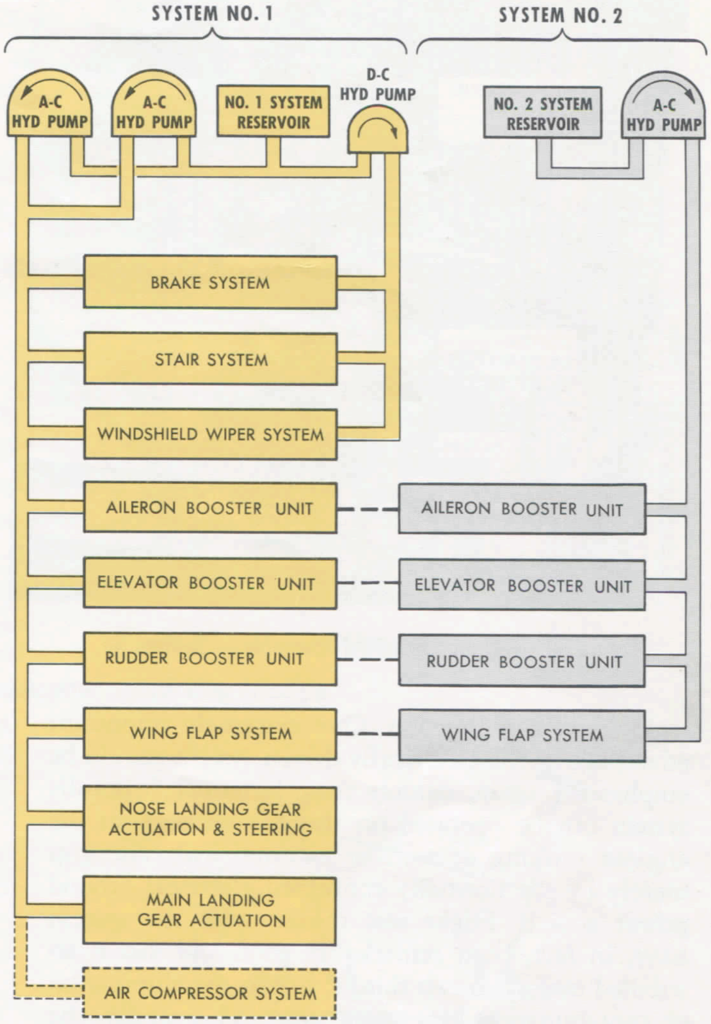


Figure 37 The Hydraulic System — Block Diagram

The location of the hydraulic center and the grouping of the components has already been described under the MAINTENANCE CHARACTERISTICS heading, and the advantages of such a light and compact arrangement providing short lines and manifolded unit assemblies are obvious. A typical Lockheed developed manifold assembly is shown in Figure 38 and it includes system relief valves, check valves, pressure transmitters, metal element filters and ground test gig connections. All of these components are connected by drilled passages in the block thus eliminating lines, connections and leakage. The example shown eliminated some 22 connections and reduced weight from 19 lb. for separate old style line mounted components to 6 lb. for the new manifold concept.

When changing power plants the elimination of hydraulic disconnections means shorter time, elimination of need for system bleeding, no risk of picking up dirt in the hydraulic fluid and no risk of hydraulic

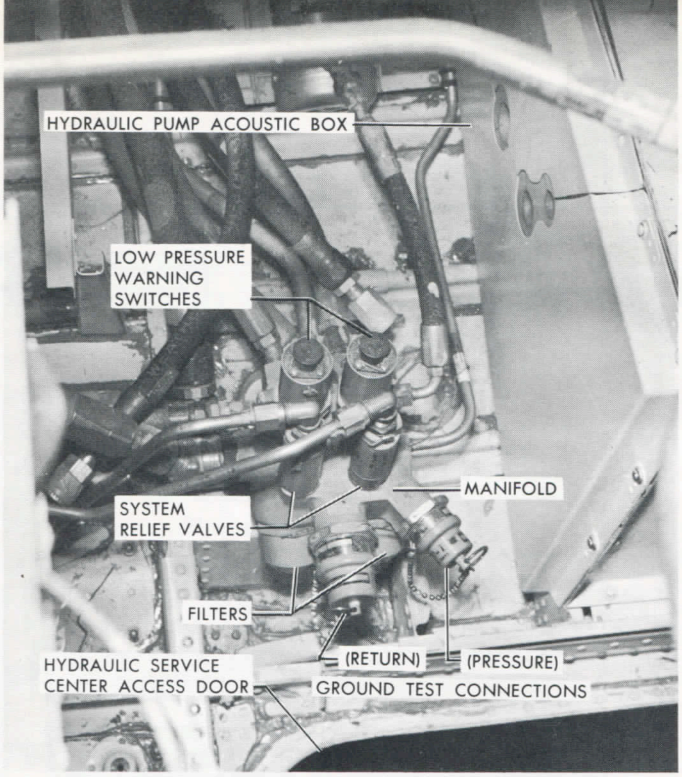


Figure 38 Hydraulic Manifold Assembly — System No. 1

leaks upon reconnection. One extremely important advantage of the electrically driven system should be emphasized again, namely that the entire hydraulic system can be operated on the ground without the engines running or without external hydraulic gigs merely by the normally connected electrical ground power source. Flight test results with the system have, in fact, been remarkably good and this is attributed mainly to two things: firstly, the elimination of contamination by ground gigs and secondly, the excellent pressure and return system filtration.

An intriguing device looking rather like a trombone is to be found in the hydraulic center (shown in the upper area of Figure 9), and is of sufficient interest to warrant an explanation here. It is named the "Quincke filter" after the British physicist who developed the principle upon which its operation depends, and its purpose is to reduce the noise emanating from the hydraulic pumps. It is mounted in the output lines from the pumps and is "tuned" to the pump piston frequency by careful design analysis and acoustic testing. The principle uses two paths for the hydraulic fluid in a loop formation, the length of each half of the loop being arranged so that the output frequency of one is exactly 180° out of phase with the other, thus cancelling the noise transmission effect. The noise attenuation provided by the device is excellent and it is, of course, light in weight and trouble-free. It is, however, essentially a narrow frequency band system and will only work satisfactorily with constant rpm pumps such as are provided by the electrically driven method.

Booster system philosophy. Most of our readers will be familiar with the Lockheed surface control booster system philosophy but there may well be some who are not — so please bear with us for a few brief paragraphs. The concept of providing hydraulic power assistance for the control surfaces was first developed by Lockheed for the P-38 Lightning aileron application in 1939 and later applied to all three control axes on the Model 049 which flew early in 1943. This original system continued through the entire life of the basic Constellation series although other airplanes, like the C-130, had meantime been able to take full advantage of the booster experience gained over the years with extensive commercial use. The Model 1649A, however, had the completely redesigned "package" system installed as a part of the new wing and other changes, and it is this development which forms the basis of the Electra booster system today.

Briefly, some of the advantages to be obtained from such a system are:

(a) Greater safety with asymmetric power conditions in emergency and lower minimum speeds for controllability with critical engine or engines inoperative.

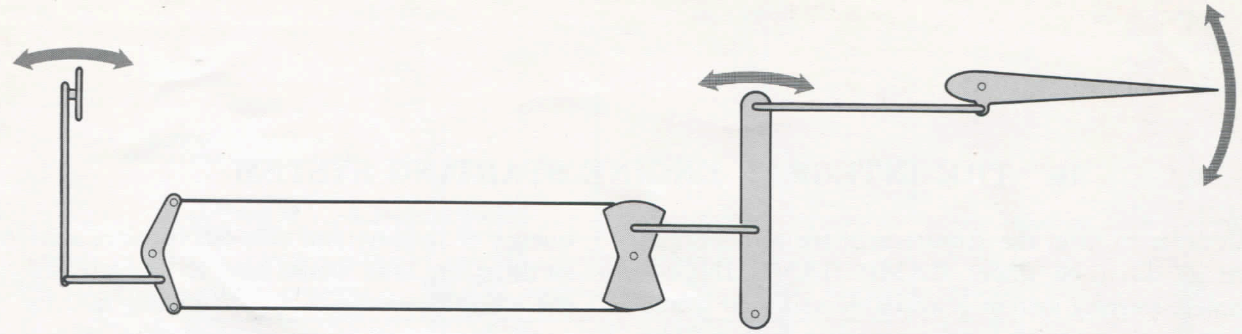
(b) Greater aileron effectiveness resulting in considerable improvement in rolling performance.

(c) Reduction in surface control areas compared to those required for aerodynamically-balanced systems due to elimination of air leakage and wastage of area caused by the aerodynamic balance. This in turn reduces the wetted areas and allows more space chordwise which can be used for fuel tankage.

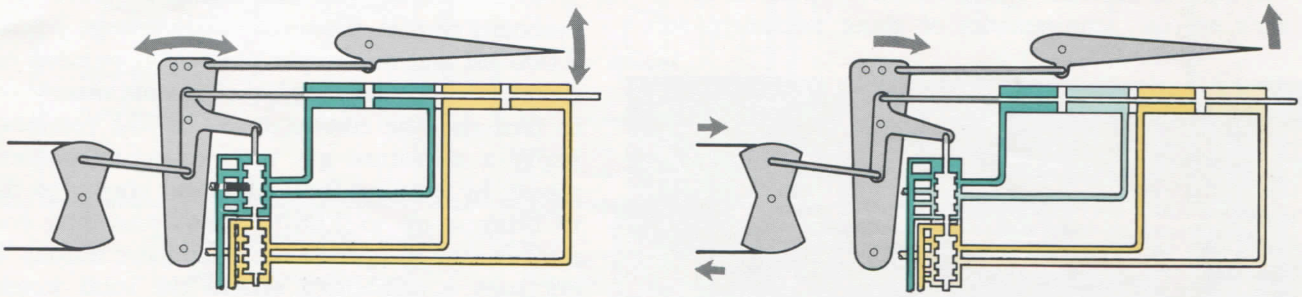
(d) Decrease in spanwise size requirements for aileron control surfaces thereby increasing efficiency by permitting the use of larger flap span. This permits a lower stall speed which materially improves the landing weight.

(e) Flexibility of surface control response and hinge moment availability as a material aid to "growth" or development of the airplane as a type when larger engines become available.

(f) Capability for greatly improved autopilot response by introducing the signals at the booster actuating cylinder control valve itself, instead of through the cable system. This eliminates inefficient autopilot servo systems.



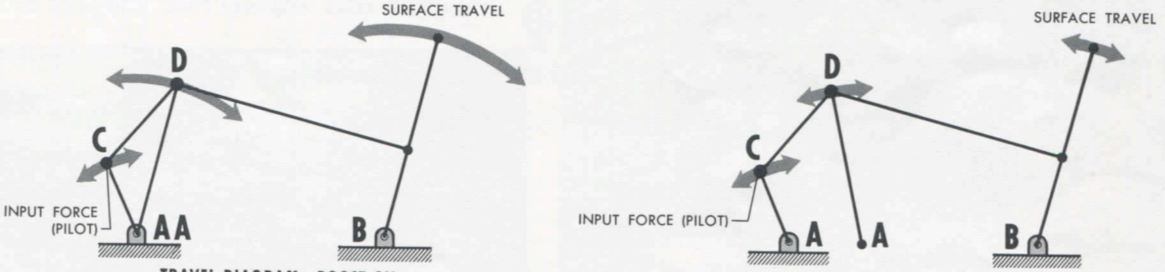
NON-BOOSTED SYSTEM



BOOSTER (NEUTRAL)

BOOSTER (OPERATING)

Figure 39 Surface Control Booster — Operating Principle



TRAVEL DIAGRAM — BOOST ON
(1:1 MECHANICAL RATIO)

TRAVEL DIAGRAM — BOOST OFF
(MORE MECHANICAL ADVANTAGE — LESS SURFACE TRAVEL)

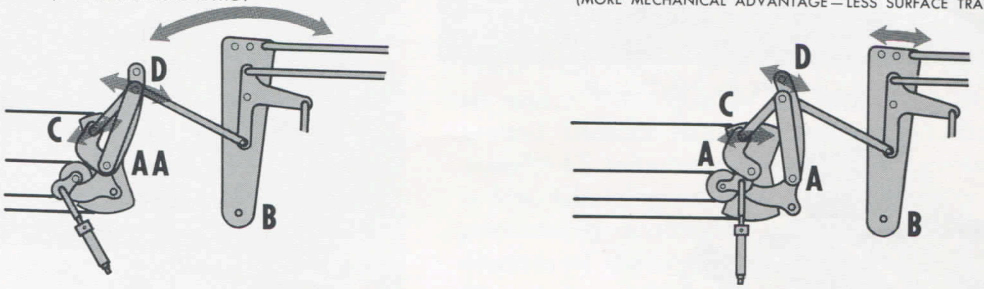


Figure 40 Surface Control Booster — Manual Change-over

(g) Elimination of the need for separate built-in gust locks which would otherwise be essential on large transports with aerodynamically-balanced surfaces.

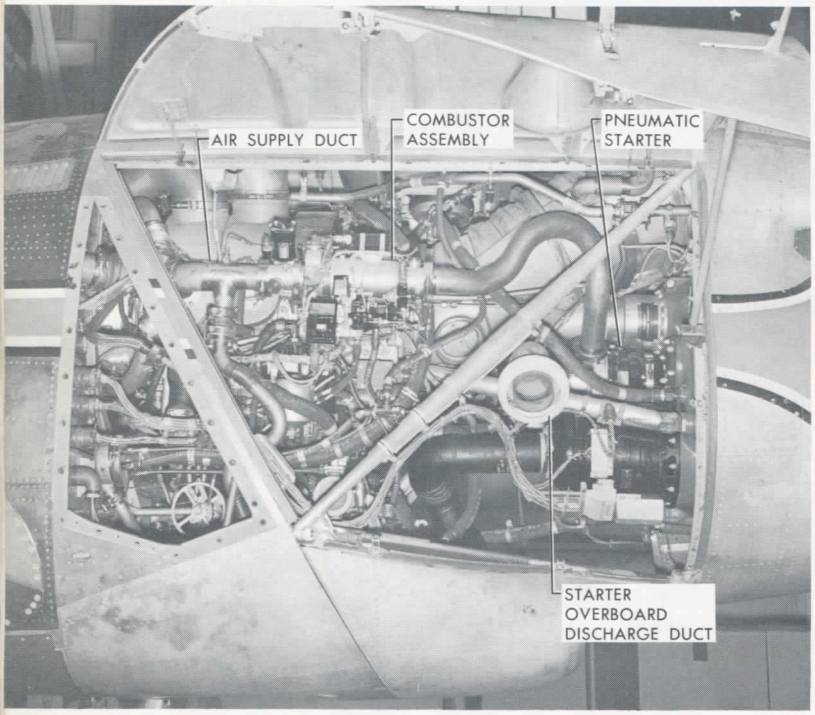
There are, of course, many more points but the really significant one is that the ease of handling of the Electra under all conditions — and the safety which results therefrom — has earned exceptionally high praise from pilots who have flown the airplane. To illustrate the booster operating principle a very simple schematic is shown in Figure 39 which is self-explanatory, while Figure 40 shows the booster-to-manual changeover system operating linkage.

The control surfaces themselves have several interesting features and will be described in detail in a future issue of this magazine. The elevator system, in particular, is worthy of note because it employs an ingenious new "force link" tab, a downspring, and a bobweight on the control column. Excellent longitudinal stability is provided and the "stick-force per g" characteristics are very satisfactory.

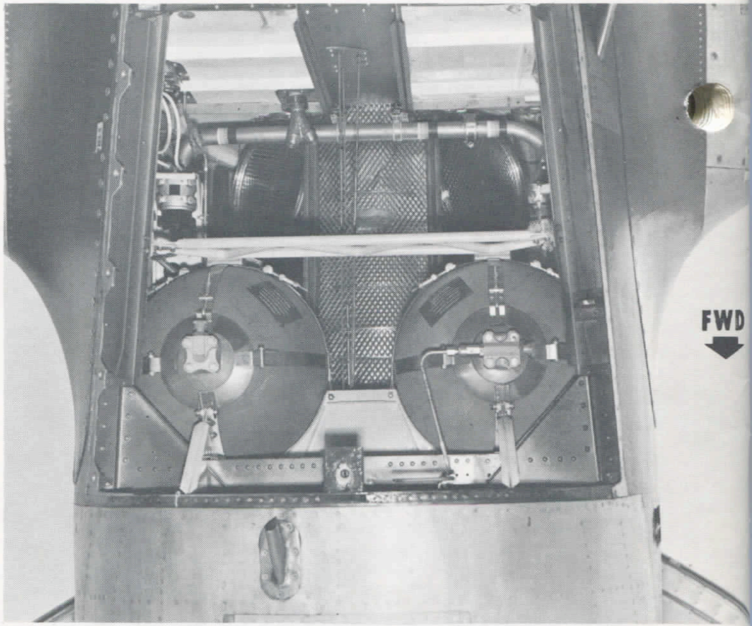
16. THE INTEGRAL ENGINE STARTING SYSTEM

In order to meet the requirement for self-containment as discussed under RAMP HANDLING, a complete starting system is available using air stored in four high pressure bottles together with a "line combustor" in each nacelle. The decision to install this optional system would be based upon an operator's specific requirements of route flexibility, frequency of landing and take-off, required station transit times, etc., and would have to be evaluated against the weight increase of approximately 600 lb.

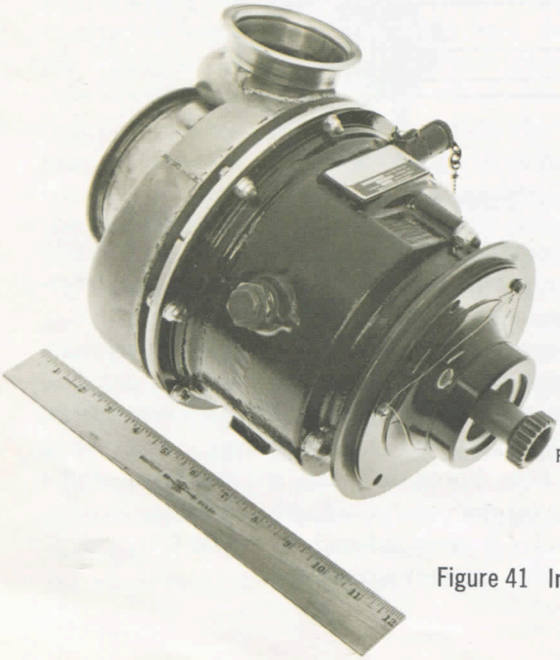
There are several variants but, in its most complete form, the system uses two pairs of 15½″ diameter spherical bottles, one pair being mounted in each outboard nacelle. Nominal bottle storage pressure is 3,000 psi and the output pressure is reduced in two stages to a regulated value of approximately 60 psi to feed the line combustors. The line combustor is really a miniature gas turbine engine burner can which, by burning fuel, adds heat energy to the air to bring it up to 1,000°F, thus providing enough total energy to operate the pneumatic starter. Without such a combustor system the total weight of stored air, if the air was to be used directly, would be prohibitive since starting loads on such a single spool engine are high and peak at around 160 hp. The line combustor uses engine fuel and has a continuous



COMBUSTOR INSTALLATION IN NACELLE



HIGH PRESSURE BOTTLES — VIEWED FROM UNDERSIDE



PNEUMATIC STARTER

Figure 41 Integral Engine Starting System Components

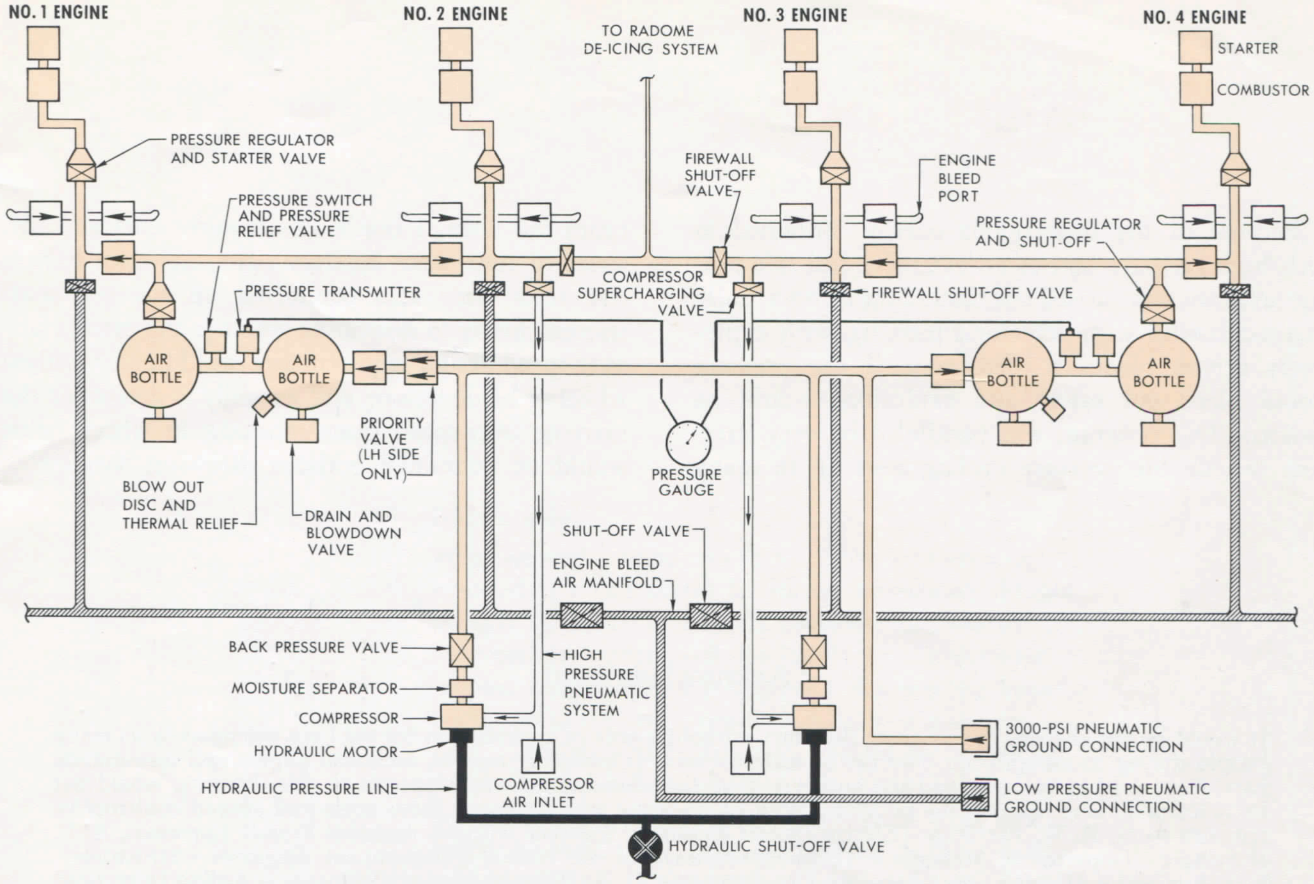


Figure 42 The Integral Engine Starting System

ignition system which, together with the control components, is entirely d-c fed so that airplane battery power can be used if necessary. Figure 41 shows the installation of the combustor together with other system components and the overboard discharge outlet for the spent air from the starter can also be seen.

No cross-over starting arrangement is provided for left-hand bottles to feed right-hand engines or vice-versa. The system contains enough air for two starts — one normally being sufficient since the remaining engines can be started by compressor air bled from the first engine and fed through the cross bleed manifold. One engine at "High Ground Idle" will start any remaining engines, whereas at the "Low Ground Idle" condition (10,000 rpm) the combined bleed from two engines is necessary. The design starting time is 15 seconds which will vary in practice up to 30 seconds depending upon altitude and ambient temperature. Recharging can be done in flight or on the ground by two small hydraulic motor driven compressors, one mounted in the aft lower area of each inboard nacelle. The system is arranged so that a priority valve permits the right-hand bottles to be fully charged first thus providing one available start before the left-hand bottles will commence to charge. The system may also be recharged on the ground by a 3,000 psi external air source coupled to the high pressure air connection provided in the right hand wing leading edge near the wing root.

The in-flight recharging time for one pair of bottles averages approximately 35 minutes depending upon the air density conditions and the state of bottle discharge. Recharging time under this condition is reduced by the use of a supercharged input to the small compressor, provided from the engine bleed air source. Consequently the recharging time on the ground without engines running is rather longer, namely 45 minutes, because the compressor output is less. Charging of both pairs of bottles takes approximately double the quoted times. A schematic diagram of the complete system is shown in Figure 42.

An airplane equipped with this integral starting system can also be started, if required, by the use of an external ground air source instead of using the internally stored air. Because the starter gear ratio for the line combustor system is different from that used in the basic airplane — which is arranged for external starting air sources only — the combustor system is required to function both for external as well as internal starts. Operation is completely automatic with either internal or external starts from the moment that the starter button is pushed until stable engine speed is attained.

Because of the tremendous energy contained in such high pressure bottles an extensive fail-safe testing program was carried out, including firing at fully charged bottles with rifles and piercing with explosively driven blades to determine if the pressure would bleed out safely and explosions would be avoided. This program was paralleled by very stringent fatigue life pressure cycling tests up to many times the normal bottle life requirements and both series of tests were satisfactorily concluded. Exhaustive tests were also conducted on the pneumatic starters, firstly to determine whether the considerable over-speed design requirements could be met without wheel or blade failure, and secondly to determine that extreme over-speed cases resulting in wheel failure would be contained without throwing shrapnel.

Acknowledgments

It would be out of place to terminate this story without a note of appreciation for the help extended by so many people during its compilation. Sources of material such as company reports, technical papers and memoranda have been used extensively and the author regrets that detailed acknowledgments in this direction would not be practicable here. Among the persons within Engineering who reviewed these notes and offered constructive criticism were: R. W. Partridge (Electra Project Engineer) together with his Assistant Project Engineers, B. L. Messinger (Department Manager – Thermodynamics), L. W. Nelson (Department Engineer – Structures), E. S. McCarthy (Design Specialist – Air Conditioning), C. R. "Chuck" Mercer (Manager – Airline Operations Engineering), J. B. Pitkin (Power Plant & Safety Staff Engineer) and M. I. Leitner (Research Specialist – Propulsion Department).

A special vote of thanks goes to C. R. Davenport (Maintenance Design Engineer) who checked the accuracy of many of the data with the specialists concerned and did a lot of the detailed work which must necessarily go into such a publication. The layout and illustrations are principally the work of Virginia Robins (Art and Illustrations Department).

J. F. McDonald

Follow-on articles. During the process of developing this article it became apparent that special attention should be given to certain subjects in future issues of the *Digest*. Because of the fundamental nature of the electrical power and distribution system we plan to deal with it at length in an early issue. The airplane control system, together with the hydraulic system, are of sufficient interest and importance to warrant a special article.

The subject of ground equipment including engine starting equipment, electrical ground power trucks, engine handling equipment and so forth demands detailed coverage which we plan to do fairly soon. Trouble-shooting equipment including review of the use of the special units developed for fast check-out of the airplane system such as electrical, air conditioning, etc., will be studied in the near future.

We should be grateful for suggestions on any special articles which our readers feel might be necessary as experience with the Electra develops in the maintenance field. Perhaps we should mention here that this magazine does not ordinarily cover subjects of an operations engineering character since a separate series of news-letters is now in being for this rather specialized subject. Please let us have your comments and criticisms so that we can tailor future issues of this magazine to your needs.