Development Highlights of the C-141 StarLifter

F. A. Cleveland* and R. D. Gilson†
Lockheed-Georgia Company, Marietta, Ga.

For the first time in this country, an airplane has been developed to both military and Federal Aviation Agency (FAA) requirements, with type certification as a requirement of the military contract. Although fundamentally an exploitation of proven state of the art, the 318,000-lb C-141 has many unusual features and represents the solution of several interesting development problems. Of chief interest are its cargo-handling features, the aerodynamic design of its modestly swept wing and of its T-tail, the derivation of its low-drag fuselage afterbody with full cross-section loadable opening, its stringent weight-control program, its long fan-duct nacelle design, its short nacelle inlets, its flight-station innovations for crew efficiency and comfort, and its unique main-landing-gear design. Rather substantial test programs are still in progress, mainly, by now, in the fatigue and flight areas. The C-141 received its FAA type certificate on January 29, 1965.

Introduction and Aircraft Description

THE Air Force's Specific Operational Requirement No. 182 led to a design competition in late 1960 and early 1961 which the Lockheed-Georgia Company was fortunate enough to win. The development program that was initiated under contract with the Air Force has resulted in the C-141 StarLifter airplane. The fundamental design philosophy employed has been one of simplicity, reliability, maximum utilization of proven state of the art, forgiving flight characteristics, and ruggedness under adverse operational circumstances. As a result, the airplane represents not a major across-the-board advance in the technical state of the art, but rather the integration of many localized refinements in various aspects on a basic framework of relatively conventional design. It is our intent in this paper to choose the particular areas that are to some degree different from what has been built in the past and point out the problems and the successes in such areas. We do not intend, therefore, to cover all of the design areas normally covered in such a paper but only those selected for some unusual characteristic or problem encountered. Some of the more conventional aspects of the design configuration are covered in Ref. 1.

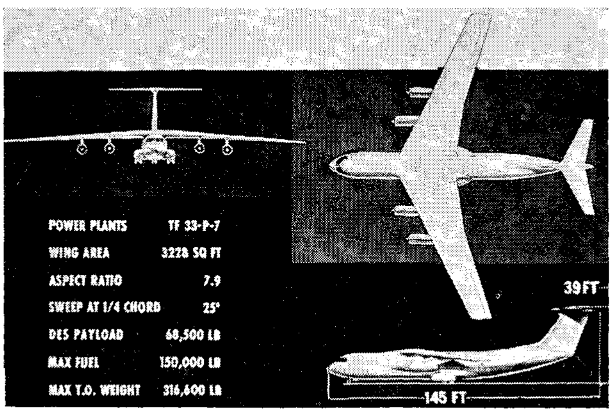

Fig. 1 C-141A general arrangement.

No discussion of the C-141 development would be complete without a recognition of the interrelationship among the FAA, the Air Force as represented by its System Program Office, and Lockheed. Because this was to be the first military airplane ever developed with a requirement for FAA type certification in the contract, a great many special programs, team concepts, and resolution of civil/military technical conflicts had to be worked out. We do not propose to discuss this in detail, but the working relationship that was evolved among the three agencies has proved practical and sound. Many design problem areas were discovered and fixed early in the program because of the constant cross-monitoring among us. A great deal of the credit for whatever success has been enjoyed to date belongs to the other members of the tripartite team.

The C-141 general arrangement appears in Fig. 1; it is a high-wing airplane designed for truck-bed-height loading of cargo through the aft end. It is powered by four Pratt & Whitney TF 33-P-7 turbofan engines, each rated at 21,000-lb thrust at takeoff power. The engines are mounted in pods under the wings and are completely interchangeable. The StarLifter is 145 ft long, has a wing span of 160 ft, and is 39 ft high to the top of the T-tail.

Design payload is 68,500 lb, but the airplane possesses structural capability considerably in excess of that. Maximum ramp weight is 318,000 lb, and maximum takeoff weight is 316,600 lb. Twenty-three thousand gallons or 150,000 lb of fuel are carried in 10 integral wing tanks.

Figure 2 is the C-141 inboard profile. The basic cargo envelope cross section is 9 ft 1 in. high by 10 ft 3 in. wide. This cross section is uncompromised by the main landing gear, which consists of a four-wheel bogie arrangement mounted in external pods. A 14-in. clear walkway is provided the en-

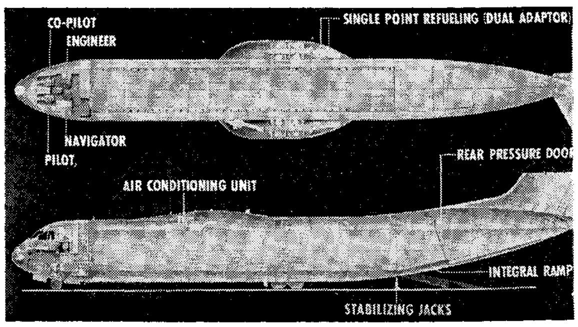

Fig. 2 C-141A inboard profile.

Presented as Preprint 64-596 at the AIAA Transport Aircraft Design and Operations Meeting, Seattle, Wash., August 10–12, 1964; revision received February 10, 1965. Credit must be given to the guidance and technical support of the Air Force C-141A System Program Office and the Southeastern Region of the Federal Aviation Agency. Their continued reviews of fault analyses, surveillance items, systems analyses, design criteria, structural reports, and design methods added greatly to the depth of design and experience built into the C-141A.

* Assistant Chief Engineer. Associate Fellow Member AIAA.
† C-141 Engineering Program Manager. Associate Fellow Member AIAA.

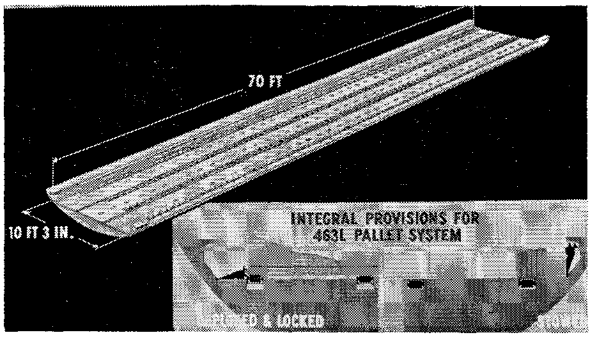

Fig. 3 463L rail and roller installation.

tire length of the cargo compartment. The floor is 70 ft long to the ramp hinge line, and an additional 11 ft is provided by the integral cargo ramp. The ramp can be lowered to a position even with the floor for air dropping of cargo or for loading from trucks and the 463L system mechanized loaders. When lowered to the ground, it forms an 11° incline for vehicular or bulk loading.

The airplane is pressurized to 8.2 psi from the radar bulkhead to the pressure door at the aft end of the cargo ramp. This provides a sea-level cabin up to 22,000 ft and an 8000-ft cabin at 41,000 ft. The pressurization and air-conditioning units are mounted in the forward wing-to-fuselage fairing. A gas-turbine auxiliary power unit is installed in the forward end of the left main gear pod.

The entire aircraft structure is designed to be fail-safe in accordance with FAA requirements and, at the same time, fatigue-resistant in accordance with military requirements. This combination of design philosphies is an ideal one for this kind of an airplane. Fail-safe design will ease fatigue problem areas, whereas fatigue-resistant design in the first place substantially reduces the likelihood of such encounters.

The airplane was designed with material handling system 463L equipment as an integral part of the airplane, as illustrated in Fig. 3. Four sets of rollers run lengthwise in the cargo compartment. When the system is in use, the restraint rails and rollers accommodate the pallets as shown in the lower left-hand view. When the 463L system is not in use, the rails and rollers are stowed as shown in the lower right-hand view to provide a clear cargo floor for vehicular or bulk loads. In addition, 10,000- and 25,000-lb cargo tiedown fittings, as well as continuous seat tracks, are provided throughout the main cargo compartment; the former cover the ramp as well.

The StarLifter was conceived as a troop carrier as well as a cargo airplane; this capability is summarized in Fig. 4. Utilizing six-abreast airline-type seats, 138 troops can be carried. One hundred fifty-four ground troops or 123 paratroops can be transported in standard aircraft troop seats as shown in the center and right-hand views. When a mission requires the use of a comfort pallet, these numbers are slightly reduced.

As shown in Fig. 5, 68,500 lb can be carried for 3800 naut miles using MIL Spec reserves. Over 61,000 lb can be carried 4000 naut miles, and over 29,000 lb can be transported 5500

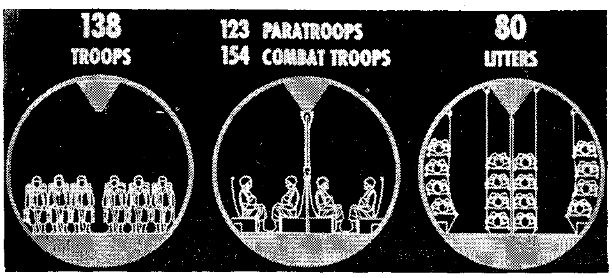

Fig. 4 Cargo compartment seating.

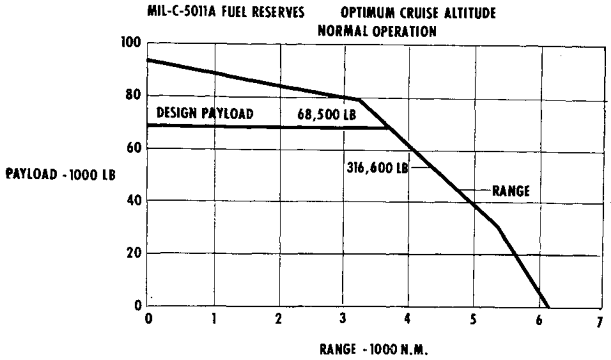

Fig. 5 Payload/range performance.

naut miles. This performance exceeds the original Specific Operational Requirements (SOR) of 50,000 lb of payload for 4000 naut miles and 20,000 lb for 5500 naut miles.

Aerodynamic Development

Several years prior to the initiation of the C-141 SOR, a research effort was initiated to find a fuselage afterbody configuration that would provide complete airdrop and aft-loading freedom without paying any drag penalty over a conventional afterbody. The goal was to accomplish this with no weight penalty over the then-conventional C-130 style afterbody. The key, found about a year before the competition, was to provide a fuselage crownline upsweep beginning just forward of the ramp hinge line. This gives enough added fuselage depth to allow planview fairing to eliminate the platypus effect found on the C-130. The side elevation can then assume a nearly conventional shape, and, most important, fuselage cross-section cuts at about 20° to the horizontal show an aerodynamic shape to which the air could be expected to stick. Wind-tunnel tests confirmed that there was, indeed, no longer a cruise drag penalty, and, although drag at dive lift coefficients was appreciably higher than conventional, climb and loiter drag was actually lower than that of a conventional nonairdrop afterbody, as illustrated in Fig. 6.

A substantial effort was devoted to minimizing wheel-pod drag. The dual trucks on the main gear gave the pod sufficient span so that wind-tunnel data originally showed a great deal of inboard wing-lift loss due to wheel-pod interference. The essence of the solution was to keep the wheel-pod nose as far aft of the wing leading edge as possible while, of course, providing gentle afterbody boat-tail angles. Finally the fuselage flow streamlines were determined in cruise, through wind-tunnel model oil-flow photographs, and the wheel pods were contoured to conform. The pod drag is now within two counts of the theoretical skin friction minimum and about half that of the original configuration.

Shifting now to the wing, two or three points of interest stand out. The original theoretical calculations showed that about 25° of wing sweep was the maximum that could be

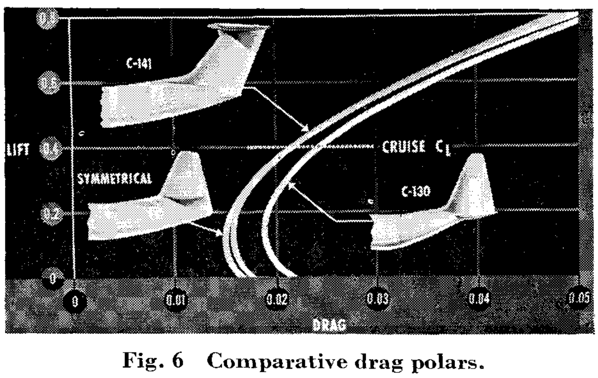

Fig. 6 Comparative drag polars.

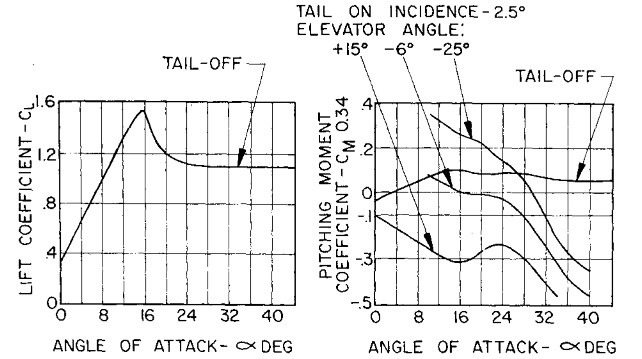

Fig. 7 Lift and moment coefficients at high angles of attack.

used to retain conventional aileron control and an uncluttered wing leading edge while still achieving good stall characteristics and acceptable maximum lift coefficients. With the sweep angle chosen, the wing airfoil sections are generally dictated by required cruise performance. Calculations and available airfoil data led to utilization of NASA 00-series airfoils modified, 13% thick at the root, 10% at the tip, with maximum thickness at the 40% chord and a conventional camber variation of a C_{L_i} of 0.15 at the root to 0.3 at the tip.

To achieve good stall characteristics, the wing is twisted $5\frac{1}{2}°$, and the leading-edge radius index varies from 1.1 at the root to 2.2 at the tip. Enough forward camber is added on the outboard portion of the wing to minimize the effect of the large outboard leading-edge radius on cruise drag and to delay tip stall further. Finally, inspired to extra caution, wind-tunnel tests were run to 40° angle of attack in all configurations. The wind-tunnel results, shown in Fig. 7, were programed into an analog computer, and every conceivable type of stall entry was exercised to assure that there was no way that a pilot could stall the C-141 and be unable to recover.

The C-141 was originally proposed to have inflight-operable thrust reversers and ground-operable spoilers. As detailed airplane design and load analysis proceeded, however, the problem of adequately predicting the effects of these reversers on wing airload distribution, nacelle and pylon loads, and maximum lift coefficient in time to avoid expensive design changes caused reconsideration. A study was made of deflecting the spoilers to sufficient angles to meet the target jet penetration rates of sink; a wing weight penalty of thousands of pounds was enountered because of airload distribution shifts. Deflecting the flaps a small amount to counteract the inboard lift spoilage caused by spoiler deployment was studied, but this caused a substantial flap weight penalty. Luckily there was just enough wing lower surface ahead of the leading edge of the stowed flap and aft of the wing rear spar which could be hinged and actuated simultaneously with the upper surface spoiler, as shown in Fig. 8. This resulted in no wing-box weight penalty at all for the inflight spoiler capability, and the longitudinal trim shift caused by spoiler deflection was minimized.

The flaps are the simple, single-slotted Fowler variety found on the P2V, the Electra, the C-130, and many other airplanes. They were wind-tunnel tested at Reynolds numbers up to about 7×10^6 to set the flap-wing geometry so that no difficulty was expected in flight. Unfortunately, they proved to have unacceptable buffet at deflections beyond about 80%. Inflight tuft movies revealed a separation pattern emanating from the flap tracks and spreading rapidly towards the flap trailing edge. The largest wind-tunnel model possible in available low-speed tunnels was 0.06 scale, and so it was essentially worthless to help attack this problem. Several aerodynamic fixes were tried on the airplane with only partial success. Finally, a portable 500,000-ft^3/min blower was rigged to bring the wind tunnel to the airplane effectively. The blower provided a 7-ft-diam cylinder of air at 130 knots over the separating portion of the flap, allowing our aerodynamics personnel to operate on the problem at close range and to evaluate quickly many configurations to arrive at a fix. The final solution was a leading-edge slot in the flap sections with internal guide vanes to control the flow in the flap support track regions.

Early in the C-141 development, it was found that it was quite important to keep the leading edges of our pylons at the wing intersection aft of the wing stagnation point in cruise. Use of the conventional shape coming up over the leading edge would have cost about 5–10 drag counts. This is a function of the wing chordwise pressure distribution and does not necessarily apply to a different wing. With the pylon leading edge at about 2% of the local wing chord, theory is that some pylon camber as well as toe-in should be used. The wind-tunnel results, however, showed that, although the computed toe-in (1° outboard, 2° inboard) was helpful in drag reduction, the camber was actually harmful, and so it was abandoned.

Choice of the T-tail configuration for the C-141 was based on a number of factors, including the following:

1) A high horizontal is less apt to be damaged by ground vehicles during loading operations.

2) The vertical tail end-plating reduces its required area and drag.

3) The high horizontal is in a more favorable downwash field so that its area requirement is also minimized.

4) In spite of the extra vertical tail torsional stiffness thus required, there was a net weight saving by this approach.

5) The reduced net empennage area resulted in a drag savings of six counts and a gross weight saving of about 6000 lb.

The horizontal stabilizer was mounted on the vertical in the best structural location, which meant that the maximum thicknesses of both surfaces were lined up, producing maximum aerodynamic interference. This was to be eliminated by a bullet fairing at the intersection. Early small-scale wind tunnel tests showed an empennage drag somewhat higher than expected, but this was not recognized as bullet problem until a tufted flutter model showed considerable flow separation emanating from the bullet area at cruise Mach numbers. A bullet-development program was immediately instituted based on more extensive area-ruling of the intersection, and the resulting configurations were evaluated at the Ames 11-ft tunnel. The chosen bullet eliminated the separation and the excessive empennage drag. Flight tests now show no bullet region flow disturbance out to beyond 0.80 Mach number.

Flutter Program

A very comprehensive flutter program, both analytical and experimental, has been conducted on the C-141. Since the airplane is designed to a 2.50 load factor, stiffness has dictated a considerable amount of the structural design. Basically flutter has designed to a large extent the structure of the vertical fin, the horizontal stabilizer, the engine pylons, and a large portion of the wing. The movable control sur-

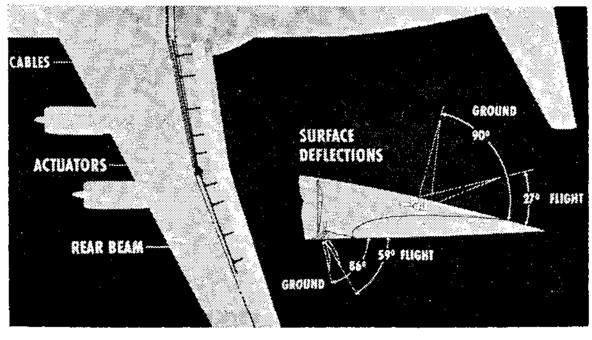

Fig. 8 Spoiler operation.

faces are designed to preclude flutter both in a powered condition and in manual operation. The ailerons are mass-balanced by a single tip balance weight and the elevators by spanwise distributed mass balance, but the rudder has no mass balance, due primarily to its very low-weight design, which results in a relatively high aerodynamic frequency that does not couple with any critical tail modes.

An extensive flutter wind-tunnel program was initiated early in development which was instrumental in establishing wing and empennage design stiffnesses and wing fuel tank arrangement and fuel usage. Low-speed testing was conducted with a complete airplane model and an empennage model and occupied about 1300 wind-tunnel hr.

After the guidance from the low-speed tests had been incorporated into the airplane design, a series of high-speed tunnel tests was run using a $\frac{1}{19}$ scale model of the complete airplane. This model was supported by cables so as to be essentially free in six degrees of motion and was controlled by movement of its control surfaces. These high-speed tests, consisting of 180 transonic hr, constituted the final substantiation that the flutter speed in compressible flow was in excess of 120% of design dive speed. A plot of the speed regimes explored is shown in Fig. 9

Since the stiffness design of the C-141 was quite critical, special static test programs were conducted to verify experimentally the stiffness distribution of the wing, vertical fin, horizontal stabilizer, fuselage, and engine pylons. These measurements were accomplished by the use of techniques that employed mirrors and transits to measure bending slopes and twist-angles directly. The results showed that the design and measured stiffness values agreed exceptionally well, in most cases within 5%.

Ground shake tests were conducted on the first production aircraft to measure the airplane coupled vibration modes and to establish the correlation with the modes measured on the high-speed flutter models and those computed theoretically. The results were in excellent agreement.

The final substantiation of the flutter safety of the C-141A was accomplished by flying the aircraft up to its limit dive speed with inflight excitation of the wings and empennage. This excitation was produced by aerodynamic vanes, located on each wing and stabilizer tip, which are controlled by electrohydraulic servo-controlled drives. The vanes were capable of being oscillated at frequencies from 0 to 25 cps at controlled amplitudes.

Weight Program

In the fall of 1961, it was realized that the weight of the airplane was showing an alarming increase compared to commitments. After an intensive study for about a month to determine the exact depth of the problem, a substantial number of changes were instituted to get weight back out of the airplane. At the same time, drag was reduced in certain areas so that the combined effect would permit meeting performance guarantees. This program was an excellent example of the outstanding cooperation with the System Program Office

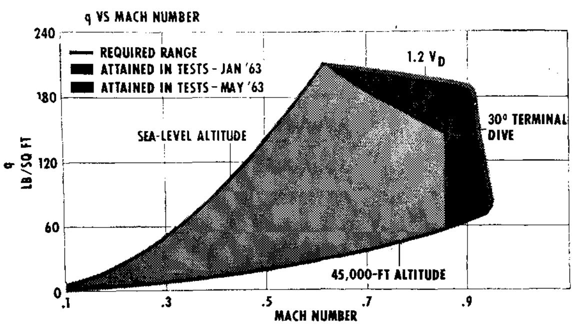

Fig. 9 Flutter-model test regime.

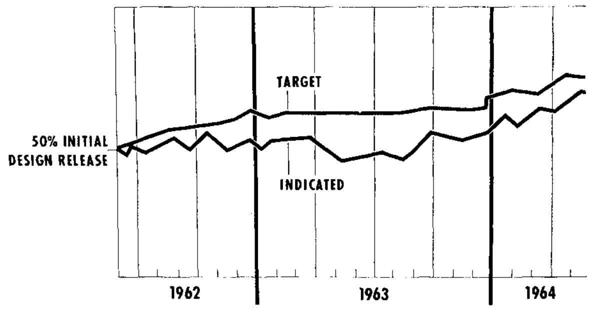

Fig. 10 Weight control.

(SPO) in that a number of the changes involved model specification items that had already been agreed to and other areas where concepts had to be jointly altered. The net result was not only a lighter airplane with less drag, but also an improved airplane in many operational respects; many design areas were explored so deeply that improvements and weight savings could be combined because of unearthing other problems at this relatively early stage of the design program.

Included in the changes were a change in wing thickness ratio distribution and a straightening of the front wing beam; movement of the wing splice 8 in. inboard; an aft movement of the inboard end of the rear wing spar; an alteration in aft fuselage shape, coupled with a reconfiguration of the petal doors; a change in the over-all concept of the aft fuselage ramp and petal door; changes in the horizontal stabilizer taper ratio, thickness ratio, and area; a reduction in rudder chord; a considerable decrease in the size of the main landing-gear pods; fuel system changes to reduce unusable fuel; movement of the air-conditioning system from the wheel pods to the wing fairing just forward of the front beam on the fuselage; elimination of the battery-inverter system in favor of a hydraulic-powered emergency electrical system; and numerous miscellaneous systems and structural changes throughout the airplane.

Having accomplished reduction of the indicated weight to the level necessary by May 1962, the date for 50% release of Project design, a very stringent weight-control program was instituted and has been maintained ever since, as shown in Fig. 10. It is the usual target weight system with which many are familiar, and it has been most successful. As one can see from the curves, the airplane has remained below target weight, and there is a high degree of confidence that this condition can be maintained. Actual weighings of the first six aircraft have resulted in values several hundred pounds below the indicated weights for these aircraft; this lends further encouragement on the over-all weight position.

Nacelle Development

A great deal of time was devoted to the nacelle design for the C-141 long before submittal of the competitive proposal. In the process it developed that the use of long fan discharge ducts to carry the fan air to the aft end of the nacelle would give better over-all performance than the use of short ducts in vogue at that time. Subsequently, wind-tunnel tests indicated that very short nacelle inlets could be used without encountering compressibility drag increases below cruise Mach number; this did, of course, save both the weight and wetted area drag of more conventional long inlets. The net benefit of these two factors was calculated to be about 4000 lb of payload on a 4000-naut-mile mission. The resulting configuration appears in Fig. 11.

The first nacelle problem encountered had to do with the short inlet. This inlet experienced a very slight separation just inside the lip at airspeeds from zero to about lift-off at high engine power, as illustrated in Fig. 12. The separation was insignificant from a performance viewpoint, but later

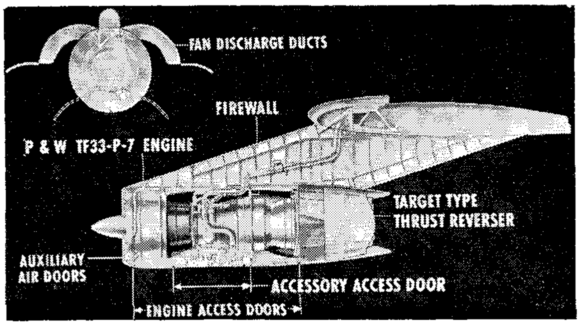

Fig. 11 Nacelle inboard profile.

evaluation of its effect on the engine showed that the separated flow excited the fan blading in an unacceptable manner insofar as fatigue life was concerned. A set of spring-loaded relief doors was therefore developed, distributed around the circumference of the nacelle, which would be sucked open under all operating conditions where the inlet area ratio was greater than unity. The first attempt at this design was successful, and, although there subsequently had to be a change in tolerances on the throat through which this relief air discharged into the inlet, the fan-blade excitation problem has been eliminated.

As a matter of fact, the inlet has been tested in conjuction with a 500,000-ft^3/min blower that bathed the inlet in a 130-knot airstream oriented 34.5° off the centerline of the engine, representing the worst possible combination of angle of attack and yaw, and no adverse effects were encountered. This is roughly the equivalent of a 90° cross wind of 73 knots, so there is effectively no significant limitation on cross wind for running up engines prior to takeoff.

The performance of the long fan discharge ducts has been equally satisfying. The high recovery predicted was finally attained with minimum flow distortion by a rather intensive program to develop both the cross-sectional area distribution and the four splitter vanes that extend from just aft of the fan discharge well back along the lengths of the ducts. As might be expected, the practical problems of joint seals have been difficult. The leakage rates that we originally encountered were far too high and would have wiped out most of the performance advantage of the long duct concept. Gradually developed improvements, however, have led to over-all performance about as anticipated.

One element of the advantage of the long duct concept is that it permits the use of single, simple target-type thrust reversers to reverse the thrust on both the primary and secondary air discharges; the arrangement appears in Fig. 13. These reversers have proved very satisfactory, giving reverse thrust percentages of about 47% at maximum continuous power, whereas the original design target was only 42%. There were initially some difficulties with opening loads on the buckets when they were stowed at high Mach number and high dynamic pressure, but the problem was solved by locking the forward ends of the actuator arms by hooks operated by a linkage from the actuator cross-head.

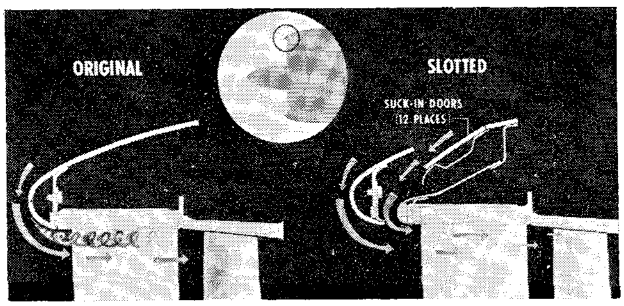

Fig. 12 Nacelle inlet air flow.

There were a number of acoustic design problems in the nacelles. Although the acoustic environment was recognized as thoroughly as possible very early in the design program, the continuing existence of both art and science in this field, plus a few intentional gambles for the sake of weight, led to some redesign. It was necessary to beef up the splitter vanes in the bifurcated ducts that first receive the fan air and in the long ducts themselves. The most serious was an increase in the wall thickness of the fan discharge ducts to eliminate some local cracking in these areas.

Flight Station

The C-141 flight station, shown in Fig. 14, is one of the show places of the airplane. Special attention was given to three principal configuration features (styling, visibility, and comfort) in this area where the flight crews must operate for long periods of time. Styling emphasis was placed on a restful color scheme, neatness and utility of arrangement, and functional integration. Visibility emphasis was placed on viewing-angle clearances (135° to the side, 18° over the nose, and 50° upward) as well as on minimal light reflections and location of items on instrument panels and consoles for ready recognition of aircraft and systems operation. A thorough

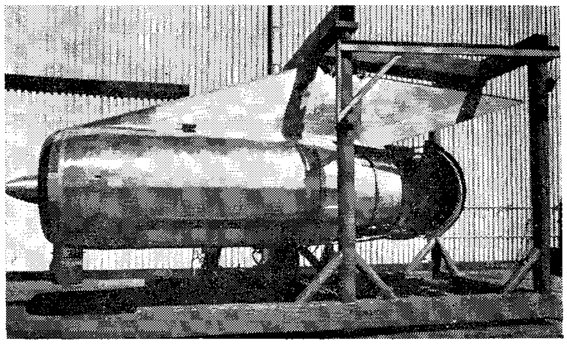

Fig. 13 Thrust reverser.

human-factors analysis of all general comfort considerations went into the final configuration of seat design and adjustability, ventilation, arm reach to equipment, table design, and accessories at all four operating stations for pilot, copilot, systems engineer, and navigator and at the four relief crew positions. The latter consist of two bunks, the lower of which has two stowable seat backs, and two semireclining seats. The galley and crew toilet are located below, and are isolated from, the flight station on the lower deck, just a few steps away.

The principal innovation in the C-141 is the use of vertical-scale flight instruments for air speed, Mach number, angle of attack, altitude, rate of climb, and for the engine functions engine pressure ratio, first- and second-stage compressor speeds, exhaust gas temperature, and fuel flow. These instruments, all electrically operated, can be seen in Fig. 15 The flight engineer also has a duplicate set of engine instruments. The eight vertical-scale instruments on the pilots panels replace 30 round-dial instruments and, with very little practice, give about 50% more rapid reading and decision making capability. Each instrument operates on the moving tape principle and has proved reliable to date.

Early in the program, the original flight station mockup was reviewed by pilots from Military Air Transport Service (MATS), SPO, FAA, and Lockheed. After all comments were received, a special lighted mockup was built for further review and refinement. The lighting mockup was then checked by the pilots in simulated missions under night flight conditions, and further refinements were made to assure complete acceptability of the arrangement, accessibility and comfort. As a result of this thorough coordination, there have been an absolute minimum number of changes in this usually controversial area.

Primary Flight Control Systems

A complete description of the primary control systems would be unwarranted, since the primary axis surfaces are normally driven conventionally by dual hydraulic irreversible power units utilizing feel and centering springs. We imposed upon ourselves, however, the requirement that a safe landing must be attainable with failures in both the no. 1 and no. 2 hydraulic systems. It was originally determined that the rudder did not have to be backed up, since yaw control could easily be maintained by slight throttle manipulation even with one engine out; the elevator could revert to manual with the operation of a ratio shifter to give the pilot adequate hinge moment to control the aircraft in pitch, in conjunction with stabilizer positioning; the aileron could revert to manual operation of a servo tab in series with the positioning valve on the aileron power unit.

Wind-tunnel tests, simulator tests, and computer analyses showed that the elevator and aileron programs required modifications. Upon loss of the second elevator hydraulic system while in approach configuration, the elevator was found to trail about 6° down, snatching the stick from the

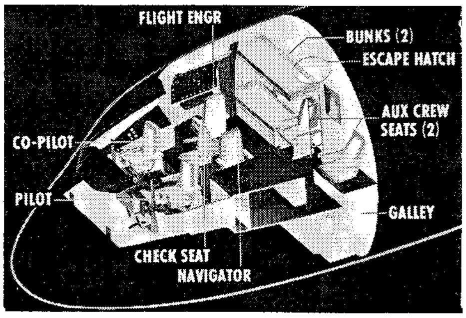

Fig. 14 General arrangement of flight station.

pilot until the electrically operated ratio shifter came into position to give him reasonable stick forces. During this time the aircraft would pitch down and lose altitude. Design alternates considered were a hydraulic-shift walking beam with dual reliability or an instant-acting direct shifter, if acceptable manual control was to be retained. Considerable review indicated that the most practical design would be to add a third hydraulic cylinder to the existing power package, independently powered by the no. 3 auxiliary electric-driven hydraulic system. This gives continuous backup after either or both of the no. 1 or no. 2 hydraulic system fails.

Stability problems in the aileron power package connected with the aileron tab could be excited by the aileron tab; therefore, it had to be disconnected from this system. Running an independent servo tab system back to the stick was one solution; the other, which was adopted, was to lock the tab out by an idler crank that could be actively repositioned by a small hydraulic cylinder connected to the no. 3 hydraulic system. Since failure to use the aileron tab would have resulted in substantial redesign, the triple-system route was not pursued on the aileron actuators; however, it might be desirable in the future to do so to save the tab balance weight penalty.

Fuel System

Although initial fuel system studies drew upon the experience of many other aircraft, some unique requirements dictated special attention to recovery of all fuel by special

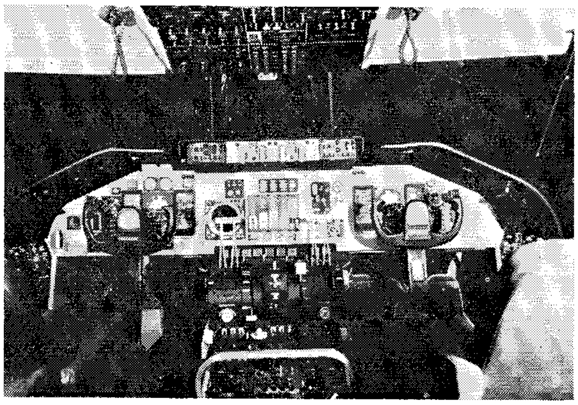

Fig. 15 Instrument panel.

means. The C-141 has negative dihedral, inducing the fuel to run outboard on the ground; in flight, the tank lower surface is practically flat. Therefore, an extensive computer analysis was set up to locate the fuel levels for gaging and residual puddles for the minimum unusable fuel analysis. This was supplemented by plastic models and a full-scale tank simulator. The system varies from 150,000 lb of fuel when full to about 800 lb of unusable fuel. Either main tanks or auxiliary tanks can be fed directly to engines; the system provides for single-point refueling and inflight jettisoning.

Two structural considerations also entered into tank shaping and location: flutter mass requirements and center-of-gravity control. Once the tanks were shaped and located as shown in Fig. 16, the puddle studies located the scavenging pickups for the fuel eductors, which return all usable fuel to the pump scavenge boxes. These eductors were developed on the C-130 and are very trouble-free ejector pumps using the main pumps for delivery of pressure to suck up fuel. It was necessary to carefully locate weep holes (riser drains) adequate in number and size to permit the fuel to flow from between the wing plank risers to the proper pickup points.

Main Landing Gear

Supporting the airplane are conventional four-wheel-bogie main landing gears with 44 × 20 wheels and tires, as shown in Fig. 17, but here the conventionality ends. The main-gear oleos must meet several requirements. They must be short enough when the airplane is at rest to provide a truck-bed-height cargo floor; they must extend several feet to provide adequate tail clearance during landing flare and takeoff rotation; and they must absorb the design 10-fps sinking speed at touchdown when in the extended condition. In addition, the gear had to retract into the rather small pod already described and yet be of great enough tread to accommodate wing-down landings without wing tip or nacelle ground contact. Once the principle of the cantilevered main trunnion attached to a

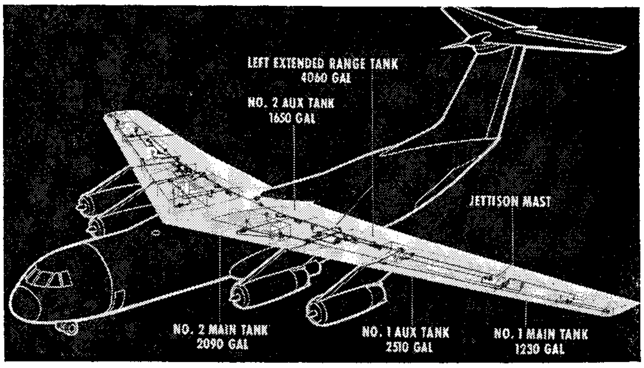

Fig. 16 Fuel-tank arrangement.

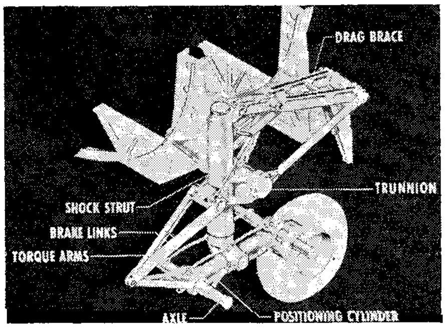

Fig. 17 Main landing gear.

main fuselage frame was conceived and the gear retraction geometry was developed to keep the bogie parallel to the airplane centerline for minimum frontal area, the major problem was accommodation of the long oleo cylinder.

The oleo is supported near the cylinder bottom and its top projects through a door in the top of the wheel pod. Retraction of the gear pulls this door closed and actuates the direct rod linkage to the lower inboard and outboard wheel doors. A beneficial side-effect of the projecting oleo cylinder is ready accessibility to its top for air and hydraulic oil servicing. Also, the oleo may be readily extended by air overcharging for adjustment of cargo floor height or aircraft jacking to aid removal of the inboard tires.

The oleo itself is unique in that it incorporates an orifice-controlled bleed-down feature in addition to its shock absorbing function. This bleed-down feature offers no resistance to gear extension as wing lift increases during takeoff but controls settling at the rate of 2 in./sec. This latter value was established from extensive computer programing of the aircraft dynamic characteristics during landing in the vertical and pitch degrees of freedom. This low sink feature is accomplished by a separate inner concentric chamber in the upper part of the strut which is connected to the outer chamber by two small orifice openings. The inner cylinder acts as the conventional air chamber in the strut for impact absorption. The orifices then permit restricted flow of hydraulic fluid into the outer chamber, allowing the piston to deflect slowly to the static position. Strut action during ground operations is conventional.

Flight tests to date have included taxiing in crosswinds of over 40 knots, crosswing landings, maximum braked landings, and extensive ground maneuvering with no main gear difficulties; pilot statements attest to the existence of exceptional ground stability.

Aft Door System

The primary configuration design problem area on the C-141 centered about the solution of the Air Force requirements for straight-in aft loading, aerial delivery capability, truck-bed floor height, and loading from the ground. Although these requirements had all been met on the C-130 aircraft, direct

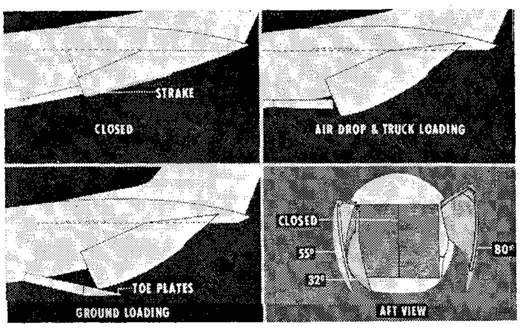

Fig. 18 Aft doors and ramp.

adoption of that door and ramp system would have resulted in the drag penalty discussed previously. The system furthermore had to be operable in flight for drops up to 200 knots in lieu of 150 knots on the C-130 and to be able to withstand internal cabin pressurization of 8.2 psi.

The evolution of the configuration of petal doors, ramp, and pressure door went through many stages, the last of which was associated with our substantial weight reduction program. The final configuration, shown in Fig. 18, features diagonally hinged petal doors, a honeycomb sandwich pressure door, and a C-130-type ramp usable with separate toe plates for "from-the-ground" vehicular and personnel loading.

The petal doors feature a box-type construction of inner and outer faces of approximately $\frac{5}{8}$-in.-thick honeycomb aluminum sandwiches and appropriate ribs and longerons. Each door has two hinges, an actuator attach point, and, when in the closed position, the two doors are pulled together at the aircraft centerline by two hydraulically actuated latches. The selection of honeycomb for this assembly was primarily dictated by weight to satisfy the critical requirements of stiffness, load concentrations at hinge and actuator points, and sonic resistance for energy levels from 143 to 149 over-all db during ground run-up with doors open and during takeoff. Tradeoff studies, carried to practically complete design of these doors of conventional skin and stringer style and of the honeycomb design, were made both before and after actual hardware was ordered to assure correctness of this choice. A saving of 100 to 200 lb compensated for the somewhat higher cost of honeycomb. The ventral strakes along the centerline edges of the doors were developed from flight and wind-tunnel load surveys to relieve a critical loading condition undetected during original wind-tunnel tests.

The top-hinged, 3-in.-thick, honeycomb pressure door swings down to latch to the aft end of the ramp, providing an ideal load path for pressurization and ramp loads. There are no side latches on the pressure door, permitting simple wiper seals and a catenary shape when loaded. Use of a basic curved shape here or a dome would have been lighter but would not have permitted unobstructed loading without serious penalty to the upper fuselage design to accommodate retraction.

Sonic Fatigue

The detail design of the primary and secondary structure of the C-141 has been based on sonic fatigue considerations. Detailed analyses and experimental panel tests were conducted early in the C-141 program in order to assure that the structure would have a satisfactory sonic fatigue life based on the latest state of the art.

From this point of view, the most critical structure on the airplane is the flaps. When fully deployed, the flaps penetrate the flow boundary of the engine exhausts and encounter a simultaneous application of extreme thermal and acoustical environments. A number of development tests were conducted in the Lockheed Siren Test Facility with simultaneous

Table 1 Aerial delivery study parameters

Configuration	Gear up, doors open
Flap settings	0°, 35°, and 45°
Fuel weight	150,000-lb max, 7500-lb min
Center of gravity	Full range
Cargo weight	70,000-lb max, single platform w 35,000-lb max
Speed	Min 100 knots to max 200 knots
Extraction rate (longitudinal acceleration)	0.25–1.5 g's
Altitude	2000–20,000 ft
Gust	±25 fps vertical and lateral
Thrust	Power for level flight
Multiple drop timing	Delay times of 0.1 to 2.0 sec

application of heat and sound to establish the best configuration of titanium and aluminum honeycomb panels for survival in this environment. A satisfactory design for the individual cover panels for the flaps was evolved from these tests.

Since sonic fatigue resistivity depends strongly upon detail design, a thorough substantiation must consider the backup structure in even greater depth than the panels themselves. This sort of substantiation is not readily obtained in a siren test, particularly if the over-all structure is not heated. Thus endurance tests were conducted of the flaps, actuators, and other wing trailing-edge structure on the engine test stand. To accomplish this, complete production wing trailing-edge, leading-edge sections and flap were attached to a simulated wing box on the test stand. All components were extensively instrumented with strain gages, accelerometers, and microphones.

The engine operating schedule provided simulation of 50 aircraft missions, involving a total of approximately 50 hr of operation at military-rated power. This is equivalent, fatigue-wise, to 1500–3000 hr of service experience on the C-141 airplane. A number of sonic fatigue deficiencies were uncovered, corrections for which were fairly simple, and have been incorporated in the flap design.

Corrosion Control

Both Lockheed and the Air Force have been extremely concerned about having adequate general corrosion protection in the C-141. Although it is impossible to evaluate completely the success of any corrosion control program until a good deal of field experience has been obtained, the steps being taken to minimize corrosion problems are highly significant.

The SPO has authorized the use of MIL Spec MIL-F-7179A type II finish on all inside surfaces of the airplane and on all bare aluminum alloys on the outside. The use of acid-resistant vinyl lacquer in the fuselage bilge area is very extensive.

The upper wing panels are shot-peened; the nonclad structural aluminum components are sulphuric-acid-anodized; all parts in the wing tanks are coated with polyurethane, and a flowcoat of polyurethane is applied to the lower 6 in. of the tanks; all fasteners passing through the wing structure from the exterior are installed wet with sealing compound; exterior cracks are filled with aerodynamic smoothing compound; and the wing structure is faying surface sealed. Also to be incorporated early in production airplanes will be wet-installed fasteners on all other exterior surfaces. These many steps will vastly decrease the corrosion problems in the airplane. In spite of all this, however, it must be recognized that good maintenance practices are essential if corrosion is to be avoided altogether.

Aerial Delivery Analyses

Some time ago the first phase of a parametric study of the aerial delivery capability of the airplane was conducted. The general ranges of the parameters are summarized in Table 1. The analysis covered three flap settings; a wide range of fuel weight and center-of-gravity locations; payloads up to 70,000 lb, with 35,000-lb maximum on one pallet; the complete operational range of speeds, extraction rates, and altitudes; added the effect of gusts; and investigated time delays between successive pallets from 0.1 to 2 sec.

All kinds of combinations of loaded pallets were examined, ranging from two 35,000-lb loads up to seven 10,000-lb loads. Also analyzed was dropping a 35,000-lb unit followed by a jump of 79 paratroops.

As an example of the results of such analysis, Fig. 19 shows, in the top band, the way in which the load on the ramp, the airplane load factor, and the pitching accelerations vary during the drop of two 35,000-lb loads. The bottom band shows the variation in floor angle and airplane angle of attack during the same sequential drop. This is the sort of basic data from

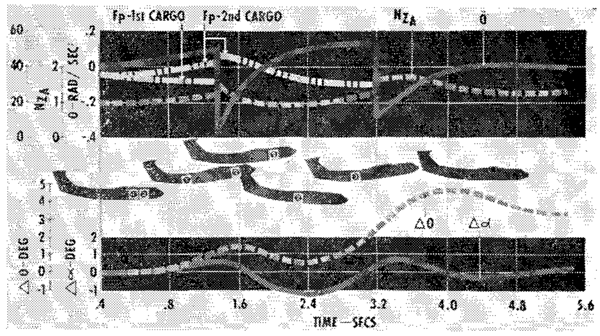

Fig. 19 Typical aerial delivery time history.

the analog computer which tell when airplane limits are reached.

The black area of Fig. 20 is the so-called cargo chimney, or the area in which the center of gravity of the cargo can be and still keep the airplane in balance. This diagram shows the cargo center of gravity before and after the drop of the first of two 35,000-lb platforms. The situation with seven 10,000-lb platforms is similar. In both cases the cargo chimney is not violated.

One of the primary concerns was with respect to the effect of dropping a second pallet too soon after the first. This has turned out to be not a problem at all. It was further learned that the airplane capabilities are not exceeded for the many combinations studied, and drops in excess of 35,000 lb should be possible.

Test Programs

Some aspects of the wind-tunnel program have already been covered, particularly those associated with flutter testing. In addition, about 2340 hr were devoted to low-speed tunnel tests in configuration development, stability and control, and performance. Another 1660 hr of transonic testing, primarily at the Ames Aeronautical Laboratory and at Cornell, covered the same areas in the higher speed regimes.

We have always been strong believers in the value of full-scale simulators. Accordingly, seven of them are in use, including the engine test stand. The fuel simulator consists of a set of four steel tanks hinged together so that wing bending can be completely simulated. It represents one complete airplane wing panel. The tanks are hung from a framework that is capable of rotation to simulate any airplane angle of attack. Of particular interest was its use in helping to solve the unusable fuel problems that have already been described. A complete test program covering all of the customary combinations of parameters for normal and failed component operation at various altitudes and attitudes with both hot and cold fuel was run.

The entire aircraft electrical system is simulated, starting with the four constant speed drives and generators driven by electrical motors and duplicating the electrical circuitry and components throughout the airplane. The designers went to

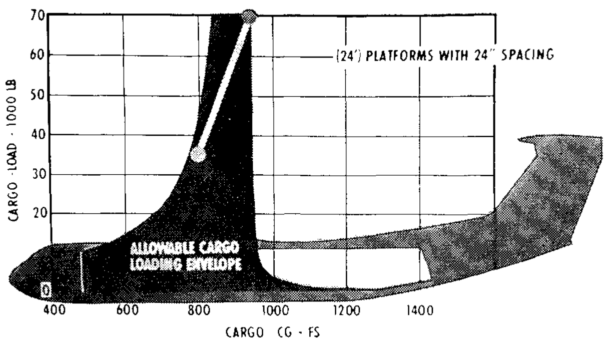

Fig. 20 Center-of-gravity travel.

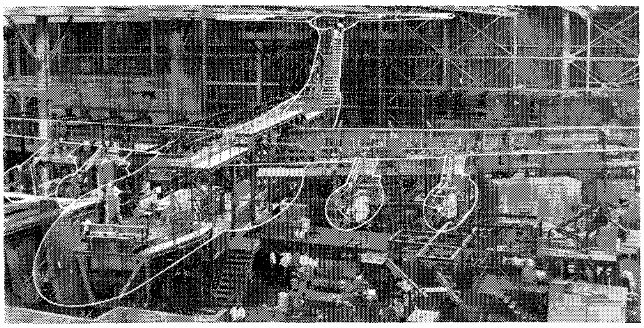

Fig. 21 Flight controls and hydraulics simulator.

extraordinary lengths to minimize electrical fire hazards in the C-141, and this attention to the electrical system has, apparently, paid off; of all simulators, this one has revealed the fewest problems during the course of its test program.

The electronic systems have also been laid out in their correct physical relationships in the electronic simulator. This has been particularly valuable because these systems include a substantial amount of government-furnished equipment so that special attention to integration of all components was mandatory. Both here and with the electrical simulator, the conclusion of the development and demonstration test program phased into a substantial reliability program, which the Air Force funded. A great deal is still being learned about the reliability of these and other aircraft systems on the ground long before there is any great amount of operational experience on the airplane itself.

A substantial section of dummy fuselage and one wing leading edge was built to create the environmental and ice-protection simulator powered by a battery of compressors and a ground furnace. It includes all of the pneumatic systems in the airplane and has been very helpful where improvements and changes were required. The special duct and joint designs for the 220-psi, 867°F bleed air from the engine compressors were worked on here, as well as the development of the wing leading edge anti-icing, the dynamic characteristics of the flow control equipment, and the distribution of air throughout the airplane.

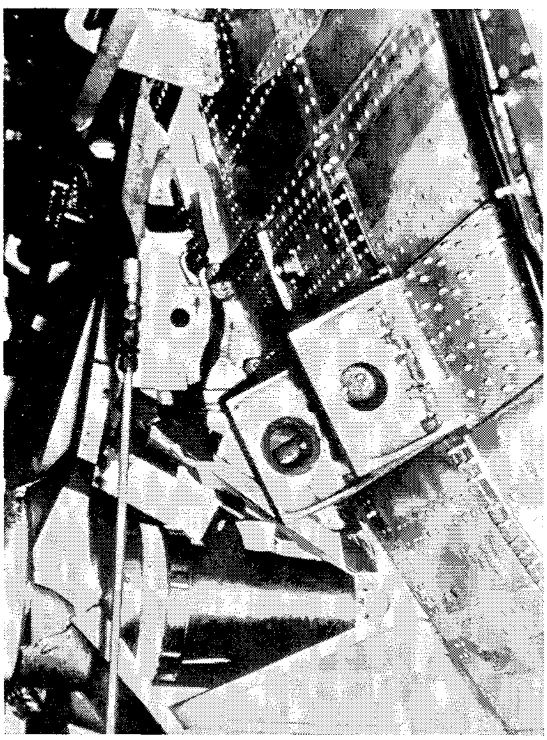

Fig. 22 Main-landing-gear frame failure.

Probably the most impressive simulator is that in Fig. 21, which is really two in one. The artist has highlighted the structure and systems that make up the combined flight controls and hydraulics simulator. These systems were built up exactly as they are in the airplane, and both development and demonstration testing have been going on for some time. The savings in both time and money by checking out changes before flight test have been of incalculable benefit to the program. For example, it was on this rig that we discovered and fixed a rudder power package mount flexibility problem, developed improved low-friction control system components and cable runs, and resolved many dynamic deficiencies in hydraulic components.

The engine test stand is conventional in concept and has been used for largely conventional purposes. On it were run the nacelle qualification and endurance test, the thrust-reverser endurance test, general engine and component compatibility with the nacelle, and numerous special test efforts. It should be stated here that the engine and its accessories have proved very satisfactory to date. The C-141 program owes a great deal to Pratt & Whitney for the very trouble-free service from their powerplant.

The concept of our static test program is a normal one; an airplane complete in all structural respects is placed within a steel framework such that all combinations of loads to satisfy military specifications and FAA requirements could be applied. Fuselage pressurization protection was afforded by a water tank out of which the wings and empennage protrude. The static test program is 90% through in number of tests as of January 1964.

Several failures have been experienced to date, one of which was in one of the main frame forgings that carries the main-landing-gear loads into the fuselage and the wing; Fig. 22 is a photograph with the broken section held in place. The cause of the failure that occurred at 130% of limit load was determined to be detailed design of a few pieces that determined how the load from the main-landing-gear trunnion was distributed into the forging. The fix altered these detailed parts with essentially no weight increase but did teach us that it is possible to remove one of these tremendous forgings from the heart of the fuselage and reinstall another one!

The only other major failure was in the vertical fin at 135% of limit load. This required the addition of some stringers in the fin and some stabilizing intercostals in fin and fuselage to correct. Fortunately, there have not been many detail minor failures during static test, in spite of the emphasis on weight reduction which increased their likelihood.

The C-141 fatigue test program is possibly one of the most extensive ever undertaken this early in an airplane develop-

Table 2 Flight-test aircraft assignments

	Tests	Locations
6001	Flutter	Marietta
	Powerplant	Marietta
	Stability and control	Edwards
6002	Performance	Edwards
6003	Structural integrity	Marietta
	ADS and jettison	El Centro
6004	Automatic control systems	Marietta
	Natural icing	North
6005	Fuel system	Marietta
	Avionic systems	Edwards
	Function and reliability	Edwards
6006	Accelerated service	Edwards
6007	All-weather	Eglin
		Wright-Patterson
		Alaska, Yuma
6008	Maintainability	Edwards
	Service suitability	Pope

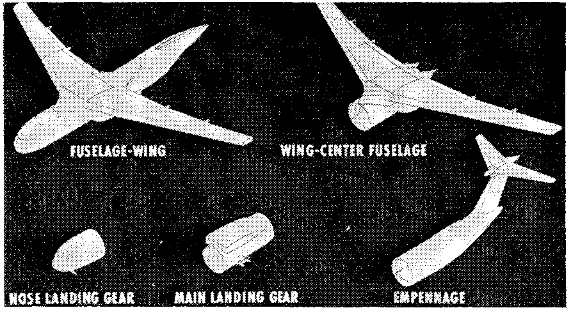

Fig. 23 Fatigue specimen configuration.

ment period. Four of the five specimens shown in Fig. 23 have been built and are in cyclic testing. All in all, the various loading conditions will combine to subject the structure to 60,000 hr of operation, which is twice the expected airplane lifetime. The loading spectra are carefully constructed to simulate the expected mission profiles in which the airplane will be operated.

The flight-test program, more than any other perhaps, characterizes most clearly the joint Air Force/FAA/Lockheed team concept. There are five airplanes for category I testing and three for category II; their assignments are illustrated in Table 2. After preliminary flights by Lockheed, the category I program includes pilots from all three agencies throughout. Similarly, the category II program includes substantial participation by both the FAA and Lockheed. The thorough test program established by the Air Force includes anti-icing flights in conjunction with a tanker, Eglin climatic hangar tests, air drops in conjunction with the Army at El Centro, desert tests at Yuma, proving tests in Alaska, and accelerated service-time acquisition at Edwards. Maintainability and service suitability will also be a special program on one aircraft and will be conducted at Edwards and Pope Air Force Bases. The flight structural program will immediately precede the aerial delivery system tests.

At this writing, the flight-test program is proceeding well; major items requiring corrective action from it have been discussed in the appropriate sections of this paper.

Conclusion

The development highlights presented in this paper have covered successes as well as problem areas with the full knowledge that those who are familiar with the development of a new aircraft must continually be alert to methods for insuring program continuity without major redesigns during the testing stages. We are convinced that no newly developed airplane can be designed, flight-tested, and released to early useful service without the tremendous amount of analysis and component and simulator testing partially described in this paper. We have established a solid basis for test variations and have the tools available for coping with the unexpected.

Reference

[1] Cleveland, F. A. and Upton, V. S., "Design for double duty—the C-141," American Society of Mechanical Engineers Paper 62-AV-10 (June 26, 1962).