REPLY TO
ATTN OF: ASOP

SUBJECT: Final Report of DAG Committee on C-141A Air Loads Problem

TO: Dr. R.T. Whitcomb
NASA Langley Research Center
Langley Station, Virginia

Dear Dr. Whitcomb

A final report of the committee is attached for your file.

Dr. Ashley indicated that he had attempted to incorporate the comments of all committee members. Essentially all suggestions have been adopted, most verbatim but some by alteration of the original text. He has asked that his sincere appreciation be expressed for your participation and the promptness of those responding with criticisms.

Charles J. Marshall
DAG Secretariat
Plans and Policy Division
Plans and Operations Office
AERONAUTICAL SYSTEMS DIVISION

FINAL REPORT OF SPECIAL COMMITTEE
ON C-141A AIR LOADS
PROBLEM
12-13 NOVEMBER 1965

at

Lockheed-Georgia Company
Marietta, Georgia

Date of Report - 30 December 1965
I. INTRODUCTION

On 12 and 13 November, 1965, a DAG committee consisting of representatives from NASA, AFSC (ASD & RTD) and private organizations convened at Lockheed-Georgia Co., for the purpose of reviewing a discrepancy between design loads on the C-141A cargo transport and actual loads encountered in supercritical flight. The chartering letter from Commanding General, ASD, sought comments on the current situation, an examination of the planned course of remedial action, and recommendations on future work to assure more accurate loads prediction on large, flexible high-speed aircraft.

The first day (Nov 12) was spent in briefings and discussions with Lockheed personnel, for whose excellent cooperation the committee expresses its warm appreciation.

It was clear to all present that the program was in a state of rapid flux, that data were being accumulated on a day-to-day basis and that new information might cause modifications to the optimum remedial steps. The committee was nevertheless asked to prepare an interim report. It must therefore emphasize that the conclusions drawn are necessarily based on the current state of knowledge, particularly as summarized in the Lockheed presentation, and might require revision in the light of a future development such as failure in a critical static test. (No such difficulty had appeared by the end of December, 1965.)

In view of the specialized nature of this report, there is no need for any introductory statements regarding the C-141A configuration development or history of the program. The committee concurs with two assertions made in the chartering letter:

1. That the loads correlation is quite good at lower Mach numbers but deteriorates above a value of about 0.8, and

2. That an outboard and aft shift of the wing center of pressure, relative to values predicted from wind tunnel tests, was observed during high-Mach flights.

Other related aspects of the problem, such as increased balancing tail forces and effects of incremental lift during certain rolling pullout maneuvers, were brought out during the briefings.

The committee has organized its responses in order of the three specific questions framed by the chartering letter, except for one slight change in the wording of the third, and these questions are restated below. The request for suggestions as to "program approaches, research, advanced development and design, and engineering criteria" is met, at least in part, by the answers which follow.
II. ("Were techniques used for establishment of loads from wind tunnel test data the best possible?")

Yes, within the state of the art both at the time the structural design was carried out and at present.

III. ("Is the present course of action planned for the C-141 adequate?")

It is understood that the following steps summarize what is meant by the planned course of action (13 November 1965):

1. Aerodynamic data based on flight tests will be used.

2. In the revised loads computations,
   a. Flight-test elevator rates will be used, and
   b. Rational buffet loads data based on C-141 experience will be used in lieu of arbitrary factors (150-50) for the empennage loads.

3. The airplane configuration will be changed as follows to reduce load levels:
   a. Ailerons will be re-rigged.
   b. Hinge moments will be reduced on the down-going aileron.
   c. Elevator will be re-rigged.

In addition, it is understood that the present static test article is to be retested to ultimate, using redefined loads, for the as-yet unproved conditions.

As a general comment, the observation is made that, if the modified configuration exhibits a positive margin of strength for the redefined loads, it is the opinion of the committee that the static strength will satisfy mission specifications. In the event of a failure of the test specimens directly attributable to the revised loading, consideration will have to be given to modifying the structure, restricting the airplane, or choosing a compromise such as restricting present aircraft and modifying later production articles.

Further, if other considerations indicate a backing off from some of the changes planned, (e.g., the aileron re-rigging), such a decision may necessitate structural modifications (beef-up) or operating restrictions on the air frame.

It should be noted that the proposed changes may affect the structural fatigue life and handling qualities of the airplane (such as roll control), so that re-study of these problems is required. Both the basic design and
the associated test program should be reviewed. It is the committee's tentative consensus, however, that the effects on handling qualities will probably be negligible, so that no large-scale review of this area is necessary.

Future developments or changes in specifications, such as the redefinition of the expected low-level gust experience that is indicated by recent B-52 studies, should be examined with respect to the basic capabilities of this airplane (as well as other aircraft) to perform the desired missions.

Those points of the structure which were brought out to be critical through use of flight loads, as well as the nature of the load changes, should of course be of special concern in any future growth considerations for the C-141A.

Control of shock location on large-scale high-speed wing configurations, characterized by Reynolds numbers in the order of 25 million and greater, is not understood at present. It is therefore recommended that the C-141A be refitted with pressure tapes in the area between the nacelles and that flight studies be made, using various simple auxiliary control devices, to investigate the means by which shock formations may be subject to control. Information gained may lead to another direct and more desirable fix for the C-141A, as well as providing for significant inputs to the design of the C-5A and other future aircraft.

IV. ("Is additional work required to account for this phenomenon when applied to larger, more flexible aircraft?"")

A. Impact of the C-141A Loads Problem on the C-5A.

The designers of the C-5A are in the unusual but desirable position of having flight loads data available on a very similar configuration early in the development program. The problems which have developed on the C-141A have served the useful purpose of indicating the need for caution in establishing the loads for the C-5A airplane.

The major discrepancy between C-141A loads derived from the wind tunnel and those measured in flight is traceable to a farther aft wing shock location at high Mach numbers in the latter case. Furthermore, this effect is traceable, in turn, to differences between model scale and full-scale boundary layer flow conditions. The C-5A wing geometry is very similar to that of the C-141A as regards planform, including engine pylon locations, and profile. In full-scale flight it is anticipated that the shock-boundary layer interaction will not be sensitive to changes in Reynolds number. Because of the almost identical geometries, therefore, boundary layer conditions on the full-scale C-5A are expected to be essentially the same as for the flight-test C-141A.
It follows that the differences between the C-5A flight pressures and those obtained on a comparable wind-tunnel model may possibly prove nearly equal to the differences between C-141A flight and wind-tunnel pressures. Discrepancies between nacelle and pylon shapes, etc., of the two aircraft may vitiate this conclusion. Nevertheless, it should be possible to develop a rational method to correct C-5A wind tunnel data using the C-141A flight and wind tunnel results.

A second factor of interest is the structural weight penalty involved in designing for uncertainty about the wing shock location. Current Lockheed studies show that adding 187 lbs. to the C-141A structure will satisfactorily cope with the present unexpected C.P. shift. That is, the structural weight in this case is not very sensitive to the exact C.P. location. It appears therefore that loads data deduced as outlined in the preceding paragraph can be used in a conservative manner for C-5A design with very little weight penalty.

In view of the discrepancies between C-141A wind-tunnel and flight data, the committee addressed itself to the proposed C-5A wind-tunnel program pertaining to loads determination. Although there was no comprehensive review of the C-5A program, a few general remarks are in order. The inadequacy of current transonic testing techniques suggests the possibility of eliminating certain models or phases from the proposed C-5A wind tunnel schedule. It should be remembered, however, that pressure-distribution model test results are employed for many loading conditions other than those which are sensitive to the shock-boundary layer interaction. In view of this consideration and of the fact that all necessary loads data cannot possibly be determined from C-141A flight tests, it does not appear desirable to eliminate wind-tunnel loads test from the C-5A program.

During the meeting it was suggested to the committee that an addition to the C-5A wind tunnel program may be required. The C-141A wind tunnel data have already shown the strong effect of Reynolds number on shock wave location and wing pitching moment at zero lift. These tests also indicated that shock wave location and wing pitching moment at zero lift (\(C_{m_0}\)) are different when the transition is fixed or is free on the model; however, this difference reduces with increasing Reynolds Number. If these results are extrapolated it would appear that the difference between fixed and free transition would become very small at a Reynolds number of approximately 15 to 20 million. Also the value of \(C_{m_0}\) would closely agree with C-141 flight test results.

For this reason it is recommended that consideration be given to building a large semi-span wing pressure distribution model of the C-5A for the AEDC 16 Foot PWT. The Reynolds number from such a test should fall in the 15 to 20 million range and provide data which could be correlated with full span model tests run in the same tunnel at Reynolds numbers of 6 to 8 million. These results could also provide a link between wind tunnel and flight Reynolds number which would have application toward the development of improved wind tunnel techniques.
There was an indication in the presentations made to the committee that a flexible static loads model would be used in the C-5A program. The data presented concerning the C-141A indicated that flexibility did not play an important role in the flight-wind tunnel discrepancies. Although a flexible dynamic model might be required for solutions to other problems (such as gust loads) it would appear that the requirements for a flexible model to handle the essentially static loads problem considered in this review has not been justified.

Returning to the subject of C-141A flight tests pertinent to the C-5A development, the committee emphasizes the importance of reconsidering such additional flight testing to obtain better loads data. Improvement is needed in the spacing of the chordwise pressure taps to ensure the accuracy and adequacy of information on shock location.

In addition, consideration should be given to the possible interference effects associated with the use of strip-a-tube pressure instrumentation. For example, experience on the X-21 indicated that the strip should be laid along local flow streamlines rather than in a chordwise direction and that it was desirable to provide fairings for the edges of the strip. Naturally the X-21 wing had a much thinner (laminar) boundary layer than the C-141A, so that application of X-21 results must recognize such differences. Nevertheless, it is recommended that such questions be reviewed before the configuration of tubing for the flight tests is fixed.

B. Considerations of Other Future Aircraft, Applied Research and Advanced Development.

The subject loads problem on the C-141A has clearly indicated that full-scale supercritical pressure distributions on the wings of subsonic cruise aircraft may not at present be reliably predicted by wind tunnel tests. Such discrepancies are possible, even for the highest Reynolds numbers obtainable, on the basis of techniques and models utilized thus far. The committee strongly urges that a substantial effort be made to resolve this difficulty, not only because of its influence on the C-141A or C-5A loads, but also because of its impact on satisfactory prediction of loads, stability and performance for all future aircraft of this type.

It is recommended that the knowledge and background obtained on the C-141A program be used as the basis for further experimental and theoretical studies in the near future. Both flight and wind-tunnel results obtained to date on this airplane have defined the problem area. Additional flight tests with augmented pressure instrumentation in the area of shock wave-boundary layer interaction, at each of the existing wing spanwise locations, would provide improved shock-location data and thus a full-scale basis for evolving tunnel techniques and theory. Both flight and wind-tunnel articles are currently available for this airplane and could be used with minimum expenditure in time and money.
Since the problem occurs within the speed regime of other aircraft of similar configuration, the committee believes that other manufacturers have encountered similar difficulties. It is recommended that a review of flight loads survey data obtained under Air Force programs be compared to the theoretical full scale loads as developed from wind tunnels, etc., to obtain additional useful background information and data appropriate to future research.

If such measurements are not already available, (cf. earlier work on the B-47 and B-52), it is recommended that full-scale pressure data be gathered from flight tests of another large subsonic aircraft having wing sweep and airfoil sections different from the C-141A. A related recent occurrence during transonic and low supersonic operation of the XB-70 should be investigated. All such work will provide a broader full-scale base for solution of the problem.

As regards research in ground facilities, it seems apparent that the discrepancy between wind-tunnel and flight pressure distributions is caused primarily by differences of the relative momentum thickness of the boundary layer ahead of the shock wave, although nacelle-pylon influence may also play a large part in some cases. Further research must therefore be carried out in an attempt to simulate in a wind tunnel the relative thickness of this layer as it exists on the airplane. The best method for accomplishing this end is not obvious at present. It may require the use of vortex generators or boundary layer suction.

Concurrent with the development of improved experimental techniques, the available theories for mixed subsonic-supersonic flow over wings and airfoils must be carefully studied to determine their applicability to the present problem. Further work on more comprehensive theories, which include three-dimensional effects and, hopefully, the influence of the boundary layer, should be initiated.

The need for larger wind tunnel test facilities for obtaining results at higher Reynolds numbers was discussed. The conclusions were that, at the present time, this does not appear to be a feasible solution to the problem.

Acknowledgement: Special appreciation is expressed by the Committee for the technical assistance and analysis provided by Mr. Warren Stauffer of Lockheed-California, as an adjunct to the presentations made by the staff of Lockheed-Georgia Corporation.

Mr. P.P. Antonatos
Mr. Irving Ashkenas
Mr. Howard Chevalier
Mr. Philip Donely
Mr. U.A. Hinders
Dr. J.C. Houbolt
Mr. R.H. Klepinger
Mr. A.C. Rainey
Dr. R.T. Whitcomb
Dr. Holt Ashley, SAB and DAG, Chairman
**CHARTER**  
1 November 1965

**DIVISION ADVISORY GROUP**

Special Committee on C-141 Air Loads Problem

1. **General**

   The C-141 is a high speed cargo transport aircraft powered by four Pratt & Whitney TF33-P-7 engines, each developing 21,000 lbs of thrust. The airplane is designed to serve as a cargo transport over the MATS World-Wide route structure. The airplane was designed to meet both military and civil (FAA) requirements. Development was started in 1961 by the Lockheed-Georgia Corporation. First flight was accomplished in December 1963. At the present time approximately 55 aircraft have been delivered to the Air Force. During the development period, a comprehensive wind tunnel program was accomplished. Concurrently structural development tests were conducted. At the present time, static testing of a complete airplane specimen is in progress. It was during the flight loads investigation that a discrepancy between design loads and actual loads was revealed. The correlation was quite good in the lower Mach number range but diverged at Mach numbers in excess of 0.8. Particularly critical at this time is an outboard and aft shift of the center of pressure on the wing. Specifics of the problem and possible corrections will be thoroughly briefed during the forthcoming meeting.

2. **Mission**

   The purpose of the DAG meeting on 12-13 November will be to investigate and to provide answers to the following three questions:

   a. Were techniques used for establishment of loads from wind tunnel test data the best possible?

   b. Is the present course of action planned for the C-141 adequate?

   c. Is additional theoretical work required to account for this phenomenon when applied to larger, more flexible aircraft?

   In addition, the reactions, comments, and suggestions of the committee are solicited as to program approaches, research, advanced development and design, and engineering criteria that will assure improvement in future aircraft design and development.
3. **Membership**

**Chairman**

Dr. Holt Ashley, M.I.T., ASD DAG (SAB)

**NASA**

Mr. Philip Donley, Langley Research Center

Mr. A.G. Rainey, Langley Research Center

Dr. R.T. Whitcomb, Langley Research Center

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Mr. Irving Ashkenas, Systems Technology Inc.

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Mr. U.A. Hinders, Systems Engineering Group, RTD

Mr. Richard Klepinger, Systems Engineering Group, RTD

Mr. P.P. Antonatos, Flight Dynamics Lab, RTD
C-141 AIR LOADS PROBLEM

AGENDA

FRIDAY - 12 Nov 65

0900 Welcome and Introduction
0915 Wind Tunnel Data
1015 Coffee Break
1030 Flight Test Results
1130 Structural Test Results
1230 Lunch
1400 Future Plans
1500 Detailed Discussion

SATURDAY - 13 Nov 65

0900 Executive Session
1200 Lunch
1330 Executive Session

All presentations by Lockheed-Georgia personnel.