ARMY AIR FORCES
AIR TECHNICAL SERVICE COMMAND
ENGINEERING DIVISION
MEMORANDUM REPORT ON

FER/efd

SUBJECT: Principles of Cockpit Seating.

Date: 28 February 1946

SECTION: Aero Medical Laboratory

Contract No.
Expenditure Order No. 695-49
Purchase Order No.

SERIAL NO. TSEAA-695-58C

A. Purpose:

1. To present a study of seating requirements for the pilot position in all types of military aircraft.

B. Factual Data:

2. The subject study is one of a series committed to the determination of the fundamental seating and position requirements of flying personnel in the various crew positions of military aircraft. The necessity for these studies becomes obvious when the human being is regarded as that essential part of flying equipment which cannot be redesigned or modified in any way, despite the purpose, but is rather to be accommodated in every way where his comfort, efficiency, and safety demand.

3. Reference is made to an earlier report which is a study of the seating and positioning requirements of pilots of aircraft in which a stick-type control column is used, ATSC Memorandum Report No. TSEAL-3-695-58, dated 25 September 1945, subject: "Principles of Seating in Fighter Type Aircraft". The present report may be considered to be supplemental to this earlier study, for it covers the position requirements of pilots of aircraft having the wheel-type control, and summarizes the results of both studies.

4. Ninety-five bomber pilots were used as subjects in the experiments described below. These men were chosen because of their experience with the wheel-type control. Certain anthropometric details concerning the subject bomber pilots are presented in Appendix I.

5. The subject study was broken down into five separate experiments which are distinguished by that dimension measured between the level of the heel rest during normal flying attitudes and the horizontal line of vision. It is always desirable in scientific experiments to have one independent variable. This dimension was selected to represent that variable for three notable reasons: first, because it is so easily controlled; secondly, because it is so fundamentally a determining factor in aircraft design, and, thirdly, because it has definite limits which depend upon the normal range of stature of flying personnel. Since it was learned during the study on fighter pilots that the limiting range of values for the heel-to-horizontal line of vision dimensions was 35 inches to 43 inches within current design practice, a range of values for this dimension at two inch intervals from 37 inches to 45 inches was chosen for the study on bomber pilots as being most commonly used in bomber designs. The shift in range by two inches was made because of the generally larger size of bomber pilots.

6. The results of the experiments conducted on pilot seating in aircraft with wheel control are presented in Appendix II, with a general summary and analysis in Appendix III.

7. An overall summary of seating in the pilot position of military aircraft, both wheel and stick type, is presented in Appendix IV.

8. A check list of certain critical seat and cockpit dimensions, based on the results of studies on fighter and bomber pilots and on current advices from the Design Branch, Aircraft Laboratory, Engineering Division, Air Technical Service Command, is presented in Appendix V.

C. Conclusions

9. The fundamental requirements of pilot seating in aircraft have been determined and have been found to be dependent upon cockpit level (vertical distance from horizontal line of vision to level of heel rest) and the type of manual control mechanism used (wheel or stick). Comfort requirements have been determined to be dependent upon the same factors and also upon seat angulation, differential support of the body over the seat contour and the positioning of the rudder pedals and control column with respect to the seat.

10. In order that standardization of cockpit and seat dimensions for any type of aircraft may be effected, it is necessary first that the maximum allowable dimensional requirements for equipment worn under and in back of the pilot be fixed.

D. Recommendations

11. That the Aircraft Laboratory, Aircraft and Physical Requirements Sub-Division, Engineering Division, Air Technical Service Command, establish criteria in the Handbook of Instructions for Aircraft Designers for various acceptable cockpit designs based on the fundamental variable of the vertical distance from the heel rest to the horizontal line of vision.

Note:- Information contained in this report is offered as information only and is not mandatory on any contract or purchase order.

Concurrence: J. W. HEIM
Technical Assistant

Prepared by: Donald J. Patt
DONALD J. PATT, 1st Lt., AC

Prepared by: Francis E. Randall
FRANCIS E. RANDALL, Capt., AC

Distribution: (See Page 3)

Prepared by:
LOYD A. GRIFFIS, Colonel, MC
Chief, Aero Medical Laboratory

Approved by: Bruce B. Price
BRUCE B. PRICE, Colonel, AC
Actg. Chief, Aircraft and Physical Rqmts. Sub-Div

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Research Division, Aviation Branch, Bureau of Medicine and Surgery, Navy Dept., Washington, D. C., 238 "E" Street, N. W., Attn: Lt.Merle Lawrence, S(A-1).
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APPENDIX I

Anthropometric Analysis of Subjects

Lockbourne bomber pilots were used as subjects for the experiments throughout, mainly because of their experience, which proved highly valuable in many respects, and also because they are a selected group with respect to temperament and body build—selected through the regular channels of cadet and primary training and combat. They are thus representative of bomber pilots as a whole.

A breakdown of the pilot subjects according to the experiments in which they were used is presented in Table I. It will be noted that there are deviations from the mean in each group, but corrections for these were made before the final results were presented.

The subjects were procured from Lockbourne Army Air Base and Smyrna Army Air Base. Their combat experience was about equally divided between B-17's (48) and B-24's (46), with one being pilot of a B-26.

Table I
Size Analysis of Subjects

Group	No.	Stature (Inches) Average	Range	Weight Average	(Pounds) Range
Exp. 1 (37" Cockpit)	20	70.1	67.1-74.2	162.5	136-204
Exp. 2 (39" Cockpit)	20	70.7	64.5-75.7	165.3	133-200
Exp. 3 (41" Cockpit)	20	69.5	66.5-72.6	158.1	141-197
Exp. 4 (43" Cockpit)	20	69.6	64.6-73.4	160.8	121-211
Exp. 5 (45" Cockpit)	15	70.5	66.3-74.3	157.5	131-173
Overall of Above	95	70.1	64.5-75.7	161.0	121-211
Aviation Cadets*	2960	69.4	62.5-78.0	154.3	110-210

*Reference: Engineering Division Memorandum Report No. ENG-M-49-695-4C, dated 5 October 1942, subject: "Anthropometric Data on Army Air Forces Personnel".

APPENDIX II

Seating Requirements in Pilot Position of Aircraft with Wheel Control

Ninety-five subjects were divided into five groups; one group for each of five experiments. The experiments were differentiated by the value selected for the dimension measured from the level of heel rest of the seated pilot to his horizontal line of vision, the values selected being 37, 39, 41, 43, and 45 inches. Henceforth these values will be termed "cockpit levels".

Each pilot, adjusted vertically to the preselected cockpit level, was first permitted to select the seating arrangement which he found to be the most satisfactory from the standpoint of comfort and efficiency and then was required to sit in the cockpit of his choice and to operate the controls for as long as to four hours as he remained comfortable. Whether or not the selected position was operationally an efficient one was determined by the subject, who, in every case, was a returnee bomber pilot. If signs of discomfort appeared, readjustment of the seating arrangements was made to restore comfort.

Records were made of all adjustments, contours, time intervals, and subjects' comments and an average for each dimension was determined from those arrangements which provided the pilots with operational comfort for the longest time interval.

Cockpit profile drawings, showing the seating and position requirements for each cockpit level, are presented in Appendix II, as figures 1, 2, 3, 4, and 5. Profiles of the average contours at three-inch intervals from the midline to a plane nine inches lateral of the midline are shown for each cockpit level in Appendix II, as figures 1a, 2a, 3a, 4a, and 5a. The space requirements for the latest personal equipment are also included in the cockpit drawings.

There are a few important points which should be noted by way of explanation of the cockpit profile drawings.

1. The dimensions of each cockpit are based on the cockpit level, the fixed vertical distance from the heel rest level to the horizontal line of vision.

2. All dimensions are given as average or, in instances where adjustability is involved, representative of mid-adjustments. The amount of adjustability which should be included in certain dimensions in order to accommodate all sizes of flying personnel are indicated by a ± value.

3. The seven-inch range of adjustability called for in the horizontal dimension may best be provided by four inches in rudder pedals and three inches fore-and-aft seat adjustability. The latter should be so effected that the full aft position may be attained with the seat full down, and the full forward position with the seat full up.

4. The amount of fore-and-aft travel of the control wheel has been arbitrarily set at 15 inches. However, certain restrictive values have been determined:

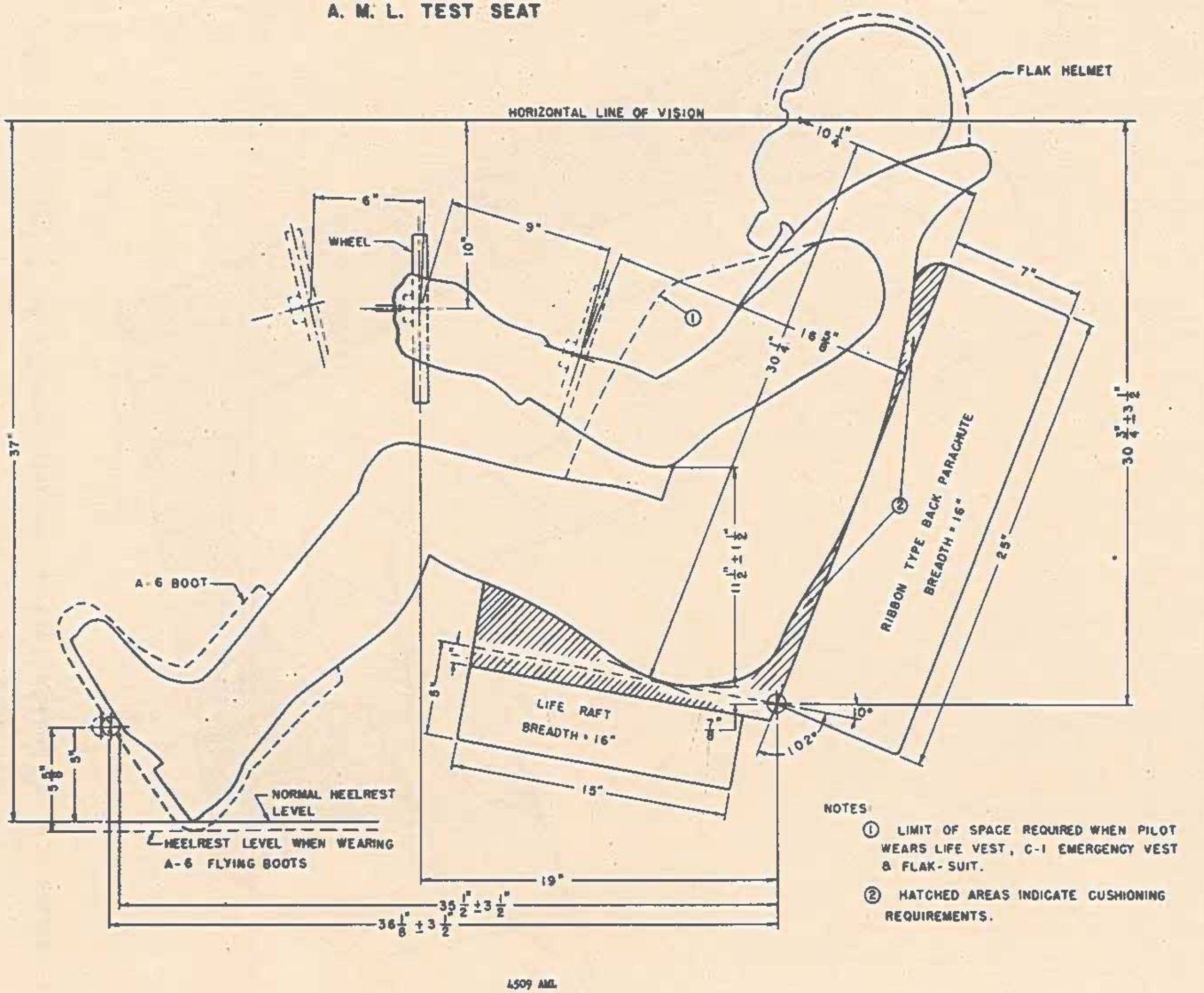
   a. The distance between the vertical components of the seat reference point and the centerline of the hand grip of the wheel at neutral position should in no case be less than 17 and 1/2 inches or greater than 20 and 1/2 inches. When the seat is at fore-aft mid-adjustment, this value should be 19 inches.

   b. The maximum allowable amount of travel of the wheel aft of neutral is 9 inches.

5. The seat and back angles given on the subject drawings are not necessarily the true or functional angles required by the pilot, but are rather the angles which are required if the shape and dimensions of the personal equipment and cushioning between the pilot and the seat are the same as pictured in the drawings. The important feature of the seat to be observed in this respect is the spatial relationship of the actual sitting surface to the seat reference point. The cushioning, personal equipment, and seat should be so integrated as to hold the pilot in the position shown, regardless of what seat and back angles may be required to attain this end.

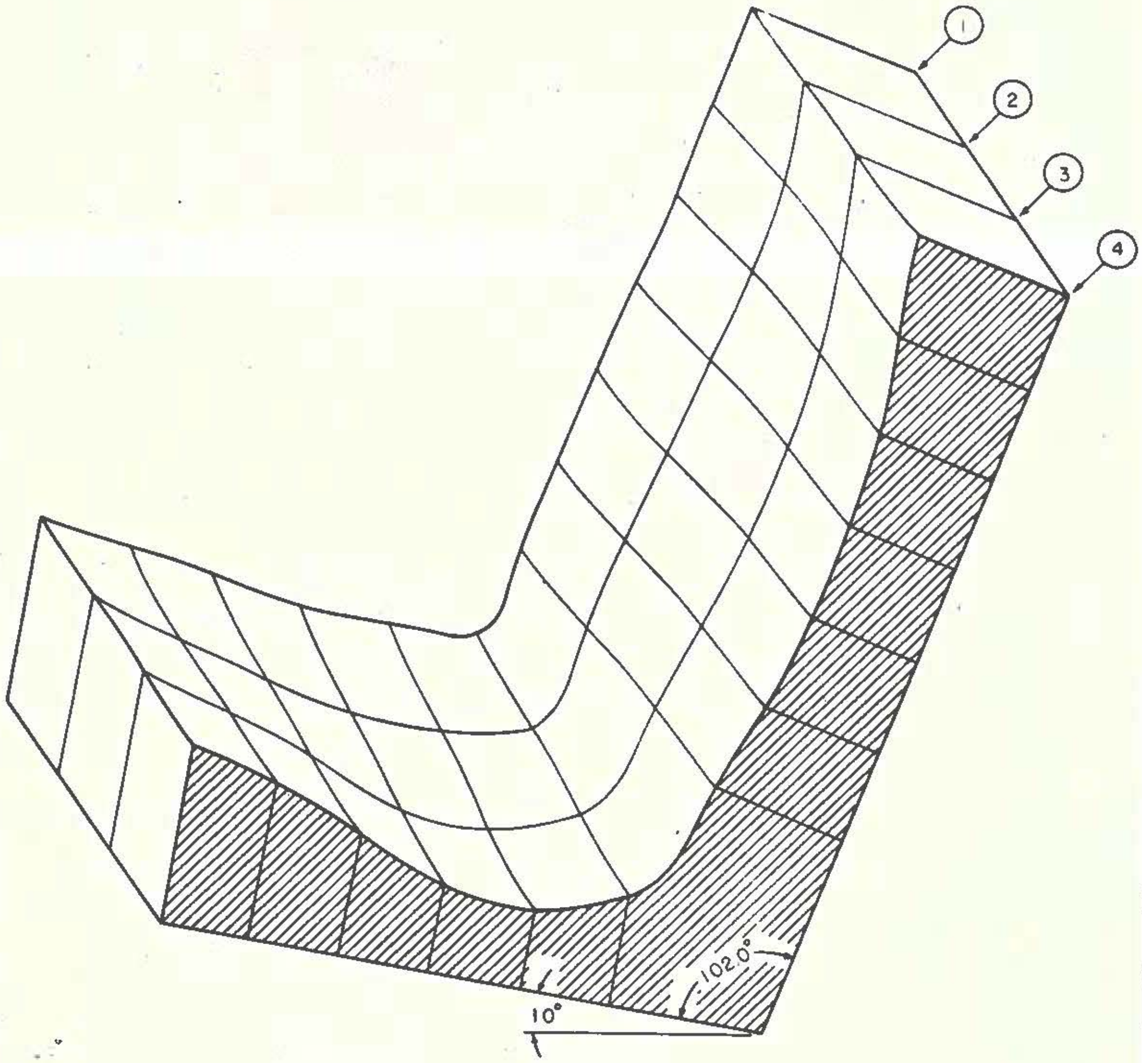
AVERAGE POSITION OF SEAT IN 37" BOMBER COCKPIT

A. M. L. TEST SEAT



APPENDIX II

Figure 1.

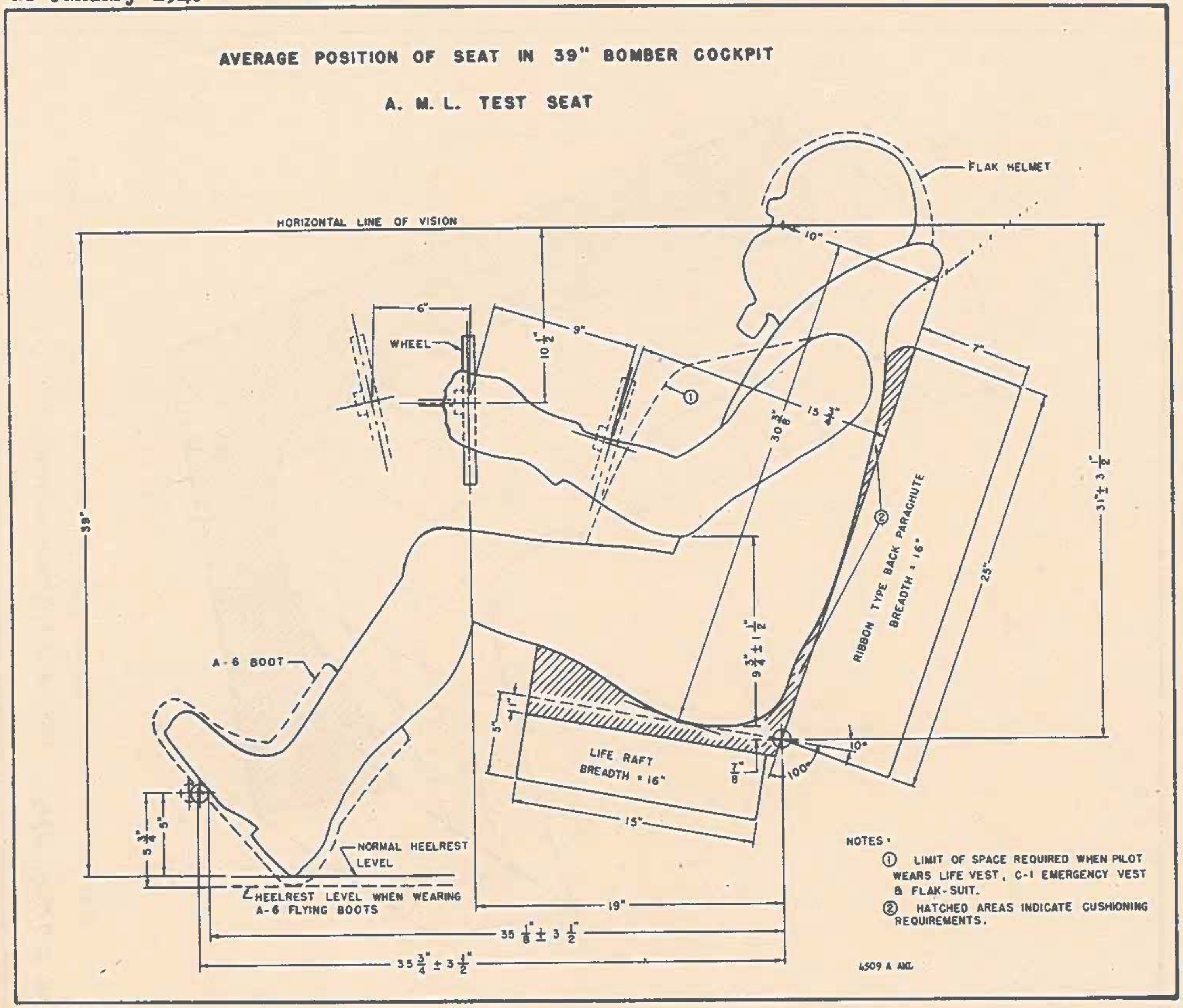


SEAT SECTION FOR 37" BOMBER COCKPIT, SHOWING PROFILES AT ℄ (4) AND AT THREE INCH INTERVALS LATERALLY (3) - (2) & (1).

4477-D. A.M.L.

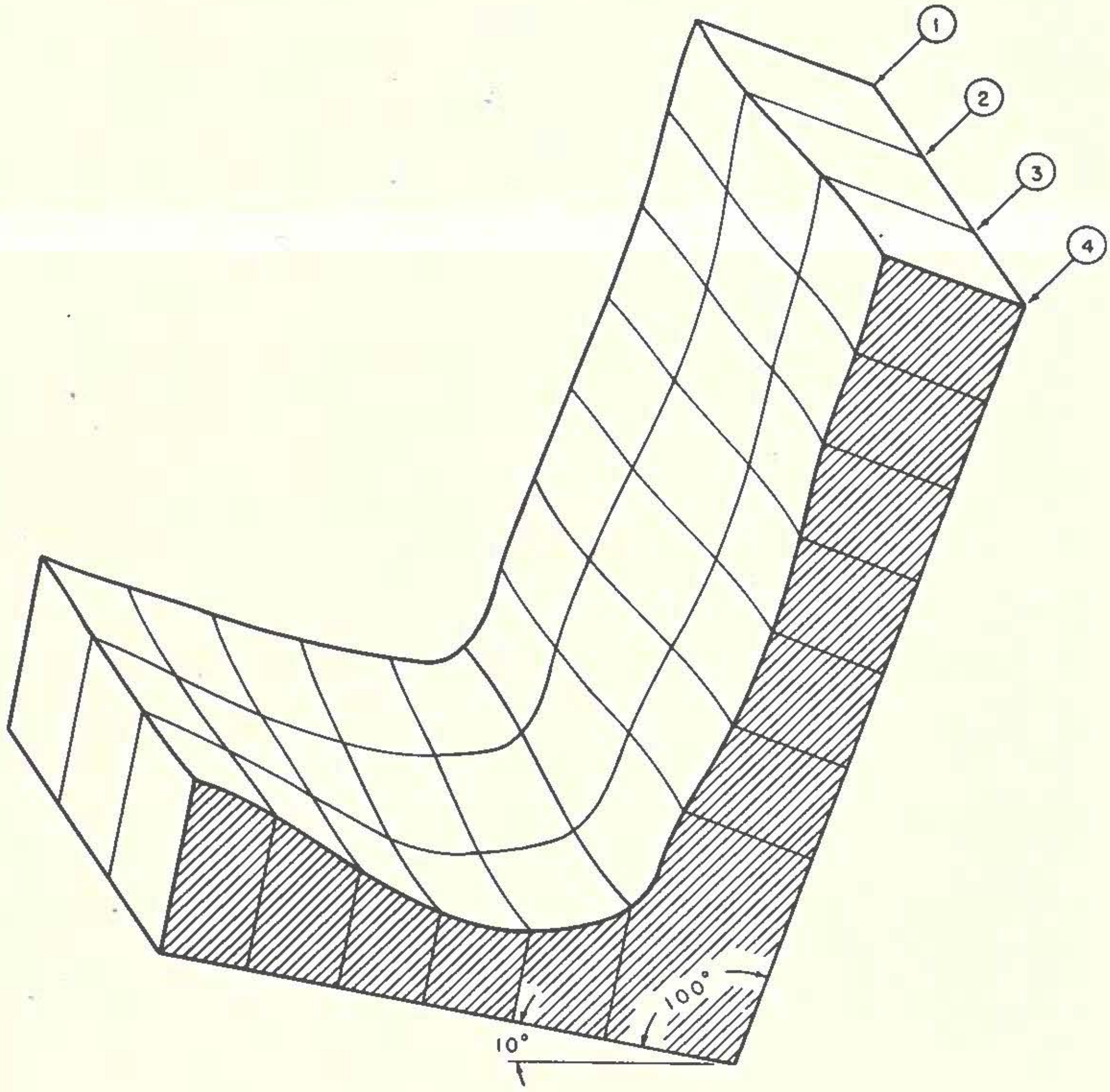
APPENDIX

Figure II, 1a.



Appendix II

Figure 2



SEAT SECTION FOR 39" BOMBER COCKPIT, SHOWING PROFILES AT ℄ (4) AND AT THREE INCH INTERVALS LATERALLY (3) - (2) & (1).

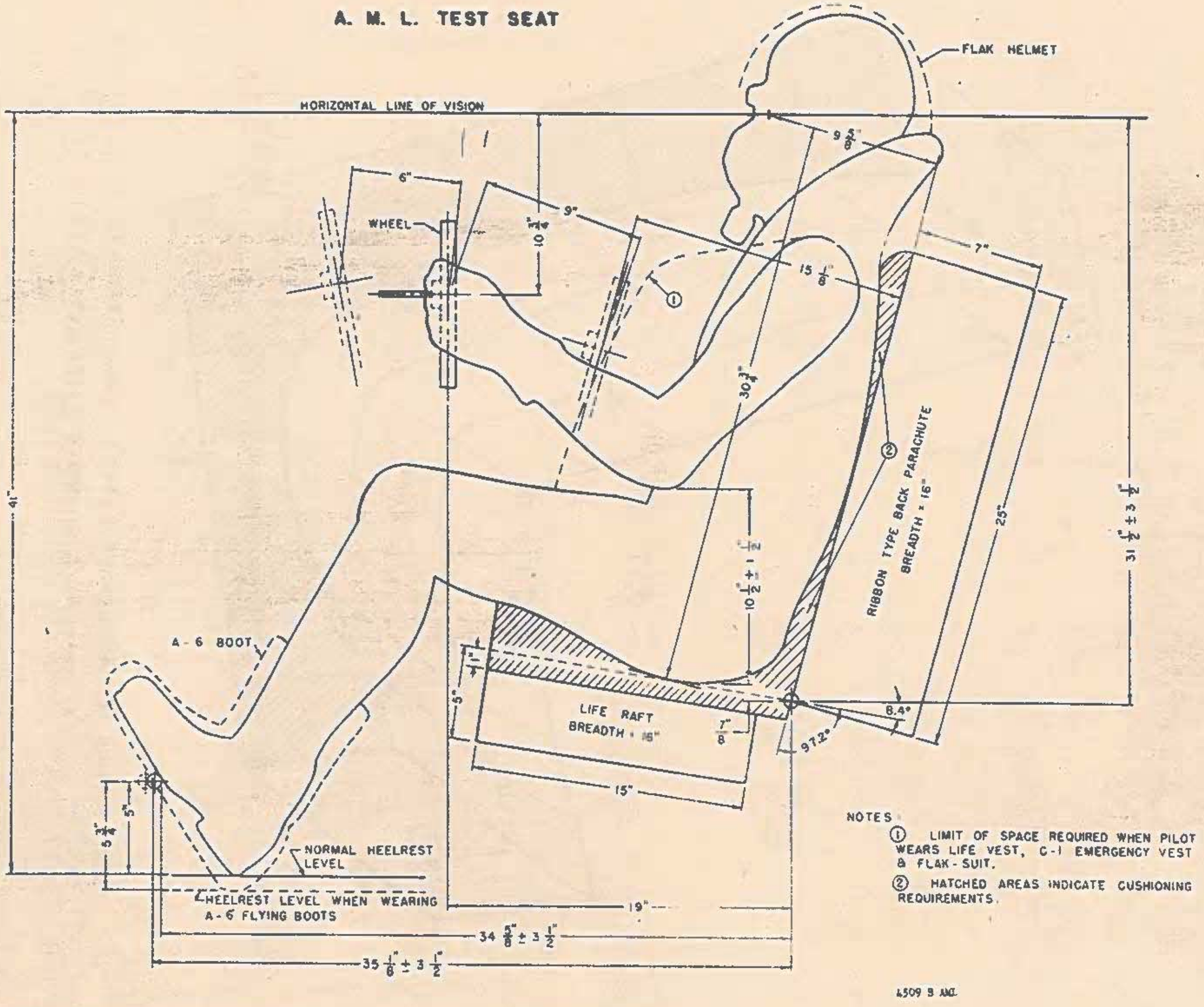
4477-C. AML.

APPENDIX II

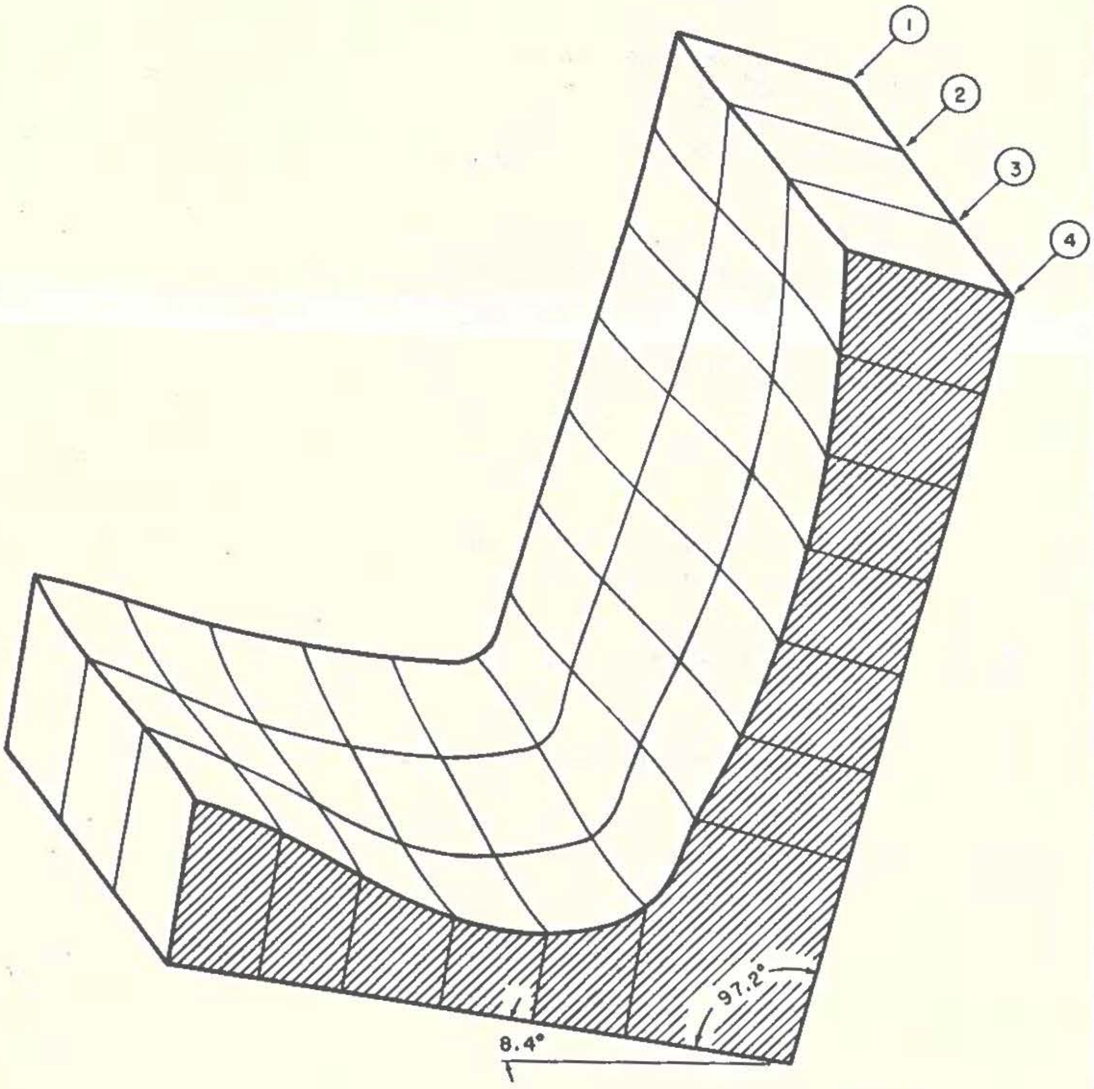
Figure II, 2a

AVERAGE POSITION OF SEAT IN 41" BOMBER COCKPIT

A. M. L. TEST SEAT



Appendix   Figure 3.

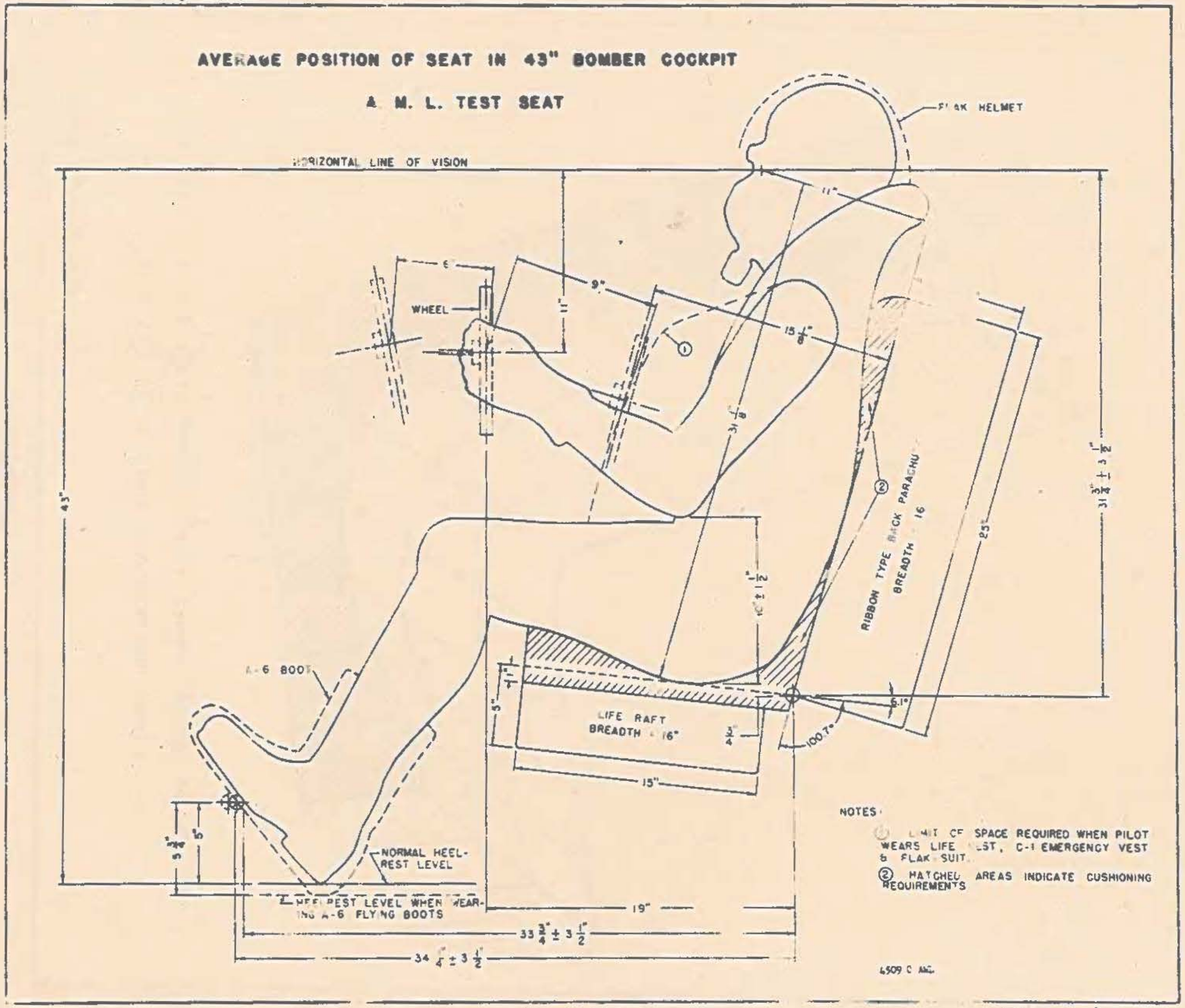


SEAT SECTION FOR 41" BOMBER COCKPIT, SHOWING PROFILES AT ℄ (4) AND AT THREE INCH INTERVALS LATERALLY (3) - (2) & (1).

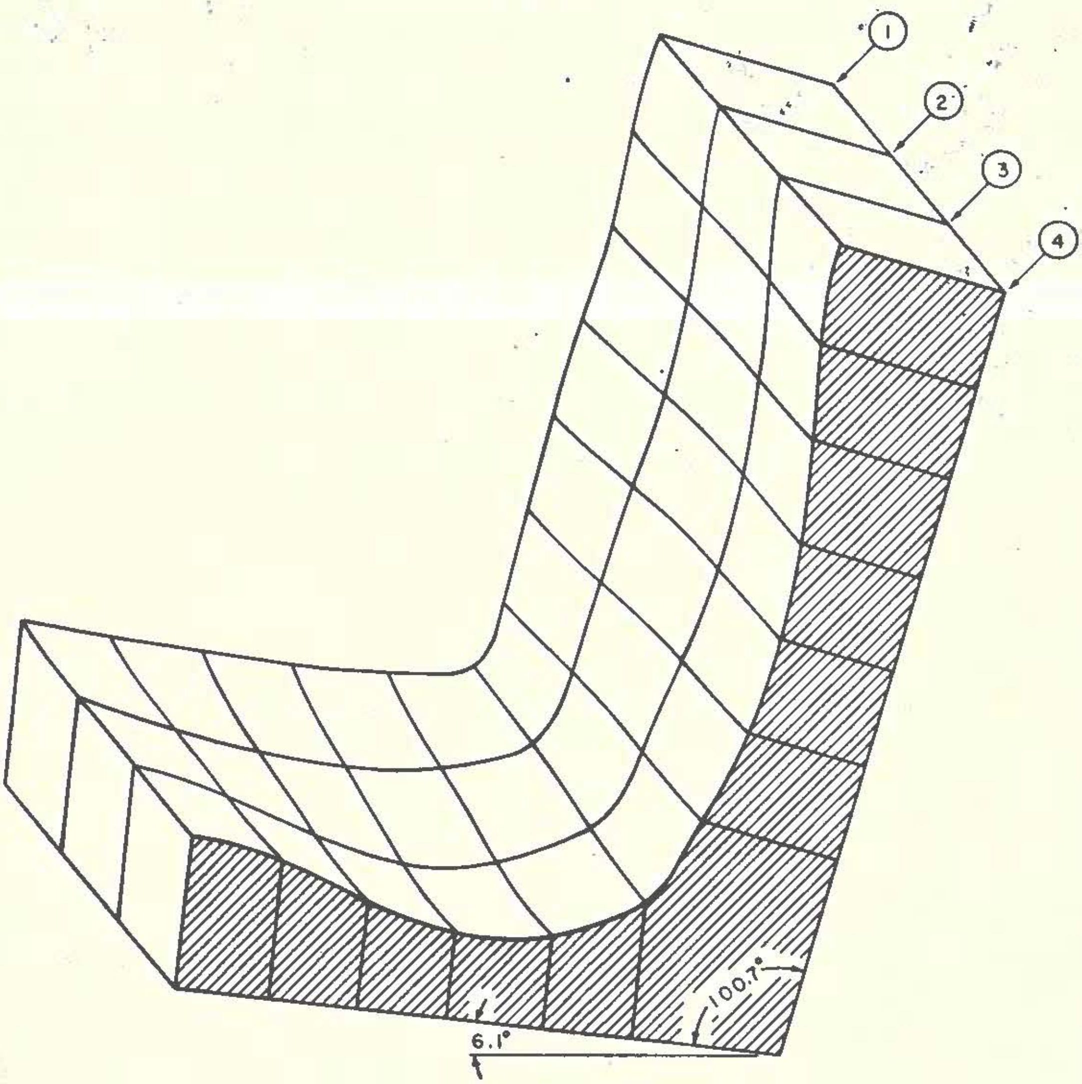
4477-B. AML.

APPENDIX II

Figure II, 3a.



Appendix 1 Figure 4.

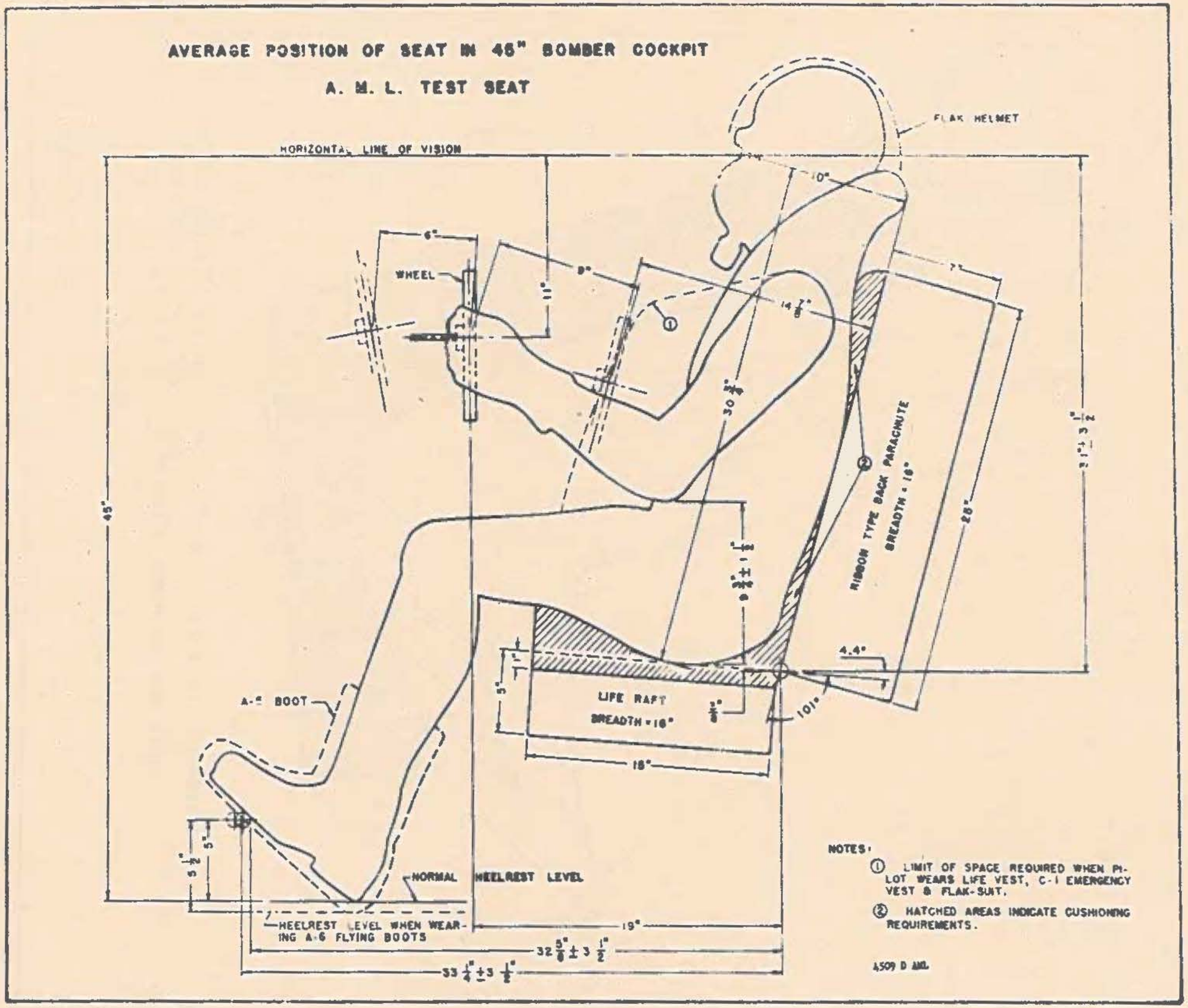


SEAT SECTION FOR 43" BOMBER COCKPIT, SHOWING PROFILES AT ℄ (4) AND AT THREE INCH INTERVALS LATERALLY (3) - (2) & (1).

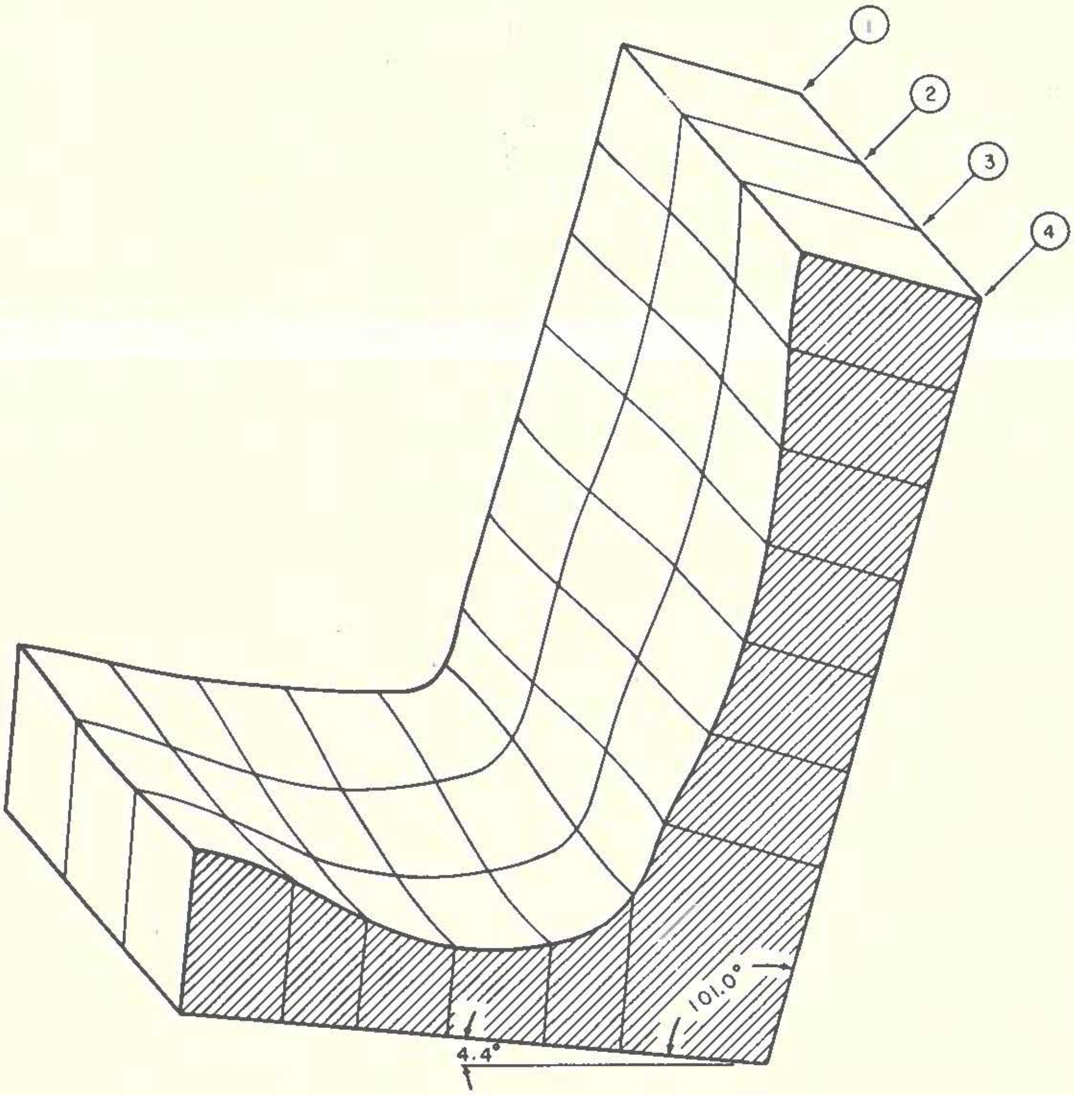
4477-A. A.M.L.

APPENDIX II

Figure II, 4a.



Appendix II Figure 5.



SEAT SECTION FOR 45" BOMBER COCKPIT, SHOWING PROFILES AT ℄ (4) AND AT THREE INCH INTERVALS LATERALLY (3) - (2) & (1).

4477 A.M.L.

APPENDIX II

Figure II, 5a.

APPENDIX III

Theoretical Aspects of Pilot Seating in Bombardment Type Aircraft

The dimension measured between the heel rest level and the horizontal line of vision is the fundamental variable which determines cockpit design insofar as the pilot's positioning is concerned. This appendix will be devoted to tracing the changes which the other cockpit dimensions undergo when the cockpit level is changed, and to demonstrating any correlations which may exist.

If comparison is made between the results obtained in the course of the subject experiments and those obtained in the study on fighter cockpits, several minor discrepancies will be noted, when, presumably, there should be none. There are certain facts, however, which should be considered at this time because they will explain these discrepancies.

First of all, the bomber pilots averaged one and one-half inches taller in stature and ten pounds heavier in weight than the fighter pilots. It follows, therefore, that the thighs, and the buttocks, are larger and the back broader in the bomber pilots. It is a simple matter to correct for stature in the subject studies, but it is both difficult and impractical to correct for weight and those differences in contour which are enforced by the differences in size and form of the thighs, buttocks, and back. The heavier pilots sink deeper into the seat and so there is an apparent loss in sitting height when it is measured from the reference point of the seat. Whether or not corrections should be made for all these factors is debatable and cannot be definitely determined until it is known what selection criteria will be used by the Army Air Forces in the future. At present, the tendency is to select the smaller men for fighters, all else being equal, leaving the generally larger men for bombers. As long as this tendency holds, there is no need to make corrections for the above factors, except by providing slightly deeper cushioning to tolerate the two groups.

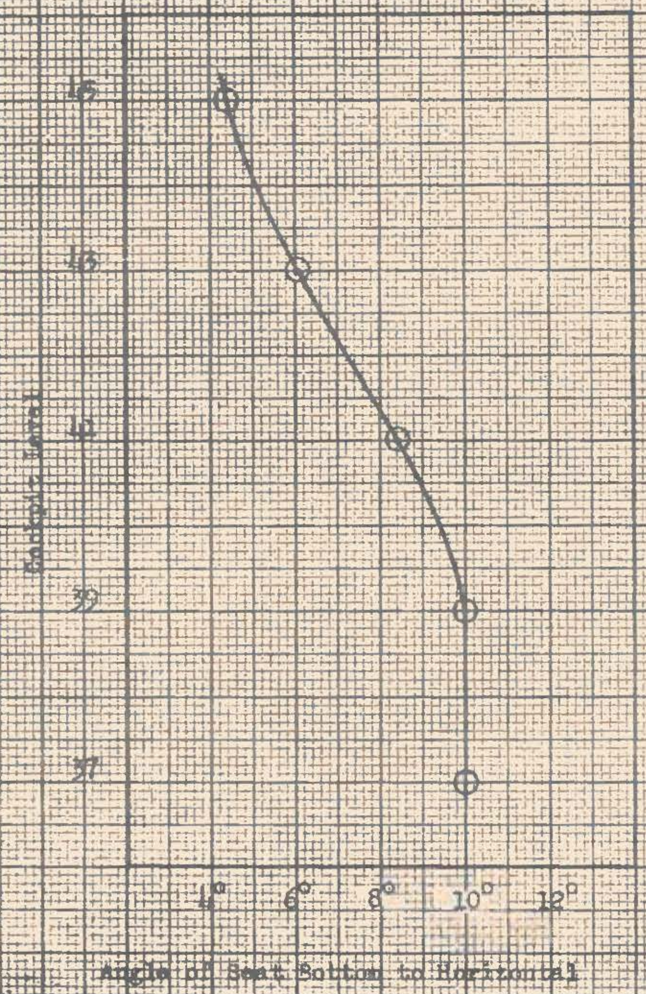
Reference is made to Figures 1a, 2a, 3a, 4a, and 5a, Appendix II, which show the contours which were determined for each of the cockpit levels. These contours are not passive ones, but dynamic, for they represent the contour of the body when it is held in a comfortable, working state by means of differential weight support. Were the contour passive, there would be no rise in the lower portion of the back, for that is the flexible portion of the body which tends to bow out when support is lacking. That support is needed in the lower back is a well known fact. The contours presented here show both the precise location and the amount of the support required. The same applies to other portions of the seating surface as well, though less strikingly. Further examination of the contours will reveal that there is little variation from the basic contour among the different cockpit levels. The upper portion of the back contour is such as to show that the shoulders should be held slightly forward in order to maintain the head and neck in balance, preventing fatigue of the large muscles in the shoulders and neck.

It has been found that the angle of the bottom portion of the seat is one of the important determining factors of seat comfort. This study has shown that, when the seat is low relative to the position of the heels, a rather large angle of upward tilt of the front edge of the seat is necessary for comfort. As the vertical distance of the seat from the heel level increases, this angle decreases (Appendix III, Figures 1a, 1b.). The range of seat angles determined for the cockpit levels studied extends from 10° at the 37" level to 4.4° at the 45" level.

In the determination of back angles, it was found that there was considerable spread about the mean in each cockpit studied. The interpretation for this is that there is a relatively high amount of variability in the skeleton, and thereby a variation in the adaptability among individuals to accommodate for a range of back angles in the order of 2° on either side of the mean. Obviously, however, the mean values are the most reliable, so the sequence of back angles plotted against the cockpit levels and the height of the buttocks from the heel level is shown in Appendix III, Figures 2a and 2b. The relationship appears to be linear, indicating that the back angle must decrease as the cockpit level increases. This is probably indicative of a requirement for a more erect sitting position at higher levels in order to maintain the body in a state of balance while looking forward horizontally.

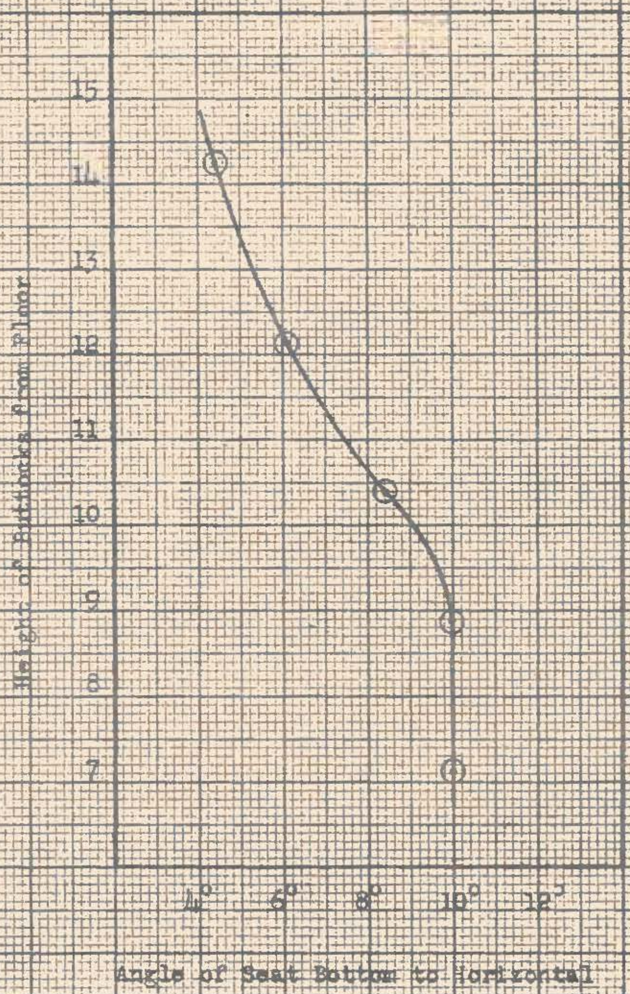
The graph of the seat-to-rudder pedal dimension in relation to the cockpit levels indicates that the higher the individual sits, the closer the pedals are in a horizontal distance from the seat. Appendix III, Figure 3. The values given are means. In order to accommodate for different leg lengths at any single cockpit level, a range of adjustability of 3 and 1/2 inches either side of the mean must be provided. Of this range, ±1 and 1/2 inches may be provided for by fore-and-aft adjustability of the seat, and ±2 inches by the pedals.

APPENDIX III



RELATIONSHIP OF SEAT BOTTOM TO COCKPIT LEVEL

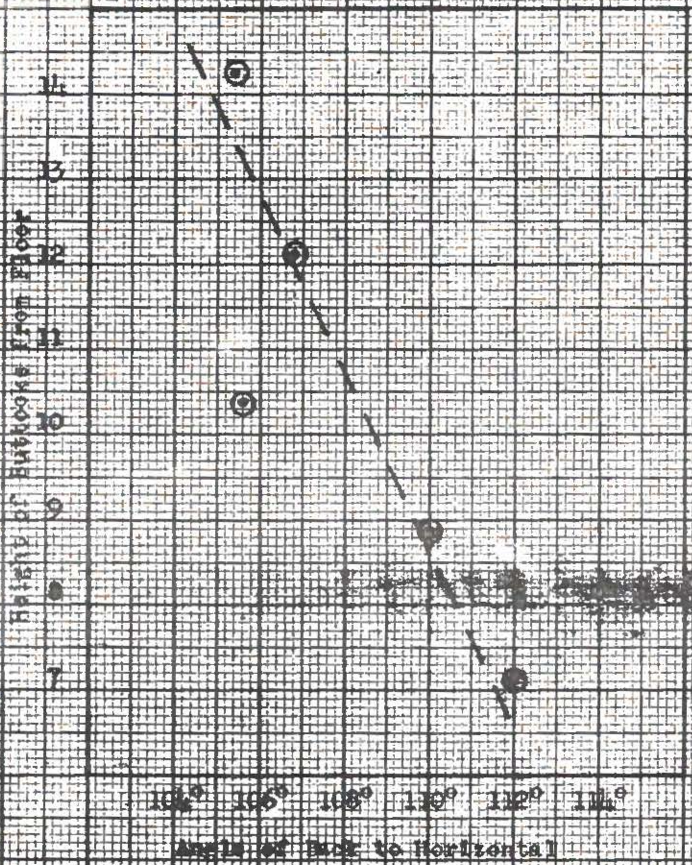
Figure 1a



RELATIONSHIP OF SEAT BOTTOM TO BUTTOCK HEIGHT

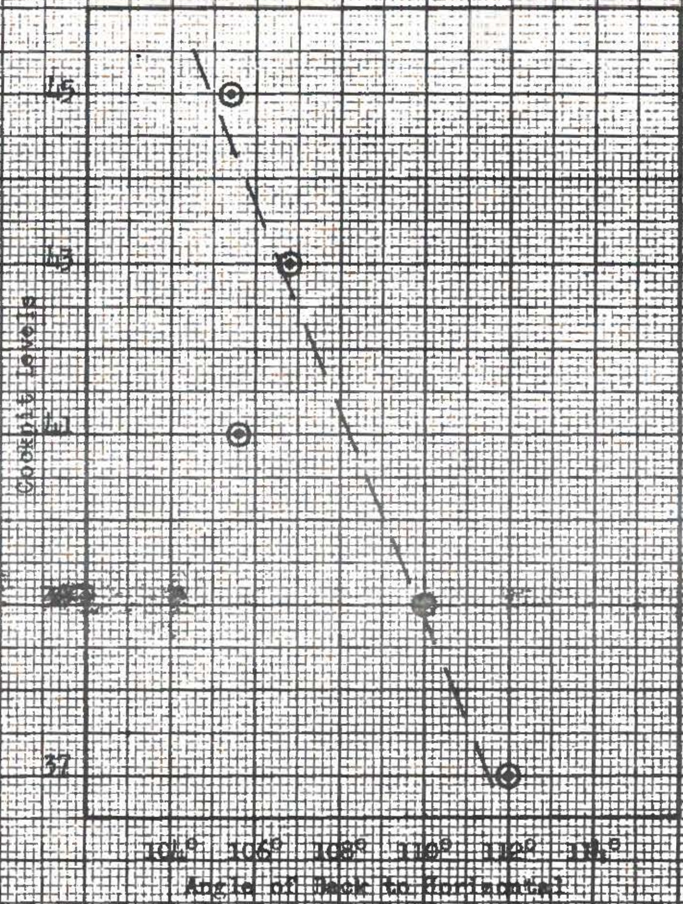
Figure 1b

APPENDIX III



RELATIONSHIP
between
BACK ANGLES AND BUTTOCK HEIGHT

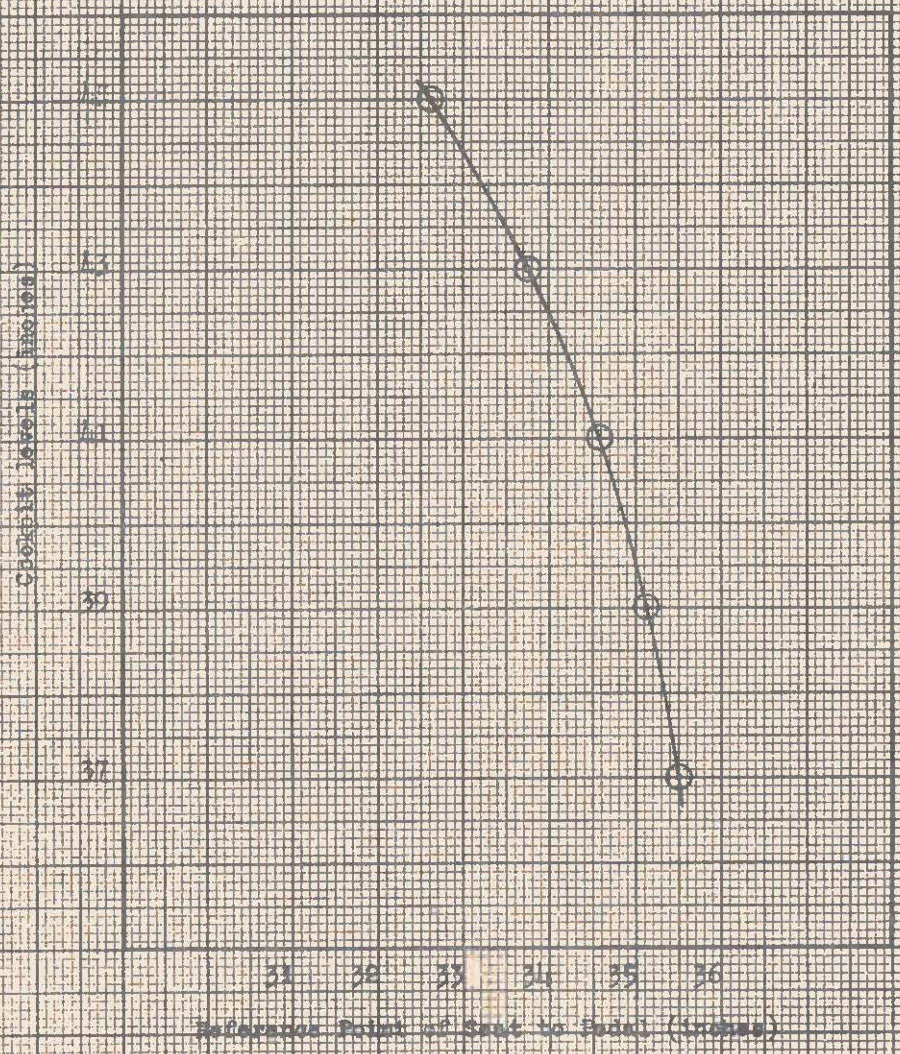
Figure 2a



RELATIONSHIP
between
BACK ANGLES AND COCKPIT LEVELS

Figure 2b

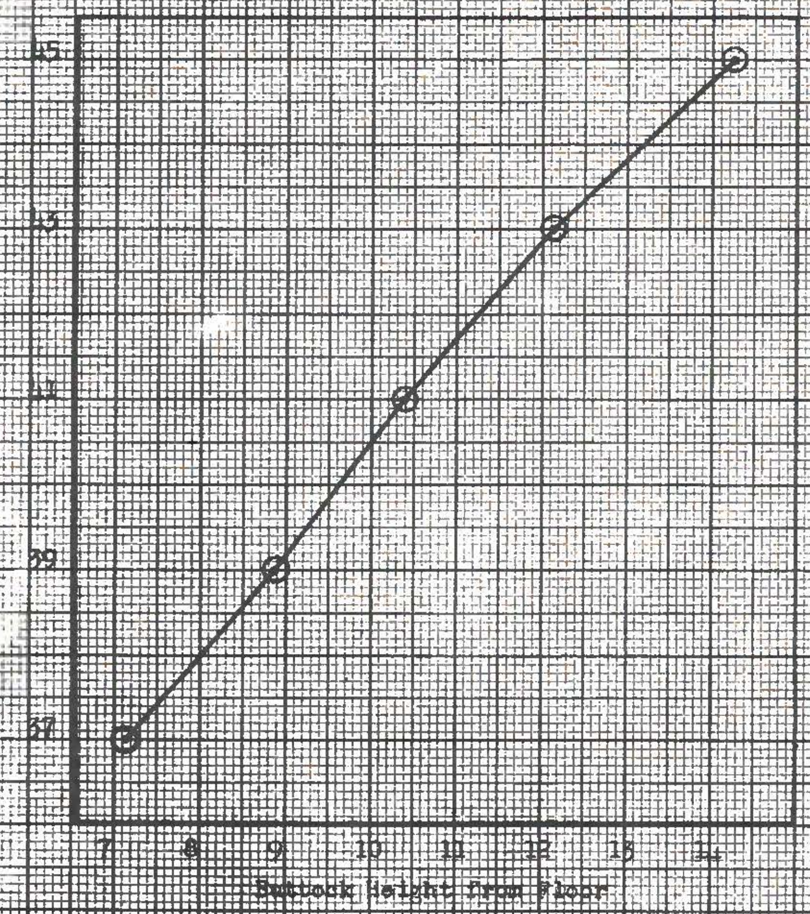
APPENDIX III



RELATIONSHIP OF SEAT TO RUDDER PEDALS AT VAR-
IOUS COCKPIT LEVELS

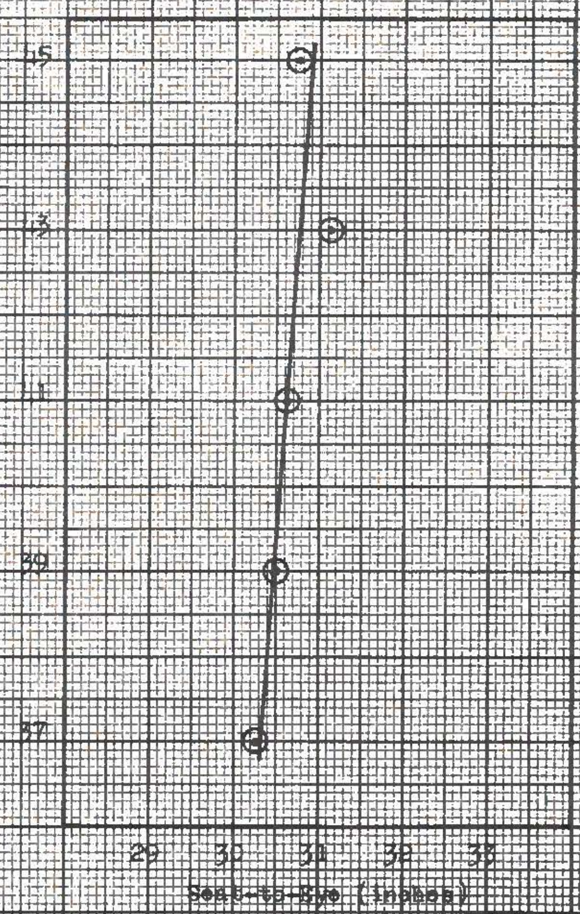
Figure 3.

APPENDIX III



RELATIONSHIP OF COCKPIT LEVEL TO BUTTOCK HEIGHT FROM FLOOR

Figure 4



RELATIONSHIP OF COCKPIT LEVEL AND SEAT-TO-EYE DISTANCES

Figure 5

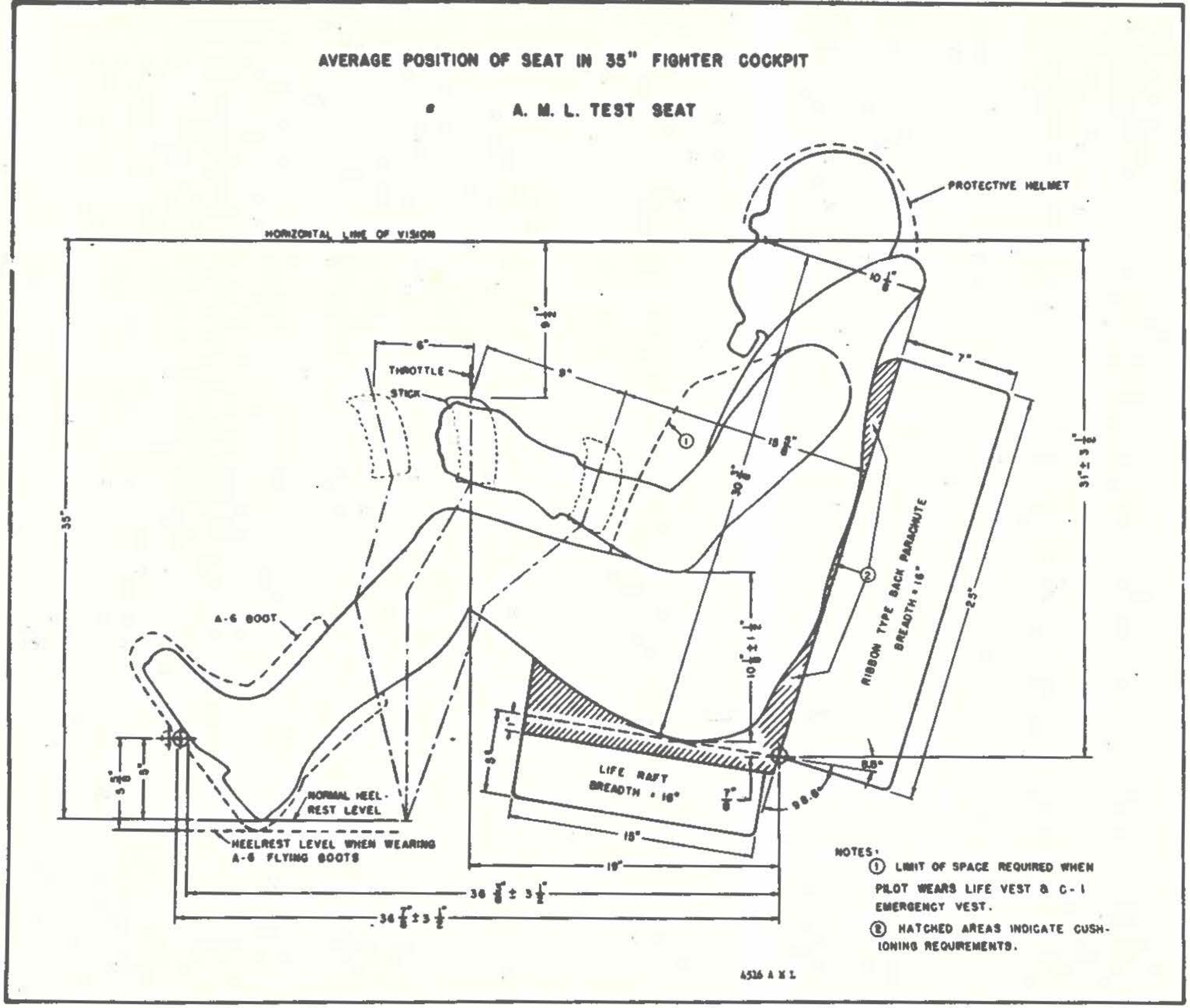
APPENDIX IV

Summary of Pilot Position Requirements in Stick-type and Wheel-type Control Systems

The report referred to above on studies of the stick-type control, fighter pilots, and their related cockpits, presented only those data directly related to pilot position. With the addition of further data regarding space requirements of personal equipment, it is now possible to add the complete pilot-personal equipment requirements. These data are presented, in addition to those for the wheel-type, in Appendix III, as new diagrams for the stick-type system in Appendix IV, Figures 1, 2, 3, 4, and 5.

In summary, it may be stated that any pilot may have to pilot any aircraft, and consequently all aircraft, so far as the seating of the pilot is concerned, must include adequate provisions for him and his personal equipment. Consequently, there are only two types of cockpits currently possible, one with stick and one with wheel. This approach will apply to definition of all cockpits; trainer, combat, and transport.

Finally, all cockpits must include provisions for the space requirements of personal equipment utilized in accomplishing the missions of the aircraft. The maximum values are given in the figures referred to.

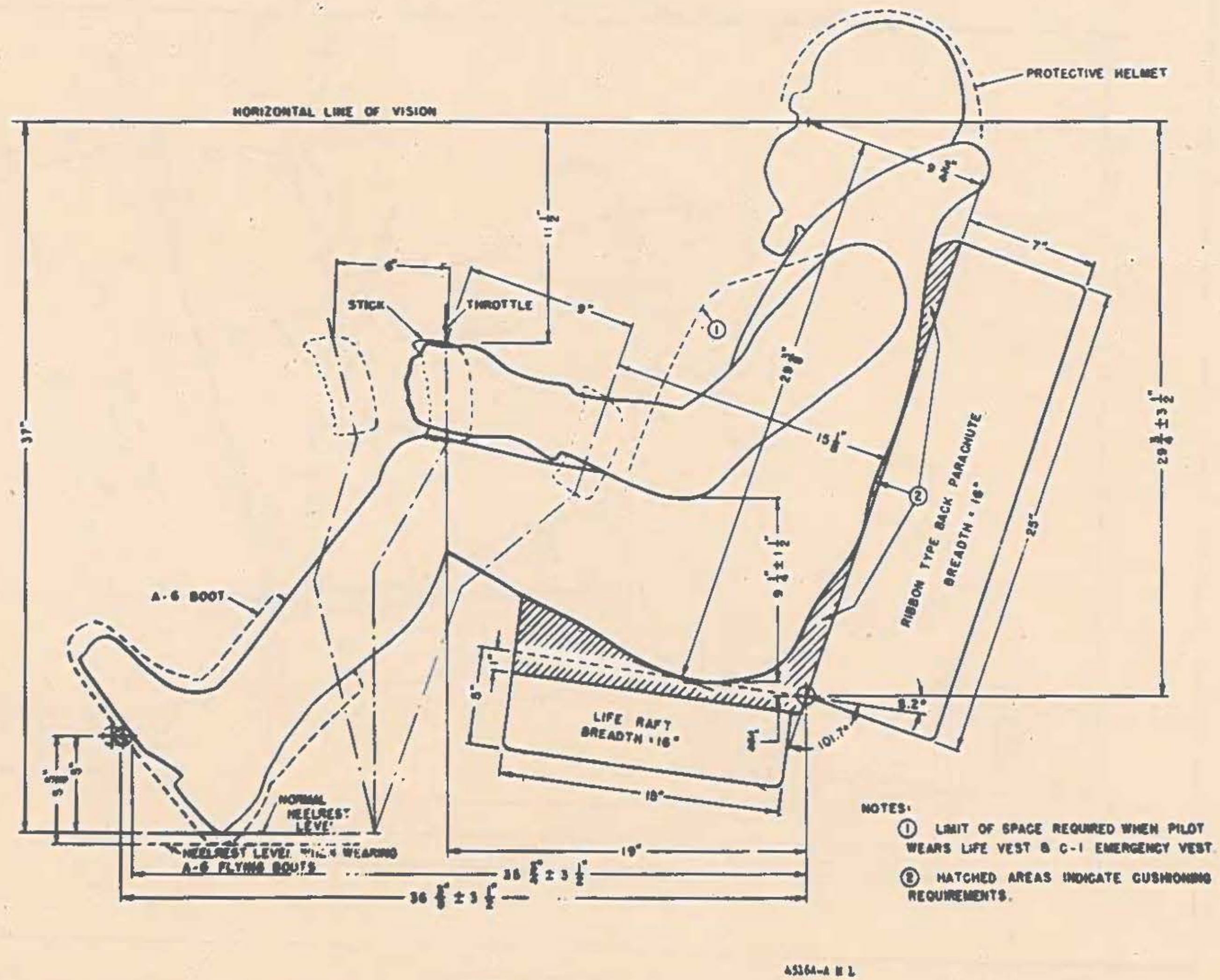


APPENDIX IV

Figure 1.

AVERAGE POSITION OF SEAT IN 37" FIGHTER COCKPIT

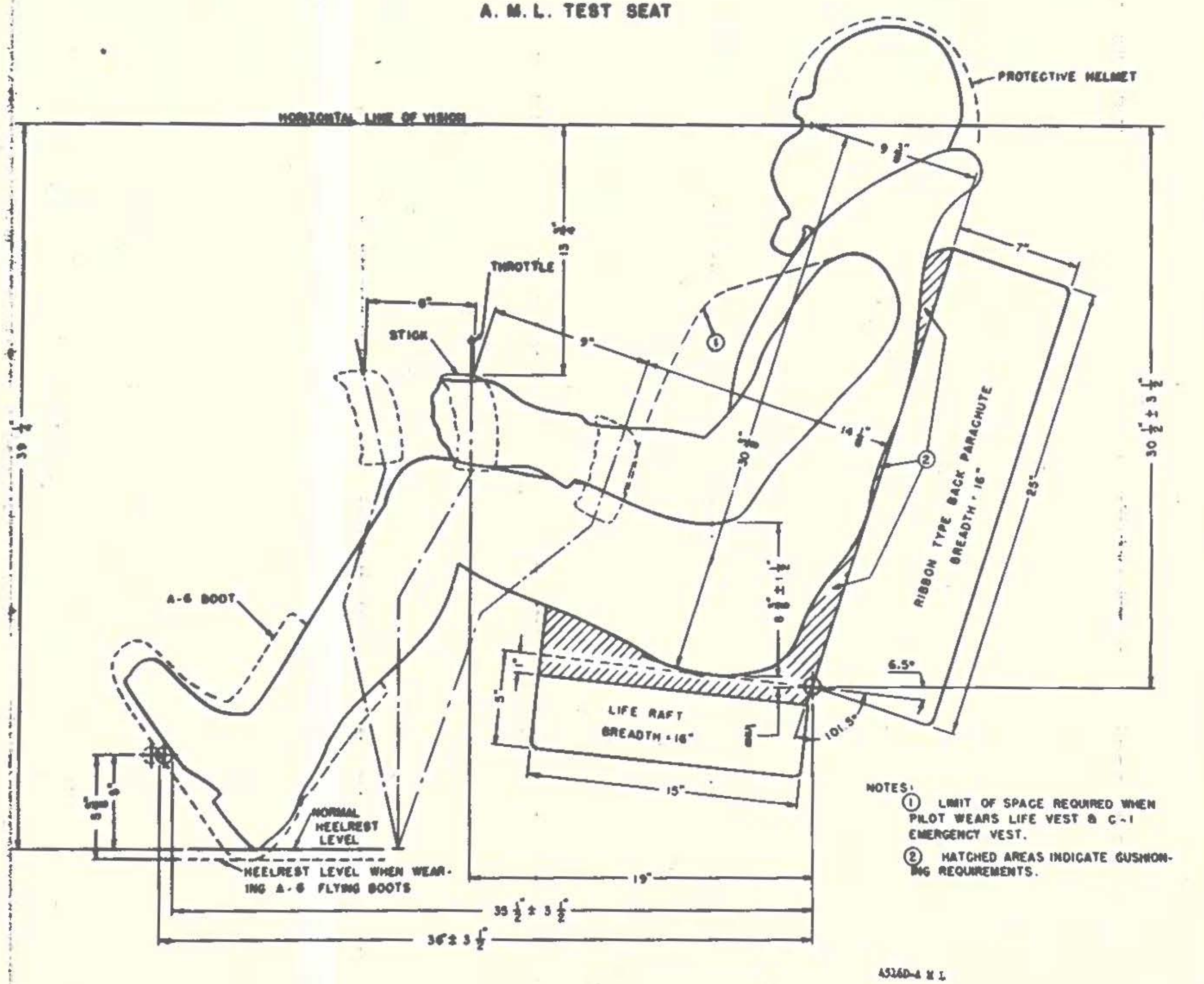
A. M. L. TEST SEAT



APPENDIX IV Figure 2

AVERAGE POSITION OF SEAT IN 39¼" FIGHTER COCKPIT

A. M. L. TEST SEAT

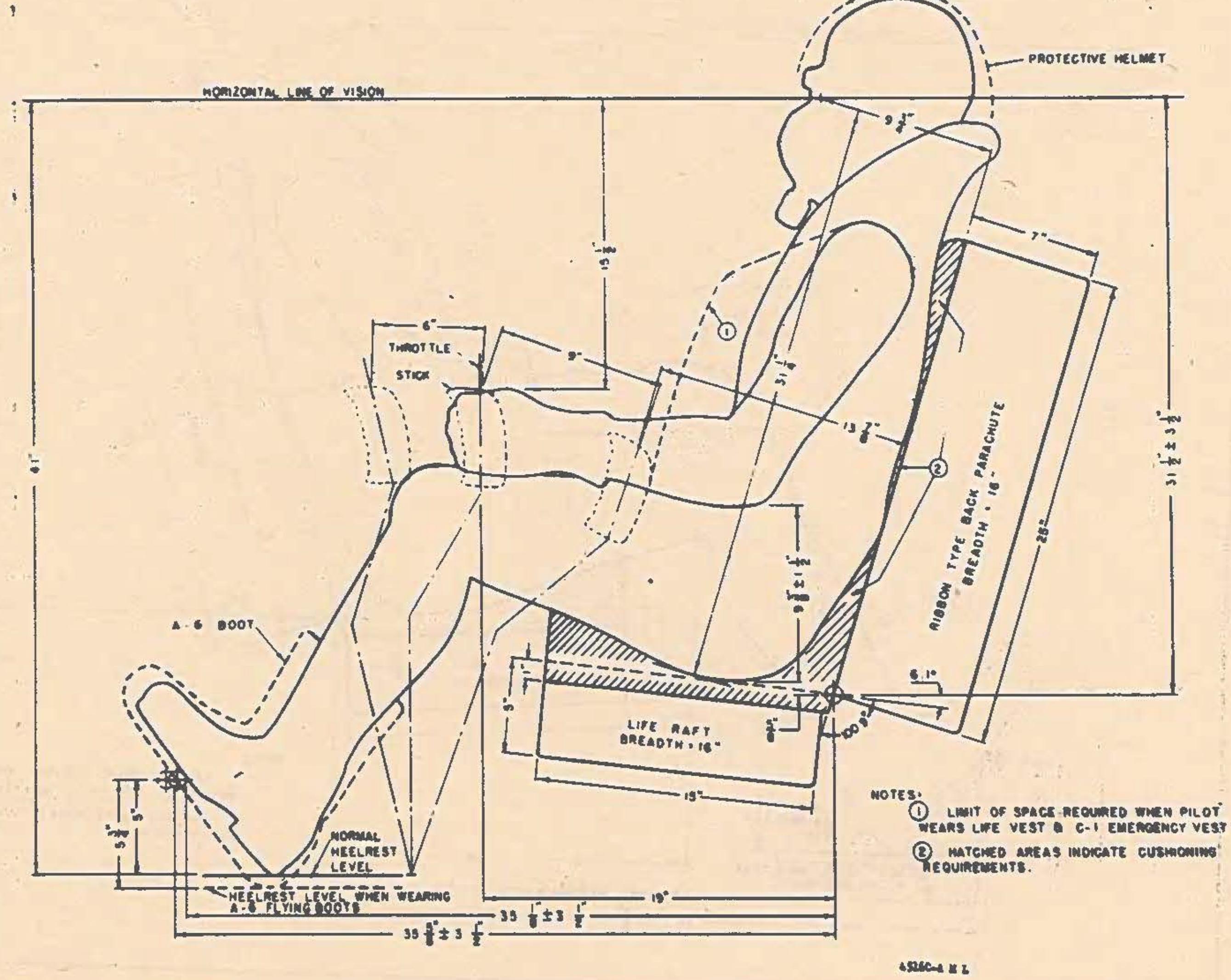


APPENDIX IV

Figure 3

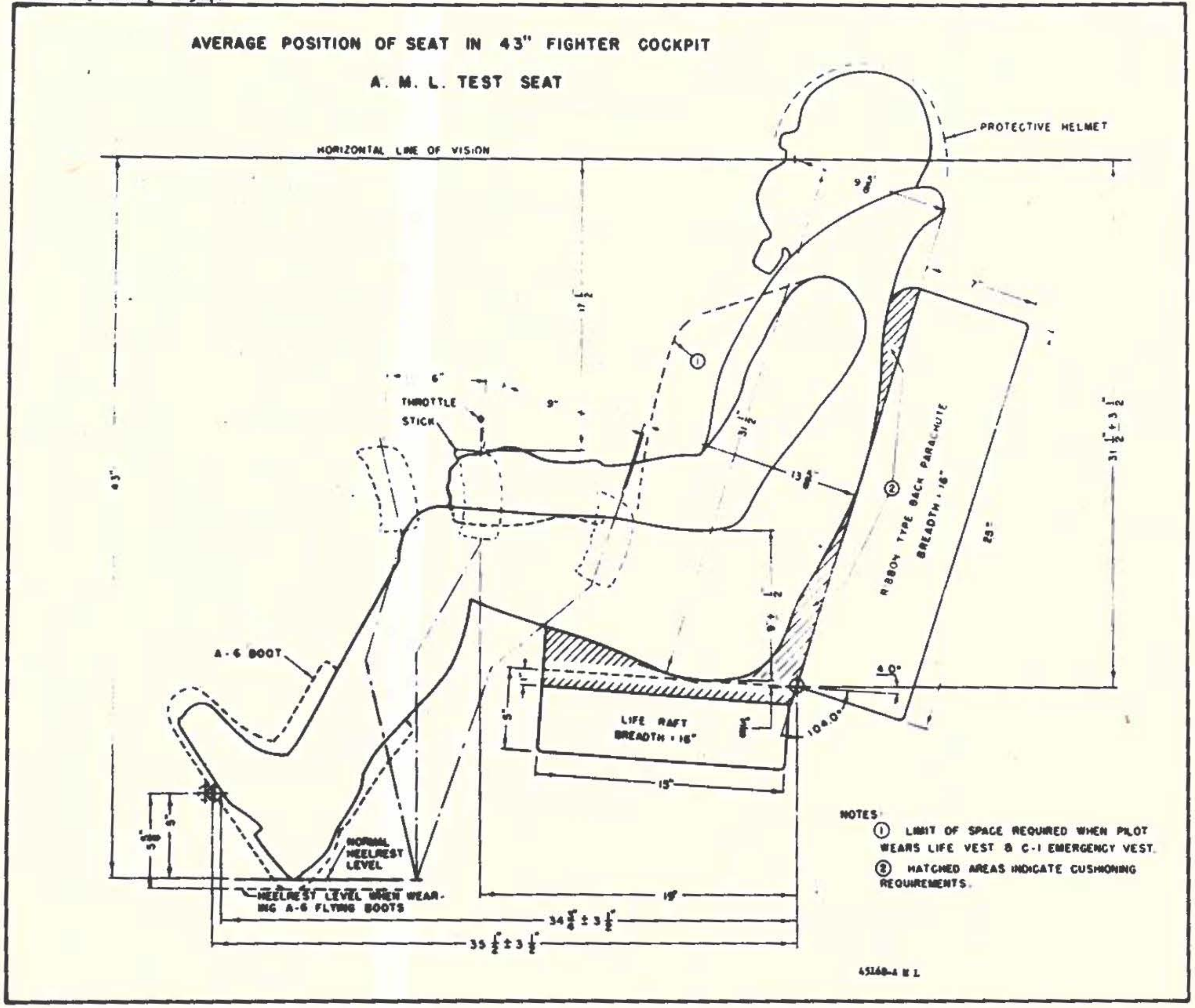
AVERAGE POSITION OF SEAT IN 41" FIGHTER COCKPIT

A. M. L. TEST SEAT



APPENDIX IV

Figure 4



APPENDIX IV

Figure 5.

APPENDIX V

Required Cockpit Dimensions for Stick and Wheel Type Controls

As referred to in Appendix IV, there are fundamentally only two types of cockpits which are required, both fitting all pilots equally well. In order to facilitate reference to required dimensions for these types, Figure 1, Appendix V, is a compilation of all dimensions for the different levels (heel level to horizontal line of vision) for both.

The method of presentation is such that it may easily be used for inspection purposes and for installation requirements in official literature.

HUMAN DIMENSIONAL REQUIREMENTS IN AIRCRAFT COCKPITS

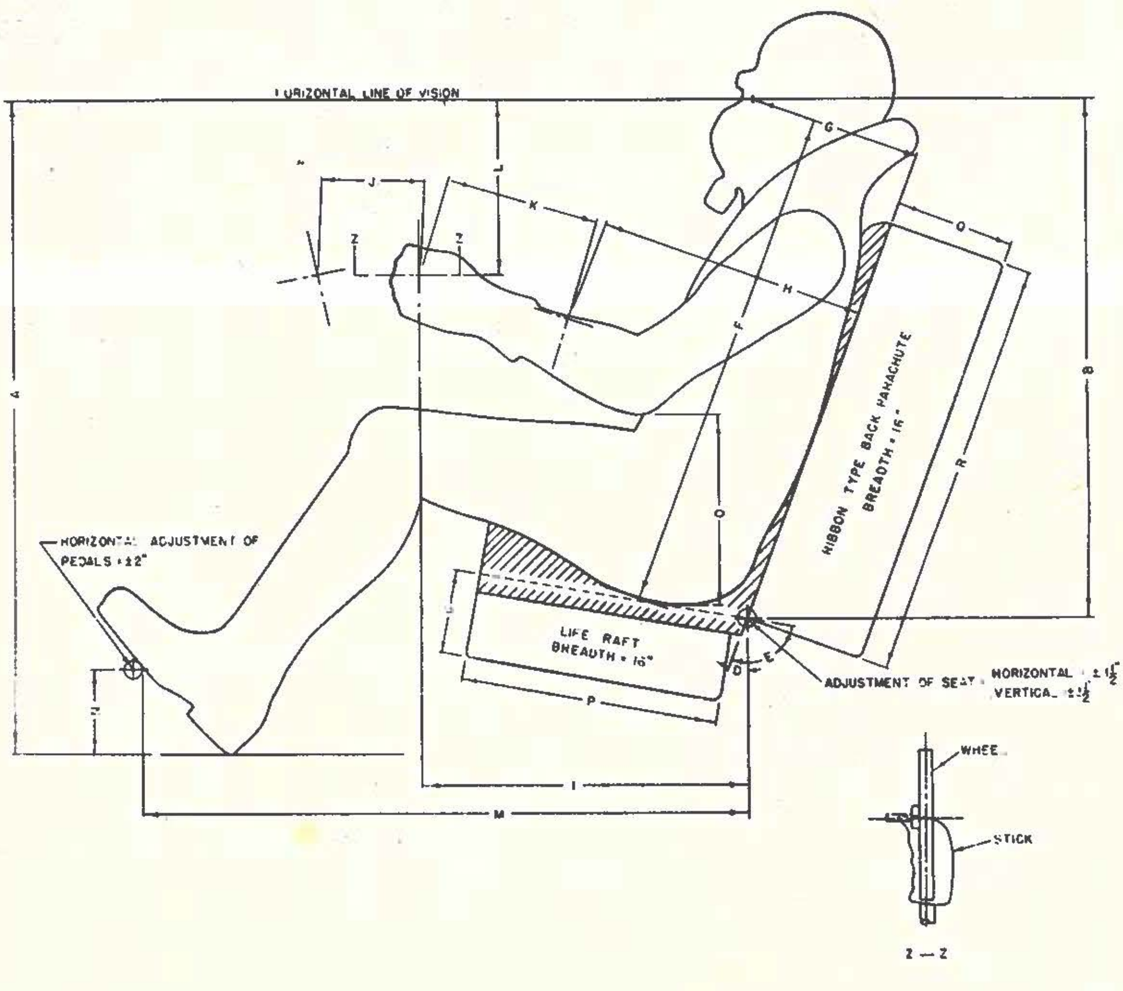


TABLE I - WHEEL TYPE CONTROL
(ALL VALUES IN INCHES UNLESS OTHERWISE NOTED)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
37	30¼	5	21°	101°	29¾	10	16⅜	19	6	9	10	36	5	9¼	15	7	25
39	30¾	5	19°	101°	30¼	9¾	15⅜	19	6	9	10½	35	5	9¼	15	7	25
41	31½	5	16°	101°	31	9¾	15⅛	19	6	9	10¾	34½	5	9¼	15	7	25
43	31¾	5	16°	101°	31¼	10	15⅛	19	6	9	11	34½	5	9¼	15	7	25

TABLE II - STICK TYPE CONTROL
(ALL VALUES IN INCHES UNLESS OTHERWISE NOTED)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
37	30¼	5	21°	101°	29¾	10	14½	19	6	9	11½	36	5	9¼	15	7	25
39	30¾	5	19°	101°	30¼	9¾	13¾	19	6	9	13¾	35	5	9¼	15	7	25
41	31½	5	16°	101°	31	9¾	13½	19	6	9	15½	34½	5	9¼	15	7	25
43	31¾	5	16°	101°	31¼	10	13	19	6	9	17½	34½	5	9¼	15	7	25

APPENDIX V

Figure 1.

No. of Pages: 11

ARMY AIR FORCES

HEADQUARTERS, AIR TECHNICAL SERVICE COMMAND
ENGINEERING DIVISION
MEMORANDUM REPORT ON

A.P.Gagge/ahf

Date 29 May 1945

SUBJECT: Human Factors in Aircraft Design.

OFFICE Aero Medical

Contract or Order No.

SERIAL No. TSEAL-3-695-53

Expenditure Order No. 695

DOWNGRADED AT 12 YEAR INTERVALS; NOT AUTOMATICALLY DECLASSIFIED. DOD DIR 5200.10

A. Purpose:

1. To enter in the Engineering record a paper on the above subject, presented 17 May 1945 at the weekly Staff Meeting, Office of the Surgeon General, War Department, Washington, D. C.

B. Factual Data:

2. The chairman of the meeting was Maj. General Norman I. Kirk, USA, Surgeon General, United States Army. The deputy chairman was Brig. General Charles A. Glenn, USA, Deputy Air Surgeon, Army Air Forces. The audience consisted of staff members from the offices of the Surgeon General and Air Surgeon.

3. In Appendix I a paper on the above subject, given by Lt. Colonel A. P. Gagge, Chief, Biophysics Branch, Aero Medical Laboratory, Engineering Division, is presented.

C. Conclusions:

4. None.

D. Recommendations:

5. None.

A. P. Gagge

Prepared by A. P. GAGGE, Lt. Col., A. C.
Chief Biophysics Branch

F. G. Hall, Lt Col AC

Approved by W. RANDOLPH LOVELACE, II,
Colonel, Medical Corps
Chief, Aero Medical Laboratory

Approved by

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APPENDIX L.

HUMAN FACTORS IN AIRCRAFT DESIGN

Lt. Colonel A. P. Gagge, A.C.,
Chief, Biophysics Branch
Aero Medical Laboratory
Wright Field, Dayton, Ohio

As an item of historical interest it would be well to note that the basic design of all the operational aircraft used at present in the Army Air Forces, namely, the Lightning (P-38), the Thunderbolt (P-47), the Mustang (P-51), the Fortress (B-17), the Liberator (B-24) and the Super-Fortress (B-29), were on the drawing boards long before Pearl Harbor Sunday. Although these aircraft have passed through several types and undergone considerable modification since their original design, the essential features of these aircraft that can be associated with the human factor have remained throughout basically unchanged. All the above aircraft of the Army Air Forces are built according to general principles and procedures outlined in the <u>Handbook of Instructions for Aircraft Designers.</u> The detail design and <u>performance is covered by the respective Specifications.</u> Careful examination of either Specifications or the Handbook will show that for these operational aircraft nothing has been written in that can be considered a Human Requirement. In each case the design for the Human Factor has been left by the AAF to the respective company engineers, who have incorporated features, which in their limited experience they believe best. An exception to this trend should be noted in the Superfortress, B-29, in which crew comfort and efficiency has been greatly improved by the use of cabin pressurization.

With the perfection of the jet propulsion engine and the rocket motor it is now within the realm of engineering possibility for aircraft to fly at speeds approaching and even exceeding the speed of sound and to climb to altitudes higher than those in which a man can survive even for a short time with pressure breathing. With increasing speeds, streamlining of fuselages and cabins has become all important and the slightest maneuver calls in play centrifugal forces greater than those normally tolerated by man. With the approach of a new era in aircraft design, the aircraft engineers and designers are rapidly realizing that, unless human requirements and limitations are carefully considered, they will produce aircraft impossible for a pilot to fly with any acceptable degree of safety.

During the present war, the efforts of the Aviation Physiologists and Flight Surgeons to improve aircrew efficiency have been devoted primarily to the current personal equipment program. An attempt has been made to make up for the deficiency in the design of aircraft for human requirements, by improving personal equipment. Three classic examples of these efforts are:

a. The development of the demand and pressure demand oxygen systems was based on a requirement for equipment to supply oxygen at high altitude and under cold conditions to an aircrew member undergoing moderate to heavy work. Cabin pressurization has reduced considerably the importance of this requirement.

b. The development of reliably warm and electrically heated clothing was based on a requirement (as revealed in 8th Air Force operations)to prevent frost bite and extreme exposure among aerial gunners in exposed positions, such as the open waist gunners of the B-17. This requirement was diminished in importance by closing the open windows and improving the heating system.

c. All our fighter aircraft were designed basically for short range operation. The change over to long range operation has been accomplished by addition of external gas tanks and without any basic change in cockpit size design. The relief of fatigue in these long range aircraft has been directed at the improvement in the comfort of personal equipment and seats rather than a rearrangement and resizing of the cockpit.

Thus, in general, our efforts in the past have been directed at correcting the human limitations of our aircraft by improving and perfecting personal equipment of aircrews. Little effort has been devoted to consideration of the human factor itself in the design of aircraft as a method reducing the need for personal equipment and of improving the efficiency of aircrews.

The human factors in aircraft design are diagrammatically summarized in the accompanying chart. The human factors are described in the inner circle. The outer circle indicates the design factor in the aircraft that must be considered. It is not the intention at the present time to give a detailed analysis of all the six major catagories indicated, but to present in a general way as follows the considerations that must be made in aircraft design for the human factor:

<u>Space and Weight Requirement</u>: In the Spring of 1942 the Air Technical Service Command (then the AAF Materiel Command) conducted an anthopometric survey of cadets at the various training centers. Of interest was not only the height and weight, but body dimensions themselves such as sitting height, arm reach, shoulder width, hip width while sitting and standing, leg reach and so on. From these dimensions the mean and the values for a top and bottom 5 per cent in a normal distribution were evaluated. Dimensions alone are not enough for an aircraft designer. The additional space required by personal equipment must be considered such as the back and seat parachutes, seat dinghies, emergency vests, emergency kits, oxygen

APPENDIX I (Cont'd)

equipment and flying clothing. In brief, the range of human sizing requirements can be summarized as follows:

a. For Fighters:

Maximum: 6'1", 180 pounds (nude), with full operational personal equipment.

Minimum: 5'4", 120 pounds (nude), with minimal personal equipment.

b. For Bombers:

Maximum: 6'3", 200 pounds (nude) with full operational personal equipment.

Minimum: 5'0", 120 pounds (nude) with minimal personal equipment.

Since a flier is never without his emergency equipment in flight, the true design weight should also include this. As a design weight for aircraft, the maximum should be:

230 pounds per man for fighters
250 pounds per man for bombers

Comfort and crew efficiency are closely related to the minimum clearances allowable in a cockpit. These may be summarized:

Above Head 2-1/2"

Across Shoulders 24" - 26"

Across Elbows 26" - 28"

Across Each Knee 6" - 8"

Above Knees and Thigh 26"

Safety is also intimately associated with size of escape hatches for bailout, ditchings and crash. The following are minimum requirements:

a. Bottom Openings (bailout):
20" x 29", when leaving aft edge
20" x 32", when leaving from fore edge

b. Side Openings (bailout):
20" x 31"

APPENDIX I (Cont'd)

c. Top Openings (ditching and crashes):

18" circular or square and shoulders must protrude, while flier uses inside step.

21" circular or square without inside step.

With the tendency to greater streamlining for speed the available cockpit and cabin space will decrease. The ideal trend for a design requirement is to keep the cockpit size up to the minimum values quoted above so that the maximum use of available personnel may be accomplished.

Altitude Tolerance

The oxygen requirements for aircrews is by now well known. Required use of supplementary oxygen begins at 10,000 feet. Above 35,000 feet pressure breathing with 100 percent oxygen has increasing advantage. The upper limit for the use of pressure breathing routinely without anoxia is conservatively chosen at 42,000 feet with six inches water pressure, but under emergency conditions limited protection may be gained at 50,000 feet with 12 inches of water pressure.

Aero-embolism becomes an increasingly significant factor above 25,000 feet at which altitude its frequency of occurence for an average flier is negligible. At 30,000 feet the chance of getting aero-embolism is one in ten for one hours exposure to 35,000 feet; one in four for one hour's exposure to 40,000 feet. Above 40,000 feet only the hardy can last more than 20 minutes without some effect from aeroembolism.

Rapid or explosive decompression as the rule is well tolerated by the average flier and as a hazard is of significance only at extremely high altitudes in pressurized fighter aircraft. In general, tolerance to explosive decompression is a function of the relative expansion of internal gases (RGE) and the time of the decompression. For an instantaneous decompression it has been shown that an RGE of 2.3 (i.e. 28,000 to 40,000 feet) is well tolerated. For a 0.15 sec decompression 4.0 RGE (15,000 feet to 40,000 feet) is tolerable. The RGE itself is a simple function of the cabin and flight altitude pressure. The time of decompression in addition to being a function of the cabin differential pressure and flight altitude is proportional to the cabin volume and inversely proportional to the explosive orifice. Thus, for a given size hole or damage the time of decompression and hence the freedom from danger of decompression both increase with cabin volume. Because of the relative size of the canopy area to cabin volume in fighter type aircraft (50 cu. ft. cabins) the maximum tolerable RGE is 2.3 for combat areas. A tentative value of 4.0 RGE is set for medium bombers (250 cu. ft. cabin) and 6.0 RGE for heavy bombers (1000 cu. ft. cabin). How high one can choose an operating RGE for combat areas depends in the final analysis on gunfire tests on a static test fuselage.

APPENDIX I (Cont'd)

The tolerable rate of compression by an average flyer is fixed by his ability to clear his inner ear. Experience shows that the optimum design rate for increase in cabin pressure is 1 psi/min.

Between 10,000 feet and 33,000 feet the requirement for supplementary oxygen varies from zero to 100 per cent. The design requirement for oxygen equipment itself is to supply this partial need with a proper margin of safety. Where night vision is a factor we shall see that a 5000 foot cabin or the use of oxygen from the ground up is required.

Cabin pressurization may be used either to completely eliminate the need for continuous use of oxygen,to prevent only aeroembolism,or just to reduce the cabin altitude to a level where use of pressure breathing is not required.

It is interesting to note on the basis of the principles outlined above that for fighter aircraft it is impossible to fly above 53,000 feet in combat without seriously increasing the hazard from explosive decompression (exposure to a greater RGE than 2.3) or without the risk of anoxia while using pressure breathing above 42,000 feet, or both; in any case the flier would be seriously exposed to the effects of aeroembolism. On the basis of what is known at present of human limitations alone, the success of any type of combat at 50,000 feet will be significantly limited.

Heat and Cold Tolerance:

In any consideration of heat and cold tolerance aside of dry bulb temperature the most important variables are the degree of clothing and the humidity. For indefinite exposure times the tolerance limit for a sitting-resting pilot to cold is set by the hands and feet regardless of the amount of body clothing used. This has been found to be approximately 32°F., if dexterity is to be maintained. For continued exposure at lower temperature electrically heated clothing will likely have to be used.

For the case of a sitting-resting flier dressed in an OD uniform and worsted coverall the comfort zone and the range of tolerable temperature extremes in terms of time are well known. Toward the colder temperatures the tolerance time is set by the dry bulb temperature only, and is practically independent of humidity. For this special case, the lower limit of comfort is approximately 67°F. However, 55°F is tolerable for two hours: 44°F for one hour and 32°F even for 1/2 hour.

For the warmer temperatures the effect of humidity on comfort is great. For practical design purposes the maximum probable absolute humidity (30 mm of HG vapor pressure) on the earth's surface should only be considered. For this absolute level of humidity, the upper comfort limit is 80°F; 95°F is tolerable for four hours; 107°F for two hours; and 120°F for two hours.

APPENDIX I (Cont'd)

These values therefore can well be used as a design requirement for aircraft without reference to its geographical use.

In general, it should be pointed out that the tolerance limits to heat are much more sudden and severe than to cold. Collapse from heat can well result in sudden unconsciousness while collapse from cold will result in local numbness, pain, and shivering.

In the design of cabin heating and ventilating systems for aircraft the factor of solar radiation must be considered. For high speed aircraft the degree increase from ram rise is great. In jet type aircraft the air from the jet air compressor for cabin pressurization is often as high as 400°F, creating a requirement for air cooling. In multi-passenger aircraft in which pressurisation is used, recirculation and purifying the air may be required because of the low capacity of the superchargers. These, briefly, are some of the factors that must be considered under this very general heading.

Sound:

The most important human requirement in the design of aircraft as it concerns sound is the maintenance of communication for aircrew in flight. Using the familiar decibel system for measuring sound, communication is impossible for an overall noise of 120 decibels. Voice conversation is difficult at 90 decibels, where auditory fatigue is significant during flight. Since nearly all conventional aircraft have overall noise levels in this range, great care must be used in the design of radio and intercommunication equipment.

Recent work has shown that for conventional aircraft the overall decibel level is usually set by the horsepower of the engines, and it will take an extraordinary amount of sound proofing to reduce this overall level. The current practice is to reduce the transmission in the high frequency (500 cps and greater) range by proper insulation, since sound in this part of the spectrum affects intercommunication the most. At present, sound proofing is applied to military aircraft to reduce the decibel level to 85 in the spectral range, 1000-2000 cps. For commercial aircraft a level as low as 75 decibels in this range is desirable.

There has been no indication to date that sound control will be a serious consideration in jet propelled type aircraft.

Vision:

By selective methods the flight surgeon is providing for the Army Air Force pilots and aircrews with the best possible (a) visual acuity by use of the Snellen Chart, (b) depth perception by use of the Howard-Dolman apparatus, and (c) night vision with AAF-Eastman or AML night vision

APPENDIX 1. (Cont'd)

testers. The problem for the aircraft designers is to provide windscreens, sighting blisters, and cockpit lighting that preserve to the fullest extent these visual faculties of the pilot.

In conventional aircraft with which we are most familiar windscreens have been made from flat glass segments. Use of flat glass of high optical quality is the ideal method of preserving visual efficiency of aircrews. However, with the trend to high speeds and the consequent need for wide visual fields clear plastic canopies, domes, and blisters are being used with increasing frequency. When the optical quality of windscreens and sighting blisters is allowed to be reduced by the use of molded or blown plastic, the following may be expected.

a. Loss in Range of Vision: This effectively is an integration of the effect of distortion, loss of transmission, and dirty windscreens. For any windscreen the loss in range reduces greatly with increasing angle of incidence (the angle between the line of vision and the normal to the windscreen or sighting blister). For example, with high grade plate glass, the loss in range of 5% for 40° angle incidence; 7% for 60° angle; and 10% for 70°. The corresponding figures for a curved plastic surface such as used in a bubble canopy are 9% for 40° angle, 20% loss for 60°, and 30% for 70° angle. If the plastic surface is dirty or scratched the loss at a 70° angle is as high as 50%.

b. Loss in Depth Perception: As above, with increasing angles of incidence, the depth perception of the pilot becomes increasingly poorer. This is especially true for angles of incidence above 50°. At any angle of incidence the depth perception through plastic is about three times poorer than through high grade glass, as measured on a Howard-Dolman apparatus. Depth perception is of greatest importance during landings and take-offs, when judgment of actual distances from the ground is all important.

c. Loss in Transmission: This factor, too, varies with the angle of incidence and in addition to its effect on the loss of range, as indicated above, it can cause an equivalent loss in night vision. It is therefore essential for night fighter aircraft to use as good optical glass as possible, or when plastic surfaces are used, to keep the line of sight as normal as possible to the sighting screen.

d. Deviation in the line of sight must be considered in use of the astrodome for navigation and the sighting blisters for gun fire.

An important factor in the preservation of night vision is the proper choice of cockpit lighting conditions. Ideally, red cockpit lighting is the best we have for preserving night visual efficiency. Experimental evidence shows that for dimmed fluorescent lights, as currently used in

APPENDIX I (Cont'd)

the AAF, night vision is only slightly impaired. In any case, all exposed lights should be avoided in cockpits and cabins of tactical aircraft at night. Of utmost importance is the shielding of all light from reflecting on the windscreen as this decreases the contrast of objects seen through the windscreen and will greatly reduce the visual range outside the aircraft at night.

Acceleration:

The two types of accelerative forces important in aircraft design are centripedal and linear. Centripedal forces are associated with changes in course of any aircraft and become greater the shorter the radius of curvature of the path. The most frequently encountered of the centripedal forces is that directed to the floor of the cockpit (positive G-force). However, tolerance to this force has been carefully studied on centrifuges as well as in flight and is well known. As in all tolerance studies, the intensity of the force as well as the time the force acts must be considered. A further factor for consideration is the position of the pilot during application of the G-force.

In cockpit design three pilot positions are of practical interest, the normal sitting, the semi-reclining, and the prone. For an exposure of ten seconds the average G-forces tolerable by a normal pilot as is as follows:

Sitting	4.5 to 5.5 G
Semi-reclining	5.0 to 6.0 G
Prone	12 to 14 G

Thus, we can see if G-tolerance is a factor to consider in the design of aircraft, the prone would be the most effective. The practical difficulty in the application of the prone position is to support the head during application of the G-force.

An improvement in tolerance by a factor of two G may be expected by the pilots' use of an anti-G-suit. This suit consists of a pneumatic garment, which exerts pressure by bladders on the abdomen, thighs, and calves and prevents pooling of blood during G maneuvers. The suit pressure increases proportional to the applied G forces.

Fighter aircraft have a wing design capable of withstanding at least 10 G during combat. Unless the wings are reenforced to withstand very high G forces, the most practical approach to giving G protection to the pilot is the use of the anti-G-suit rather than changing to an abnormal position for the pilot.

Tolerance of pilots to negative centripedal force (directed toward the head) is low and is approximately 2 G. This force is rarely encountered

APPENDIX I (Cont'd)

voluntarily during aircraft maneuvers and is, therefore, not significant as a human design factor.

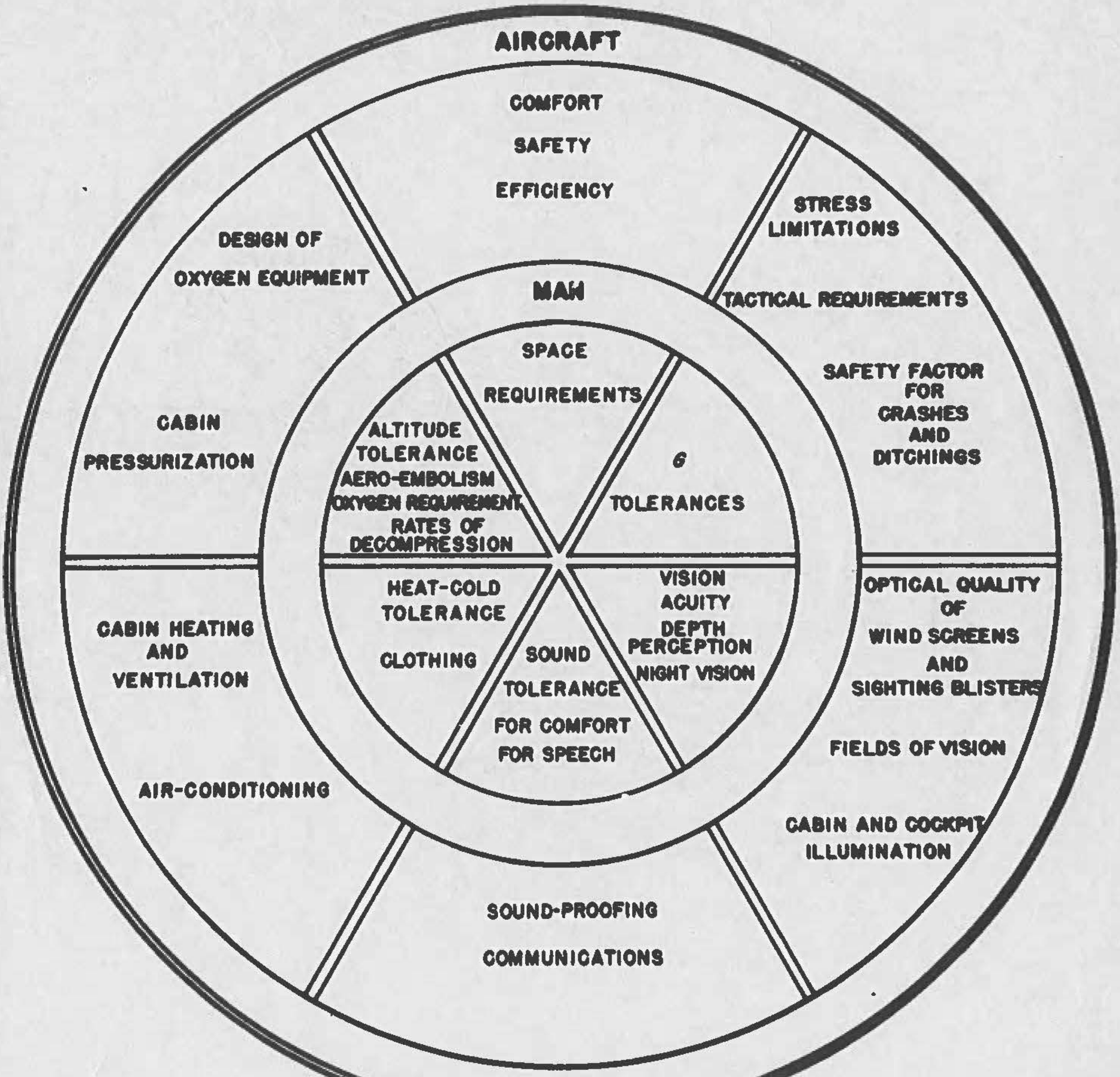
Linear acceleration, such as normal and catapault take-offs (approximately 3.5 G), has also proven to be a problem of no significance as it is related to human tolerance. Linear deceleration, on the other hand, is of vital interest in ditching and crashes. At present, little is known on tolerable or allowable decelerative forces for aircrews nor has there been any systematic evaluation of these forces during crashes and ditchings. The best evidence available indicates that such forces range between 25 to 40 G and indicate the degrees of structural support that must be considered in aircraft design and in the use of safety harnesses.

For the newer types of high speed aircraft considerable interest has been expressed in devising an ejection system for emergency escape by the pilot. If such a system can be perfected, vertical linear accelerative forces along the spinal column must be considered that are of sufficient intensity and duration to clear the pilot from the ship but at the same time cause no spinal or physical injury to the pilot. From the meager experimental evidence now available, it appears that the maximum allowable value for this force is approximately 25G applied for a fraction of a second.

In conclusion, the future aim of the Aviation Physiologist and Flight Surgeon should be to stress and improve the human factor in aircraft design. The first step in this direction has been taken by the inclusion of a new section in the forthcoming edition of the <u>AAF Handbook of Instructions for Aircraft Designers</u>, covering a <u>preliminary evaluation of the human factors in the design</u> of aircraft outlined above. In the long run the surest way to improve pilot and aircrew efficiency is to reduce his concern for personal equipment by the proper design of the aircraft itself.

Eng. Div. Memo. Report
No. TSEAL-3-695-53
29 May 1945

HUMAN FACTORS IN AIRCRAFT DESIGN



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ENGINEERING DIVISION TECHNICAL NOTE

Serial No. TSEAL3-2

SUBJECT: Visual Factors Relating to the Design and Operation of Aircraft.

DATE: 7 June 1945

1. General. The job of flying is more dependent on vision than on any other of man's senses. The term vision, as used here, denotes a number of different functions. Flying personnel need good depth perception to land, take off, and accurately judge the altitude of aircraft during low level strafing and bombing runs. They need good visual acuity to identify and hit targets. They need good night vision to see at night especially under war-time blackout conditions. For these reasons, the Army Air Forces have established elaborate examination procedures to insure the excellence of the vision of air crew personnel. But all the advantages of careful selection are lost if the aircraft is not so designed as to enable the aircrew members to make effective use of their excellent vision. The field of view must be as unhampered as possible in all directions; the windscreens and canopies must have good optical properties; and the cockpit must be provided with lighting which will not impair night vision.

2. Field of View. The impetus for analyzing the field of view from military aircraft originates in complaints and unsatisfactory reports from combat operational groups concerning visibility. First, there are many complaints of poor forward visibility in fighter aircraft while taxiing with resulting accidents. Also, some pilots complain of the loss of visibility in landing after the nose of the plane is raised. Secondly, the reports often refer to poor visibility over the nose in fighter aircraft while in combat. For reasons of safety, fighter aircraft must often stay on the deck. It is seldom that they can see the target at this altitude because there is so little visibility over the nose. With the development of computing gunsights for fighter aircraft the requirement for visibility over the nose increases. Gunsights now make possible deflection shots from 15° to 20° but visibility over the nose is restricted to less than 8° or 9°. In the Me-410, (Table I) 12° downward visibility over the nose is achieved in the taxiing position, while 20° is readily available in the flight attitude. In the British Meteor, from 25° to 30° downward visibility over the nose appears possible while in the flying attitude. On the other hand, none of the AAF fighters studied offers more than 9° downward visibility.

a. Measurement of visual fields is accomplished with an instrument similar to an astrolabe. It consists of a self-leveling vertical scale for reading angles of elevation and depression mounted on a directional gyro which provides the azimuthal scale. (Figures 1

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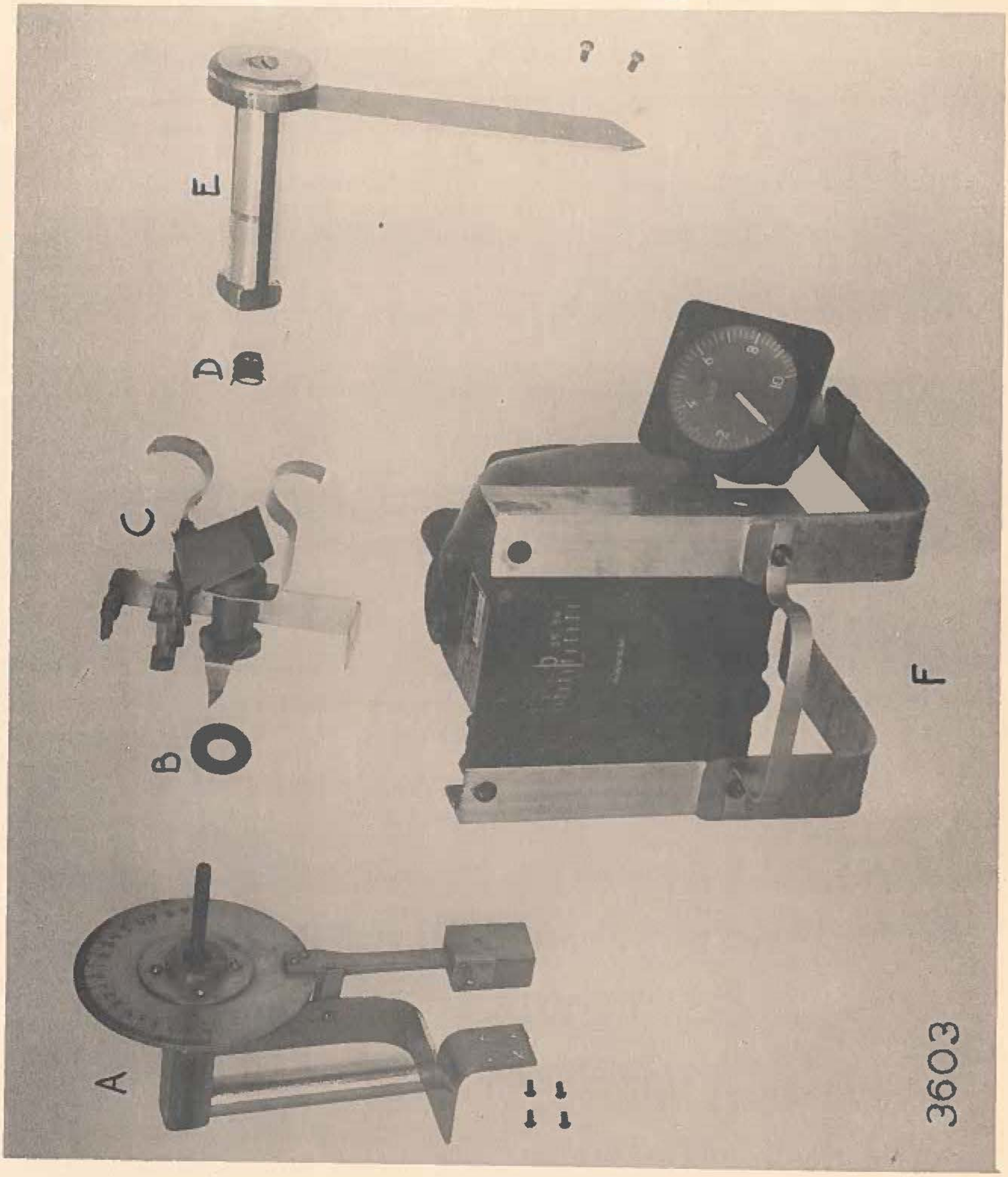

Figure 1.
VIEW OF PARTIALLY DISASSEMBLED INSTRUMENT.

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(A) Vertical scale unit with left hand grip and supporting brace. (B) Rubber friction clutch washer. (C) Sighting and indicating unit with finger grip and mirror. (D) Compression spring. (E) Right hand grip and supporting Brace. (F) Azimuthal scale unit (directional gyro indicator) in mount.

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Figure 2.
INSTRUMENT IN OPERATING POSITION
WITH VACUUM HOSE ATTACHED.

and 2). Estimations are made at 5° intervals around the entire 360° azimuth. Visual field size is computed from these angles and is expressed quantitatively in steradians. The instrument is hand supported and enables the observer to move about in the cockpit within the limits of the shoulder harness and seat belt - thus providing estimation of a functional field of vision and simulating natural movements a pilot would make when pursuing an object or target visually.(6)

b. Table I makes possible quick comparison of aircraft studied. From these data, it is apparent that fighter aircraft differ significantly in the size of the total field of vision and the amount of visibility over the nose. The P-63 has the largest total field of vision and the P-38 the smallest, a difference of 12%. The Me-410 gives the largest angle of downward visibility over the nose while the P-51B and P-47 are poorest in this respect.(9) The total fields of vision from faired P-51B canopy and the B-51D bubble canopy are almost identical. It should be emphasized, however, that canopy structural members constitute handicaps for the pilot. The bubble type canopy is universally preferred over, the older, ribbed and reinforced types, even though the total amount of visual field is not greater with the bubble canopy.

c. On the basis of the data and experience thus far accumulated, certain general recommendations regarding visibility and aircraft design can be made.

(1) Tricycle landing gear should be used to provide adequate forward visibility for taxiing.

(2) A minimum of 10° forward visibility over the nose in flight attitude should be provided; 15° for high speed aircraft. This is measured from the horizontal viewing plane of the pilot.

(3) Visibility in the aft portion of the field of vision should be at least 5° below the horizontal viewing plane.

(4) Lateral portions of the field should provide no less than 50° downward visibility, except where this is impossible because of the structure of the wing.

(5) Structural parts of canopies should be eliminated as far as possible, commensurate with strength and safety.

(6) Cockpit lights, instruments, ventilation panel handles etc., should not protrude above the fuselage into the transparent sections.

TABLE I.

Fields of Vision in Fighter Aircraft.

Aircraft Designation	Total Field of Vision (Steradians)	% of Maximum* Possible Field	Aircraft Designation	Downward Vision Over Nose When Taxiing (Degrees)	Downward Vision Over Nose When Flying (Degrees)
P-63	9.238	73	Me-410	12 below	24
YP-80A	8.835	70	YP-80A	6 below	9
Spitfire VII	8.787	70	P-38	3 below	8
Zero	8.772	70	P-63	1 below	8
FW-190	8.673	69	Zero	5 above	7
P-47	8.616	69	Spitfire	7 above	5
P-51B	8.585	68	P-51D	7 above	6
P-51D	8.456	67	P-40	8 above	5
Me-410	8.123	65	FW-190	8 above	5
P-40	8.056	64	P-47	11 above	0
P-38	7.748	61	P-51B	12 above	0

*This is calculated on the basis that the maximum field of vision would be a complete sphere (4π or 12.566 steradians).

3. Design of Transparent Sections.--Of equal importance with provisions for an adequate field of view are the optical properties of the transparent sections themselves. Although the optical quality prevailing in aircraft glass and plastics is of primary concern to the manufacturer of these materials, this factor cannot be divorced from design considerations because of the limitation in optical quality attainable in both glass and plastic transparencies. This limitation must be realized and taken into account by the designer in order that satisfactory vision be possible through the transparent sections of the finished aircraft.

a. Frequent complaints are received from flying personnel about the optical properties of the transparent materials behind which they fly. Pilots flying the A-30 airplane were found to develop motion sickness from observing undulations of the horizon through distorted windscreens in low level flying.(2) In the nose of the early B-17G's, the complex curvature of the nose and the large angle of incidence to the front gunner's line of sight resulted in his seeing two targets instead of one in certain directions. In other planes, deviation errors in plastic turrets contributed more to the error in the boresighting of guns than all other factors combined. The early B-29's were originally built with curved plastic panels in the pilot's compartment. These had to be replaced with flat glass to reduce the distortion.(3) Unsatisfactory reports complaining of distortion have been received from pilots flying C-46's,(1) P-40's, P-51's and A-26C's. Most of these conditions can be corrected by altering the angle of the transparent section, its curvature or position. If however, they had been anticipated at the design stage, it would have resulted in a real saving to the Army Air Forces not only in terms of dollars and cents but also in terms of increased visibility for the air crew. Better visibility means greater combat efficiency and reduced casualties.

b. The unsatisfactory conditions reported above are gross defects which can be readily seen by anyone. It is not generally realized, however, that even minor defects may impair operational visibility seriously. Returning combat pilots often state that the factor of suprise may affect the results of combat to a greater extent than the number of aircraft, performance and armament, and that taking the enemy by suprise (or avoiding being taken by suprise) depends on the "clearness of view" through cockpit panels.(7) With modern high speed aircraft, only a few seconds advantage in spotting enemy aircraft first may mean the difference between combat success and failure. The record of this war is replete with accounts of allied aircraft and ground installations attacked by our own planes and of enemy planes passed by or mistakenly identified.(8) Recognition from a fast moving plane in the air is an extremely difficult task. The differences between a Jap Tabby and U. S. C-47 (See Figure 3), Zeke 52 and P-51, Jack and Navy F6F, and Takanami Class destroyer and U. S. Fletcher Class destroyer are very small and might easily be obscured by small amounts of distortion in the windscreen.

c. In the scientific study of transparent sections, it is necessary to distinguish between displacement, deviation and distortion.

(1) Displacement occurs when rays of light pass through a piece of glass in which both sides are flat and parallel (Figure 4a). The emergent ray is always parallel to the incident ray but is displaced by some small amount. Simple displacement is too small an error to be of any real consequence.

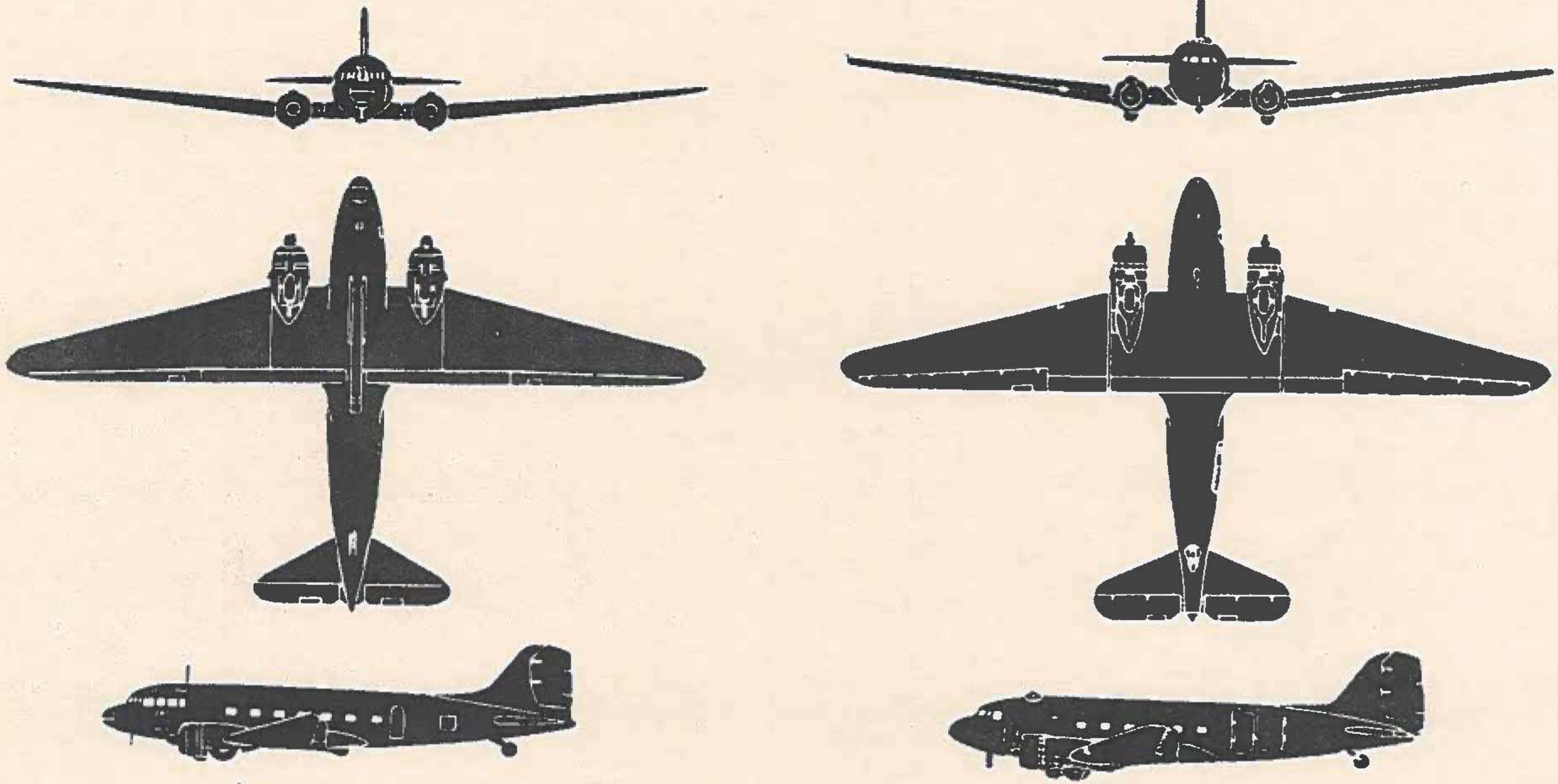

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Figure 3.
Aircraft recognition silhouettes of a Japanese Tabby and USAAF Skytrain (C-47). Combat recognition often depends on small details which may easily be obscured by minor flaws in the windscreen.

Neg. No

(2) Deviation occurs when the two surfaces of the glass are flat but not parallel. In this case, the emergent ray of light goes off in a different direction from the incident ray (Figure 4b). If the amount of non-parallelism is great, deviation may become a very serious factor. The effect of deviation is that an object, while seen clearly, is not seen where it actually is.

(3) Distortion results from the fact that the two surfaces of glass are very seldom absolutely flat. Rays of light passing through such a piece of glass emerge in a number of directions (Figure 4c). Straight lines and runways seen through such a piece of glass appear wavy and distorted.

d. Certain general rules can be stated regarding methods of improving visibility through transparent sections:

(1) Glass is better than plastic because it is harder and less easily scratched, is more stable under the influence of heat and strain and has fewer optical defects or flaws.

(2) Flat sections are better than curved sections, because displacement and deviation become more irregular when the transparent material is curved; hence, distortion is increased.

(3) Wherever curved sections are used, the radii of curvature should be large and the eye of the pilot should be close to the panel. Small radii of curvature and complex curves should be avoided.

(4) For all types of panels, small angles of incidence (glass more nearly perpendicular to the line of sight) are much better than large angles of incidence.

e. As an illustration of some of these principles, British studies have shown in actual field tests that visibility through glass is always better than visibility through plastic. Large angles of incidence increase this difference. A plane which can be seen a mile away with unobstructed vision can be seen only 0.9 of a mile away through a piece of clean glass at a 70° angle of incidence, 0.7 of a mile away through a piece of clean plastic, and only 0.5 of a mile through a piece of scratched plastic at the same angle.(7) (Figure 5.)

f. Type 1, Grade "A" glass has a deviation of no more than three minutes of arc. This amounts to a deviation of only 10 inches at 1,000 feet or 26 feet at 30,000 feet. The deviation through the same piece of glass at a 70° angle of incidence may amount to over 4 feet at 1,000 feet or 125 feet at 30,000 feet (Figure 6). Studies have shown that in general, a poor piece of glass placed perpendicularly to the line of sight is much better optically than a very good piece of glass placed at a large angle of incidence. For example, a study was made of

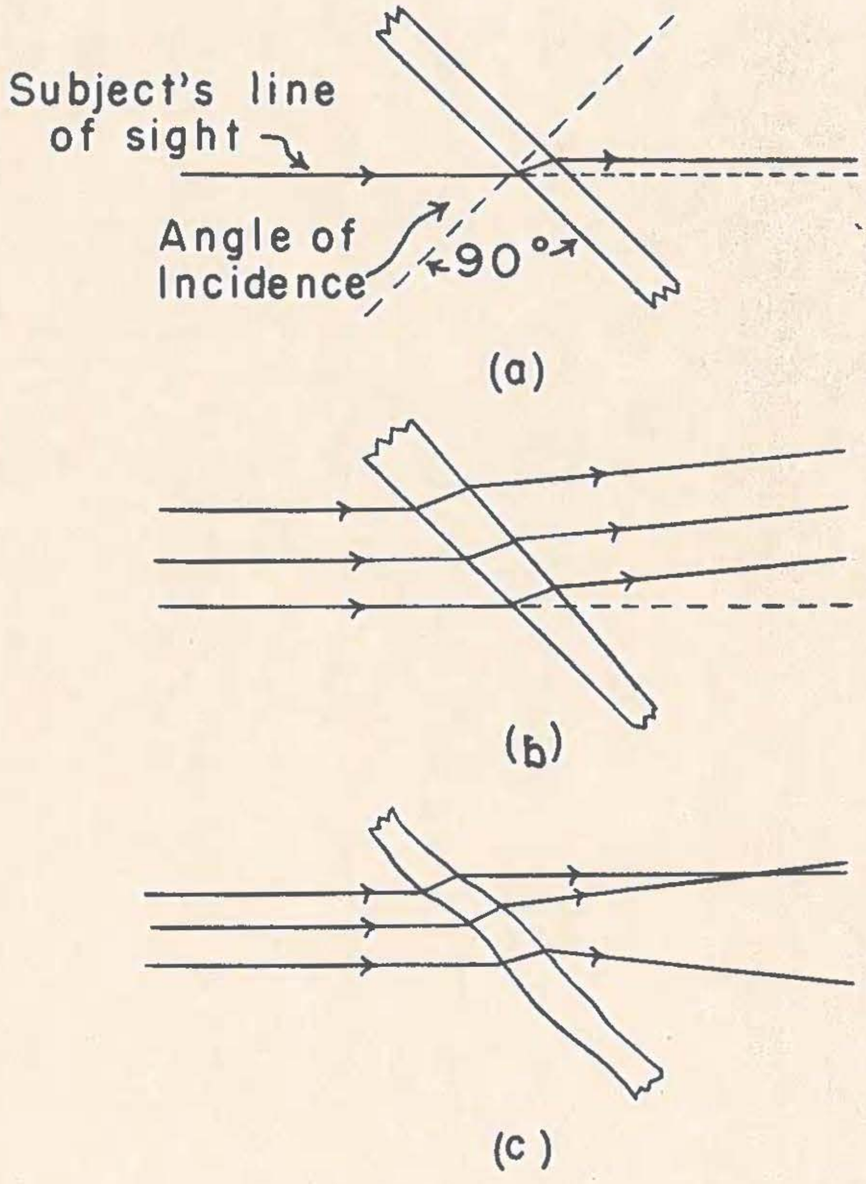

Figure 4.

Diagrams showing the effect on light beams of (a) displacement, (b) deviation, and (c) distortion.

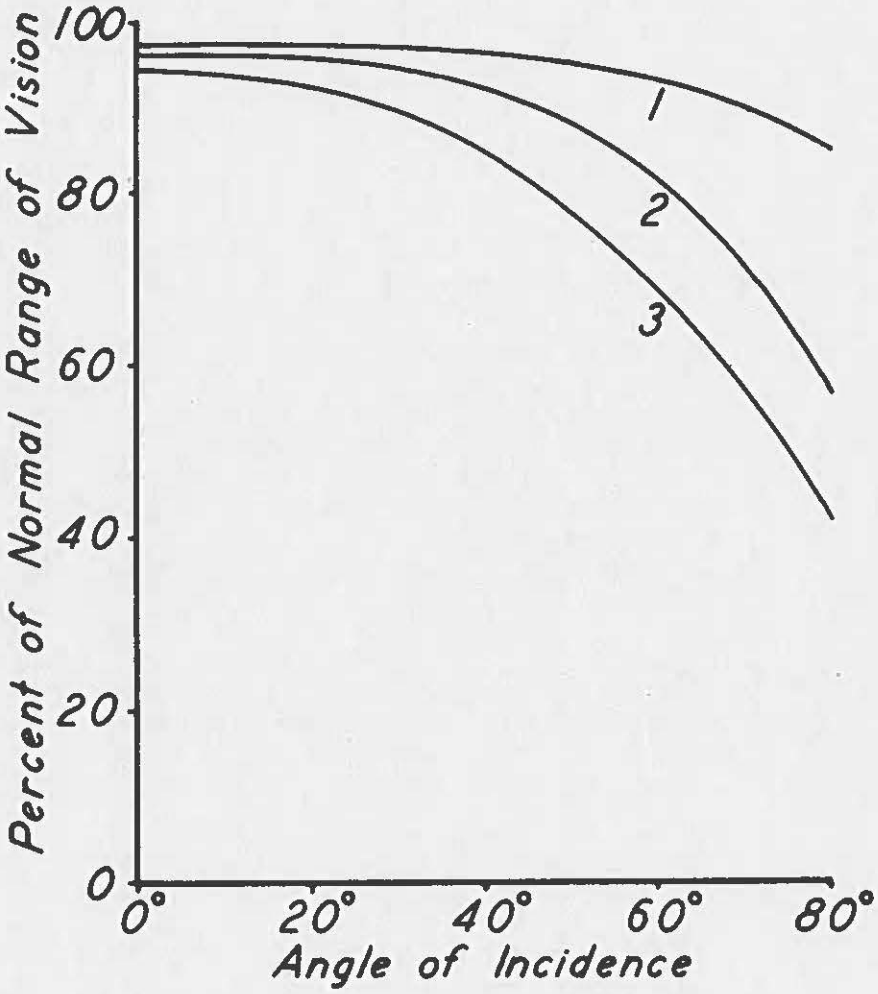

Figure 5.

This chart shows the loss of range of vision through a plate glass (1), clean plastic (2) and dirty plastic (3) windscreen at various angles of incidence. Range of vision is defined as the greatest distance at which a plane of a certain size can be seen on a clear day. Note that visibility is greatly reduced at angles of incidence greater than 40°.

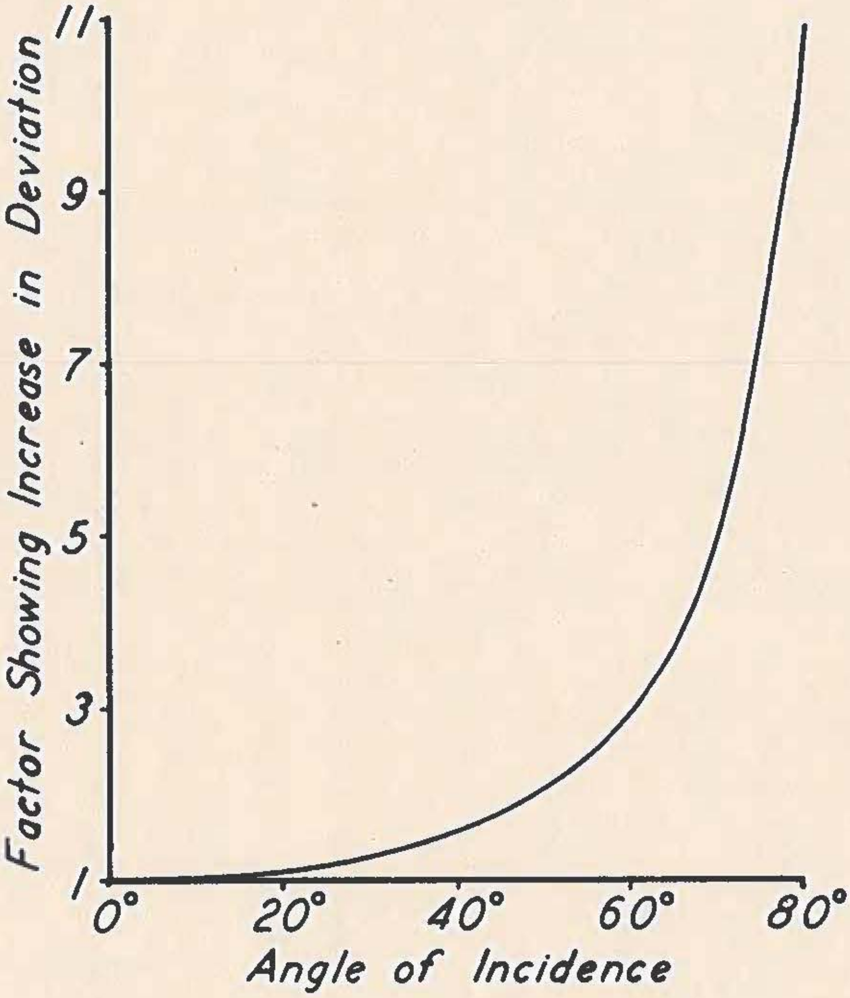

Figure 6.

This curve shows the amount by which the deviation of rays of light passing through a windscreen is increased at various angles of incidence. This curve is calculated for rotation in the direction of wedginess. Note that inherent deviations in the glass increase markedly, at angles of incidence greater than 40°.

depth perception in which the judgments of depth on the Howard-Dolman apparatus were made with glasses of varying quality set at different angles of incidence between the subject and the apparatus. The difference between the glass samples is apparent, but the greatest difference is that which arises when the glass is placed at angles of incidence greater than 50° (Figure 7).

g. The effect of various combinations of radii of curvature and angles of incidence on the deviation of lines of sight through curved panels is illustrated in Figure 8.

h. It is important that the critical angle of incidence at which all these defects appear is 55°. Poor depth perception, loss of transmission (Figure 9), decrease in visibility, and increase in deviation all become excessive at angles greater than this. For this reason, it is recommended that no transparent sections used for vision during taking off, flying, gun sighting, and landing be set at angles of incidence greater than 55° if Type I Grade "A" glass or equivalent is used, or greater than 35° if flat or curved panels of Type I Grade "B" quality are used. It is important to emphasize that these data on loss of transmission and deviation in Figures 6, 8, and 9 are calculated for theoretically perfect pieces of glass and are derived from the laws of refraction and reflection.

i. Aircraft designers in this country seem to have placed the greatest emphasis on aerodynamic properties and small entering profiles in the design of cockpit enclosures and windscreens. Considerations of weight have also been given high priority while very little attention has been given to the effects of these designs on optical properties. The trend appears to be toward a greater use of plastics instead of glass, and towards the use of curved instead of flat panels, set at large angles of incidence. In most instances, this is the result of tendency to think of visibility in terms of pre-war or commercial standards. The preceding sections of this note have emphasized that standards of combat visibility must be very high. It is interesting to note that both the British and Germans appear to be ahead of the U. S. designers in this regard.(5) An analysis of German aircraft indicates that in many cases their designers chose to sacrifice aero-dynamic efficiency to some extent in order to provide good visibility. In the Me-109F, the sacrifice, however, amounted to a decrease of only 3 mph at top speed. In the B-29, the change from curved to flat panels resulted in no detectable change in aero-dynamic characteristics(3) although visibility was improved markedly. Data such as these suggest the need for a reorientation in our attitudes toward the relative weight which should be assigned to these factors.

j. Recently, tinted plastic canopies have been installed in certain types of fighter aircraft to reduce the amount of radiation coming into the cockpit. The infra-red transmission through all of the

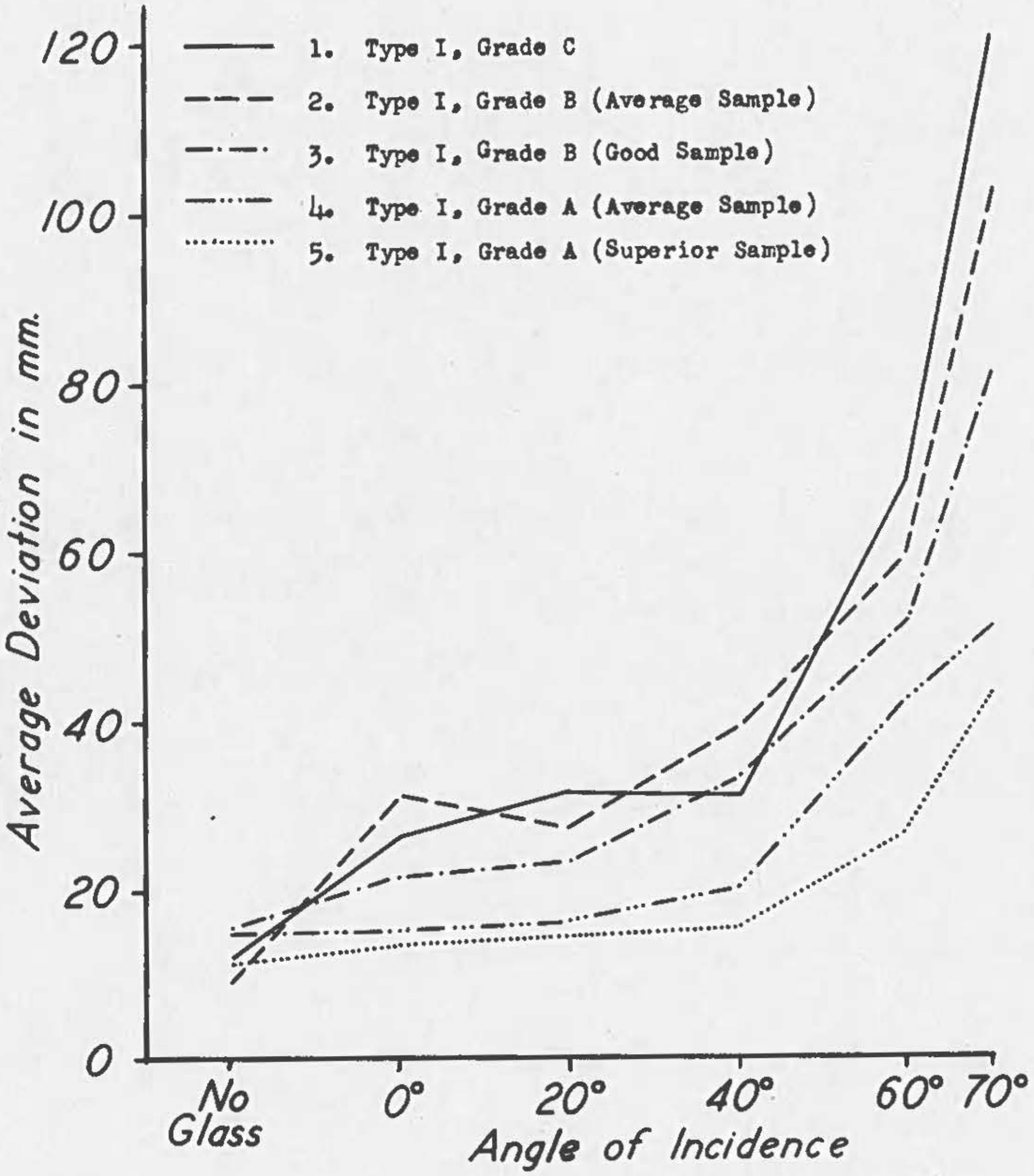

Figure 7.

Each curve represents the average errors of five subjects who judged the separation of two vertical rods seen through five samples of glass, sample #1 being of very distorted glass, and sample #5 being an exceptionally flawless glass. Note that although glass quality makes a difference in the errors, angles of incidence greater than 40° contribute much more to errors in depth perception.

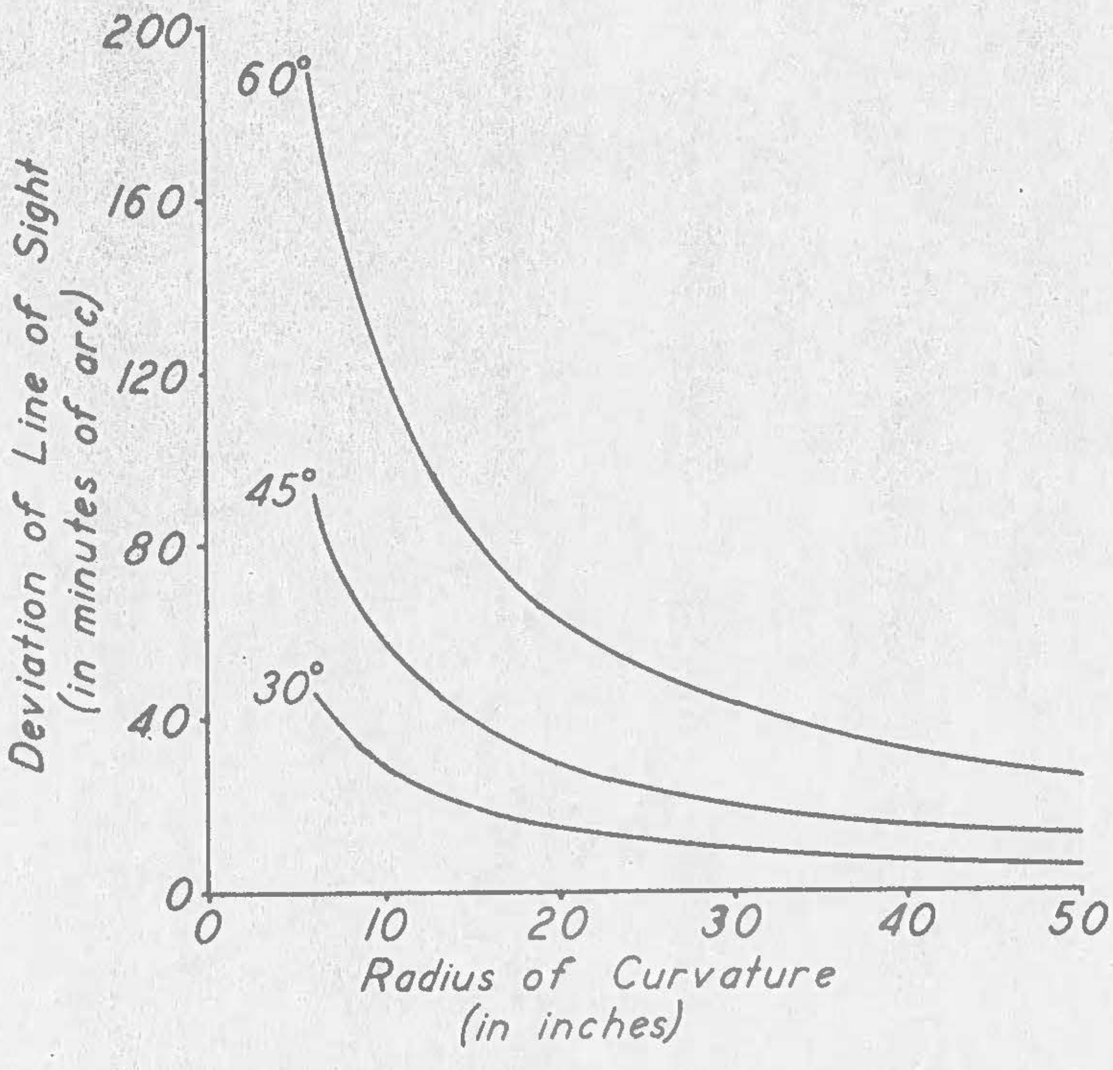

Figure 8.

The curves show the deviation of a line of sight passing through perfect spherical sections of various radii at angles of incidence of 30°, 45°, and 60°. Note that the deviation increases with smaller radii of curvature and larger angles of incidence. A deviation of only 10 minutes of arc means that an object 1,000 feet away will be seen 3 feet to one side of its true position.

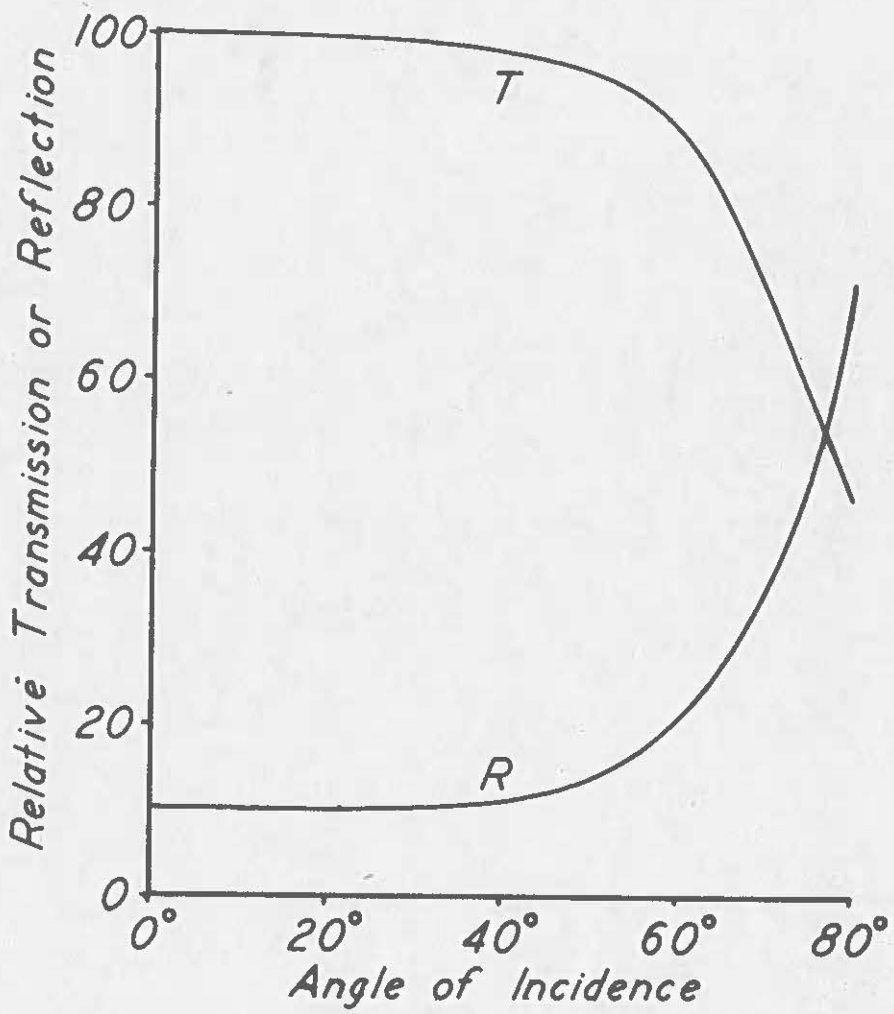

Figure 9.

These curves show the relative light transmission (T) and reflection (R) at various angles of incidence for a piece of 1/8 inch plate glass laminated with 0.080 inch vinyl plastic. Note that light transmission through the glass decreases and reflection increases at large angles of incidence. These factors are especially important in dim illuminations and at night.

canopies examined has been as high as through clear or untinted canopies. As a result, much less radiant energy is screened from the cockpit than might be expected on the basis of the reduction in visible radiation transmitted. Another, more unfortunate aspect of the tinted canopy is its considerable absorption of light of the shorter wave-lengths (blue-green). Since the dark adapted eye is more sensitive to light of shorter wave-lengths, a serious reduction in night visual efficiency results from the use of tinted plastic canopies. This reduction is far out of proportion to the actual loss in transmission in daylight, since the amount of light involved in night vision is almost infinitesimal compared to the levels of illumination available for day vision.

4. Provision for Night Flying. The tinted canopy furnishes a good example of designing for daylight conditions to the exclusion of considerations of the third visual factor in aircraft design: night vision. Studies of night accidents show that aircraft, such as the P-61, designed for night flying have a lower night accident rate than other ships.(4) Provisions for night flying may moreover be incorporated in aircraft intended for day missions without altering their characteristics on such missions, with the advantage that night operations will be much safer. It will be recalled that one of the reasons for the superiority of glass over plastic is that glass scratches less easily. This is particularly important at night since any loss through diffusion of light due to scratched windscreens is much more harmful to night vision than to day vision. Another factor in designing for good night vision is proper cockpit and instrument illumination. It is important to attend to every detail in eliminating all light not absolutely essential to the operation of the aircraft. Light leaks must be eliminated, and warning and pilot lights masked. The essential instruments must be evenly illuminated, and those which are not essential should be left dark. Light sources must be so placed that neither they nor the instruments they illuminate cause glare reflection. Flat paints should be used for cockpit interiors. A coaming over the instrument panel is often helpful in this respect. Internal reflections may be a source of great confusion: flyers often cannot tell whether the lights they see on the windscreen are inside reflections or are outside the aircraft.

a. Complete control of the illumination must be provided so that the brightness can be reduced to the point where the instrument markings are just barely legible on the darkest night, and yet so that it may be raised to provide for easy reading at twilight. Greater legibility may be achieved in instrument dials by making the markings clearer and eliminating those which are unessential. Simplified, consolidated instrument panels are a necessity for the night flyer.

b. It is well known that red, and to a lesser extent, orange light provide considerable reduction in the amount of light which affects the night visual mechanism, without sacrificing legibility. The use of orange fluorescent dial markings with ultraviolet light sources adjustable as to intensity is probably the best compromise between legibility and the preservation of night vision. The ultraviolet lamps must be carefully placed so as not to shine in the flyers' eyes, which would cause fluorescence in the crystalline lens. Indirect red lighting may also be used either without the ultraviolet or as an auxiliary source. Any lights provided for general illumination of the interior, or of chart tables, etc. must be red.

5. Summary. The requirements which must be met to provide adequate vision for air crew may then be summed up as follows.

a. For gunsighting the minimum angle of visibility in any direction should not be less than the maximum angle required for accurate deflection shooting. The downward visibility over the nose when the aircraft is in a taxiing position should be such as to provide a clear view of the runway directly ahead at a distance equal to that required for quick stopping from normal taxiing speeds. Flat panels in those areas used for vision in taking off, flying, aiming guns, and landing should be placed at an angle of incidence no greater than 55° if Type I Grade "A" glass or plastic is used. Curved or flat panels of Type I Grade "B" quality may be used in those areas only if the angle of incidence at any point on the transparent section does not exceed 35°. Wherever curved sections are used, the radii of curvature should be large, and complex curves should be avoided. Orange fluorescent instrument marking should be employed, in conjunction with red light for general illumination.

b. In the consideration of the factors involved in the design of aircraft, compromises must be made. Proper evaluation must be put on such factors as aerodynamic efficiency, weight, profile and contour, cost and visibility. Whatever juggling is done with other problems of aircraft design, one requirement cannot be avoided: adequate provision for the human beings who fly the aircraft. Tremendous speed, great firepower, and heavy armament have reduced value if the aircrew do not see the target or see it in a distorted position.

Concurrence:

Prepared by: *Ernest A. Pinson*
ERNEST A. PINSON
Major, Air Corps
Chief, Vision Unit

Prepared by: *Walter J. Romejko*
WALTER J. ROMEJKO
Captain, Medical Corps

Prepared by: *Alphonse Chapanis*
ALPHONSE CHAPANIS
1st Lieutenant, Air Corps

Prepared by: *Richard O. Rouse*
RICHARD O. ROUSE
2nd Lieutenant, Air Corps

Engineering Div. Tech. Note
Serial No. TSEAL3-2
7 June 1945

(Concurrence continued)

Approved by: A. P. GAGGE
Lt. Colonel, Air Corps
Chief, Biophysics Branch

Approved by: FRANK G. HALL
Lt. Colonel, Air Corps
Acting Chief, Aero Medical Lab.

Approved by: for P. H. KEMMER
Colonel, Air Corps
Chief, Aircraft & Physical Requirements Subdivision

Approved by: F. O. CARROLL
Brig. General, U. S. A.
Chief, Engineering Division

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Engineering Div. Tech. Note
Serial No. TSEAL3-2
7 June 1945

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AAFMC-266-WF-3-8-42-200M

ARMY AIR FORCES
MATERIEL XXXXXXX COMMAND
ENGINEERING DIVISION
MEMORANDUM REPORT ON REH:HJH:gob:51

SUBJECT: Effect of Compressibility on Drag and Terminal Velocity.

Date 29 September 1943

XXXXXXX AIRCRAFT LABORATORY

SERIAL No. ENG-51-4589-5

Contract No.
Expenditure Order No. 458
Purchase Order No.

~~CONFIDENTIAL~~

Classification Cancelled
Auth: Dir, ATSC
Robert E. Hage, Capt., A.C.
Date: 1-4-45

A. Purpose

1. To present methods for determining high speed and terminal velocity of an airplane with compressibility effects considered.

B. Factual Data

1. Appendix 1 contains a graph of the effect of compressibility on airplane drag, Figure 1, and a method of computing high speed in level flight. This graph differs slightly from that presented in Memorandum Report ENG-51-4589-3 dated 30 July 1943.

2. Appendix 2 contains a derivation of a method for the determination of terminal velocity and a graph of terminal Mach number, Figure 3, based on the data contained in Appendix 1. Figure 2 is an extrapolation of Figure 1.

C. Conclusions

1. Procedure and curvesof Appendices 1 and 2 provide a simple determination of high speed and terminal velocity of an airplane with compressibility effects considered.

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29 September 1943

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2. Further wind tunnel and flight test drag investigations may provide the basis for a more exact method of analysis.

D. Recommendations

1. It is recommended that the proposed methods be used until more precise methods can be developed.

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Robert E. Hage
Prepared by ROBERT E. HAGE, 1st Lt., A.C.

Prepared by H. J. HEIMER, 1st Lt., A.C.

Concurrence:

Frank G. Fogan, Col., A.C.
Approved by: for PAUL H. KEMMER, Colonel, A.C.
Chief Aircraft Laboratory

Y-62797

Approved by: F. O. CARROLL, Brig. General, U.S.
Chief, Engineering Division.

Major Gilbert - ELA-2B 3 Cy

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Engineering Division
M. R. Serial No. ENG-51-4589-5 CONFIDENTIAL
29 September 1943

APPENDIX 1

DETERMINATION OF HIGH SPEED IN LEVEL FLIGHT

W = gross weight in pounds

D = airplane drag in pounds = $C_D (1/2) \rho v^2 S$

C_D = drag coefficient of entire airplane

$C_{D_{inc}}$ = incompressible drag coefficient of entire airplane

C_L = lift coefficient of entire airplane

v = airplane speed in feet per second

V = airplane speed in miles per hour

a = speed of sound at altitude in feet per second

S = wing area

P_R = thrust HP required

ρ = mass density of air in slugs/ft.^{3}

σ = air density ratio = ρ/ρ_0

M = free-stream Mach number = v/a

M_{CR} = critical Mach number

Subscript zero = refers to standard sea level conditions

Critical Mach number is the free-stream Mach number at which the highest local air velocity is equal to the speed of sound. On the inclosed graphs M_{CR} of the wing-root airfoil section at C_L = 0 is used for all calculations. This value of M_{CR} should be determined wherever possible from high-speed wind tunnel pressure distributions. If high speed tests are not available, low-speed pressure distributions should be corrected by the use of the Karman-Tsien relationship between the incompressible and compressible pressure coefficients. (Reference ACTR No. 4524, Revision 1, dated 7 July 1943).

APPENDIX I (continued)

DETERMINATION OF HIGH SPEED IN LEVEL FLIGHT FROM FIGURE 1

1. High speed is the intersection of the power available and compressible power required curves.

2. Assume values of speed near the high speed of the airplane and calculate corresponding lift coefficients.

$$C_L = \frac{W}{(1/2)\rho V^2 S}$$

3. Determine corresponding values of $C_{D_{inc}}$ from basic airplane polar

4. Compute Mach numbers corresponding to assumed speeds

$$M = \frac{V}{a}$$

5. Determine M_{CR} of the wing root at $C_L = 0$

6. From Figure 1 determine values of $C_D/C_{D_{inc}}$ corresponding to computed values of M/M_{CR} from (4) and (5).

7. Calculate values of C_D from

$$C_D = \left(\frac{C_D}{C_{D_{inc}}}\right) C_{D_{inc}}$$

8. Calculate new points on power required curve from

$$P_R = \frac{C_D \sigma S V^3}{146600}$$

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EFFECT OF COMPRESSIBILITY ON DRAG

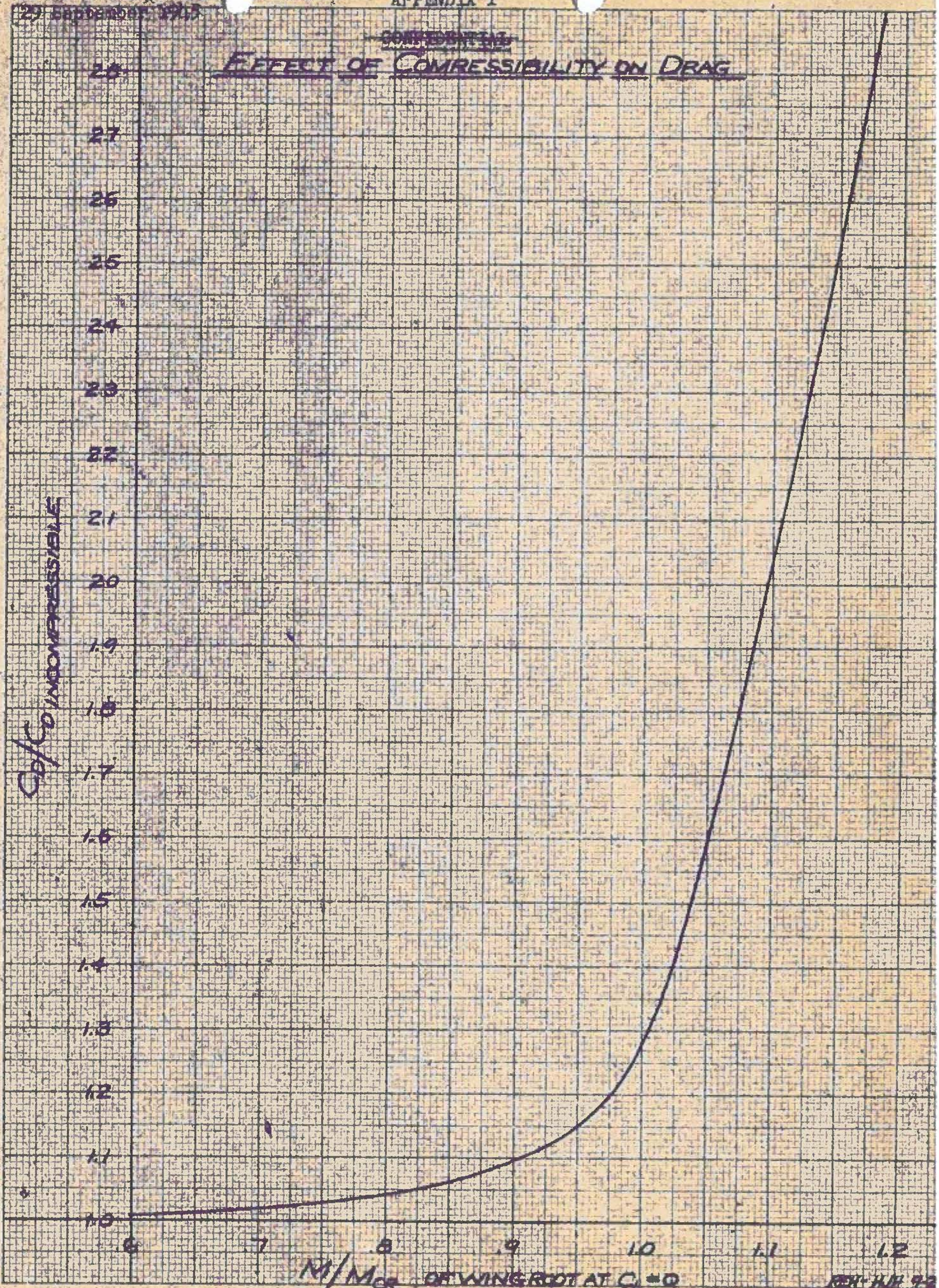

FIG. 1

APPENDIX 2

DETERMINATION OF TERMINAL VELOCITY

f = equivalent parasite area in square feet

C_{D_f} = equivalent parasite drag coefficient

$$C_{D_f} = \frac{f}{S}$$

T = propeller thrust

θ = angle of glide

a_x = longitudinal acceleration

p = static pressure in standard atmosphere

γ = ratio of specific heat at constant pressure to specific heat at constant volume for gases $= \frac{C_p}{C_v}$

Subscript T refers to terminal velocity.

TERMINAL VELOCITY

Assuming $T = 0$, $a_x = 0$, $C_L = 0$, $\theta = 90°$, $C_{D_f} = C_{D_{inc}}$ at $C_L = 0$,

$$W = D = C_D (1/2) \rho {v_T}^2 S \qquad (1)$$

$$W = \left(\frac{C_D}{C_{D_{inc}}}\right)(1/2)\, \sigma \rho_o \left({M_T}^2 a^2 S C_{D_{inc}}\right) \qquad (2)$$

$$\frac{C_D}{C_{D_{inc}}}\left(\frac{M_T}{M_{CR}}\right)^2 = \frac{2W}{C_{D_{inc}}\, \rho_o\, \sigma a^2 {M_{CR}}^2 S} \qquad (3)$$

APPENDIX 2 (continued)

DETERMINATION OF TERMINAL VELOCITY

$$\gamma = \text{Const.} = \frac{\rho a^2}{p} = \frac{\rho_o a_o^2}{p_o} \qquad (4)$$

$$a^2 = \frac{p}{p_o} \cdot \left(\frac{a_o^2}{\sigma} \right) \qquad (5)$$

Substituting equation (5) in (3)

$$\frac{C_D}{C_{D_{inc}}} \left(\frac{M_T}{M_{CR}} \right)^2 = \frac{2}{\rho_o a_o^2} \cdot \frac{W}{C_{D_{inc}} S \, M_{CR}^2 \, p/_{p_o}}$$

$$= \frac{2}{.002378 \times (1116)^2} \cdot \frac{W/_S}{C_{D_{inc}} M_{CR}^2 \, p/_{p_o}} \qquad (6)$$

$$\frac{C_D}{C_{D_{inc}}} \left(\frac{M_T}{M_{CR}} \right)^2 = \frac{W/_S}{1481 \, p/_{p_o} \, C_{D_f} \, M_{CR}^2} \qquad (7)$$

Using Figure 2, $\frac{C_D}{C_{D_{inc}}} \left(\frac{M}{M_{CR}} \right)^2$ is plotted versus $\frac{M}{M_{CR}}$ to obtain Figure 3.

Using equation (7) the coordinates of Figure 3 become

$$\frac{W/S}{1481 \, p/_{p_o} \, C_{D_f} \, M_{CR}^2} \quad \text{and} \quad \frac{M_T}{M_{CR}}$$

APPENDIX 2 (continued)

DETERMINATION OF TERMINAL VELOCITY FROM FIGURE 3

1. From airplane parameters and standard atmospheric tables, compute

$$\frac{W/S}{1481\ p/p_o\ C_{D_f}\ M_{CR}^{\ 2}}$$

2. Determine $\frac{M_T}{M_{CR}}$ from Figure 3 for corresponding value of $\frac{W/S}{1481\ p/p_o\ C_{D_f}\ M_{CR}^{\ 2}}$

3. Calculate M_T from

$$M_T = \left(\frac{M_T}{M_{CR}}\right) M_{CR}$$

4. Calculate V_T from

$$V_T = \left(\frac{60}{88}\right) M_T a$$

APPENDIX 2

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EFFECT OF COMPRESSIBILITY ON DRAG

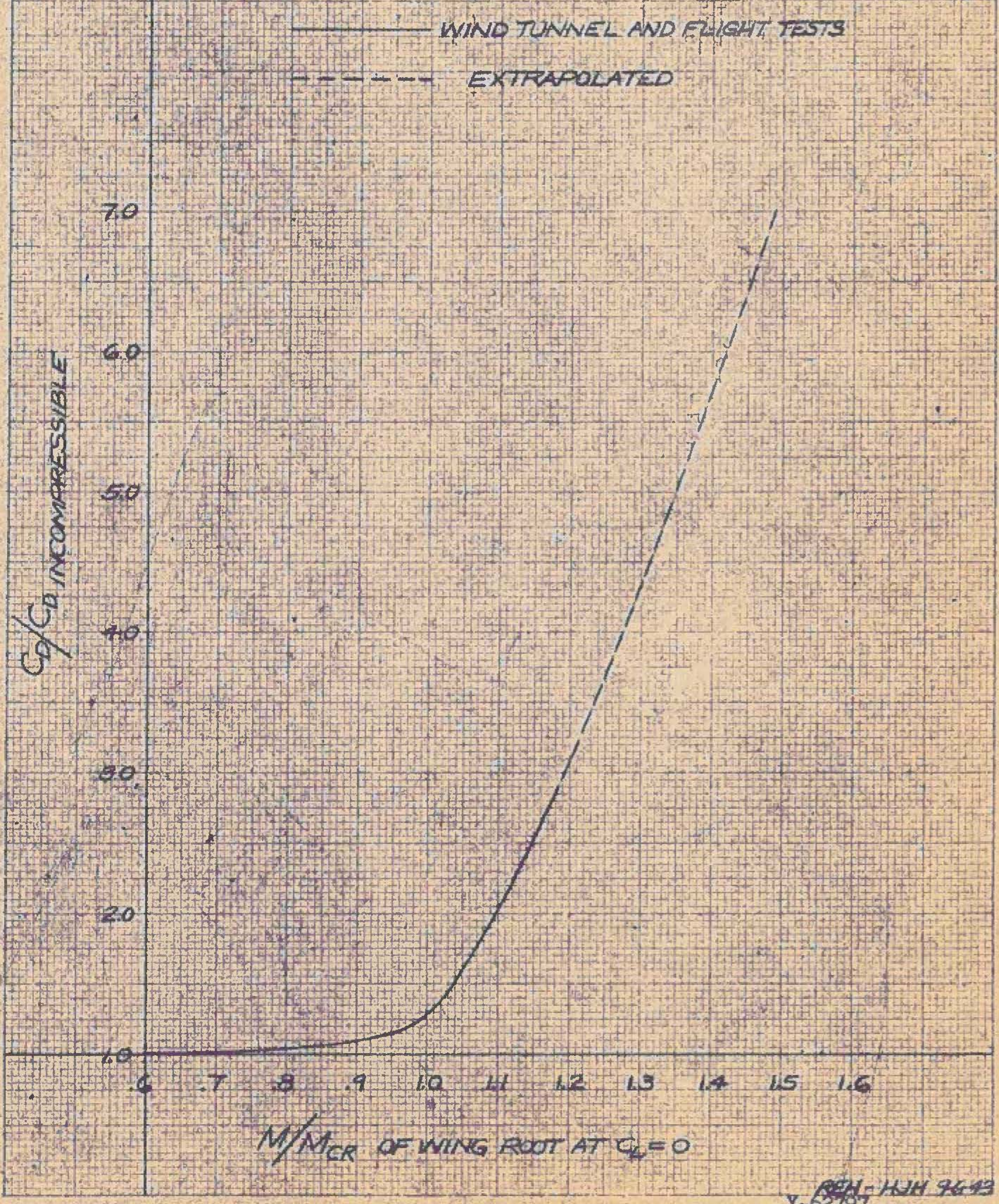

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FIG. 2

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29 September 1943

APPENDIX 2

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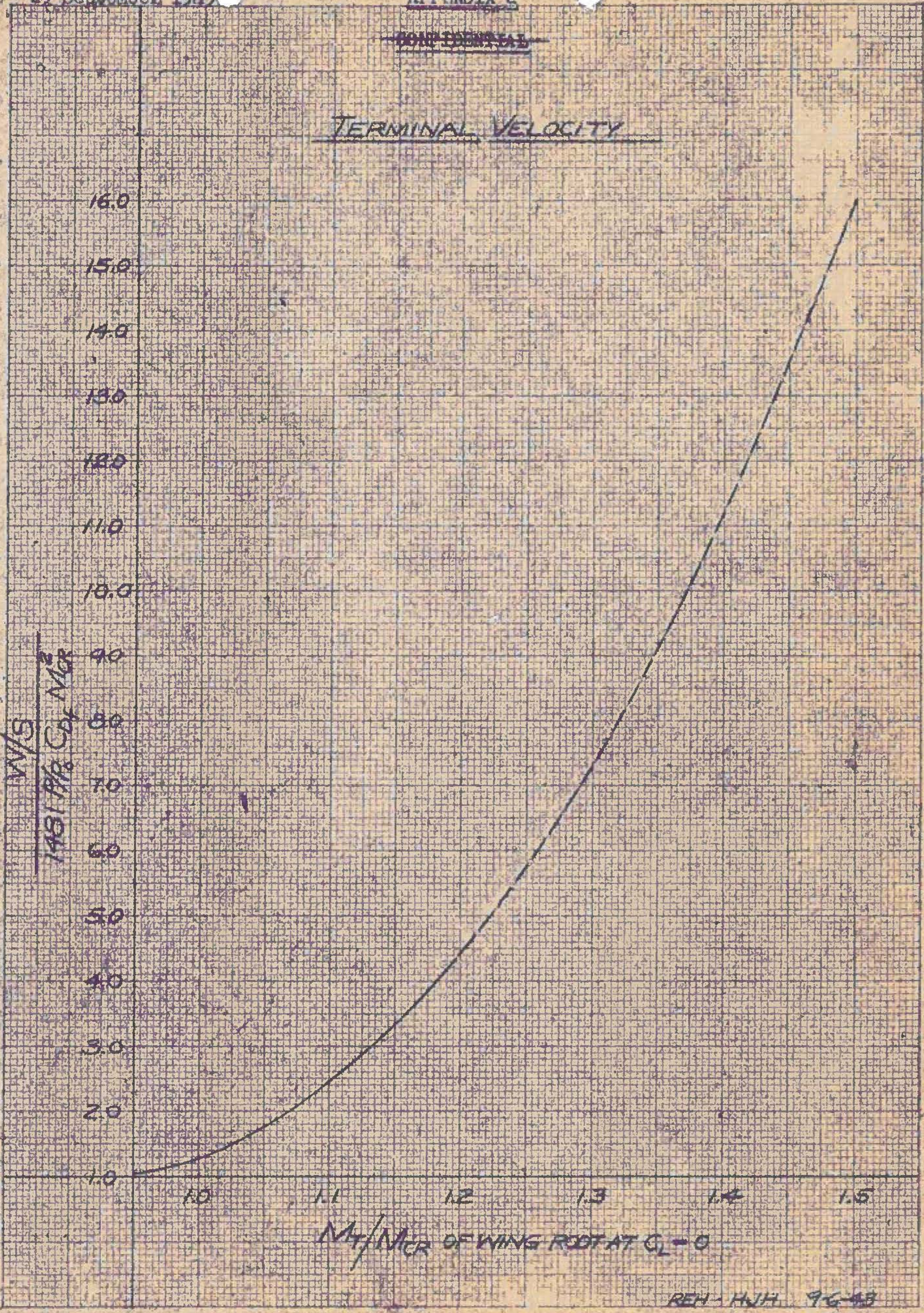

FIG. 3

Appendix 2.

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ARMY AIR FORCES
MATERIEL CENTER
ENGINEERING DIVISION
MEMORANDUM REPORT ON

Maj. H. W. Sibert
po:51 Ext. 20165

SUBJECT: Compressibility correction to Airplane Speed.

Date 31 July 1944

SECTION Aircraft Laboratory

SERIAL No. ENG-51-4589-8

Contract No.
Expenditure Order No. 456
Purchase Order No.

~~CONFIDENTIAL~~

Classification Cancelled
Auth: Dir, ATSC
Robert E. Hage
Robert E. Hage, Capt., A. C.
Date: 1-4-85

A. PURPOSE

1. To present curves for determining the compressibility corrections to the speed of both jet-propelled and propeller-driven airplanes.

B. FACTUAL DATA

1. In Figure 1 of Engineering Division Memorandum Report No. ENG-51-4589-5 a curve of $C_D/C_{D_{Incompressible}}$ versus M/M_{CR} is given, M_{CR} being the critical Mach number of the wing root at $C_L = 0$. This curve was determined from experimental data on a number of airplanes.

2. In Figure 1 of Appendix 1 are given two curves for determining the compressibility correction to airplane speed for the cases of same thrust (jet-propelled airplanes) and same power (propeller-driven airplanes) at the corrected and uncorrected speeds. The derivation of these two curves from Figure 1 of Memorandum Report No. ENG-51-4589-5 is given in Appendix 1.

3. Some designers may prefer to use curves for corrected (compressible) versus uncorrected (incompressible) speed at arbitrarily chosen values of altitude and M_{CR}. Such curves, although not necessary, can be easily obtained from Figure 1 of Appendix 1 since $V_{CR} = M_{CR} \times$ (speed of sound) is known as soon as the altitude and M_{CR} are specified.

4. When more flight-test data on high-speed airplanes are available, it may become necessary to revise Figure 1 of Memorandum Report No. ENG-51-4589-5. If this is done, the corresponding curves in Figure 1 of Appendix 1 can be obtained from a table similar to Table 1 of Appendix 1.

C. CONCLUSIONS

1. The curves in Figure 1 of Appendix 1 give a convenient method for obtaining the compressibility correction to airplane speed for both jet-propelled airplanes (same thrust at V_{INC} and V) and propeller-driven airplanes (same power at V_{INC} and V).

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Engin. Div. Memo. Rep. Serial No. ENG-51-4589-8
31 July 1944

2. Although the assumption of same thrust or same power at the corrected and uncorrected speeds may be somewhat in error (generally, not more than 5 miles per hour), these two assumptions are justified by the simplicity of the resulting corrections to airplane speed, and by the small magnitude of the possible errors incurred.

D. RECOMMENDATIONS

1. It is recommended that Figure 1 of Appendix 1 be used for determining the compressibility correction to the speed of both jet-propelled airplanes (same thrust at V_{INC} and V) and propeller-driven airplanes (same power at V_{INC} and V).

H. W. Sibert

Concurrence:

Prepared by Maj. H. W. Sibert
(Name)

Frank T. Moyers, Col, AC

Approved by PAUL H. KEMMER, Col., A.C.
Chief, Aircraft Laboratory

Marcus F. Cooper,

Approved by H. Z. BOGERT, Col., A.C.
Acting Chief, Engineering Division.

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APPENDIX 1

V, M = Airplane speed and Mach number

D, C_D = Airplane drag and drag coefficient

p, p_o = Atmospheric pressure at altitude and sea level

P, T = power available and thrust available

W, S = Weight and wing area

q = Dynamic pressure
a = speed of sound
θ = angle of dive or climb (positive when in a climb)

CR (as subscript) = critical

INC (as subscript) = incompressible (based on low-speed drag data)

NOTE: V, M, T, P, D, and C_D without subscripts refer to the compressible (or corrected) speed.

DERIVATION OF CURVES IN FIGURE 1

Values of $C_D/C_{D_{INC}}$ at various values of M/M_{CR} are listed in column 2 of Table 1. They were obtained from Figure 7 of Memorandum Report No. ENG-51-4589-5. Values of M/M_{CR} times the square root and cube root of $C_D/C_{D_{INC}}$ are listed in columns 5 and 6, respectively, of Table 1.

It is well-known that q = 1481 M^2 p/p_o. Then,

$$D = q\,C_D S = (1481\,S\,p/p_o)\,M^2 C_D \qquad (1)$$

$$DV = DMa = (1481\,S\,ap/p_o)\,M^3 C_D \qquad (2)$$

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APPENDIX 1

For straight-line flight at zero acceleration,

$$T = D + W \sin \theta \qquad (3)$$

$$T_{INC} = D_{INC} + W \sin \theta \qquad (4)$$

$$T - T_{INC} = D - D_{INC} \qquad (5)$$

Since the incompressible (uncorrected) speed and the compressible (corrected) speed occur at the same altitude, it follows from Equations (1) and (5) that

$$M^2 C_D = M^2_{INC} \, C_{D_{INC}}, \text{ (if same thrust at } V \text{ and } V_{INC}) \qquad (6)$$

$$\frac{M}{M_{CR}} \sqrt{\frac{C_D}{C_{D_{INC}}}} = \frac{M_{INC}}{M_{CR}} \sqrt{\frac{M^2 C_D}{M^2_{INC} \, C_{D_{INC}}}}$$

$$= \frac{M_{INC}}{M_{CR}}, \text{ (if same thrust at } V \text{ and } V_{INC}) \qquad (7)$$

For straight-line flight at zero acceleration (see Equations (2) and (3)),

$$P = D\,V + W\,V \sin \theta \qquad (8)$$

$$P_{INC} = D_{INC} \, V_{INC} + W \, V_{INC} \sin \theta \qquad (9)$$

$$P - P_{INC} = D\,V - D_{INC} \, V_{INC} + (V - V_{INC}) \, W \sin \theta \qquad (10)$$

If the airplane is also in level flight ($\theta = 0$), it follows from Equations (2) and (10) that

$$M^3 C_D = M^3_{INC} \, C_{D_{INC}}, \text{ (if same power at } V \text{ and } V_{INC}) \qquad (11)$$

APPENDIX 1

$$\frac{M}{M_{CR}}\sqrt{\frac{C_D}{C_{D_{INC}}}} = \frac{M_{INC}}{M_{CR}}\sqrt[3]{\frac{M^3 C_D}{M^3_{INC}\,C_{D_{INC}}}}$$

$$= \frac{M_{INC}}{M_{CR}}, \text{ (if same power at } V \text{ and } V_{INC}) \qquad (12)$$

From Equations (7) and (12), columns 5 and 6 of Table 1 are equal to M_{INC}/M_{CR} when the thrust and power, respectively, are the same V and V_{INC}. Hence, the same-thrust and same-power curves of Figure 1 were drawn with abscissas from column 1 of Table 1 and ordinates from columns 5 and 6, respectively. It should be noted that $M/M_{CR} = V/V_{CR}$ and $M_{INC}/M_{CR} = V_{INC}/V_{CR}$.

Although the same-power curve of Figure 1 was derived for a propeller-driven airplane in level flight, it can also be applied to such an airplane in a climb or dive provided the term $(V - V_{INC})W \sin\theta$ in Equation (10) is only a small fraction of P_{INC}.

Note that the same-thrust curve of Figure 1 applies to a jet-propelled airplane in a climb or dive as well as in level flight.

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Engineering Division
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APPENDIX 1

Table 1

1	2	3	4	5	6
$\frac{M}{M_{CR}}$	$\frac{C_D}{C_{D_{INC}}}$	$\sqrt{\frac{C_D}{C_{D_{INC}}}}$	$\sqrt[3]{\frac{C_D}{C_{D_{INC}}}}$	$\frac{M}{M_{CR}}\sqrt{\frac{C_D}{C_{D_{INC}}}}$	$\frac{M}{M_{CR}}\sqrt[3]{\frac{C_D}{C_{D_{INC}}}}$
.6	1.008	1.004	1.003	.602	.602
.7	1.020	1.010	1.007	.707	.705
.8	1.042	1.021	1.014	.817	.811
.9	1.095	1.046	1.031	.941	.928
.95	1.150	1.072	1.048	1.018	.996
1.00	1.277	1.130	1.085	1.130	1.085
1.025	1.410	1.187	1.121	1.217	1.149
1.05	1.595	1.263	1.168	1.326	1.226
1.075	1.805	1.344	1.218	1.445	1.309
1.10	2.035	1.427	1.267	1.570	1.394
1.125	2.280	1.510	1.316	1.699	1.481
1.15	2.535	1.592	1.364	1.831	1.569
1.175	2.805	1.675	1.410	1.968	1.657
1.185	2.900	1.703	1.426	2.018	1.690

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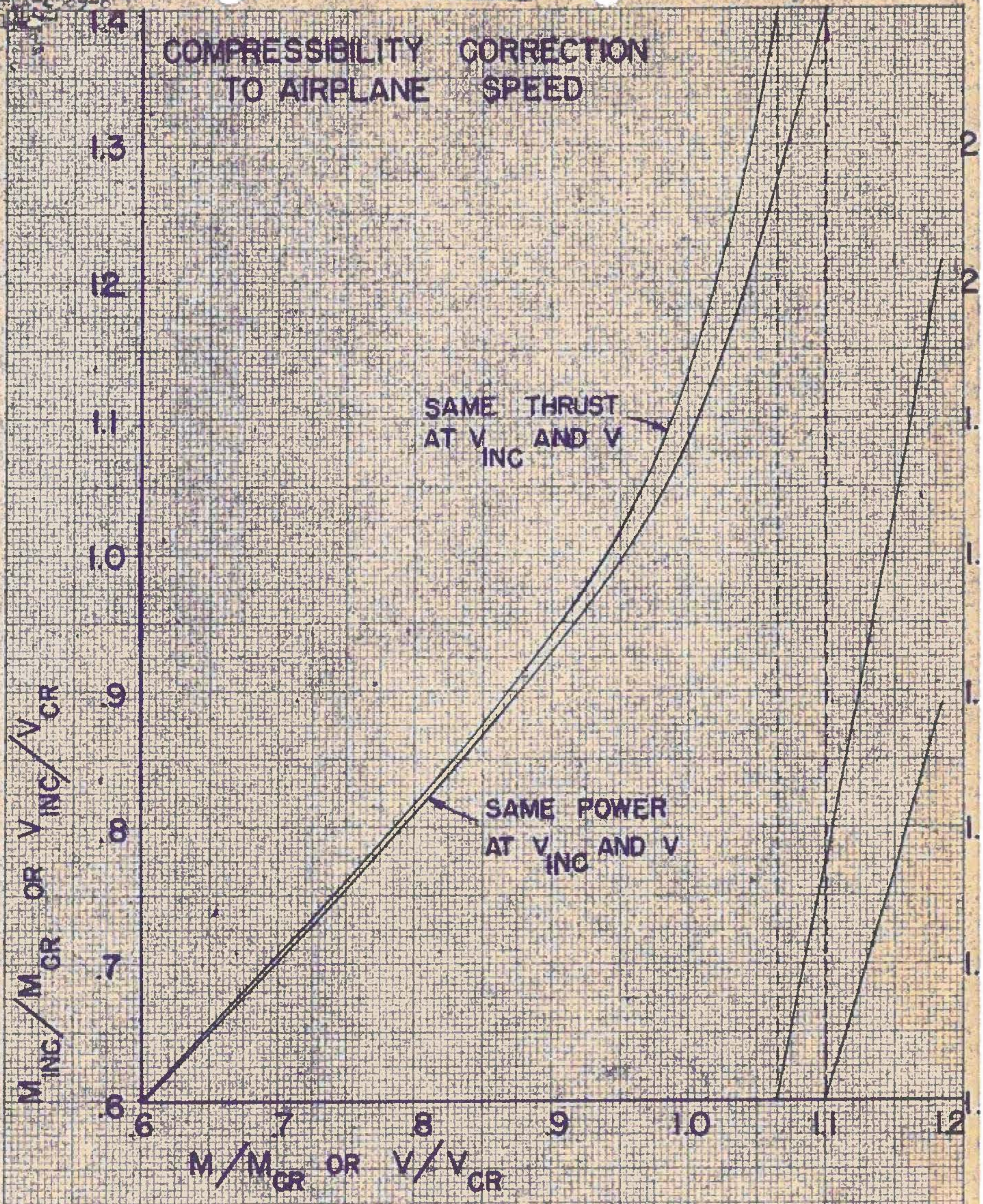

NOTE: USE M_{CR} OF WING ROOT AT $C_L = 0$

FIGURE 1