673

356(9)
313

ON THE MECHANICS OF TRANSITION PRODUCED BY PARTICLES PASSING THROUGH AN INITIALLY LAMINAR BOUNDARY LAYER AND THE ESTIMATED EFFECT ON THE LFC PERFORMANCE OF THE X-21 AIRCRAFT

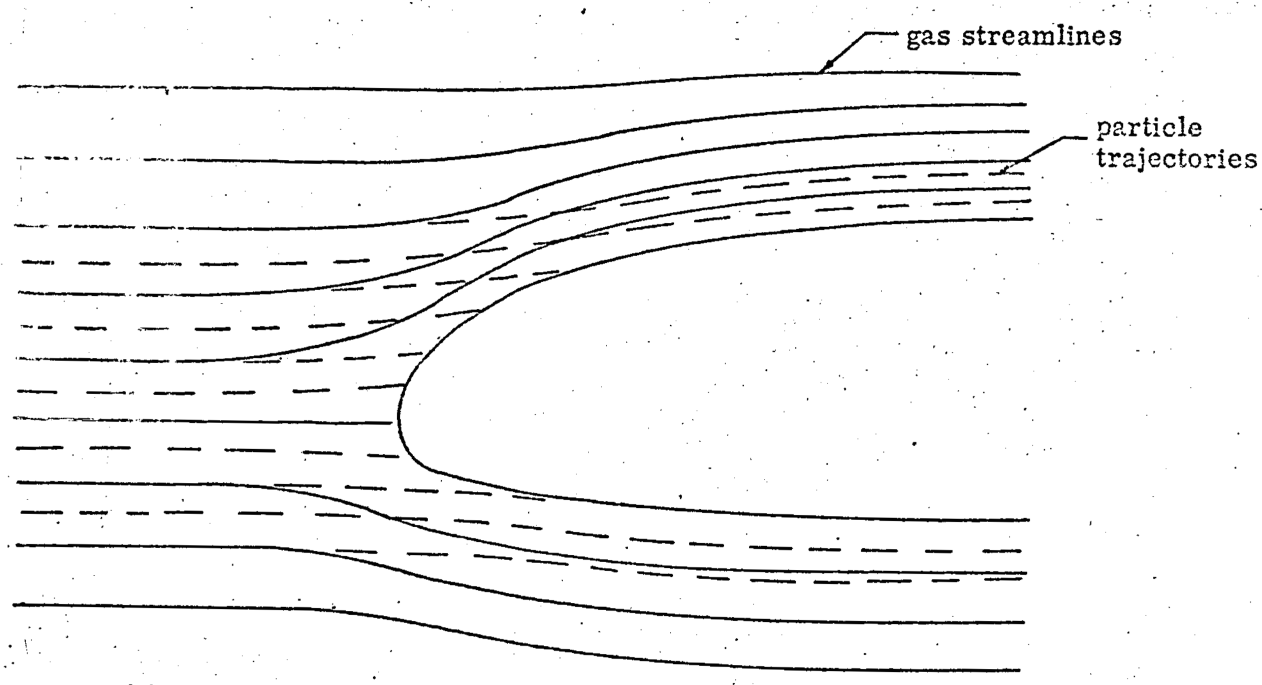
G. R. Hall, Northrop
October 1964

I. INTRODUCTION

Numerous flight tests of the X-21 aircraft have shown total loss of LFC while flying within, or in the proximity of, visible clouds. In addition, erratic LFC performance has been observed in conditions of light haze when the humidity of the air is relatively high.

An investigation of the phenomena which might account for loss of LFC in, or near clouds and for the erratic performance in light haze has been conducted. The phenomena considered in the investigation are classified as either thermodynamic effects or mechanical effects. The results derived from the study of thermodynamic effects are documented in Reference 1. All of the thermodynamic phenomena considered appeared highly unlikely in contributing to the loss of LFC in clouds and light haze conditions. The results and conclusions from the study of mechanical effects, which have led to probable identification of the problem, are presented in this document. Recommendations for follow-on work are also presented.

II. GENERAL CONSIDERATIONS OF THE FLOW DYNAMICS



Consider the heterogeneous flow of a gas-particle suspension approaching an airfoil. The obstruction produced by the presence of the airfoil alters the gas velocity magnitude and direction in the vicinity of the airfoil. The presence of the particles, if low in concentration, does not appreciably affect the inviscid flow field of the gas. The boundary conditions imposed on the gas flow require that the gas velocity be zero at the airfoil surface with gas streamlines virtually parallel to the surface in the region immediately adjacent to the airfoil. The "flow" direction and speed of the particles, however, are not governed by these boundary conditions and in general will deviate from the gas streamlines and gas speeds. In the limiting case of very small particles, the gas-particle suspension will act as a mixture of two gases, one having a high molecular weight. For this limiting case aerodynamic forces will determine the particle motion and the particles will follow the gas streamlines and maintain a speed equal to that of the gas, with no impingement of the particles on the airfoil surface. In the limiting case of very large particles, the particle inertial forces will predominate and the particles will travel in straight lines at free stream velocity until they impinge on the airfoil surface. This condition obviously gives rise to a relative velocity between the gas flow and the particle "flow" within the region of influence of the airfoil. The trajectory and speed of any finite size particle will lie between the above two limiting cases, although the particle size and gas flow conditions of interest in the current study approach the latter limiting case. That this is in fact the case will be shown in a subsequent section of this document.

For the above condition, in which a sizeable relative velocity exists between the particles and the gas flow in the vicinity of the airfoil surface, or more specifically, within the boundary layer itself, the following question is posed: By what basic mechanism could particles passing through the laminar boundary layer cause transition to a turbulent boundary layer? A review of literature on the nature of transition from laminar to turbulent flow by both natural transition and artificial disturbances provides some insight to the problem. Although different qualitative descriptions of the fine details of the transition process exist depending upon the nature of the disturbance, the particular experiment, and the investigator's personal interpretation of the results, there appears to be general agreement on the basic mechanism of turbulence initiation and propagation.[1] A general description of the transition mechanism follows.

III. TRANSITION MECHANISM

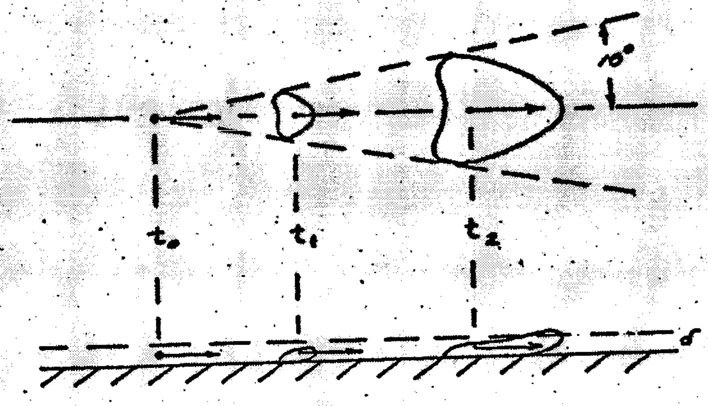
Natural transition.[2] Consider the flow of a viscous fluid over a wall in the absence of all external disturbances, and in the absence of an adverse pressure gradient. Under these conditions an initially laminar boundary layer would remain laminar at indefinitely high Reynolds numbers. In any real flow, however, small random disturbances such as random motions in the freestream, surface irregularities, and surface vibration, exist. Each of these individual disturbances to which the boundary layer is subjected is either amplified or dampened as it is propagated through the laminar boundary layer, depending on the amplitude and frequency of the disturbance and on the stability limit of the boundary layer at the point of the disturbance. As the Reynolds number of the boundary layer is increased, and the stability limit is reduced, the amplitude and frequency produced by a small disturbance will be sufficient for the disturbance to feed on the mean shear motion of flow rather than decaying. This will result in amplification of the disturbance to a high enough energy level to cause a local breakdown of the laminar flow into a three-dimensional vortex loop[3], or tiny turbulent spot. The turbulent spot is then convected downstream, eating into the adjacent laminar shear flow of the boundary layer in all directions relative to the fluid carrying it. The rate of growth of the turbulence into the adjacent laminar shear flow as it is convected downstream is such that the turbulent patch sweeps out a wedge with time whose half-angle is approximately 10^{o} for subsonic flow.

---

1 See References 2 through 8.

2 Natural transition is defined here as transition caused by the small random disturbances present in any real flow as opposed to artificial transition which is defined as transition produced by introducing artificial disturbances in the flow.

3 The formation of a three-dimensional vortex loop is a necessary prerequisite to the formation of a turbulent spot. (Reference 18)



Propagation of a Turbulent Patch

The above described disturbance amplification process occurs at randomly distributed times and positions within the boundary layer in the transition regime. Thus, the flow at any point in the transition regime will be intermittently laminar and turbulent. That is, each point in the boundary layer in the transition regime will be laminar except during those periods of time during which a turbulent patch is convected by. Since the turbulent patches grow as they are convected downstream, the flow becomes increasingly turbulent as one progresses downstream, until at some distance downstream the turbulent patches coalesce and fully cover the surface. At this point the transition region ends and a fully developed turbulent boundary layer prevails.

Artificial Transition. Various transition experiments have been conducted in which transition is induced by introducing artificial disturbances into the laminar boundary layer. Of particular interest in the current study are experiments in which transition was induced by point source artificial disturbances. The results of experiments of this type indicate a transition mechanism essentially identical to that described above for the process of natural transition. The results from two experiments in which transition to turbulence was induced by point source artificial disturbances follow.

The first experiment consists of fixing spherical, cylindrical, or conical "tripping" elements on the surface at an arbitrary position in a region of laminar flow[1]. Provided the Reynolds number of the boundary layer is greater than the critical value below which a disturbance of any amplitude is dampened,[2] three distinct patterns may exist: (1) the element may be small enough such that any disturbance created by the presence of the element is dampened; (2) the element's size is such that the disturbance produced is amplified in the manner described previously for random disturbances, developing into a turbulent spot at some distance downstream of the element; or (3) the element size is large enough to produce a turbulent spot immediately behind the element. For the first condition the total flow is undisturbed by the presence of the element. For the second and third condition a stationary turbulent wedge is produced downstream of the initial turbulent spot. The half-angle of the turbulent wedge is essentially the same as the wedge swept out by the propagation of a turbulent patch of a natural transition process (i.e., approximately 10°). The mechanism of the turbulence propagation downstream from the initial turbulent spot is the same as that for the natural transition process, the only difference being that the turbulent spot is continuous, rather than localized, in time for the case of the fixed tripping element.

Another rather interesting transition experiment pertinent to the current study is that of inducing turbulence by artificial disturbances localized in time[3]. In these experiments point disturbances were produced by a spark discharge into the boundary layer and by popping a small projection into the boundary layer from the undersurface. The time duration of all the disturbances was less than .005 seconds[4]. For these experiments the mechanism of propagation of a turbulent patch downstream of the initial disturbance was identical to that described for the process of natural transition. That is, a turbulent patch, of the same shape as for the natural transition process, originated at the initial disturbance and was convected downstream, sweeping out a wedge with time whose half-angle was approximately 10°.

1 References 14 and 16.

2 From here on such a boundary layer will be referred to as a boundary layer of infinite stability limit. For a flat plate the region of "infinite" stability limit is $Re_x < 60,000$ ($Re_\theta < 162$). For the X-21 aircraft, the region of "infinite" stability is approximately $Re_\theta \lesssim 100$ which corresponds to the first few tenths of an inch from the stagnation point.

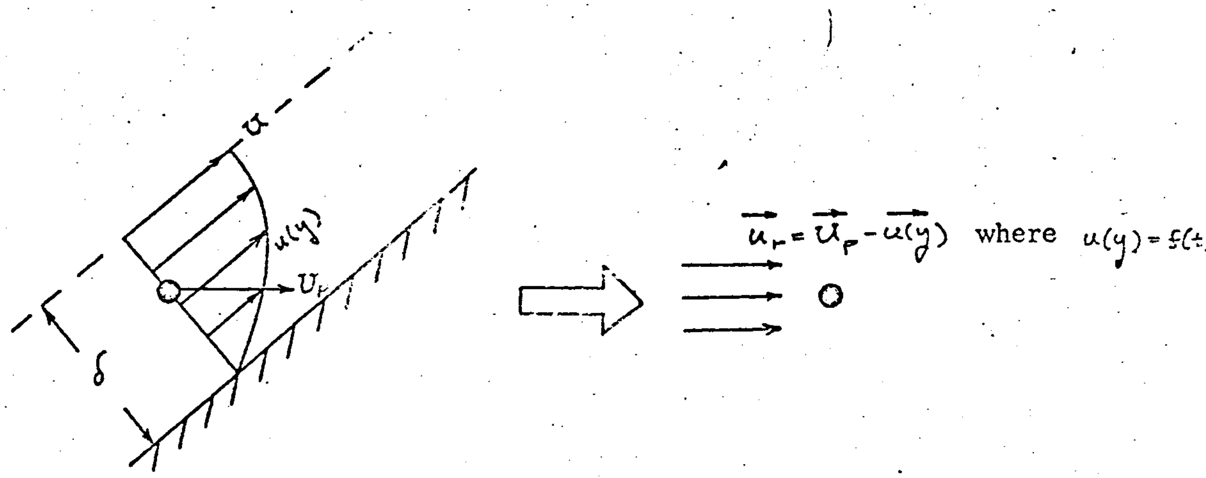
3 Reference 6.

4 The minimum duration for the disturbances was not stated.

Having gained some insight for the basic mechanism of turbulence initiation and propagation from a point source disturbance leads one to the pertinent conclusion that a necessary and sufficient condition for the production of a growing turbulent patch in an otherwise laminar boundary layer is the introduction of a very small turbulent spot, provided the boundary layer has a finite stability limit. A necessary condition for the creation of a turbulence spot is a three-dimensional vortex loop. Furthermore, the duration of the disturbance that produces the turbulence spot need be only a brief instant in time. Then, the general problem at hand of determining the basic mechanism by which particles passing through the boundary layer could cause transition is reduced to one of determining the criteria by which particles passing through the boundary layer produce a small turbulent spot. This is the subject of the next section.

IV. INITIATION OF TURBULENT SPOTS

Consider a particle passing through a laminar boundary layer at a generally oblique angle to the surface. A coordinate system which moves with the particle reduces the problem to one of a non-stationary flow past a fixed particle as shown.[1]



[1] Although the flow is actually non-stationary relative to the particle, a quasi-stationary condition is assumed to exist at any instant for the discussion that follows. In addition, the particle is assumed small compared to the boundary layer thickness such that the particle "sees" a uniform approaching flow rather than a flow with a velocity gradient.

The question to be answered is: Over what range of relative velocities $u_r = U_p - u(y)$ is any turbulence produced in the flow field by the presence of the particle? The answer to this question is provided by a study of the wake structure behind the particle. The wake structure, or wake configuration, is a function of the particle Reynolds number and geometry of the particle and may fall into one of four categories. This is illustrated in Figure 1 which shows the Reynolds number regime for various wake characteristics for a cylinder and a sphere in subsonic flow.

At low values of Reynolds number (i.e., $R \lesssim 40$ for a cylinder) a steady laminar wake is formed behind the particle[1]. This wake configuration is a stable viscous configuration in which a laminar free shear layer (the separated boundary layer) separates the wake region from the external flow. An equilibrium rate exists between the generation of vorticity in the boundary layer and the diffusion of vorticity from the wake into the mainstream. As the Reynolds number is increased, the steady laminar wake is transformed into a periodic laminar wake. For this configuration, the generation of vorticity in the boundary layer is greater than the rate at which vorticity can be continuously diffused from the wake into the mainstream. This results in the release of vorticity from the wake at regular intervals by shedding of free viscous vortices which move downstream with no further possibility of the fluid within the vortex to become turbulent. The periodic laminar wake configuration is a stable viscous configuration as is the steady laminar wake.

As the Reynolds number continues to increase, the laminar-turbulent transition regime prevails ($150 \leq Re \leq 300$ for a cylinder). In this wake configuration turbulent spots occur in the inherently low stability free shear layer itself.[2] As in the case of the periodic laminar wake, free vortices are shed from the wake, although at less periodic intervals. These vortices which break away from the

1 If the Reynolds number is very low ($Re \lesssim 10$) there will be flow separation behind the particle.

2 Free shear layers are inherently less stable than boundary layers in that there is no surface present to dampen disturbances.

wake into the mainstream in the transition range, are predominately composed of turbulent fluid. In the transition range the wake behind the particle takes on irregular asymmetric characteristics. At still higher Reynolds numbers ($Re \geq 300$ for a cylinder) the free shear layer becomes totally turbulent, shedding turbulent vortices at irregular intervals. The primary reason for the higher Reynolds number for a given wake structure for a sphere compared to a cylinder as seen in Figure 1 is attributed to the lower velocity at the separation point of the sphere for the same free stream velocity (i.e., free stream Reynolds number). This results in a lower characteristic Reynolds number of the separated free shear layer.

From the above description of the wake characteristics behind a bluff body one can conclude that the initiation of turbulent spots into the mainstream[1], which is a sufficient condition for the production of a growing turbulent patch in a boundary layer flow of finite stability, is coincident with the onset of wake transition. Furthermore, it is seen that the onset of wake transition is dependent only on the particle Reynolds number and geometry of the particle, both of which are constants for subsonic speeds[2]. The observation that a turbulent spot introduced into the boundary layer is a very localized effect, both in time and position, carries very significant overtones. This observation leads to the powerful implication that turbulence produced by particles in passing through the initially laminar boundary layer is independent of all other effects such as boundary layer Reynolds number, free stream turbulence, pressure gradient, surface condition, suction quantity, vibration, heat input, etc., within the usual

1 It is recalled that "mainstream" as defined in this section is the boundary layer flow of the overall problem being investigated.

2 The particle Reynolds number at the onset of wake transition increases with Mach number at supersonic speeds.

limits of these parameters[1]. These effects, all of which combine to affect the stability of the boundary layer and/or the point of natural transition, should not affect the basic process described previously by which a turbulent spot is initiated by a very small particle passing through the boundary layer.

The next section of this report will attempt to provide further credence to the hypotheses put forth in the above arguments, namely: (1) that the onset of particle wake transition is the proper criterion for the breakdown of laminar flow; and (2) that the process by which this laminar flow breakdown takes place is, to the first order, independent of the usual parameters which affect the boundary layer stability and the location of natural transition.

V. SURFACE ROUGHNESS EXPERIMENTS

Various experiments have been conducted to determine the effects of two-dimensional roughness elements, three-dimensional roughness elements, and distributed roughnesses on boundary layer transition[2]. Although these experiments differ from the current problem in that the roughness elements are fixed on the surface, the basic phenomena involved in producing transition of the laminar boundary layer are the same. The results obtained from these experiments support the hypotheses put forth in Section III. The salient features of these experiments as related to the current study are given below.

The results from several experiments on the effect of three-dimensional roughness or "tripping" elements on boundary layer transition have been reported. The roughness elements used in these experiments were predominantly spherical, cylindrical, and conical elements attached to the surface. The results

---

1 Obviously, extremes of most of these parameters must be excluded. For instance, a boundary layer Reynolds number or pressure gradient for which the boundary layer is of infinite stability, ultra high frequency free stream turbulence or vibration of the same order as the vortex shedding frequency of the element (0 (10^6)/sec), suction to the extent of essentially sucking off the entire boundary layer and re-establishing a new boundary layer, etc.

2 References 13 through 20.

of these experiments, which have been correlated on an empirical basis, have shown the roughness Reynolds number, that is, the Reynolds number based on the particle height, k, and on the velocity in the undisturbed boundary layer at the particle height, u_k, to be the only significant parameter upon which transition of the laminar boundary layer depends.[1] These data show no effect of the roughness element below a certain critical roughness Reynolds number (i.e., $Re_k \approx 600$ for a sphere). Above the critical roughness Reynolds number premature transition of the boundary layer occurs, moving rapidly to the roughness element as the roughness Reynolds number is increased further. A turbulent wedge such as described in Section III is formed behind the roughness element provided the local boundary layer has a finite stability limit. These experiments have shown that a region of infinite stability exists in which the laminar boundary layer is unaffected by a particle of any size. This region of infinite stability has been found to correspond very closely to that predicted by Tollmien[2] (i.e., $Re_x < 60000$ for a flat plate) for small amplitude two-dimensional disturbances[3].

The results from experiments of the effects of two-dimensional roughness or "tripping" elements on boundary layer transition have been generally similar to those of three-dimensional elements, although with some differences. The roughness elements used in these experiments were predominantly cylindrical wires attached to the surface in a direction perpendicular to the oncoming flow. The results of these experiments show the best correlation of the data by plotting the boundary layer transition Reynolds number as a function of the non-dimensional roughness height k/δ^*. However, a reasonably good correlation is also obtained by plotting the transition Reynolds number as a function of the roughness Reynolds number as was done for the three-dimensional elements. Presented in this form,

---

1 This was originally postulated by Schiller prior to any roughness experiments. (Reference 20).

2 Reference 2, Chapter 16.

3 It is interesting that a region of infinite stability exists for the type of disturbance produced by a three-dimensional roughness element in that the infinite stability region predicted by Tollmien should apply, theoretically, only to small amplitude two-dimensional wave type disturbances.

the data indicate a critical roughness Reynolds number of $Re_x \approx 200$. Again, as for the case of three-dimensional roughness elements, a region of infinite stability is indicated in which the boundary layer is unaffected by a tripping element of any size.

The basic difference between the data of two-dimensional and three-dimensional elements is that for the two-dimensional element the point of transition does not move abruptly to the point of disturbance at the critical roughness Reynolds number, but instead approaches the element rather gradually as the roughness Reynolds number is increased beyond the critical value. That the transition point approaches the roughness element rather gradually is explained by the argument that the two-dimensional element produces two-dimensional vortices which must develop into three-dimensional vortices before eventually disintegrating into turbulence[1]. On the other hand, a three-dimensional element is more straightforward in producing three-dimensional vortices, thus causing transition to move rather quickly to the element.

These roughness element experiments have shown, as one would predict from the local nature of the disturbance, virtually no effect of the local boundary layer Reynolds number (provided the boundary layer is not infinitely stable), pressure gradient, and free stream turbulence on the critical roughness Reynolds number. Furthermore, considering the nature by which the roughness elements cause transition, one would not expect an appreciable influence of surface condition, suction quantity, vibration, or heat transfer as suggested in Section IV. On the other hand, Mach number has been shown to have a significant effect on the critical roughness Reynolds number in the supersonic regime. The critical roughness Reynolds number has been found to increase with Mach number in the supersonic regime which is consistent with the increase in wake transition Reynolds number with Mach number in the supersonic regime.

Figure 1 shows the range of observed critical roughness Reynolds numbers from several experiments both for cylindrical and spherical roughness elements.

---

1 A three-dimensional vortex is considered a necessary prerequisite to turbulence.

It is of significance that the range of critical roughness Reynolds numbers for both the cylindrical and spherical elements corresponds closely to the range of wake transition Reynolds numbers for these elements. Although the roughness element Reynolds number at the onset of transition in the wake behind the element fixed on the surface would not be expected to be exactly the same as that for the same element placed a finite distance from the surface, one would not expect a great difference between the two conditions.

An investigation of the velocity profile in the wake of a semi-cylindrical two-dimensional roughness element was made by Liepmann[1]. The results of this investigation indicated that at subcritical values of roughness Reynolds numbers, the flow separated at the element, remained laminar, and reattached to the plate forming a laminar boundary layer. However, for supercritical value of roughness Reynolds numbers, transition occurred in the separated free shear layer and the reattached boundary layer was turbulent.

In summary, the results of roughness element experiments are seen to strongly support the hypotheses of Section IV, namely that (1) the onset of transition in the wake of a particle passing through a laminar boundary layer is the criterion for the spread of turbulence into the adjacent laminar flow and (2) that the local nature of the process renders it independent of the usual parameters which affect boundary layer stability and the location of natural transition.

VI. ENGINEERING CONSIDERATIONS

Having reviewed the physical characteristics of boundary layer transition and postulated a criterion for the production of a turbulent spot by a particle passing through the boundary layer, it is now appropriate to apply the results to the original problem being investigated, that is, to determine whether or not the particles encountered by the X-21 aircraft are of sufficient size, and remain in the boundary layer for a sufficient length of time, to cause turbulent spots. In addition, an equally important consideration in connection with the observed degraded LFC performance

---

1 Reference 19.

in clouds and light haze is to determine whether or not the incident particle flux is high enough to result in a discernible effect. That is, "occasional" encounters of turbulent spots over the wing will not produce a discernible effect on a time-average basis. Then it is seen that three independent criteria must be satisfied to produce a discernible loss of LFC on a macroscopic time scale: (1) The incident particles must be of sufficient size (i.e., sufficient particle Reynolds number) to produce a turbulent spot; (2) the particles must remain in the boundary layer for sufficient duration to introduce turbulence; and (3) the incident flux of particles satisfying the first two criteria must be high enough to result in a significant area of turbulence over the wing on a time-average basis.

<u>Ice crystal size.</u> Quantitative data from sampling of ice particles in natural clouds is practically nil. However, some quantitative statements on "typical" ice particle sizes and crystalline structure in cirrus clouds have been found in the literature. Reference 21 states that ice crystals in cirrus clouds are of a columnar configuration, typically 50 to 200 microns long, with a length to diameter ratio varying from 2 to 5. Reference 22 states that ice crystals in cirro stratus clouds are typically hexagonal prisms approximately 100 microns in length and 40 microns in diameter. Reference 23 states that ice crystals in natural clouds below $-25^{\circ}C$ are predominantly hexagonal prisms, typically 500 microns in length with a length to diameter ratio varying from one to five. Although differing in the magnitude for typical ice crystal size, all three references agree on the predominant crystalline structure. Therefore, for the current numerical study, the ice crystals encountered in cirrus cloud and haze conditions above 25,000 feet will be assumed to be hexagonal prisms with a length to diameter ratio of 2.5. The size of the particles will remain a variable of the problem.

The explanation for the equilibrium existence of ice crystals in clouds at conditions of relative humidity below 100% is that the saturation vapor pressure of ice is less than that of supercooled water and that relative humidity readings, as a matter of convention, are referenced to the saturation vapor pressure of supercooled water. Therefore, ice crystals will exist at relative humidity readings below 100%.

An ice particle of the hexagonal prism configuration with a length to diameter ratio of 2.5 can probably be considered as a two-dimensional cylinder from the point of view of selecting the critical value of particle Reynolds number for the onset of wake transition.[1] On the other hand, the particle will probably act as a three-dimensional element from the standpoint of rapid development of three-dimensional vortices, and associated turbulence, downstream of the element due to vortex shedding from the ends. Then, the critical particle Reynolds number, based on the particle diameter and the relative flow velocity between the particle and the gas in the boundary layer, will be taken as $R_{e_{crit}} = 150$ (i.e., onset of wake transition for flow over a cylinder) for the current study.

From particle trajectory studies defining the velocity of the particles relative to the airfoil, along with vector addition of these velocities with the local gas velocities in the boundary layer, it may be shown that the maximum relative velocity between the particles of interest in the current study and the gas is, at some point in the boundary layer, at least equal to free stream velocity for all values of impingement angles. Therefore, the nominal value of the relative velocity between the particles and the gas in the boundary layer will be taken as free stream velocity.

Then, based on $R_{e_{crit}} = 150$ and the relative velocity nominally equal to the free stream velocity, the critical particle diameter required to disrupt laminar flow is found to be 17 microns at an altitude of 25,000 feet and 32 microns at an altitude of 40,000 feet for a free stream Mach number of $M_{\infty} = .75$.

Particle duration. The average time spent in the boundary layer by a particle impinging within 1 foot from the leading edge as measured along the

---

[1] This appears to be substantiated by the data of Reference 16 for cylindrical roughness elements of $L/D = 2.5$.

airfoil surface[1] is estimated to be approximately 1×10^{-5} seconds. This is based on a free stream Mach number of $M_\infty = .75$ and an average boundary layer thickness over the first 1 foot of surface of .03 inch. Further, it assumes that the particles impinge the surface at free stream velocity relative to the surface and are specularly reflected at the same velocity (i.e., elastic impact on a smooth surface).

A clue to the minimum duration required to initiate a turbulent spot is afforded by looking at the vortex shedding frequency of the particles. The periodic shedding frequency appears in the non-dimensional Strouhal number which has been determined experimentally to be only a function of the particle Reynolds number and the particle geometry. For the range of particle Reynolds numbers and particle geometries of interest in the current study, the vortex shedding frequency is approximately 1×10^6 vortices/second. This means that, on the average, the number of vortices shed by a particle in passing through the boundary layer is of the order of 10. In the wake transition Reynolds number regime, these vortices are predominantly composed of turbulent fluid. Therefore, the above considerations would indicate that the particles remain in the boundary layer considerably longer than the minimum time required to initiate a turbulent spot.

Incident particle flux. The degree of LFC performance degradation due to particles passing through the boundary layer is obviously dependent on the incident particle flux as well as the particle size and particle duration in the boundary layer. In order to relate the incident particle flux to the free-stream particle flux,[2] and to substantiate the previous assumption that particles of interest in the current study may, to a first approximation, be assumed to impinge the wing at free stream velocity in the region of the leading edge, a

---

1 For spherical particle diameters less than 50 microns, at least 90% of all particles that impinge the airfoil will do so within $s = \pm 1$ ft from the leading edge.

2 This ratio is more commonly referred to as the "collection efficiency."

calculation of the particle impingement dynamics for the X-21 aircraft was necessary. The particle impingement dynamics have been evaluated from the general treatment of the problem given in Reference 26. This generalized treatment gives various particle impingement parameters as a function of free stream velocity, air viscosity and density, particle diameter and density, and airfoil size and shape for spherical particles. The results for the X-21 aircraft are presented in Figures 3 through 5 for a free stream Mach number of $M_\infty = .75$ and altitudes of 25,000 feet and 40,000 feet. The airfoil shape was approximated by a 5:1 aspect ratio ellipse which is shown superimposed on a typical X-21 wing cross-section in Figure 2. The 5:1 ellipse approximation is seen to be a very good representation of the true airfoil section within the region of possible particle impingement (i.e., the first 25% chord). The particles were assumed to be solid ice crystals of 0.9 density and neutrally charged such that no static-electric forces exist.

For the above conditions it is seen from Figure 3 that particles less than 4 microns in diameter will not impinge on the airfoil surface while particles greater than approximately 50 microns will impinge at very nearly free stream velocity and free stream intensity in the proximity of the leading edge. Similar results were obtained by approximating the leading edge of the wing by an equivalent cylinder and utilizing the results of Reference 27, which presents a general treatment of particle impingement on a cylinder.

Figures 4 and 5 show the local particle collection efficiency for particles of various sizes at altitudes of 25,000 feet and 40,000 feet, respectively. The slightly broader intensity distribution at 40,000 feet primarily reflects the reduction in air density, and hence, a reduction in drag force or influence of the airflow on the particle trajectory.

Having determined the local incident particle flux in terms of the free stream particle flux, the local duration of particles in the boundary layer, and knowing the growth dynamics of turbulent spots, one may estimate the free stream particle flux necessary to give a specified time-averaged turbulent area of the X-21 wing produced by particles passing through the boundary layer.

Further, it is a simple matter to relate the free stream particle flux to particle concentration, or cloud density, and free stream velocity. Then one can relate the time-averaged turbulent area produced by particles passing through the boundary layer directly to the cloud density and free stream velocity.

Visibility. The particle concentration, or density, of clouds and haze is usually expressed in terms of a particle weight per unit volume. Although expressing cloud densities in this manner is precise in a quantitative sense, it lacks tangibility for those not accustomed to thinking in these terms. On the other hand, expressing cloud densities in terms of visibility provides a more tangible, although less quantitative, means of expressing cloud densities.

An equation has been derived which relates visibility to particle size and concentration, where visibility has been arbitrarily defined as 90% sight attenuation. That is, when looking at an object through a cloud of particles, the limit of visibility was defined as the cloud optical thickness at which the object was 90% obliterated by particles between the observer and the object. The general validity of the equation was substantiated by favorable comparison to an empirical curve of visibility as a function of particle concentration for the special case of fog and low clouds and was then applied to the high altitude ice clouds of interest in the current study.

VII. DISCUSSION OF RESULTS

The results obtained from the engineering considerations delineated in the previous section are presented in Figures 6 and 7 for altitudes of 25,000 feet and 40,000 feet, respectively, and for a free stream Mach number of $M_{\infty} = .75$. The ice particle configuration is assumed to be a hexagonal prism with a length to diameter ratio of 2.5. Although presenting the results in terms of an equivalent sphere diameter offers convenience and, at first impression, might appear to give more generalization to the results, it was avoided in that it introduces ambiguity and begs erroneous conclusions. For instance, the "equivalent sphere" from the standpoint of particle volume equivalence is different from the "equivalent sphere" from the standpoint of turbulence production equivalence[1]. Therefore the only unambiguous way of presenting the results is a presentation for specific ice particle geometries.

Figures 6 and 7 show the estimated region of degraded LFC performance over a wide range of particle sizes and free stream particle flux levels. The region of degraded LFC performance is bounded on the left by a constant critical particle size, below which it is estimated the particles are too small to cause turbulence. The region is bounded from below by the boundary labeled "threshold of erratic operation," below which the particle flux is too low to cause a significant loss of LFC, even for large particle sizes. The "threshold of erratic operation" boundary was arbitrarily defined and calculated as a time-average 10% area of turbulence produced by particles over the wing.

In the upper half of the region is a line separating the region of degraded LFC performance into "partial loss of LFC" and "total loss of LFC." This line corresponds to the estimated impending level of particle flux which just results in a time-averaged 100% turbulent wing area. Although the incident flux for a given percentage of turbulent wing area is not dependent on particle sizes for particle sizes greater than the critical value, the required free stream flux to give a specified turbulent area is seen to decrease with particle size. This reflects the increase in the particle collection efficiency with particle size which was observed in Figures 3 through 5.

The upper boundary of the region of degraded LFC performance is the maximum anticipated ice crystal concentration in clouds at 25,000 feet and 40,000 feet. Reference 26 gives this maximum as approximately 1.0 gm/M^3 while Reference 25 gives a maximum of 0.1 gm/M^3. Personal observations by X-21 Flight Test pilot,

---

1 As an example, at 25,000 feet the critical particle size is seen to be 17 μ x 42 μ based L/d = 2.5. The equivalent volume "equivalent sphere" is D = 27μ. On the other hand the critical size for a true sphere at this condition is estimated to be D = 68μ due to a higher critical partical Reynolds number for the sphere than for a cylinder. (See Figure 1)

Dick Thomas, based on visibility considerations, tend to favor the former number[1].

Tangibility is introduced into Figures 6 and 7 by showing various lines of constant visibility. In addition, a "typical" cirrus cloud condition as defined in Reference 22 is shown in which the ice particles are of the hexagonal prism configuration, $100\mu \times 40\mu$ in size, and in a concentration of .01 gm/M^3.

Although no quantitative correlation of the X-21 LFC performance as a function of cloud and haze parameters exists, the results of the current study appear to be in good agreement with qualitative observations of the X-21 LFC performance in clouds and haze. For example, total loss of LFC has been observed in cloud conditions in which the visibility has been described as being several thousand feet. This is in good agreement with Figures 6 and 7 which would predict total loss of LFC for visibilities of the order of 5,000-10,000 feet and for typical particle sizes greater than the critical size. Another example is that LFC performance has been observed to be erratic and partially degraded in conditions of light haze, where light haze has generally been described by flight test engineers and flight test pilots to be approximately 30 - 60 miles horizontal visibility. This is in good qualitative agreement with Figures 6 and 7 which would predict a moderate LFC performance degradation for a visibility condition of 50 miles and particle sizes greater than the critical size.

Before ending this section, a comment should be made on the effect of particle size distribution on the interpretation of the results of the current study. The results presented imply that at a given condition either all of the particles in a cloud are greater than the critical particle size or all the particles are less than the critical particle size. This condition is closely approximated if the average particle size at a given condition is significantly greater than, or less than, the critical particle size and the size distribution spectrum is relatively narrow. If the average

---

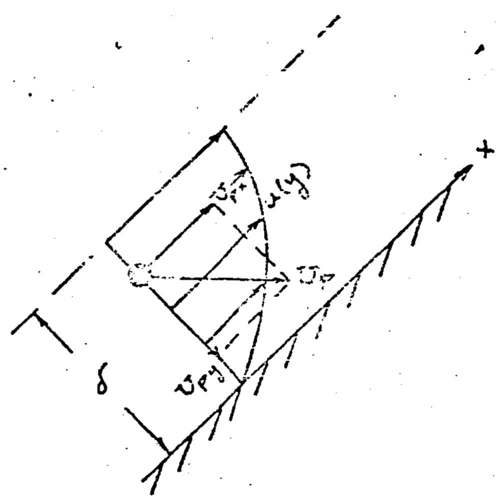
1 Cirro-Stratus clouds have been observed at both 25,000 feet and 40,000 feet in which visibility has been reduced to approximately 300 feet. Visibility of this range is seen from Figures 6 and 7 to favor an ice particle concentration of 1 gm/M^3.

particle size is close to the critical particle size, and the size distribution function is not sufficiently narrow, the above condition is not closely approximated. The result would be an over prediction of the effect of clouds for particle distributions giving an average particle size only slightly greater than the critical particle size, and an under prediction for particle distributions giving an average particle size slightly less than the critical particle size. As an example, without consideration for size distribution, if the particle flux is 10^6/sec. ft^2 and the particle size is $60\mu \times 24\,\mu$ in Figure 7, one would predict there is no effect of this cloud condition on the LFC performance. On the other hand, if the particle flux is 10^6/sec. ft^2 and the average size particle is $60\mu \times 24\mu$, but 10% of the particles are greater than $80\mu \times 32\mu$ thus giving 10^5/sec. ft^2 of particles greater than the critical particle size, one would predict a moderate degradation in LFC performance.

VIII. MOMENTUM INTERCHANGE

One other mechanism by which particles passing through the boundary layer might potentially cause premature transition was investigated. The mechanism considered was a direct interchange of momentum between the particles and the gas in the boundary layer.

Consider a particle passing through a boundary layer as shown below:



In traversing through the boundary layer a time dependent drag force in the X-direction results from the X-direction velocity differential, $u(y) - U_{px}$. The resulting drag force integrated over the time spent in the boundary layer gives the impulse exchanged between the particle and the gas in the boundary layer. Multiplying this impulse by the flux of oncoming particles gives a force per unit length of surface. This force acts to decelerate the flow for large impingement angles[1] in the same manner as an adverse pressure gradient. In fact, the phenomenon may be evaluated in terms of an equivalent adverse pressure gradient. This has been done for the current study. The results of a numerical calculation for the X-21 aircraft show that the particle flux is far too low to result in a significant momentum interchange, or adverse pressure gradient.

1 Assuming a Blasius velocity profile, this force acts to accelerate the boundary layer for impingement angles less than 40°.

IX. CONCLUSIONS

The conclusions derived from the current study are as follows:

1. The onset of transition in the wake of a particle in passing through a laminar boundary layer is suggested to be the criterion for the spread of turbulence into the adjacent laminar flow.
2. The disturbance produced by a particle in passing through a laminar boundary layer is localized in time and space and is therefore independent of the usual parameters which affect the boundary layer stability and point of natural transition.
3. The size of "typical" ice crystals in clouds above 25,000 feet is probably greater than the critical size required to initiate a turbulent spot in the boundary layer of the X-21 aircraft. The critical diameter is estimated to be 17 microns and 32 microns at altitudes of 25,000 feet and 40,000 feet, respectively.
4. The duration of a particle in passing through the boundary layer is probably an order of magnitude greater than the minimum time required to initiate a turbulent spot in the boundary layer of the X-21 aircraft.
5. The incident ice particle flux in cirrus clouds of horizontal visibility of the order of 5,000-10,000 feet is predicted to be high enough to result in total loss of LFC on the X-21 aircraft.
6. The incident ice particle flux in light haze is predicted to be high enough to result in degraded LFC performance of the X-21 aircraft.
7. The results predicted by the current study appear to be in good agreement with qualitative observations of LFC performance of the X-21 aircraft in clouds and light haze.
8. A calculation of the momentum interchange between ice particles and gas in the boundary layer indicates this phenomenon to have an insignificant effect on LFC performance of the X-21 aircraft.

X. RECOMMENDATIONS FOR FOLLOW-ON WORK

The preliminary analyses of the effects of various thermodynamic and mechanical atmospheric phenomena on the LFC performance of the X-21 aircraft are concluded. These analyses have provided probable identification of the basic mechanism causing degraded LFC performance in clouds and light haze. Continued effort in the area should be predominately experimental in nature, although study of the mechanism of boundary layer transition phenomena should be carried on in parallel. Experimental investigations of the transition of a laminar boundary layer caused by particles passing through the boundary layer should proceed along two lines: (1) controlled laboratory experiments, and (2) flight testing.

Controlled laboratory experiments offer several advantages over flight testing. In the controlled experiment, the fundamentals of the problem can be examined in detail, thereby enhancing one's basic understanding of the problem. Generalized criteria may be sought out such that the results obtained are not restricted to one configuration at one operating condition. On the other hand, flight testing provides evaluation of the gross characteristics of the problem for a given configuration at limited operating conditions, but provides little insight to understanding the fundamentals of the problem and does not provide data of a generalized nature which may be applied with confidence to predict the performance of other configurations operating at other flight conditions.

Controlled Laboratory Experiments

Investigation of this problem by a series of controlled experiments should probably begin with a "simple-minded" experiment in which single particles are suspended within, or bounced through, the boundary layer over a flat plate parallel to the flow and a flat plate in stagnation flow. Suspending a particle within a boundary layer (or other shear flow) would allow study of the development of the particle wake in a shear flow, and the mechanism by which turbulence is spread to the adjacent laminar flow. A critical particle Reynolds number could be obtained in this manner. Bouncing particles through the boundary layer would introduce more realistic dynamics into the problem[1] but provide less opportunity to correlate particle wake characteristics to the onset of transition in the boundary layer. In either the case of suspending a particle within the boundary layer or bouncing particles through the boundary layer, the fluid utilized, the range of free stream velocities selected, the drop velocity of the particles for the latter case, and the plate size would be chosen to give a thick boundary layer so that the range of particle sizes would be large rather than microscopic. It would probably be desirable to superimpose the effects of free stream turbulence, suction, and surface condition into these tests.

Fundamental experiments of the type described above would lead to more elaborate experiments in which controlled particle sizes were introduced into the freestream in large numbers, and the flat plate replaced by airfoil to give better simulation of particle impingement dynamics and to introduce the effect of pressure gradient.

Flight Testing

The problem of evaluating the effect of ice particles on the LFC performance of the X-21 aircraft by flight testing was discussed in a recent meeting with Meteorological Research Inc.[2] The primary objectives should be to: (1) establish a correlation of LFC performance with ice particle concentration and size distribution, and (2) establish, on a statistical basis, typical levels of ice concentrations, particle configurations, and size distributions at altitudes between 25,000 and 40,000 feet. Ideally, the data from objective (2), when combined with the results of the controlled laboratory experiments, would allow one to predict the effects of ice particles on the LFC performance for any general LFC aircraft at any flight condition.

---

1 One would have to be careful to insure that the particle impact would not produce undesirable vibration side effects.

2 A summary of this meeting is given in Norair Memo 1931-64-87.

The instrumentation selected to sample the ice particles in the flight test operation should be capable of sampling all particles greater than approximately 4 microns in diameter. Although the flight test results will provide LFC performance for various combinations of ice particle concentrations and size distributions, it may be difficult to determine the critical particle size and particle flux[1] from these data. For instance, given one measurement of degraded LFC performance and their associated ice particle distribution spectrum, one doesn't know whether only the largest 10%, the largest 50%, or the largest 90% of the particles are causing the degraded LFC performance. However, given several measurements of LFC performance and their associated ice particle distribution spectrums, one could probably extract the critical particle size and critical flux level by simultaneous consideration of the data, provided there were various degrees of overlap in the particle size distribution spectrums.

1 If the critical particle size could be ascertained from the data, the critical particle flux can also be established.

REFERENCES

GENERAL

1. Hall, G.R., "Effects of Atmospheric Thermodynamics on LFC Performance," Norair Memo 3711-64-50, September 1964.

2. Schlichting, H., "Boundary Layer Theory," 4th Edition, McGraw-Hill Book Company, 1959.

BOUNDARY LAYER TRANSITION

3. Dryden, H. L., "Some Aspects of Transition From Laminar to Turbulent Flow," Lecture at University of Maryland, November 1955.

4. Emmons, H.W., "The Laminar-Turbulent Transition in a Boundary Layer," Harvard University, November 1950.

5. Schubauer, G.B. and Klebanoff, P.S., "Contributions on the Mechanics of Boundary Layer Transition," NACA TR 1289, 1956.

6. Mitchner, Morton, "Propagation of Turbulence From an Instantaneous Point Disturbance," Readers' Forum, Jour. Aero. Sci., vol. 21, no. 5, May 1954, pp. 350-351.

7. Morkovin, M.V., "Transition from Laminar to Turbulent Shear Flow - A Review of Some Recent Advances in its Understanding," Trans. ASME 80, 1958.

8. Gazley, C., "Boundary Layer Stability and Transition in Subsonic and Supersonic Flow," Jour. Aero. Sci., 20, 1953.

WAKE STRUCTURE

9. Roshko, A., "On the Development of Turbulent Wakes From Vortex Stresses," NACA TR 1191, 1954.

10. Magarvey, R.H. and Bishop, R.L., "Transition Ranges for Three Dimensional Wakes," Canadian J. of Physics, 39, 1961.

11. Magarvey, R.H. and Bishop, R.L., "Wakes in Liquid - Liquid Systems," Physics of Fluids, 4, 1961.

12. Fay, J.A. and Goldburg, "The Unsteady Hypersonic Wake Behind Spheres," ARS Preprint 2676-62, November 1962.

ROUGHNESS EXPERIMENTS

13. Tani, I., "Effect of Two-Dimensional and Isolated Roughness on Laminar Flow," Boundary Layer and Flow Control, vol. 2, Pergamon Press, 1961.

14. Klebanoff, P.S., Schubauer, G.B., and Tidstrom, K.D., "Measurements of the Effect of Two-Dimensional and Three-Dimensional Roughness Elements on Boundary-Layer Transition," J. Aero. Sci., 22, 1955.

15. Dryden, H.L., "Review of Published Data on the Effect of Roughness on Transition from Laminar to Turbulent Flow," J. Aero. Sci., 20, 1953.

16. Gregory, N. and Walker, W.S., "The Effect on Transition of Isolated Surface Excrescences in the Boundary Layer," A.R.C. R&M No. 2779, 1956.

17. Smith, M.L. and Clutter, O.W., "The Smallest Height of Roughness Capable of Affecting Boundary Layer Transition," J. Aero. Sci., 25, 1958.

18. Hama, F.R., "An Efficient Tripping Device," J. Aero.Sci., 24, 1957.

19. Liepmann, H. W. and Fila, G.H., "Investigations of Effects of Surface Temperature and Single Roughness Elements on Boundary Layer Transition," NACA TR 890, 1947.

20. Schiller, L., "Handbook of Experimental Physics," vol. 4, pp. 189-192, Leipzeg, 1932.

CLOUD PHYSICS

21. Tank, W. G., "Optical Phenomona in Ice Crystal Clouds," AIAA Paper No. 64-312.

22. Aufm Kampe, H.J. and Weickmann, H.J., "Physics of Clouds," Meteorological Monograph No. 3, AMS, Boston, 1957.

23. Mason, B.J., "The Physics of Clouds," pp. 174-179, Oxford, England, 1957.

24. Malone, T.F., "Compendium of Meteorology," American Meteorological Society, 1951.

25. Campen, C.F., et al, "Handbook of Geophysics for Air Force Designers," Geophysics Research Directorate, 1959.

IMPINGEMENT DYNAMICS

26. Bowden, D.T., Gensemer, A.E., Skeen, C.A., "Engineering Summary of Airframe Icing Technical Data," FAA, TR-ADS-4, December 1963.

27. Tribus, M., "Modern Icing Technology, " Engineering Research Institute, University of Michigan, January 1952.

FORM 20-10A
(R.12-63)

ENGINEER	NORTHROP CORPORATION NORAIR DIVISION	PAGE
CHECKER		REPORT NO.
DATE		MODEL

WAKE CHARACTERISTICS AND TRIPPING ELEMENTS
AS RELATED TO REYNOLDS NUMBER FOR CYLINDERS AND SPHERES.

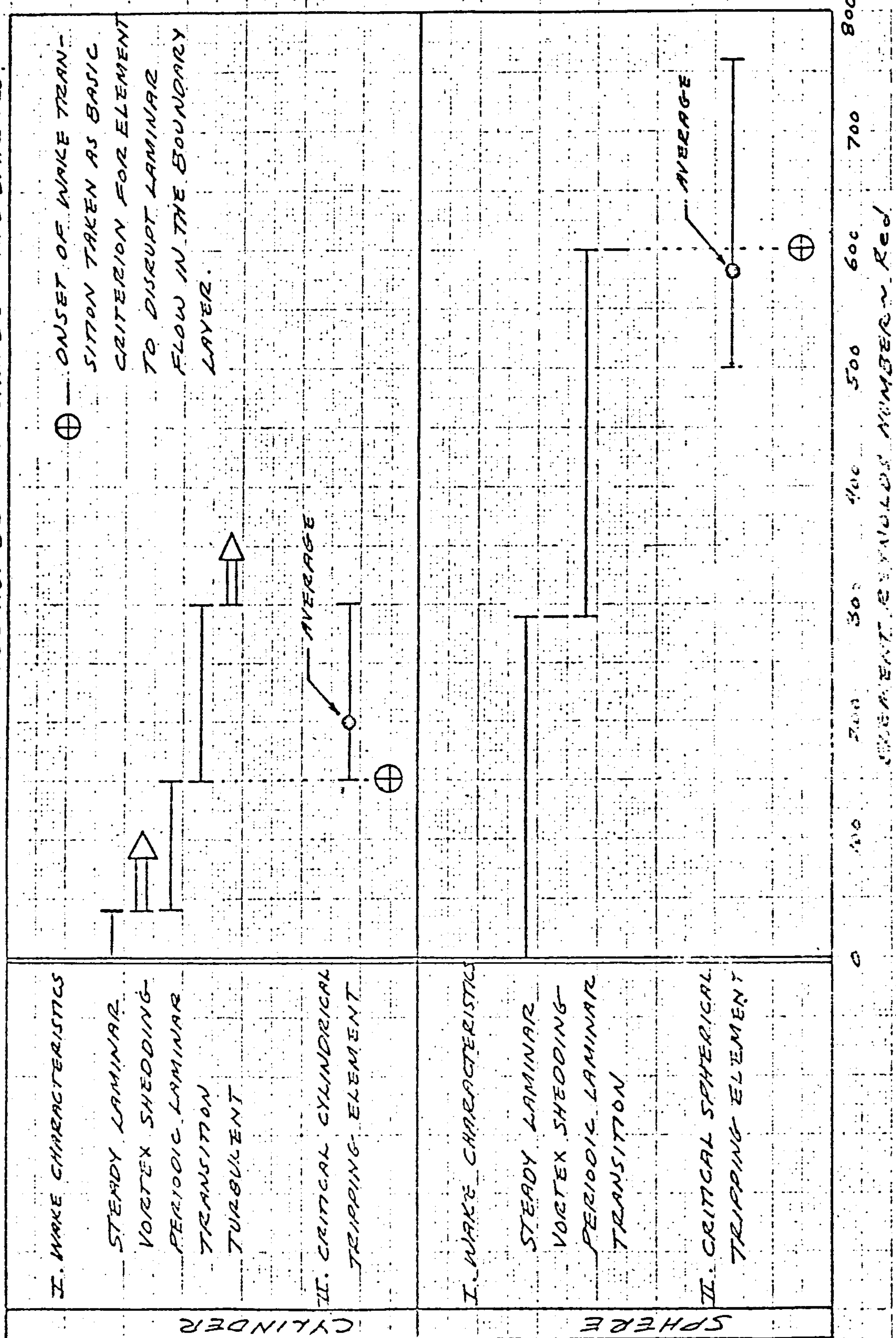


FIGURE 1

FORM 20-10A (R. 12-63)

ENGINEER	NORTHROP CORPORATION NORAIR DIVISION	PAGE
CHECKER		REPORT NO.
DATE		MODEL

OVERALL COLLECTION EFFICIENCY, STAGNATION POINT COLLECTION EFFICIENCY, AND $(y/b)_{MAX}$ AS A FUNCTION OF PARTICLE DIAMETER.

$M_\infty = .75$

PARTICLE DENSITY = .9

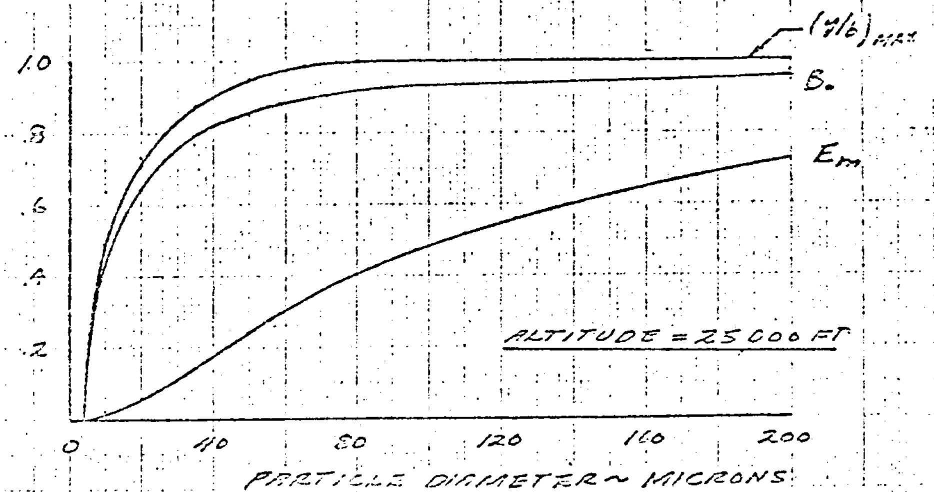
$$E_m = \frac{\int_{y/b=-1.0}^{y/b=1.0} n \, d(y/b)}{2 n_o}$$

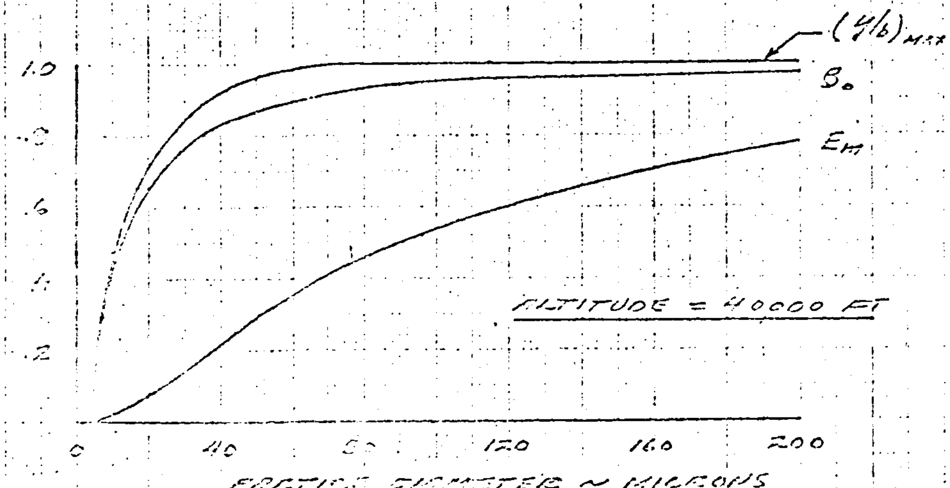
$$B_o = \left(\frac{n}{n_o}\right)_{\substack{STAGNATION \\ POINT}}$$

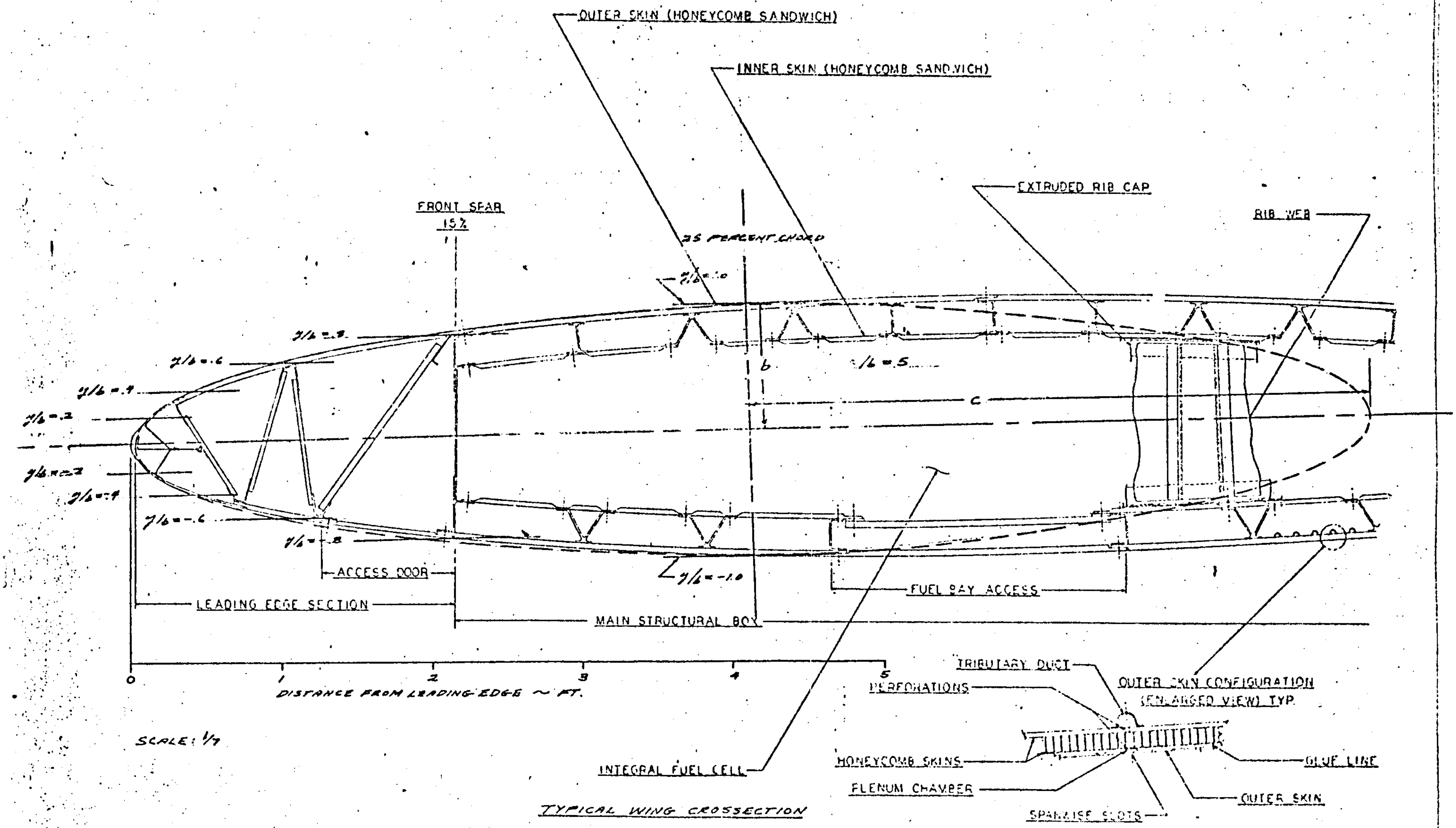
n = LOCAL INCIDENT FLUX

n_o = FREESTREAM FLUX

$(y/b)_{MAX}$ = PARTICLE IMPINGEMENT LIMIT







TYPICAL WING CROSSECTION

FIGURE 2

FORM 20-10A (R. 12-63)

ENGINEER	NORTHROP CORPORATION NORAIR DIVISION	PAGE
CHECKER		REPORT NO.
DATE		MODEL

LOCAL COLLECTION EFFICIENCY FOR VARIOUS PARTICLE DIAMETERS.

ALTITUDE = 40 K

$M_\infty = .75$

PARTICLE DENSITY = .9

$\beta = \left(\frac{n}{n_0}\right)_{y/b}$; n = LOCAL INCIDENT FLUX, n_0 = FREESTREAM FLUX

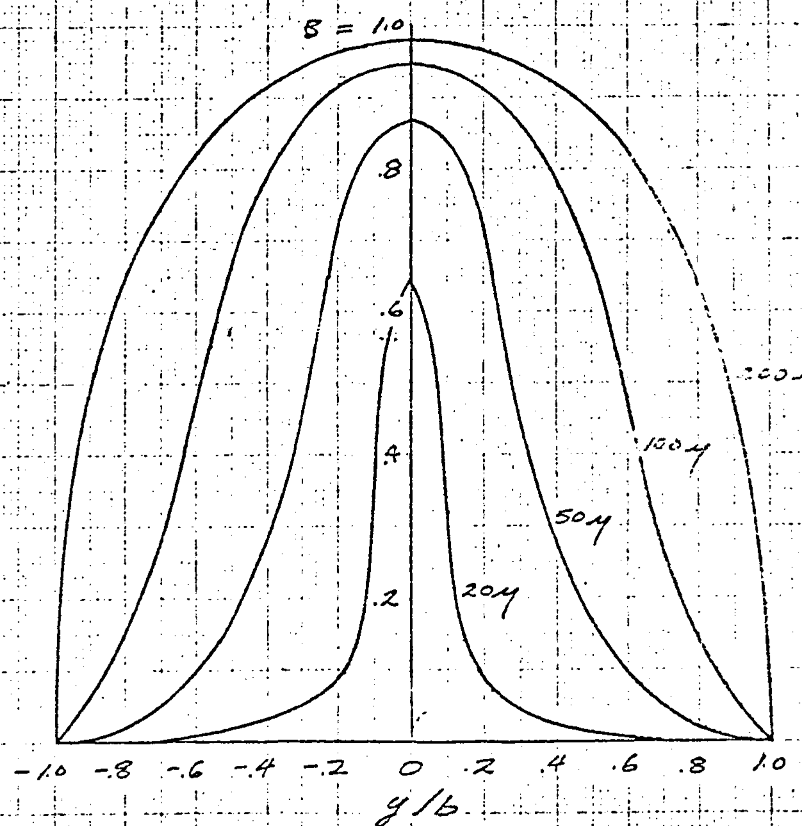


FIGURE 5

FORM 20-107 (R.12-63)

ENGINEER	NORTHROP CORPORATION NORAIR DIVISION	PAGE
CHECKER		REPORT NO.
DATE		MODEL

LOCAL COLLECTION EFFICIENCY FOR VARIOUS PARTICLE DIAMETERS.

ALTITUDE = 25K

$M_\infty = .75$

PARTICLE DENSITY = .9

$B = \left(\frac{n}{n_o}\right)_{y/b}$; n = LOCAL INCIDENT FLUX, n_o = FREESTREAM FLUX

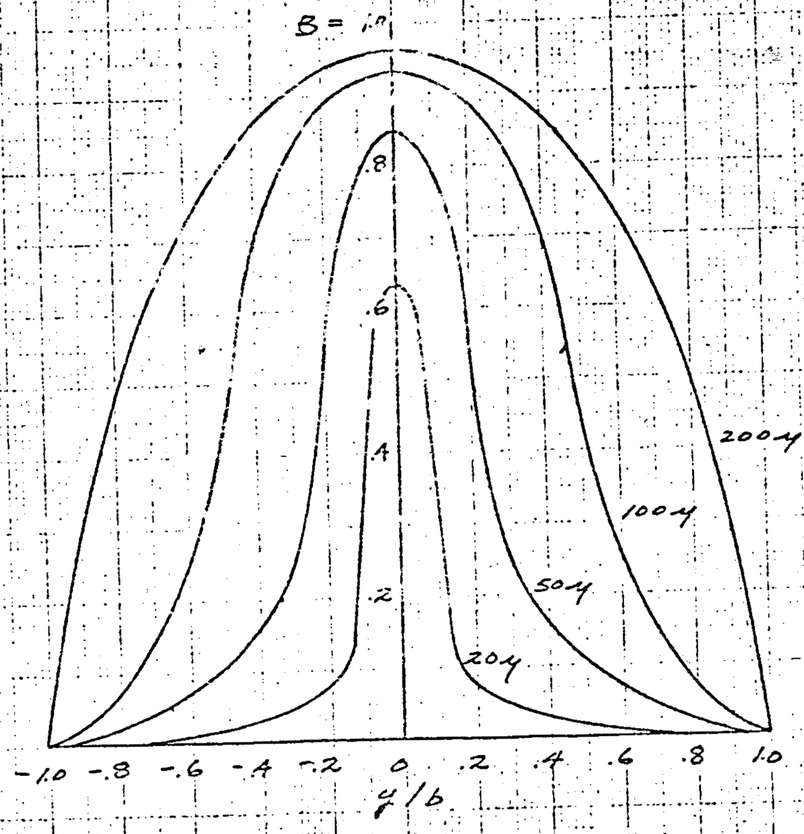
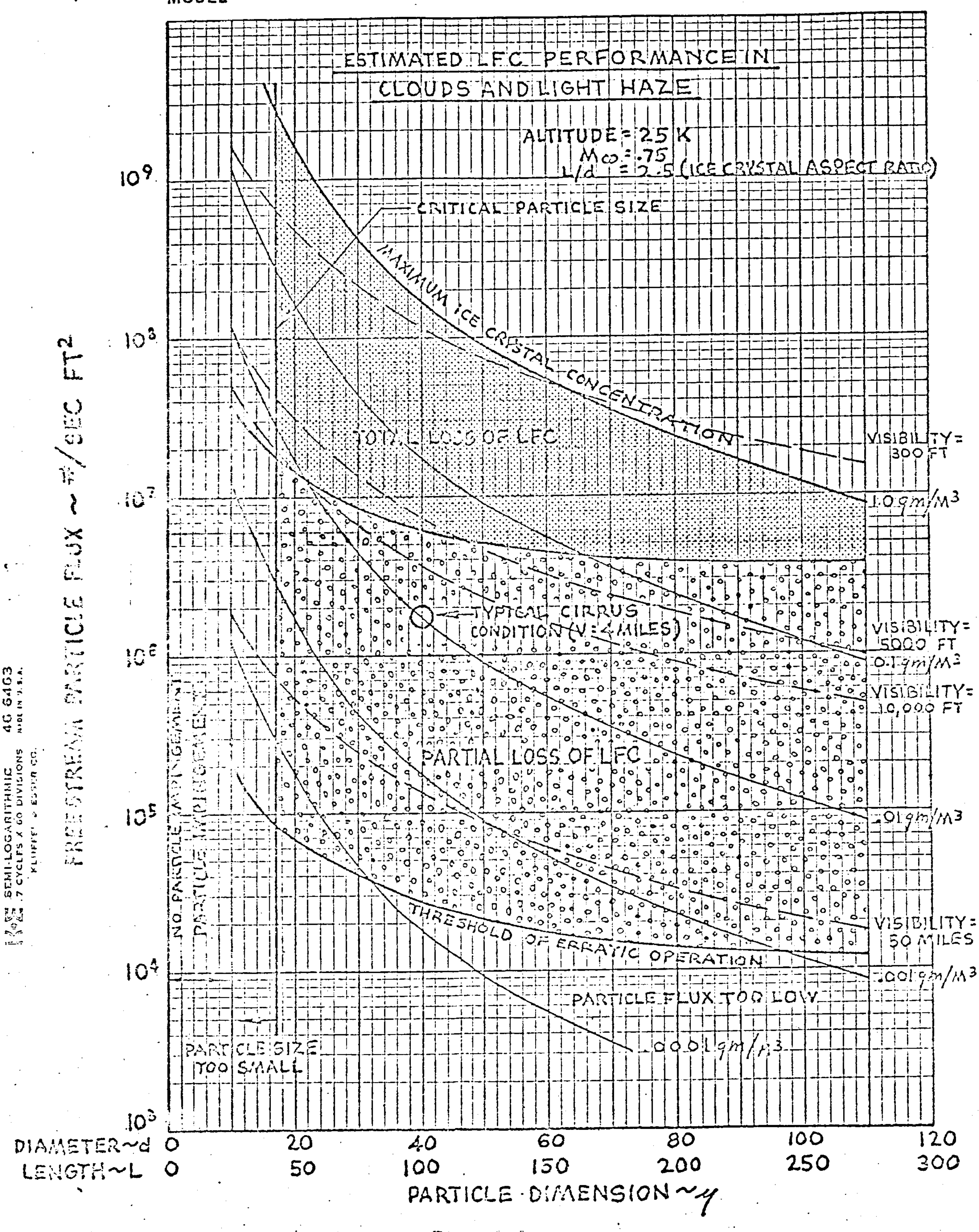


FIGURE 4

MODEL

DATE



ESTIMATED LFC PERFORMANCE IN CLOUDS AND LIGHT HAZE
ALTITUDE = 25 K
M∞ = .75
L/d = 2.5 (ICE CRYSTAL ASPECT RATIO)
CRITICAL PARTICLE SIZE
MAXIMUM ICE CRYSTAL CONCENTRATION
TOTAL LOSS OF LFC
TYPICAL CIRRUS CONDITION (V = 4 MILES)
PARTIAL LOSS OF LFC
THRESHOLD OF ERRATIC OPERATION
PARTICLE FLUX TOO LOW
PARTICLE SIZE TOO SMALL
NO PARTICLE IMPINGEMENT
PARTICLE IMPINGEMENT
VISIBILITY = 300 FT
1.0 gm/M³
VISIBILITY = 5000 FT
0.1 gm/M³
VISIBILITY = 10,000 FT
.01 gm/M³
VISIBILITY = 50 MILES
.001 gm/M³
.0001 gm/M³
FREE STREAM PARTICLE FLUX ~ #/SEC FT²
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
DIAMETER ~ d 0 20 40 60 80 100 120
LENGTH ~ L 0 50 100 150 200 250 300
PARTICLE DIMENSION ~ μ
K+E SEMI-LOGARITHMIC 46 6463
7 CYCLES X 60 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

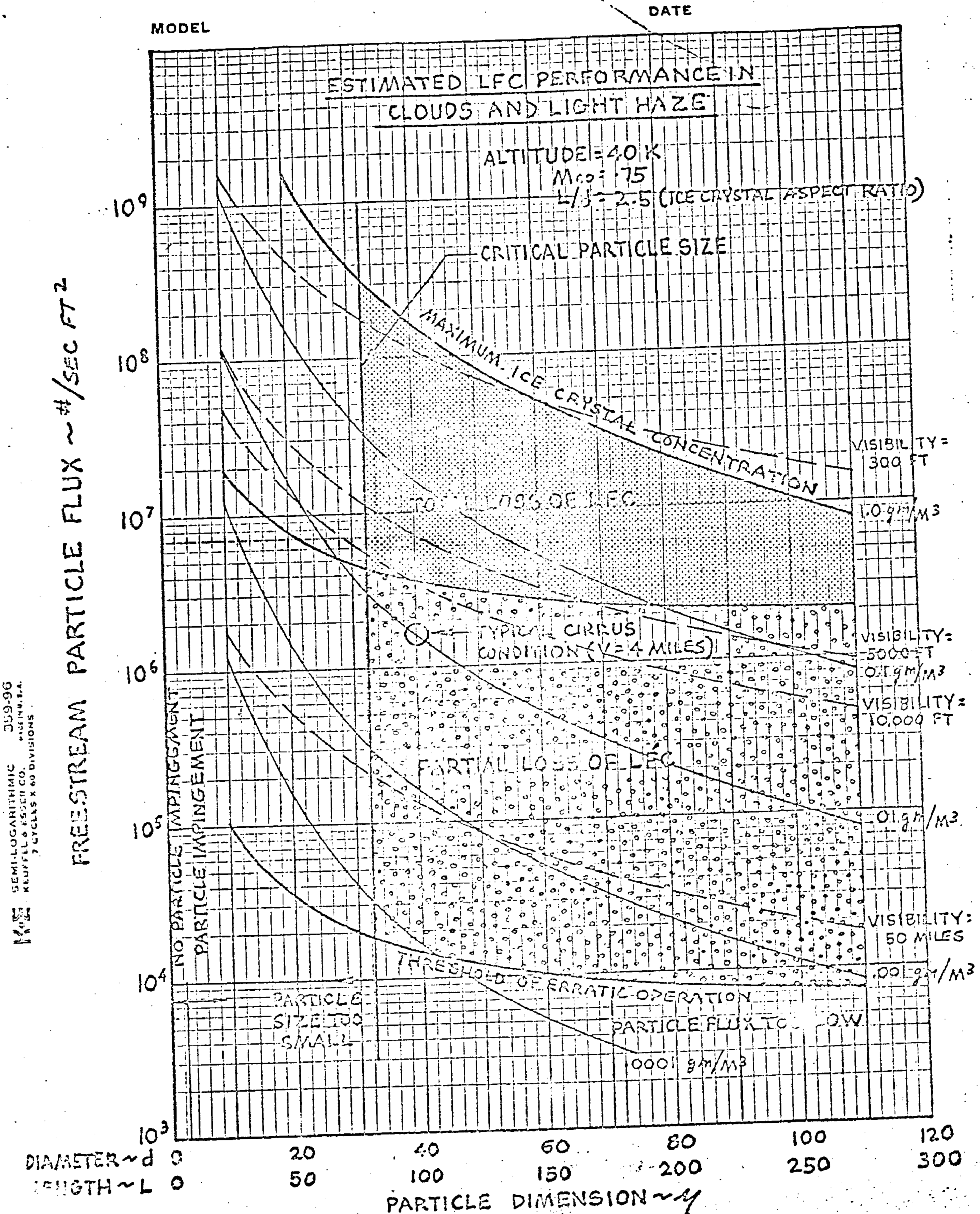

MODEL
DATE
ESTIMATED LFC PERFORMANCE IN
CLOUDS AND LIGHT HAZE
ALTITUDE = 40 K
M∞ = .75
L/d = 2.5 (ICE CRYSTAL ASPECT RATIO)
CRITICAL PARTICLE SIZE
MAXIMUM ICE CRYSTAL CONCENTRATION
TOTAL LOSS OF LFC
VISIBILITY = 300 FT
1.0 gm/M³
TYPICAL CIRRUS CONDITION (V = 4 MILES)
VISIBILITY = 5000 FT
0.1 gm/M³
VISIBILITY = 10,000 FT
PARTIAL LOSS OF LFC
.01 gm/M³
VISIBILITY: 50 MILES
.001 gm/M³
THRESHOLD OF ERRATIC OPERATION
NO PARTICLE IMPINGEMENT
PARTICLE IMPINGEMENT
PARTICLE SIZE TOO SMALL
PARTICLE FLUX TOO LOW
.0001 gm/M³
FREESTREAM PARTICLE FLUX ~ #/SEC FT²
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
DIAMETER ~ d 0 20 40 60 80 100 120
LENGTH ~ L 0 50 100 150 200 250 300
PARTICLE DIMENSION ~ μ
K&E SEMI-LOGARITHMIC 359-96
KEUFFEL & ESSER CO.
7 CYCLES X 60 DIVISIONS

FIGURE 7

APPENDIX

The probable mechanism by which turbulence is introduced into the laminar boundary layer by particles has been discussed in detail in the body of this report. The mechanism proposed is that of shedding turbulent vortices from the wake of the particle into the adjacent laminar flow. Although this appears to be the probable mechanism of turbulence introduction into the local flow, another possible mechanism has been considered which results in approximately the same value of critical particle Reynolds number as that of the shedding of turbulent vortices. This criterion is that when the vortex shedding frequency falls within the range of frequencies for disturbance amplification as predicted by Tollmien instability theory, turbulence will develop in the flow downstream of the disturbance.

Although Tollmien instability considerations theoretically apply only to small amplitude two-dimensional waves, it is of interest to note that a region of infinite stability has been observed experimentally for three-dimensional surface roughness elements. This region of inifinite stability corresponds closely to the region of infinite stability predicted by Tollmien instability theory for small amplitude two-dimensional waves. This leads one to consider the possibility that a three-dimensional periodic disturbance of the same frequency predicted to be critical by Tollmien instability theory might be amplified to a subsequent turbulent condition.

The critical Reynolds number at which the vortex shedding frequency lies within the range of frequencies predicted for disturbance amplification by Tollmien theory has been determined to correspond to the initiation of vortex shedding for a sphere and is found to lie between the initiation of vortex shedding and the onset of wake transition for a cylinder. It is curious that the vortex shedding frequency lies within the range of disturbance amplification frequencies for any value of Reynolds number in that the range of critical frequencies at any Reynolds number as predicted by Tollmien instability theory is a relatively narrow band. That the vortex shedding frequency lies within this band is probably coincidental, although at the same time should not be entirely discounted as a possible criterion of turbulence initiation. The critical particle Reynolds number based on this criterion is approximately one-half the value for the criterion of wake transition.