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High-Speed Aerodynamics

Lecture by W. B. Mitchell
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Transcribed by: Sherry Yin

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Time	Transcription
00:00	Marian Longstreth: The students, it is a pleasure to welcome you, who really come to these lectures because we the sponsoring groups feel that we are offering you a great privilege. The world today stands in one of the great transitional periods and through this lecture series of Meet the Scientist, you have had the privilege of meeting some of the men who are forecasting the age that we are about to enter. Today is the last lecture of the Spring Meet the Scientist series, which is sponsored by the Theatre and Arts Foundation of San Diego County, Convair, Convair Astronautics, General Atomic, and the Scripps Institution of Oceanography. We are fortunate in having as our speaker, the head of the aerodynamics group at Convair Astronautics, a graduate of the University of Oklahoma. He has been with Convair in engineering since 1946 then moving on to Convair Astronautics to become a part of the Atlas Ballistic Missile Program in 1955 and now heading the aerodynamics division. He will speak to us today on high-speed aerodynamics. I take great pleasure in introducing to you, Willis B. Mitchell.
01:34	[Audience Clapping]
01:42	W.B. Mitchell: Thank you very much, Mrs. Longstreth. My subject this afternoon is the general field of high-speed aerodynamics. What I hope to accomplish in the relatively short time that we have available is to acquaint you with some of the basic concepts which serve as the foundation of the subject. And actually, high-speed aerodynamics is a career field and we could devote a whole series of lectures to its various aspects. Perhaps the best place to start is to tell you what aerodynamics is and what the aerodynamicist does in industry. Aerodynamics may be defined as the branch of the general science of physics, which deals with the dynamics of air in motion. In particular, it’s concerned with the flow of air around an aircraft and the forces on the aircraft which result from this motion. From the theoretical standpoint, we may study the motion of air around aircraft by purely mathematical methods. Indeed, a vast amount of research has been done along these lines and it's been limited only by the complication of the problems involved. And as a parallel to this, much testing has been done in laboratories in an attempt to check the theoretical work and to gain new knowledge where the mathematical solutions have not been reached.
03:32	W.B. Mitchell: In industry where the science of aerodynamics must be applied to the design of an aircraft, the job of the aerodynamicist falls into certain well-defined areas. In the first place, he must determine the forces which act on the aircraft as a result of its motion through the air or what is the same thing from the, from the aerodynamics point of view, the motion of the air over the aircraft. These forces may be resolved into the lift component which supports the aircraft in flight and into the drag component which acts in the direction opposite to the motion of the aircraft

in search to retard it. These forces have to be known in the design of the aircraft in order that the designer may properly apportion the structure, make it strong enough to take the loads which result in flight. So it's also necessary to know these loads in order that the stability and the performance of the aircraft may be determined. These last two tasks, stability, and performance, also fall to the aerodynamicists. The concept of aerodynamic stability is one which, with which you are already familiar, although you may not be aware of it. It's that property of an aircraft which tends to return it to its original flight direction when disturbed from that direction. I'm sure that you all know that if you were going to make an arrow it would be necessary to put feathers on the tail in order to make it fly properly with the point first. Well, this is aerodynamic stability at work. In order to understand perhaps a little bit about why it works, let's look at the first slide.

05:24 W.B. Mitchell: Here I have shown in schematic form two aircraft configurations in side view. On the left, we see one in which I have indicated a wing and I've intended to indicate no tail surface on here. Some of the symbols shown here are the, the weight indicated acting downward through the center of gravity of the aircraft. The center of gravity of course is that theoretical point within the aircraft wherein the weight could be considered as being concentrated. It's also the point at which, about which the aircraft would rotate if it's disturbed in the air. And here I've indicated the lift of the wing. In this case, we'll assume that that's the only lift that's acting on the aircraft and of course, it's acting up in the region of the wing. The aircraft is at an angle of attack with respect to the airflow. This is the angle of attack in here. When it's in an angle of attack in this direction, which we refer to as positive, then the lift is upward, which we also refer to as positive. As you can see with the configuration as shown, when the aircraft pitches to an angle of attack, positive as shown, the lift results here and the motion result in motion around the CG [center of gravity] is as indicated by the arrow, which means, which indicates that the aircraft will continue to pitch in the same direction that it started by the force that's acting on it.

06:55 W.B. Mitchell: Consequently, if it's in level flight and it's disturbed upward instead of returning to its original direction it will continue to pitch over and it's unstable. What can we do to correct this situation? What is done in aircraft of course is we install tail surfaces on the aircraft, as is indicated here. Now again, we still have the weight acting through the center of gravity. We still have the lift of the wing acting through the center of the, of the wing. We still have our airflow here with the positive angle of attack, but now we've added another lift component at the tail. If the tail is properly proportioned, then its lift, plus the lift of the wing makes the total, goes to make up the total lift of the aircraft which I've indicated here again with the long arrow. However, if the size of the tail is properly proportioned, then the lift of the tail will be such that the total lift of the aircraft will act at the approximate position that

I've shown here, behind the CG [center of gravity], the center of gravity, resulting in a motion about the center of gravity as is shown by the arrow in this case.

08:05 W.B. Mitchell: Now what happens? As the aircraft pitches to the angle of attack again as indicated, the lift which acts, acts behind the center of gravity tending to rotate the body about the center of gravity back into the flight direction. The position of this lift force is determined by the size of the tail surface, the larger the tail surfaces you put on the further aft will this force move. If the lift, if the tail surface is too small then the lift force will act either at or ahead of the center of gravity, similar to the situation that we have here and the body is still unstable. This serves to give you some idea of the relationship of the forces involved on an aircraft and the meaning of the term aerodynamic stability. It's one thing that perhaps is not obvious and that is if we go to a negative angle of attack, our airplane doesn't always fly like this. While it's flying through the air it may be disturbed by a gust such that it goes to a negative angle of attack. In that case, if the angle of attack is negative and the body is pitched down, then these forces act down also. Consequently, the resultant, the resultant motion about the center of gravity would be in the opposite direction tending to bring again the aircraft back to its original direction. That's enough for that slide.

09:42 W.B. Mitchell: The common weather vane, which I'm sure most of you are familiar with, also demonstrates the principle of aerodynamic stability. Of course, the stability, the importance of stability in a manned aircraft is, is fairly obvious in that it improves the flying qualities. The airplane partially flies itself so that the pilot doesn't have so much work to do. In missiles, this quality is equally important in that the pilot is replaced by an automatic pilot but this automatic pilot must still be able to fly the aircraft. If the aircraft is stable, the autopilot has an easier job, easier job and can therefore be smaller and be lighter. It's the job of the aerodynamicists then to ensure that the wings and the stabilizing surfaces, the tail surfaces, and the control surfaces are properly proportioned so that the aircraft has the flying qualities desired. The other major tasks of the aerodynamicist that I mentioned concern with performance.

10:47 W.B. Mitchell: Combining these known characteristics of the power plant, the air loads which act on the aircraft, you must be able to calculate what the performance will be. What's the range? What's the top speed? What's the landing characteristics? How high will it fly? How much will it carry? How much of a load can we put aboard? Of course, these things could be determined by test after the plane was built but this might be a rather expensive way to find out that the wing wasn't large enough and the engine wasn't powerful enough. So it's necessary that the aerodynamicists keep track of these things as the design progresses and to make the necessary recommendations to ensure that the required performance is met. During this day of satellite vehicles and talk of trips to the moon and voyages through outer space, you may inquire or wonder if there's any further use for the aerodynamicist since even the definition of aerodynamics has to do with air and consequently the atmosphere of the Earth. But of course, it's true that anything that, any vehicle that goes up through the atmosphere to Mars or Venus or any other destination in space must traverse the atmosphere.

12:05 W.B. Mitchell: During this time of course it's subject to the laws of aerodynamics and must be properly designed. We are also interested these days in the possibilities of man in space travel, of putting a man into space. This implies, of course, I imagine the pilot hopes that it implies that we're going to return to Earth and certainly here the aerodynamicists will play an extremely important role. This gives you some idea of what aerodynamics is and what the type of problems the aerodynamicist deals with but we also want to talk about high-speed aerodynamics this afternoon. So what's different about high-speed aerodynamics? To understand this, we must first consider the medium that we are working with, with which we are working. In aerodynamics, we're dealing entirely with air. We're considering it as a fluid in much the same way as if it were water or molasses or some other medium for which flow is possible.

13:02 W.B. Mitchell: Air, of course, has certain distinguishing characteristics such as its chemical composition. It's made up of oxygen and nitrogen. It has density. It has so much weight in pounds per cubic foot. It has viscosity like molasses, although not nearly so much. All of these things are of importance to the aerodynamicist because they all enter into determining what the forces are on the aircraft. But what we want to talk about here, so far as high-speed aerodynamics is concerned is compressibility. The air is compressible, which may sound a little foolish since we are all familiar with the use of compressed air for various purposes. One of the most important is to hold up the tires on our automobile. Yet it's this compressibility that will characterize high-speed aerodynamics. When we consider the dynamics of the flow of air at low speeds, it's found that a very small error will occur in theoretical calculations and in practice if we consider the air as an incompressible fluid like water. And for the first 50 years of aerodynamic research, this rather crude approximation proved itself to be very valuable in solving many practical problems of aircraft design. This approximation is still used in designing aircraft for low speeds. The state of affairs was changed fundamentally, however, as high-speed aircraft became common and as the speeds increased the air behaved less and less as an incompressible fluid.

14:46 W.B. Mitchell: And it was necessary to account for the variations in density in the mathematical formulations. And it soon became clear that the engineer needed a full grasp and full knowledge of the fluid mechanics of air over the entire speed range extending from low incompressible flow speeds, up to velocities very large in comparison to velocity of sound. So the lower boundary of high-speed aerodynamics, we will consider to be that speed at which the compressibility effects of air must be taken into account. And at this point in the discussion, it's important that we understand the part played by the speed of sound in aerodynamic phenomenon at high speeds and in this day of high-speed aircraft, you're all probably familiar with the use of the term Mach number to designate speed. Mach number is defined as the velocity, or speed, at which you're traveling divided by the speed of sound. This gives you a number. So Mach number one indicates a velocity equal to the speed of sound. Mach number two is twice the speed of sound, and so forth. The importance of speed of sound lies in the fact that small pressure changes, small pressure disturbances in air are propagated at the velocity of sound. They travel through air at the velocity of sound. My voice comes to you as a small pressure change in the air and it travels from me to you at the speed of sound.

16:31 W.B. Mitchell: An aircraft moving through the air gives rise to small pressure disturbances around it, around the wings, and around the fuselage. These small pressure disturbances are also transmitted through the air at the speed of sound. It's evident then that the effect of these small pressure changes produced in the air by a body moving faster than the speed of sound cannot reach points ahead of the body. It may be said that the body is unable to send signals ahead, this is the fundamental difference between low-speed flow and high-speed flow. In order that we can perhaps understand this a little more clearly, the next slide shows a series of diagrams which illustrate this propagation of sound from stationary and for moving sources and shows the effects of the motion of the source. The upper left diagram shows the case for a stationary source where the sound is emitted from the central point, say in a series of pulses, from this central point here in a series of pulses. Say that the sound wave which this outer circle represents was emitted say five seconds ago and this one four, three, two, one, and now is represented by the point in the center.

17:56 W.B. Mitchell: You can see that the sound is propagated in a series of circles outward from the central point and it reaches all through space equally. But let's consider what happens in the upper right diagram if our source of sound is moving. And here instead of having one central source, I show five. Let's consider that this point represents the time this instant now. This point represents an instant five seconds ago and the sound which was emitted five seconds ago is represented by the circle here. The sound which was emitted four seconds ago here and three here and so forth, two here, one here. And here we are at the present time. You can see why this, what the effect of motion of the source of sound has, is. It has served to compress the sound waves ahead of the body and the sound of the source and the sound which was emitted five seconds ago is now the sound wave is much closer to the source of sound than it was in the case with no motion.

19:19 W.B. Mitchell: Let's extend this a little bit further. This, this case over here would be a case where in the motion of the source of sound was at a velocity considerably less than the speed of sound, about half say. Let's look at the diagram here. This is the case where the source of the sound pulses is moving at the speed of sound. Now we see that the sound pulse which was emitted say five seconds ago and the sound pulse which we emit at this instant are both at the same point. We, the source of sound is moving at the velocity of sound. One that was emitted four seconds ago reaches back to here in the rearward direction, it only reaches to here forward. Three seconds ago to here but it is also to here. Two to here but only to here forward. So we're traveling at this, then the velocity U equal to speed of sound. We see that it is impossible for the source of sound to transmit any pressure disturbances ahead of itself. This region ahead of this, of the source of the sound pulses, I've called the zone of silence or the zone of forbidden signals, indicating that no pressure pulses from the sound source can be transmitted into this region prior to the time the sound source gets there. As a matter fact, they're both going at the same velocity.

20:53 W.B. Mitchell: This region behind this line I've called the zone of action, indicating that this is the region wherein pulses originating from the body or from the sound source can be experienced. The last diagram on the right is for the case wherein the source of pulses or the source of pressure disturbances is moving at a velocity in excess of the speed of sound and we begin to see a familiar pattern. Again, here's minus five, minus four, three, two, one and this is instant, say now. We can see again that the sound source, the sound wave which emanated from this source five seconds ago, has now reached this point, the same diameter as this one, the same diameter as this one or this one. So its spread in this direction is the same. However, you will notice that the source of sound has far outrun the sound wave which is, which was emitted at this point. And the sound, the circles representing the sound waves now begin to overlap each other and we can draw a line which is, which, a tangent to these circles, which represents an envelope of these circles and we notice that it forms on this flat surface a triangle. In space, of course, it would be a cone.

22:14 W.B. Mitchell: This cone is called the Mach cone. It, like Mach number, is named after a German physicist in the 1800s who investigated a lot of these phenomena mathematically. Again, we have the zone of silence or the zone of forbidden signals ahead of, ahead of these sorts of sound and this asterisk at this point indicates again the zone of action. Now, it's only in this region inside the Mach cone in which pressure disturbances emanating from the sound source can be felt. A point here is not aware of the presence of this sound source. A point here is not aware of the presence of this sound source. Certainly, nothing out here is aware of the presence of this sound source. What, what then is the significance of this, of this phenomenon? Well, this serves to give you a physical explanation of the onset of the compressibility. At subsonic speeds, the motion of the body through the air is telegraphed ahead as you can see and the pressure signals generated from the body could be felt ahead. This forewarning allowed the air ahead of the body to move aside as the body approached and consequently, the air could flow around the body much as if it were water, and actually, that's what it does. At supersonic velocities, however, the air ahead of the body no longer has this warning at all. Presence of the body is not felt until such time as, as the body arises or until the Mach cone is intercepted. This then results in an instantaneous changes in the density of the air at this point, giving rise to the compressibility phenomenon.

24:30 W.B. Mitchell: This incidentally brings us to the discussion of another phenomenon which appears in supersonic flow, the shockwave. Physically, the shockwave is a very thin region in the air ahead of a supersonic aircraft in which these previously mentioned changes in density occur. As I mentioned, they occur practically instantaneously. They occur in this very thin layer which is called the shockwave, also associated with the shockwave are changes in pressure, and changes in temperature. Depending on the Mach number and the shapes of the, of the aircraft fuselage, this shockwave may be either what is referred to as a normal shock meaning that it is perpendicular to the axis of the fuselage or it may be attached to the nose of the body and inclined sharper to the rear in a cone as a cone. Shockwaves also have been studied theoretically for a number of years. The concept of shockwaves and compressible flow goes back more almost a century. You probably notice the Mach cone in the last slide which I indicated to you. How does a shockwave differ from a Mach cone? Well, it doesn't actually. As I mentioned to you, the shape of the shockwave is dependent upon the shape of the body. For very sharp bodies then the shockwave begins to approach a Mach cone. For very blunt bodies, the shockwave becomes normal and stands out in front of the body. So the Mach cone can be considered to be a shockwave which occurs for very, very small disturbance; it’s the limiting condition for a shockwave.

26:33 W.B. Mitchell: We can learn a little bit more about shockwaves if we look at the next slide, which shows some of the regions of flow about an airfoil moving through an airstream and shows some of the shockwaves associated with different speeds of flow. Case A at the top of the slide indicates the pure subsonic incompressible flow condition. You can observe this condition for yourself in shallow water by, slow moving shallow water, by inserting a stick into it and scattering some dust or something on the water and watch the flow around the, around the stick. This is, this is incompressible low-speed flow. As we increase the velocity more and more, we can reach a condition somewhere at a Mach number between 0.7 and 0.8, greater than 0.7 and less than 0.8 wherein we have supersonic flow and small regions around the, call it a wing in this case. This arrow, this arrow is wrong; it shouldn't be here. Only this one indicates the small region in here, the maximum thickness of the wing wherein we can have a small region of supersonic flow without shockwaves. This occurs only for a very small Mach number range. As we increase the Mach number a little bit more to a condition wherein the Mach number is say greater than 8/10ths but still less than one, shockwaves begin to appear in the flow, in this region in here and in here.

28:17 W.B. Mitchell: These shockwaves stand on the wing. They divide this supersonic from the subsonic region right in here and they serve to, in practical case, they cause buffeting an aircraft. They cause an increase in the drag considerably. It's some of these phenomena which in earlier times led to serious aircraft accidents when aircraft were unwittingly dived at speeds in excess of what they should have been flown at. This is the transonic region wherein the basic flow Mach number ahead of the vehicle may be high subsonic due to the fact that the flow acts as an incompressible fluid as it flows around the wing it must speed up. It speeds up. It exceeds the speed of sound and the Mach number becomes greater than one in local regions. The next case shown on the left then, in case D, is the case where we have the Mach number is greater than one between the region of say 1 and 1.2 for the particular wing shown here. Here the shockwaves which appeared on the wing in case of C have disappeared. They've moved back to the rear of the wing and formed trailing edge shockwaves and a normal shock, or a standing shockwave, has appeared ahead of the wing and serves to separate the, the free stream supersonic flow from the flow of the wing.

30:06 W.B. Mitchell: And then finally, as our Mach number increases still higher, we approach the last condition which is shown in case E where the Mach for the flow is supersonic everywhere in the stream around the wing. The shockwaves are attached at the wing and attached at the tail and they begun, begin to take on the inclined appearance that we saw in the last slide, in the case of the Mach cone. Now in this case I might point out this heavy shock standing in front of the wing here has subsonic flow behind it in a small region indicated by the dotted line. This comes about due to the change in the pressure and the change in the temperature and the density across the shockwave, results in a reduction in the, in the Mach number in this region. However, the air quickly accelerates again to a supersonic region, to the supersonic flow on over the wing. Here in this case where the, where the shockwave is attached to the body at this point, the flow is everywhere supersonic. Purpose of this slide has been to give you some idea of the different regions of flow and how they occur as you go from subsonic to supersonic velocities. I think that's all for that slide.

31:35 W.B. Mitchell: The significance of the shockwave in high-speed aerodynamics is primarily that its appearance causes a considerable alteration of the pressure distribution about the fuselage of the aircraft and the wings and, and the tail. The location of the forces which act on these surfaces change. There is an associated increase in drag, and often separation of the flow occurs over the wings. These effects cause changes in the aerodynamic forces, which the aerodynamicists must be able to compute. The wing shown in the last slide here was, had a sharp nose. Consequently, the shockwave was attached to the front of the wing. If the wing leading edge had been blunt, the shockwave would never have attached. It would have remained as it was in the case D, ahead of, ahead of the wing. This would have resulted in extremely high pressures on the front of the wing and very high drag. And for this reason, bodies that when wings and tails that must travel at supersonic speeds normally have very sharp noses which tend to reduce this wave drag. To give you some idea of what the shockwave, the effect of the shockwave at, in high-speed flow, this, the next slide shows some of the conditions behind the shockwave in air at various Mach numbers.

33:22 W.B. Mitchell: You will note that for each Mach number on the table, we show the pressure and the density behind the shockwave compared to those values in the free stream ahead of the shockwave. This is shown as a ratio, a pressure ratio, indicating it’s the pressure behind the shockwave divided by the pressure in front of the shockwave. At a Mach number of one, these pressures are one, indicating that the shockwave at Mach number of one is, is very, very weak. It actually doesn't exist. I's just beginning to exist and has no change in pressure or density. However, as the Mach number increases, you can see that the pressure behind the shockwave and the density behind the shockwave go up rapidly and drastically. Let's take the case of Mach number three with a pressure ratio of 10. If we were, if we wanted to fly an airplane at a Mach number of three at sea level where the pressure is approximately 15 pounds per square inch, then the pressure behind the shockwave and on the leading edges of the aircraft on the aircraft nose could be as high as 150 pounds per square inch. A square inch of course is very small. You can see then immediately that if you would like to multiply 150 pounds per square inch times 144 square inches per square foot, you can see that on an one square foot area of exposed aircraft, the load gets to be in the thousands of pounds. The density ratio shown on the right, I've put here to indicate this compressibility effect that we were talking about earlier. The density ratio starts at one at a Mach number of one, as the Mach number increases, the density goes up indicating that the weight of the air behind the shockwave is also increased.

35:16 W.B. Mitchell: That's good for that slide. These very high drags associated with the formation of shockwaves and at the nose of an aircraft created the so-called sonic barrier or sound barrier, which for some time prevented the achievement of supersonic flight. It wasn't until the advent of the reaction propulsion engines, which Mr. Radcliffe discussed two weeks ago, that supersonic flight was possible and the public is frequently made aware of the existence of shockwaves through the rather disturbing medium of the sonic boom. The sonic boom is actually caused by a shockwave emanating from an aircraft, which is flying at supersonic speeds and the, this shockwave is intersecting the ground. The pressure behind the shockwave is higher than it is ahead of the shockwave. This results in a pressure disturbance in the air and of course, your ears detect the pressure disturbance in the air as sound. And in this case, it's a sufficient intensity to, to, to cause your ears to detect it as a dull explosion or a sharp explosion depending on how close you are. The shockwave from supersonic air flight craft flying nearby could be quite dangerous and that the pressure generated behind the shockwaves could exceed the design loadings on buildings and on structures and structural damage could result. Suitable precautions will have to be taken in the future to prevent supersonic aircraft from flying at low altitudes or in the vicinity of other aircraft.

37:03 W.B. Mitchell: And one other effect of high-speed flow that I want to talk about this afternoon is perhaps the overriding factor in the design of any vehicle for high-speed flight. It’s the problem associated with aerodynamic heating of the structure. This problem depends upon the boundary layer over the aircraft. If you consider the encounters that you have with airflow in your own existence, such as riding in your car for example, it may seem that the air slips smoothly past any surface exposed to it. This however is not the case. As I mentioned earlier, air has viscosity just as molasses has viscosity although, of course, it's not nearly so great. And if it were possible for you to see the air molecules as they flow past a surface, then you would observe that in the successive layers of, of the air as you approach nearer and nearer the surface, the velocity would become slower and slower. Until finally, the last layer of molecules right down next to the surface would actually stick to the surface and ride along with it.

38:17 W.B. Mitchell: This region next to the surface where the air is slowing down is known as the boundary layer. It normally is quite thin, depending on the velocity and altitude in the density of the air, its thickness however can become appreciable. Our interest in the boundary layer in aerodynamics comes from two effects. In the first place, the boundary layer gives rise to the drag component which is called friction drag or viscous drag. This comes about due to the viscosity of the air. In addition, the boundary layer also contributes to the problem of aerodynamic heating. The air flowing past the aircraft by virtue of its motion possesses a considerable amount of kinetic energy. As you slow the air down in the boundary layer and bring it to zero speed relative to the aircraft, then it gives up all of this kinetic energy and the kinetic energy appears then as heat, heat in the boundary layer, and this heat is experienced in the form of the temperature, known as the recovery temperature indicating it’s a recovery of the kinetic energy in the flowing air.

39:37 W.B. Mitchell: At the speeds normally encountered in subsonic flight, this, this recovery temperature is quite low and very seldom taken into account. At very high speeds, however, the temperature has become quite appreciable and must be considered. And on the next slide, I have shown the recovery temperature in the boundary layer as a function of Mach number. This will give you some idea of the temperatures for which high-speed aircraft must be designed. Again, at a Mach number of one, the temperature has risen some 180 degrees which is relatively moderate. I'm taking as a base case here a temperature of 80 degrees which I assume is a normal spring day in San Diego. The Mach number of one and a half, we see that the, the recovery temperature in the boundary layer is now 300 and so forth. Two, 500. Mach number three, 1000. Mach number five, 2800 degrees. These are in degrees Fahrenheit which you're familiar with.

40:42 W.B. Mitchell: It's good, thank you. So it's the job of the aerodynamicists then also to determine what these temperatures are and to specify to the designers the temperatures that will be experienced by the aircraft. Now, I want to emphasize that the temperatures that, that were shown to you here are boundary layer recovery temperatures. They are not the temperature of the aircraft surface. The temperature of the aircraft surface would depend upon the material of which the surface is constructed and then also a factor known as the heat transfer coefficient. Heat transfer coefficient determines how much of the heat that's in the boundary layer is transferred to the material. This transfer process is part of the thermal dynamic phenomenon. Since these temperatures then depend upon a specific flight condition and a specific material, I have shown you here only the recovery temperature. But this is, gives you some, an idea of what the potential temperature is, how much it could be at a stagnation point, and by stagnation point I mean a point on the front of a wing or in the front of a fuselage which is perpendicular to the airflow. The temperature shown here could be experienced.

42:03 W.B. Mitchell: And just as the high drag of the transonic region that we were referring to a little bit earlier created the so-called sound barrier or sonic barrier, the high temperatures that I have indicated on this slide have given rise to the so-called thermal barrier. A good deal of research in the materials is being done to determine materials to withstand these temperatures. Up to this point in the discussion we have been considering what we, might be termed conventional high-speed or supersonic aerodynamic phenomenon. These are generally associated with the flight of turbojet aircraft or rocket-powered aircraft at a Mach number range up to say two and a half or three. Because of the rapid development of rocket propulsion and with the advent of missiles which make it possible to escape the atmosphere, we are entering however an entirely new regime in flight. And I would like to spend just a few minutes here discussing some of the problems which are peculiar to this very high-speed flight regime, which has come to be called hypersonic aerodynamics. Hypersonic flight can be considered to occur at Mach numbers somewhere between five and ten.

43:25 W.B. Mitchell: Basically, it's considered to occur when the air properties again begin to change rapidly and where there are changes in air dynamics phenomenon which have to be considered. An understanding of hypersonic aerodynamics, hypersonic flow I should say, requires in addition to aerodynamics, a knowledge in the fields of atomic and molecular physics, and chemical physics, chemical kinetics, surface chemistry, and in statistical mechanics. This then in short is the creation of a whole new discipline. It’s come to be called aerophysics. To point out some of the problems encountered in hypersonic flight, let's examine again some of the conditions encountered say, behind this normal shock that we talked about earlier, and which I showed you in the slide. At Mach number of five if you recall, with an air, with a blunt body moving in a Mach number five, the pressure behind the shockwave was about 29 atmospheres, 29, the pressure ratio was 29 or about 30. At sea level, this would give you a pressure on the front, front of the blunt-body of about 450 pounds per square inch, temperature about 2800 degrees.

44:50 W.B. Mitchell: If we consider a Mach number 10, the pressure goes up to 130 atmospheres, up by a factor of four. The temperature goes up to 10,000 degrees Fahrenheit. Mach number 15, the pressure goes up to 300 atmospheres. At the Mach number of 25 which is approximately the velocity required to orbit the Earth, the pressure behind the shockwave approaches 1,000 atmospheres and the temperature 20,000 degrees Fahrenheit. If we examine the composition of the air behind this normal shock traveling at these high velocities, we discover some very drastic changes have taken place. As you begin to approach a Mach number 10, the oxygen in the air begins to dissociate into atomic oxygen. That is, oxygen normally appears as two atoms in a molecule, O_2. It separates into separate atoms and electrons are detached from the, from the molecule and appear as free electrons in the area. New chemical compounds such as nitric oxide are formed.

46:00 W.B. Mitchell: As the speed increases still further, the air begins, becomes ionized as more and more electrons are knocked out of the, out of the atoms to the extent that high-frequency radio communication becomes difficult because of this high concentration of electrons. And then, at still higher Mach numbers of the order of 20, the nitrogen in the air also begins to dissociate into atomic nitrogen. And this simple air that we breathe has been transformed at high speeds into a dissociating and ionizing and a reacting gas. The simple methods of supersonic flow analysis are certainly no longer applicable. The analysis of the flow and heat transfer problems requirements becomes extremely difficult under these conditions and requires a knowledge of chemical kinetics and Teutonic physics. At these speeds, the heat transferred from the air to the object may be large enough to cause melting or oxidation of the surfaces.

47:00 W.B. Mitchell: The shockwave which we showed you in some of the earlier slides standing off from the nose of the wings in this case becomes literally wrapped around the body at very high speeds and it no longer is a discrete line but rather it is a broad region between the shock and the body itself. The gas in this shock layer, rather than the shockwave, then becomes so highly ionized and that becomes so at such a high temperature that it actually radiates and glows. And recent pictures taken of the re-entry of nose cones from long-range ballistic missiles show this radiating region quite clearly and the body appears as a meteor re-entering the atmosphere. Of course, the velocities that we've been discussing are not likely to be achieved at sea level or relatively low altitudes but the problems do become extremely important when we consider the re-entry situation where it may be necessary to return a nose cone from a missile or a manned re-entry vehicle back into the atmosphere.

48:06 W.B. Mitchell: The other problem that I might, that I mentioned briefly that I might spend just a second on is the transmission of radio signals through this ionized shock layer behind the shockwave becomes increasingly difficult as the velocity of the, of the object increases. And if the transmission of radio signals is a requirement such as it might well be in a manned reentry vehicle then the degree of ionization of the air in the shock layer might very well serve as was an upper limit to the speed at which the object could enter the atmosphere. There’s one more area here that I'd like to talk about just a minute, it’s concerned with the problems involved in testing. Some of the areas that we've been discussing here just for the last few minutes are extremely difficult to treat theoretically. As I had mentioned, a very wide range of, of knowledge is required and it’s become obvious that methods of experimentally obtaining the extremely high temperatures and the extremely high flight velocities in the laboratory setup will be necessary in order to obtain a better understanding of these flows.

49:34 W.B. Mitchell: Well, in the years past, when we were dealing with subsonic flow or with conventional high-speed supersonic flow, wind tunnel test were an extremely valuable tool with which to obtain experimental data. Unfortunately, the conventional wind tunnel cannot yield usable information at Mach numbers much above five, six. The difficulty arises from the fact that in order to obtain high velocities in a wind tunnel, you trap air into a large storage sphere, and increase its pressure, and then allow it to expand through a nozzle. As it expands through the nozzle, its temperature drops. It’s the basic characteristic of air or any fluid. If we expand the air sufficiently for it to reach a Mach number of five to seven, however, we find that the temperature drops to the point that the oxygen and the nitrogen in the air liquefy and fall out as a fog and a phenomenon called compression shocks occur. In order to get around this difficulty, it’s necessary to heat the air, which can be done.

50:45 W.B. Mitchell: And by heating the air, we can extend the range of usability of wind tunnels after about a Mach number of 10. However, by the time we reach a Mach number of 10, the temperature that we have to add to the air is so high and the heating of the wind tunnel itself is so great that long-term running in the wind tunnel is impossible because melting of the throat and overheating of the walls of the tunnel in the model. Consequently, new methods for, for simulating the extremely high velocities and temperatures of hypersonic flight have become necessary and in recent years, such things as shock tubes and shock tunnels, and mass accelerators have become very valuable. And generally, these devices provide a means for obtaining very high temperatures and very high velocities but for extremely short periods of time. By short periods of time, I mean thousandths or even millionths of a second. The temperatures involved then do not have sufficient time to cause difficulties in these very short periods.

51:47 W.B. Mitchell: But we've traded one problem for another because now we must measure the phenomenon that we're interested in a half of a thousandths of a second, 500 microseconds or one or two-thousandths of a second, one or two milliseconds. So a new field has arisen, the development of specialized instrumentation to make measurements in, in these extremely short time periods. In summary, we can say that aerodynamics can be defined as that branch of the general science of physics which deals with the dynamics of air and motion, an industry where the science of aerodynamics must be applied to the design of aircraft. The job of the aerodynamicist falls into the areas of determination of air loads, investigation of problems can turn to concern with stability and control, and computational performance. The lower boundary of high-speed aerodynamics can be considered to be that speed at which the compressibility effects of the air must be taken into account in the mathematical formulations.

52:54 W.B. Mitchell: Important concepts in supersonic aerodynamics are the compressibility effects, the importance of the speed of sound as the velocity of the propagation of small pressure disturbances, the concept of the zone of action in the so-called zone of silence in supersonic flight, significance of the Mach cone, the importance, the understanding of the shockwave, and the importance played by aerodynamic heating in the design of high-speed vehicles. That's been my attempt in this lecture to give you a brief sketch of some of the problems in high-speed aerodynamics and in aerophysics and to show how these problems affect the design of high-speed aircraft. I would be very pleased if, if I have awakened an interest in some of you in these particular areas or if perhaps as a result of hearing me, you should decide to pursue studies in these areas. The problems involved are many and varied and extremely interesting. Theoretical treatment, most of these problems require a complete understanding of the use of mathematics, and a thorough background in science is embraced by physics and chemistry. Does anyone have any questions? No questions at all?

54:24 Marian Longstreth: Mr. Mitchell, what would you say was the greatest challenge that you as an aerodynamicist have had to combat yourself in your work with Convair Astronautics?

54:35 W.B. Mitchell: Well, the greatest challenge undoubtedly is keeping up with the rapidly changing events, the rapidly changing complexion of the whole field of, of aerodynamics and aerophysics research. As you mentioned a few moments ago, what is common practice today is old hat next fall so far as some of these phenomena are concerned. So you must study constantly at every opportunity. You must keep track of what is being done by other people in the schools and industry. You have to go to school and keep going to school.

55:25 Marian Longstreth: No escape?

55:26 W.B. Mitchell: No escape.

55:28 Marian Longstreth: Another question, back here?

55:30 W.B. Mitchell: Yes.

55:31 Speaker 1: What can you do in the case of ionization of these particles of air?

55:35 W.B. Mitchell: Well, nothing actually except to keep the temperature down. This ionization is a function of the molecular activity, which is a function of temperature. As the temperature of the air increases, then the molecules become excited, and their activity increases. Of course, this is the definition of temperature and this is what causes the temperature and the pressure and as they do so then, they lose electrons which result in ions. So you keep the temperature down to, by remaining at lower speeds, then you can prevent the ionization.

56:16 Speaker 2: You mentioned something about a shock tube, could you explain briefly how it works?

56:20 W.B. Mitchell: Yes. A shock tube is a cannon actually. It consists of a long tube at one end of which you, you close it off for the diaphragm and pump it up to a high pressure so that you now have a long tube, yea big around, may. At one end, we have a small region which is pumped up to an extremely high pressure, maybe 1,000 maybe 2,000 pounds per square inch. It’s separated from the rest of the tube by a thin diaphragm. The section that we are going to test in is down at this end of the tube now where there is nothing. Then to initiate the testing procedure you break the diaphragm so that the air that was firmly compressed at 2,000 pounds per square inch in a very small area expands rapidly down the tube and it goes shooting out through the tube and out the other end. Then in a very small period of time, for a thousandths or two-thousandths of a second, as the flow goes past your model you have a very high velocity, very high-temperature flow. You must get your testing done in this short period of time. That's basically what it is, is that clear? Of course, there are many ramifications involved but I've said here is just a very short explanation of it.

57:42 Speaker 3: You mentioned that you need a very high temperature as well and I was wondering the high, the very temperature in the shock tube. I was wondering since when air expands it tends to lose the [unclear], how this high temperature is achieved.

58:00 W.B. Mitchell: Well, the high temperature in the shock tube becomes, because of the expansion process, the expansion process however, means that air is rushing down the tube at a velocity which is very high, then it pushes ahead of it the shockwave. The shockwave is a compression phenomenon so the, as the air moves down the tube, right behind the shockwave is a region which has been very highly compressed by the shock, shockwave. This I neglected to mention and the reason that the thing is called the shock tube because when you break the diaphragm and this air which was formerly trapped at 2,000 pounds per square inch goes rushing down the tube, it causes a shockwave which precedes it down the tube. The shockwave then causes the compression and the heating so there's a very short slug of air right behind the shockwave which is at very high temperature and very high velocity. It goes by very rapidly. Then behind that where the air is expanding, then it is cooling. After that, the temperature then drops off.
It's only in this very short region, right behind the shockwave, that you must do the testing. You can vary the temperature and the velocity in this region by varying the amount that you pump up your little chamber initially, how high do you, how much pressure do you put into it. The more pressure you put in, the stronger is the shockwave, the higher is the temperature behind it. You can also vary the gases in the tube. You can use helium in the, in the compression chamber and air in the tube, or you can evacuate the tube or you can put nitrogen in it. By using different combinations of gases, different combinations of pressures, you could achieve all sorts of conditions. Yes.

59:50 Speaker 4: How else can you achieve a shockwave?

59:53 W.B. Mitchell: It's limited only by the pressures I guess that you can, can get to. Speed is difficult to, to talk about. The speed can go up very high, the Mach number, however, has a limit of about 3.0 because Mach number is a function of speed of sound as I, as I pointed out to you earlier. The speed of sound is a function of temperature. So the temperature behind the shockwave is very high so consequently, the speed of sound behind, behind a shockwave is very high. And since the speed of sound is very high then the Mach number is low, so all the velocity may be measured in five, ten, or fifteen thousand feet per second behind the shockwave. The Mach number may be three, to get higher Mach numbers then it's necessary to put a wind tunnel on the end of this shock tube and allow these gases to expand through the wind tunnel. In this fashion then, you can get higher Mach numbers if you want to investigate Mach number phenomenon rather than just purely velocity phenomenon. Yes.

1:01:10 Speaker 5: What kind of instrument do you use to measure the lift and the drag in your models at such high speeds in such a short time?

1:01:17 W.B. Mitchell: In the shock tube? This is a very good question in a difficult area to answer. One of the types of mechanisms which have been considered is actually a very old one. I's called a ballistic pendulum in which you hang the model on a, on an arm and swing it in the so that it can swing back and forth in the tunnel. Then as the shockwave goes by the model has drag and will cause the arm to swing back. The amount that it swings back, swings back tells you through suitable calibration what the forces were on it during that period of time. This is one method which can be adapted to measure these forces. Others are more difficult by the use of, by the use of suitable pressure instrumentation, you can measure the pressure distributions over a model and then by adding up all these pressures all the way around, you can determine what the forces are. This is merely summing the pressures on an area. If I have an area one foot square and the pressure on it is one pound per square foot then the total force on it is one pound. Similarly, if I have a model and I can measure all the pressures all over it and I add up all these pressures that tells me what the total force was on the model. So by utilizing electric, electrical gauges which have been developed and also piezo-electric gages which have been developed, it's possible to make determinations on pressures very rapidly.

1:02:50 W.B. Mitchell: Summing these up then can give you forces. These are two ways that it can be, that forces can be determined. Temperatures in the shock tube are determined by the use of thermocouples. A thermocouple, you may know, is a junction of two dissimilar metals, which when heated gives rise to an electric current in the circuit to which they are attached. This is a means for determining temperatures at very high, at very high temperatures where you couldn't stick a thermometer in the thing. So a thermocouple then by virtue of the electric current which flows, you can calibrate the electric current by sticking the thermocouple in ice and measuring how much current you get by sticking it in boiling water which you know the temperature in determining how much current you are trying to get and consequently in this fashion, you can calibrate the thing. So by using what they call thin-film thermocouples, it’s possible to develop instrumentation which will react very quickly. These thin films then are maybe two films of dissimilar metals which are vapor-deposited one on top of the other of a molecules or so thick. They are so thin and they react very quickly to any heat input. Using instrumentation of this type it’s possible to measure temperatures. Do we have any more questions? Thank you very much.

1:04:10 Marian Longstreth: Thank you very much.

1:04:11 [Audience clapping]