Seymour M. Bogdonoff
and the Princeton Gasdynamics Laboratory

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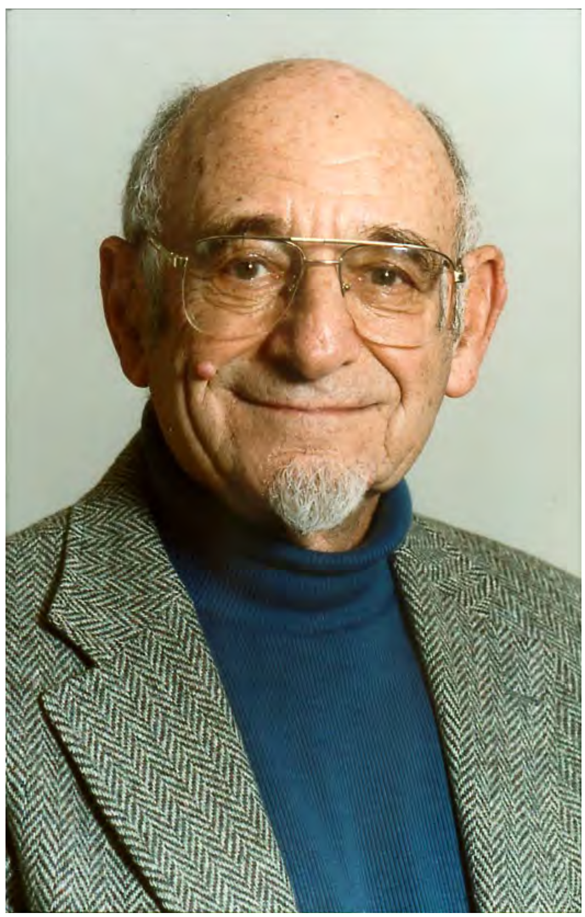
The Princeton Gasdynamics Laboratory was founded in about 1950 by Lester Lees and Seymour Bogdonoff. Bogdonoff became its Director in 1953, and remained in that post until 1989. Under his direction the Laboratory became a national powerhouse in aeronautical research. At its peak, the laboratory employed about six or seven faculty, maybe 50 graduate students, and 10 or 12 research associates and technicians, all working with a large range of wind tunnels designed by Bogdonoff, often aided by his close associate Irwin Vas. Here, we review some of the history and accomplishments of the Gasdynamics Laboratory.



Professor Seymour Moses Bogdonoff, 1921–2005.

*Fellow

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I. Introduction

Seymour Moses Bogdonoff, Robert Porter Patterson Professor of Aeronautical Engineering Emeritus, died on January 10, 2005 in Helene Fuld Hospital, Trenton, of injuries sustained in a fall in his home in Princeton, N. J.

Professor Bogdonoff, known to many simply as "Boggy," was born in New York City in 1921. He studied at Rensselear Polytechnic Institute and received his BSE degree in Aeronautical Engineering in 1942. Boggy started his career as an aeronautical engineer at NACA at Langley Field, where he met and married Harriet, a mathematician who, like Boggy, worked under Arthur Kantrowitz. They came to Princeton in 1946, when Lester Lees took a faculty position in the Aeronautics Department, and Boggy joined him as his assistant. He earned his Master's degree in the newly formed Department of Aeronautics in 1948, and he was immediately appointed an Assistant Professor. The department was only six years old in 1948, and under Dan Sayre and later Court Perkins it was expanding very quickly. Sayre and Perkins recruited the brightest people they could find, especially those like Boggy, who had experience in high-speed flight and rocketry.

It was obviously a very special time and place. The department brought together brilliant, often very young people, to work on some of the most exciting problems of the day. They were in the true sense rocket scientists, and they were challenging barriers in speed, altitude, and eventually, to reach space itself.

Boggy's interests were in high-speed aerodynamics, at supersonic and hypersonic speeds, where shock waves form and give rise to phenomena that had been completely unexplored at the time. At supersonic speeds, shock waves create enormous mechanical and heat transfer loads on vehicles. At even higher speeds, exceeding 10,000 mph, air is ripped apart by the impact under conditions like those found at the edge of space. Boggy pioneered this world, and he spent a lifetime exploring its challenges. His work was instrumental in developing the nation's space program, and was crucial to solving the problems of safe re-entry. His development of testing facilities and wind tunnels for these flow conditions was highly influential, especially in Europe where he was widely recognized for his contributions as an experimentalist.

At Princeton, Professor Bogdonoff was promoted to Associate Professor in 1952, and Full Professor in 1957. He was known as a skilled and demanding teacher, and his students went on to dominate all aspects of gasdynamics. He became the Robert Porter Patterson Professor of Aeronautical Engineering in 1964, and in the same year was elected to The National Academy of Engineering. He became his department's Chairman in 1974, and served for nine years. His skills as a consultant were widely sought by industry and government, advising the National Science Foundation, the Office of Science and Technology Policy, the Defense Science Board and NASA. He was nationally and internationally recognized for his work, and he had enormous influence on shaping research activities and research policies. He served on the Air Force's Scientific Advisory Board, which helps guide the Air Force's research and development plans, for 23 years from 1963 to 1986, which must be a record for unbroken service. He was a key advisor to NATO through his activities in the Advisory Group for Aerodynamics Research and Development, and helped to found and then nurture the European efforts in high-speed aerodynamics and space, and for this work he was recognized with numerous honors, including membership in the French Academy of Air and Space. At the same time, he maintained close contacts with Soviet scientists, helping to maintain vital scientific links at a time when governments were engaging in cold war brinkmanship.

But Boggy was much more than a very good scientist and engineer. He was a born leader. After Lester Lees left in 1953, Boggy took over the Princeton Gasdynamics Lab, and under his direction it became a national powerhouse in aeronautical research. At its peak, the laboratory had about six or seven faculty, maybe 50 graduate students, and 10 or 12 research associates and technicians, all working with a huge range of wind tunnels designed from scratch by Boggy, often aided by his close associate Irwin Vas.

From that research flowed a torrent of papers and reports that helped shape our understanding of high-speed flight. But more than that — literally hundreds of students went out from the lab to support the national programs in supersonic flight and the race for the moon, and these students, trained in the Gasdynamics Lab, went on to dominate all aspects of gasdynamics research and engineering. That legacy continues today, with the original students going on to train a second, as third and even a fourth generation of aeronautical engineers. You can still go to places like the Air Force Research Lab in Dayton Ohio, or to the von Karman Institute in Brussels, or DLR in Gottingen, and find wind tunnels that are exact copies of those designed by Boggy, run by people who were trained by Boggy. In 1954, he and Antonio Ferri co-authored the first general description of the design and operation of intermittent supersonic wind tunnels,[65] an enormous influential guide to experimental work for the burgeoning interest in high-speed flows. It was published as AGARDograph # 1, literally and figuratively at the start of a new age.

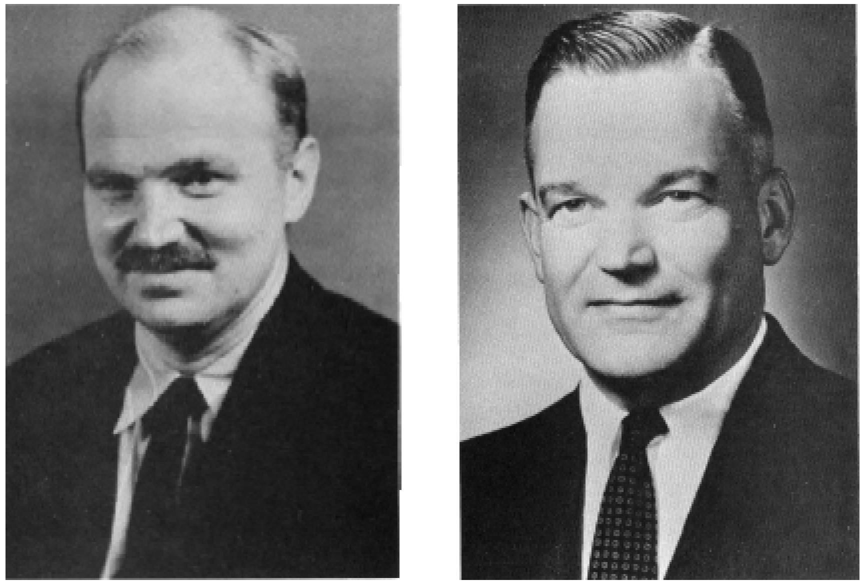

Figure 1. Daniel Sayre and Courtland Perkins.

From his early days he loved cars, and it was one of his personal passions throughout his life. He was a superb mechanic and an expert driver, honing his skills with his Porsche at Watkin Glenn. He challenged the Division of Motor Vehicles by bringing a red Citroen Deux Cheveaux from France and working through the bureaucratic nightmares to triumphantly drive it to work. In his later years, he was working to establish a driver education program for senior citizens.

Boggy was a man who held strong beliefs, and defended them passionately. He was renowned as a severe critic. If you disagreed with him, you'd better come prepared, and be as tough as Boggy himself. Even if you agreed with him you might have an argument on your hands. As a number of people have said to us, he was a force of nature. He has also been called the grain of sand that makes the pearl in the oyster. He challenged those around him to be better, to be stronger, and although it may not always have been pleasant at the time, it was an excellent education, and many students remember his help and guidance, often warmly.

At heart he was a generous, charming and kind man. He did many things for many people, all in a very quiet way, and he is remembered fondly by those who knew him well.

He is survived by his wife, Harriet, three children, Sondra Bogdonoff of Portland, ME, Zelda Bogdonoff, of Bethlehem, PA., and Alan Bogdonoff, of New London, CT., and five grandchildren.

II. The Gasdynamics Laboratory

Seymour Bogdonoff came to Princeton in 1946, just three years after the Aeronautics Department was established under the leadership of Dan Sayre (figure 1). At the time, the department consisted of Sayre, Alexander Nikolsky (an expert in rotorcraft and aircraft structures), Courtland Perkins (controls and dynamics, see figure 1), Lester Lees (theoretical aerodynamics), and Joseph Charyk (jet propulsion). One of the first new research appointments was Seymour Bogdonoff who had been a colleague of Lees at the NACA. He came to Princeton in 1946 with Lees to become his Assistant in Research and to work out a Master's degree. Bogdonoff was soon heavily engaged in setting up the blowdown tunnel facility (figure 2).

The Aeronautical Engineering Department started as a single office occupied by Dan Sayre in the Mechanical Engineering Laboratory, but soon was housed in two small cinder block buildings on the lower campus just above Lake Carnegie and in back of the Observatory (for a short history of the MAE Department at Princeton, see Smits and Perkins[25]).

"Project Squid" originated at the end of World War II when the Navy became interested in the possibilities of pulse jets and ram jets, and in 1946 it provided Princeton with significant funds for research. In particular, it provided support for the construction of a number of supersonic blowdown wind tunnels under Lees to study shockwave boundary layer interactions (figure 2). Lees' program developed ultimately into the Princeton

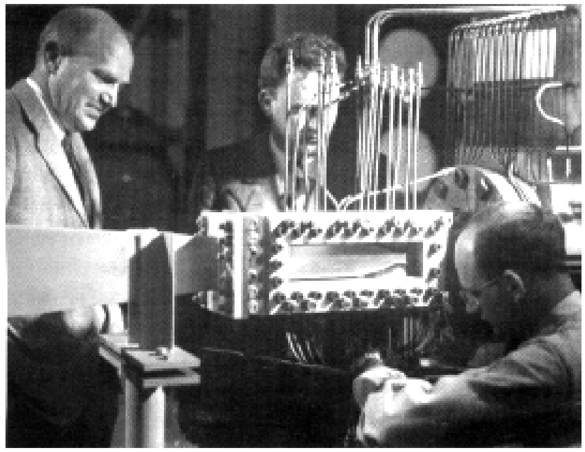

Figure 2. Chairman Daniel Sayre and Lester Lees look on as Seymour Bogdonoff adjusts a supersonic wind tunnel, circa 1949.[19]

Gasdynamics Laboratory.

By 1950 the Department had grown rapidly, although it was still housed in the cinder block buildings that Dan Sayre had developed on the lower campus. Research facilities had been expanded into areas of the campus that permitted makeshift construction, primarily temporary structures just behind Palmer Stadium, neighbors to Walker Bleakney's Shock Tube Laboratory and, a little farther away, George Reynold's Cosmic Ray Laboratory, both part of the Physics Department.

One of the major foci of the Department's activities was a deep interest in high speed aerodynamics, led by Lester Lees and Seymour Bogdonoff. They taught both graduate and undergraduate courses in this area, but spent a great deal of effort in developing one of the world's first supersonic blowdown wind tunnels. They were studying, both theoretically and experimentally, the problems of boundary layers and their interaction with shock waves. Many graduate students were interested in this area and one of them received one of the department's first Ph.D.s in 1949.

The faculty in the fall of 1950 included Dan Sayre (Chairman), Nikolsky, Perkins, Lees, Charyk, Crocco, Bogdonoff, Summerfield and Seckel. Some of these people are shown in figure 3. Six out of these nine were subsequently elected to The National Academy of Engineering after it was formed in 1964. Besides a faculty of nine in 1950, there were 40 graduate students, twelve of them in the Ph.D. program. Nineteen were civilians, 14 were Air Force, 4 were Navy, and 3 were Army. Total staff of all ranks amounted to 70. The value of the sponsored research program totaled about $550,000. At that time only the Physics Department had a larger program; the rest of the Engineering School was not building up equivalent programs.

In 1949 and early 1950, Dan Sayre and Court Perkins started to study seriously how they could better house the sprawling Department. Every cubic foot in the original buildings was filled, and the distance from the rest of the University was workable but inconvenient. The cinder block or wooden construction hardly conformed to Princeton architecture and was barely adequate for the department's needs. "Charyk's work was both noisy and noisome, producing malodorous fumes that did even less to endear the department to the astronomers in the nearby FitzRandolph Observatory. Adding to the cacophony of roaring test engines was the caterwaul of the so-called 'blowdown' wind tunnel used by Lees and Bogdonoff."[13]

Sayre and Perkins made a drawing of a possible new building, between the Stadium and Prospect Street, where the University built its Computer Center some years later. Lawrence Rockefeller, at that time a member of the Departmental Visiting Committee, helped with the study and made suggestions for raising the million dollars it was estimated to cost. Within a few weeks a remarkable event forced a solution to these housing problems that dominated the life of the Department for many years to come. The Rockefeller Institute was going to close down their Princeton Division and the land, buildings, and improvements were being put up for sale. With considerable help from the Rockefellers, the University purchased the property for $1,500,000, with another $500,000 for the renovation and conversion of facilities.[13] The whole Aeronautical Department was moved into this area and it was also used to house expanding research interests of other departments. The whole area was named The James Forrestal Research Center after the United States' first Secretary of Defense, who served from 1947 to 1949. Forrestal was a Princeton graduate, Class of 1915, and

Figure 3. Rear two rows, from left to right: Arthur Kovitz, John Scott, Edward Kepler, George Sutherland, Richard John, Irvin Glasmman, Gary Mallard, Andrew Hammitt, Sydney Reiter, Daniel Bershader, David Harrje, Walter Warren, Bud Marshall. Second row from front, left to right: Unknown, Joseph Charyk, Lester Lees, Ronald Probstein, Seymour Bogdonoff, Arnold Brooks, Edward Potlein. Front row, left to right: Daniel Sayre, Luigi Crocco, Theodore von Kármán, Dean Kenneth Condit, Walter Davis, Martin Summerfield. Circa 1950.

a former Charter Trustee.

According to Perkins:[14] "The decision to move ended what I like to refer to as the 'cinder block' era of the Department. No longer were we almost sitting on top of each other in makeshift facilities. Nevertheless, we had all been having a grand time. We had built up a nationally ranked Department of Aeronautical Engineering, and at little cost to the University. We all felt euphoric about our situation. We had a very friendly group of about 75 in 1950, including faculty, research staff, technicians, graduate students, mechanics, and secretaries. As a majority were married, it was a large group of people when we all got together, which we did quite often. The Department became famous for its Christmas parties, and many of our friends outside the Department were delighted to be invited to these festive occasions. These activities were usually led by our super party man, Dan Sayre, but he was ably supported by the rest of us, including Nikolsky, our vigorous Russian, and our most enthusiastic graduate students." "..... this was a highly motivated, friendly and successful group. We were delighted with what we were accomplishing and enjoyed being together."

On February 19, 1951, Court Perkins replaced Dan Sayre as Chairman of the Department.

After the move, the Aeronautical Engineering Department started a relatively rapid expansion of their facilities in this new area. An aerial view is shown in figure 4. Moving the high speed aerodynamics work of Lees and Bogdonoff into one of the long shed-like animal research laboratories required a great deal of modification to house not only the supersonic throats, but also the reciprocating compressors and

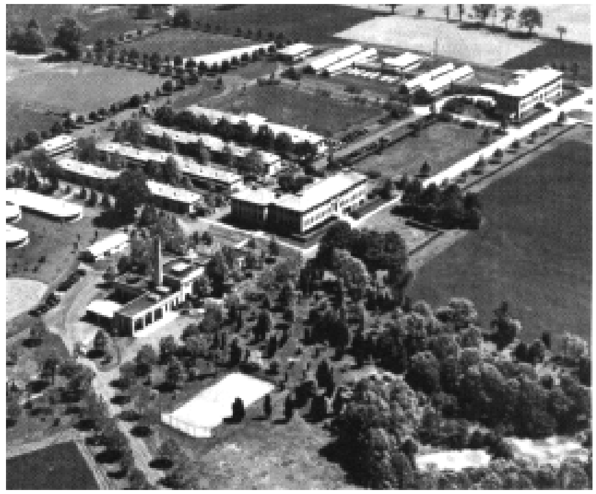

Figure 4. Aerial view of the Forrestal Research Center (Princeton University Archives).

the high pressure bottle farm. This was a most difficult transition, particularly as the sponsors of this program were nervous about continuing their support despite long delays. The distance problem continued to nag the Department for many years, but Forrestal campus provided a remarkable area for expanding departmental operations, that now included five Laboratories. These Laboratories were entitled: the Flight Research Laboratory; the Gas Dynamics Laboratory; the Guggenheim Propulsion Laboratory; the Low Speed Aerodynamics Laboratory; and the Rotor Dynamics Laboratory. Here, in 1950, with the establishment of the Forrestal Campus, and the dedication of the Mach 3 tunnel (figure 5), we have the official beginning of the Princeton University Gasdynamics Laboratory.

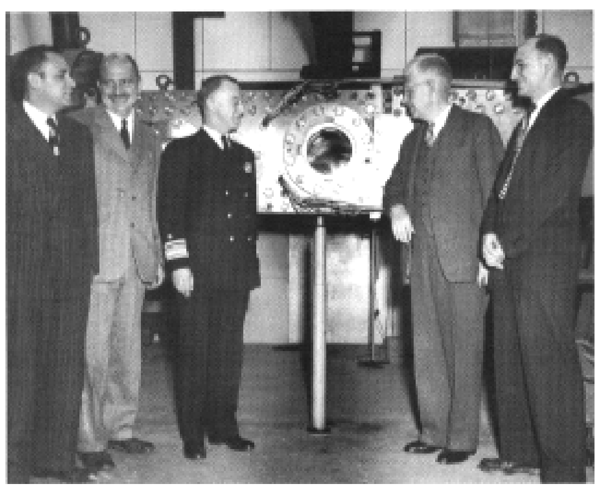

Figure 5. Dedication of the Mach 3 wind tunnel (1950). Left to right: Lester Lees (project head), Chairman Daniel Sayre, Rear Admiral Thorvald A. Solberg (chief of the Office of Naval Research), President Harold W. Dodds, and Seymour Bogdonoff (project engineer).[17]

In 1953 Lester Lees left to accept a Full Professorship at CalTech, and Seymour Bogdonoff took over running this program. Since Bogdonoff was basically an experimentalist, a search was started to find a theoretical person to fill the shoes of Lees. This brought Dr. Wallace D. Hayes to Princeton in 1954. Hayes had achieved considerable fame for his theoretical work in transonic flows, and laid down some of the theoretical basis for the experimental work done by Whitcomb of the NACA, that brought the Area Rule into prominence. Hayes had received his Ph.D. from CalTech and then worked as a theorist, first for Lockheed, and later for the U.S. Navy. He was later to write a most influential book Hypersonic Flows Theory with Ronald Probstein*52, as well as another on Gasdynamic Discontinuities. Hayes and Probstein also edited

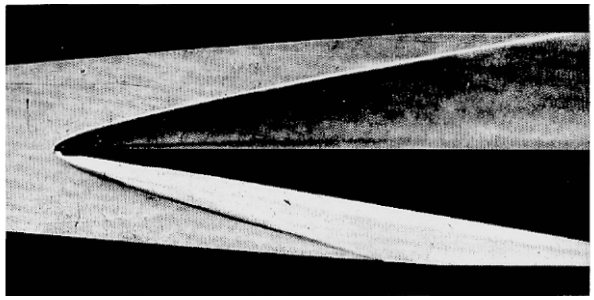

Figure 6. Schlieren photograph of a blunted flat plate in helium at Mach 11.6. The boundary layer is visible over the top of the plate. The shock shape is close to a power-law shape, with a measured exponent of 0.66 ± 0.01. This may be compared to the theoretical value by Hayes & Probstein of 0.667. Photo courtesy of the Gas Dynamics Laboratory, Princeton University.

the English translation of Zel'dovich and Raizer's book "Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena" in 1966.

Some excellent research talent was attracted to the staff of this Laboratory, many of them ending up on the faculty. Among these were Sin I. Cheng, Harvey S. H. Lam, George Bienkowski, Enoch Durbin, and Jerome A. Smith. Two very able Senior Research Associates, Andrew Hammitt and Irvin Vas, also played an important role in the development of this Laboratory. Bogdonoff rapidly had this group working smoothly with a very sophisticated program in super and hypersonics, both theoretical and experimental in the Gasdynamics Laboratory. The combination of experimental and theoretical work proved a powerful combination (figure 6). By the end of the decade this group was full of graduate students and running a renowned program in high speed theoretical and experimental aerodynamics.

At the end of 1963 the department had 70 graduate students and an equivalent number of undergraduates. The sponsored research funds totaled just over $1,000,000, and the total staff came to 250. At this time a national survey of Departments of Aeronautical Engineering rated Princeton the number 2 school in the country.

A new office-type building was built to house the Gas Dynamics Laboratory, as well as a few ancillary buildings for new blowdown wind tunnels and facilities to recover the working fluid when it was helium.

This was the state of affairs at the start of the 1963-64 academic year. At this time the Mechanical Engineering Department was falling on difficult times, and it was merged with the Aeronautics Department on May 31, 1964. Perkins was asked by President Goheen to Chair this new Department, and after much study and argument the newly merged Department was named the Department of Aerospace and Mechanical Sciences (AMS). This new department combined the full activity of the old AE Department based at Forrestal with the activities of the old ME based in the Engineering Quadrangle, a new building completed in 1962 to house the entire School of Engineering and Applied Science.

At first Perkins maintained the Departmental offices in Sayre Hall on the Forrestal Campus, and set up another office in the old ME Chairman's office in the Quadrangle. Slowly but surely, however, the Departmental office in the Engineering Building became headquarters and office space was provided for AE faculty members in the Engineering Quadrangle. This arrangement went a long way to alleviate the problem of distance from the department's students and the rest of the University faculty. The final move to the Engineering Quandrangle was really the work of AMS faculty member Robert Jahn, and was completed shortly after he assumed the Deanship in 1971. He undertook the relocation of the AMS Department to the Engineering Quadrangle as one of his primary missions, since our Department constituted the principal research entity in the School. He wanted to build closer ties with the undergraduates and foster the cross disciplinary programs that he was initiating.[11]

At the same time the move started to take attention away from the Forrestal Campus and back to the main campus. Inevitably the tightly knit group that had formed in the old AE Department was starting to break up, and the department was never were quite the same again. Nevertheless, from 1963 to 1966 the AMS Department grew to be one of the largest in the University, with 29 regular faculty members and a large research staff, 130 graduate students and a sponsored research program of over $3,000,000, most of which was based on the activities at Forrestal.

The 60's saw the development of Princeton as a center for fundamental studies in engineering and applied science. It became particularly noted for its efforts in developing the fundamental understanding of fluid mechanics and combustion processes. In fluid mechanics, Francis R. Hama's contributions to the understanding of laminar-to-turbulent transition over the entire speed range from hypersonic to incompressible flows are still widely recognized for their importance. The work in hypersonic and supersonic flows continued unabated under the direction of Bogdonoff, Cheng, Hayes, and Bienkowski. Early on Boggy recognized the importance of lasers in gasdynamics and brought Richard B. Miles to Princeton in 1972 to work with Harvey Lam, George Bienkowski and Jerry Smith on gasdynamic lasers and laser diagnostics. This work led in 1978 to the first demonstration of planar laser fluorescence imaging diagnostics for high speed flows.

In 1974, after a record 23 years, Court Perkins stepped down as Chairman, and was succeeded by Seymour Bogdonoff. The department continued to prosper under Bogdonoff, who served as Chairman from 1975 to 1983. The Gasdynamics Laboratory, however, slowly declined in size as DoD spending on basic research was curtailed. By 1981, there were two Research Staff members (Gary Settles, who completed his PhD with Boggy in 1975, and David Dolling, who had arrived from London in 1978), one postdoc (Kyo Hayakawa), four technicians (Robert Bogart, Gary Katona, Richard Gilbert, and William Stokes), with five or six graduate students in residence, and Boggy, Richard Miles, and Alexander Smits as the principal active faculty. Smits became the Associate Director in 1985, and then the Director in 1989, the same year Boggy retired.

III. Research

Boggy's research interests ranged widely over the hypersonic and supersonic Mach number range, and covered laminar and turbulent flows, in two and three dimensions. In the next paper to be presented in this session,[4] Professor Chernyi will review Boggy's work in hypersonic flow. Here, we would like to highlight some of Boggy's contributions to supersonic flow. We have picked four particular examples: his work in measuring base pressure distributions on blunt-based bodies of revolution, his investigations of two-dimensional shock-wave boundary-layer interactions as exemplified by the Mach 3, compression corner interactions, his study of the reattaching shear layer problem, and his wide-ranging investigations of three-dimensional shock-wave boundary-layer interactions, as exemplified by the Mach 3 sharp fin interactions.

A. Base pressure

One of the first research tasks tackled by Boggy was the measurement of the base pressure on a streamlinbed body with a blunt base. Missiles and projectiles often have this body shape, and the drag of these bodies is dominated by pressure losses so that the base pressure is a direct measure of the drag on the body. Typically, the base pressure is very difficult to compute since it is related to the losses in the flow due to separation and turbulence. In supersonic flow, the losses due to shock waves is an additional complicating factor, and experiments become essential. Experiments on base pressure, however, have their own difficulties, the most challenging being the influence of the supports on the measurements. If the body is held from the rear on a sting, the presence of the sting obviously will disturb the base flow and lead to inacccuracies in measuring the base pressure. If the body is held by a support attached to any other part of the body, it will disturb the incoming flow, and lead to similar uncertainties in the data.

Boggy found an ingenious solution. He used a rear sting to support the body, but made a series of measurements for as he reduced the diameter of the sting, reasoning that as the sting diameter goes to smaller and smaller values he would recover the "correct" value, that is, the value corresponding to free flight. The trouble with his approach, of course, is that the support may fail under the enormous loads experienced in supersonic flow (especially during the start-up of an intermittent, or blowdown, tunnel). In response, Boggy made a large number of models out of plastic, and took failure in his stride. All he needed was one model to stay intact for as long as it took to make his pressure measurements, and eventually he found a model that did. The complete data set was presented by Boggy in the Journal Of The Aeronautical Sciences in 1952.[67] In 1965, Boggy, aided by Irwin Vas and Earll Murman, repeated this approach to study the wakes of spheres at $M = 16$ in helium.[56]

The 1952 paper on base pressure also introduced the Mach 3 high-Reynolds number blowdown facility, completed in 1950, to the world (see figure 5). It was the first major facility of the Gasdynamics Laboratory, and it had a fixed nozzle and a working section measuring 4×8 in. It was later modified to have a 8×8 in. working section, the famous "8 by 8" tunnel still used today. A close copy is also still in use at the Air Force Research Laboratory in Dayton, Ohio.

B. Two-dimensional shock-wave boundary-layer interactions

Perhaps the most famous set of experiments that came out of the 8 by 8 tunnel is the highly detailed studies of compression corner flows at Mach 3. Already in 1952, Boggy had started work in studying shock-wave boundary-layer interactions[66] (SWBLI), and in 1954 published two papers on interactions strong enough to produce separated flow.[63,64]

The systematic study of the mean flow behavior of these flows and their scaling with Reynolds number was described in a landmark series inspired by the Ph.D. work of Gary Settles.[43,48,50–53] The experiments covvered a range of Reynolds numbers based on boundary layer thickness from 520×10^3, to 7.90×10^6, and ramp angles of 8°, 10°, 14°, 16°, 18°, 20°, and 24°. The data included surface flow and shadowgraph visualizations, wall pressure, skin friction, and mean velocity measurements (see figures 7, 8, 9, and 10).

The shadowgraph visualizations shown in figure 7 reveal a wrinkled shock surface, and indicate that the turbulent mixing is considerably enhanced across the shock, with these trends becoming more pronounced as the shock strength increases. The incursions of freestream fluid appear to become much deeper, suggesting that the length scales of the turbulent motions have correspondingly increased. At the smallest corner angle, the shock remains quite distinct almost to the surface, but as the corner angle increases the shock appears to fan out and break into a system of compression waves that start well ahead of the corner. Shadowgraphs, however, represent a spatial average across the flow and do not give a good indication of the behavior in any given streamwise plane. Muck et al.[37] found that in addition to its motion in the streamwise direction, the shock front is wrinkled in the spanwise direction. The work by Poggie et al.[16] suggests that the shock can also split in the spanwise direction, leading to a highly three-dimensional distortion of the shock front. Dolling and Bogdonoff[40] showed that the mean wall pressure begins to rise well ahead of the average shock position because of this unsteady motion of the shock. This *upstream influence* is seen in the wall-pressure distributions (figure 8) and it increases with corner angle, indicating that the unsteadiness of the shock system becomes more important as the shock strength increases. This figure also indicates that only part of the total compression and turning occurs across the wave system, and compression and streamline curvature continue for several boundary layer thicknesses downstream of the corner.

For the compression corner interaction, the mean pressure distributions begin to develop a *plateau* region for turning angles greater than 16° (see figure 8), which indicates the onset of mean flow separation: the condition at 16° is called *incipient* separation.[48] The instantaneous flow will show signs of reversal at smaller turning angles, but at 16° the mean skin friction becomes zero at some point[21] (see figure 9). Both the 20° and 24° corners exhibit regions of separated flow, and the mean velocity profiles (figure 10) display a region of reversed flow that agrees in location and extent with the skin-friction measurements shown in figure 9. Adverse pressure gradients in a compressible boundary layer flow can cause the skin friction to increase because of the thinning of the layer. Here we see that if the pressure gradients are strong enough, the skin friction can decrease suddenly, and the flow can separate. Downstream, however, the overall increase in pressure can still cause the skin friction to rise above its usual value at the same Reynolds number, again because of the thinning of the layer.

An important aspect of shock wave-boundary layer interactions is the prediction of the onset of separation. Local interaction ideas attempted to couple the onset of separation to the local pressure rise, but work at the Gasdynamic Laboratory identified the important role played by the incoming boundary layer in terms of Reynolds number effects and shock unsteadiness. Figure 8 demonstrates that the wall pressure does not rise sharply in the region of separation. Instead, it rises gradually, levels off somewhat in the fully separated zone (the "pressure plateau"), and then starts to rise again in the region of reattachment, eventually reaching its maximum value some distance downstream of the mean reattachment line. The region of *upstream influence* is defined as the distance from the corner to the point where a straight line drawn to fit the slope of the initial pressure rise intersects the pressure level corresponding to the incoming boundary layer. Now, even in a perfectly steady (laminar) interaction, we expect there to be an upstream influence. The pressure rise generated by the flow deflection can propagate upstream through the subsonic part of the flow near the wall, causing the streamtubes below the sonic line to thicken, and producing a flow deflection upstream of the corner. However, the upstream propagation distance depends on the thickness of the subsonic layer, and the sonic line rapidly approaches the wall as the Mach number increases. For the case shown in figure 8, the sonic line for the incoming boundary layer is located at a distance less than 0.01δ from the wall, and the steady upstream propagation distance is expected to be very short. Indeed, measurements of the instantaneous wall pressure show that the shock appears as a very rapid rise in the pressure signature: there is no sign of an instantaneous upstream propagation of pressure. However, the unsteady motion of the shock occurs over a

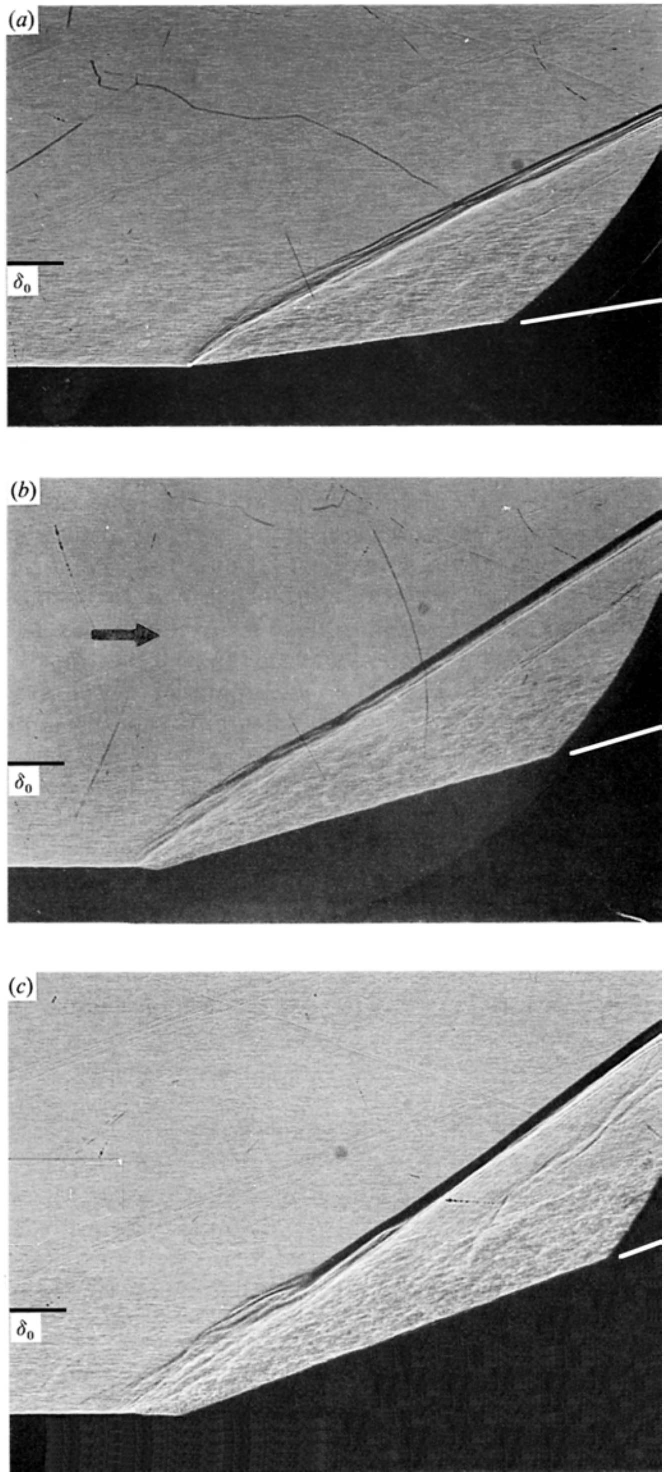

Figure 7. Shadowgraphs of compression corner interactions at a Mach number of 2.9 with turning angles of 8°, 16°, and 20°. The curved boundaries on the left and right of the pictures are the edges of the circular window, not parts of the model.[48]

much greater distance than the steady upstream propagation distance, and it is this unsteady motion that is primarily responsible for the upstream influence seen in the wall pressure distributions. The mechanism is illustrated in figure 11. Note that the extent of the upstream influence is a strong function of Reynolds

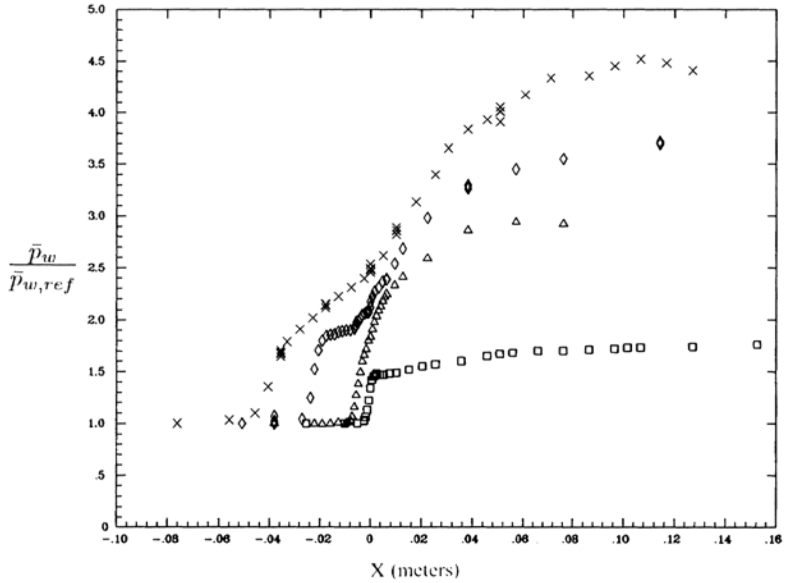

Figure 8. Pressure distributions in compression corner interactions at $M = 2.9$: $\square$, 8°; $\triangle$, 16°; $\diamond$, 20°; $\times$, 24°. The pressures are normalized by the value of the wall pressure measured upstream of the interaction, and the distance x is measured from the start of the compression corner.[48]

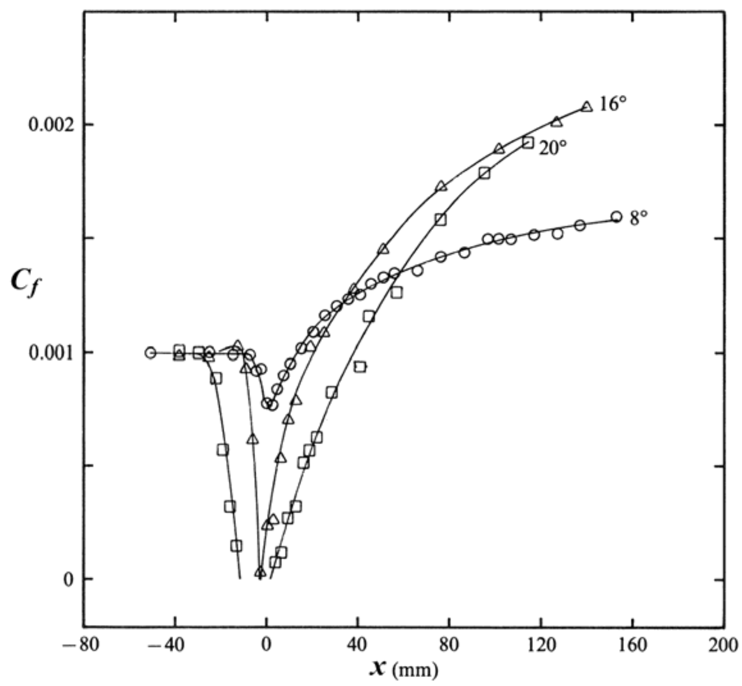

Figure 9. Distributions of C_f in compression corner interactions at Mach 2.9. The wall stress is non-dimensionalized using "effective" edge conditions based on tunnel stagnation and local static pressures. (Figure adapted from Smits,[24] showing data by Settles.[48])

number[3,51,52]).

Within the region of shock motion, the wall pressure signal is intermittent, as seen in the figure. The values of pressure upstream and downstream of the shock are consistent with the pressure rise through the

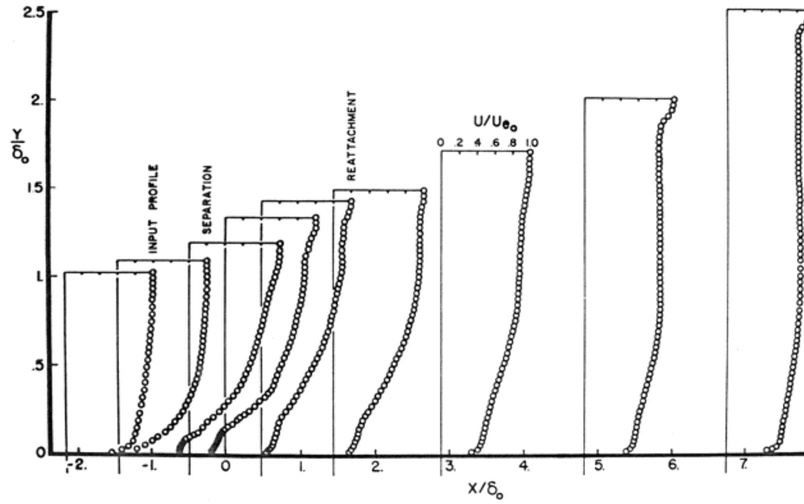

Figure 10. Development of the mean velocity profiles through a 24° compression corner interaction at Mach 2.9, with Re_θ = 72,100. Distances and velocities normalized by upstream values. (Figure adapted from Settles.[51])

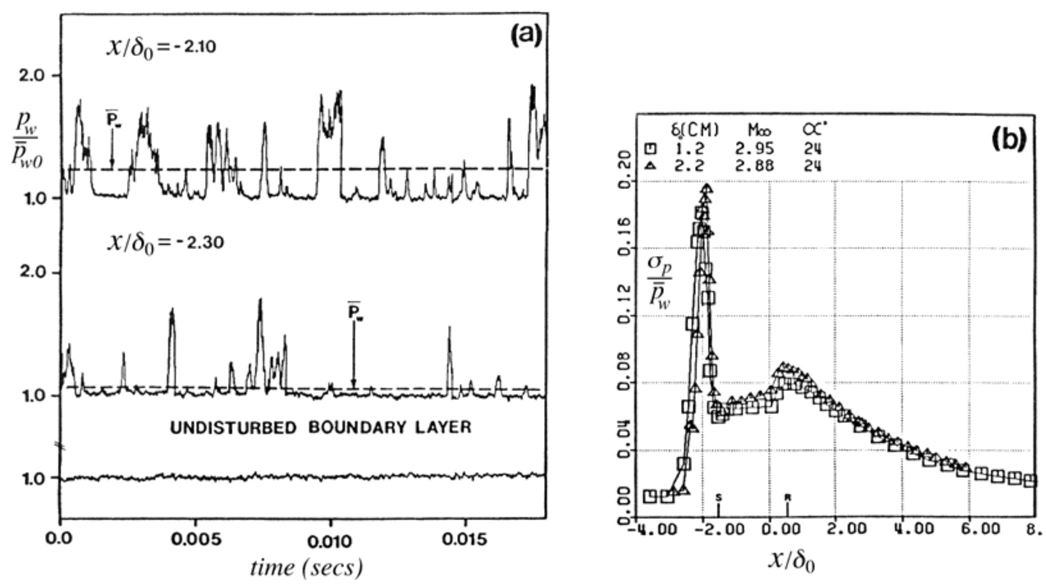

Figure 11. (a) Wall pressure time histories, and (b) *rms* wall pressure levels, in a 24° compression ramp at Mach 3. The lines of mean separation and reattachment are marked by S and R, respectively. The pressures were non-dimensionalized using the upstream mean wall pressure, $\overline{p_{w0}}$; σ_p is the *rms* wall pressure level.[40]

mean shock at its foot. The local mean wall pressure at a given location is simply the result of the pressure rise across the shock foot, weighted by the time the shock is upstream of that location. This result was a key concept developed at the Princeton Gasdynamics Laboratory.

As far as the turbulence behavior is concerned, we could anticipate from the shadowgraphs shown in figure 7 that the turbulence levels in the interaction would be strongly amplified. The hot-wire measurements for the Mach 2.9 compression corners indicate that the mass-flux fluctuation intensity, for example, can increase by factors of four to fifteen, and the amplification of the mass-weighted shear stress is even greater.[24]

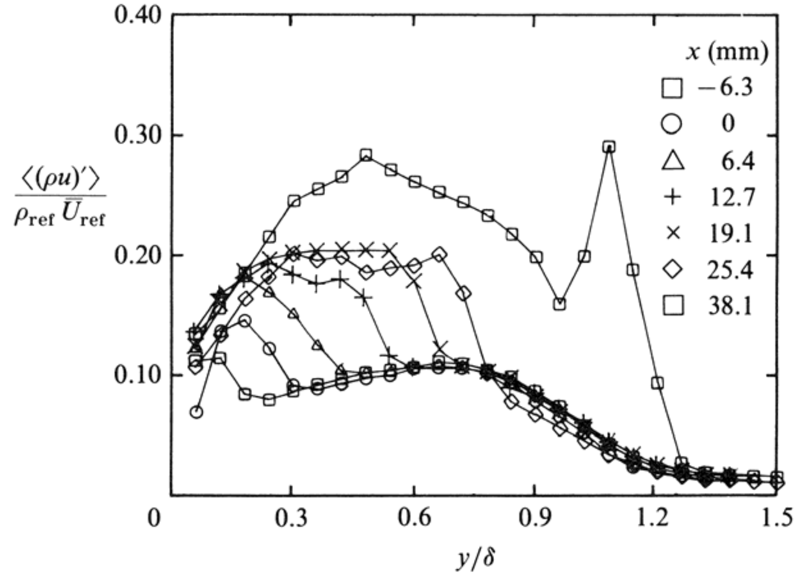

Figure 12. Distributions of $(\rho u)'$ in 16° compression corner interaction, in the region near the corner.[24]

The increase in the mass flux fluctuations across the shock is illustrated in figure 12 for the 16° compression corner.

Compression corner studies confirmed earlier studies that interactions produce a large increase in turbulence activity: for a 20° deflection at Mach 2.9,[24] found that the maximum level of $\overline{u'^2}$ increased by a factor of about 12. The unsteady shock motion smears the region over which the amplification occurs, and it sometimes produces a local peak in the intensity profiles. The results given in figure 12 show this behavior clearly. It appears that the region directly affected by the shock has a thickness of about 0.1δ for the 8° case, and 0.2δ for the 16° case. The extent of the unsteady shock motion at the wall measures approximately 0.15δ and 0.3δ for these two cases.[40] Clearly, the shock motion extends throughout the layer, and the amplitude of the motion is approximately constant with distance from the wall.

Finally, measurements of the heat transfer in a 16° compression corner interaction at Mach 2.84 demonstrate that the Reynolds Analogy factor s, the ratio of the Stanton number to the skin-friction coefficient, strongly deviates from a constant value in the region downstream of the interaction. Evans and Smits[7] found that s initially increased by a factor of about three, relaxed quickly to a value equal to twice its upstream value at a distance $3\delta_0$ from of the corner, and then showed no obvious signs of further relaxation further downstream.

C. Reattaching shear layer

To study the reattachment region more closely,[15,16,22,38,42,44,45] conducted experiments in a backward-facing step flow where the separation point was fixed, and a relatively large recirculation zone was formed. The freestream Mach number was 2.9. The reattachment occurred on a 20° ramp, and the ramp was adjusted so that the upstream boundary layer separated without deflection. The pressure fluctuations on the ramp reached very high levels, and a peak value equal to about 11% of the local mean wall pressure was found just downstream of the mean reattachment line. Multiple shocks were observed in this region, interacting in complex patterns. Shocks typically formed at the upstream edges of the large-scale structures in the reattaching shear layer and redeveloping boundary layer. Double-pulsed Rayleigh scattering images showed the formation and progressive strengthening of these shocks as the structures convected through the reattachment zone (figure 13). The spectra of the wall pressure did not display the low-frequency peak commonly observed in compression corner interactions, supporting the notion that it is the expansion and contraction of the separation bubble that is responsible for low-frequency shock motion in those flows. In the case of the reattaching shear layer, it is the incoming turbulence that is the primary cause for the shock motion and the intense levels of fluctuating pressure that occur near the mean reattachment line.

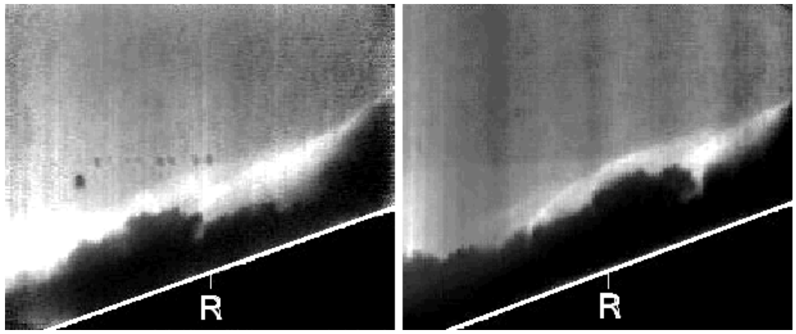

Figure 13. Rayleigh scattering flow visualization of a reattaching shear layer. The incoming flow is a free shear layer formed by a backward-facing step, with a freestream Mach number of 2.9. The visualization is just downstream of attachment which takes place on a 20° ramp. The flow is along the ramp, from left to right, and the average position of reattachment is indicated by the letter R. The right image was taken 20 μs after the left image. The shocklets are visible as bright fronts, shrouding the darker large-scale features in the boundary layer.[15]

D. Three-dimensional shock-wave boundary-layer interactions

Some of the more common configurations used to study shock wave-boundary layer interactions at the Gasdynamics Laboratory and elsewhere are illustrated in figure 14. In three-dimensional interactions, the shock may be generated by a sharp fin placed at an angle of attack to the incoming flow, by a blunt fin where the leading edge has a finite radius of curvature, or by a cone or other protrusion rising from the surface. The fins may also be swept in the streamwise direction, so that the shock sheet in the freestream is angled in two directions with respect to the upstream flow. The geometries of these interactions have many degrees of freedom, and they can become quite complex. A large range of possibilities were studied at Princeton by Bogdonoff, Dolling, Settles and Kimmel,[30,32–36,40,41,43,46,47,49] among others. Further complexities are introduced when shocks interact with each other, as in crossing-shock interactions.[31] In addition, the Mach number plays a crucial role in governing the inviscid flowfield. For example, as the Mach number increases for a given shock generator configuration, the inviscid shock may change from being detached to being attached, producing large changes in the near field. Even if the inviscid shock is attached, the reduced Mach number within the boundary layer may cause detachment at some point, and this can change the entire flow pattern. Variations in Reynolds number will also play a role, but for fully-turbulent flows its influence appears to be relatively minor because most interactions are pressure dominated.

Most three-dimensional interactions can be classified according to four basic types: sharp-fin, swept-corner, swept-step, and blunt-fin. These in turn can be broken into two classes: the first two types are in the class of being "non-dimensional" interactions in that there is no characteristic dimension associated with the shock generator, and the second two types are in the class of "dimensional" interactions in that the shock generator has a characteristic dimension, such as the diameter of the fin or the height of the step. This distinction was explored extensively at the Gasdynamics Laboratory. In all cases, apart from a small inception region (located either near the upstream extent of the compression corner, or near the leading edge of the fin), the flow develops a helical flow with its axis closely aligned with the shock.

Two relatively simple examples of non-dimensional interactions are shown schematically in figure 15. In the first view, the interaction is generated by a swept compression corner, and in the second view it is generated by a sharp fin placed at an angle of attack to the incoming flow. Both examples display lines of accumulation of dye upstream and downstream of the inviscid shock location: the *line of convergence* is sometimes called the line of separation, and the *line of divergence* is sometimes called the reattachment line. These figures illustrate relatively weak interactions: as the strength of the shock increases, multiple secondary flows can be observed.

Settles[21] suggested that the non-dimensional interactions represent examples of *cylindrical* similarity and the dimensional interactions display *conical* similarity. For example, in the compression corner flow the cross-section of the secondary flow becomes constant (cylindrical similarity), whereas for the sharp-fin flow it scales with distance from the virtual origin of the flowfield (conical similarity). The flows become two-dimensional when viewed in the appropriate coordinate system, similar to what happens in the inviscid flow

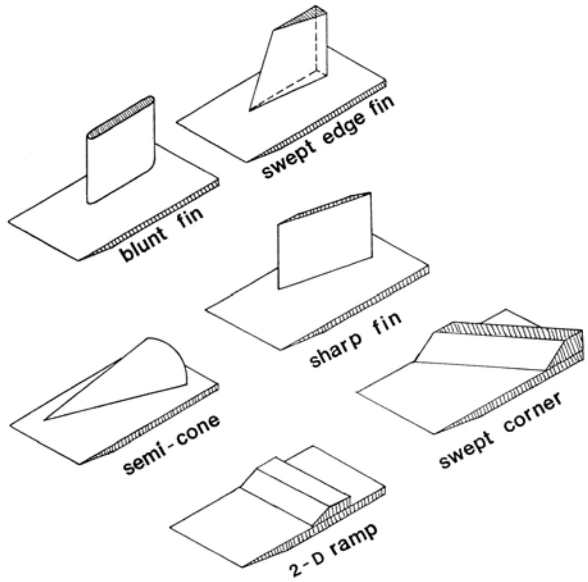

Figure 14. Examples of two- and three-dimensional shock wave-boundary layer interaction geometries studied in the Gasdynamics Laboratory.[27]

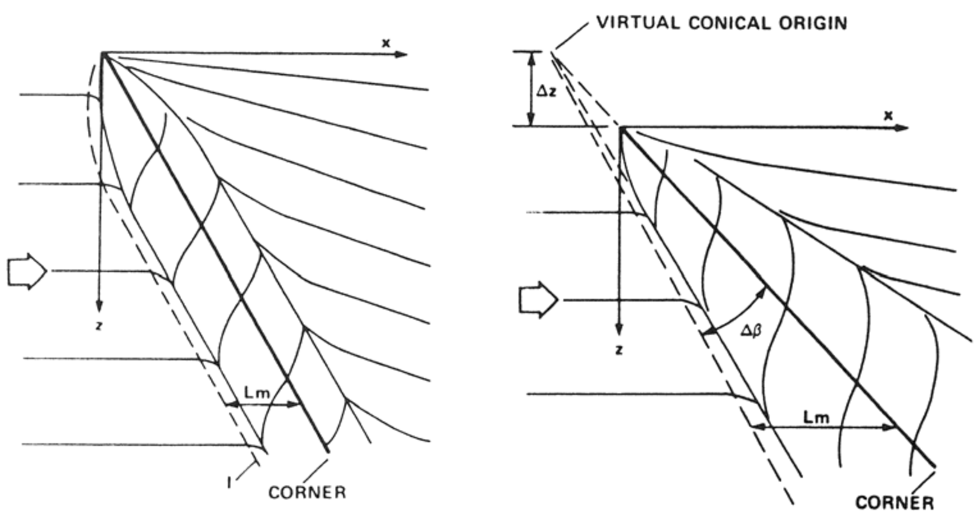

Figure 15. Schematic representations of the surface flow patterns produced by (a) swept compression, and (b) sharp-fin interactions.[21]

over an infinitely swept wing, or a cone.

E. Sharp-Fin Interactions

We now consider briefly one example of non-dimensional flows studied at the Gasdynamics Laboratory, the interaction formed by a sharp-fin placed at an angle of attack to the incoming flow. Here the oblique shock sweeps across the incoming boundary layer, and strong secondary flows can be produced by the spanwise pressure gradients. Typically, one or more large-scale vortical motions are induced that sweep the low-momentum fluid from the near-wall region of the incoming boundary layer in the direction along the shock (see figure 16). The high momentum fluid in the outer part of the boundary layer passes over the vortex

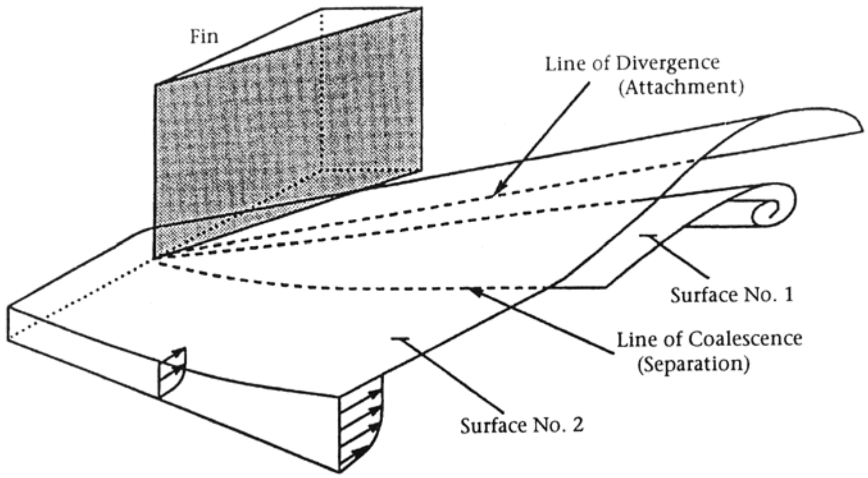

Figure 16. Structure of three-dimensional shock wave-boundary layer interaction generated by a sharp fin at an angle of attack.[33]

with a turning angle more typical of the inviscid deflection associated with the shock, and it is then swept close to the wall. The skin-friction and heat-transfer levels seem largely unaffected by the strong secondary motions, but the values rise sharply in the region closer to the fin where the high momentum fluid "scours" the wall. The turbulence response is not well understood. Very few experimental results are available, but measurements by Tan at the Gasdynamics Laboratory (reported by Konrad et al.[12]) suggest that the turbulence levels are strongly amplified, and Tran[27] found that the shock is unsteady, leading to strong wall pressure fluctuations. In these respects, three-dimensional interactions appear to be similar to their two-dimensional counterparts, but the detailed response of the turbulence is clearly quite different. In particular, the turbulence amplification and the unsteady pressure loading are weaker.

In the interaction generated by a sharp fin, the shock sweeps across the incoming flow at an oblique angle to the upstream flow direction. In contrast to the swept compression corner interaction, the shock in the freestream is normal to the wall over which the incoming boundary layer is developing. However, the response of the flow is very similar in the two interactions. A streamtube encountering the shock is turned, compressed, and decelerated. When the pressure gradient is strong compared to the entering momentum flux, the flow is turned in a direction away from the direction of the pressure gradient. The degree of turning increases as the Mach number decreases. Therefore, for a boundary layer entering a pressure gradient, the gradient in Mach number will cause the flow near the wall to turn through a greater angle than the flow away from the wall (as long as the pressure gradient dominates). The differential turning leads to a helical secondary flow, as illustrated in figure 16.

The shock bifurcates in response to the formation of this secondary flow, in a manner very similar to that seen in two-dimensional separated compression corner flows. There is an initial turning and compression by a well-defined shock which is slanted forward (the "separation" shock), and a stronger trailing shock, where broadly speaking the two shock structures encompass the large-scale vortical flow. When the flow is viewed along the axis of the helix it appears similar to the cross-section of a two-dimensional separated flow (see figure 17). In that view, a bubble-type separated flow is observed, and the flow characteristics typically scale in conical coordinates.[8] The experiments show that the wall pressure distribution and the total pressure distribution can be collapsed in conical coordinates. One feature that deserves particular attention is the "impinging jet", found in close proximity to the fin itself. As the model by Garg and Settles[8] makes clear, the jet is formed by high-momentum fluid from the outer regions of the incoming layer (including the freestream) curved towards the surface as the low-momentum fluid near the wall is removed in the spanwise direction by the main vortical flow. Not surprisingly, the maximum skin-friction and heat-transfer rates occur near the jet impingement location.

The unsteadiness of the sharp-fin interaction was first studied by Tan and Tran.[26,27] Although these studies were confined to a single Mach and Reynolds number, they discovered many of the same features seen

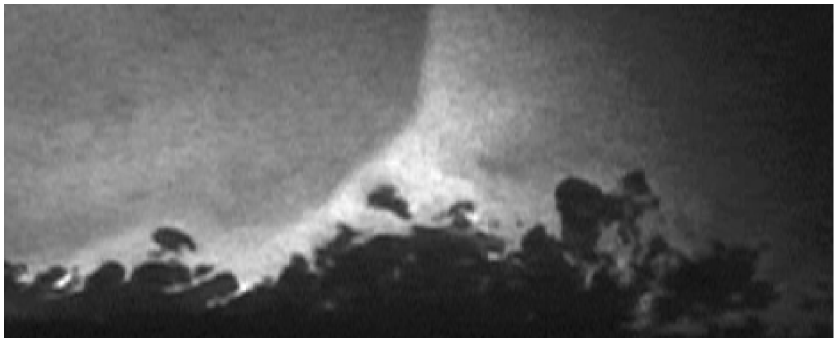

Figure 17. Filtered Rayleigh scattering image of a sharp-fin interaction at Mach 8, with $Re_\theta = 2400$. The view is in a plane aligned with the incoming flow direction. Incoming flow is from left to right. Within the interaction, the flow is out of the page at approximately 16°.[2]

in two-dimensional interactions, particularly the intermittency of the pressure signal in the upstream influence region. The Rayleigh scattering visualizations by[23] showed the movement of the separation shock clearly, and also revealed the motion of the triple point where the separation shock meets the main shock. Later work by Garg and Settles,[8] among others, demonstrated that the mean and *rms* pressure distributions scale in conical coordinates. The wall pressure signals near separation were clearly intermittent and qualitatively similar to those in two-dimensional flows. As expected, the amplitude of the *rms* pressure fluctuations increased with the fin angle, and in agreement with the data from the swept compression corners, the shock frequencies increased with the sweep angle of the separation line, at least up to an angle of about 25 to 30°.

One of the few investigations to make turbulence measurements in three-dimensional interactions was performed by Tran and Tan (unpublished) in a 10° sharp-fin interaction at Mach 2.9. Their results are shown in figure 18. The inviscid shock position in the freestream is evident through the local maximum in

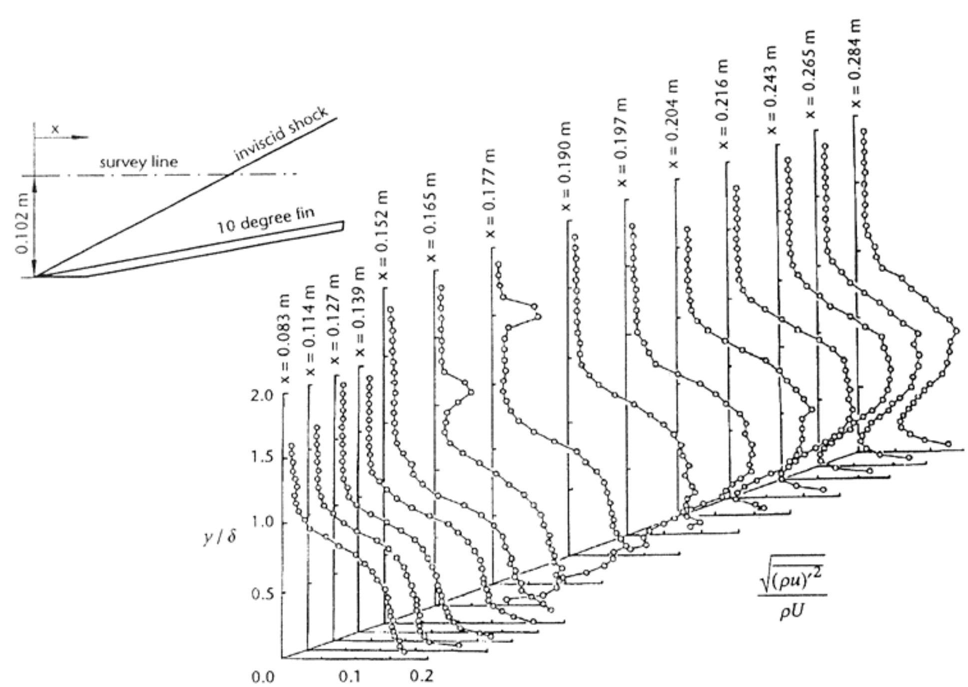

Figure 18. The evolution of the *rms* mass flux intensities for a 10° sharp-fin interaction at Mach 2.9. Data from Tran and Tan (unpublished). (Figure from Konrad.[12])

the distributions at $x = 0.165$ m and 0.177 m. The turbulence levels in the outer flow increase substantially, and there is little sign of the start of a relaxation process. Near the wall, the levels are strongly attenuated, and at first sight it appears as though an internal layer has formed. This is misleading in that it neglects the three-dimensionality of the flow: in fact, the lower turbulence levels indicate that high-momentum, low-turbulence fluid has been brought into the region near the wall. The maximum amplification of the *rms* mass flux intensity for this 10° fin is about 30%, which may be compared to the case of the unswept 8° compression corner at the same Mach number where an increase of about 35% was observed. The small decrease observed in the amplification level may be due to the three-dimensionality, but the uncertainties in the data are too large to be sure.

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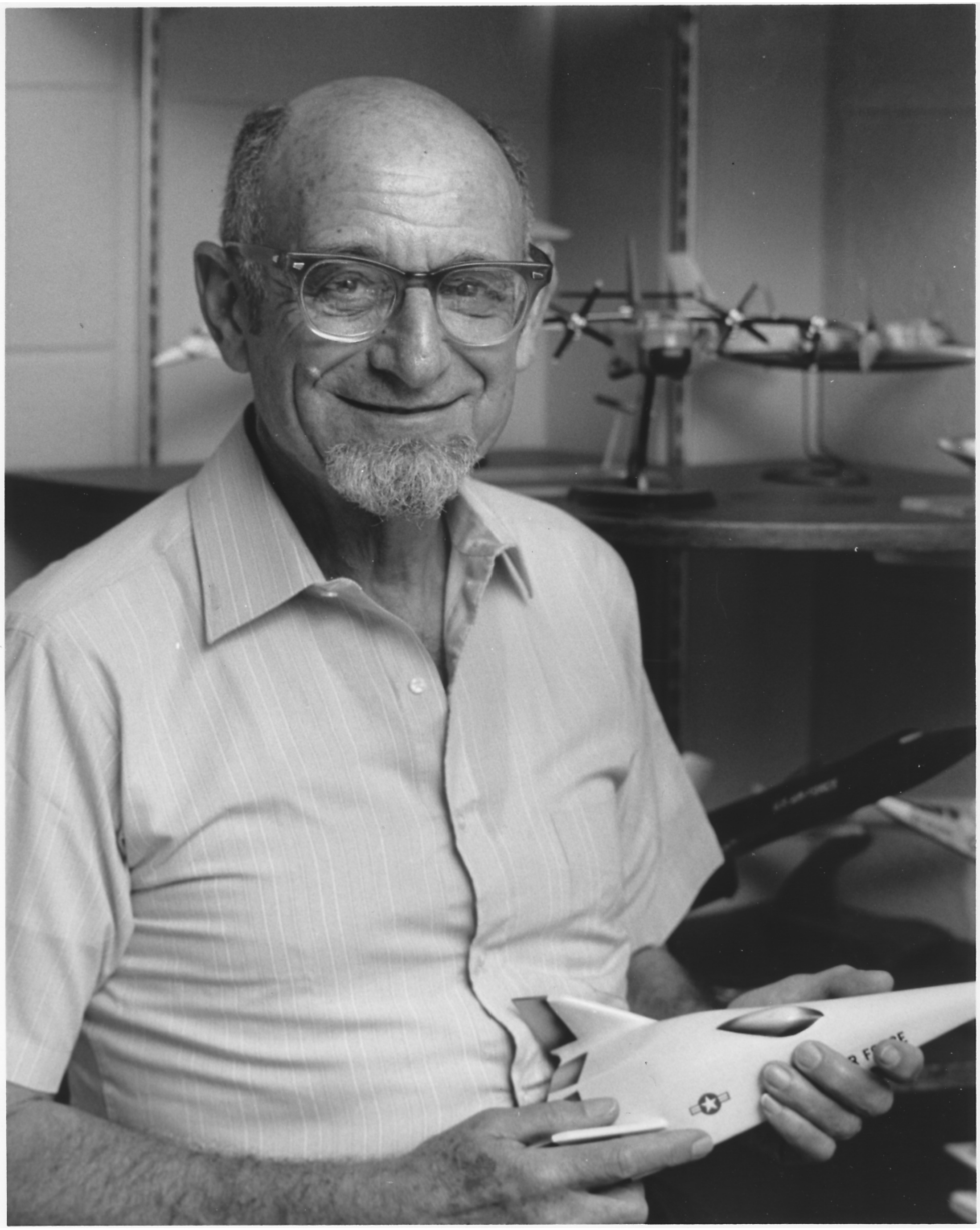

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