Transonic area rule pdf

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Area Rule and Transonic Flight Can you explain what "Area Rule" is and what planes were developed thanks to this theory? - question from Brunno Hartmann The area rule is an important concept related to the drag on an aircraft or other body in transonic and supersonic flight. The area rule came into being in the early 1950s when production fighter designs began pushing ever closer to the sound barrier. Designers had found that the drag on these aircraft increased substantially when the planes traveled near Mach 1, a phenomenon known as the transonic drag rise illustrated below. This increase in drag is due to the formation of shock waves over portions of the vehicle, which typically begins around Mach 0.8, and this drag increase reaches a maximum near Mach 1. Because of its source, this type of drag is referred to as wave drag. Increase in wave drag at transonic Mach numbers Since the physics of supersonic flight were still largely a mystery to manufacturers, designers had no idea how to address this problem except to provide their aircraft with more powerful engines. Even though jet engine technology was rapidly advancing in those days, the first generation of jet-powered fighters was hampered by relatively low-thrust engines which limited them to subsonic flight. The US Air Force hoped to overcome this deficiency with its first dedicated supersonic fighter, the F-102 Delta Dagger. Since the transonic drag rise was still not fully understood, the F-102's designers chose an engine they believed would provide enough thrust to reach a maximum speed of about Mach 1.2. However, initial flight tests of the YF-102 prototype indicated that the aircraft couldn't even reach Mach 1. The Convair engineers were baffled by this lack of performance until a NACA researcher named Dr. Richard Whitcomb developed the area rule. Whitcomb experimented with several different axisymmetric bodies and wing-body combinations in a transonic wind tunnel. What he found was that the drag created on these shapes was directly related to the change in cross-sectional area of the vehicle from the nose to the tail. The shape itself was not as critical in the creation of drag, but the rate of change in that shape had the most significant effect. For the mathematically inclined, we can say that wave drag is related to the second-derivative (or curvature) of the volume distribution of the vehicle. Whitcomb area rule test models: (a) cylindrical fuselage, (b) fuselage with wings, (c) bulged fuselage, (d) waisted fuselage with wings To illustrate the point, four of Whitcomb's experimental models are drawn above, representing a simple cylindrical fuselage, the same fuselage with wings attached, a bulged fuselage, and a "pinched" fuselage with wings. What Whitcomb discovered was that the addition of wings to the basic cylinder produced twice as much drag as the cylinder alone. He also found that drag rose by the same amount if a simple bulge were added to the cylinder, the bulge being of equivalent volume as the wings. However, if he reduced the cross-sectional area of the fuselage over the region were the wings were attached, shown as body "D," the total drag was about the same as that of the cylinder alone. The conclusion of this research was that shaping the vehicle to create a smooth cross-sectional area distribution from the nose to the tail could drastically reduce the drag on an aircraft. The area rule tells us that the volume of the body should be reduced in the presence of a wing, tail surface, or other projection so that there are no discontinuities in the cross-sectional area distribution of the vehicle shape. Effect of the area rule on overall vehicle shape Whitcomb's findings are related to a more theoretical concept called the Sears-Haack body. This shape yields the lowest possible wave drag for a given length and volume. The variation in cross-sectional area for a Sears-Haack body, illustrated in the following figure, tells us that wave drag is minimized when the curvature of the volume distribution is minimized. The closer the volume distribution of an aircraft or other high-speed vehicle comes to the ideal Sears-Haack body, the lower its wave drag will be. Volume distribution of a Sears-Haack body Whitcomb's research was a major breakthrough in supersonic aerodynamics and had an immediate effect on the design of the aforementioned F-102 fighter. Convair engineers quickly redesigned the aircraft's fuselage, taking the area rule concept into account, to create the "waisted" or "coke-bottle" fuselage. This modification, plus a new engine, allowed the aircraft to easily exceed Mach 1 and achieve a maximum speed over Mach 1.5. Effect of the area rule on the F-102 Today's supersonic fighters are fitted with much more powerful engines than were available in the 1950s, so the area rule is not as essential to their design as it used to be. However, it has found greater application to subsonic aircraft, particularly commercial airliners since they cruise at the lower end of the transonic regime. A good example is the Boeing 747, known for its distinctive "hump." This hump, which houses the cockpit and upper passenger deck, increases the cross-sectional area of the forward fuselage and has the effect of evening the volume distribution over the length of the aircraft. As a result, the 747 is able to cruise efficiently at a slightly higher speed than most other airliners since the increase in transonic wave drag is delayed. - answer by Jeff Scott, 24 November 2002 Related Topics: Read More Articles: Home Technology Cars & Other Vehicles Chapter 5 The Whitcomb Area Rule: NACA Aerodynamics Research and Innovation by Lane E. Wallace As the 1940s came to a close, military aircraft manufacturers in the United States faced a disturbing problem. The Bell X-1 had broken the so-called "sound barrier," and both the Air Force and the Navy were looking for next generation aircraft that could operate at supersonic speeds. But preliminary tests of models indicated that even the best designs put forth by industry engineers were not going to be able to achieve that goal. A sharp increase in drag at speeds approaching Mach One was proving too much for the limited-power jet engines of the day to overcome. The solution to this frustrating impasse was found by Richard T Whitcomb, a young aerodynamicist at the National Advisory Committee for Aeronautics (NACA) Langley Research Center in Hampton, Virginia. His development of the "area rule" revolutionized how engineers looked at high-speed drag and impacted the design of virtually every transonic and supersonic aircraft ever built. In recognition of its far-reaching impact, Whitcomb's area rule was awarded the 1954 Collier Trophy. Yet it is not just the significance of the concept that makes the discovery and application of the area rule interesting. The story of its development provides insights on how innovations are "discovered" and how, even at a time when research projects were growing bigger and more complex in scope, a single, creative individual could still play a critical role in the development of new technology. In addition, while the area rule concept was applied almost universally to supersonic aircraft designs, that "success" also illustrates some of the factors that influence whether industry applies a given technology, regardless of its inherent worth. The Transonic Drag Problem and the Area Rule Researchers in the Langley Research Center's wind tunnels had begun working with transonic airflows and the problem of transonic drag (at speeds approaching and surpassing the speed of sound) even before the end of World War II. In 1943, John Stack, head of Langley's Eight-Foot High-Speed Tunnel branch, obtained approval to increase the power in the tunnel from 8,000 horsepower to 16,000 horsepower. The upgrade, completed in the spring of 1945, allowed researchers to produce reliable airflow data in the tunnel for speeds up to Mach .95. 1 One of the researchers working with Stack in the Eight-Foot High-Speed Tunnel was a young engineer named Richard Whitcomb. Whitcomb had been fascinated with airplanes and aerodynamics since he was a young boy, building and testing airplane models 1. James R. Hansen, Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958 (Washington, DC: NASA SP-4305, 1987), pp. 313-14. 135 136 THE WHITCOMB AREA RULE: NACA AERODYNAMICS RESEARCH AND INNOVATION NACA/NASA Langley engineer Richard T. Whitcomb was awarded the 1954 Collier Trophy for his development of the "area rule, " an innovation that revolutionized the design of virtually every transonic and supersonic aircraft ever built. Here Whitcomb inspects a research model in the 8-Foot Transonic Tunnel at Langley. (NASA photo no. LAL 89118). made out of balsa wood. He was hired by the Langley Research Center in 1943, aft receiving an engineering degree from the Worcester Polytechnic Institute. The Langley managers initially wanted him to work in the Flight Instrument Division, but Whitcomb stubbornly insisted that he wanted to work in aerodynamics. Fortunately, he was granted his preference and was assigned to Stack in the 8-foot wind tunnel. Initially, Whitcomb was assigned the task of performing test monitoring for other researchers. But for an eager young engineer, the key to advancement was to "run the tests and keep your eyes open, your ears open," Whitcomb recalled. "I kept coming to Gene (Draley, Stack's replacement as head of the 8-foot tunnel) and saying maybe it ought to be done this way. Let's try this. And somewhere along the way, Gene says 'OK, go try it,' and that's where I got started." 2 By july 1948, Whitcomb had developed a reputation as "someone who had ideas" 3 and was starting to pursue his own research experiments. He proposed a series of wind tunnel tests in the repowered 8-Foot High-Speed Tunnel for a variety of swept wing and fuselage combinations. He hoped the tests would uncover a configuration with significantly lower 2. Richard T. Whitcomb, interview with Walter Bonney, March 27, 1973. 3. Richard T. Whitcomb, telephone interview with author, May 2, 1995. FROM ENGINEERING SCIENCE TO BIG SCIENCE 137 drag at transonic speeds. The tests were run in late 1949 and 1950, but the results were both perplexing and discouraging. None of the combinations had much effect on reducing the drag of the models as they approached Mach One.4 Clearly, the researchers needed to know more about the behavior of airflow in the transonic region in order to figure out what was causing such a stubborn drag problem. Unfortunately, this data was difficult to obtain. Even the upgraded eight-foot wind tunnel at Langley could only reach speeds of .95 Mach. Because of the limitations of the available wind tunnels, researchers in the mid-1940s had resorted to several "stopgap" methods to try to learn more about transonic airflow. One series of experiments involved dropping instrumented test missiles from a B-29 Superfortress. Test airfoils were also mounted on the wing of a P-51 Mustang fighter plane that was then put into a high-speed dive. With this configuration, the airplane's speed remained subsonic but the airflow over the portion of the wing holding the test airfoil surpassed the speed of sound. A third approach used rocket models launched from Wallops Island, a remote beach location across the bay from the Langley Research Center. All three methods had their drawbacks, however. The falling-body and wing-flow techniques offered less precise data than that obtained in a wind tunnel. The rocket tests produced more precise data, but they were "100 times as expensive as a wind tunnel test" and could only explore a single parameter at a time. Furthermore, the Schlieren photographs that illustrated the shock wave patterns of high-speed airflow could only be obtained in a wind tunnel.5 Consequently, it was not until Stack and his team of engineers, which included Whitcomb, developed a "slotted-throat" modification for the 8-foot wind tunnel in 1950 that transonic flows could be thoroughly explored.6 The slotted-throat modification prevented the choking that had limited the speeds in the test section of the tunnel and allowed the air to go through the speed of sound. For the first time, researchers had a tool to investigate precisely what airflow did in that speed range and what might be causing the puzzling drag they had observed. Actually, the slotted throat wind tunnel was only one of the tools Whitcomb and his associates used to investigate transonic airflows. But once that was in place, they could then employ other existing research tools to look at what the airflow was doing. In late 1951, Whitcomb tested a swept-back wing-fuselage combination in the now-transonic Eight-Foot High-Speed Tunnel.7 Tuft surveys, which used small pieces of yarn taped onto airfoil and fuselage sections, were conducted to look at airflow disturbances. Coverings with pressure-sensitive openings were put on model sections to determine the velocity of the air over particular areas, and Schlieren photographs were used to look at the shock wave characteristics of the model at transonic speeds.8 4. Richard T. Whitcomb, "A Proposal for a Swept Wing Fuselage Combination with Small Shock Losses at Transonic Speeds," Langley Central Files, AH 321-1, July 1948; Hansen, Engineer in Charge, pp. 332-33. 5. Richard T Whitcomb, telephone interview, May 2, 1995; Hansen, Engineer in Charge, pp. 261-70. 6. The development of the slotted-throat transonic wind tunnel at the Langley Research Center proved important enough to merit its own Collier Trophy, awarded to Stack and his associates in 1951. 7. The time delay between each of Whitcomb's initial ideas and the actual wind tunnel tests of them was a result of Langley's typical but long process of designing and building wind tunnel models. It was not at all unusual for that process to take fifteen-eighteen months. Nevertheless, the time delay was frustrating and Whitcomb sometimes worked directly with wind tunnel technicians to incorporate modifications in the tunnel to avoid the delay of going through normal channels. 8. Richard T. Whitcomb and Thomas C. Kelly, "A Study of the Flow over a 45-degree Sweptback Wing-Fuselage Combination at Transonic Mach Numbers," NACA RM L52DO1 June 25, 1952; Dr. Richard T. Whitcomb, "Research on Methods for Reducing the Aerodynamic Drag at Transonic Speeds," address presented at the ICASE/LaRC Inaugural Eastman Jacobs Lecture, Hampton, VA, November 14, 1994, pp. 1-2; Hansen, Engineer in Charge, pp. 332-33. 138 THE WHITCOMB AREA RULE: NACA AERODYNAMICS RESEARCH AND INNOVATION The results, especially those revealed by the Schlieren photographs, showed that the shock waves created as the airflow approached the speed of sound were different and bigger than anticipated. Undoubtedly, it was the losses from these unexpected shock patterns that was causing the sharp increase in drag at transonic speeds. But the question of what was causing the shockwaves still had to be answered before researchers could try to find a way to combat the phenomenon. Several weeks later, a world renowned German aerodynamicist named Dr. Adolf Busemann, who had come to work at Langley after World War II, gave a technical symposium on transonic airflows. In a vivid analogy, Busemann described the stream tubes of air flowing over an aircraft at transonic speeds as pipes, meaning that their diameter remained constant. At subsonic speeds, by comparison, the stream tubes of air flowing over a surface would change shape, become narrower as their speed increased. This phenomenon was the converse, in a sense, of a well-known aerodynamic principle called Bernoulli's theorem, which stated that as the area of an airflow was made narrower, the speed of the air would increase. This principle was behind the design of venturis,9 as well as the configuration of Langley's wind tunnels, which were "necked down" in the test sections to generate higher speeds.10 But at the speed of sound, Busemarm explained, Bernoulli's theorem did not apply. The size of the stream tubes remained constant. In working with this kind of flow, therefore, the Langley engineers had to look at themselves as "pipefitters." Busemann's pipefitting metaphor caught the attention of Whitcomb, who was in the symposium audience. Soon after that Whitcomb was, quite literally, sitting with his feet up on his desk one day, contemplating the unusual shock waves he had encountered in the transonic wind tunnel. He thought of Busemann's analogy of pipes flowing over a wing-body shape and suddenly, as he described it later, a light went on. The shock waves were larger than anticipated, he realized, because the stream tubes did not get narrower or change shape, meaning that any local increase in area or drag would affect the entire configuration in all directions, and for a greater distance. More importantly, that meant that in trying to reduce the drag, he could not look at the wing and fuselage as separate entities. He had to look at the entire cross-sectional area of the design and try to keep it as smooth a curve as possible as it increased and decreased around the fuselage, wing and tail. In an instant of clarity and inspiration, he had discovered the area rule. In practical terms, the area rule concept meant that something had to be done in order to compensate for the dramatic increase in cross-sectional area where the wing joined the fuselage. The simplest solution was to indent the fuselage in that area, creating what engineers of the time described as a "Coke bottle" or "Marilyn Monroe" shaped design. The indentation would need to be greatest at the point where the wing was the thickest, and could be gradually reduced as the wing became thinner toward its trailing edge. If narrowing the fuselage was impossible, as was the case in several designs that applied the area rule concept, the fuselage behind or in front of the wing needed to be expanded to make the change in crosssectional area from the nose of the aircraft to its tail less dramatic.11 9. A venturi, named after the 19th century Italian physicist G.B. Venturi, is one method used to generate the suction or vacuum power necessary to drive aircraft instruments. A venturi is mounted on the outside of air aircraft, paralleling the fuselage. As the speed of airflow through the cinched neck portion of the venturi increases, it is accompanied by a decrease in air pressure, creating suction that runs the instruments connected to the system inside the plane. 10. Whitcomb, interview, March 27, 1973. 11. Richard T Whitcomb, "A Study of the Aero-Lift Drag-Rise Characteristics of Wing-Body Combinations Near the Speed of Sound," NACA Report 1273, Langley Aeronautical Laboratory, Langley Field, Virginia, 1956, pp. 1, 20-21; Whitcomb, interview, March 27, 1973; Whitcomb, "Research on Methods for Reducing the Aerodynamic Drag at Transonic Speeds," p. 3. FROM ENGINEERING SCIENCE TO BIG SCIENCE 139 The Pieces of the Puzzle: Creative Innovation Although the pieces may have come together in a flash of insight, there were actually several important elements and processes that contributed to Whitcomb's discovery. Whitcomb had developed a reputation as something of a "Wunderkind" at Langley because of his unique combination of knowledge and intuition about airflows; a combination that undoubtedly contributed to his discovery of the area rule. 12 The intuition may have been a gift, but his knowledge of airflow behavior was certainly enhanced by his seven years of experience working with Langley's 8-foot wind tunnel. The discovery of the area rule concept was also dependent on the previous invention of the slotted-throat tunnel design. Without that piece of technology, Whitcomb could not have gathered the information necessary to understand the causes of transonic drag. In fact, the very existence of the wind tunnels at Langley was a critical factor in allowing a new approach in design to surface and be tested. If the information had to be obtained through an elaborate, expensive flight test program, fewer ideas could have been investigated, and Whitcomb might not have had the opportunity to test his innovative theory. At Wallops Station, in tidewater Maryland, in 1953, Langleys Pilotless Aircraft Research Division (PARD) tested rocket-powered models of the delta-winged Convair F-102 before, (left) and after (right) modification to take advantage of Whitcomb's "area rule. " (NASA Photo). 12. Eugene S. Ferguson, Engineering and the Mind's Eye (Cambridge, MA: MIT Press, 1992), p. 54; Hansen, Engineer in Charge, p. 332. 140 THE WHITCOMB AREA RULE: NACA AERODYNAMICS RESEARCH AND INNOVATION In addition, the projects conducted at Langley were still fairly small, individual research efforts that allowed for experimentation. This kind of atmosphere, while not entirely unique among government-funded facilities in the early 1950s, was becoming more unusual. At one time, individual or small-group research efforts had characterized many research laboratories. But the exponential growth of technology and complex technological research during World War II began to change that. The Manhattan Project, responsible for the development of the atom bomb, symbolized for many a significant shift in technological research from small, independent projects conducted by single laboratories to large, complex research programs involving many people, broad resources and funding, and multiple disciplines.13 In a bigger and more complex research environment, with approvals and decisions dependent on higher-level program managers, Whitcomb might not have had the latitude or opportunity to develop and test the area rule concept. But the NACA Langley environment offered a middle ground between a small, independent laboratory and a large research program. Whitcomb had expensive technological tools at his disposal, such as the slotted-throat wind tunnel, but he still had the independence and flexibility to develop and test a radical new concept on his own.14 Whitcomb was also assisted by the informal management environment and the orientation toward experimental research at the Langley Research Center, both of which were conducive to individual innovation. As John Becker explained in his case histories of four NACA programs, Management (at Langley) assumed that research ideas would emerge from an alert staff at all levels.... On a problem of major proportions such as transonic facilities, any scheme for research that survived peer discussions and gained section and division approvals was likely to be implemented ... and very little (paperwork) was required in the simple NACA system. Occasional chats with his division chief or department head, or a brief verbal report at the monthly department meeting were about all that was required of the NACA project engineer.15 This kind of environment was particularly well-suited to an introspective thinker like Whitcomb. Managers knew he was a talented aerodynamicist, and they were wise enough to keep his paperwork to a minimum and give him the space and freedom to think, experiment, and explore.16 Langley's orientation toward hands-on, experimental research was a significant factor in Whitcomb's discovery, as well. As opposed to research centers that focused more on theoretical research, Langley encouraged exploratory experiments such as the wind tunnel tests Whitcomb devised to investigate wing-body combinations and airflow at transonic speeds. The breakthrough on the transonic wind tunnel itself, in fact, was a result of a researcher asking himself, "I wonder what would happen if I turned up the power?" That simple question —"I wonder what would happen if. . ." instigated numerous experiments at Langley that , in turn, led to significant discoveries. 17 13. James H. Capshew and Karen A. Rader, "Big Science: Price to the Present," OSRIS, 2nd series 7 (1992): 19; Thomas P. Hughes, American Genesis: A Century of Invention and Technological Enthusiasm (New York, NY. Penguin Books, 1989), pp. 440-42. 14. John V Becker, The High-Speed Frontier: Case Histories of Four NACA Programs. 1920-1950 (Washington, DC: NASA SP-445, 1980), pp. 117-18. 15. Ibid. 16. Hansen, Engineer in Charge, p. 341. 17. Whitcomb, interview, May 2, 1995; information on transonic wind tunnel development also in Hansen, Engineer in Charge, p. 322; and in Ch. 1 of this book. FROM ENGINEERING SCIENCE TO BIG SCIENCE 141 This curiosity-driven, experimental approach was especially significant in discovering the area rule, because there was no available theory to explain the unusual drag encountered at transonic speeds. Researchers had to come up with a creative way of reaching beyond the known, and the exploratory experiments conducted by Whitcomb and others yielded the data that allowed him to understand the cause of the transonic drag and shockwave phenomena. Conducting hands-on experiments with an aircraft model in a wind tunnel also helped Whitcomb "see" the airflow behavior in a way mathematical formulas would not have. Still, these factors only provided the tools and environment that made Whitcomb's discovery possible. The breakthrough still required the insight of a creative mind; a mind able to "see" the problem and able to step back from accepted rules of design to contemplate a solution based on an entirely new approach. The process by which Whitcomb was able to do that offers insight itself as to how scientific or technological innovation occurs. Science and technology are often viewed as fields completely divorced from any of the arts. Common phrases that distinguish something as "a science, not an art" and describe "the scientific method" as a way to discern an unassailable truth indicate our collective view of science as a rational, logical, linear, mathematical and precise process. Yet since almost the beginning of time, artistic vision has played a critical role in the advancement of technology and science. Undoubtedly, even the first cave dweller to invent the wheel first had a picture in his or her mind of what the device would look like. Albert Colquhoun, a British architect, asserted that even scientific laws are "constructs of the human mind," valid only as long as events do not prove them wrong, and applied to a solution of a design problem only after a designer develops a vision of the solution in his head.18 This artistic vision becomes even more important when a scientist or engineer needs to go beyond the leading edge of knowledge, where existing theories cease to explain events. At this point, a designer's imagination is critical in envisioning potential new solutions. As one analyst of technological development said, "The inventor needs the intuition of the metaphor maker, some of the insight of Newton, the imagination of the poet, and perhaps a touch of the irrational obsession of the schizophrenic."19 Whitcomb was not the only person to look at the problem of transonic drag. As early as 1944, German aerodynamacist Dietrich Kuchemann had designed a tapered fuselage fighter plane that was dubbed the "Kuchemann Coke Bottle" by American intelligence personnel. Kuchemann's design was not aimed at smoothing the curve of the cross sectional area to displace the air less violently, however. He had simply observed the direction of air flow over a swept-wing design and was trying to design a fuselage that would follow the contours of that flow.20 Whitcomb's area rule was also, in retrospect, said to be implicit in a doctoral thesis on supersonic flow by Wallace D. Hayes, published in 1947. But the mathematical formulas employed by Hayes, as well as several other researchers working on the general problem of transonic and supersonic air flows, did not lead their creators to the necessary flash of inspiration that crystallized the area rule for Whitcomb. Why didn't they see what Whitcomb did? The answer, in part, may lie in the precise fact that they were working with mathematical formulas, instead of visual images. The answer may have been imbedded in the numbers in front of them, but they couldn't see it. 18. Ferguson, Engineering and the Mind's Eye, p. 172. 19. Hughes, American Genesis, p. 76; Hansen, Engineer in Charge, p. 311; Ferguson, Engineering and the Mind's Eye, pp. 172-73. 20. David A. Anderson, "NACA Formula Eases Supersonic Flight," Aviation Week & Space Technology 63 (September 12, 1955): 13. 142 THE WHITCOMB AREA RULE: NACA AERODYNAMICS RESEARCH AND INNOVATION What led to Whitcomb's insight was his talent to see and work with visual metaphora skill described by Aristotle as a "sign of genius" and an important tool for seeing things from a fresh perspective, or discovering new truths about existing objects or ideas.21 In his history of American technological progress, Thomas Hughes also stressed the importance of visual metaphors in developing innovative ideas, noting that "although they are articulated verbally, the metaphors of inventors have often been visual or spatial. Inventors, like many scientists, including Albert Einstein, Niels Bohr, and Werner Heisenberg, show themselves adept at manipulating visual, or nonverbal, images." 22 When Adolf Busemarm used his "pipefitting" metaphor to describe the behavior of transonic air flow, Whitcomb painted a vivid picture in his mind of air "pipes" flowing over an aircraft. He then incorporated into that image the other information he had obtained through his experiments with transonic air flow. Suddenly, he "saw" what was causing the unusual shock waves and what could be done to combat the problem. In order to see a solution that went beyond existing theory, however, Whitcomb also had to be willing to break free from accepted rules, or paradigms, of aerodynamics.23 In the late nineteenth century, Ernst Mach had shown that a bullet-shaped body produced less drag in flight than any other design. This accepted "paradigm" of aircraft design led to the basic fuselage shape employed by transports, World War II fighter planes, and even the Bell X-1 rocket plane. It was also still the accepted rule of thumb as engineers began to design the first turbojet-powered supersonic aircraft. The assumption that a bullet-shaped fuselage was the most efficient aerodynamic shape, however, led researchers to look elsewhere for elements that could be modified to reduce the drag of aircraft at transonic speeds. To see the solution that Whitcomb envisioned —indenting the fuselage in the area of the wing to reduce the dramatic changes in the aircraft's overall cross-sectional area from nose to tail— required going against a "truth" that had worked and had been accepted for over fifty years. The same paradigm that had helped advance aircraft design for half a century became, ironically, one of the barriers that kept researchers from advancing aircraft design beyond subsonic flight. Why was Whitcomb able to step back and consider an approach that broke this accepted rule? For one thing, the circumstances required it. Kuhn noted that "the failure of existing rules is the prelude to a search for new ones."24 Certainly, the stubborn problem of transonic drag presented Whitcomb with a situation where existing theories and rules were not working. Secondly, Kuhn observed that "almost always, the men who achieve ... fundamental inventions of a new paradigm have been either very young or very new to the field whose paradigm they change ."25 When he came up with the area rule concept, Whitcomb was only 30 years old. Possibly, the fact that he had not spent twenty years designing bullet-shaped fuselages contributed to Whitcomb's ability to conceive of a different design. He was also something of an introspective thinker and individualistic researcher, which may have made him more able to contemplate a "fringe" idea that broke from his peer group's assumptions. In any event, Whitcomb was willing to step back from accepted truths and 21. Aristotle, Poetics, translated by Ingram Bywater, in The Rhetoric and the Poetics of Aristotle (New York: Random House, 1954), p. 255. 22. Hughes, American Genesis, p. 82. 23. Thomas Kuhn described paradigms as "familiar notions," or "examples that provide models from which spring particular coherent traditions of scientific research." On the one hand, these accepted notions can help lead to more detailed further research in a particular area. But Kuhn cautioned that paradigms could also insulate the research community against seeing new solutions. From: Thomas S. Kuhn, The Structure, of Scientific Revolutions, 2nd ed., Foundations of the Unity of Science Series: Vol. II, Number 2 (Chicago: University of Chicago Press, 1970), pp. 10-11, 24, 37. 24. Ibid., p. 68. 25. Ibid., p. 90. FROM ENGINEERING SCIENCE TO BIG SCIENCE 143 simply look at what his data was showing him; paint a visual picture of it in his mind and see not what he expected to see, but what was really there. While this may seem a simple and obvious solution to outsiders with forty years of hindsight, Whitcomb's ability to break free of the design doctrines that dominated aeronautics in his day was, in fact, a unique and remarkable ability that truly set him apart from many others in his field. Once someone comes up with an answer, it often seems obvious. But the researchers struggling with transonic drag were not aware they were caught in a paradigm that did not work. They were focused on trying to cut a workable path through a dense forest they knew as real and immutable. Whitcomb's genius was his ability to see that the problem was not the path, but the forest itself. From Idea to Application When Whitcomb presented his concept of the area rule to some of his colleagues at Langley, he encountered skepticism. After all, it was a radical approach to aircraft design. But division chief John Stack still allowed Whitcomb to present the idea at the next technical seminar. And listening to Whitcomb's presentation, this time, was Adolf Busemann, whose stature in the aerodynamics community was such that his opinion carried a great deal of weight. Busemann, whose visual pipefitting metaphor had provided the catalyst to Whitcomb's discovery, understood what Whitcomb had seen. He told the others present that Whitcomb's idea was "brilliant." The skepticism among some of the others, including Stack, remained. But the support from Busemann was enough to get Whitcomb the go-ahead to test his theory.26 Throughout the first quarter of 1952, Whitcomb conducted a series of experiments using various area-rule based wing-body configurations in Langley's 8-Foot High-Speed Tunnel. As he expected, indenting the fuselage in the area of the wing did, indeed, significantly reduce the amount of drag at transonic speeds. In fact, Whitcomb found that "indenting the body reduced the drag-rise increments associated with the unswept and delta wings by approximately 60 percent near the speed of sound," virtually eliminating the drag rise created by having to put wings on a smooth, cylindrical shaped body.27 In a simple world, this validation of Whitcomb's theory would have been sufficient for the principle to be applied to all new industry designs. All that would have been necessary would have been to notify the aircraft manufacturers that a better design approach had been developed. The world is not that simple, however, and the inherent worth of an innovation is rarely enough for it to be incorporated into commercial products. As Louis B.C. Fong, director of the Office of Technology Utilization at NASA (National Aeronautics and Space Administration) commented in 1963, "In this age of automation, there is nothing automatic about the transfer of knowledge or the application of an idea or invention to practical use ... there is resistance to new ideas and new technologies; part psychological, part practical ... and often economic."28 26. Whitcomb, interview, May 2, 1995; Hansen, Engineer in Charge, p. 336. 27. Whitcomb, "A Study of the Aero-Lift Drag-Rise Characteristics of Wing-Body Combinations Near the Speed of Sound," pp. 20-21. 28. Louis B.C. Fong, Dir., NASA Office of Technology Utilization, "The NASA Program of Industrial Applications," address at the Third National Conference on the Peaceful Uses of Space, Chicago, IL, May 8, 1963, NASA Historical Reference Collection, NASA History Office, NASA Headquarters, Washington, DC. 144 THE WHITCOMB AREA RULE: NACA AERODYNAMICS RESEARCH AND INNOVATION NACA or NASA engineers tend to measure the success of a new idea or technology strictly in terms of technical objectives met. Industry, on the other hand, measures innovative success in terms of profit dollars generated within a specified payback period.29 Consequently, a new approach or technology, even if it is technically "better," may be rejected by industry if its use involves extra costs for the manufacturer. These costs can be in retooling for a new design, replacing machinery, or even in retraining employees or changing the traditional ideas and approaches of its engineers. All of these factors can produce resistance to a new idea or technology within a company, and overcoming that resistance can be a difficult process.30 There are a couple of situations in which new technology may be rapidly assimilated into commercial products, however. One is if it can be incorporated with minimal extra cost, and a second is if it solves a problem that a manufacturer needs to solve.31 When Whitcomb developed his area rule, there was a manufacturer in each of these situations, and that fact played a significant role in the speed with which his innovation began to impact the design of new aircraft. While Whitcomb was conceiving and testing his area rule concept, the Convair Division of General Dynamics was developing what it hoped would be the company's first supersonic aircraft. The Convair F102 "Delta Dagger" was designed to be a long-range interceptor, with delta wings and the most powerful turbojet engine available at that time, the Pratt & Whitney J-57. Early test results of an F-102 model in Langley's 8-Foot High-Speed Tunnel, however, seemed to indicate that the design's transonic drag might be too high for the aircraft to surpass Mach One. The NACA had immediately classified any information pertaining to the area rule, as it had the research on the slotted throat wind tunnel that allowed the area rule to be developed. In 1952, the United States was engaged in heated and high-stakes competition for military superiority with the Soviet Union, and NACA realized the importance of transonic research in developing superior military aircraft. Although the classification was necessary, it made dissemination of information about the area rule more difficult. Fortunately, NACA's history of successful technology transfer efforts had been less a product of published writings than the various levels of informal NACA-industry cooperation and researcher-to-engineer discussions.32 The area rule would prove no exception. In mid-August 1952, a group of Convair engineers were at Langley to observe the performance of the F102 model in the Eight-Foot High-Speed Tunnel. Shown the disappointing test results, the engineers asked the Langley engineers if they had any suggestions. Whitcomb's first research memorandum on the area rule would not be published for another month, but he had completed his tests on the various wing-body combinations using indented fuselage shapes. He explained his findings and the area rule concept to the Convair team. Intrigued, the Convair engineers worked with Whitcomb over the next few months to experiment with modifying the F-102 design and building a model that incorporated the area rule concept. At the same time, however, the company continued work on the original F102 prototype. The engineers may have been open to exploring a possible new 29. Denver Research Institute, "NASA Partnership with Industry: Enhancing Technology Transfer," NASA CR-180-163, July 1983, pp. xx, Appendix D-3; William D. Mace and William E. Howell, "Integrated Controls for a New Aircraft Generation," Astronautics & Aeronautics 16 (March 1978): 48-53. 30. Denver Research Institute, "NASA Partnership with Industry," pp. xx, Appendix D-3; R. P. Schmitt, et al., "Technology Transfer Primer," Wisconsin University-Milwaukee, Center for Urban Transportation Studies, FHWA/TS-84/226, July 1985, pp. x, 1-5. 31. Schmitt, et al, "Technology Transfer Primer," p. 5. 32. Denver Research institute, "NASA Partnership with Industry," p. xiv. FROM ENGINEERING SCIENCE TO BIG SCIENCE 145 option, given the uncertainty produced by the wind tunnel tests of the original F-102 model, but the company had already made a commitment to the Air Force to build two prototypes of the original F-102. In addition to any mental and institutional resistance Convair might have had to changing a design which it had touted so highly and had already made a commitment to build, the company's commitment also created an issue of cost. By mid-1952, when Convair tested the F-102 model at Langley, the company had already begun setting up a production line at its San Diego, California, facility for manufacturing the aircraft. To change the design would mean not only delays and additional engineering costs, but revamping the production line, as well. Consequently, far from being receptive to a new design approach, Convair had a significant stake in proving that its new aircraft could perform just fine without it. 33 Nevertheless, the company could not totally ignore the doubtful test results of its original design, so its engineers began working on a "Plan B" with Whitcomb while production of the prototype F-102s continued. Starting in May 1953, the Convair engineers and Whitcomb began testing models of a modified, area rule-based, F-102 design in Langley's wind tunnel. By October 1953, they had developed a model that could meet the Air Force performance specifications. Convair noted the results but continued working on the original F-102 prototype, which flew for the first time on October 24, 1953. 34 The first prototype was severely damaged on its maiden flight, so test flights had to be postponed until January 11, 1954, when the second prototype flew for the first time. The results of the flight tests, however, proved to be largely the same as those predicted by the wind tunnel tests of the F-102 model in 1952. The aircraft performed below expectations and could not attain supersonic speeds in level flight. 35 Even at that point, Convair might have continued to press for production of the design as it was, given that the tooling and production line in its San Diego plant was already set, except for one crucial factor. The Air Force officials working on the F-102 design were aware of Whitcomb's area rule and the fact that a modified F-102 model, based on that concept, had achieved supersonic speeds in wind tunnel tests. Consequently, the Air Force realized that the F-102 was not the best that Convair could do. Whitcomb's experiments had proven that a supersonic airplane was possible, and the Air Force decided to settle for no less. The F-102 program manager at Wright Field in Ohio informed Convair that if the company did not modify the F-102 to achieve supersonic flight, the contract for the fighter/interceptor would be cancelled. 36 Incorporating Whitcomb's innovative design approach involved extra expense, but nothing compared to the cost of losing the entire F-102 contract. Convair immediately halted the F-102 production line and began working on the modified design Whitcomb and the company engineers had developed and tested. In only 117 working days, the company had built a new, area rule-based prototype, designated the F-102A. The F-102A flew for the first time on December 24, 1954, and surpassed the speed of sound not only in level flight, but while it was still in its initial climb. The area rule had improved the speed of the F-102 design by an estimated twenty-five percent. 37 33. Donald D. Baals and William R. Corliss, Wind Tunnels of NASA (Washington, DC: NASA SP-440, 1981), p. 62; Hansen, Engineer in Charge, p. 337; Whitcomb, interview, May 2, 1995. 34. Bill Gunston, ed., The Illustrated History of Fighters (New York, NY. Simon and Schuster, 1984), p. 194. 35. Baals and Corliss, Wind Tunnels of NASA, p. 63. 36. Whitcomb, interview, May 2, 1995; Whitcomb, "Research on Methods for Reducing the Aerodynamic Drag at Transonic Speeds," November 14, 1994; Hansen, Engineer in Charge, pp. 337-39. 37. Baals and Corliss, Wind Tunnels, of NASA, p. 63; Hansen, Engineer in Charge, p. 338; Whitcomb, interview, May 2, 1995. 146 THE WHITCOMB AREA RULE: NACA AERODYNAMICS RESEARCH AND INNOVATION While Convair was struggling with its F-102 design, the Grumman Aircraft Engineering Corporation was also working to develop its first supersonic carrier-based fighter, the F9F/F-11F Tiger.38 Although the area rule research was classified, the NACA released a confidential Research Memorandum on the subject to appropriately cleared aircraft manufacturers in September 1952. Just two weeks after receiving that memorandum, Grumman sent a group of its engineers to Langley to learn more about it. The information they brought back to Bethpage, New York, was immediately incorporated into the design, and in February 1953, Whitcomb was flown in to review the final design plans before construction on the prototype was begun. On April 27, 1953, the Navy signed a letter of intent with Grumman for the fighter, based on the Whitcomb-approved design. On August 16, 1954, the Grumman F9F-9 Tiger "breezed" through the sound barrier in level flight without the use of the afterburner on its Wright J-65 turbojet engine.39 The enthusiastic incorporation of Whitcomb's innovation by Grumman stands in stark contrast to the qualified experimentation and resistance that characterized Convair's response. But the two companies were in different situations. Convair had already completed a design for the F-102 and had begun construction of two prototypes and a production line. Grumman, on the other hand, was still working to design the F11F Tiger when Langley published its confidential report on Whitcomb's area rule breakthrough. It was the perfect time to incorporate a better design idea, and involved few extra costs to the company. At the same time, the Navy had not yet contracted for the fighter, and Grumman may well have recognized that its chances of winning the contract would be improved by incorporating any available new technology into its design; especially something that might improve its speed. In any event, Whitcomb's innovative idea was incorporated into two production military aircraft only twenty-four months after he completed his initial wind tunnel tests on the concept. This incredibly "successful" example of technology transfer was a result of two important factors. First and foremost, there was a "problem looking for a solution" 40 that the area rule was able to solve. Transonic drag was a real and seemingly unsurmountable obstacle to supersonic flight. Whitcomb's area rule was not one of a number of potential solutions; it was the only approach anyone had developed that had proven itself capable of overcoming that barrier. It also had the backing of a very powerful customer: the United States military. When the Air Force decided to hold firm on its demand that Convair's aircraft fly supersonically in level flight, Convair could not simply sell its F-102s to another customer. The Air Force was its only client, just as the Navy was for Grumman. But another important element, especially with regard to Convair, was the cooperation and individual relationships that existed between the Langley researchers, including Whitcomb, and the industry engineers. The modified F-102A model that proved to the Air Force that a fighter could achieve supersonic flight was a cooperative effort between Whitcomb and Convair engineers. Without that cooperation, or the informal discussions at Langley that launched that work, the fate of the F-102 might have been different. 38. The prototype was designated first as the F9F-8, and then as the F9F-9, although the original Grumman F9F-2 design was the straight-wing Pantherjet, and the F9F-6 was the swept-wing Cougar. The Tiger was really an unrelated design, but the prototypes were still labeled as variants of the F9F design. The production model Tigers, however, were called F11Fs. 39. Michael J.H. Taylor, ed., Jane's Encyclopedia of Aviation (New York, NY Portland House, 1989), pp. 447-48; Gunston, Illustrated History of Fighters, p. 192; Hansen, Engineer in Charge, pp. 339-40. 40. Numerous NASA and industry engineers, including Whitcomb himself (Whitcomb, interview, March 27, 1973), have used this phrase to describe the kind of situation that tends to lead to quick acceptance of a new technology. FROM ENGINEERING SCIENCE TO BIG SCIENCE 147 The area rule undoubtedly would have been incorporated into aircraft designs eventually, regardless of the individuals involved. But that timeframe could have been different, which could have had an impact on the kind of air defenses the United States had at its disposal in the early days of the Cold War. As it was, the success of the area rule-based F-102 and F11F was followed by the incorporation of the area rule in virtually every supersonic aircraft built after that point. The Vought F8U "Crusader" fighter and the Convair B-58 "Hustler" bomber, both of which were on the drawing board at the time the area rule was developed, were redesigned using Whitcomb's approach. The F-106, which was Convair's follow-on design to the F-102A, adhered even more to the area rule. It was able to incorporate a much deeper indentation in the fuselage than its predecessor, because it was an entirely new aircraft, unencumbered by existing design elements. The fuselage of the Republic F-105 "Thunderchief" fighter/bomber, which flew for the first time in 1955, incorporated the area rule in a slightly different manner. It could not be indented because of its complex engine inlets, so a bulge was added to the aft region of the fuselage to reduce the severity of the change in the cross sectional area at the trailing edge of the wing. The Rockwell B-1 bomber and the Boeing 747 commercial airliner also used the addition of a cross-sectional area to reduce their drag at transonic speeds. Both the B-1 and the 747 have a vertical "bump" in the forward section of the fuselage ahead of the wing. It is perhaps more visible in the 747, where it houses the airliner's characteristic second story, but both airframe modifications were added to smooth the curve of the design's crosssectional area .41 The Collier Trophy Whitcomb's Area Rule research was classified until September 1955, so he did not receive any immediate accolades or press on his discovery. But two months after his work was made public, Whitcomb received the National Aeronautic Association's Robert J. Collier Trophy in recognition of his achievement the previous year, when the Grumman F9F-9 Tiger and the Convair F-102A prototypes demonstrated just how significant the area rule was. The Collier Trophy citation read, "For discovery and experimental verification of the area rule, a contribution to base knowledge yielding significantly higher airplane speed and greater range with the same power. " 42 Conclusion Although an engineering design approach using formulas or algorithms does not lend itself to the kind of notoriety that a project like the X-1 generated, the development of the area rule was no less significant. The X-1 proved the sound barrier could be broken. The area rule made that discovery practical by enabling production aircraft to operate at that speed. The fact that the area rule was discovered by an engineer sitting with his feet up on his desk, contemplating a vision in his mind, also shows the importance of creativity and the individual in advancing technology. Postwar science and research projects may have been growing in complexity and size, but Whitcomb's discovery was a reminder that the 41. Whitcomb, interview, May 2, 1995; Whitcomb, "Research on Methods for Reducing the Aerodynamic Drag at Transonic Speeds," November 14, 1994, p. 3. 42. Bill Robie, For the Greatest Achievement: A History of the Aero Club of America and the National Aeronautic Association, (Washington, DC: Smithsonian Institution Press, 1993), p. 232; Richard T. Whitcomb, telephone interview with author, May 15, 1995. 148 THE WHITCOMB AREA RULE: NACA AERODYNAMICS RESEARCH AND INNOVATION individual researcher was more than a cog in a scientific, process-driven wheel. Experimentation and the visions in the mind of an individual able to put available information together in a new way have led to many innovative "breakthroughs" in technology and knowledge. The history of the area rule research also illustrates that even a "breakthrough" discovery does not always win immediate acceptance by those who might implement it. As opposed to projects that were wholly funded, developed and implemented by the NACA and its successor, the National Aeronautics and Space Administration (NASA), or other government agencies, Whitcomb's breakthrough was just an idea. It may have been developed at a NACA laboratory, but it was not up to NACA to apply it. In order for the innovation to have any impact at all, industry had to agree to use it, which is not always as simple a process as it might seem. Whitcomb's area rule was the answer to a tremendous problem that industry needed to solve, but the enthusiasm with which it was received differed greatly between Convair and Grumman. The advantages offered by the innovation were the same; the costs of implementing it differed. But even in the application of the area rule concept, individuals played an important role. An Air Force demand was the primary reason Convair incorporated the area rule into the F-102, despite the added cost. But the Air Force might not have had the confidence to make that demand if it had not been for the model work performed by a small number of individuals at Langley and Convair. As scientific and engineering research and projects became more expensive, complex, and systems-oriented, it was easy to lose sight of the individuals that made those systems work. Richard T. Whitcomb, in developing and helping to win acceptance for a concept that revolutionized high-performance aircraft design, was a reminder that the individual still mattered.

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