Canada's Encounter with High-Speed Aeronautics

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The war years from 1939 to 1945 were years of dramatic growth for the Canadian aeronautical industry. Yet, while the volume of output by 1945 was prodigious, in terms of design and development capability Canada was still an infant country: most design work was British or American. The war years were also the time when high-speed aeronautics was an infant enterprise; until the mid-1940s, flight at speeds approaching or exceeding the speed of sound had remained the exclusive domain of gun-launched projectiles. But, with supersonic speeds having become feasible, in 1945 Canada embraced high-speed aeronautics in the hopes of gaining a place in the forefront of technological progress.

The vision was short-lived, though the efforts devoted to achieving it were not insignificant. In the years following the war, the Canadian government spent hundreds of millions of dollars to establish a presence in the field.[1] Hundreds of engineers and technicians were lured from abroad, laboratory facilities were developed, and large aircraft and engine plants built. These efforts took place against the backdrop of similar activities in the United States, Britain, France, and other countries.

Before the end of the war, high subsonic speeds had been attained by propeller and jet aircraft, and by pulsed-ramjet missiles (FZG76 or V-1). Supersonic speeds in excess of a Mach number of 4 (i.e., four times the speed of sound) had been achieved by long-range rockets

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[1]Unless otherwise noted, current Canadian dollars are quoted.

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(the first ballistic missiles, A4 or V-2).[2] These developments were much more advanced in Germany than in the Allied countries. Indeed, a U.S. Army Air Forces intelligence report issued shortly before the war's end warned that "German development in jet-propelled aircraft . . . may well be regarded as the greatest potential threat . . . to Allied air superiority."[3]

When Allied forces overran German aeronautical research facilities following the landings in France in 1944, the evidence collected by technical intelligence promised attractive new vistas of development, for both military and civil applications.[4] Almost immediately, the major Western powers and the Soviet Union stepped up the development of jet and rocket engines, high-speed subsonic and supersonic aircraft, and missiles. They also began developing major new laboratory facilities.

Canada's desire to be a part of this activity was hardly surprising. After all, it had become fashionable and prestigious for governments, industries, and universities to involve themselves in high-speed aeronautics. Furthermore, conventional wisdom dictated that nations ought not be dependent on other nations for armaments. And economists reckoned that "the design, development and production of modern weapons has a spin-off that raises the whole technological and economic level of a nation."[5]

Added to these arguments were powerful political priorities. As the war drew to a close, the reigning Liberal government did not relish the

[2] German and Allied designations, respectively.

[3] *German Air Force Jet-Propelled Aircraft*, USAAF Intelligence Report, February 10, 1945.

[4] "The highlights of the German research work were known fairly completely to us by about August, 1945," said R. Smelt in a comprehensive review of information on German research obtained by the British ("A Critical Review of German Research on High-Speed Airflow," *Journal of the Royal Aeronautical Society* 50, no. 432 [December 1946]: 899–934). For other reports on Allied technical intelligence in 1944–45, see: P. R. Owen, *Note on the Apparatus and Work of the W.V.A. Supersonic Institute at Kochel, S. Germany*, Royal Aircraft Establishment, Farnborough, United Kingdom, RAE Tech Note Aero 1711, 1712, October 1945; 1722, November 1945; 1742, January 1946; L. C. Pooler, "German Aerodynamical Institutes and Interviews with German Scientists," *Symposium on Aerodynamics*, Johns Hopkins University, Applied Physics Laboratory, Bumblebee Report no. 29, December 6–7, 1945; R. V. Jones, *Most Secret War: British Scientific Intelligence 1934–1945* (London, 1978); and J. V. Becker, *The High-Speed Frontier: Case Histories of Four NACA Programs, 1920–1950* (Washington, D.C., 1980). For assessment of military potential see, for example, *Toward New Horizons*, a twelve-volume report prepared on behalf of the U.S. Army Air Forces Scientific Advisory Board by Theodore von Kármán and submitted to Gen. H. H. Arnold, Commanding General, AAF, on December 15, 1945.

[5] M. Lamontagne, *A Science Policy for Canada, Report of the Senate Special Committee on Science Policy*, 1, *A Critical Review: Past and Present* (Ottawa, 1970).

prospect of shutting down the country's huge military aircraft industry. The attendant unemployment would do nothing to improve the government's fortunes in the impending elections. Moreover, Canada had attained a certain status as a major wartime aircraft manufacturer, and there appeared to be legitimate reasons to believe it might be able to sustain a viable industry in peacetime as well. It was thus that Canada came to be one of the many countries deciding to undertake—each on its own—the original development and manufacture of high-speed military aircraft, jet engines, and missiles.

As recounted below, the Canadian effort was brief and for the most part unsuccessful. By 1959, all major projects had been halted. The only legacies of the country's ambitious venture into high-speed aeronautics were a relatively minor program of aerodynamic and aeroballistic research that continued into the 1960s and the establishment of a large British-owned conglomerate of mostly heavy industries. The Canadian experience will be reviewed here under two headings: large industrial-scale projects and the more modest research efforts. This examination from a perspective a quarter-century later points clearly to the basic causes of failure[6] and suggests strategies that might have been more likely to succeed. And yet, a brief look at current developments shows that the lessons of the 1950s have not been heeded and that the remaining Canadian aircraft industry will likely continue to experience serious difficulties.

The political, institutional, and bureaucratic aspects of this episode cannot and should not be divorced from the essentially technical factors involved. Indeed, technical questions are particularly significant where innovation is involved, as in the case of intermittent wind tunnels.

Industrial-Scale Programs: Jet Aircraft, Turbojets, and Missiles

During World War II Canada produced more than 16,000 military aircraft of British and American design; at its peak in 1944, the Canadian aircraft industry employed 116,000. As early as 1943, planning for the industry's postwar future was initiated. An interdepartmental committee recommended the continuation of government support "for at least the next ten years" and asserted that "politically, commer-

[6] These failures were not identified in the following major investigations of Canada's science policy conducted in the 1960s: Ibid.; *The Royal Commission on Government Organization (Glassco Report)*, 4, *Scientific Research and Development* (Ottawa, 1963), Section 23, pp. 183–322.

cially and as a measure of defence, it is essential to encourage the design and development of aircraft in Canada."[7] Conditions favorable to the "expansion of [private] business and employment" were to be created through the release of war surplus assets to industry and the creation of financial incentives to encourage research, development, and capital investment.[8]

In the aircraft and engine sector, the government relied on A. V. Roe Canada Ltd. (commonly known as Avro) to achieve these objectives.[9] Avro was incorporated in September 1945 (as a subsidiary of the British Hawker Siddeley Group), following an agreement with the government stipulating "the establishment in Canada of a design, research and development organization to promote . . . design and manufacture in Canada" of military and commercial aircraft and gas turbine engines.[10] After taking over government-owned Victory Aircraft Ltd. in Malton near Toronto (the largest aircraft plant in Canada), Avro began work in 1946 on jet fighter, turbojet, and commercial jet projects. In 1955, Avro Aircraft Ltd. and Orenda Engines Ltd. became the A. V. Roe Canada subsidiaries responsible for aircraft and engine programs.

The government's support of the Avro enterprise reflected the aspirations of the Royal Canadian Air Force, which saw for itself an independent role in air defense requiring an independent air industry. When the RCAF found there was no plane in production or on the drawing board that would be suitable as an all-weather fighter for

[7] J. de N. Kennedy, *History of the Department of Munitions and Supply* (Ottawa, 1950), p. 30; RG 28A, vol. 155, Public Archives of Canada, Ottawa.

[8] *White Paper on Employment and Income*, Department of Reconstruction and Supply, Ottawa, April 12, 1945, p. 1.

[9] Avro's projects, particularly the aborted Arrow supersonic fighter (see below), have been the subject of a highly emotional but poorly documented controversy in Canada, as evident from contributions by M. Peden, *Fall of an Arrow* (Stittsville, Ont.: Canada's Wings, 1978); E. K. Shaw, *There Never Was an Arrow* (Toronto: Steel Rail Educational Publishing, 1979); and R. Organ, R. Page, D. Watson, and L. Wilkinson, *Avro Arrow* (Cheltenham, Ont.: Boston Mills Press, 1980), among others. A study by J. Dow, *The Arrow* (Toronto: J. Lorimer, 1979), offers a more balanced assessment and refers to some primary sources. Canada's air defense policy and the Arrow cancellation are also discussed in Prime Minister John Diefenbaker's *One Canada, Memoirs of the Right Honourable John G. Diefenbaker*, vol. 3, *The Tumultuous Years 1962–1967* (Toronto, 1977), especially pp. 17–76. For an overview of Canadian aeronautics, see R. D. Hiscocks, "Aircraft Design in Canada from Silver Dart to Challenger and Dash 8," *Canadian Aeronautics and Space Journal* 30, no. 2 (June 1984): 99–113.

[10] "Hawker buys Malton Aircraft Plant," *Canadian Aviation* 18, no. 8 (August 1945): 157. The agreement was a personal priority for both C. D. Howe, minister of munitions and supplies and of reconstruction, and Sir Roy H. Dobson, a director of Hawker Siddeley and managing director of A. V. Roe & Co. Ltd. of Manchester, England.

northern defense, it commissioned the Avro CF-100 and Orenda programs.[11] These were to be the only Avro projects which saw production beyond the prototype stage. The CF-100 Canuck was the first fighter constructed by Avro. A twin-jet subsonic aircraft, it first flew in 1950 and entered service with the RCAF in 1953. The total cost of the program was about $750 million for 692 aircraft, engines, and spare parts.[12]

Even before the first Canuck flew, the RCAF had started (in 1948) to look for a successor to the CF-100. Again it found nothing suitable for "Canadian requirements."[13] In December 1953, however, Avro was given a $27-million, five-year contract to build two prototypes of a new design; it was to be a large (50,000 pounds plus), twin-jet, supersonic (Mach 2), two-seat, long-range interceptor. In 1954, it was given the designation of CF-105 Arrow. The Arrow prototype (fig. 1) was rolled out on October 4, 1957, the day the Soviet Union launched *Sputnik*. The Arrow's first flight was on March 25, 1958, with Avro's chief development pilot Jan Żurakowski at the controls; on April 3, it achieved supersonic speed, and on November 11 it flew at Mach 1.96, the highest Mach number it ever attained.[14] Three months later, the Arrow project was canceled by the Conservative government of John Diefenbaker.[15] In 1962 the Malton plant was sold to de Havilland Aircraft of Canada Ltd. (also of the Hawker Siddeley Group), and Avro became Hawker Siddeley Canada Ltd.

In engine development, Avro had somewhat more success.[16] The first project was the Chinook, a small 3,000-pound-thrust experimental engine (only three were made) which first ran in 1948. The 7,000-pound Orenda was the next design; it first ran in 1949 and was produced in large numbers in the 1950s (3,824 were built) to power the

[11] According to Air Marshal W. A. Curtis, chief of the air staff (1947–53) and subsequently vice-chairman of the Avro board of directors ("Developing Canada's Air Defences," *Saturday Night* 68, no. 30 [May 2, 1953]: 7–8).

[12] Lamontagne (n. 5 above), p. 81; Dow (n. 9 above), p. 77.

[13] The U.S. F-101 was among the aircraft considered and rejected; in 1961, Canada acquired sixty-six F-101s in a complex exchange arrangement with the United States.

[14] A former pilot in the Polish Air Force and, after 1947, a test pilot with the Gloster Aircraft Co. in England, Jan Żurakowski joined Avro in 1952. He enjoyed a reputation of "the most brilliant test pilot," a man with "a built-in ability to diagnose airplane responses." Flying the Gloster Meteor F-8 in 1951, he invented the cartwheel figure, the first new aerobatic stunt in twenty years ("Twin-Jet Pinwheel," *Time* [Canada ed.] 58, no. 23 [December 3, 1951]: 45–46; Dow [n. 9 above], pp. 79, 153).

[15] After twenty-two years of uninterrupted Liberal rule, the Conservatives came to power in June 1957 and governed until the Liberals were returned to office in April 1963.

[16] See B. A. Avery, "The Orenda History," *Canadian Aeronautics and Space Journal* 25, no. 2 (1979): 134–41.

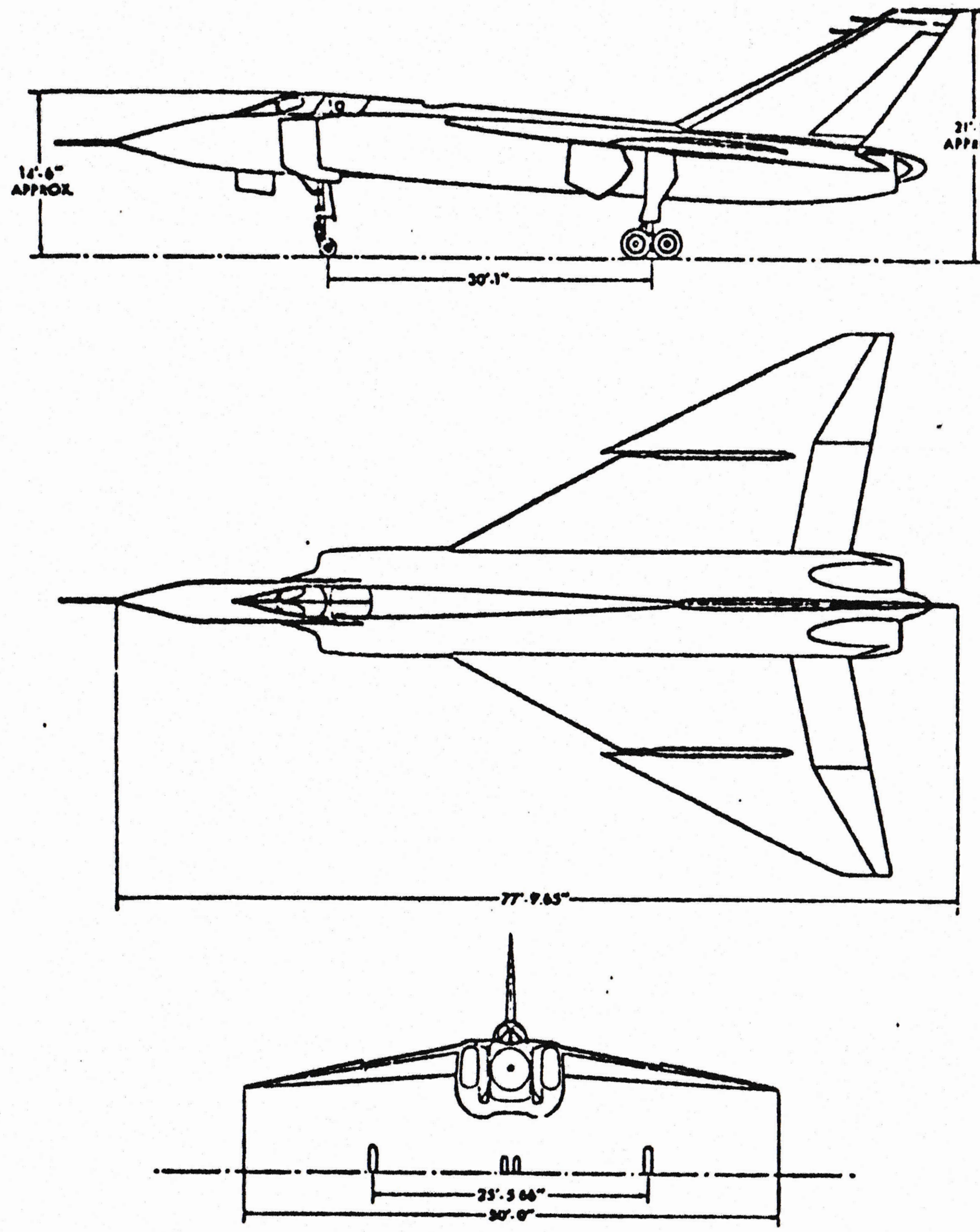

FIG. 1.—Mark I Avro Arrow CF-105 fighter which first flew in 1958; the aircraft and engine projects were canceled by the Canadian government in 1959. Mark II Arrow (with Iroquois engines) was to have a combat radius of 290 miles with five minutes of combat at Mach 1.5. (J. Woodman, "Flying the Avro Arrow," *Canadian Aeronautics and Space Journal* 25, no. 1 [1979]: 2.)

Avro CF-100 and the North American F-86 Sabre (built by Canadair Ltd. of Montreal). In 1953 work began on the 20,000-pound-thrust PS13 Iroquois, intended for the CF-105 Arrow. The project was highly successful, and Iroquois were installed in the sixth and seventh Arrows, the first Mark IIs.[17] The assembly of these aircraft was almost completed when the Iroquois program was canceled on the same day the

[17]Before the Iroquois was ready, the Pratt & Whitney J75 engine was used in Mark I prototypes; see below.

Arrow was scrapped. Since then, Orenda Engines Ltd. has manufactured U.S. turbojets, Orenda industrial gas turbines, and spare parts, and has provided engineering and test services to the industry.

Originally, Avro's design and development responsibility for the Arrow was to have been limited to the airframe; British or American engines and an American armament system were to have been used.[18] But within two years the development of British and American engines intended for the Arrow was cut off, and the Arrow had to be switched to a third engine (the Pratt & Whitney J75) of much smaller thrust; further redesign was needed to install the Orenda Iroquois engine in the Mark II prototypes.[19] Even greater difficulties plagued the Arrow's armament system. In 1955, the RCAF chose the Douglas Sparrow air-to-air missile and the Hughes Aircraft Co. fire control system. When Hughes, the manufacturer of the Falcon missile, declined to participate, the RCAF contracted with the Radio Corporation of America for Astra, a fire control system to be developed to the RCAF's specifications. After the Sparrow development was abandoned in 1956, the RCAF "patriated" it for completion in Canada. In September 1958, both the Sparrow and the Astra were canceled to reduce costs, and Avro was given a contract to procure yet another missile and fire control system from Hughes.

And so the CF-105 program, which as originally conceived involved only one major development—the airframe—in Canada, had grown to unmanageable proportions through the addition of engine, missile, and fire control projects. Moreover, the procurement originally forecast at 500–600 CF-105s was reduced to about 100 by 1957. These changes in development and production plans brought delays and cost escalations. The Avro's cost estimate for forty aircraft (including development) rose from $118 million in 1954 to $298 million a year later.[20] As the cancellation of the program was being considered, efforts were made to rescue the Arrow through sales abroad. The British and Americans were approached in 1955, 1958, and 1959, but repeatedly turned the Arrow down.[21]

The final decision to cancel the Arrow came in 1959. To soften the impact, the cancellation was carried out in two stages. In September 1958 the government halted production of the CF-105; on February

[18]See J. C. Floyd, "The Canadian Approach to All-Weather Interceptor Development," *Journal of the Royal Aeronautical Society* 62, no. 576 (December 1958): 845–66.

[19]The J75 engine had a sea-level thrust of 12,500 pounds compared to the 19,250-pound thrust of the Iroquois.

[20]Avro Brochure AD15, September 1954; Campney to Howe, November 24, 1955, C. D. Howe Papers, Public Archives of Canada, Ottawa.

[21]Dow (n. 9 above), pp. 45, 117, 124.

20, 1959, it terminated all Arrow and related contracts.[22] The decision was justified in military as well as financial terms. Prime Minister John Diefenbaker stated that outstanding achievements in the development of Arrow had been "overtaken by events." With the introduction of missiles the bomber threat had diminished and manned fighter aircraft had become obsolete; the Arrow would be "out of date by the time it got into production." In any event, "substantially cheaper U.S. interceptors would be available . . . to meet the . . . demands of North American or European defence."[23] The new plan called for Canada to acquire U.S. ground-to-air Bomarc nuclear warhead missiles and the SAGE (Semi-Automatic Ground Environment) defense network. Canadian industry was to share in the production of military equipment "for North American defence generally."[24]

Ironically, it was the Bomarc that "was very soon proven to be virtually obsolete before it was set-up" (as Diefenbaker admitted in his memoirs).[25] And so as early as 1960, Canada was buying U.S. aircraft to replace the aging CF-100s and F-86s. The F-101s were followed with purchases of F-104s, F-5s, and, currently on order, F-18s.

As if to ensure that no trace of the Arrow venture would remain to haunt it, the Canadian government had all evidence physically destroyed—Avro's technical reports, records, drawings, films, and photographs—in what can only be regarded as a mindless and paranoid

[22]Ironically, this occurred almost to the day on the golden anniversary of the first powered aircraft flight in Canada made by J. A. D. McCurdy in the Silver Dart on February 23, 1909, near Baddeck, Cape Breton Island, Nova Scotia, over the frozen surface of Lake Bras d' Or.

[23]*House of Commons Debates, Official Report, 2,* Ottawa, February 20, 1959, p. 1221; Diefenbaker (n. 9 above), pp. 36, 33. Regarding missiles, this was also the view of a retired chief of the Canadian Army staff who announced that "the day of the airplane as a defence mechanism is finished. . . . It has been replaced by missiles as the primary weapon. The Arrow is . . . the last of its line and kind" (*The Telegram,* Toronto, September 24, 1958). Canadians were not alone in making such naive forecasts. Following the launching of *Sputnik,* Nikita Khrushchev allowed that "Now the bomber and fighter can go into the museum" (*New Scientist* 95, no. 1325 [September 30, 1982]: 928).

[24]*House of Commons Debates* (n. 23 above), p. 1223. Actually, production sharing had continued throughout the Avro period and beyond, through the wartime practice of licensed manufacturing of military aircraft (by Canadair Ltd.); aircraft produced in this manner included the T-33 jet trainer and F-86 jet fighter in the 1950s, followed by the F-104 and F-5 jet fighters in the 1960s and 1970s.

[25]Diefenbaker (n. 9 above), p. 44. The Canadian government's conviction that manned aircraft for air defense would become obsolete was not shared by other members of the North Atlantic Treaty Organization or by the Soviet Union. It also contradicted statements made in 1957 and 1958 by the minister of national defence and by the Canadian deputy commander in chief of the North American Defense Command (NORAD); Dow (n. 9 above), pp. 113, 134, 156. Both superpowers continued to maintain large fleets of intercontinental bombers and manned interceptors.

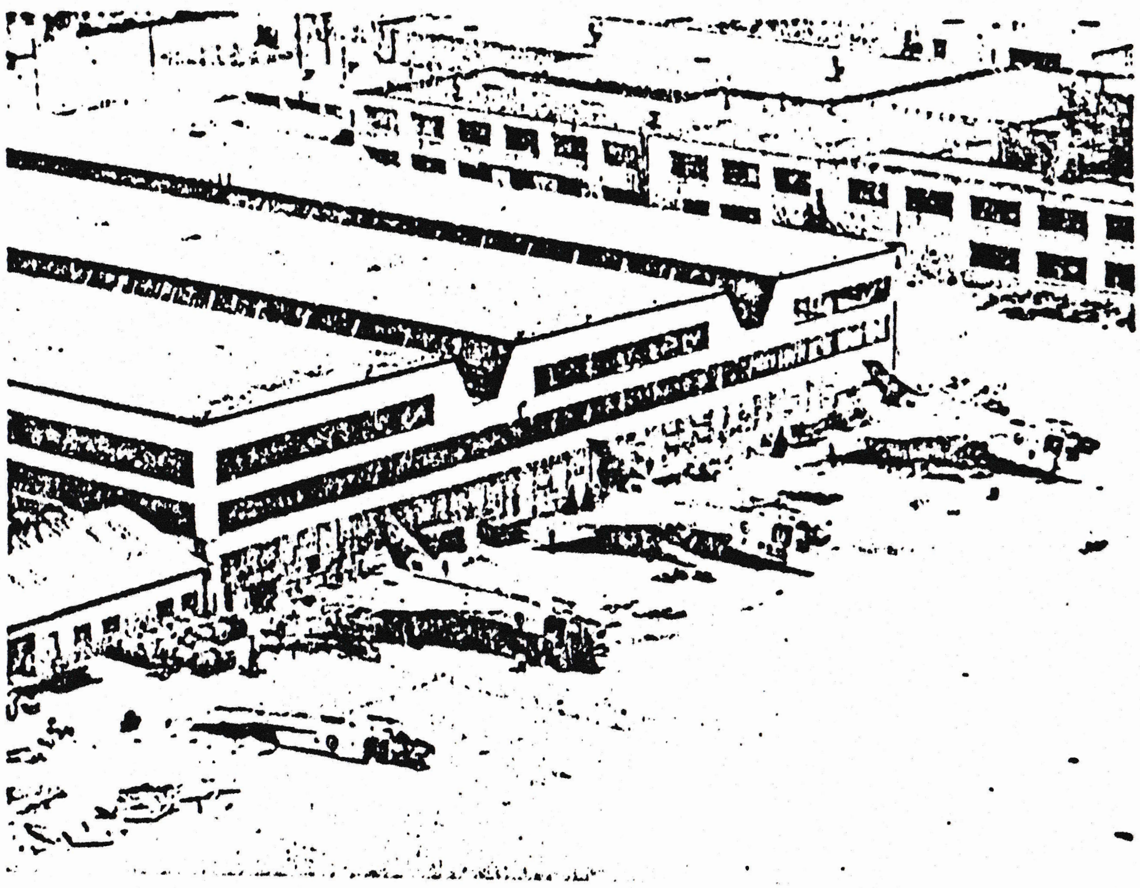

FIG. 2.—Four Mark I Avro Arrows (nos. 201, 203, 204, and 205) being reduced to scrap at the Avro Aircraft Ltd. plant in Malton on the orders of the Canadian government. Photographer Herb Nott was not allowed to take photographs inside the Avro premises; this unique picture was shot by Nott in April 1959 as he overflew the area in a rented aircraft. (Herb Nott & Co., Toronto.)

gesture. The five flying Mark I Arrows and the two almost completed Mark IIs, as well as thirty others in assembly, were cut up (fig. 2) and sold for scrap. Not a single plane was preserved for flight research or for Canada's Aeronautical Collection. Only a nose section of the first Mark II Arrow was saved; it is now exhibited in the National Museum of Science and Technology in Ottawa. As noted by test pilot Żurakowski, "we were using the experience and the knowledge of other countries . . . but we destroyed the results of our work. Does that make sense?"[20]

The cancellation of the Arrow meant a massive elimination of jobs at Avro and its 650 contractors (13,800 jobs at Avro alone) and the write-off of $400 million in public funds. But probably the most serious and costly consequence of the Arrow's demise in 1959 was the dispersal and mass exodus from Canada of so much technical and managerial

[20] Dow (n. 9 above), p. 141; Shaw (n. 9 above), pp. 87–92; J. Żurakowski, "Test Flying of the Arrow and Other High Speed Jet Aircraft," *Journal: Canadian Aviation Historical Society* 17, no. 4 (Winter 1979): 100–111, quote on p. 108.

talent, assembled and trained at great expense in the highly skilled business of aircraft and engine design and manufacture. Former employees of Avro were in great demand in the United States, where the post-*Sputnik* aerospace boom had already started. Many found work in American industry and research, and some returned to England.

Avro had two other unsuccessful ventures. The first, a medium-range commercial jet project, was initiated by Avro in 1946 in consultation with Trans Canada Airlines (TCA), the country's flag carrier. A C-102 Jetliner prototype first flew in August 1949, within two weeks of the maiden flight of Britain's de Havilland Comet, which in 1952 became the first jet to enter commercial service. But the aerodynamics of the C-102 did not reflect the state of the art: the wing was straight and thick, rather than swept and thin. And the engines expected to power the Jetliner were not ready; four Rolls-Royce Derwent Vs had to be used instead of two RR Avons. Avro would not guarantee performance, price, and delivery, so TCA refused to order the C-102. A sale to National Airlines in the United States fell through. In 1947 the Canadian government ordered two C-102 prototypes. After the first one was built, Avro was told in 1950 to concentrate all its efforts on military aircraft for the Korean War. By 1957, the expense of a thorough inspection was considered prohibitive, and the prototype C-102 was destroyed on Avro premises. The government spent $6.6 million on the Jetliner; the cost to Avro was $2.3 million.

Avro's Project Y or "flying saucer" was yet another aborted effort. It involved the development of a saucer-shaped vehicle capable of vertical and horizontal motion. Jets issuing from the vehicle's circular perimeter were to provide propulsion and control. The 1,500-mph "flying saucer" was said to be "so revolutionary that when it flies all other types of supersonic aircraft will become obsolete."[27] The RCAF gave Avro $229,000 for Project Y in the 1950s. Before termination several years later, the project was continued under a U.S. Department of Defense contract as a much more mundane subsonic Avrocar.

The cancellation of the Arrow project in 1959 put a formal end to the development of Canada's military high-speed aircraft, large jet engines, and missiles. But the development of jet aircraft continued at Canadair Ltd. with the CL-41 Tutor, a two-seat trainer produced from 1961 to 1967, and the CL-89 military surveillance drone, produced after 1969.[28] In 1976 work started on the Challenger executive jet, currently in production.

[27]According to a report in *The Times* of London, quoted in Lamontagne (n. 5 above), p. 79; see also S. Young, "Forty Years of Work at the McDonnell Douglas Canada Ltd. Plant, Malton," *Canadian Aeronautics and Space Journal* 25, no. 2 (1979): 128–32.

[28]On Canadair, see F. C. Phillips, "A History of Aerospace Research and Development in Canadair L[illegible]," *Canadian Aeronautics and Space Journal* 25, no. 2 (1979): 112–21.

As for Avro, while the government's hopes for that firm were not fulfilled, the company itself—and its British parent—had reason to be satisfied. Avro had been the brainchild of Sir Roy Dobson, an aggressive entrepreneur who had recognized—and seized—a moment of opportunity. In short order, his infant company acquired the country's largest aircraft plant and secured contracts for jet fighter and turbojet development. It also interested the nation's flag carrier in a jet transport. All this Dobson accomplished on the basis of a $2.5 million loan guaranteed by a Canadian industrialist. The venture was a risky one, but Avro took no risks. The company preferred—and the government provided—the safety of grants and cost-plus contracts. Indeed, Avro "seemed horror-struck at the prospect of having even to compete in a normal market-place situation."[29] After the Arrow was canceled, Avro's proposals for alternative work did not envisage any financial backing by the company.

When—inevitably—its aerospace projects began to decline, Avro was ready: in 1955, it launched a major diversification into heavy manufacturing, steel, and coal. In 1956, it offered one-sixth of its shares for sale in Canada. As noted by Dow, "it was to a great extent buying us out with our own money."[30] Twelve years after opening its doors at Malton in 1946, Avro became the third largest corporation in Canada; it did 45 percent of the business of the entire Hawker Siddeley Group. In 1958, Avro comprised thirty-nine companies, with 41,000 employees, and logged $371 million in net sales—but aviation production accounted for only one-third of its labor force and 40 percent of its profits.

Concurrently with Avro's jet fighter and turbojet projects, the Defence Research Board (formed in 1947 as the "fourth arm of the service") promoted the Velvet Glove, an air-to-air supersonic guided missile, to be deployed from CF-100 fighters. Having Canadians actually develop and manufacture a missile was thought to be the most effective way to keep the country abreast of this new weapon type. In contrast to the jet fighter projects, the Velvet Glove was conceived with very conservative performance specifications. It was designed to meet the threat of propeller-driven bombers of World War II vintage. The project was managed by the DRB's Canadian Armament Research and Development Establishment (CARDE) at Valcartier, Quebec. It began in 1951 and by 1955 involved several companies including Canadair, Canadian Westinghouse, and Computing Devices of Canada. Some 300 missiles were built and test fired. By the mid-1950s, however, it had become apparent that the Velvet Glove and CF-100 were inadequate to

[29] Diefenbaker (n. 9 above), p. 38.

[30] Dow (n. 9 above), p. 101.

ope with jet bombers. In July 1956 the Minister of National Defence announced the cancellation of the Velvet Glove and stated that the U.S. Sparrow missile would be produced in Canada instead. The project had cost $24 million; the Sparrow was canceled in September 1958.[31]

Research Activities: Aerodynamics Laboratories, Wind Tunnels, and Aeroballistics

The Canadian government's involvement with aeronautical research dates back to 1929, when the National Research Council's Division of Mechanical Engineering started developing aeronautical laboratories in Ottawa under the direction of J. H. Parkin (1890–1981). These laboratories were intended to provide testing for industry, to support applied research in aeronautics, and to train aeronautical engineers. Initially located in a remodeled lumber mill on John Street, during the war years the aeronautical laboratories were transferred to a new NRC site east of Ottawa. They were considerably expanded: a relatively large low-speed wind tunnel (6 × 10 foot) and a spinning tunnel (15-foot diameter) were built.

By 1948, the growing military aircraft and engine programs were straining the capabilities of the NRC and its largely nonmilitary budget. Moreover, with the creation of the Defence Research Board in 1947, the responsibilities for aeronautical research became confused. In 1950, the cabinet authorized the creation of the National Aeronautical Establishment as the single agency responsible "for the conduct of research and experiments required for the development and operation of military and civil aircraft in Canada."[32] The concept was modeled on the British Royal Aircraft Establishment at Farnborough and envisaged the consolidation of older NRC aeronautical laboratories with the new facilities which were to be constructed at Uplands Airport near Ottawa. The operation of the NAE was to be overseen by the National Aeronautical Research Committee, and funding for the new Uplands facilities was to be provided jointly by the NRC and the DRB.[33]

The proposed arrangement amounted to "shared responsibility" management; it was of questionable effectiveness. And, curiously, the five members of the National Aeronautical Research Committee, with

[31] D. I. Goodspeed, *A History of the Defence Research Board of Canada* (Ottawa, 1958); also Lamontagne (n. 5 above), pp. 74–81.

[32] See n. 6 above.

[33] See n. 31 above. The NAR Committee was composed of the president of NRC as chairman, the chairman of the DRB, the chief of the air staff, and the deputy ministers of transport and defence production.

one possible exception, had no personal experience in aeronautical research. In any case, the cabinet decision creating the NAE was never fully implemented. The NAE label was adopted in 1958 by a division of the NRC, which continued to operate the Montreal Road and Uplands Laboratories. Commenting on aeronautical research in Canada, the Glassco Report noted in 1963 that "there appears to be no single body for the coordination of aeronautical research and development programmes carried out by, or sponsored by, the Defence Research Board, the RCAF, the Department of Defence Production, the Department of Transport and the National Research Council."[34] Moreover, the RCAF "was frankly and unequivocally opposed to a separate defence research organization" (i.e., the DRB), and "relations between the Defence Research Board and the National Research Council were often strained."[35] In short, the situation was not conducive to the coordination of aeronautical research. And, in the end, the development of laboratories for high-speed aerodynamics, initiated in the late 1940s, was continued independently by the Defence Research Board and the National Research Council.

Canadian research in high-speed aerodynamics and aerophysics had been started at the University of Toronto by G. N. Patterson, who obtained a doctorate in physics there in 1935 and subsequently gained experience in aerodynamics in England, Australia, and the United States. After returning to Toronto in 1947 as a professor of fluid physics, Patterson submitted in February 1949 "A Detailed Proposal for a Supersonic Aerodynamic Laboratory." In July 1949, with a $350,000 grant from the Defence Research Board, he established the University of Toronto Institute of Aerophysics (UTIA). The institute quarters at Downsview near Toronto were inaugurated in September 1950. Its financial support came from the DRB, as well as from contracts with the U.S. Department of Defense and other agencies.

Over the years, a variety of experimental equipment was developed at the institute, starting with 5×7-inch and 16×16-inch supersonic intermittent vacuum-driven wind tunnels (the latter modeled on the Peenemünde-NOL tunnel of the same size) and shock tubes; other facilities included a 5×5-inch hypersonic blowdown tunnel, hypersonic shock tunnels and ranges, low-density and plasma tunnels, apparatus for studies of sonic boom and blast waves, low-speed tunnels, and associated instrumentation.[36] Research at the institute centered on basic studies of shock waves, rarefied gas dynamics, and aerodynamic

[34]See n. 6 above.

[35]Goodspeed (n. 31 above), p. 59; Lamontagne (n. 5 above), p. 85.

[36]UTIA, *Progress Report on Research Supported by Grants from the Defence Research Board,* 1952–53; 1953–54.

noise.[37] The institute did not participate extensively in Canadian missile and aircraft projects of the 1950s but trained many highly competent scientists and engineers. Those who continued working in high-speed aerodynamics often found employment south of the border.

Concurrently with the DRB-supported developments at UTIA and to some extent in competition with them, the NRC followed a path which led to the construction and operation, beginning in 1962, of a large 5-foot high-speed wind tunnel facility. In the immediate postwar years, a lack of engineers experienced in this new field thwarted progress. But suitable personnel were recruited in 1947 and 1948 from the Royal Aircraft Establishment and the National Physical Laboratory in England. The first proposal for NRC's High Speed Aerodynamics Laboratory was made by F. W. Pruden (1922–58) in April 1948.[38] The design was based on two compressors obtained as war reparations from Germany. They were to drive a 10×10-inch continuously running supersonic wind tunnel and a 20×20-inch intermittent, vacuum-operated supersonic tunnel. In 1949, Pruden started developing an aeroballistic range. Subsequently, more modest plans were adopted,[39] the range was dropped, and a 10-inch intermittent tunnel was built (fig. 3). The NRC's new High Speed Aerodynamics Laboratory building (on Montreal Road) was dedicated in 1950, and the tunnel started operating in March 1951.

The drive of the 10-inch tunnel was of a type used in some of the first supersonic tunnels. The concept, which offered power economy, design simplicity, and low cost, had been introduced in the late 1920s by Ludwieg Prandtl in Göttingen, applied in Aachen, and further developed in Peenemünde, the center responsible for the V-2 (A-4) rocket missile and other weapons.[40] Essentially, the drive consisted of a

[37]*Official Opening, September 26, 1950*, Institute of Aerophysics, University of Toronto; *Addresses at the Opening of the New Building*, pt. 1, *Decennial Symposium*, Institute of Aerophysics, University of Toronto, October 14–16, 1959; G. N. Patterson, *The Role of the Research Institute in University-Industry Cooperation*, Institute for Aerospace Studies. University of Toronto, 1967.

[38]F. W. Pruden, *A Proposal for a High Speed Aerodynamic Laboratory*, National Research Council, Division of Mechanical Engineering, Report MA-205, Ottawa, April 30, 1948. See also R. J. Templin, *Design Considerations of Supersonic Tunnels*, National Research Council, Division of Mechanical Engineering, Report MA-158, Ottawa, 1945.

[39]J. Lukasiewicz, "Wind Tunnels in the High Speed Aerodynamics Laboratory," *NAE & NRC (ME) Quarterly Bulletin*, vol. 4 (1952).

[40]On the concept, see A. Busemann, "Profilmessungen bei Geschwindigkeiten nahe der Schallgeschwindigkeit," *Jahrbuch der Wissenschaftlichen Gesselschaft für Luftfahrt* (1928), p. 95; C. Wieselsberger, "Die Uberschallanlage des Aerodynamischen Instituts der Technischen Hochschule Aachen," *Luftwissen*, no. 4 (1937): 301–3; L. Prandtl, *Essentials of Fluid Dynamics* (New York, 1952), p. 306 et seq.; H. H. Kurzweg, "The

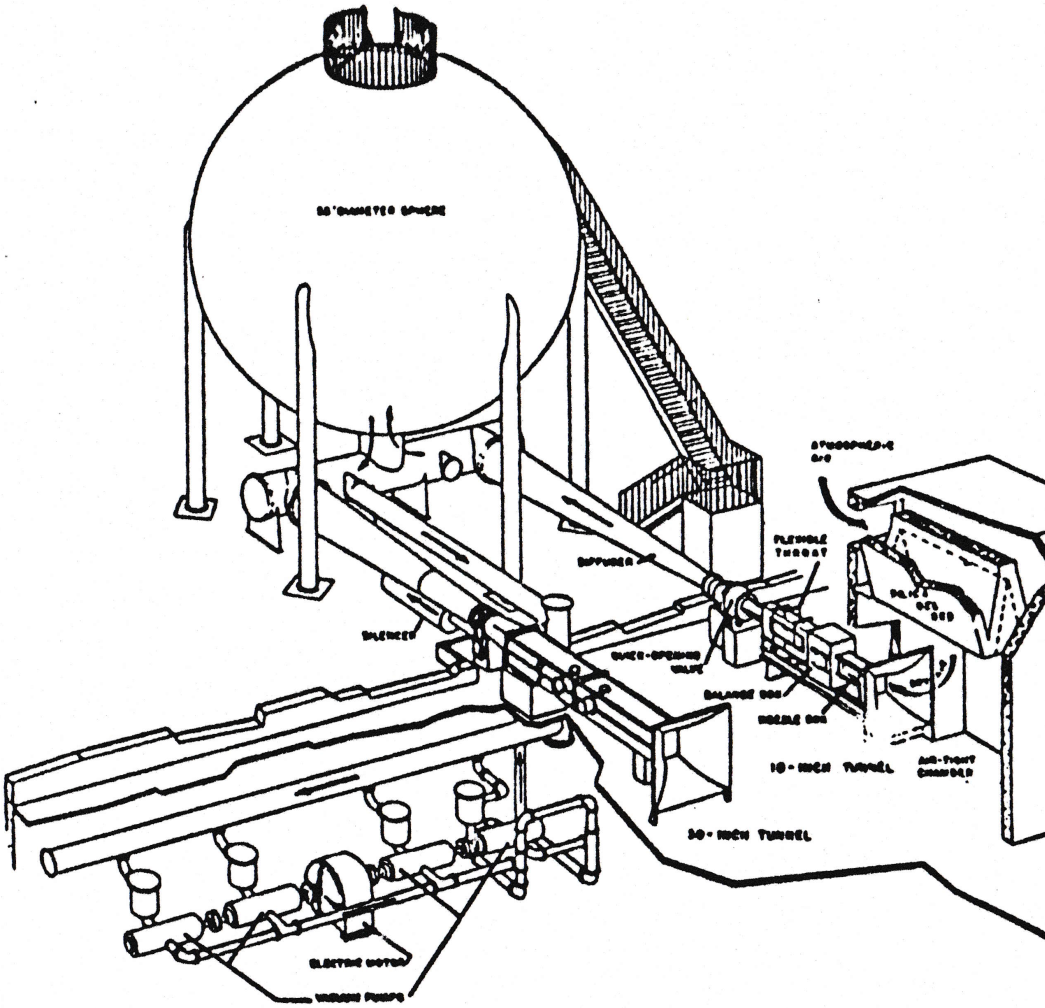

Fig. 3.—Supersonic/transonic wind tunnels at the NRC–NAE High Speed Aerodynamics Laboratory, Montreal Road, Ottawa. (See n. 39, fig. 1.)

large vessel evacuated to a low pressure, which provided the pressure drop necessary to accelerate atmospheric air through the wind tunnel duct to the required Mach number in the test section. The design allowed run durations of some fifteen seconds at Mach numbers up to

Aerodynamic Development of the V-2," pp. 50–69 in *History of German Guided Missiles Development*, ed. Th. Benecke and A. W. Quick, AGARDograph 20 (Brunswick, Germany, 1957). After the war, the two 40 × 40-cm Peenemünde tunnels were shipped from Kochel in Bavaria (moved there after the bombing of Peenemünde in 1943) to the U.S. Naval Ordnance Laboratory in Silver Spring, Md., and reactivated in 1948. See Smelt and Owen (n. 4 above); also W. Bollay, "Aerodynamics of Supersoı. Aircraft and Missiles," *Symposium on Ordnance Aeroballistics*, NOLR-1131, U.S. Naval Ordnance Laboratory, White Oak, Silver Spring, Md., June 28, 1949, pp. 27–49; and H. H. Kurzweg, "The Aeroballistic Research Facilities at NOL," *NOL Aeroballistic Research Facilities Dedication & Decennial*, NOLR-1238, U.S. Naval Ordnance Laboratory, 1959, pp. 18–37. In 1948, a 16 × 16-inch supersonic tunnel—essentially a copy of the 40-cm Peenemünde design—was built by North American Aviation, Inc., in Los Angeles (see Bollay, above). Provision for storage of dry air was introduced in this installation.

4.5. With modest pumping power, the vessel could be evacuated in a matter of minutes, so that several tunnel runs could be made every hour, and instrumentation was devised to make force, pressure, and heat-transfer measurements during each run.[41]

The design of the NRC's 10-inch wind tunnel followed German aerodynamic practice but incorporated mechanical improvements. They included good access to the model, adequate space for model support and instrumentation, and quick Mach number change made possible through the use of interchangeable integral nozzle boxes (each for a fixed test Mach number; see fig. 4). This proved to be a worthwhile scheme for a small tunnel—much less expensive than a flexible nozzle capable of covering the same wide range of Mach numbers.[42]

Nonetheless, the capability of the 10-inch tunnel was severely restricted by its small size. It was used for tests of the Velvet Glove missile but was not suitable for aircraft tests; moreover, it could not cover the transonic range of speeds. For these reasons, and in view of the impending supersonic Arrow project, a larger transonic-supersonic tunnel was planned, to be driven by the existing HSAL plant. A 30 × 16-inch test section was selected for use with half-models, so that aerodynamic simulation equivalent to that attainable in a 30 × 30-inch tunnel (with full models) could be realized. Installed in the 10-inch tunnel bay (fig. 3), the tunnel started operating in September 1952. Two years later a second vacuum sphere was erected, increasing the run duration from six to fifteen seconds.

The new tunnel was the first to offer transonic capability in Canada. It was used for some testing of the Arrow and basic aircraft

[41]See Owen (n. 4 above) and Kurzweg (n. 40 above). When Sweden embarked on indigenous design of military aircraft and missiles after World War II, it opted for the affordable, vacuum-driven intermittent tunnels and extended the German experience to larger sizes (0.5 × 0.5- and 1 × 1-m test sections, operational in 1955), driven models (see below), and unconventional vacuum storage in chambers blasted out of rock (Bo K. O. Lundberg, "Aeronautical Research in Sweden," *Journal of the Royal Aeronautical Society* 59, no. 538 [October 1955]: 647–81; *The FFA Aerodynamic Research and Test Facilities*, FFA Memorandum 33, Flygtekniska Forsoksanstalten [Stockholm, 1964]).

[42]Because of machining and handling difficulties (see, e.g., Becker, n. 4 above, p. 104), interchangeable solid nozzle blocks or integral nozzle boxes were not used in medium-size and large wind tunnels; the RAE-Bedford 3 × 3-foot (J. Y. G. Evans and A. Spence, *Development of Wind Tunnels at the RAE*, RAE Technical Report 71040, 1971) and the NACA-Langley 4 × 4-foot supersonic tunnels (dismantled in 1977; W. T. Schaefer, Jr., *Characteristics of Major Active Wind Tunnels at the Langley Research Center*, NASA Technical Memorandum TM X-1130, July 1965) were among the largest equipped with solid block nozzles. Variable geometry designs were more practical in large wind tunnels (see n. 49 below).

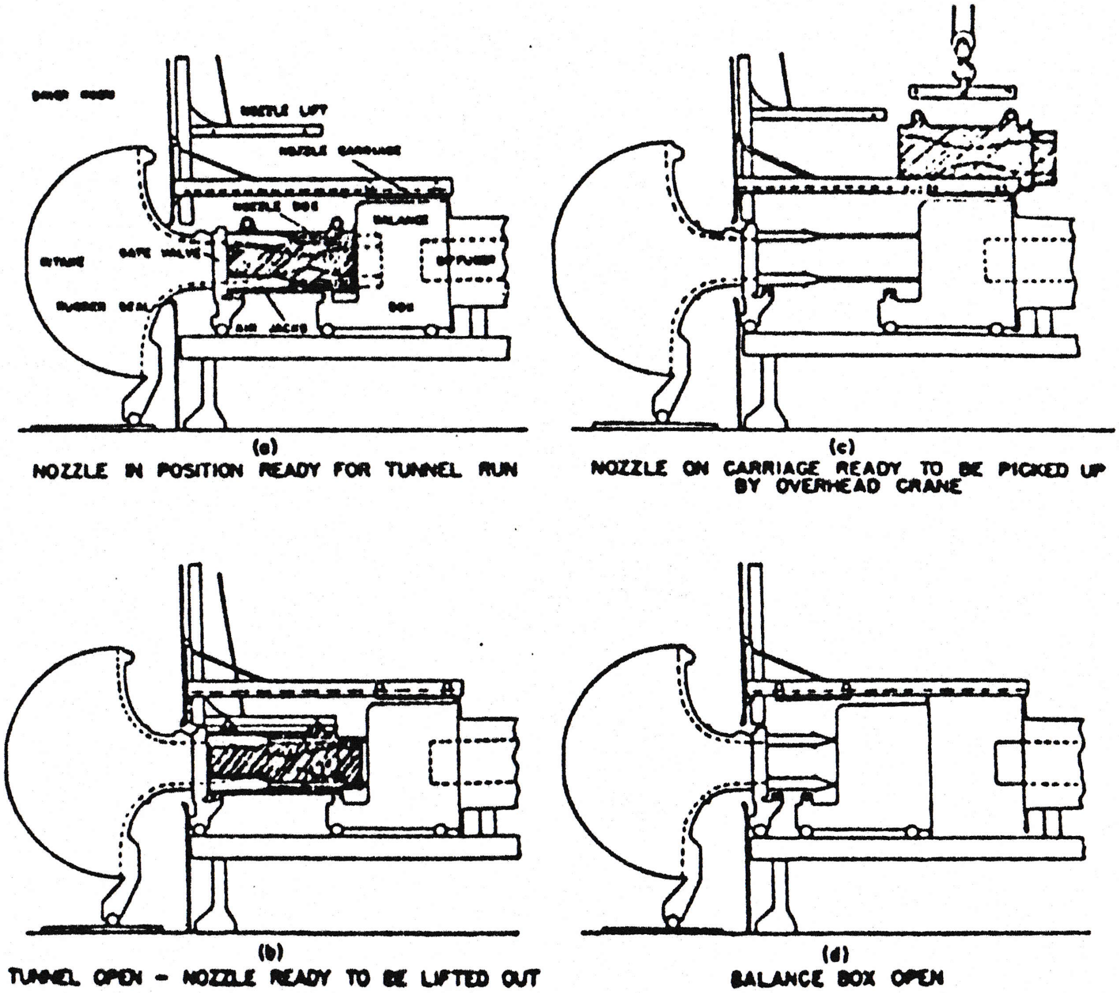

FIG. 4.—Design of the 10×10-inch HSAL's supersonic wind tunnel, first operated in 1951, provided for quick change of Mach number through the use of integral nozzle boxes. The four steps involved in a nozzle change are illustrated above. (See n. 39, fig. 5.)

configurations.[43] New test techniques were developed in both tunnels. Since 1959 the HSAL has specialized in dynamic stability research. Renamed the Unsteady Aerodynamics Laboratory, it has become widely known for experimental measurements of dynamic stability and has been engaged in many foreign projects.

The small supersonic and transonic wind tunnels that became available in Canada in the early 1950s were better suited to research than to developmental testing. Certainly, they were totally inadequate in the context of the policy of air industry self-sufficiency adopted by the government shortly after World War II. In contrast to Canada, the need for new, high-performance large wind tunnels was appreciated in the United States, Great Britain, and France. After the war, these

[43]Most testing of the Arrow was conducted in larger U.S. tunnels; also 1 : 8-scale models were tested in free flight at the CARDE-Picton and NACA-Langley ranges (see Floyd, n. 18 above).

countries correctly concluded that the potential offered by aircraft and missiles could not be realized unless adequate means were provided for research and development, and in the late 1940s they established national programs for construction of large wind tunnels, running into tens and even hundreds of millions of dollars: the U.S. Unitary Plan Wind Tunnels of 1949, the RAE-Bedford laboratories, France's ONERA wind tunnels in Modane and Paris.

The technical approach adopted in the United States and Britain in the prewar years had been followed in the construction of all large high-speed wind tunnels and in the subsequent upgrading of their performance.[44] It reflected the tradition of large, closed-circuit, low-speed facilities which ran *continuously*, a design dating to Prandtl's Göttingen wind tunnel of 1909.[45] Prandtl's closed-circuit design was well suited to low speeds: it was energy efficient (through the recovery of kinetic energy in a diffuser downstream of the test section) and allowed control of the Reynolds number (i.e., the aerodynamic scale) independently of the airspeed by varying the pressure, and hence the air density, in the tunnel circuit. However, the application of Prandtl's design to high subsonic and supersonic speeds turned out to be expensive and presented serious technical problems.[46]

The construction of a conventional, large high-speed wind tunnel for developmental testing was clearly beyond the financial reach of the Canadian government. And, in any case, the large engineering staff needed for such an undertaking was not available in Canada. But such a facility was required, and so a more economical solution had to be found. The necessary clue was provided by the approach the Germans had used in developing their supersonic tunnels, already adopted for NRC's High Speed Aerodynamics Laboratory: this was the principle of intermittent operation (or, more generally, of energy storage), which could be pushed even further to increase productivity and aerodynamic performance. If measurements could now be taken with a driven model—a model driven over a full range of incidence during each run—the data productivity of an intermittent tunnel could easily match, or even exceed, the productivity of traditional, continuously running installations. Moreover, intermittent operation would provide excellent model and test-section accessibility: with instantaneous tunnel starting and stopping, long run-up, shutdown, and pumping

[44] The following major tunnels were upgraded in the years indicated: NACA-Langley: 8-foot diameter, 1945; 4×4 foot, 1950; 16-foot diameter, 1951; NACA-Ames: 16-foot diameter, 1955; 6×6 foot, 1956; RAE-Farnborough: 10×7 foot, 1956.

[45] D. G. Tietjens, *Applied Hydro- and Aeromechanics* (New York, 1957), pp. 253–54.

[46] This was recognized by Prandtl some twenty years earlier and led him to the concept of intermittent tunnels (see n. 40 above).

periods would be eliminated.[47] The aerodynamic performance (or scale, measured by Reynolds number) could be increased by operating the tunnel from pressurized air storage to the atmosphere rather than from the atmosphere to a vacuum vessel. This would require the use of an automatically controlled valve which would maintain constant pressure in the wind tunnel as the stored air pressure decreased during the run and a heat exchanger (of passive storage type) to maintain constant temperature of the air entering the tunnel (the temperature would otherwise decrease because of expansion of the stored air). A layout of the proposed scheme is shown in figure 5.

The technical feasibility of this type of high-performance and high-productivity intermittent wind tunnel depended on the development of instrumentation and controls more sophisticated than any that had been previously used in wind tunnels. But it was the view of F. W. Pruden and this writer that the "state of the art" in these two areas was sufficiently advanced to render the novel wind tunnel concept practical. The first engineering analyses of the new design and a proposal for a 4 × 4-foot blowdown intermittent wind tunnel were completed in September 1950.[48] These demonstrated the advantages of the new concept, including the ability to cover the whole trisonic (i.e., subsonic, transonic, and supersonic) Mach number range in a single tunnel.[49]

[47]The use of driven models in intermittent tunnels was envisaged at North American Aviation, Inc., in 1949 (Bollay, n. 40 above), but the "driven model technique" was developed at NAA only after 1952, when the large intermittent project was started. The benefits of intermittent test technique were realized in the 1960s in continuously operating wind tunnels, an "intermittent" model being injected into a continuously running wind tunnel test section for the brief period of test (see J. Lukasiewicz, "A Critical Review of Development of Experimental Methods in High Speed Aerodynamics," in *Progress in Aerospace Sciences*, ed. D. Kuchemann [Oxford, 1973], pp. 1–26). However, it should be noted that intermittent operation is not suitable for air-breathing propulsion testing, for which relatively long duration flows are usually required.

[48]J. Lukasiewicz and F. W. Pruden, *An Economic High Speed Wind Tunnel of High Performance, with Notes on Contraction Ratio and Reynolds Number Control*, National Research Council, Division of Mechanical Engineering, L.O. 5850-A, File LM2-9-1, Ottawa, September 22, 1950. Results of subsequent studies were reported in J. Lukasiewicz, *Development of Intermittent High-Speed Wind Tunnel Installations and Testing Techniques*, National Aeronautical Establishment Laboratory Report, LR-75, Ottawa, July 17, 1953, and "Development of Large Intermittent Wind Tunnels," *Journal of the Royal Aeronautical Society* 59, no. 4 (1955): 259–78.

[49]Trisonic was a term introduced by North American Aviation, Inc. (now Los Angeles Division, Rockwell International Co.); see W. Daniels, Jr., *Design and Development of North American Aviation Trisonic Wind Tunnel*, AGARD (Brussels, 1956). Trisonic operation called for a practical method of varying the test section Mach number [illegible] wide range. By the time the design of large intermittent tunnels started, the fully flexible nozzle provided the required solution. The basic idea of a continuous curvature aerodynamic contour compatible with the elastic shape of a flexed nozzle wall and the flexible nozzle

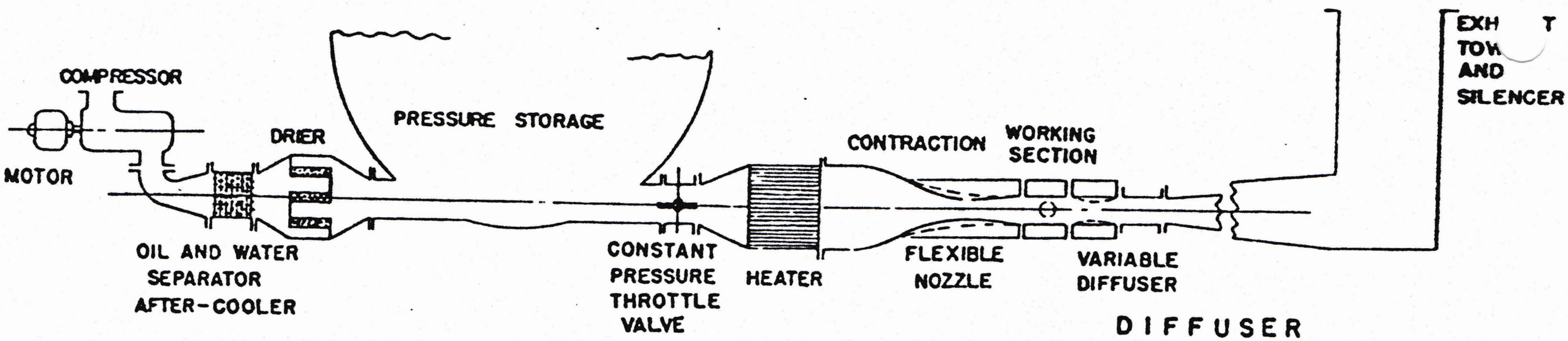

FIG. 5.—Schematic layout of a pressurized, blowdown wind tunnel installation first proposed in 1950. In the actual 5-foot wind tunnel completed in 1962, the storage-type heater was located inside the pressure storage, upstream of the constant pressure throttle valve. (See n. 48: Lukasiewicz, 1953, fig. 3, and 1955, fig. 2.)

Notwithstanding its favorable characteristics, acceptance of the novel tunnel system did not come easily. Conventional designs pursued by the most reputable (and also well-funded) laboratories were considered the only sound and practical ones. In the United States and Britain, in spite of difficulties that surfaced from the initial planning stages for large high-speed wind tunnels,[50] the intermittent option was apparently never considered by the organizations in charge of national wind tunnel programs.[51]

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design were pioneered by the Jet Propulsion Laboratory, California Institute of Technology, and the Sandberg-Serrell Co., both of Pasadena, Calif. (A. E. Puckett, "Supersonic Nozzle Design," *Journal of Applied Mechanics* 13 [December 1946]: A-265–A-270; *Design and Operation of a 12-Inch Supersonic Wind Tunnel*, Institute of the Aeronautical Sciences preprint no. 160 [New York, 1948]; H. N. Riise, *Flexible-Plate Nozzle Design for Two-Dimensional Supersonic Wind Tunnels*, JPL, CIT, Report no. 20-74, Pasadena, Calif., June 9, 1954; J. T. Kenney and L. M. Webb, *A Summary of the Technique of Variable Mach Number Supersonic Wind Tunnel Design*, AGARD, AGARDograph no. 3 [Paris, 1954]). The JPL 12 × 12-inch supersonic tunnel was the first to be equipped, in 1948, with a successful flexible nozzle. The design was subsequently used in larger JPL tunnels, in the large intermittent tunnels, in several tunnels at the Arnold Engineering Development Center (up to 16 × 16-foot size), in the NACA-Lewis propulsion test tunnels, in the RAE-Bedford 8-foot and 3 × 4-foot tunnels, among others.

[50]The most fundamental problem involved matching the pressure ratio–volume flow characteristics of the tunnel to those of the compressor (a problem encountered already in the 1930s in the design of the first continuous supersonic wind tunnel—see J. Ackeret, "High Speed Wind Tunnels," *Proceedings, Fifth Volta Congress* [Rome, 1935]; NACA TM 808, 1936), and providing the extremely high power (in the 50,000- to 200,000-horsepower range) needed to attain the desired Mach and Reynolds numbers. The aerodynamic and structural design of compressors had to be pushed to the limit, and variable-speed electric motor drives had to be developed for power levels not encountered before. The structural and mechanical design of the closed wind tunnel circuit presented serious difficulties. For a comprehensive discussion, see R. F. Huntsberger and J. P. Parsons, "The Design of Large High-Speed Tunnels," pp. 127–42; W. Wadkin and T. Barnes, "Notes on the Design and Construction of the Welded Steel Structure for the 8 Foot × 8 Foot High Speed Wind Tunnel at the National Aeronautical Establishment, Bedford," pp. 153–66; J. Clark, "Design and Construction Aspects of High Power Wind Tunnel Drive Systems and Large Diameter Compressors," pp. 167–91 in *Papers Presented at the Fifth Meeting of the Wind Tunnel and Model Testing Panel*, AGARD, AG15/PC (Paris, 1954); J. Lukasiewicz, "Development of Large Intermittent Wind Tunnels," *Journal of the Royal Aeronautical Society* 59, no. 4 [1955]: 259–78, and n. 47 above; L. J. Cheshire, J. Y. G. Evans, W. A. Goodsell, and P. H. W. Wolff, "The Design and Construction of the Compressor for the 8 Foot by 8 Foot High-Speed Wind Tunnel at R.A.E. Bedford," *Proceedings of the Institution of Mechanical Engineers* 176, no. 15 (1958): 549–84; E. P. Hartman, *Adventures in Research: A History of Ames Research Center 1940–1965* (Washington, D.C., 1970); and D. D. Baals and W. R. Corliss, *Wind Tunnels of NASA* (Washington, D.C., 1951).

[51]When Ames Unitary Plan project was found to require three, instead of one, different continuous tunnels to cover the stipulated Mach number range from 0.7 to 3.5, an intermittent operation was not envisaged. Indeed, it was asserted that "no single tunnel

The National Advisory Committee for Aeronautics and the air force in the United States and the RAE in Britain had virtually no experience in short-duration wind tunnel testing. Not surprisingly, NACA and RAE showed no interest in the intermittent technique; they were already committed to extensive and expensive construction of continuous wind tunnels.[52]

The intermittent concept, proposed in 1950 in Canada, was first used in 1956–57 by American aircraft builders, to whom the idea appealed because, as flight speeds had increased into the supersonic range, the quantity of aerodynamic data required for aircraft design and the cost of obtaining them had escalated. The F-100 (the first operational U.S. supersonic fighter) required over 50 percent more wind tunnel test time than the subsonic F-86, with 60 percent of it in high-speed wind tunnels, compared with only 17 percent for the F-86. Clearly, new initiatives were required; North American Aviation, Inc., and Boeing Airplane Co. were among the first to take them.

The projects were completed in 1957. The NAA design featured a 7×7-foot, Mach 0.2–3.5 facility with a 10,000-horsepower drive: Boeing's was a 4×4-foot, Mach 1.2–4.2 supersonic tunnel. The favorable characteristics of the intermittent design were fully realized at a fraction of the cost of the conventional tunnels. To obtain sixty seconds of test time per hour, the intermittent tunnels required as little as 5 percent of the power needed by the continuous facilities, and the cost of the intermittent tunnels was down to about 15 percent of that of the conventional ones. As shown in figure 6, the Reynolds number matched or exceeded that available with the continuous installations over the whole Mach number range.

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can properly cover the entire range of aircraft and missile flight." See Baals and Corliss (n. 50 above), p. 66. The Canadian proposal was discussed in New York with W. G. A. Perring, director, and other members of the RAE delegation during their visit to the United States in October 1950; they showed no interest in the intermittent design.

[52]The literature of the period reflects a lack of familiarity with the intermittent technique, a situation that persisted even after large intermittent tunnels became operational in 1957. H. W. Liepmann and A. E. Puckett, authors of one of the first American texts on compressible flow (*Introduction to Aerodynamics of a Compressible Fluid* [New York, 1947]), wrote in 1947 that, "aside from the short operating time," the chief disadvantage of a blowdown wind tunnel operating from pressurized air storage to the atmosphere "is the impossibility of controlling the density . . . [which] varies continuously." Evidently, the use of a pressure control valve was not considered. Neither the 1954 review of *Design and Operation of Intermittent Supersonic Wind Tunnels* by A. Ferri and S. M. Bogdonoff, AGARD, AGARDograph no. 1, Paris, nor the definitive 1961 Princeton (N.J.) monograph series on *High Speed Aerodynamics and Jet Propulsion*, 8, pt.2, *Wind Tunnel Techniques*, ed. F. E. Goddard, pp. 427–770, mentions the application of intermittent operation to large wind tunnels or the use of driven models.

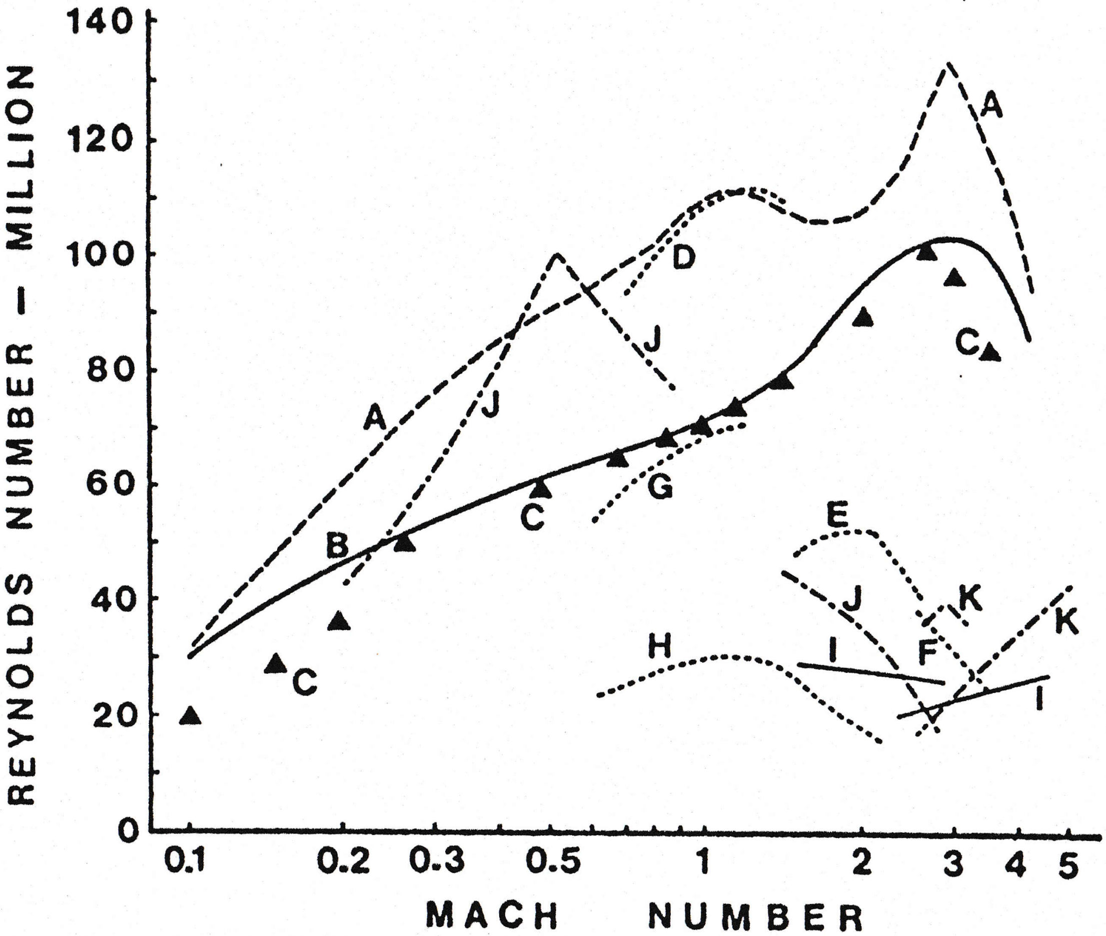

FIG. 6.—Maximum Reynolds number (based on the square root of test section cross-sectional area) of large intermittent and continuous wind tunnels. Wind tunnel owner, test section size (feet), drive power (horsepower), and year operational in parentheses; usable run time given for intermittent tunnels. Intermittent trisonic: NRC (5 × 5, 11,500, 1962) A—3 seconds, B—10 seconds; NAA (7 × 7, 10,000, 1957) C—10 seconds. Continuous: NASA-Ames: D(11 × 11), E(9 × 7), F(8 × 7), unitary (216,000, 1957); G(13.5 × 13.8, 110,000, 1956); H(6 × 6, 60,000, 1956); NASA-Langley: I, unitary (4 × 4, 100,000, 1956); RAE-Bedford: J(8 × 8, 80,000, 1957); K(3 × 4, 88,500, 1960). (See n. 42 and *Rockwell International Trisonic Wind Tunnel, User's Manual*, NA-78-258, Rockwell International, Los Angeles, rev. March 1983; AGARD, *The Need for Large Wind Tunnels in Europe*, AGARD-AR-60, Paris, 1972, p. 78; D. Brown, *Information for Users of the National Research Council's 5 × 5 Foot Blowdown Wind Tunnel at the National Aeronautical Establishment*, NAE-LTR-HA-6, Ottawa, September 1977; *Research Facilities Summary, V. II, Wind Tunnels*, NASA Ames Research Center, Moffett Field, California, December 1965; *Technical Facilities Catalog*, I. NHB 8800.5 A [I], NASA, Washington, D.C., October 1974 edition.)

Following the lead of North American and Boeing, other U.S. companies built large blowdown, intermittent wind tunnels: Chance Vought and General Dynamics/Convair in 1958, Douglas Aircraft and McDonnell Aircraft in 1959, and Lockheed-California in 1960.[53] By 1960, all of the major U.S. aeronautical firms were operating such

[53]*Wind Tunnel List*, Supersonic Tunnel Association, Nineteenth Semi-Annual Meeting, May 1963.

facilities. A 4×4-foot test section became a widely accepted standard, and tunnels of this type were later built in England (English Electric), The Netherlands (NRL), Sweden (FFA), India (NAL), Romania (INCREST), and Yugoslavia (VTI).

The NAA facility, proposed in 1952, was *completed* within five years. But in Canada, the 1950 proposal *awaited approval* for four years. In that period, major efforts were devoted to solving the crucial problems of driven model instrumentation and data-handling systems.[54] By 1953 the feasibility of the driven model technique had been firmly established through tests in the 10-inch and 30-inch tunnels. And it is unlikely that the novel tunnel design would ever have been approved without these tests.

In 1952, even as these activities progressed, another group at the NRC began considering a large, continuous high-speed tunnel. Predictably, their work showed the performance limitations and high costs of the conventional design. In 1953, I again proposed the intermittent solution; and in April 1954 a pressure-driven, 5×5-foot test section design (with air stored at 300 pounds per square inch) was approved by the NRC. Authorization to proceed with the preparation of design specifications came in November 1954.

A complete 1:12 scale pilot of the planned facility was built and started operating at the HSAL in November 1955. It provided invaluable information for the full-scale design, particularly on heat storage, valve controls, aerodynamic noise generated by the control valve, flow stabilization, diffuser configuration, transonic test-section design, and Mach number regulation.[55]

In April 1955, the government announced approval for construction of the 5-foot tunnel at an estimated cost of $3.5 million, and the design contract was awarded in June 1956 to Dilworth Ewbank, Consulting Engineers of Toronto. But the fragmentation of responsibility for aeronautical research and mounting difficulties with the Arrow program delayed the project.[56]

Funding was frozen in 1957.[57] Then, following protracted reviews, the project was reinstated in November 1958, largely through the efforts of J. L. Orr, at that time in charge of aeronautical research at DRB. Construction began in 1958, and the project was completed

[54] J. Lukasiewicz, "Some Problems of Design and Operation of Blowdown Wind Tunnels," *Journal of Applied Mathematics and Physics, ZAMP IXb*, no. 5/6, (Basel, March 17, 1958): 422–37; also n. 48 (1953 and 1955).

[55] Lukasiewicz (n. 54 above).

[56] J. Lukasiewicz, "Scientific R&D Activities of the Government of Canada: Diagnosis and Cure" (unpublished study, October 1963).

[57] "PC Economy Drive Delays Wind Tunnel," *Montreal Star*, January 25, 1958.

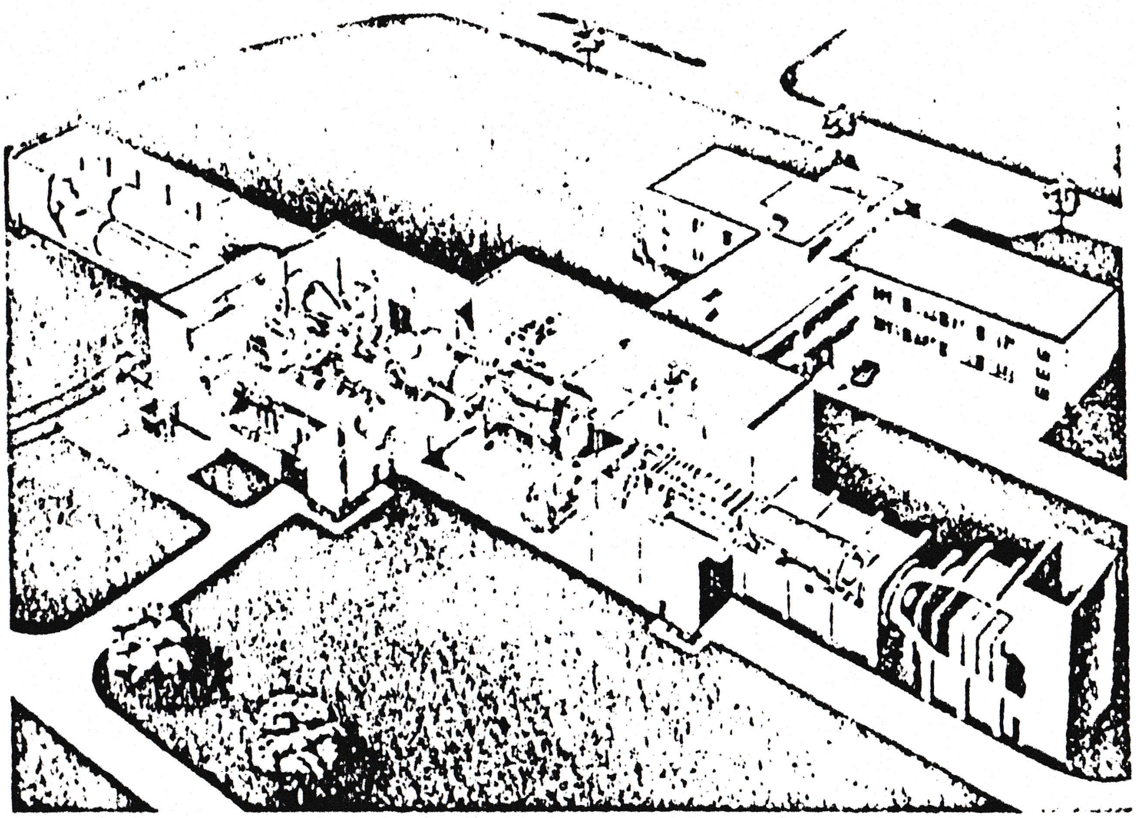

FIG. 7.—Trisonic 5×5-foot wind tunnel at Uplands near Ottawa. This cutaway view shows, from left: 50,000-cubic-foot, 300-pounds-per-square-inch compressed air storage; pressure control valve and 11,500-horsepower compressor plant; settling chamber, contraction, and flexible supersonic nozzle; transonic section, removed from the circuit; model support; variable and fixed diffusers, silencer, and exhaust stack. Control and instrument rooms, shops, and offices are seen in the upper right. (See n. 58: Rainbird and Tucker, fig. 1.)

under the direction of W. J. Rainbird. The tunnel first ran in August 1962 and became operational in early 1963.[58] (See fig. 7.)

The tunnel had taken twelve years to complete, much longer than similar facilities in the United States. At $9 million, the final cost of the project was more than double the original estimate. This drew the attention of the auditor general "because of the extent to which the project and its cost have expanded since the original authorization was given and also because, while some seven years elapsed since the work has commenced, the project is not yet complete."[59] In 1963, the Glassco

[58] W. J. Rainbird and N. B. Tucker, "The Five Foot Blowdown Wind Tunnel at the National Aeronautical Establishment," *Proceedings, Decennial* [illegible], Institute of Aerophysics, University of Toronto, 1959, pp. 194–213; K. F. Tupper, P. B. Dilworth, and L. A. Jenkins, *The N.A.E. Five Foot Supersonic Wind Tunnel*, Engineering Institute of Canada 1961 Annual General Meeting Paper no. 40, 1961; L. H. Ohman, "The Role of the NAE 5×5-Foot Wind Tunnel in the Development of Modern Airfoil Sections," *Canadian Aeronautics and Space Journal* 22, no. 1 (January-February 1976): 1–22.

[59] "How to Spend Money," *Time* (Canada ed.) 79, no. 7 (February 16, 1962): 9.

Royal Commission on Government Organization had this to say about the 5-foot wind tunnel project: "Although the 5-ft wind tunnel is the chief government aeronautical project in hand, it is usually considered independently of the current National Aeronautical Establishment programme . . . the project has suffered from lack of coordination; at the time of review the tunnel was still not in operation after ten years' work, although similar facilities have been established in the United States in three to four years and at less cost."[60]

The Canadian tunnel cost about twice as much as similar facilities built several years earlier by the U.S. aircraft industry. This reflected not only a much longer design and construction period, but also Canada's very limited in-house engineering resources and lack of experience in the design and fabrication of large, yet highly precise wind tunnel components. Government procurement procedures, which involved some twenty contractors, also contributed to cost escalation and delays.[61]

The final approval of the 5-foot wind tunnel in November 1958 coincided with the Arrow's cancellation. With the Velvet Glove missile program already scrapped in 1956, Canada had no projects able to benefit from its new, industrial-scale test facility. And yet, curiously, the government decided to complete the project, saying the facility would be needed for the development of missiles (which, recall, were naively expected to replace manned aircraft) and supersonic transports. These were clearly unrealistic objectives in the light of recent Canadian experience, but history was put forward as an argument in support of the wind tunnel. Even if Canada used aircraft and missiles from other countries, there would always be the need to modify them, and this required wind tunnel facilities—or so the argument went. Not completing the wind tunnel was also seen as preventing Canada from developing high-speed aerospace projects in the future—not that the government had any such plans. After its completion, the 5-foot tunnel, cashing in on its performance, was used largely by U.S., Swedish, and French clients, including NASA, NAA, Boeing, Convair, Lockheed, McDonnell Douglas, ONERA, SAAB-SCANIA, and FFA.[62]

While supporting research at the Institute of Aerophysics in Toronto, the DRB was also promoting supersonic aerodynamics at its CARDE laboratories. An experimental technique in which freely flying models are launched from special guns, known as aeroballistics, was

[60] *Glassco Report* (n. 6 above), p. 278.

[61] See Rainbird and Tucker (n. 58 above). According to the NAA data, the cost of trisonic, pressure-storage type tunnels ranged from $2 to $4.5 million (U.S.) for test sections from 4 × 4 foot to 7 × 7 foot, respectively; see Daniels (n. 49 above).

[62] *National Aeronautical Establishment*, National Research Council, Ottawa, 1980.

used. G. V. Bull, who had come to CARDE in 1951 after developing supersonic tunnels at UTIA, directed the work, and indeed directed the bulk of aeroballistics activities in Canada for over twenty-five years. Under his leadership, aeroballistic ranges were developed and expanded at CARDE; munitions, aircraft, and Velvet Glove models were tested; and novel, efficient test techniques were devised.[63] After the Canadian missile and supersonic fighter projects were canceled, CARDE embarked on a joint program (with the U.S. Department of Defense Advanced Research Projects Agency) of reentry physics studies in support of ballistic missile development. Several new hypersonic ranges were developed and operated at a cost of about $2.5 million per year. Their work was terminated in 1970, and since then CARDE (renamed the Defence Research Establishment Valcartier or DREV) has been occupied with more conventional ballistics problems. For this purpose, one of the ranges was used as a vacuum reservoir to drive a 2 × 2-foot transonic-supersonic wind tunnel.[64]

In the 1960s Canada became active in original large-scale developments in aeroballistics. They were likewise the brainchild of G. V. Bull, who left CARDE in 1961 for McGill University in Montreal. There, as head of the Space Research Institute, he directed the High Altitude Research Project (HARP), a joint venture with the U.S. Army Ballistic Research Laboratories (BRL) in Aberdeen, Maryland. The project dealt with the application of guns to launching high-altitude probes for study of the upper atmosphere; it was funded by the U.S. Army, McGill University, and, after 1964, the Canadian Department of Defence Production. Bull was responsible for development of 16-inch caliber launchers. In 1962, a range facility was established on Barbados using 16-inch, smooth-bored, U.S. Navy surplus guns (fig. 8). Later, additional range facilities were developed at the U.S. Army's Yuma Proving Ground in Arizona, and at a range straddling the Canadian–U.S. border between Highwater, Quebec, and North Troy, Vermont. Smaller launchers (5- and 7-inch calibers) were operated by BRL on the

[63]G. V. Bull, "Some Aerodynamic Studies in the C.A.R.D.E. Aeroballistics Range," *Canadian Aeronautical Journal* 2, no. 5 (May 1956): 154–63; G. V. Bull, *Aeronautical Studies in the Aeroballistics Range*, CARDE Report no. 302/57, July 1957; *1957 Jahrbuch der Wissenschaftlichen Gesellschaft für Luftfahrt*, p. 247; G. V. Bull and H. F. Waldron, "Summary of Aerodynamic Studies in the CARDE Aeroballistics Range," *Decennial Symposium*, Proceedings, pt. 3, Institute of Aerophysics, University of Toronto, October 14–16, 1959, pp. 288–319.

[64]P. Solnoky, "An Economic Analysis of the Operation of the Aerodynamic and Laser Test Facilities of the Defence Research Board of Canada," and "Problèmes généraux relatifs aux moyens d' essais aérodynamiques," *Proceedings, 8ᵉ séminaire du groupe sur la défense de l'OTAN*, Institut Franco-Allemande de St. Louis, May 4–7, 1971 (St. Louis, France, 1971), pp. 119–65.

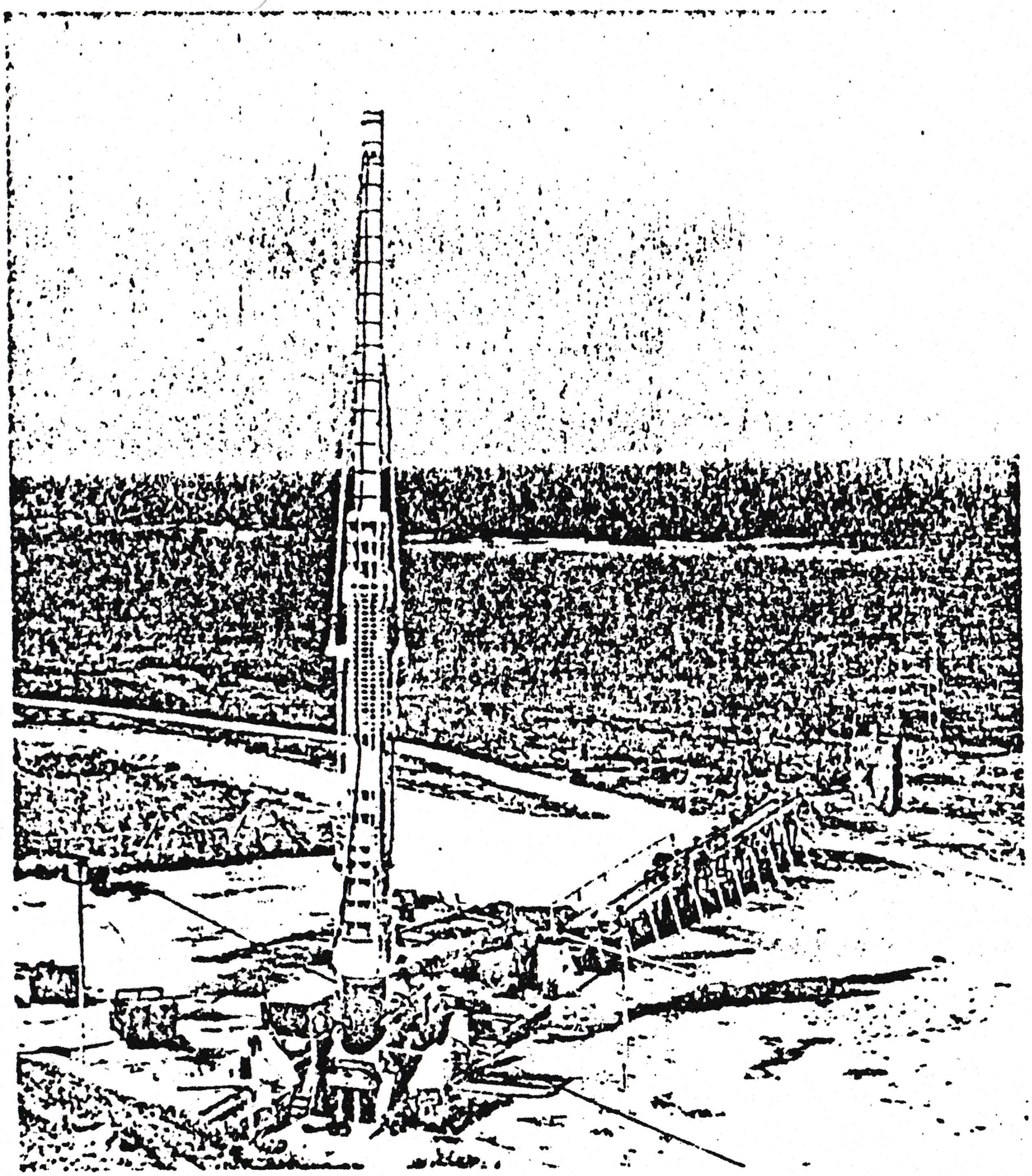

FIG. 8.—HARP launcher in elevated firing position on Barbados, B.W.I. The system consisted of two 16-inch U.S. Navy surplus guns smooth-bored to 16.4-inch diameter and joined to form a 119-foot 5-inch long, 200-ton barrel, the largest gun in the world. A powder charge up to 980 pounds has been used. A muzzle velocity of 7,100 feet per second (maximum acceleration at launch of 15,000 g) was attained with a 400-pound shot weight, a 185-pound payload reaching an altitude of 595,000 feet (181 km). (Courtesy of Space Research Institute, Montreal.)

East Coast. Altitudes of up to 181 km were reached with the 16-inch gun system and up to 75 km with the 5-inch gun. Profiles of electron density and wind were measured in the upper atmosphere. In Highwater, a 16-inch horizontal launcher was used for aerodynamic studies of ballistic missile nose cones. With a shot weight of 270 pounds, 100-pound cone models could be launched at velocities as high as 8,700 feet per second, that is, at a Mach number of about 8—a remarkable result when compared to the standard 2,800 feet per second performance of 16-inch guns.[65]

Later, rocket-assisted payloads were developed to augment the performance of the guns, and the feasibility of gun-launched satellites was studied. It was estimated that a 60-pound payload could be placed in orbit using a three-stage, rocket-assisted, 2,000-pound vehicle in a 16-inch gun.[66] A 32-inch caliber launcher was also considered (fig. 9). But the HARP project was terminated in 1967 after Canada withdrew

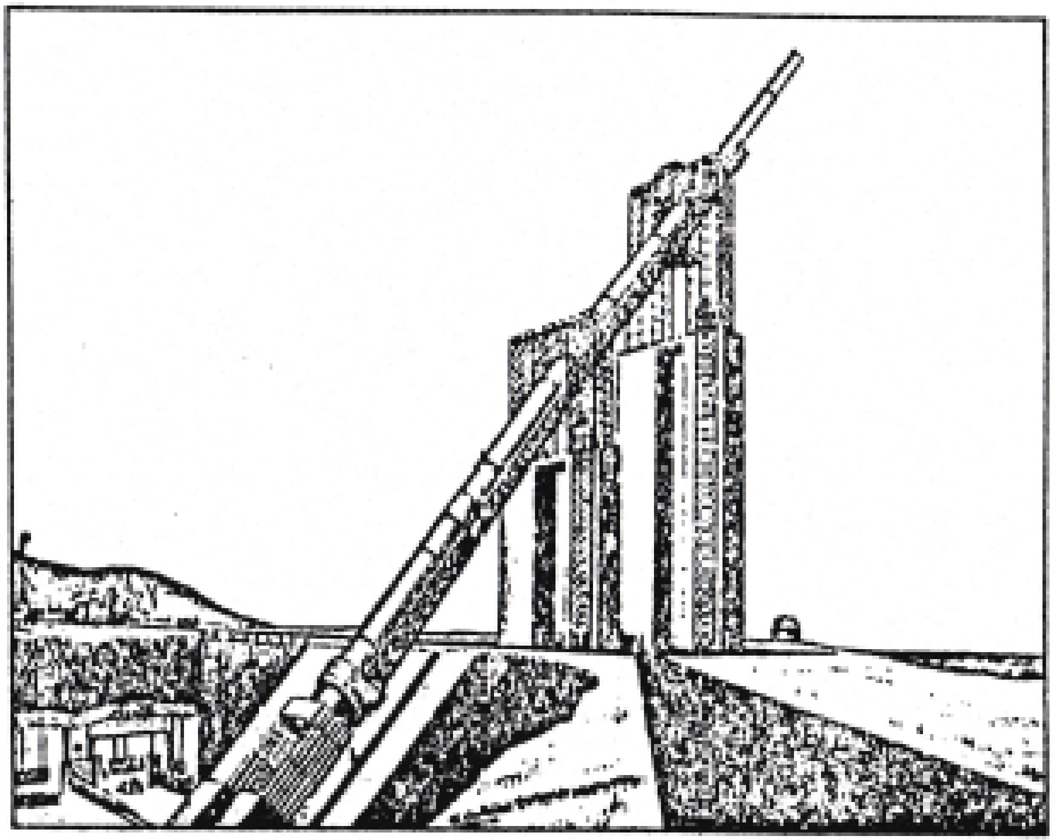

FIG. 9.—According to the estimates made by the HARP project team, a 1,000-pound payload could be placed in the earth's orbit using a three-stage rocket vehicle launched from a 32-inch gun, sketched above. This proposal represented modern embodiment of the technique described by Jules Verne in his 1865 novel *De La Terre à la lune*. (See n. 66, fig. 17.)

[65] G. V. Bull, "Development of Gun-Launched Vertical Probes for Upper Atmosphere Studies," *Canadian Aeronautics and Space Journal* 10, no. 8 (October 1964): 236–47; C. H. Murphy and G. V. Bull, "Review of the High Altitude Research Program (HARP)," *The Fluid Dynamic Aspects of Ballistics*, AGARD Conference Proceedings no. 10, North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development, September 1966, pp. 403–37.

[66] G. V. Bull, D. Lyster, and G. V. Parkinson, *Orbital and High Altitude Probing Potential of Gun Launched Rockets*, SRI-H-R-13, Space Research Institute, McGill University, Montreal, October 1966.

its support. A total of about $9.5 million was spent on HARP; Canada's share amounted to $4.3 million.[67]

Bull continued ballistic research at Space Research Corporation, a company he established at the Highwater–North Troy range, with offices in Montreal and additional test facilities on Barbados and Antigua. The SRC was successful in developing long-range artillery shells and guns, but in 1980 the company went bankrupt.[68]

The truly original technique of high-altitude launches from large-caliber guns offered certain advantages over conventional rocket launchings, notably the relatively low cost and high accuracy and reliability. But the idea came too late to gain general acceptance; by the time it was developed, a large variety of rocket vehicles was commercially available and governments had invested heavily in rocket range facilities. Moreover, rocket launchings did not subject payloads to the very high acceleration loads present in gun launchings (50,000 g's in 5-inch guns and 15,000 g's in 16-inch guns).

HARP's studies of the upper atmosphere duplicated a much larger Canadian–U.S. program which used rocket-propelled probes.[69] This program was run between 1954 and 1978 from the Fort Churchill rocket range in Manitoba. Over the years, it involved several Canadian and U.S. organizations (NRC, CARDE, the Defence Research Telecommunications Establishment, NASA, the Canadian and U.S. Armies, the U.S. Air Force and Navy, among others). In Canada these activities led to the development of the Black Brant series of rockets. Highly successful, they were sold and used throughout the world.

The Anatomy of Failure

The decision to undertake the Arrow program has not been questioned in Canada, but its abandonment has been widely condemned. According to conventional wisdom, Arrow was a weapon system well ahead of its time, and its cancellation robbed the country of the opportunity to establish an international presence in high-speed aeronautics.[70] The present analysis, the similar experiences in other countries, and the structuring of more recent aircraft projects do not

[67] M. Wojaechowski, "Harp Fiasco," *Science Forum* 3, no. 1/13 (1970): 12–16.

[68] The SRC saga ended in detention for G. V. Bull when the company was fined a total of $100,000 by Canadian and U.S. courts after pleading guilty of illegal exports of munitions to South Africa. See "Case of Dr. Bull Reaches Its Bitter End," *The Gazette*, Montreal, March 21, 1981.

[69] R. E. Barrington, "Canadian Space Activities in the Past Quarter Century," *Canadian Aeronautics and Space Journal* 25, no. 2 (1979): 153–69.

[70] See n. 9 above.

support this assessment and indicate that the Arrow was a classic example of how a country such as Canada should *not* approach development of sophisticated, advanced, and expensive technology.

Canada's venture into high-speed aeronautics was characterized by technical and managerial incompetence, inept organization, and bureaucratic inefficiency. But the failure of the enterprise resulted from a more fundamental cause: the unrealistic goal of achieving industrial and military sovereignty and self-sufficiency in military aviation. Throughout the 1950s, Canadian decision makers in the military, political, and bureaucratic domains allowed themselves to be swayed by visions of prestige and national pride. They failed adequately to assess and appreciate the resources, experience, and large markets necessary to pay for research and development costs. Erroneously, the country's record as a wartime manufacturer of aircraft was regarded as a significant foundation for original design work. Even private ventures such as Avro—a new company with imported talent and generous government funding—badly misjudged the extent of the task before them.

The costly experiment was rooted in a poorly conceived military strategy, which rejected a joint role for the RCAF and the U.S. Air Force in favor of a separate RCAF role in northern defense. The operational requirements that flowed from this imperative yielded specifications for an extremely complex weapon system (the Arrow), of a performance exceeding that of any aircraft then in production or under development.[71] (Similarly, off-the-shelf missiles and electronics were not acceptable.) The scale and complexity of the program forced adoption of major components from abroad. Indeed, even during the initial planning for the Arrow, the use of a U.S. armament system and American or British engines was envisaged, thus defeating one of the purposes of the program—to establish an independent Canadian presence. Ironically, efforts to rescue the Arrow through foreign sales "were blocked by the very logic that led Canada to build its own aircraft in the first place."[72] In the United Kingdom and the United States, as in Canada, depending on foreign sales for weapons was seen as a potential threat to national security, and exporting know-how and jobs in a vital defense industry was not acceptable.

As in the case of the Arrow, unrealistic premises were at the root of the Velvet Glove missile fiasco. The development of an original missile was considered necessary to ensure operational familiarity with a new

[71]As noted by J. C. Floyd, Avro's vice-president, engineering, responsible for the Arrow: "the CF-105 was, of necessity, a considerable advancement over contemporary aircraft, and there were few reports or tests . . . on which to base . . . design" (n. 18 above, p. 847).

[72]Dow (n. 9 above), p. 46.

weapon type.[73] But in light of the Canadian forces' experience with foreign weapons in both world wars, this was an obviously untenable proposition, and an expensive and uncertain method of acquiring missile know-how. Moreover, the desire to keep the project simple (given limited capabilities and resources) resulted in technical specifications that addressed the threat of the previous rather than the future war and thus sealed the fate of the Velvet Glove as an obsolete weapon even before it was developed.

Although managerial and technical incompetence were not the chief causes of these various failures, they were nevertheless much in evidence. Neither the RCAF nor Avro had any experience in the procurement and engineering management of complex weapon systems such as the Arrow; both underestimated the impact of specification and equipment changes.[74] As a rule, designing an aircraft on the basis of an engine still under development is avoided; and yet this course was followed by Avro. On two occasions (C-102 and CF-105), designs had to be changed drastically when the selected turbojets were unavailable. Frequent changes in the engine and the armament system intended for the CF-105 forced expansion of the project well beyond its planned scope and contributed to an intolerable escalation of costs. The aerodynamic design of the C-102 was obsolete, and the plane suffered from many potentially hazardous deficiencies (the Air Transport Board concluded that years of work would be needed before a production aircraft could be certified).[75] Project Y (the "flying saucer") demonstrated an unhealthy tendency toward unorthodoxy for its own sake accompanied by publicity that verged on science fiction. The available resources and expertise were not adequate to carry on missile development.

Only in the field of jet engines did Avro achieve outstanding success. Avro's Orenda, a state-of-the-art engine in the Rolls-Royce Avon class, was produced in large numbers and exported successfully. The Iroquois, a large supersonic turbojet, featured the application of advanced materials (more titanium was used in its construction than in

[73] Goodspeed (n. 31 above).

[74] Only a year before the cancellation an RCAF office was set up to coordinate the Arrow program. As noted later by the head of the new office, "... costing was done by somebody, equipment was purchased someplace else, contracts were let all separately ... within the Air Force in the early days [project management] was all parcelled out in different directorates and with different people doing different things" (quoted by Dow [n. 9 above], pp. 110–11).

[75] Dow (n. 9 above), p. 49.

any other engine at the time) and developed a higher thrust and had a larger thrust-to-weight ratio than competing designs.[76]

The government's abandonment of all Avro programs and its decision to destroy all evidence demonstrated clearly that (rhetoric notwithstanding) neither the politicians nor the military understood the process of innovation and industrial strategy. Missile technology, then in its early years, had been heralded naively as a substitute for manned aircraft. The largest R&D investment ever made by the government was wiped out overnight with no attempt to salvage any part of it. And the Avro enterprise was viewed, not in the context of a broad industrial strategy, but in the narrowest of political, military, and budgetary terms.

Canada's experience in high-speed aeronautics was not unique; other countries which embarked on similar policies after 1945 were equally unsuccessful. Argentina, for example, tried to develop a modern independent aircraft industry with the help of a German team headed by Dr. Kurt Tank, former technical director of the Focke-Wulf concern. As if anticipating events in Canada, Tank's jet plane designs were named *Palqui*—meaning Arrow. But the project was abandoned in 1956, and the plant was converted to automobile manufacture. Tank moved to India that same year to develop the HF 24 Marut, a subsonic fighter powered by British engines produced under license. After some 140 HF 24s were built, the development of indigenous jet aircraft in India was also discontinued. In 1962, Egypt attempted to enter the field through the licensing of jet designs developed in Spain by Willy Messerschmitt. These projects were canceled in 1969, even before the first flight of a delta-wing fighter with an Egyptian engine. Clearly, notions of sovereignty and national pride can provide a powerful motivation toward the achievement of extraordinarily difficult technical tasks, as in the case of the U.S. "Man on the Moon" Apollo project. But such motivation alone cannot ensure success; it must be matched by adequate resources and markets.[77]

[76] Avery (n. 16 above). In 1957 the French became interested in the Iroquois for their Dassault-Mirage IV fighter but in view of the uncertain future of the Arrow program did not order the engine.

[77] Notwithstanding its past failures, Argentina is reported to be planning again (in the wake of its 1982 defeat in the Falklands) the development of combat jet aircraft ("Aircraft Builder Moves Towards Combat Sales," *Aviation Week & Space Technology* 119, no. 4 [July 25, 1983]: 35–36). Egypt, on the other hand, is going into limited production of U.S. and West European designs ("Egypt Seeks Technology Transfer," *Aviation Week & Space Technology* 119, no. 7 [August 15, 1983]: 129–39). Even some of the world's most highly industrialized and economically powerful countries have reached the limits of resources

Among the lesser powers which embarked on independent high-peed aircraft development after the war, Sweden represented a no-able exception. Its neutralist policy was successfully backed up by a eliance on war matériel developed and produced domestically, in-luding advanced aircraft and missiles. Furthermore, extensive re-earch and test facilities were provided to assist the industry. The key to weden's success was the depth of its technological culture and the xistence of a strong industry-government-university partnership sup-orted by a decisive and consistent policy.[78] Nevertheless, Sweden's eliance on foreign equipment is increasing. Its latest combat plane, the AS-39 Grippen, will be equipped with American engines and missiles.

In 1958, Canada's independent air defense policy was superseded by NORAD, the joint United States–Canada continental air defense orga-ization. Only then was the fallacy of the rationale behind the Arrow and other military projects clearly exposed. Under NORAD, the inclu-ion of special "Canadian requirements" in military aircraft specifica-ions was no longer relevant or necessary. Neither was a Canadian nsistence on an independent domestic supply of aircraft; the RCAF's quipment needs became part of the integrated requirements of NORAD and NATO. If there is a lesson to be learned from the perspective of the past twenty-five years, it is that the goals of military and industrial sovereignty are no longer attainable in the increasingly nterdependent and integrated world of industrialized countries. Although "nations continue to act as though they were sole masters of their fate," sophisticated technologies require a larger base than most states can provide.[79] Increasingly, international military alliances such as NATO and various transnational industrial operations provide the answer. They offer both the diversified industrial infrastructure needed for advanced and complex projects and the large market needed to pay very high research and development costs.

Particularly in aeronautics, international cooperation and coproduction have become the norm. Examples include the British-German-Italian Tornado combat aircraft, the Anglo-French Jaguar supersonic fighter trainer, the Franco-American CFM power plant, and Franco-German antiship and antitank missiles. In civil aviation, there is the highly successful Airbus wide-body jet, produced by a consortium of

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and markets. Witness Soviet, British, and French efforts to develop supersonic transports. The Soviet Tu-144 never entered regular service, while the Anglo-French Concorde proved a technical success but an economic disaster; only 16 production models were built, and by 1983 three Air France aircraft were being cannibalized for spare parts.

[78]See Lundberg (n. 41 above).

[79]The quote is from E. B. Skolnikoff, "Technology and the Future Growth of International Organizations," *Technology Review* 73, no. 8 (1971): 38–47.

French, British, German, and Spanish companies and relying heavily on American-made components. Among the latest examples are the U.S.–British–West German–Japanese–Italian International Aero Engines V2500 turbofan and the Future European Fighter Aircraft, scheduled to enter service in 1995 with the air forces of Britain, France, West Germany, Italy, and Spain.

The lesson for Canada, as for many countries, is plain: the key to effective participation in the aerospace enterprise is industrial collaboration on an international level.[80] And, ideally, such collaboration should involve Canadian firms over the whole cycle of research, development, manufacturing, and worldwide marketing for a component or range of products.

Such full-cycle world mandate responsibility has seldom been achieved. Since the Arrow, Canada has been limited largely to sporadic licensed production of U.S. equipment for the RCAF or to the fabrication of components for American aircraft companies. An exception has been the operation of Pratt & Whitney Canada Inc., which develops and manufactures small gas turbine engines for air, land, and marine application. This Canadian subsidiary has the support of its giant parent (United Technologies) and has sole responsibility for this particular class of power plants, for which it has captured a large share of the world market.[81]

Notwithstanding the lessons of the Avro venture and the subsequent development of international cooperation in the air industry, the Canadian government again embarked on an independent jet aircraft project in 1976. This time, the company was Canadair Ltd. and the project was the Challenger, a wide-body executive jet.[82] Originally the

[80] Indeed, it is through international collaboration that Canadians first became involved in aeronautics as members of the Aerial Experiment Association established in 1907 by Alexander Graham Bell, who came from Scotland to Canada and moved to the United States in 1872. The association included two Canadians, F. W. Baldwin and J. A. D. McCurdy, and two Americans, T. E. Selfridge and G. H. Curtiss; they constructed several kites, gliders, and man-carrying power-driven biplanes and conducted test flights near Hammondsport, N.Y., and Baddeck, Nova Scotia. The activities of the AEA concluded with the development in 1908–9 of the Silver Dart biplane, in which McCurdy made the first powered flight in Canada (J. H. Parkin, "The Evolution of the Silver Dart," *Canadian Aeronautical Journal* 5, no. 2 [February 1959]: 39–46; see n. 22 above).

[81] See C. B. Wrong, "The Story of Pratt & Whitney Aircraft of Canada," *Canadian Aeronautics and Space Journal* 25, no. 2 (1979): 142–52.

[82] See *Aviation Week & Space Technology* 118, no. 20 (May 16, 1983): 63–69; 118, no. 25 (June 20, 1983): 24–25; 119, no. 13 (September 26, 1983): 121–22; also, *A Report by Senator Jack Austin on Canadair Ltd. to the Standing Committee on Public Accounts and to the Standing Committee on Finance, Trade and Economic Affairs*, Minister of State, Ottawa, June 7, 1983; and J. Lukasiewicz, "The Arrow: A Canadian Object Lesson in Failure," *The Globe and Mail* (Toronto), February 20, 1984, p. 7. Canadair Ltd. was purchased from General Dynamics Co. in 1976 for $46.6 million.

development of the Challenger was expected to cost $106 million, with a break-even point of 136 planes sold (to be reached early in 1982). But once again unrealistic specifications could not be met: the plane was much heavier, had a shorter range, and needed a longer runway than anticipated. Once again, an unproved engine was selected and another one substituted. And 1,200 major modifications had to be made. In 1983, the company posted a loss of $1.4 billion, the largest corporate loss (in current dollars) ever recorded in Canada,[83] and the estimated break-even point rose to 389 planes sold by 1992. As this familiar pattern emerged, it seemed that nothing had been learned from the Avro episode.[84]

Applied research activities suffered from the same lack of realism and competence that marked the Avro and Velvet Glove projects. Given the fragmentation of responsibilities among organizations (each jealously protecting its overlapping interests), it is not surprising that the magnitude of research and test support required by the aircraft industry was not appreciated and programs were not coordinated, either with industry or among the laboratories.[85] The cancellation of the Arrow was coincident with the final approval of the 5-foot trisonic wind tunnel, reflecting the confused R&D scene in the 1950s. The development of experimental facilities was conducted independently by the NRC's High Speed Aerodynamics Laboratory, the DRB's

[83]$370 million in 1958 dollars, i.e., an amount about equal to the cost of the Arrow project.

[84]Similar difficulties were experienced by de Havilland Aircraft of Canada Ltd., the other aircraft company owned by the Canadian government (since 1974). Because of high development costs and few sales of its commuter-type aircraft, between 1982 and 1984 de Havilland required an infusion of $500 million in government funds; a further $1 billion was estimated necessary to keep the company operating through 1988 (see James Rusk, "De Havilland Woes May Cost $1 Billion," *The Globe and Mail* (Toronto), April 10, 1984, pp. 1–2. Rather than continue massive subsidization, the Canadian government decided in December 1985 to sell de Havilland to Boeing Co. of Seattle, Washington, one of the world's largest aerospace manufacturers. This may result in an operation similar to that of Pratt & Whitney Canada Inc., mentioned above, with de Havilland carrying for Boeing a global mandate for the development and construction of commuter-type aircraft.

[85]These problems were tackled more effectively in the United States as a result of such studies as the above-mentioned 1945 von Kármán report for the AAF (n. 4 above) and NACA's National Aeronautical Research Policy proposal of 1946, endorsed by all the agencies concerned (*Government and Aircraft Industry Concur on National Aeronautical Research Policy*, NACA Press Release, April 1, 1946; see also, *NACA 33rd Annual Report 1947*; Hartman [n. 50 above], p. 120). Years later, when the Soviet *Sputnik* spurred an expansion of aerospace R&D, a new institutional framework was established through the creation, on October 1, 1958, of the National Aeronautics and Space Administration, which took over from the forty-three-year-old NACA and carried a much broader mandate.

CARDE organization, and the DRB-supported University of Toronto Institute of Aerophysics. Jurisdictional disputes delayed the completion of major test facilities, as in the case of the 5-foot wind tunnel. Upper-atmosphere study projects were duplicated through the simultaneous development of two different techniques.

The deficient management of applied research did not altogether prevent worthwhile developments from occurring; rather, their potential was not recognized and they were not exploited commercially. In the case of the novel wind tunnel design, the comparison of Canada's handling of the need for adequate aerodynamic test facilities to the U.S. experience makes this very clear. In the United States an industrial organization such as North American Aviation, Inc., was able to come up with a novel solution (technically and economically appropriate) and have corporate management "buy" the untried concept, build and operate a pilot model, and design, fabricate, and erect the facility—all within five years. Confidence in technical judgment at all levels, the constraints of a limited budget, and pressing need for aerodynamic data were responsible for the remarkable performance. In Canada, the opposite situation prevailed: hesitation and bureaucratic inefficiency led to delays and excessive costs. Furthermore, no attempt was made to exploit innovation: public funds were used to develop technology but nothing was done to protect it through patents and to take it to the marketplace. Innovations in aeroballistics were similarly neglected. Canadian government agencies failed to exploit the expertise acquired through CARDE and SRI/HARP activities and later used by Space Research Corporation. More vigorous government support for innovation in the design of guns and shells could have led to the establishment of a commercially viable industry, with good export potential (SRC sales in 1979 came close to $40 million).

Canada's experience shows that the probability of "spin-off" is small when applied research is not linked to viable industrial activity, particularly if the work is confined to government establishments. Although Canada's novel wind tunnel design was not commercially exploited by the government, private engineering consultants have ensured that the design experience acquired in Canada through the 5-foot tunnel project will not be completely lost. Indeed, it is being preserved and expanded and has led to the participation of Canadian consultants and industry in many foreign wind tunnel projects. Dilworth, Secord, Meagher and Associates (DSMA) of Toronto has been responsible for blowdown tunnels of the NAE 5-foot type constructed in India, Romania, and Yugoslavia; for vacuum-operated transonic-supersonic tunnels at DREV, Valcartier, Quebec, and at Fuji Heavy Industries in Japan; and for several wind tunnel design studies for NATO and others. DSMA holds a license for the application of cryogenic techniques to blowdown intermittent tunnels. The firm has also designed low-speed wind tunnels in Ottawa (NAE 30 foot) and automotive wind tunnels in Canada (Imperial Oil), Sweden (Volvo), Germany (Ford), the United States (Chrysler, Amoco, Exxon), and England (British Leyland). In a highly competitive environment, DSMA has gained an international reputation as a designer of modern aerodynamic test facilities.

In addition to its relevance to Canadian aeronautics, the history of the development of large intermittent wind tunnels recorded here is more generally significant as an example of the obstacles which often get in the way of innovation. It illustrates how institutionalized engineering conservatism can make it difficult for experienced practitioners to adopt, or even merely consider, nontraditional approaches. In this case, decades of experience limited to continuous wind tunnel testing prevented the largest and most reputable aeronautical research organizations—the NACA in the United States and the RAE in Great Britain—from considering a short-duration technique. It was left to uninhibited newcomers, lacking the resources available to their peers, to come up with novel solutions offering superior economy and performance.[86]

The history of continuous versus intermittent wind tunnels was reenacted to an extent in the 1970s, when efforts were made to develop techniques for attaining the high Reynolds numbers required to simulate large aircraft and rocket aerodynamics at transonic speeds.[87] Again, the bias toward continuous flow operation may have been a factor in the rejection of the Ludwieg-tube and other short-run systems and the selection of continuous, cryogenic wind tunnel design for the new National Transonic Facility (NTF) completed in 1983 at the NASA Langley Research Center.[88] Again, those faced with limited

[86]Examples of engineering conservatism in the development of hypersonic wind tunnels are noted by Lukasiewicz (n. 47 above).

[87]See, e.g., J. Lukasiewicz, "The Need for Developing a High Reynolds Number Transonic Wind Tunnel in the U.S.," *Astronautics & Aeronautics* 9, no. 4 (1971): 64–70.

[88]In cryogenic wind tunnels stagnation temperatures down to about 100 degrees K (−280 degrees F) are obtained through evaporation of liquid nitrogen. Operation at such temperatures allows attainment of much higher Reynolds numbers with smaller drive power than at normal temperatures. For example, at a pressure corresponding to a ten-second run in the NRC 5-foot trisonic wind tunnel, a four-times-larger Reynolds number (per unit length) is obtained in the NTF, at a stagnation temperature of 110 degrees K. For a history of the cryogenic wind tunnel development, see E. C. Polhamus, "The Large Second Generation of Cryogenic Tunnels," *Astronautics & Aeronautics* 19, no. 10 (1981): 38–51.

resources and those experienced in short-duration testing opted fo intermittent-type facilities.[89]

The paradox of major organizations, active at the leading edge of technology progress and yet technologically conservative, has been noted before. It seems clear that resistance to change is as much a trait of human nature as are inventiveness and creativity.[90]

[89]The Douglas Aircraft Co. in the United States and ONERA/CERT in France; see Polhamus (n. 88 above).

[90]See, e.g., E. E. Morison, *Men, Machines, and Modern Times* (Cambridge, Mass., 1966); and J. Lukasiewicz, "The Institutionalization of Obsolescence," in *The Railway Game* (Toronto, 1976), pp. 240–45.