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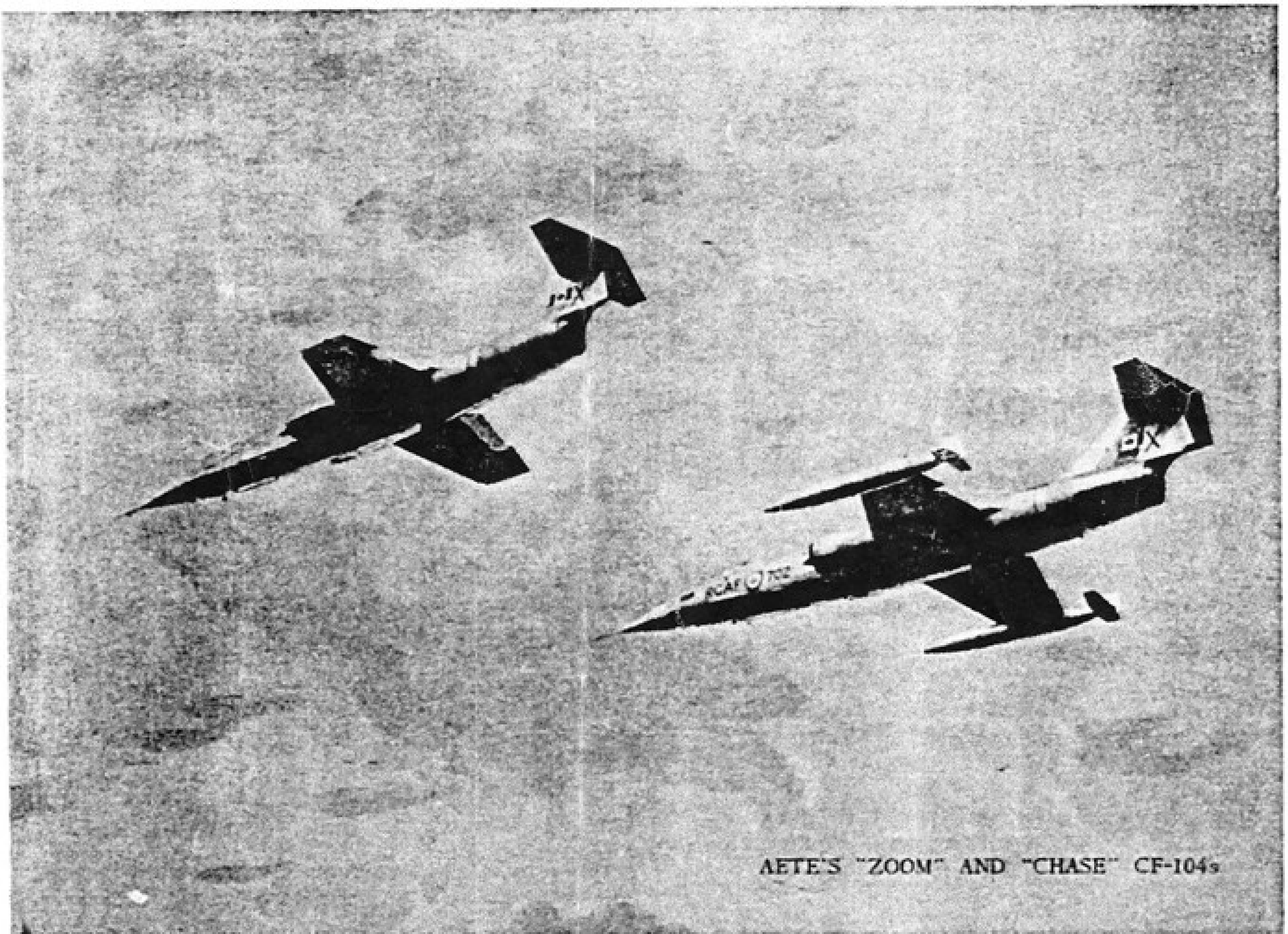


AETE'S "ZOOM" AND "CHASE" CF-104s

Volume 14 Number One 1968

GETTING UP IN THE WORLD

by Lt Col R.A. White C.D.

Setting an altitude record is not just a matter of climbing into a souped-up aircraft and rocketing straight up until everything quits and aircraft and pilot start fluttering earthward again.

Internationally acceptable measurement standards require the use of special radar; the aircraft itself presents special control problems at high altitudes and low dynamic pressures; and careful planning, co-operation and equipping were necessary over a prolonged period of time by a large number of people. To avoid falling into the dangerous flat spin, the aircraft had to be flown on a constant angle of attack and an instrument sensitive enough to measure this angle had to be especially devised. Despite falling short of the altitude objective, however, the project is considered a success.

Our 42nd flight and it was clear we had failed! Each of us struggled with a gnawing sense of frustration and disappointment. We had tried so hard and come so far together, that failure seemed so unfair! These were the inner thoughts of all of us last December at the termination of Canada's assault on the World's Absolute Altitude Record.

Yet in retrospect, the "Centennial Project" was a wonderful attempt; one which all Canadians can view with pride. Much of Canada's research and development aerospace talent had joined hands in a programme that encompassed some six months of study and planning, two months of modifications, and 2½ months of flying. In all we flew 42 flights, "zoomed" on 25 of them, and ultimately reached 100,110 feet to set a Canadian National Altitude record as our consolation prize.

The full story of the "Centennial Project" has yet to be committed to print. In fact, the Project Report is still in the draft stage! However, the article in the March issue of the Sentinel attempted to provide a description of the project in quasi-layman's terms, and this more technical discussion will presume a knowledge of that earlier article. In this way, I can describe at some depth three interesting aspects of the Centennial Project without being forced to cover the entire programme. Accordingly, this article will provide only the briefest of backgrounds, and will concentrate on (1) the method of measuring flight path, (2) the problem of the "flat spin", and (3) our method of flying on Angle of Attack (Alpha).

MEASURING FLIGHT PATH

In order to beat the Russians and capture the World's Absolute Altitude Record for Canada in Centennial Year, we had to get above 117,000 ft and prove we had been there. Assuming we could get there, how could we prove it? The rules of the Federation Aeronautique Internationale (FAI) required that our system of measurement have a total system accuracy of at least 1 per cent with a confidence of at least 99.74 per cent (3σ), and that our data substantiate this accuracy. Two options were open to us. We could measure pressure or otherwise relate our aircraft to the atmosphere, or we could measure our "tape-line" height above ground and Mean Sea Level.

To utilize the first option, we worked for months to find an accurate method of measuring static pressure. Actually, we came closest by employing a Metraphysics Inc. instrument that measured the variation in electrical conductivity of air and related it to ICAN pressure. In addition, we had a National Aeronautical Association (USA) Barograph, and a NRC/National Aeronautical Establishment Barograph/Oscillograph, as well as our aircraft pressure instruments which we photo-recorded. But while we could keep our instrument error down, we never could come to grips with our total system error. Lag was a problem, but the greatest unknown was "position error"! We finally went over the top at an Indicated Airspeed of 77 Kts. (At 100,110 ft that is 583 Kts true airspeed, Mach 0.995, and +1/20 "G"). How could we extrapolate "Tower fly-by" and low level "pacer" calibrations to these apogee conditions? Well, we might have done it in time, but I doubt it. In any event we were saved by the Defence Research Telecommunication Establishment (DRTE) at Shirley's Bay, Ottawa.

Both the Russians and Americans had utilized the second option and authenticated by "tape-line" using Phototheodolite measuring systems. However, we had predicated the Centennial Project on utilizing the cores of high energy jet streams, and so were constrained geographically to the St. Lawrence Valley area where our meterological studies showed the highest incidence of good jet streams during September through December. Accordingly, much of our flying would be "on top" of cloud, and we could not consider visual "tape-line" measuring systems. And it soon became apparent that the radar measuring systems at our disposal did not have the required total system accuracy.

It was at this point that our previous work with DRTE's Satellite Tracking System paid off, and we were able to use their capabilities in a novel way. We installed their power supply and 4GHz* beacon in our "zoom" CF-104's electronic bay, ran coaxial cables through the cockpit into the radome nose compartment, and set up a switching arrangement with three antennae in the nose. The signal from the aircraft's 4GHz beacon system was acquired manually and tracked automatically in azimuth and elevation by the 30 ft precision tracking antenna system at DRTE Shirley's Bay.

* 4GHz = 4 million million cycles per second.

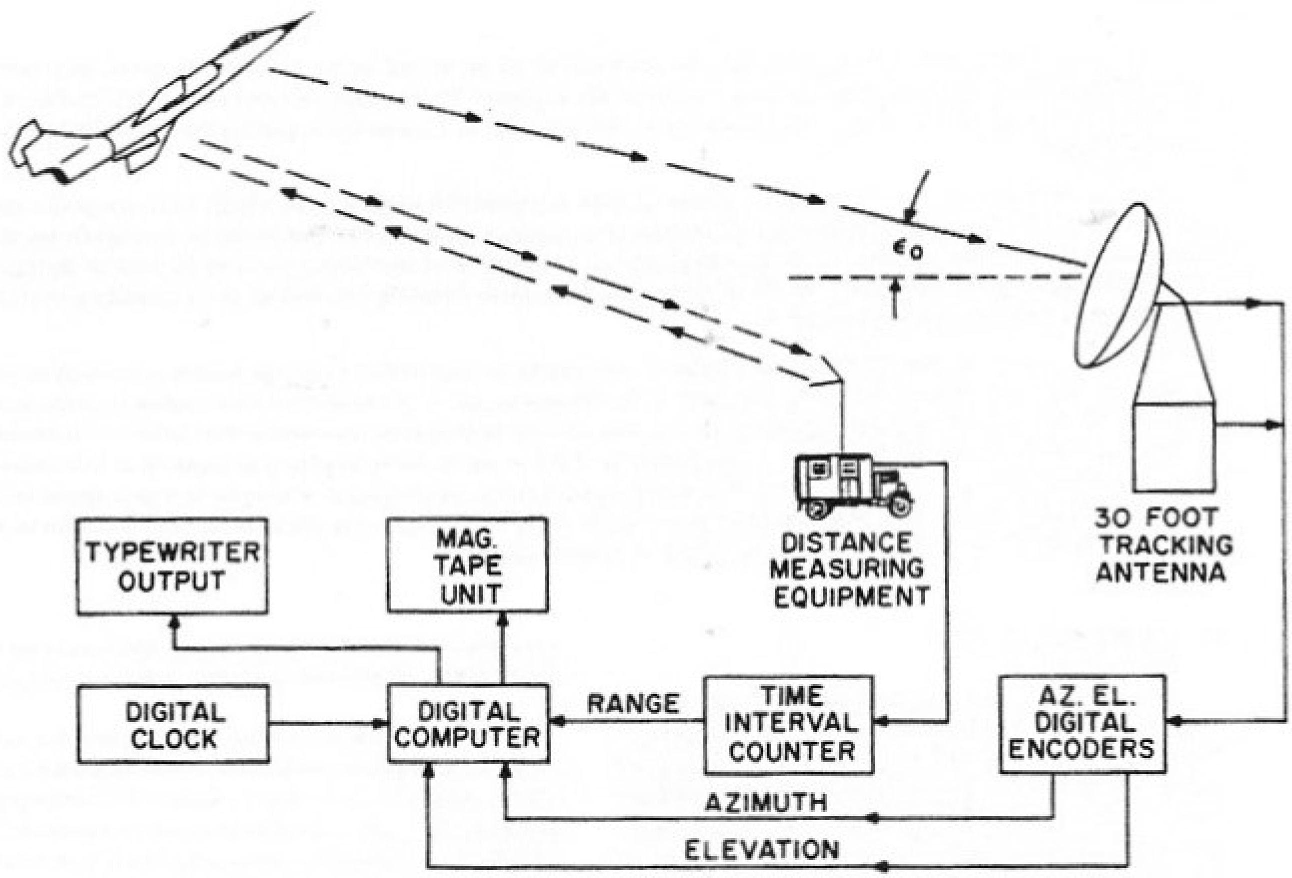


Figure 1 Altitude Measuring System

Range to the aircraft was measured by using a 1GHz pulse transmitter-receiver on the ground at Shirley's Bay and the standard IFF/SIF transponder mounted in the aircraft, and measuring the total time delay from the ground station to the aircraft and back. This use of IFF/SIF as range measuring equipment had been developed by the National Research Council and had been employed during AETE's Microwave Attenuation Studies using a CF-100 during 1966-67. Figure 1 illustrates the system.

The Zoom CF-104 was acquired by Shirley's Bay at about 47,000 ft, 100 nm to the West, during the final portion of the turn onto the Mach run heading. Mach number was held down to Mach 0.9 until the DRTE Tracking System locked in "autotrack", whereupon I would go full afterburner, dive through the low excess thrust speed range, level out at and accelerate at 35,000 ft. During this period, Shirley Bay's 30 ft antenna automatically tracked the aircraft's beacon which was radiating through the front antenna. Just before Mach 2.4, DRTE would "count-down" a switch to the side antenna, and, if the tracking system held autotrack, they would clear me to "zoom". Their system then continued to track the aircraft through the climb to apogee and during the descent.

During the period when DRTE's systems were tracking the aircraft, the tracking antenna's digital computer took data every tenth of a second of time from a digital clock; azimuth and elevation angle from the digital shaft angle encoders of the 30 ft tracking antenna; and return trip time delay from the distance measuring equipment. The four parameters were sampled in 175 microseconds, recorded on a digital magnetic tape recorder, and eventually processed on a digital computer. However, during the flight the computer conducted real-time computations every five seconds on a single data sample and provided an electric typewriter read-out of altitude.

As might be expected, the accuracy of the DRTE data depended as much on the rigor of their theoretical studies and error analysis as on the calibration of their equipment. It is a great credit to DRB that the FAI have accepted their record figure of 100,110 feet and their error analysis determination that the total system percentage error was +0.19 to -0.24 per cent. These percentage errors were calculated by considering the worst case peak errors, and are well inside the required 1 per cent. Moreover, the standard deviation of 50 measured apogee points about the second-degree least-squares fit curve was only 25 feet, and at 100,110 feet that's something!

The DRTE team under John Day and "Stew" McCormick, was a vital link in the Centennial Project. Their equipment and technical competency provided the proof required by the FAI and those of us on the project will long remember DRTE for their team spirit and hard work during the long hours of overtime.

THE FLAT SPIN PROBLEM

The CF-104, like many "Century Series" aircraft, pitches up at the stall.[2] During the flight test programme on the F-104, the USAF and Lockheed conducted a detailed investigation of "pitch-up", and then went on to research spins entered from pitch-up manoeuvres. While the gyroscopic effect of the engine's rotating mass coupled aircraft pitch and yaw motions to provide a wild ride, pitch-up and spin recovery was always possible using aircraft control deflections. From 1954 (when the XF-104 made its first flight) until 1961, not one aircraft was lost due to pitch-up or non-recovery from a spin, and it appeared that the flight test programme was adequate. On this basis, Capt Joe Jordan of the USAF tackled and captured the World's Altitude Record - secure in the knowledge that, even if he got into a pitch-up or spin, he could effect a safe recovery!

This happy state of affairs was shattered in late 1961 by the loss of a CF-104 from Canadair. The test pilot reported that on a 1'G' stall approach, the aircraft pitched up violently and eventually settled into a "flat-spin" from which he was unable to recover. Then in 1963 during a high altitude programme on the rocket-boosted NF-104A, two more "flat-spins" occurred. The unique feature of all of these spins was that, while they all resulted from excessive angle of attack, none of them displayed the characteristics of a "normal" spin. While a "normal" spin was characterized by sizeable oscillations in pitch, roll and yaw, the "flat spin" appeared to lack these oscillations about the aircraft axes. Moreover, the "flat spin" was unique in that the aircraft's attitude was almost level in both pitch and roll.

Shortly after the loss of a NF-104A, an F-104A was lost at Edwards AFB. A student at the Aerospace Research Pilots School was going over the top of his "Zoom" profile at 83,000 feet when he felt an inadvertent stick kick. By the time his nose had dropped below the horizon, he had yawed to the left through 135 degrees! Eventually the aircraft settled into a "flat spin" against which the application of recovery controls had no apparent effect. "The spin characteristics were a rotation rate of approximately one revolution every six seconds, nose approximately 10 degrees below the horizon, wings level or slightly right wing down, and no oscillations about any (aircraft) axis." After a number of unsuccessful recovery attempts, "at 4,000 feet the pilot ejected and the aircraft continued to spin to impact".[3]

The loss of these aircraft resulted in a comprehensive re-examination of the F-104's handling qualities at low dynamic pressure (q). The analog simulations and computer studies clearly revealed negative damping and dynamic lateral-directional instability at low "q", and demonstrated the importance of engine gyroscopic effects when aerodynamic restoring forces become low. In effect, these studies validated the existence of the "flat" spin, and confirmed the difficulty of effecting recovery. Zoom flights were shown to be especially susceptible, and it was clear that the Centennial Project could not follow Joe Jordan's 1959 approach.

FLYING ON ALPHA

Our basic answer to the flat spin was to keep from getting into one! To do this we needed an extremely sensitive method of measuring angle of attack (alpha), an instrument panel that would allow the entire zoom manoeuvre to be flown on instruments, and a power system that would not fail in the low pressures of 100,000 feet. With such a sensitive and reliable system, we felt that we could safely proceed in cautious steps right up to the limits of aircraft control.

The CF-104 has an Automatic Pitch Control (APC) system which measures angle of attack (alpha) and pitch rate, and warns the pilot when these parameters are marginal (Shaker) or critical (Kicker). Unfortunately, we were convinced that the standard wedge-shaped vanes would not be accurate nor responsive enough at the peak of our zooms. An appropriate Yaw-and-Pitch Sensor (YAPS) head was available, but it would have required a sturdier nose boom. This would have increased the thickness of the airflow boundary layer and reduced our power and Mach. Even worse, we would have had to modify our radome to the metal configuration to support a larger boom and YAPS head.

It was at this point that the National Aeronautical Establishment (NAE) joined the Centennial team! This establishment of the National Research Council was engaged in atmospheric turbulence studies using a T-33 with very sensitive yaw and pitch vanes. Although these vanes were constructed from balsa wood, NAE were able to extrapolate their vane aerodynamics to our supersonic requirements. In a few weeks they were able to design, manufacture and test vanes which formed the basis for our flight instrumentation. The

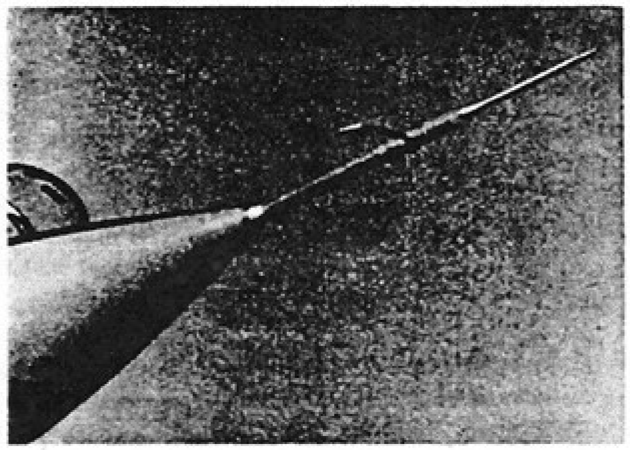


Figure 2 Alpha Vane on CF104 Nose Boom

NAE vanes successfully withstood the high dynamic pressure (q) and aerodynamic heating associated with flight at Mach 2.4, and yet produced accurate angle of attack and yaw read-outs in the low "q" regime at the top of the zoom profiles. These aerodynamically damped flow vanes were typical of the hardware and knowledge that were by-products of the Centennial Project! (Figure 2)

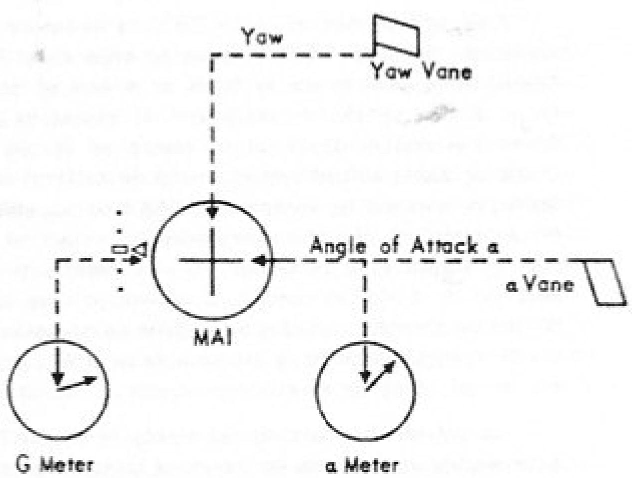


Figure 3 Information Display System

Since there was not enough space available in the zoom CF-104 nose boom to install synchro transducers to sense the vane angles, NAE's Flight Research Section workshops mounted miniature potentiometers in the vane stems. The potentiometer signal was filtered and processed by a solid state amplifier which fed the cockpit display. This display consisted of a raw "alpha" indicator and a Main Attitude Indicator (MAI Type 4060C). The vertical bar of the MAI was fed with side-slip angle from the yaw vane,[4] the horizontal bar with angle of attack from the alpha

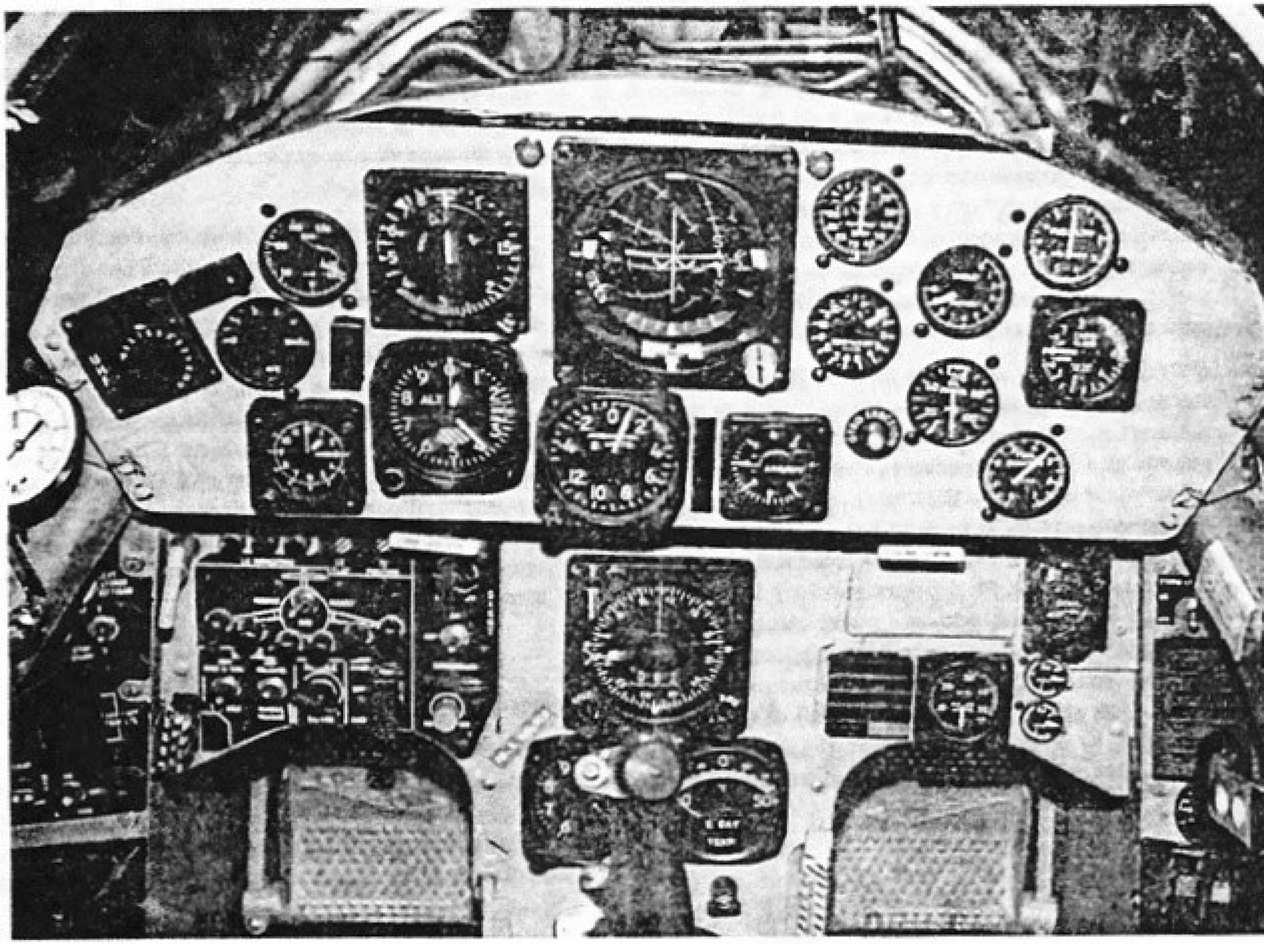
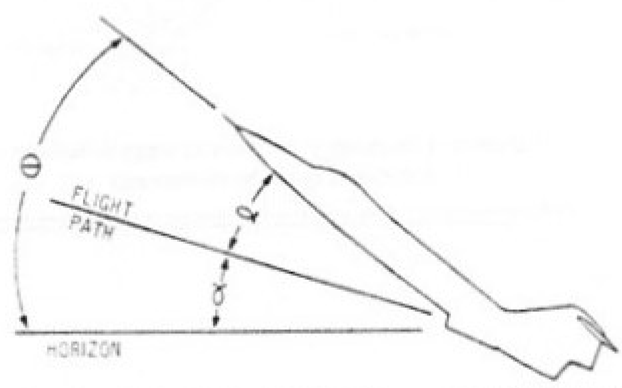


Figure 4 Cockpit Display Panel

vane, and the glide slope pointer with "G". Since our computer and analog simulations had established optimum pull-up at 2½ "G" and optimum "alpha" at 8 degrees during the zoom manoeuvre, we zeroed the "G" pointer and Alpha horizon bar at these values. For attitude, the MAI provided roll and pitch with the MD-1 gyro as the vertical reference, and a specially calibrated sensitive "Mechanical G" meter provided "G" on an expanded scale. (Figure 3 and 4)

During the acceleration run at 35,000 ft, I would try to get my MAI aligned and level and trim out any side-slip. Then, once I had switched to the side antenna and received a "Go" from Shirley's Bay, I would slowly "ramp" up to 39,000 ft while maintaining Mach 2.4. (This would get me through some 5 to 7 degrees of pitch change without loss of Mach.) At 39,000 ft I would pull 2½ "G" using the "G" pointer and the heading lines on the MAI globe. After rotating through 35 degrees pitch angle, I would follow a reducing "G" profile, until approximately 5 degrees short of the target pitch angle, when I would switch over to the Alpha bar. From then on all flying was done on "alpha" and all control movements were for attitude control alone. (Figure 5)



θ (PITCH ANGLE) = γ (FLIGHT PATH ANGLE) + α (ANGLE OF ATTACK)

Figure 5 Pitch Angle Components

During the course of the Project, a cautious and progressive approach was essential. Primarily, this involved a gradual increase in both Mach number (starting at Mach 2.0 and increasing to Mach 2.4), and climb angle ($50\frac{1}{2}$ degrees was finally achieved). This approach took us higher and higher while allowing us to progressively evaluate handling qualities under decreasing "q" and increasing pitch rate requirements at the apogee. Our two "over-the-shoulder" cameras recorded the instrument panel display, and the film was used to assess pilot technique and to update our engineering computer analysis.

Once I had switched from "G" to alpha during the pull-up, the pitch angle would increase (hopefully achieving the desired maximum pitch angle programme) and then decrease (as the zoom trajectory became increasingly ballistic). Approaching apogee, the nose-down pitch rate requirement increased, and gyroscopic yaw left had to be controlled. On flights above 95,000 feet, full right rudder (or as much as I could apply from within my constraining suit) was required. And on the last two flights, I found it necessary to reduce the nose-down pitch rate to maintain control of yaw. By that I mean I had to check back on the "pole" to stop the left yaw! (Figure 6) At that point, critical angle of attack and digression into the flat spin constrain stick movement. Holding back on the stick at apogee when the flight path angle is decreasing will allow the angle of attack to increase to the pitch-up. Moving the stick forward too fast produces an uncontrollable left yaw and an angle of attack beyond the critical. An interesting corner of the flight envelope!

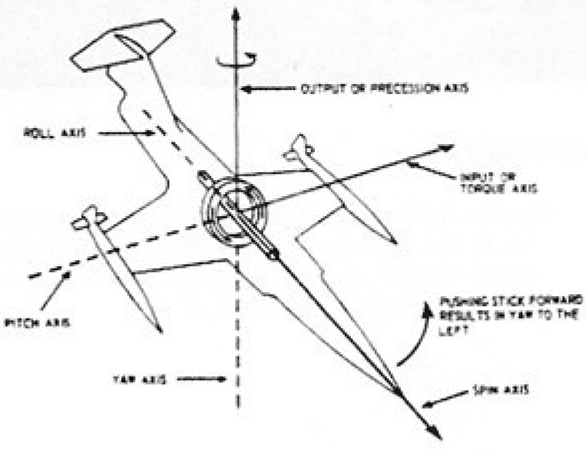


Figure 6 Resultant Yaw from Engine Rotation and Control Surface Movement

Once over the top and on the way down, dive brakes were extended and alpha was increased to the "shaker" boundary for maximum braking. Speed and Mach number continued to increase inexorably. And as if to demonstrate the mechanics of ballistic trajectories, the dive angle increased almost precisely to the maximum climb angle achieved on the way up! The engine always relit nicely at Mach 1.8 passing 60,000 ft, and by 35,000 feet I was usually level and flying by external visual reference. By this time I could relax and try to find Capt Jim Reed in the chase as I hurried home. Next time I must remind him to bring my crayons!

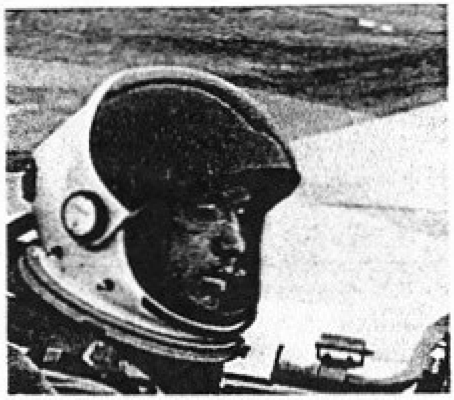
Footnotes

1. Position Error here refers to the fact that calibration of altimeters is done at relatively low level. However, the non-linear change with altitude in parameters which affect altimeter operation, make accurate extrapolation to high altitude impossible.

2. The CF-104 does not stall in the classical sense (viz. mush down), but on the contrary, "stall" is "pitch up". Like the classical stall, pitch up will occur as the result of excess angle of attack for a particular "G" loading, and accelerated stalls (pitch ups) can be precipitated by rough control motions. And pitch up leads to a spin!

3. Investigation of F-104 Spin Modes - G.L. "Snake" Reaves, (Lockheed Test Pilot).

4. In actual fact the yaw vane, mounted on the nose boom forward of the alpha vane, came off during the 15th flight. Because AETE found that the alpha vane worked better without the disturbing proximity of the yaw vane, Lt Col White completed the project without it by using the ball located at the bottom of the MAI.



By Lieutenant-Colonel R. A. White
Senior Test Pilot
Aerospace Engineering Test Establishment

100,110 feet One for the record

In December of 1966 my USAF Exchange Test Pilot, Capt Jim Reed, came to me with an exciting idea. It was this: beat the Russians and capture the World's Absolute Altitude Record for Canada in Centennial Year.

Of the hundreds of records in the realm of aeronautical competition, only six are termed "World's Absolute" by the International Aviation Federation, (the "FAI"), the governing body for aerospace records. Not only is "Altitude" one of these six, but it is well known by the general public and greatly coveted by the technical community. Over the years, the World's Altitude Record has been hotly contested by the major powers; in one year alone, 1959, it was held in turn by the Russians, the US Navy, and by the United States Air Force. In 1961 Colonel Georgi Mossolov captured the record for Russia in a rocket-boosted MIG-21, called E-66A, when he attained 113,892 ft. His record still stood in 1967, beating it by the requisite three percent became our goal!

Our attempt would be based on three keystones. First we would use our high speed "pacer" aircraft CF-104 Number 700. It was lighter than a standard *Starfighter* and it could be easily modified and instrumented. Secondly, we would take advantage of the high energy jet winds along the axis of the St. Lawrence valley to increase our total kinetic energy. By starting our pull-up from within the core of a jet wind, we estimated that we could increase our maximum height by some 5,000 feet for every 50 knots of jet wind. Finally, we felt that we could improve our zoom profile over that achieved by the Americans in their 1959 record flights. We postulated that by initiating our pull-up from 35,000 to 40,000 feet and then pulling only low levels of "G" we would carry more energy into the vertical, and thus reach greater heights.

Our proposal drew enthusiastic support from Canadian Forces Headquarters, and General Allard personally approved the Centennial Project on 14 August 67. We were off and running!

Our first task was to get an uprated engine, and it was here that Materiel Command and Orenda joined the Centennial team. Simultaneously, we began to modify "700". We had to extend the inlet cones to better position the shock wave across the engine intakes for the higher supersonic speeds. Lockheed Aircraft Corporation helped by lending us the cone extensions and helping us mount them. The electrical system was completely revised as we added two new batteries and a "zoom" inverter. And the pressurization system had to be changed out of all recognition. Captured by the spirit of it all, most of us worked well into the night and almost every week-end for five months!

In 1959 when Capt Joe Jordan of the USAF captured the world's altitude record, the existence of the F-104 "flat-spin" was unknown. Since then, however, a number of Canadian and American pilots had to jump out of 104's. Lockheed studies revealed a stable and deadly spin mode, and it was apparent that if we were not extremely cautious our Centennial zooms could easily get us into a flat spin. So we had to approach our task with unique instrumentation. Principally this meant an extremely sensitive vane to measure angle of attack, an instrument panel that would allow the entire zoom manœuvre to be flown on instruments, and a power system that would not arc out in the low density conditions of inner space.

The Flight Research Section of the National Aeronautical Establishment (NAE) came up with the design of an "Alpha" vane to measure angle of attack. They fabricated the vanes, tested them in their wind tunnels and installed them on our Centennial "Bird". NAE gave us a great deal of help!

We needed full pressure suits! The Institute of Aviation Medicine secured these for us through the Surgeon General of the USAF, and in September Major Ron Hayman and I flew down to Tyndall Air Force Base in Florida to pick them up.

Later on we obtained valuable assistance and special check-out gear from the Physiological Test Squadron at Edwards Air Force Base.

We finally got airborne in the first week in October, and our first task was to work the speed up to Mach 2.4 and determine engine performance. We progressed cautiously, but even then we ran into serious control and damper problems before we could start into perfecting the zoom manœuvre.

Starting from Mach 2.0 and 25 degrees climb angle, we gradually began to increase our Mach number and climb angle. During these days it seemed as if problem followed problem. Always the team overcame them, sometimes with almost superhuman effort, but time began to run out on us. Too soon Ron Hayman had to leave for the RAF Staff College in Bracknell! Then on our 29th flight, I got to 96,000 feet from Mach 2.2 with a light following wind. I felt we had it made!

But then we began to have engine inlet guide vane problems. We tried everything, but it wasn't until we had changed engines and rescheduled inlet guide vanes that we got our thrust back. And lo and behold, a light jet stream was still overhead!

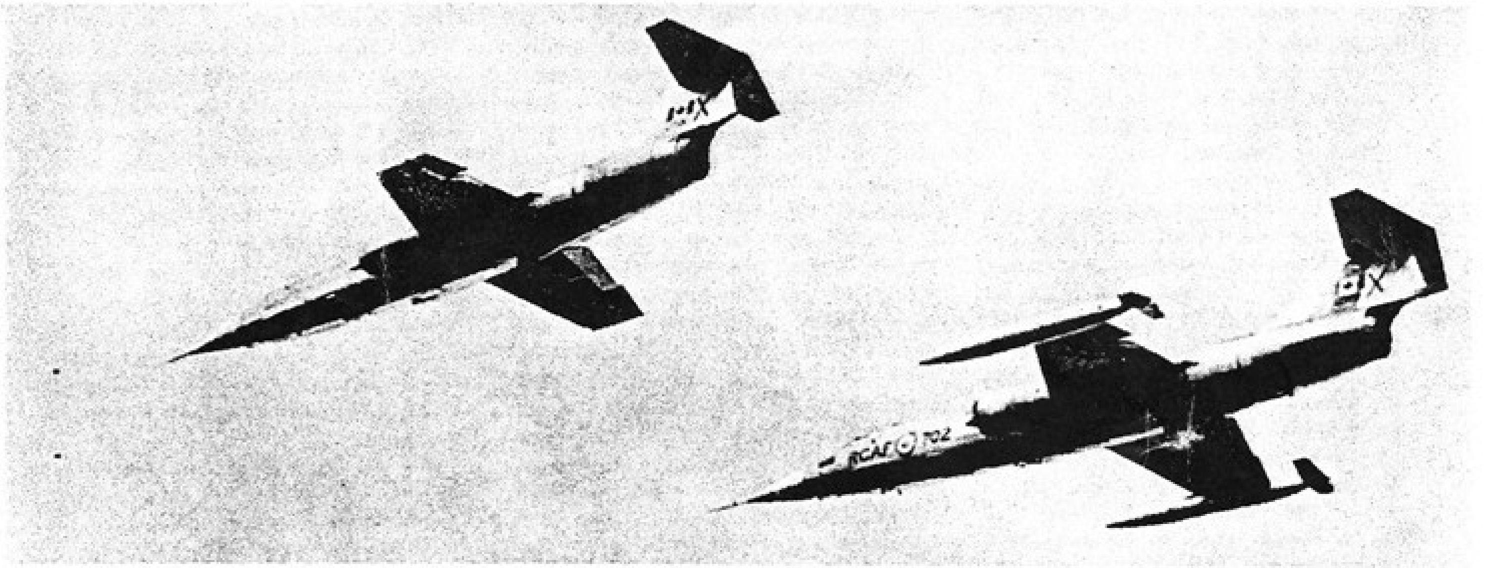
By the third flight on the 14th of December, the engine was producing the required thrust, and NAE's T-bird located the jet wind core to the south of Ottawa. Profile "David" (after my eldest son!) was filed with Air Traffic Control and the countdown for our 41st flight began. Scores of Air Traffic controllers in Toronto and Montreal began vectoring aircraft around our profile airspace, and Ottawa Terminal Control began to clear our route. Profile "David" traversed the most densely travelled airspace in Canada, between Toronto and Montreal, at high speeds, and required a most unique arrangement with the Department of Transport. (But, by then, we had worked together for two and one-half months and everything went like clockwork!)

I took off and began my climb out to the west of Ottawa, while Jim Reed in the chase (a standard CF-104) carefully checked me over. At 35,000 feet, I dumped cabin pressure and checked out my suit during the climb to 47,000 feet. At 100 miles west of Ottawa, I started a slow turn around to the east, and the DRTE (Defence Research Telecommunications Establishment) Satellite Tracking System at Shirley's Bay began to track by beacon. Their tracking data was the vital bit of "proof" we needed to establish any record of our height. Once DRTE had me on "autotrack", I went full power and dove to 35,000 feet. I was supersonic almost at once, and by 35,000 feet was up to Mach 1.4. I continued to accelerate! Bypass on! through T-2 Reset! Mach 2.0! Shirley's Bay told me to switch antennae. Mach 2.35! A gentle ramp up to 39,000! Mach 2.4! Pulling 2.4G! At 57 degrees pitch angle I seemed to be going straight up! My angle of attack "Alpha" gauge was centered, so I was right on zoom schedule. At 75,000, the afterburner blew out, and at 84,000 I shut the engine down to prevent it overheating.

From the time I had established my climb angle, at about 70,000 feet, I was just like a fly riding on an artillery shell! I could control the altitude, but I could make almost no change in the trajectory. Altitude control was critical, and, with the gyroscopic effect of the still-rotating engine, any loss of control could get me into a flat spin! Following my "Alpha" gauge, I gradually began to push my nose down as "700" arced over the top. Almost Zero "G", and over the top at 65 knots; but I'm still supersonic! Dive brakes out as I start to accelerate downward, and a gentle turn towards home. The Mach number continues to rise as I re-enter, even with maximum braking angle of attack, it rises to Mach 1.8 when I reach 60,000 feet and relight the engine. "Relight!!" This is the one word from me that relieves the people on the ground, who are sweating it out with me. Then events come in quick succession as DOT radar vectores me home, my chase catches me, checks me over and we come straight in because of my low fuel.

When DRTE told me I had peaked at 100,110 feet, I was discouraged. It was apparent to me that we were not going to be able to beat the Russians. The following day, I confirmed this on our 42nd flight, and terminated the program.

Now that time is eroding some of the pangs of failure, I can see that we did something significant. First of all, we got to 100,110 feet and proved it, to the satisfaction of the Royal Canadian Flying Clubs Association, who monitored all of our flights for the FAI. We established a Canadian National altitude record that has only been beaten by one other pure jet in the world. And, of the 25 zoom flights, we managed to make 12 flights safely above 95,000 feet. No one else has ever spent that much time in a jet at those levels!



But I think the main benefit was that we exercised all of our national aerospace research and development organizations. In the same way that an operational squadron exercises to enhance its combat readiness, we exercised our capabilities, and all of us, individually and collectively, gained valuable experience that could not have been acquired in any other way. Moreover, we obtained data about the CF-104 that can be directly related to the operational CF-104 squadrons in Europe.

But the thing about the Centennial Project that I will always remember best was the way people worked together, especially our ground crew. Every man on the team worked his heart out to capture the record for Canada. And you can't ask for more than that!