# Ezra Kotcher and the Configuration Aerodynamics of the Bell X-1 and X-2

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**This paper presents photographs, memoranda, reports, and contemporaneous notes taken by Ezra Kotcher during his involvement in the development of the Bell X-1 and X-2 supersonic research aircraft. This material, made available to the author, during his time as a visiting faculty fellow at the Air Force Institute of Technology, provides tremendous insight into the state-of-the-art regarding experimental aircraft design during the mid 1940's. From these documents, we can see evidence of a truly modern viewpoint towards aerodynamics as well as a surprising level of attention towards ensuring basic flying qualities and structural integrity. The success of the X-1 and relative failure of the X-2 arose from an intense desire to build aircraft that "worked." Both aircraft legitimately represented an attempt for "form to follow function;" in this era technology was an enabler rather than the principal driver of vehicle specification and definition.**


"Those who cannot remember the past are condemned to repeat it" – George Santayana

## I. Introduction

THE BELL X-2 rocket plane was a less-than-successful follow on to the Bell X-1, in which Chuck Yeager broke the "sound barrier" in 1947. Both of these aircraft, the famous and the infamous, were the brainchilden of Ezra Kotcher. While the X-1 has been a prominent player in both popular and technical history, the X-2 languishes in comparative obscurity.[1][2][3] In the summer of 2023, during my stay as a Summer Faculty Fellow at the United States Air Force Institute of Technology, I had the opportunity to examine Colonel Kotcher's personal technical correspondence

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relating to these programs as they had been donated to AFIT by his daughter. In this work, I will reveal interesting details of the X-1 and X-2's design process and highlight which elements contributed to success or failure.

During the late 1930's and early 1940's, as aircraft grew faster and more powerful, pilots began to experience anomalous flying qualities at high air speeds. In a high-speed dive, pilots of the Lockheed P-38 would encounter violent buffeting along with major changes to pitch trim and a loss of control surface effectiveness. Sometimes these effects would become so strong as to lead to in-flight structural failure.[4][5] We must remember that the P-38 was a piston-engine propeller-drive aircraft; the development of turbojet engines during wartime highlighted the urgency of the need to resolve these problems.

By the end of the Second World War, it became clear that turbojet and/or rocket engine technology could conceivably propel aircraft through the transonic and into the supersonic flight regime. In August 1945, Theodore Von Karman, scientist, professor and founder of Aerojet, Inc, warned U.S. Army Air Force General Hap Arnold that "we cannot hope to secure air superiority in any future conflict without entering the supersonic speed range."[6] This further elevated the need to determine how could engineers design and build a piloted aircraft to survive the transition from subsonic to supersonic and back.

James Young, from the History Office at the Air Force Flight Test Center, Edwards AFB describes the genesis of the X-1 and X-2 as the byproduct of the ideas of two men. "Major Ezra Kotcher, from the Engineering Division at Wright Field, and John Stack, director of the Compressibility Research Division at the National Advisory Committee for Aeronautics' (NACA) Langley Memorial Aeronautical Laboratory (LMAL)."[3] They set out to demonstrate to the aeronautical community the belief that the "so-called "sound barrier" was "just a steep hill.""[4][7]

The October 1947 mission, where Captain Chuck Yeager exceeded the speed of sound in the Bell X-1, is "arguably the most important flight since Kitty Hawk."[8] However heroic Yeager may seem to us, we must remember that the aircraft was the product of years of preparatory work. The X-1 was a "joint project of NACA and the U.S. Army Air Forces, built by Bell Aircraft of Buffalo, New York."[8] The team, led by "Larry Bell, head of Bell Aircraft, his chief design engineer Robert Woods, Ezra Kotcher, then an Army major, and John Stack, a research scientist at the National Advisory Committee for Aeronautics (NACA)" sought to learn "how to fly through the buffeting of the transonic zone."[8] On that day, it attained a speed of Mach 1.06 at an altitude of 43,000-ft and forever changed history. The Smithsonian Magazine sums up that morning as the day when "one of us rose and flew faster than the roar of our own hopes, and for a moment, everything seemed possible." By the time of the fatal crash of the Bell X-2 some eight years later, everything **had** changed for wing-borne flight; we engineers had become much wiser, but only with significant costs in life and treasure.

## II. Who Was Ezra Kotcher?

From his obituary as published in the New York Times on November 14, 1990:

> "Colonel Ezra Kotcher, the first director of the United States Air Force Institute of Technology, died Thursday at the United States Naval Hospital in Oakland, Calif. He was 87 years old and lived in Oakland.
> …
> During and after World War II, as an officer in the Air Materiel Command, he perfected in-flight fueling and directed development of the X-1 and X-2 jet planes.
>
> Colonel Kotcher, a native of Brooklyn, was a graduate of the University of California at Berkeley and held a master's degree in aeronautical engineering from the University of Michigan.
>
> In 1928 he became an instructor at Wright Field in Ohio, later the Air Corps Engineering School [*the predecessor to today's Air Force Institute of Technology -T*] He was a senior professor there when the United States entered World War II and he went on active duty. After the war, he served

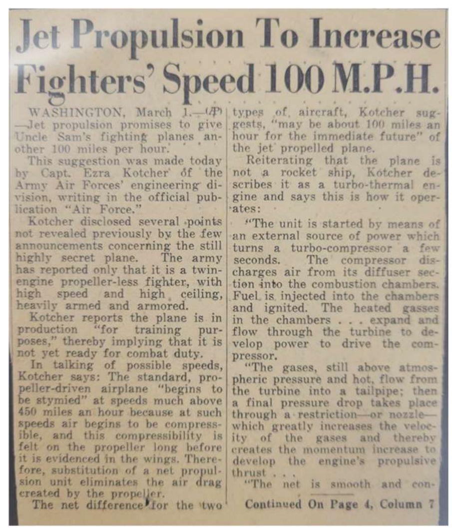
as head of technical intelligence for the Air Force in Japan before returning to Wright-Patterson Air Force Base to head the Air Force Institute.

After the Korean War, he was named director of the Wright Air Development Center, a post he held until he retired in 1961."[9]

Young, from the USAF history office at Edwards AFB, determined that Kotcher, as a civilian instructor, was the earliest US military advocate of gas-turbine or rocket propelled aircraft; see FIGURE 1.[3] In August 1939, Kotcher submitted a report where he recommended the establishment of transonic flight research program powered by such systems as he correctly noted that the compressibility limitations on propeller driven aircraft at high speeds would prove intractable.[3] Young notes that Kotcher was persistent. After being called to active duty and assigned to the Engineering Division at Wright Field, as a uniformed officer he continued to press for rocket powered transonic flight research aircraft. The controllability problems of the P-38, along with military intelligence learning of Nazi German efforts to produce both gas-turbine (the Me 262) and rocket propelled (the Me 163) high-speed combat aircraft, led to broader support for Kotcher's ideas.[10][11]

FIGURE 1 - Ezra Kotcher – in civilian attire during his time as instructor at the US Army Air Corps Engineering School

By early 1944, Ezra Kotcher (along with co-conspirators John Stack at the NACA and Walter Diehl at the Navy) had each convinced their respective management that a piloted research airplane was essential to unlock the challenges of transonic flight.[3] All three decided to join forces, at least in spirit. Stack (at NACA) and Diehl (at the Navy) favored a turbojet powered aircraft to explore the near-sonic; this is the genesis of the Douglas D-558-1.[12] Captain Kotcher at the Army Air Force (with some backing from Von Karman at Caltech) argued for a rocket propelled aircraft that could exceed Mach 1; this is the genesis of the Bell X-1.[3] In hindsight, we must recognize that Kotcher was concurrently involved in the development of the turbojet powered Bell XP-59 and Lockheed XP-80 experimental fighter aircraft; he was aware that the proposed D-558-1 would offer little performance advantage over forthcoming military prototypes, see FIGUREs 2 and 3.[13]



Jet Propulsion To Increase Fighters' Speed 100 M.P.H.

WASHINGTON, March 1.—(AP)—Jet propulsion promises to give Uncle Sam's fighting planes another 100 miles per hour.

This suggestion was made today by Capt. Ezra Kotcher of the Army Air Forces' engineering division, writing in the official publication "Air Force."

Kotcher disclosed several points not revealed previously by the few announcements concerning the still highly secret plane. The army has reported only that it is a twin-engine propeller-less fighter, with high speed and high ceiling, heavily armed and armored.

Kotcher reports the plane is in production "for training purposes," thereby implying that it is not yet ready for combat duty.

In talking of possible speeds, Kotcher says: The standard, propeller-driven airplane "begins to be stymied" at speeds much above 450 miles an hour because at such speeds air begins to be compressible, and this compressibility is felt on the propeller long before it is evidenced in the wings. Therefore, substitution of a net propulsion unit eliminates the air drag created by the propeller.

The net difference for the two types of aircraft, Kotcher suggests, "may be about 100 miles an hour for the immediate future" of the jet propelled plane.

Reiterating that the plane is not a rocket ship, Kotcher describes it as a turbo-thermal engine and says this is how it operates:

"The unit is started by means of an external source of power which turns a turbo-compressor a few seconds. The compressor discharges air from its diffuser section into the combustion chambers. Fuel is injected into the chambers and ignited. The heated gasses in the chambers . . . expand and flow through the turbine to develop power to drive the compressor.

"The gases, still above atmospheric pressure and hot, flow from the turbine into a tailpipe; then a final pressure drop takes place through a restriction—or nozzle—which greatly increases the velocity of the gases and thereby creates the momentum increase to develop the engine's propulsive thrust . . .

"The net is smooth and con-

Continued On Page 4, Column 7

FIGURE 2 - Newspaper Clipping Citing Captain Kotcher from March 1944.


FIGURE 3 – Bell XP-59 Prototype Straight-Wing Turbojet Fighter

## III. Ezra Kotcher and the Development of the Bell X-1

Young suggests that the final step towards making the Bell X-1 a reality occurred on November 30, 1944 when Robert J. Woods, chief engineer and co-founder of the Bell Aircraft Corporation, dropped by Ezra Kotcher's office for a chat.[3] Kotcher's vision was to build a rocket powered aircraft with at least a two-minute high-speed endurance capability and an ability to achieve 800 mph at 35,000-ft.[4] Absent clear military specifications, Bell would only have to guarantee its safety and controllability up to a speed of Mach 0.8.[4] Woods is said to have committed Bell to support the project at this meeting.

The Bell X-1 was formally born shortly after a December 1944 group meeting at NACA/Langley. At that meeting, Kotcher reiterated his

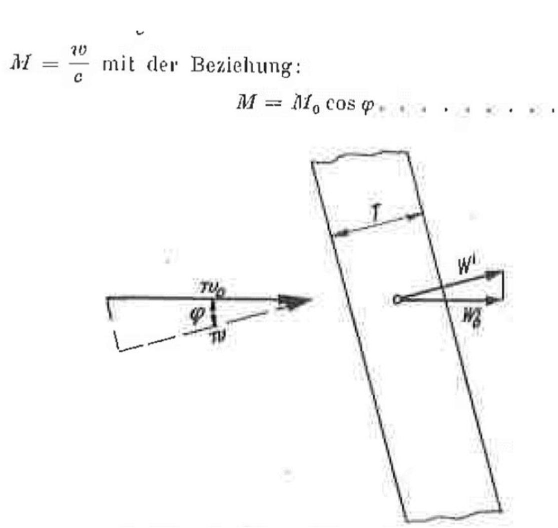



FIGURE 4 – Buseman's 1935 Treatise on Sweep claims that the dominant flow condition controlling shock wave formation relates to the Mach Number normal to the leading edge.[15]

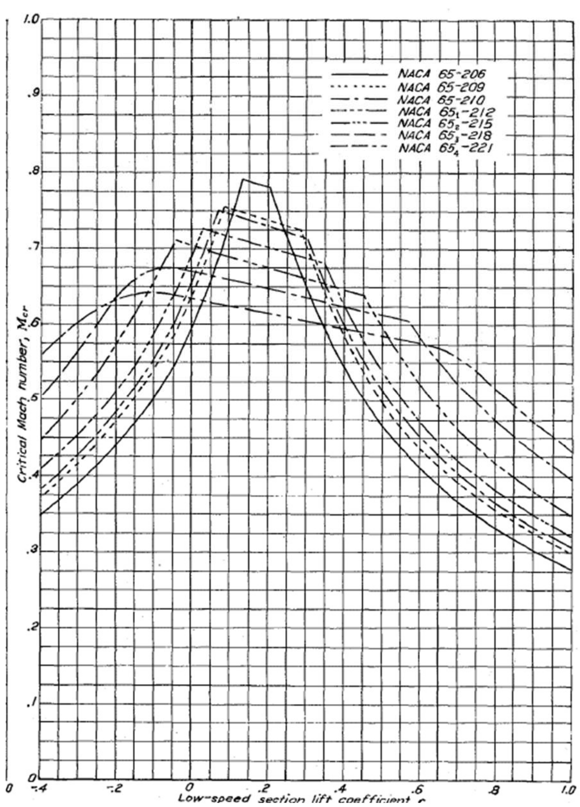



FIGURE 5 – Critical Mach number vs Low-Speed Lift Coefficient Trends for NACA 65-xyy airfoils similar to that employed on the Bell X-1. Thinner airfoils have a higher critical Mach number than thicker airfoils near their design *CL*.[17]

preference for a rocket propelled aircraft. Once again, he reminded the conferees that the primary objective of the project was to "attain a Mach number slightly greater than 1."[3]

Although Stack disliked Bell's initial design effort, Kotcher's connections to Bell (through the XP-59 program) prevailed.[3][7][14] Bell was then given further clarification to design an aircraft with: 1) a maximum speed well above its critical Mach number (for a thin, straight wing aircraft that means a $M$>0.85), 2) with at least two minutes of endurance at full power, 3) with an ability to be fitted with wings of various thickness-to-chord ratios, and 4) with an ability to carry a significant instrumentation payload.[3]

Kotcher conceptualized the X-1 as a straight-wing (unswept) aircraft.[3] While Adolf Buseman's observations regarding the potential effectiveness of wing-sweep were well known after his landmark publication at the 1935 Volta conference, no swept wing transonic aircraft had yet flown; see FIGURE 4.[15] We must remember that the Northrop XP-79 rocket propelled flying wing prototype fighter was under construction at the time and did not fly or crash until 1945.[11] While the XP-79 features some amount of wing sweep, its sweep angle was selected for stability & control rather than transonic performance reasons as its planform was shared with its much slower piston-powered flying wing predecessors.[16]

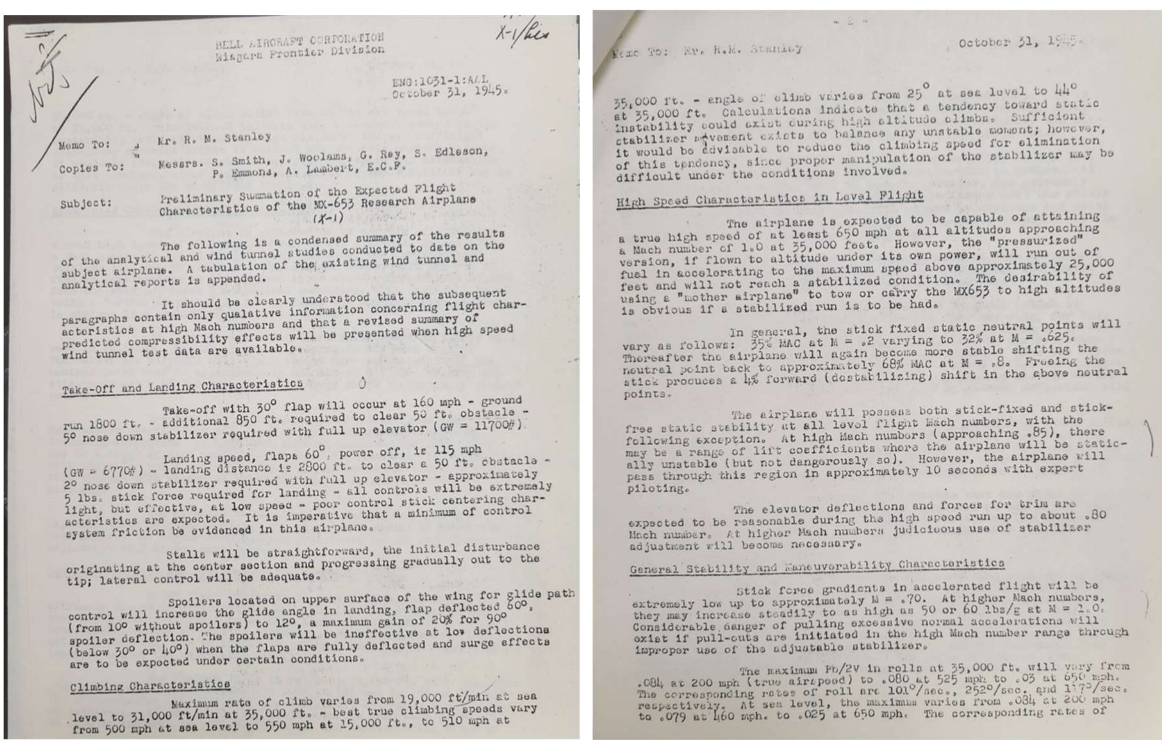
The NACA clearly shared its 2-D airfoil test data with Kotcher during these meetings. As later released as part of NACA TR-824,[17] the correlation between Critical Mach number, and the camber and thickness of 2-D airfoil sections was a matter of intense interest; see FIGURE 5. The X-1 was conceptualized to be built with a "thin" and a "thick" wing option. Both wings were to be built from airfoils engineered to have a low-speed design *CL* of 0.1; both used the NACA $65_1$ thickness form. The thinner wing (NACA $65_1$-108) had $t/c$=8%; the thicker wing (NACA $65_1$-110) had $t/c$=10%. We can interpolate existing data to infer that the 2-D Critical Mach Number of the thinner wing was ~0.73 and the thicker wing ~0.75; thus, the Critical Mach number of the thinner section should be about $\Delta M$~0.02 greater than the thicker section near the design *CL*. It is interesting to note that neither the NACA 65-108 nor the 65-110 sections actually employed on the X-1 were part of the publicly released dataset found in NACA TR-824.[17] It is also interesting to note that the NACA $65_1$-110 airfoil section was also employed on the contemporaneous Douglas D-558-1.[18]

Another earlier conceptual design decision arose from the December 1944 meetings, that to make the $t/c$ of the tailplane no thicker than that of the main wing; Bell used a 65-008 tailplane section in conjunction with the NACA $65_1$-110 airfoil main wing.[19] NACA TR-824 predicts a Critical Mach Number of ~0.80 for that 8% section at low lift coefficients. Similarly, Bell used a 65-006 tailplane section in conjunction with the NACA $65_1$-108 airfoil main wing.[19] NACA TR-824 predicts a Critical Mach Number of ~0.82 for this thinner section at low lift coefficients. The idea was to ensure that the main wing exceeded its Critical Mach number before the thinner tail; thus, hoping to improve controllability as the aircraft accelerated. The airfoil selection, in retrospect, indicates that the designers separated these two values by $\Delta M$~0.05 on the X-1. To further improve longitudinal control authority, "Stack and Gilruth also recommended mounting the elevator on a fully pitch trim adjustable horizontal stabilizer in lieu of a standard configuration which would have featured a fixed horizontal tail with a movable elevator."[3]

As all parties expected pilots to encounter controllability issues, both the Air Force and the NACA insisted that the aircraft be designed to withstand extremely violent dynamic maneuvers; the X-1 was to be stressed to withstand an ultimate load factor of 18-gees (12-gees nominal notwithstanding the traditional 1.5 factor-of-safety).[3][4] The extremely robust construction of the X-1 family would prove a pivotal role later in its flight test program, as the several pilots – Chuck Yeager inclusive – lost control of the aircraft.[20][21]

According to Young, the official contract for Bell to detail design and construct three XS-1 airplanes was issued on March 16, 1945.[3] An extensive search at the AFIT library along with the NASA NTRS has revealed no archival wind-tunnel data report associated with any developmental configurations. All published wind tunnel data seems to have been produced retrospectively for the "as delivered design."[19]

The final design goals of the Bell X-1 may be found in an October 1945 Bell Aircraft Corporation memo from the Aerodynamics team to Bell Chief Test Pilot R.M. Stanley, as preserved in the Ezra Kotcher collection; see FIGUREs 6a and 6b.[22] Bell designed the X-1 for horizontal takeoff and landings, but by this point, realized that with the high fuel consumption of its rocket engine, it would exhaust its fuel supply long before it could climb to 35,000-ft; this paved the way for the X-1 to be air-dropped for its high-speed research mission. At the same time, the airframe was otherwise engineered to have very reasonable takeoff and landing speeds. The slightly tapered $AR$=6 wing was set up with 1° of washout; [19] Bell predicted this to have "straightforward" stall characteristics.



BELL AIRCRAFT CORPORATION
Niagara Frontier Division

X-1/Res

ENG:1031-1:A/L
October 31, 1945.

Memo To: Mr. R. M. Stanley

Copies To: Messrs. S. Smith, J. Woolams, G. Rey, S. Edleson, P. Emmons, A. Lambert, E.C.F.

Subject: Preliminary Summation of the Expected Flight Characteristics of the MX-653 Research Airplane (X-1)

The following is a condensed summary of the results of the analytical and wind tunnel studies conducted to date on the subject airplane. A tabulation of the existing wind tunnel and analytical reports is appended.

It should be clearly understood that the subsequent paragraphs contain only qualative information concerning flight characteristics at high Mach numbers and that a revised summary of predicted compressibility effects will be presented when high speed wind tunnel test data are available.

Take-Off and Landing Characteristics

Take-off with 30° flap will occur at 160 mph - ground run 1800 ft. - additional 850 ft. required to clear 50 ft. obstacle - 5° nose down stabilizer required with full up elevator (GW = 11700#)

Landing speed, flaps 60°, power off, is 115 mph (GW = 6770#) - landing distance is 2800 ft. to clear a 50 ft. obstacle - 2° nose down stabilizer required with full up elevator - approximately 5 lbs. stick force required for landing - all controls will be extremely light, but effective, at low speed - poor control stick centering characteristics are expected. It is imperative that a minimum of control system friction be evidenced in this airplane.

Stalls will be straightforward, the initial disturbance originating at the center section and progressing gradually out to the tip; lateral control will be adequate.

Spoilers located on upper surface of the wing for glide path control will increase the glide angle in landing, flap deflected 60°, (from 10° without spoilers) to 12°, a maximum gain of 20% for 90° spoiler deflection. The spoilers will be ineffective at low deflections (below 30° or 40°) when the flaps are fully deflected and surge effects are to be expected under certain conditions.

Climbing Characteristics

Maximum rate of climb varies from 19,000 ft/min at sea level to 31,000 ft/min at 35,000 ft. - best true climbing speeds vary from 500 mph at sea level to 550 mph at 15,000 ft., to 510 mph at

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Memo To: Mr. R.M. Stanley October 31, 1945.

35,000 ft. - angle of climb varies from 25° at sea level to 44° at 35,000 ft. Calculations indicate that a tendency toward static instability could exist during high altitude climbs. Sufficient stabilizer movement exists to balance any unstable moment; however, it would be advisable to reduce the climbing speed for elimination of this tendency, since proper manipulation of the stabilizer may be difficult under the conditions involved.

High Speed Characteristics in Level Flight

The airplane is expected to be capable of attaining a true high speed of at least 650 mph at all altitudes approaching a Mach number of 1.0 at 35,000 feet. However, the "pressurized" version, if flown to altitude under its own power, will run out of fuel in accelerating to the maximum speed above approximately 25,000 feet and will not reach a stabilized condition. The desirability of using a "mother airplane" to tow or carry the MX653 to high altitudes is obvious if a stabilized run is to be had.

In general, the stick fixed static neutral points will vary as follows: 35% MAC at M = .2 varying to 32% at M = .625. Thereafter the airplane will again become more stable shifting the neutral point back to approximately 68% MAC at M = .8. Freeing the stick produces a 4% forward (destabilizing) shift in the above neutral points.

The airplane will possess both stick-fixed and stick-free static stability at all level flight Mach numbers, with the following exception. At high Mach numbers (approaching .85), there may be a range of lift coefficients where the airplane will be statically unstable (but not dangerously so). However, the airplane will pass through this region in approximately 10 seconds with expert piloting.

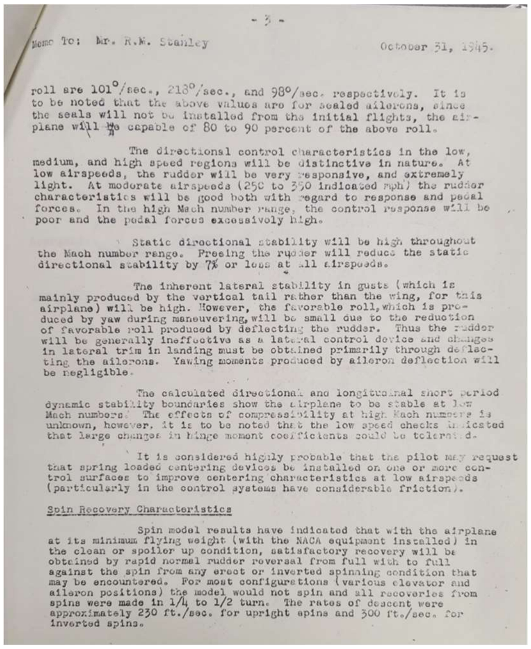
The elevator deflections and forces for trim are expected to be reasonable during the high speed run up to about .80 Mach number. At higher Mach numbers judicious use of stabilizer adjustment will become necessary.

General Stability and Maneuverability Characteristics

Stick force gradients in accelerated flight will be extremely low up to approximately M = .70. At higher Mach numbers, they may increase steadily to as high as 50 or 60 lbs/g at M = 1.0. Considerable danger of pulling excessive normal accelerations will exist if pull-outs are initiated in the high Mach number range through improper use of the adjustable stabilizer.

The maximum Pb/2V in rolls at 35,000 ft. will vary from .084 at 200 mph (true airspeed) to .080 at 525 mph to .03 at 650 mph. The corresponding rates of roll are 101°/sec., 252°/sec. and 137°/sec. respectively. At sea level, the maximum varies from .084 at 200 mph to .079 at 460 mph. to .025 at 650 mph. The corresponding rates of

FIGURE 6a – Bell Aircraft Corporation Internal Memo [22]



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Memo To: Mr. R.M. Stanley October 31, 1945.

roll are 101°/sec., 218°/sec., and 98°/sec. respectively. It is to be noted that the above values are for sealed ailerons, since the seals will not be installed from the initial flights, the airplane will be capable of 80 to 90 percent of the above roll.

The directional control characteristics in the low, medium, and high speed regions will be distinctive in nature. At low airspeeds, the rudder will be very responsive, and extremely light. At moderate airspeeds (250 to 350 indicated mph) the rudder characteristics will be good both with regard to response and pedal forces. In the high Mach number range, the control response will be poor and the pedal forces excessively high.

Static directional stability will be high throughout the Mach number range. Freeing the rudder will reduce the static directional stability by 7% or less at all airspeeds.

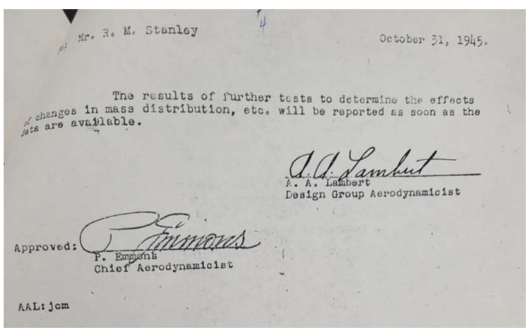
The inherent lateral stability in gusts (which is mainly produced by the vertical tail rather than the wing, for this airplane) will be high. However, the favorable roll, which is produced by yaw during maneuvering, will be small due to the reduction of favorable roll produced by deflecting the rudder. Thus the rudder will be generally ineffective as a lateral control device and changes in lateral trim in landing must be obtained primarily through deflecting the ailerons. Yawing moments produced by aileron deflection will be negligible.

The calculated directional and longitudinal short period dynamic stability boundaries show the airplane to be stable at low Mach numbers. The effects of compressibility at high Mach numbers is unknown, however, it is to be noted that the low speed checks indicated that large changes in hinge moment coefficients could be tolerated.

It is considered highly probable that the pilot may request that spring loaded centering devices be installed on one or more control surfaces to improve centering characteristics at low airspeeds (particularly in the control systems have considerable friction).

Spin Recovery Characteristics

Spin model results have indicated that with the airplane at its minimum flying weight (with the NACA equipment installed) in the clean or spoiler up condition, satisfactory recovery will be obtained by rapid normal rudder reversal from full with to full against the spin from any erect or inverted spinning condition that may be encountered. For most configurations (various elevator and aileron positions) the model would not spin and all recoveries from spins were made in 1/4 to 1/2 turn. The rates of descent were approximately 230 ft./sec. for upright spins and 300 ft./sec. for inverted spins.



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Mr. R. M. Stanley October 31, 1945.

The results of further tests to determine the effects of changes in mass distribution, etc. will be reported as soon as the data are available.

A. A. Lambert
Design Group Aerodynamicist

Approved: P. Emmons
Chief Aerodynamicist

AAL:jcm

FIGURE 6b – Bell Aircraft Corporation Internal Memo [22]


FIGURE 7 – Bell X-1 First Flight.[32]

Bell predicted a top speed near Mach 1 at 35,000-ft.[22] Such flight, at ~575 KTAS represents only 325-KIAS; thus, the design dynamic pressure was not unusually high – only the design *Nz* =+12-gee loading.

Bell designed the X-1 to be statically stable in pitch, both stick-fixed and stick-free.[22] Bell had some concerns right at Mach 0.85; just as the horizontal tail section exceeds its Critical Mach number. Bell also expected the pilot to adjust the X-1's all-moving tailplane as a function of flight Mach number to keep stick forces and force gradients manageable.

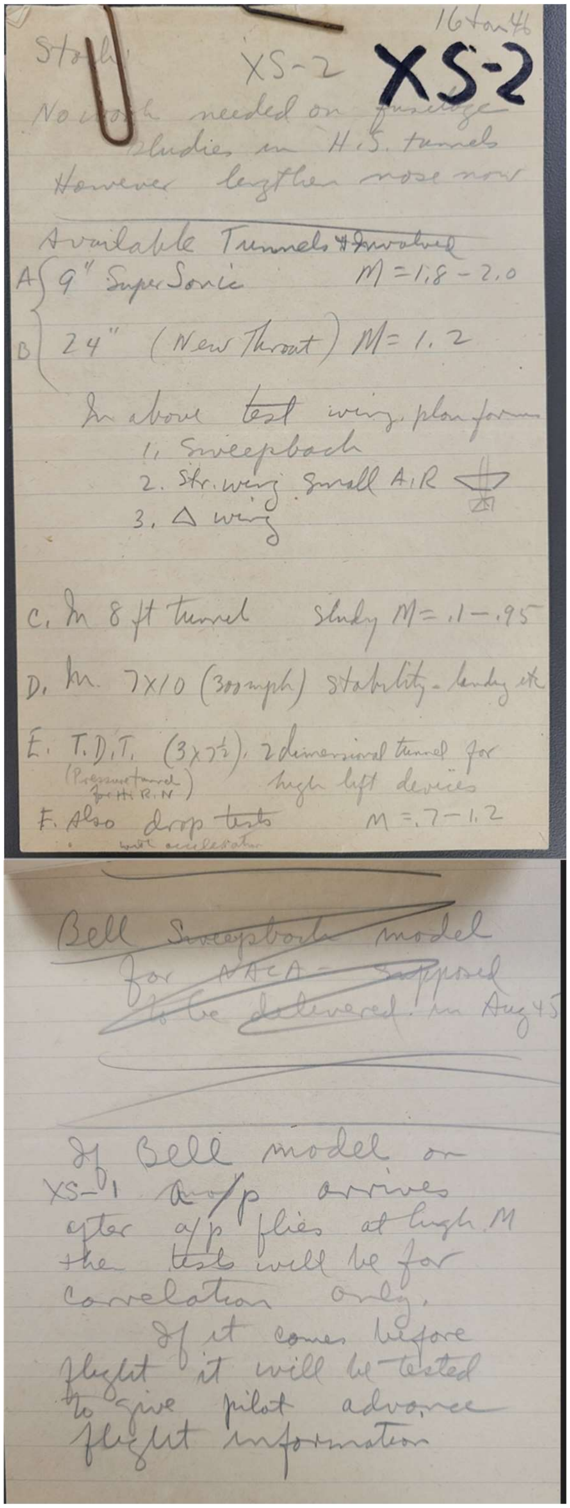
The Bell team paid careful attention to lateral-directional stability through aileron, rudder, and vertical tail sizing.[22] They predicted maximum roll rates in excess of 180°/sec under high-dynamic pressure conditions.[22] While the vertical was large enough to ensure static directional stability across the anticipated flight envelope, they worried about a loss of rudder effectiveness at higher Mach numbers (probably due to the vertical fin exceeding its Critical Mach number).[22]

It is prescient that Bell commented on latent control-coupling issues; noting that "favorable roll, which is produced by yaw during maneuvering, will be small."[22] The interaction between adverse yaw and the inherent lateral-directional stability of an airframe is and remains a major issue in flight control.[20][22][23][24][25][26][27] Indeed, the X-1A suffered from serious lateral-directional control problems when flown above Mach 2.[20]

Bell also comments on predicted longitudinal short-period and Dutch-Roll frequencies. Future MIL specifications such as MIL-STD-8785C and MIL-1797-A did not exist at the time, but the designers at Bell were cognizant to ensure that the modes were stable and that the frequencies seemed reasonable.[22][30][31]

On December 27, 1945, Bell rolled out a completed aircraft from its Niagara Falls, New York factory. It was quickly transported south to Pinecastle AAF (today's McCoy AFB) near Orlando, FL for initial flight testing.[3]

On January 25, 1946, test pilot Jack Woolams took command of the X-1 on its first glide. He cleanly separated from beneath a flying Boeing B-29 carrier aircraft, then glided back to the airfield.[3] With a relatively poor L/D, the X-1 proved tricky to land as it would require an early flare.[32][33] Indeed, Woolams managed to undershoot his intended touch-down point; the first flight of the X-1 ended ignominiously with the aircraft on the grass with light damage; see FIGURE 7.[3][34]


Stapl 16 Jan 46
XS-2 XS-2
No work needed on fuselage studies in H.S. tunnels
However lengthen nose now

~~Available Tunnels & Involved~~
A { 9" Super Sonic M = 1.8 - 2.0
B { 24" (New Throat) M = 1.2
In above test wing plan form
1. Sweepback
2. Str. wing small A.R
3. △ wing

C. In 8 ft tunnel study M = .1 - .95
D. In 7x10 (300 mph) stability - landing etc
E. T.D.T. (3x7½) 2 dimensional tunnel for high lift devices
(Pressure tunnel for H.R.N.)
F. Also drop tests M = .7 - 1.2
with accelerator

~~Bell Sweepback model for NACA - supposed to be delivered in Aug 45~~

If Bell model on XS-1 a/p arrives after a/p flies at high M the tests will be for correlation only.
If it comes before flight it will be tested to give pilot advance flight information

FIGURE 8 – Ezra Kotcher meeting Notes on Bell X-2 from January 16, 1946.[33]

## IV. Ezra Kotcher and the Development of the Bell X-2

Just one week before the X-1 flew its initial gliding flight, Ezra Kotcher began serious discussions relating to its successor the "XS-2." Meeting notes from Kotcher at NACA/Langley dating from January 16, 1946, reveal plans for a swept-wing follow up aircraft; see FIGURE 8.[35] At that point, both the NACA and the US Army Air Force had become aware of Nazi German progress in both Swept Wing research and in Swept Wing Aircraft Design.

A careful reading of Busemann's 1935 Volta conference paper on wing sweep (return to FIGURE 4), reveals a discussion based purely upon fully supersonic flow.[15] His arguments basically describe the flow conditions across an oblique shock wave; one where the components of the flow can be fully decomposed into vectors aligned both normal to a sweepback line and orthogonal to that line. This perfectly explains the turning action of flows as they traverse a classic oblique shock; there is no change in the velocity component of the flow orthogonal to the shock while the velocity change of the flow normal to the shock follows the classic Normal Shock relationship (and jumps from supersonic to subsonic).[36]

"Simple Sweep Theory," a literal application of Busemann's theory to subsonic and transonic flows, was first published in June 1945 as NACA TR-863.[37] R.T. Jones notes that Busemann did not "consider angles of sweepback greater than the Mach angle."[37] Jones did postulate that "by increasing the angle of sweepback so that the normal component of velocity not only is subsonic but is less than the critical speed of the airfoil sections," a shock free transonic wing could be designed.[37] This "theory" was recognized as speculative at the time, and needed to be explored in tunnel and flight.

At the same time at the RAE in Farnborough, Bickley developed a competing (ultimately more accurate) theory.[38] He follows Busemann in terms of considering that the angle of interest is a virtual angle – not necessarily aligned with a geometric feature like the leading edge – but aligned with the local sweep angle or an "isobar" line. Isobars are virtual lines joining points where the pressures (i.e., local velocities) are the same. Bickley's criterion is that incipient shock waves form when the flow component normal to an isobar line exceeds the speed of sound.

Similarly, Ira Abbott, author of the famous 1945 NACA Report on 2-D airfoil data,[17] "stunned many in the world of aeronautics by commenting that he was surprised that Langley's airfoil research had such an impact on the design of aircraft wings."[39] As he stated at a NASA

Advanced Airfoil Conference in 1978, "Wing design depends on many three-dimensional effects, not just an airfoil section."[39] As early as 1945, Stack & Lindsay had clearly noted how low Aspect Ratio wings had improved drag divergence characteristics compared to 2-D.[40][41]

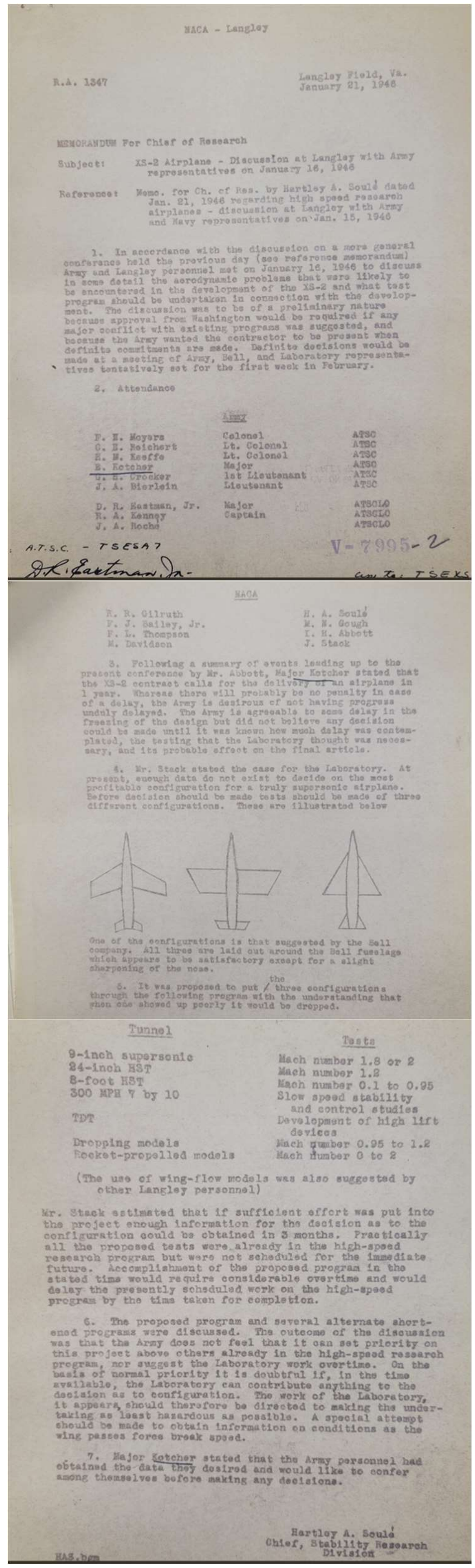
In a follow up memo, dated January 31, 1946, Hartley Soulé (Chief of Research at NACA/Langley) further memorializes this outcome of the meeting; see FIGURE 9.[42] It is clear from the context, that Bell was already the de-facto as well as the de-jure contractor to build the follow from the X-1. It is also clear that the initial expectation was for a swept wing X-2 to be delivered by early 1947.

The distribution list itself is fascinating.[42] On the NACA side were: 1) Hartley Soulé, the Chief of Research, 2) Bob Gilruth, who had expertise in the piloted flying qualities of aircraft, 3) F.J. Bailey, who worked in rotorcraft aerodynamics (hence compressible flow), 4) F.L. Thompson, who seems to have expertise in aircraft performance, 5) Ira Abbott, who had just completed wind tunnel testing a large compendium of 2-D sections and 6) John Stack, who similarly, had extensive wind tunnel test expertise as well as considerable involvement in the X-1 program. Stack himself, along with Lawrence Bell (proprietor of Bell Aerospace) and Chuck Yeager, would later win the Collier Trophy for the X-1. Interestingly, R.T. Jones – the author of the recent paper promoting wing sweep – was not on the distribution list.

This memo [42] also indicates that John Stack clearly stated that there was insufficient "hard data" to decide the aerodynamic configuration: whether the X-2 should have tapered swept wings (as it ultimately did), or some other planform. As seen in FIGURE 9, plans were made to wind-tunnel test Swept Wing, Delta Wing ($TR$~0) and a Straight Leading Edge but pointed wing tip ($TR$~0) derivatives of the X-1 at a variety of NACA facilities at speeds as high as Mach 2. We can see that the NACA's supersonic test capability was extremely limited at the time. Test data at Mach 1.8 and above was limited to either a 9-inch supersonic section (implicitly demanding a tiny model) or to a free-flight test atop a sounding rocket.

The memo indicates that wind tunnel and/or free-flight testing was imminent, and that some preliminary data would be available to influence decision making during the Spring of 1946; "could be obtained in 3 months."[42] This memo concludes with an expectation that the Army Air Force (i.e., Major Kotcher and his team) would review such data and "confer among themselves before making any decision."[42]

In NACA RM L6K08c, published in 1947 but drawing on earlier data for inspiration, Mathews & Thompson substantiated the efficacy of swept wings.[43] They found that transonic drag rise was substantially mitigated if they changed an unswept NACA 65-009 section wing to a 45° swept NACA 65-009 section wing.[43] While sweep led to "an appreciable reduction in drag between Mach numbers of 0.95 and 1.2," they noted that sweep had little effect at higher Mach numbers.[43]


NACA - Langley

R.A. 1347

Langley Field, Va.
January 21, 1946

MEMORANDUM For Chief of Research

Subject: XS-2 Airplane - Discussion at Langley with Army representatives on January 16, 1946

Reference: Memo. for Ch. of Res. by Hartley A. Soulé dated Jan. 21, 1946 regarding high speed research airplanes - discussion at Langley with Army and Navy representatives on Jan. 15, 1946

1. In accordance with the discussion on a more general conference held the previous day (see reference memorandum) Army and Langley personnel met on January 16, 1946 to discuss in some detail the aerodynamic problems that were likely to be encountered in the development of the XS-2 and what test program should be undertaken in connection with the development. The discussion was to be of a preliminary nature because approval from Washington would be required if any major conflict with existing programs was suggested, and because the Army wanted the contractor to be present when definite commitments are made. Definite decisions would be made at a meeting of Army, Bell, and Laboratory representatives tentatively set for the first week in February.

2. Attendance

Army

| | | |
|---|---|---|
| F. H. Moyers | Colonel | ATSC |
| C. E. Reichert | Lt. Colonel | ATSC |
| H. M. Keeffe | Lt. Colonel | ATSC |
| E. Kotcher | Major | ATSC |
| G. E. Crocker | 1st Lieutenant | ATSC |
| J. A. Bierlein | Lieutenant | ATSC |
| D. R. Eastman, Jr. | Major | ATSCLO |
| R. A. Kenney | Captain | ATSCLO |
| J. A. Roche | | ATSCLO |

A.T.S.C. - TSESA7
D.R. Eastman, Jr.

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TSEXS

NACA

| | |
|---|---|
| R. R. Gilruth | H. A. Soulé |
| F. J. Bailey, Jr. | M. N. Gough |
| F. L. Thompson | I. H. Abbott |
| M. Davidson | J. Stack |

3. Following a summary of events leading up to the present conference by Mr. Abbott, Major Kotcher stated that the XS-2 contract calls for the delivery of an airplane in 1 year. Whereas there will probably be no penalty in case of a delay, the Army is desirous of not having progress unduly delayed. The Army is agreeable to some delay in the freezing of the design but did not believe any decision could be made until it was known how much delay was contemplated, the testing that the Laboratory thought was necessary, and its probable effect on the final article.

4. Mr. Stack stated the case for the Laboratory. At present, enough data do not exist to decide on the most profitable configuration for a truly supersonic airplane. Before decision should be made tests should be made of three different configurations. These are illustrated below

One of the configurations is that suggested by the Bell company. All three are laid out around the Bell fuselage which appears to be satisfactory except for a slight sharpening of the nose.

5. It was proposed to put the three configurations through the following program with the understanding that when one showed up poorly it would be dropped.

| Tunnel | Tests |
|---|---|
| 9-inch supersonic | Mach number 1.8 or 2 |
| 24-inch HST | Mach number 1.2 |
| 8-foot HST | Mach number 0.1 to 0.95 |
| 300 MPH 7 by 10 | Slow speed stability and control studies |
| TDT | Development of high lift devices |
| Dropping models | Mach number 0.95 to 1.2 |
| Rocket-propelled models | Mach number 0 to 2 |

(The use of wing-flow models was also suggested by other Langley personnel)

Mr. Stack estimated that if sufficient effort was put into the project enough information for the decision as to the configuration could be obtained in 3 months. Practically all the proposed tests were already in the high-speed research program but were not scheduled for the immediate future. Accomplishment of the proposed program in the stated time would require considerable overtime and would delay the presently scheduled work on the high-speed program by the time taken for completion.

6. The proposed program and several alternate shortened programs were discussed. The outcome of the discussion was that the Army does not feel that it can set priority on this project above others already in the high-speed research program, nor suggest the Laboratory work overtime. On the basis of normal priority it is doubtful if, in the time available, the Laboratory can contribute anything to the decision as to configuration. The work of the Laboratory, it appears, should therefore be directed to making the undertaking as least hazardous as possible. A special attempt should be made to obtain information on conditions as the wing passes force break speed.

7. Major Kotcher stated that the Army personnel had obtained the data they desired and would like to confer among themselves before making any decisions.

Hartley A. Soulé
Chief, Stability Research Division

HAS.bgm

FIGURE 9 – Hartley Soulé memo on X-2 from January 31, 1946.[42]

In Kotcher's personal notes from a February 13, 1946, meeting with Soulé, flying qualities of swept wing aircraft were on the top of the agenda.[44] These notes are revealing, as congenital lateral-directional instability led to the hull-loss of the final X-2 and the death of test pilot Mel Apt in 1956.[23][24][27][45][46]

Let us begin with Page 1; see FIGURE 10.[44] Here we see a discussion of effective dihedral (-*dCl/dβ*) as a function of lift coefficient (*CL*). They note that the effective dihedral (-*dCl/dβ*) rises with angle of attack ($\alpha$) and hence lift coefficient (*CL*). Turn next to FIGURE 11, where we can see the results of vortex-lattice modeling of the as-built X-2 in comparison to the as-built X-1 reflect this trend.[21][46][47][48] At the same time, we note that the swept wing X-2 does not have substantially different dihedral effect than the X-1. Thus, from the outset Kotcher and Soulé had a solid concern for the need to consider lateral-directional stability in the preliminary design of the X-2.

Next consider the second sketch on Page 1; returning to FIGURE 10.[44] This reflects a plot of "effective" directional stability as a function of "effective" dihedral; what appears to be a plot of *dCn/dβ* as a function of -*dCl/dβ*. They correctly note that an aircraft with excessively positive directional stability and minimal dihedral effect tends to spiral divergence; i.e., to "corkscrew" out of control. Conversely, if the dihedral effect is strong, the vehicle will exhibit a pronounced, but stable Dutch Roll mode. The sketch indicates a desire to keep the X-2 free from spiral divergence while avoiding an energetic Dutch Roll mode. The notes indicate that the NACA believed that aircraft should have *dCn/dβ*~0.01.

Turning next to FIGURE 12, where we can see the results of vortex-lattice modeling of the as-built X-2 in comparison to the as-built X-1.[21][46] Our analysis shows that at low speeds the X-1 had about half the desired directional stability. At the same time, the "as-built" X-1 had considerably greater (about 4x) directional stability than the "as-built" X-2, which was only weakly directionally stable at low angles of attack (roughly 1/3 to 1/10 the recommended level). While the X-2 avoided spiral divergence at low speeds, its weak static directional stability would prove to be its downfall.[24][46]

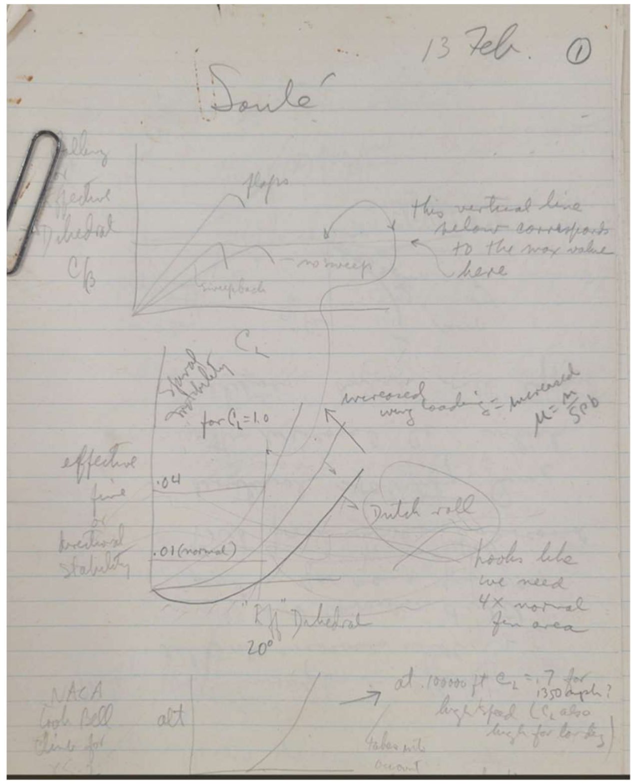

FIGURE 10 – Kotcher meeting notes with Hartley Soulé from February 13, 1946 – Page 1.[44]

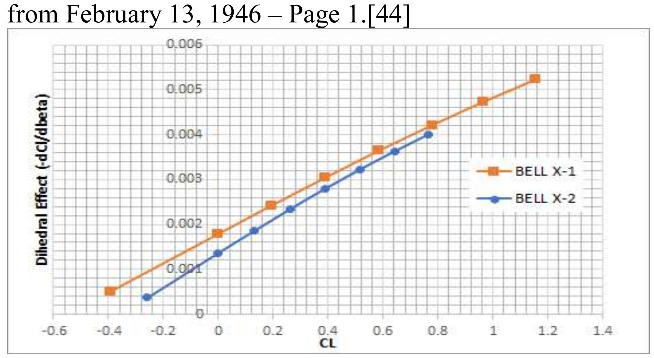

FIGURE 11 – VORLAX solutions of lateral stability (-*dCl/dβ*) vs Lift Coefficient (*CL*) for the "as-built" Bell X-1 and X-2 configurations. Mach=0.1.

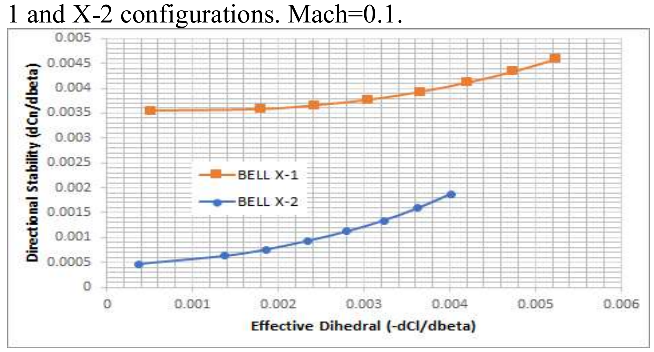

FIGURE 12 – VORLAX solutions of directional stability (*dCn/dβ*) vs lateral stability (*dCl/dβ*) for the Bell X-1 and X-2 configurations. Mach=0.1.

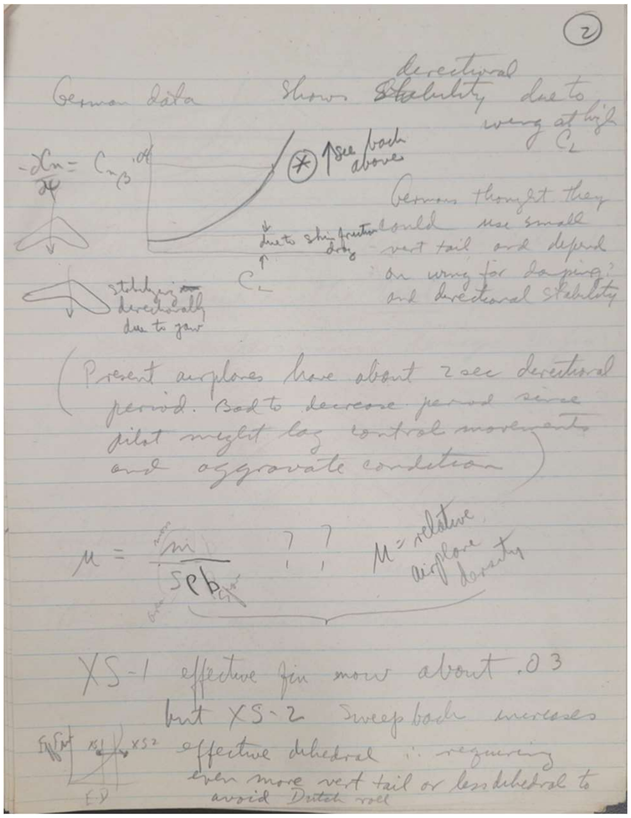


FIGURE 13 – Kotcher meeting notes with Hartley Soulé from February 13, 1946 – Page 2.[44]

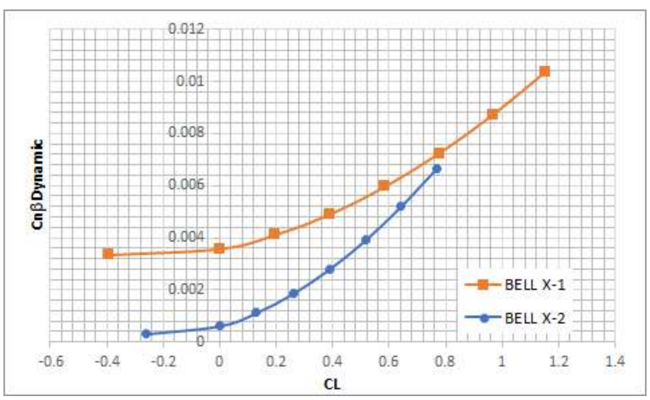


FIGURE 14 – VORLAX solutions of Dutch-Roll (combined lateral-directional) stability (*Cnβ* dynamic) vs Lift Coefficient (*CL*) for the "as-built" Bell X-1 and X-2 configurations. VORLAX solutions run at Mach=0.1.

FIGURE 13 continues the line of reasoning. It begins with the observation that "German data shows (that) directional stability (increases) due to the (swept) wing at high *CL*."[44] It explains that "Germans thought they could use a small vertical tail and depend on the wing for … directional stability."[44] It continues noting that "present airplanes have about 2-second directional period;" this reflects the stable Dutch Roll mode with a frequency of ~0.5-Hz ($\omega_{DR}$ ~3.1-rad/sec). The modern MIL 8785C recommends that $\omega_{DR}$ be faster than 1-rad/sec (a ~6-sec period) for LEVEL I flying qualities.[30] Thus, there was evidence of a desire to have the X-2 exhibit "LEVEL I" Dutch Roll characteristics.

What becomes obvious in hindsight is that the *Cnβ* discussed in 1946 is what today, we would call *CnβDynamic*.[23][24][29] Recall that the Dutch-Roll frequency in radian/sec may be estimated by:

$$\omega_{DR} \approx \sqrt{\frac{57.3\, C_{n\beta dynamic}\, \bar{q}\, Sref\, b}{I_{zz}}}$$

Where:

$$C_{n\beta dynamic} = \frac{dCn}{d\beta}\cos(\alpha) - \frac{dCl}{d\beta}\sin(\alpha)\left(\frac{Izz}{Ixx}\right)$$

If *Cnβdynamic* goes negative, the aircraft will not oscillate; it will depart.

At low angles of attack, *Cnβdynamic* is dominated by the static weathercock stability (*dCn/dβ*). As the angle-of-attack increases, the dihedral effect plays an additional stabilizing role (*dCl/dβ<0*).[24][29]

We may compute *Cnβdynamic* from our aerodynamic data and our known mass properties. For the Bell X-1, *Izz/Ixx*~ 5.4; for the Bell X-2, *Izz/Ixx* ~ 5.8.[21][24][46] In FIGURE 14, we can see the exact trends as discussed between Kotcher and Soulé when we plot *Cnβdynamic* as a function of *CL*. With its swept wings and relatively small tail, arising from the "German school," the X-2 has weaker Dutch Roll action than the X-1 at low *CL* and somewhat stronger Dutch Roll action as *CL*> 0.7. Kotcher and Soulé correctly note that a swept wing aircraft requires either wing anhedral or increased vertical tail area to present a well damped Dutch Roll. In retrospect, Skow in AGARD CP-235 [48] recommended that *Cnβdynamic* be greater

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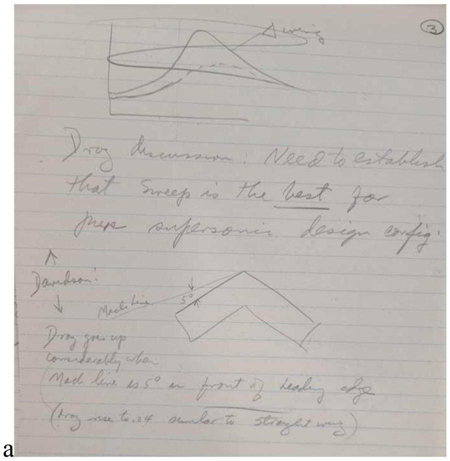


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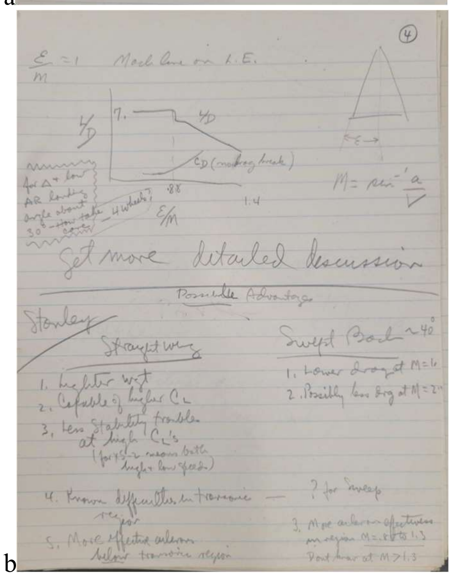


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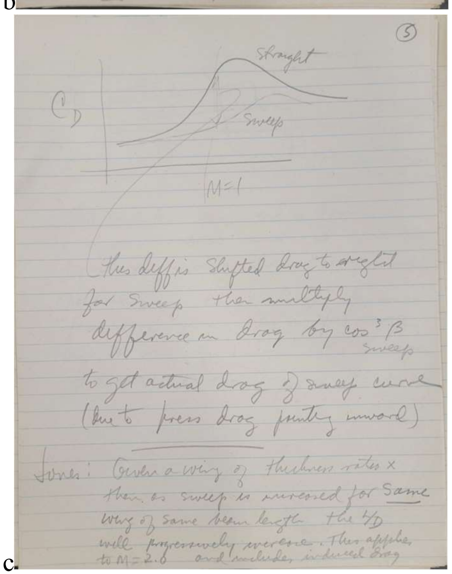


FIGURE 15 – Kotcher meeting notes with Hartley Soulé from February 13, 1946 – Pages 3,4 and 5.[44]

than +0.004 to ensure adequate stability to prevent yaw departures regardless of the implied Dutch-Roll frequency; author Takahashi concurs.[24] While the X-1 satisfies Skow's Criteria at positive *CL* at low Mach numbers, the X-2 was never given sufficient vertical tail area to have satisfactory Dutch Roll characteristics at low *CL*.

Kotcher and Soulé fretted over the "need to establish that sweep is the best for pure supersonic design;" see FIGURE 15a.[44] They noted that "drag goes up considerably when the Mach line is 5º in front of the leading edge" of the wing.[cite] A highly swept delta wing was considered briefly; but quickly discarded for difficulties associated with excessive nose-high attitudes needed for a slow landing; see FIGURE 15b. To continue on with a higher powered aircraft with a straight wing (what was eventually built as the Bell X-1A through Bell X-1E) [45] was lower risk in that the straight wing would be lighter, and capable of higher *CL* with fewer known stability issues (i.e. excess Dutch Roll and better aileron performance) but would the resulting airframe would continue to experience sub Mach 1 transonic issues common to other straight wing aircraft. They predicted the 40º swept wing design to have demonstrably lower drag right around Mach 1 and probably have lower drag at Mach 2. With transonic buffet reduced, they expected the swept wing design to have better aileron control in the critical 0.8 < M < 1.3 range.

In FIGURE 15c, we see that RT Jones seems to have joined the conversation. He noted that if we increase the sweep of a wing of fixed *t/c* ratio holding the "beam length" (i.e., tip-to-tip wingspan) constant, the aerodynamic efficiency should increase. He held that this increase would still be evident at Mach~2, where the leading-edge flow would be fully supersonic.

All taken, the X-2 team seems to have settled on a leading-edge sweepback angle of ~40º; this represents a design where drag rise would likely onset around Mach 1.2 and the wing leading edge would transition from subsonic to supersonic flow at Mach 1.3. Above Mach 1.3, through the eventual Mach 3+ top-speed, the wing would experience fully supersonic leading-edge flow.

The possibility of practical supersonic flight led the NACA to also consider airfoil shapes that fundamentally differed from conventional blunt leading-edge profiles. Studies undertaken in 1946 compared and contrasted round-nose against sharp-nose airfoils.[49] Not only did sharp-nosed airfoils promise substantially better supersonic performance than round-nosed airfoils, but Alexander's work found that the "Bi-Convex" or "circular-arc" airfoil had only marginally inferior transonic performance to the 65-xyyy series.[49]

With flight speeds in excess of Mach 2 contemplated, it seemed obvious to incorporate the "Bi-Convex" section onto the X-2.

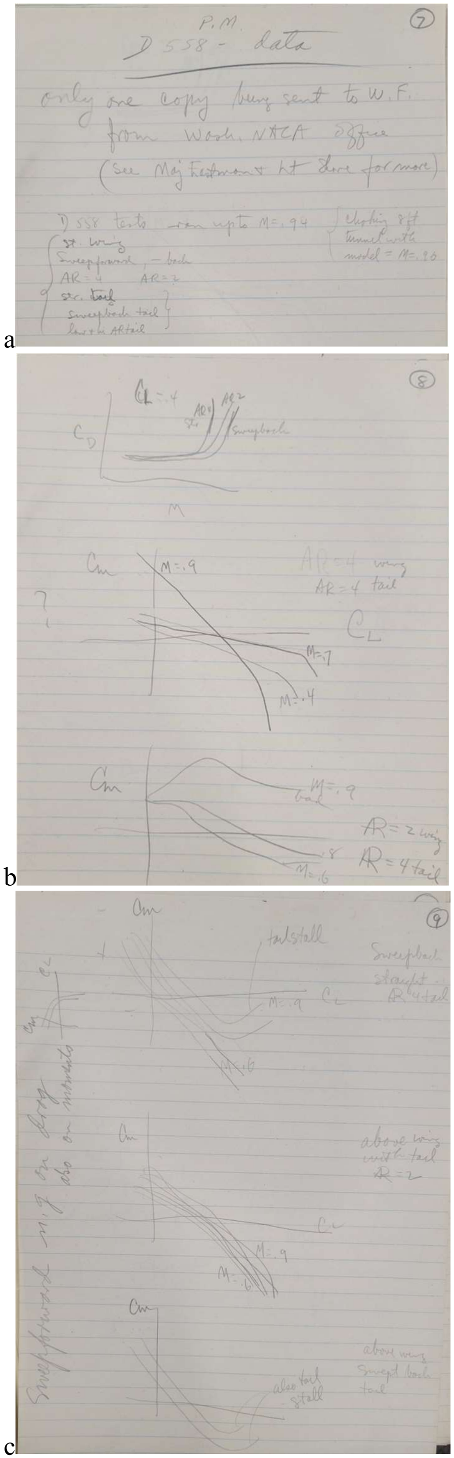


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FIGURE 16 – Kotcher meeting notes with Hartley Soulé from February 13, 1946 – Pages 7,8 and 9.[44]

The conversation next turned to longitudinal stability.[44] Kotcher had a desire to understand what sorts of things had the NACA and Douglas discovered during the development of their D-558 Phase I turbojet transonic research aircraft. As a Navy project, the NACA shared only limited information with the Army Air Force office at Wright Field. In these discussions we realize that the NACA was unable to attain wind tunnel data above Mach 0.94 freestream as a result of shock formations ("choking") at the 8-ft tunnel.

Evidently, the NACA had already wind tunnel tested the D-558 in both straight ("as flown" for Phase 1), forward-swept (abandoned) and aft-swept ("as flown" for Phase 2) wing configurations. The higher *AR* straight wings had inferior transonic drag performance as compared to the low *AR* configurations; wing sweep further improved transonic drag.[44] These trends are all consistent with extensive computational studies led by author Takahashi in 2010.[50].

- The *AR*=4 straight wing / *AR*=4 tail configuration exhibited strong changes in its aerodynamic-centre location; growing considerably more stable as the configuration approached sonic.

- The *AR*=2 straight wing / *AR*=4 tail configuration exhibited strong changes in its aerodynamic-centre location; this configuration tended towards neutral or instability as the configuration approached sonic.

- Forward sweep wings were poor regarding pitching moments and aerodynamic stability.

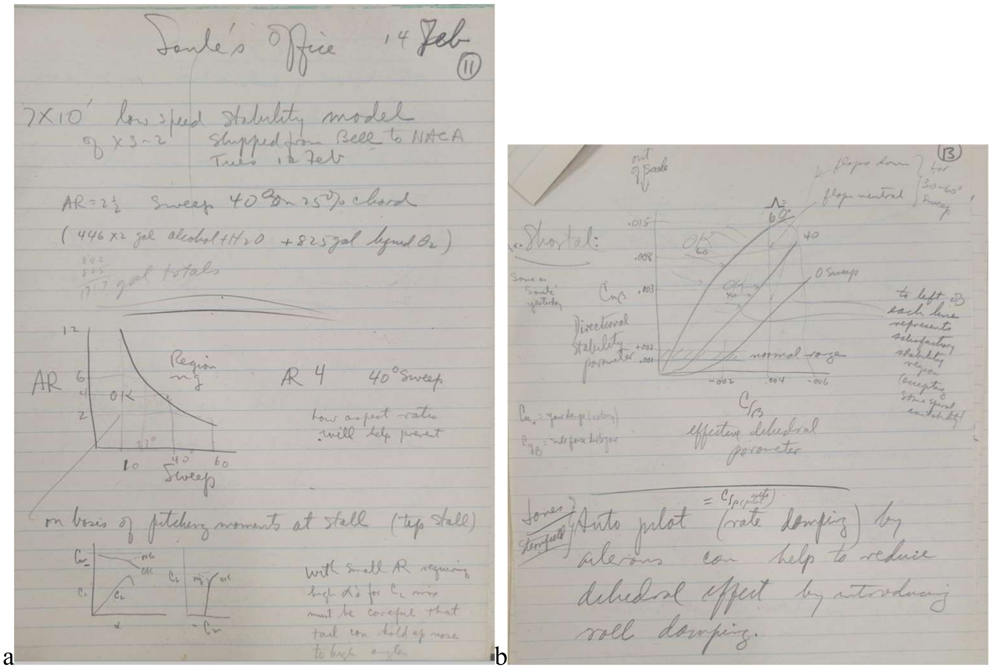
- The sweptback wing / *AR*=4 straight tail configuration had relatively benign basic stability; but tended towards a "tail stall" driven unstable pitch-up at high *CL* at transonic speeds.

- Only the swept back wing with the *AR*=2 tail configuration had benign and desirable stability across the tested speed and *CL* envelope.

With that, Kotcher adjourned the day.

The next morning, February 14, 1946, the working meeting began afresh in Soulé's office; see FIGURE 17 (overleaf).[51] Examining pitch-break data later published by Shortal & Magin [52], they determined the benign stall region of design space for an aircraft with 40$^{o}$ of wing sweep. Shortal & Magin's data indicated that *AR*<4 to guarantee favorable longitudinal flying qualities at high-angles-of-attack; see FIGURE 18 (overleaf). Kotcher noted that with "small *AR*'s requiring high $\alpha$'s for *CLmax*,[we] must be careful that [the elevator on the horizontal] tail can hold up [the] nose."[51]

Thus, set the stage for the basic swept wing configuration for the X-2. Kotcher was convinced that pitching moment characteristics could be tamed with a straightforward horizontal tail design, it would proceed forwards with a 40$^{o}$ *AR*=4 wing.



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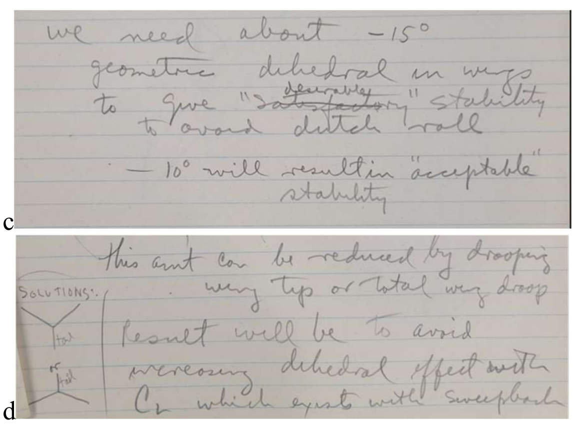

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FIGURE 17 – Kotcher meeting notes with Hartley Soulé from February 14, 1946.[51]

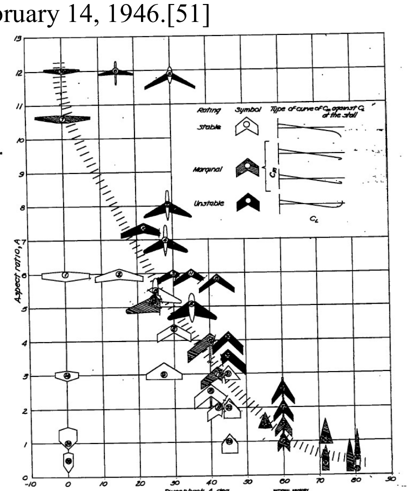



FIGURE 18 – Shortal & Magin Empirical Chart for longitudinal Stability from NACA.[52]

With Shortal in the room, the conversation returned to lateral-directional stability and controllability. The necessary directional stability ($dCn/d\beta$) and hence vertical tail size became the topic of discussion. With relatively strong dihedral effect arising from the wing ($dCl/d\beta \sim -0.006$), Shortal recommended the design to have $dCn/d\beta$ greater than +0.008 to ensure favorable flying qualities; "to the left of each line represents satisfactory stability region accepting some spiral instability."[51] This this is even more stable than Skow [48] or Takahashi, Griffin & Grandhi [24] would suggest many years in the future. It also is in concurrence with MIL 8785C [30] and the modern MIL-1797A [31] both of which accept some degree of spiral instability (i.e., with Spiral Mode time-to-doubles no shorter than 4-sec) in an aircraft so long as the Dutch Roll mode is clearly stable.

The issue of excess aerodynamic Dihedral continued to vex the team. R.T. Jones seemed to be an early advocate of the idea that the "computer can fix it" when he suggested that an "autopilot" could provide synthetic roll damping that would help mitigate the excess Dihedral effect.[51] Other ideas included having the wings express significant anhedral (-10 to -15°) or having a ventral vertical fin (a "Y" tail) or configuring the horizontal tailplane to have significant anhedral (an "inverted Y" tail).

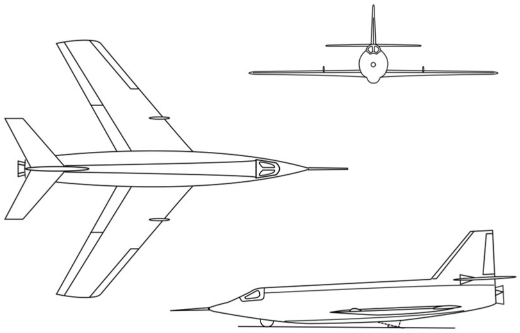
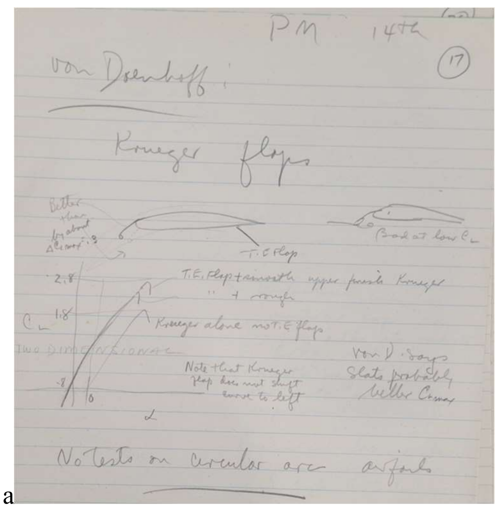


FIGURE 19 - “As Flown” X-2 Configuration with zero geometric Dihedral and a simple “inverted T” tail. Note presence of outboard leading-edge slats, inboard trailing edge flaps, stall fences.[44]



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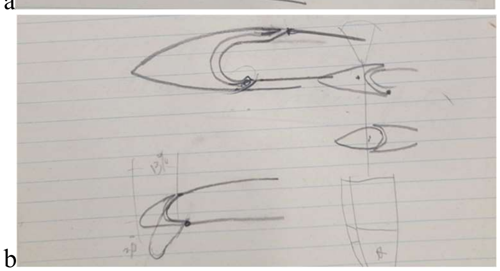
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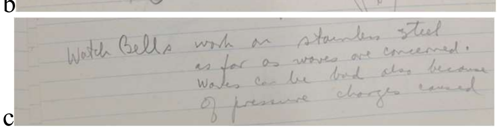

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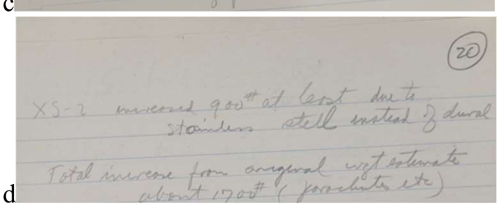

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FIGURE 20 – Kotcher meeting notes with Hartley Soulé and Albert von Doenhoff from February 14, 1946.[51]

On the afternoon of February 14, 1946, Kotcher met with Albert von Doenhoff.[51] They discussed the need for the X-2 to incorporate high-lift (low-speed) devices.

As we can see from FIGURE 19, the “as-flown” X-2 features outboard leading-edge slats, inboard trailing edge flaps and stall fences.[53] It is clear from this meeting that the preferred main wing would feature a “circular arc,” bi-convex airfoil. Von Doenhoff noted that no tests had yet been completed of flapped versions of such an airfoil; see FIGURE 20.[51] He noted that a Krueger (simple) leading edge flap could considerably increase the stall angle of attack and that a Krueger leading-edge plus a trailing edge flap could lead to section *CL*’s as high as 2.8 at stall. He correctly speculated that a true leading-edge slat would prove even more effective. Together they sketched out various “drooped snoot” leading edge configurations.

With Mach 3+ performance expected, the team had realized that friction heating would render uninsulated Aluminum useless for the primary structure. Stagnation temperatures were expected to exceed 600ºF. We can see here that a change from aluminum to stainless-steel construction could lead to waviness in the “as-built” geometry that would negatively impact aerodynamic performance. There was also concern about the weight impact of such a materials change. The aluminum Bell X-1 had an operational empty weight of ~7,000-lbm; the team estimated that the X-2 would clock in with at least a 900-lbm penalty in structural weight due to the materials substitution. In hindsight, this was highly optimistic; see FIGURE 20. When actually completed, the X-2 had an operational weight of ~12,375-lbm; with no further revision to wing or tail area.[45][53]

The meeting adjourned.

The whole group reconvened the next morning, February 15, 1946; see FIGURE 21 (overleaf).[54]

The following action items arose:

- Bell would send NACA (John Stack) drawings in ~2-weeks (early March 1946)

- NACA would test 2-D sections of the “circular arc” airfoil, with both trailing-edge and a variety of leading-edge flaps.

- NACA will make all high-speed (Mach 0.8 to choking) data available for circular arc sections.

- Within 90 days (i.e., by the end of June 1946), NACA would perform low-speed tests of a full configuration wind tunnel model “resembling” the Bell proposed configuration. It would have a variety of wings and tails, including “vertical tips below wing,” slanted tips, “cathedral” (i.e., anhedral), more vertical fin area (limited by B-29 captive carry constraints), “circular arc” (i.e., Bi-Convex) airfoils, Krueger flaps and trailing edge flaps.

- NACA will test the X-2 in the Mach 1.4 to 2.0 range in the 9-inch supersonic tunnel. In addition to getting pitch data, the NACA will rotate the supersonic model 90° to get some amount of sideslip data (albeit at $\alpha \sim 0^{\circ}$)

The urgency of these tests relates to the need to “have possible influence on [the X-2] airplane design.”[54]

## V. Aerodynamic Data arising from Kotcher’s X-2 Development Meetings

The results of some of these tests have been preserved in the open literature.

The initial high-subsonic speed “circular arc,” 2-D bi-convex airfoil data is found in NACA TN-1211, dated March 1, 1947.[55] This compendium includes Schlieren imaging as well as lift, drag, pitching moment and surface pressure results tested at freestream Mach numbers from 0.3 through ~0.9 (where tunnel choking became severe). A NACA 2S-50 “circular arc” section, very similar to that used on the “as-built” X-2 was among the many sections tested; see FIGURE 22. Test data noted transonic lift divergence around Mach 0.85 at $C_L \sim 0.2$ with almost no change in pitching moment through the troublesome transonic region. This seemed like a good omen for the X-2.

We find wind tunnel test data of a swept circular arc wing both in the cruise configuration and with deployed inner-part-span split flaps and outer-part span leading edge slats is documented in NACA RM L7H23, L7E13 and L7I30, all dating from 1947; see FIGURE 23, overleaf.[56][57][58] This is almost identical to the “as built” configuration of the Bell X-2. In the clean configuration, *CLmax* was ~0.8; with flaps and larger slats deployed, *CLmax* rose to ~1.4 at $\alpha \sim 20^{\circ}$ with a stable stall break. “Comparison of the characteristics of the circular-arc wing with those of a wing of NACA $64_1$-112 sections showed that the circular arc wing had a rapid decrease in effective dihedral with lift coefficient above a lift coefficient of 0.35; whereas for the NACA $64_1$-112 wing, the effective dihedral increased continuously up to the maximum lift.”[58] Once again, this seemed to support the basic configuration of the X-2.

Total configuration aerodynamics as tested in the Langley 7x10-ft subsonic tunnel are found in NACA RM L7G28 and L7G31, dating

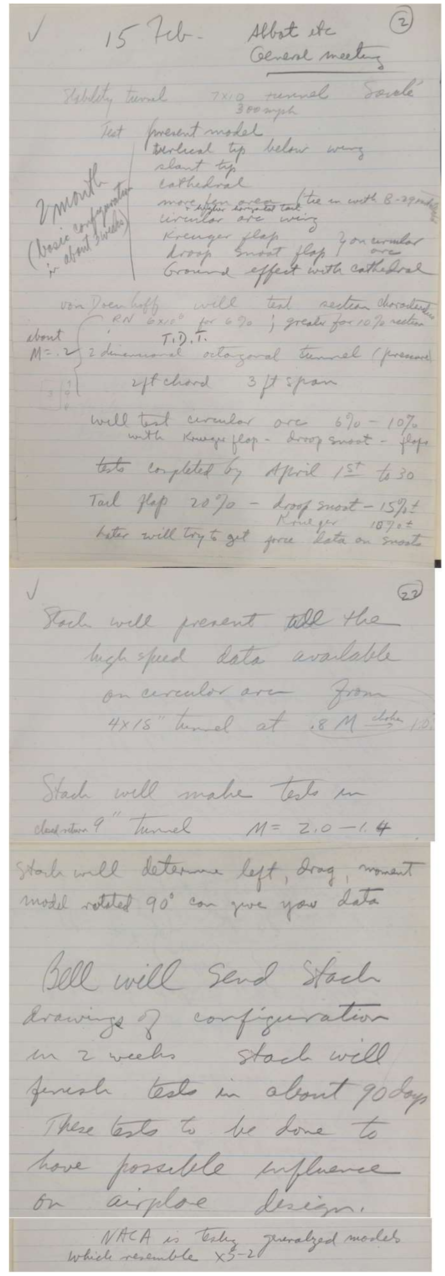

15 Feb. Albot etc General meeting
Stability tunnel 7x10 tunnel Scale 300 mph
Test present model
vertical tip below wing
slant tip
cathedral
more fin area (tie in with B-29)
circular arc wing
Krueger flap
droop snoot flap } on circular arc
Ground effect with cathedral
2 month (basic configuration in about 3 weeks)
von Doenhoff will test section characteristics RN 6x10^6 for 6% ; greater for 10% section
about M=.2 T.D.T. 2 dimensional octagonal tunnel (pressure)
2 ft chord 3 ft span
will test circular arc 6% – 10% with Krueger flap – droop snoot – flaps
tests completed by April 1st to 30
Trail flap 20% – droop snoot – 15% ± Krueger 18% ±
later will try to get force data on snoots
Stack will present all the high speed data available on circular arc from 4x18" tunnel at .8 M
Stack will make tests in 9" tunnel M = 2.0 – 1.4
Stack will determine lift, drag, moment model rotated 90° can give yaw data
Bell will send Stack drawings of configuration in 2 weeks Stack will finish tests in about 90 days These tests to be done to have possible influence on airplane design.
NACA is testing generalized models which resemble X-2

FIGURE 21 – Kotcher close out meeting notes from February 15, 1946.[45]

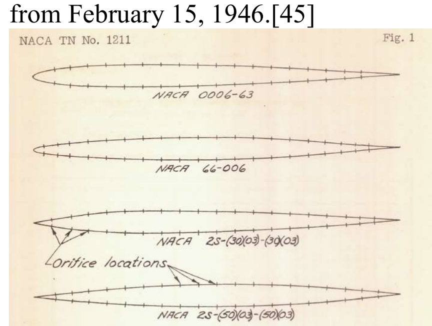



FIGURE 22 – Early Circular Arc Airfoil Test Data from NACA TN-1211, 1946.[46]

from October 1947.[59][60] This model is visually nearly identical to the "as-built" X-2; see FIGURE 24. As discussed in February, the NACA produced a reconfigurable model.

Parametric studies involved wing dihedral or anhedral ("cathedral") as well as low and mid wing mounting of the wing. The cruciform junction of the horizontal tailplane to the vertical could be moved up and down. We also see parametric sizing studies regarding the vertical fin; they tested a "small"(12% of the main wing) and a "large" (16.4% of the main wing) variant.

With a clean wing, the airframe became longitudinally unstable at moderate angles of attack. Stall control fences "remove the longitudinal instability present below-stall in the flaps-neutral condition."[59] They believed that "the stalling tendency … will nevertheless not be unduly dangerous."[59] Raising the height of the horizontal tail on the vertical made for a "considerable improvement in the [flap retracted] stability in the high lift range."[59]

Initial tests revealed that the effective dihedral for the mid-wing zero-dihedral configuration peaked just as the main wing stalls. Effective dihedral was reduced with a low-wing configuration. Additional geometric dihedral increased aerodynamic dihedral. All of these effects are to be expected.[60]

The test also revealed that the baseline "small" vertical tail was extremely undersized. The directional stability of the mid-wing configuration was very low below stall and unstable post stall. With the low-wing configuration, the static directional stability was better at all angles of attack.[60]

The test also indicated that the "large" vertical tail remained undersized. With the low-wing and large vertical tail, $dCn/d\beta \sim +0.001$; this closely matches the VORLAX computations shown above in FIGURE 12 and remains far below Shortal's +0.008 recommendations. At $CL{\sim}0.3$, $dCl/d\beta{\sim}{-0.002}$; this also closely matches VORLAX computations shown above as FIGURE 11.

Total configuration aerodynamics as tested in the Langley 9-inch supersonic tunnel are found in NACA RM L7J15 dating from December 1947.[61] The authors freely state that the "configurations tested do not represent designs approximating optimums from present-day considerations, since their basic lines were conceived in the early part of 1946."[61] The hint at the X-2 by stipulating that "the models represent two versions of a supersonic research airplane."[61] Despite these reservations, we can see that the "low wing" variant is remarkably close to "as-built" X-2 and reflects essentially the same geometry tested in the low speed tunnel; compare FIGURE 25 with FIGURE 24. Given the tiny tunnel cross section, this small model lacked control surfaces. The model was configured to be tested both upright (giving angle-of-attack lift, drag and pitching moment data) or rotated (to give sideslip dependent side force and yawing moment data). There was no provision to obtain rolling moment (i.e., dihedral effect) data from this test.

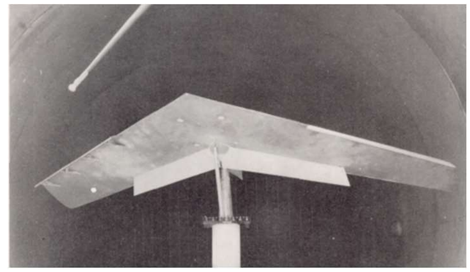


FIGURE 23 – Low-Speed WT test of ~40º sweep "circular arc" wing with part span TE split flap and part span LE slat. NACA RM L7I30.[49]

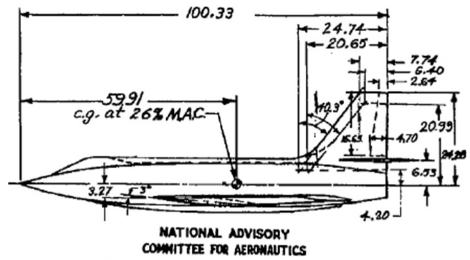



FIGURE 24 – Low Speed WT test geometry (low-wing, "large" vertical tail) from NACA RM L7G31.[51]

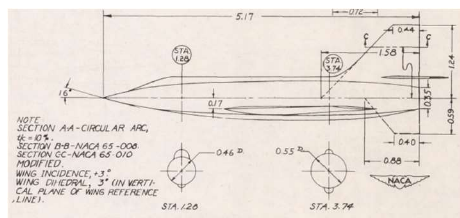


FIGURE 25 - High Speed Test Geometry from NACA RM-L7J15.[52]

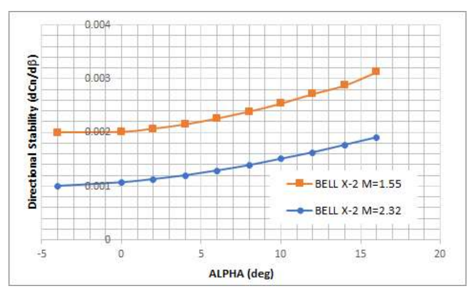



FIGURE 26 – Bell X-2 VORLAX Predicted Supersonic Directional Stability

The facility had a three-position nozzle that could develop freestream flows at Mach ~1.55, ~1.90 and ~2.32. Test data found $dCn/d\beta \sim +0.0025$/deg at $\alpha=0^o$, Mach 1.55 declining to +0.001/deg at $\alpha=0^o$, Mach 2.32.[61] We find these trends generally match VORLAX computations and fall far below Shortal's +0.008 recommendations.

As of test completion for both low-speed and high-speed (presumably sometime during 1946 based on the report dates), it should have become clear to the team that the static directional stability of the X-2 was lacking due to its substantially undersized vertical tail.

What is also clear, in hindsight, is that minimal aerodynamic configuration changes were made to the X-2 between the initial "sketch" from early 1946 and the "as-flown" configuration. In addition, the "design freeze" was made in the absence of any but the most rudimentary stability-and-control analysis – zero-lift directional stability, subsonic-only lateral stability, no aileron, or rudder data.

FIGURE 27 – Bell L-39-2 Swept Wing Testbed Aircraft with "Circular Arc" Airfoil Wing [53]

We must also remember that Bell was busy during 1946.

In addition to supporting the design effort for the X-2, Bell had to ready their X-1 for powered flight. After that inauspicious first glide flight at Pinecastle, Jack Woolams flew nine additional flights through early March 1946 whereupon the airframe returned to Buffalo for rocket motor installation. It would take more than six months before the X-1 was ready to fly again. In the meantime, Jack Woolams died in a P-39 crash in August 1946; thus, other test pilots would have to complete the program.

FIGURE 28 – Vertical Tail Fin Modifications to the Bell L-39-2 Swept Wing Testbed Aircraft.[54]

Conspiring with the US Navy, Bell had also built and flown a swept, "circular arc" wing on a modified P-63 piston engine fighter; see FIGURE 27.[62] This aircraft, designated the L-39-2, was used to flight test the wing concepts described in NACA RM L7H23, L7E13 and L7I30.[62][56][57][58] Absent part span slats, it is said to have had poor stall characteristics.[62] Control coupling was prevalent; test Pilot John Griffith wrote that "the L-39 was the first airplane I ever flew in which you could push on the left rudder and the airplane would roll right."[63] Bell also found weak directional stability and enlarged the vertical tail on more than one occasion during its brief flight test program.[62][64]

Ezra Kotcher was also busy; he moved on to become the founding director of the Air Force Institute of Technology.

With a now absent "father," both the X-1 and X-2 would go on to live and or die by decisions made in early 1946.

## VI. Initial Flight Testing of the X-1 did not Reveal any Lateral-Directional Stability Issues

After Woolams experiences with the initial glide test program at Pinecastle, both Bell and the Army Air Force decided to relocate to Muroc AAF (now Edwards, AFB).

With rocket motor installed and X-1 No. 2 (10% *t/c*) and B-29 carrier aircraft transferred to Muroc, flight testing could continue. Woolams' replacement, "Slick" Goodlin was able to complete his first glide test flight on October 11, 1946. "Goodlin reported that he had "considerably" over controlled the airplane because of the lightness of its controls and he recommended that the friction in the control system should be increased."[3]

The X-1 had its first powered flight on December 9, 1946. Air launching at ~27,000-ft, Goodlin ignited two of the four rocket chambers and climbed to 35,000-ft and attaining Mach 0.795 before cutoff. With the increased friction in the control stick, Goodlin judged the low to moderate speed handling characteristics of the XS-1 to be very good.[3] By the end of February 1947, Goodlin had completed 12 powered flights in the No. 2 aircraft reaching Mach 0.828.

The thin wing X-1 No. 1 (8% *t/c*) arrived at Muroc in the Spring of 1946. After a single glide flight, it was first flown under rocket power on April 11, 1946.[45] By early June, Bell completed its airworthiness "certification" with a total 15 glide and 22 powered flights and turned the aircraft over to the Government.[3][45]

Absent Kotcher, the NACA and the Army Air Force began to squabble. The NACA sought a very cautious envelope expansion program focusing on flights just in excess of the anticipated Critical Mach number; the Air Force was much more aggressive. As early as April 1946, Colonel George Smith informed NACA management that "if the NACA was unwilling to fly in [a potentially hazardous flight] regime, …. the aircraft would be returned to AAF jurisdiction."[3] Young muses that "NACA would proceed with extreme caution and probably consume a lot of time before it attempted to make an actual assault on Mach 1 [as] the test plan … would take at least a year to complete and it had never directly addressed the issue of breaching the sonic wall."[3] He also re-iterates that "from the Army Air Force's point of view … achieving Mach 1 in the shortest possible time was … the primary objective of the XS-1 program."[3]

With the NACA dragging its feet, Colonel Smith pressed Bell to take on a fixed-price contract to continue flight test and exceed Mach 1; Bell demurred.[3] On May 1, 1947, Smith began a serious effort to move flight test responsibility directly to the Army Air Force Flight Test Division; on June 24, 1947, General Spaatz agreed.[3] Now it was time for the Air Force to deliver. Shortly thereafter, Colonel Boyd, Chief of the Flight Test Division at Muroc, selected a young combat ace, Charles "Chuck" Yeager as his test pilot.[3] The rest is history; see FIGURE 29.

Flying the rebuilt, thin-wing X-1 No. 1, Yeager rapidly proceeded through an envelope expansion program. His first gliding flight was on August 6, 1947.[45] By August 29, 1947, he moved onto powered flights.[43] Yeager noted light buffeting beginning at an indicated Mach number of 0.86 increasing in severity as he accelerated faster.[3] Pitch trim controls became erratic, and the aircraft needed ~50% available aileron in order to remain in wings-level flight.[3] Careful adjustment of the all-moving horizontal tailplane (rather than the elevator) was needed to maintain pitch trim; the all moving horizontal tail was a fundamental part of the X-1 design, not a last minute "fix."[3]

EXTRA

RACE RESULTS

Los Angeles Times

Pictorial

VOL. LXVII — MONDAY MORNING, DECEMBER 22, 1947 — DAILY, FIVE CENTS

U.S. MYSTERY PLANE TOPS SPEED OF SOUND

Suicide Pact Fatal to Man; Wife May Die

Pair Take Sleeping Pills and Write Loving Note to Son

CRACKS SOUND WALL—The mystery American rocket plane XS-1 which pierced the wall of sound for the first time is depicted above by Times Staff Artist Harlan Kirby as it might have looked when dropped from the belly of a Superfortress over desert for its historic flight.

Test Pilots Pierce Dread Barrier at 70,000 Feet Altitude Above Desert

BY MARVIN MILES

Three Americans have pierced the wall of sound!

The dread barrier to supersonic flight was first conquered at Muroc Air Base early last month when Capt. Charles Yeager, Air Force pilot, hurtled the XS-1 rocket plane through the wall at approximately 70,000 feet, The Times learned from reliable sources.

Howard Lilly and Herbert Hoover, test pilots for the National Advisory Committee for Aeronautics, duplicated Yeager's feat in the same bullet-like experimental ship after being dropped from the belly of a Superfortress over the desert base.

Three Win International Race

In cracking through the invisible ocean of compressibility the three men won an international race for supersonic honors and on at least one flight the world's aircraft altitude record—56,336 feet—was toppled by the bright orange Bell speedster.

None of the three pilots experienced any ill effects from hurtling through the barrier nor was the XS-1 damaged in any way from the gargantuan pounding, it was learned.

The Air Force first announced the experimental ship last year with the words: "The plane has been designed to reach about 1700 m.p.h. at 80,000 feet altitude."

Just what speed was attained remains a closely guarded military secret, but it is known that the wall was probably pierced at about 664 m.p.h. at altitudes ranging from 40,000 to 70,000 feet.

Speed Past Barrier Almost Unlimited

Before the flights were made theorists estimated that any plane that broke through the heaving turbulence could slide on up to almost any speed, depending on the amount of fuel available.

Hence the speed attained by any one of the three XS-1 pilots might have touched anywhere from 664 m.p.h. up to the Air Force estimate of 1700 m.p.h.

Best estimate, however, with the present rocket power available in the XS-1, is 900 to 1000 m.p.h. The original Air

FIGURE 29 – Newspaper reports of Chuck Yeager "Breaking the Sound Barrier" with Bell X-1 Rocket Plane.[65]

On October 14, 1947, Yeager successfully expanded the flight envelope past the sonic limit.[1][2][3][19][45] Igniting three of the four available rocket cambers, he rapidly accelerated to an indicated speed of Mach 0.98. After some momentary fluctuations, the meter passed the end of its scale. Yeager felt no violent buffeting or any other indication that he had just passed through a dreaded "barrier." Post flight analysis determined he reached a speed of Mach 1.06 at ~45,000-ft before shutting down his engine, then descending in a glide to home at Muroc. Despite its inherently weak static directional stability, the X-1 was a success.

The Air Force continued to test the X-1 throughout the fall of 1947 and on into 1948 and 1949.[45] Yeager topped Mach 1.45 on Mach 26, 1948.[43] Once the speed envelope had been explored, the X-1 flew a series of alternative missions collecting surface pressure measurements. The Air Force flight test program concluded on May 12, 1950, with Yeager at the helm flying a mission supporting the filming of the Hollywood move “Jet Pilot.”[45]

Meanwhile the NACA began its flight test program on the thicker wing X-1 No. 2.[45] Test pilot Bob Hoover made his first flight on October 21, 1947. Following a systematic and cautious schedule, Hoover broke the sound barrier on his tenth flight, on March 10, 1948. The NACA continued to regularly fly X-1 No. 2 throughout 1949 and 1950. Test Pilot Joe Walker flew the last first series X-1, the 157$^{th}$ of the program, on October 23, 1951.

## VII.Higher Powered X-1 Derivatives Suffered from Inadequate Directional Stability

In 1944, the NACA and Army Air Force commissioned Bell Aerospace to build three additional X-1 airframes.[45] The third first-series X-1 went basically unused; it was converted to become the X-1E and join three other new-construction second generation airframes: the X-1A, X-1B and X-1D. These second-series X-1 aircraft featured a more conventional canopy, a fuselage stretched 4.5-ft to greatly increase fuel capacity and a revised turbo-pump driven higher thrust rocket motor. The X-1A and B were intended to further explore flying qualities (fitted with an 8% *t/c* NACA 65-108 section wing) while the X-1D was instrumented to better understand aerothermal heating associated with high-speed flight. The still-born X-1C was to be an armaments testbed. The X-1E featured a unique 4% *t/c* section wing. Delivery of these aircraft fell far behind schedule, with initial deliveries spanning 1951 (X-1D), 1953 (X-1A),1954 (X-1B) and 1955 (X-1E).

On July 24, 1951, the X-1D flew its only mission, an unpowered glide ending with a damaged landing gear.[45] On its first scheduled powered flight, the engine exploded prior to release and the airframe was lost. Fortunately, Test Pilot Pete Everest survived.

The X-1A was far behind schedule as well. [45] It made its first powered flight on February 21, 1953. It was not until November 21, 1953, that it exceeded Mach 1 with none other than Chuck Yeager at the helm. The X-1A was involved in a number of near fatal mishaps due to its weak directional stability and poor lateral-directional controllability. Turning to FIGURE 30, which represents a VORLAX estimation of the static directional stability of the X-1/X-1A as a function of Mach number, we see that the low-speed directional stability was marginal – but due to Prandtl-Glauert and Ackeret effects, so long as the vertical fin was not overwhelmed by buffet, stability actually increases into the favorable ($dCn/d\beta > +0.004$) range throughout the transonic range. As the aircraft further increases in speed, directional stability declines, becoming unstable as flight speeds pass Mach 2.3.

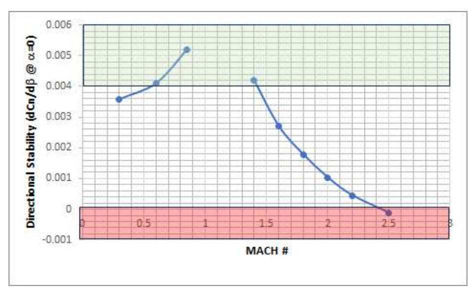


FIGURE 30 - Bell X-1 VORLAX Predicted Supersonic Directional Stability at $\alpha$=0$^{o}$. Various Mach Numbers.

Yeager’s prior flights to Mach 1.45 did not prepare him for what was to come at higher speeds. Yeager recalls that on his second flight of the X-1A, he “took the airplane to [Mach] 1.5 at 50,000-ft and it flew very good.”[66] On December 8, 1953, he attained Mach 1.9 without issue; “I took it on up to 65,000-ft - just under our aim altitude of 70,000 ft - left it there and went on out to [Mach] 1.9; it handled very well.”[66]

On Yeager’s fourth powered flight in the X-1A, all havoc broke loose. In his own words: “the drop … went beautifully [but] I ended up too steep and … couldn’t get level by 70,000-ft so I overshot … and ended up level just under 80,000-ft.”[66] He remembers that “the Bell engineers had told us that as you go through 2.3 Mach number, the airplane will probably become a little bit unstable."[66] Indeed, he lost directional control just as he "went through [Mach] 2.35, [and] the airplane began to yaw."[66] Yeager reminisces: "I pushed on the rudder … [and] the airplane kept yawing to the left and I watched the Mach meter go through roughly 2.5; at this point I was at burnout."[66] When he run out of propellant, "the airplane was yawed 40 degrees to the left and I had full rudder and full right aileron in."[66] He did not regain control until 88 seconds had passed, and the X-1A had slowed to subsonic speeds and fallen to ALT~25,000-ft.

The cause of the spin is often attributed to "inertia coupling."[45] In 1948 Phillips noted that high-speed aircraft "include short wing spans, fuselages of high density and flight at high altitude" also have rolling mass moments of inertia (*Ixx*) much smaller than their pitching (*Iyy*) or yawing (*Izz*) moments of inertia.[67] For "body heavy" vehicles like the X-1A, mass moments of inertia in yaw overwhelm those in roll. The ratio, $\left|\frac{Ixx-I}{Izz}\right|$, provides insight as to how easy it is for oscillatory energy in the Short-Period to cross over into the Dutch-Roll. For the X-1A this value is ~0.67; this makes it **somewhat** prone to inertia couple.[21]

Inertia Coupling can only occur when the Short-Period frequency, the Dutch-Roll frequency or other pilot-induced inputs closely align in the frequency-domain.[23][24][25] As the X-1 and X-1A only "inertial coupled" at high speeds, let us consider whether this is an intrinsic function of speed **or** was this byproduct of the loss of directional stability due to the undersized vertical tail.

We approximate the inherent Short-Period rigid-body oscillatory mode of the aircraft (frequency in rad/sec) at a given speed (*M*) and angle-of-attack (*α*) as:

$$\omega_{SP} \approx \sqrt{\frac{-57.3\frac{dCm}{d\alpha}\bar{q}\ Sref\ \bar{c}}{Iyy}}$$

Where *dCm/dα* is given in terms of customary units, per degree.[24][29] In an aircraft with irreversible control surfaces lacking a feedback control system to alter the short-period frequency, the value *dCm/dα* represents the inherent vehicle aerodynamic properties with the control surfaces deflected to attain pitch trim (*Cm* = 0). For the X-1A, *dCm/dα* varies over a narrow range with Mach number. Thus, the Short Period frequency is dominated by a term proportional to the square root of the dynamic pressure. Whereas the Dutch Roll frequency will be dominated by a term proportional to both the square root of the dynamic pressure and a term proportional the *CnβDynamic*; *CnβDynamic* is driven by *dCn/dβ* at small angles of attack. Thus, we see that as the Mach number increases and the static directional stability decreases, the Dutch Roll frequency must trend slower. When the airframe is neutrally stable (for the X-1A, this is around Mach 2.3), the frequency is zero. It seems obvious that there will be a point where the Dutch Roll frequency is likely to overlap the longitudinal Short Period frequency – when the frequencies align, inertia coupling sets in.

As Yeager accelerated to Mach 2.44 and directional stability declined to zero, he lost lateral-directional control. Reading the report carefully, we note that it was not inertia coupling alone that led to the loss of control.[20] "A slow rolling motion to the left started and aileron, then rudder were applied for control"[20] In a classic display of control coupling, "the airplane responded … rolling more rapidly to the right."[20] When "attempting to correct for this condition, … caused the airplane to snap abruptly into a rapid roll to the left."[20] "The uncontrolled motions of the airplane resembled an oscillatory spin."[20]

After this incident, the Air Force placed a speed restriction on the X-1A airframe, with a specific instruction not to exceed Mach 2.0.[45]

On a later flights of the Bell X-1A (May 28, 1954), test Pilot Arthur Murray equally found himself in a supersonic spin. Following instructions, he did not attempt to exceed Mach 2 at any time. On the May 28,1954 flight, Murray lost lateral-directional control at Mach~1.95 and ALT~82,000-ft; shortly before rocket motor cutoff. "The motions … were not as violent as during [Yeager's flight] apparently because of the higher altitude and lower Mach number."[20] The spin lasted for over one minute; Murray regained control at Mach~1.8 and ALT~60,000-ft. Post flight analysis found that the Short Period and Dutch Roll modes did NOT overlap, but that the X-1A **was** lateral-directionally divergent.[20]

In retrospect, the biggest lesson learned from the second-series X-1 program should have been to revisit tail sizing when uprating the propulsive performance of an airframe. A vertical tail appropriated sized for a lower speed aircraft may prove dangerously inadequate at higher speeds.

## VIII. Predestined Doom - Flight Testing the X-2

As with the second-series X-1 airframes, Bell fell far behind schedule with the X-2. The first completed airframe rolled out on November 11, 1950, ahead of the X-1D.[43] The first captive carry flight with the X-2 under a modified Boeing B-50 did not occur until July 1951. The aircraft continued to struggle with teething problems and did not arrive at Edwards AFB until early 1952.

By 1950, the NACA brought larger supersonic wind tunnels on-line. NACA's estimates, based on a collection of wind tunnel data from various sources (the subsonic 7 by 10-ft tunnel, the 4 by 4-ft supersonic tunnel and the 9-in supersonic tunnel) suggested that directional stability improves from $dCn/d\beta \sim +0.001$ at low speed to $dCn/d\beta \sim +0.0025$ around Mach 1.4 then declining to $dCn/d\beta < +0.005$ above Mach 3.[68][56][57][58][59][60][69][65][71][72][73] While these trends match VORLAX solutions very closely (see FIGURE 31), they continue to indicate that the X-2 had, at best, marginal directional stability at all speeds. Despite mounting evidence of weak static directional stability, Bell did not enlarge the vertical tail area.

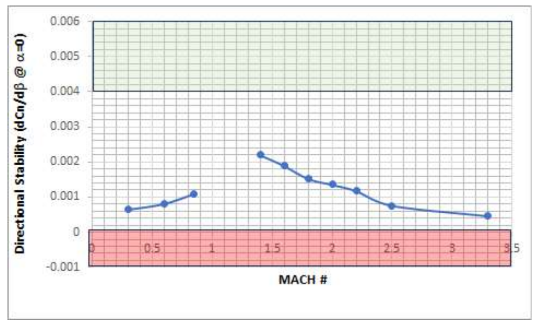



FIGURE 31 - Bell X-2 VORLAX Predicted Supersonic Directional Stability at $\alpha=0^{o}$. Various Mach Numbers.

The X-2 originally was to incorporate an advanced electrically driven Bendix Corporation flight control system; this was later abandoned after consuming two years of effort and substantial financial resources. [74] It was replaced by a "quick fix" purely mechanical flight control system for the initial unpowered glide flights beginning on June 27, 1952. On that day, Bell test pilot Skip Ziegler veered off the runway after touchdown, damaging the airframe; see FIGURE 32.[45] Both Ziegler and X-2 No. 2 were lost in an in-flight explosion of its propulsion system under circumstances eerily similar to that of the X-1D a few years before.

FIGURE 32 - Bell X-2 after its first gliding flight.

The flight test program continued, albeit slowly.[43] With the project many years behind schedule, the X-15 rocket plane nearing completion, and prototype "Century series" fighters entering flight test, political pressures mounted. The X-2 was then fitted with an irreversible simplex hydro-mechanical set up installed to drive the all-moving horizontal stabilizer and ailerons for the remainder of the test program and for all powered flights.[74] It was not until November 18, 1955, that X-1D survivor Pete Everest managed the first successful powered flight of the X-2. On his final flight, Everest attained Mach 2.87 at 68,000-ft; a new "unofficial speed record." [75]

The X-2 exhibited very relaxed stability in pitch and yaw at higher Mach numbers, creating concerns about controllability as speeds and altitude continued to increase. [74][75]

The USAF next assigned Captains Iven C. Kincheloe and Milburn G. "Mel" Apt continued flight test responsibilities.[45] Kincheloe only flew the X-2 on four occasions; on his last flight he flew the X-2 to a peak altitude of 125,907-ft and set an "unofficial altitude record." Later that month, on September 27, 1956, Apt made his first flight attempt. He flew a precise profile, becoming the first man to exceed Mach 3. Attaining Mach~3.2 at engine cutoff, Apt attempted to bank and turn; at that moment, the X-2 departed from controlled flight – much in the same way that Yeager experienced in the X-1A three years before.[27] The X-2 tumbled violently out of control – retrospectively, according to Day, due to “inertia coupling” and “control coupling.”[23][27] These are the same control problems that cursed the X-1A.[21] Apt was unable to bail out and died in the wreckage; see FIGURE 33.

FIGURE 33 – Bell X-2 After its Crash

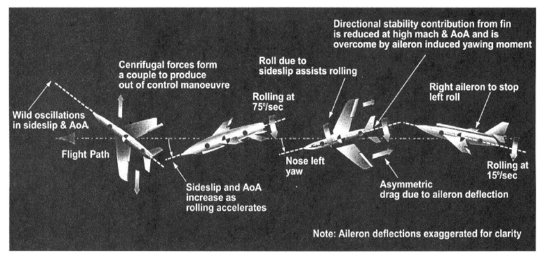



FIGURE 34 - Inertia Coupling / Adverse Yaw

As stated previously, Day claims that the X-2 crashed due to its propensity to inertia couple.[23][27] We agree, noting that $\left|\frac{Ixx-Iyy}{Izz}\right| \sim 0.70$ for the X-2; a value which places it as “coupling prone.” Like the X-1 and X-1A, inertia coupling did not present itself across the entire flight envelope; it only became prevalent under specific high-speed flight conditions where the Short Period and Dutch Roll frequencies closely aligned. Test Pilot Apt flew into such a region of the flight envelope as he passed Mach 3 at high altitude in his last few seconds of controlled flight.

That said, me and my collaborators believe that inertial coupling was not the proximate cause of the crash; instead, it was the X-2’s tendency to have adverse-yaw “control coupling” that proved fatal.[46][76]

“Control coupling” is a byproduct of weak (or unstable) directional stability and the aerodynamic configuration of the roll control surfaces. For the X-2, these were outboard wing mounted ailerons; when the pilot deflects them, adverse yaw occurs due to differences in drag resulting in a yawing moment. If this yawing moment helps self-coordinate a turn; it is called proverse yaw. If the induced yawing moment is destabilizing, it is called adverse yaw. Pilots (or autopilots) must correct significant yaw, either proverse or adverse. If left uncorrected, any unintended yaw can drive the vehicle to substantial sideslip angles. The aircraft will spin if the sideslip exceeds a critical angle, where the vertical tail begins to stall.

Recall that Kotcher and Bell configured the X-2 as a classic wing/body/tail aircraft; refer back to FIGURE 19. It had wing mounted ailerons for roll control, an all moving horizontal tail for pitch control, and a vertical tail mounted rudder for yaw. Because the X-2’s rudder proved ineffective at high speeds, it was mechanically locked in place for high-speed flight; this left the pilot with virtually no control over the aircraft’s yaw axis. [1]

FIGURE 34 illustrates how excessive adverse yaw led to the X-2 simultaneously experiencing both a lateral-directional and longitudinal departure.[77] The adverse yaw of the X-2 was sufficient that a roll command at high speeds led to the formation of a high-sideslip angle. That high-sideslip angle, interacting with the static dihedral effect of the airframe ($dCl/d\beta$<<0) caused a lagging opposite rolling motion. Through Inertia Coupling, the energy in this nascent oscillation is also cross-coupled into pitch disturbances. The sequence of events leading to the X-2’s demise is not disputed.

The need to worry over excessive adverse yaw from ailerons was understood from the beginning. Recall the 1945 Bell memo with concerns over the lack of favorable roll (the adverse yaw during maneuvering) for the X-1.[22]

It was not until after the X-2 crash and subsequent accident investigation did the concept of Lateral Control Departure Parameter (*LCDP*) become formalized.[23][24]

*LCDP* measures the coupling between the roll and yaw effects of the primary roll controller and the inherent lateral and directional stability of an airframe.[23][24][28][29]

$$LCDP = \frac{dCn_{Body}}{d\beta} - \frac{dCl_{Body}}{d\beta} * \frac{\left(\frac{dCn_{Body}}{d\ aileron}\right)}{\left(\frac{dCl_{Body}}{d\ aileron}\right)}$$

If $LCDP$ is positive, adverse yaw from the ailerons are unlikely to overpower the inherent directional stability of the airframe. If $LCDP$ is negative, adverse yaw from the ailerons will eventually drive the aircraft into sufficient sideslip (β) that the dihedral effect ($dCl/d\beta * \beta$) will overpower the rolling moment the ailerons generate. A vehicle with negative $LCDP$ will behave just as the X-2 did; a command to roll left will result in significant sideslip developing which makes the vehicle eventually roll to the right. Absent precise turn coordination (i.e., rudder / aileron scheduling), the vehicle will experience pilot-induced oscillation, then spin. That a spin was inevitable given the pilots inability to coordinate a high-speed turn due to the locked rudder.

FIGURE 35 demonstrates how dangerously weak was the X-2's static directional stability.[46] If we compute the sideslip equilibrium trim that arises for 10° of aileron command, $dCn/daileron\ /\ dCn/d\beta$, we can see that in the absence of a rudder command that the aircraft must develop substantial sideslip from its static directional stability to balance the adverse yaw arising from aileron inputs. 10° of aileron leads to more than 10° of sideslip developing; this trend is found across the entire flight envelope. At all speeds and angles-of-attack even the most delicately applied roll commands need to be balanced with rudder in order to keep the aircraft from yawing into a high sideslip condition. With the rudder locked, the aircraft was doomed to depart if given any substantial roll input.

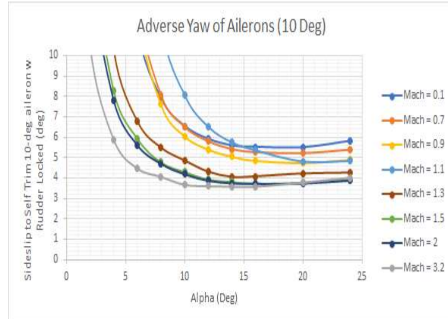


FIGURE 35 – Adverse Yaw of Ailerons, Sideslip to Trim out 10° Aileron Input (rudder locked) [46]

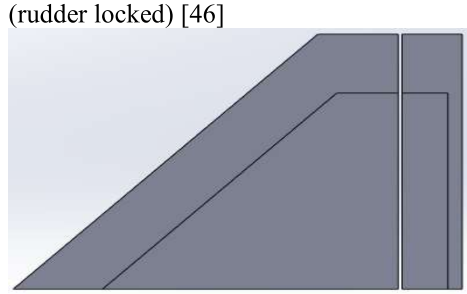


FIGURE 36 - Hypothetical Revised X-2 Vertical Tail vs Original.[70]

These characteristics may be mitigated by enlarging the dorsal vertical tail/rudder, as studied by O'Brien & Takahashi.[76] For purposes of argument, we scale up the baseline X-2 tail upwards to have 30% more tip and root chord as well as 30% greater exposed height); a 70% increase in area; see FIGURE 36. A greatly enlarged vertical tail will increase $dCn/d\beta$ and improve both lateral-directional stability ($C_n\beta\ dynamic$) and lateral-directional controllability ($LCDP$).

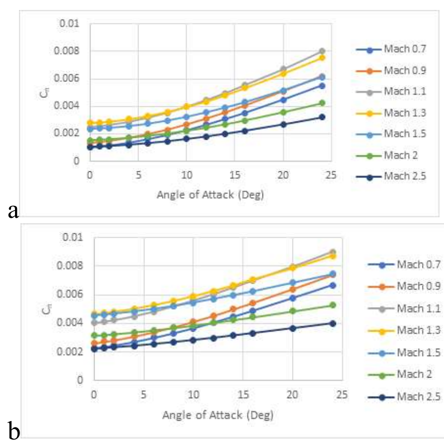


FIGURE 37- $dC_n/d\beta$ vs α - a. Baseline, b. Enlarged [70]

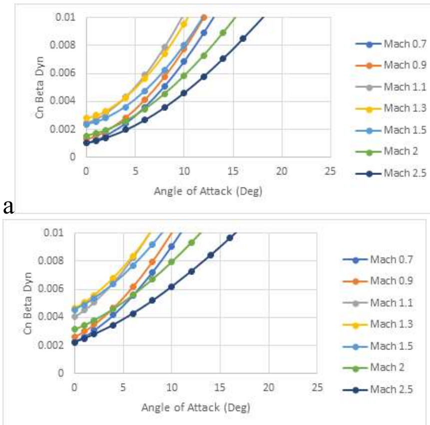
First, we consider the larger vertical tail/rudder.[76] For the larger vertical tail analysis, we scale the dimensions of the baseline tail upwards by 30% (i.e 30% more tip and root chord as well as 30% greater exposed height). FIGURE 37 shows a comparison between the orignal vertical tail and rudder versus the scaled up version. Using VORLAX, we may estimate the impact vertical tail area has on the static lateral and directional stability.

We can see through FIGURE 37, that the enlarged vertical tail ensures that $dCn/d\beta > +0.002$ at all speeds and angles of attack.[76] This hardly makes the revised X-2 directionally stiff, as it does not begin to meet Shortal's 1945 target value of +0.008; nonetheless, it is a marked improvement over the baseline.

Turning next to FIGURE 38, we see that the larger vertical tail has a moderate effect on $Cn\beta dynamic$ as energetics of the Dutch Roll mode are dominated by the dihedral effect at higher angles of attack. The vertical tail increases the Dutch Roll stability at all speeds and attitudes. It has the most impact at low angles of attack where the static directional stability plays a greater role in the formation of a stable Dutch Roll. Even with the enlarged vertical, $Cn\beta dynamic$ does not satisfy Skow's criteria for desirable flying qualities; $Cn\beta dynamic > +0.004$. [24][48]

Finally, with FIGURE 39, we see where the larger vertical tail makes the most difference; that is improving *LCDP*. For the original configuration at Mach 2-2.5, *LCDP* trends negative if the nose is elevated above $\alpha$=15$^o$; with the larger vertical *LCDP* remains favorable past $\alpha$=20$^o$. This is a massive improvement in lateral controllability, especially if the pilot needs to command a roll while developing a significant load factor (such as in a pull-up or banked turn).

All taken together, with a greatly enlarged vertical tail the Bell X-2 would have expressed substantially better flying qualities in comparison with its baseline tail. Thus, in retrospect, we see that the undersized vertical tail was the proximate cause for both inertia coupling and the control coupling. With an enlarged vertical tail, it is unlikely that Capt. Apt would have died as he did since the airframe would have been much less prone to spin.



a b

FIGURE 38 - CnβDynamic vs $\alpha$ (Top Original, Bottom Large Vertical) [76]

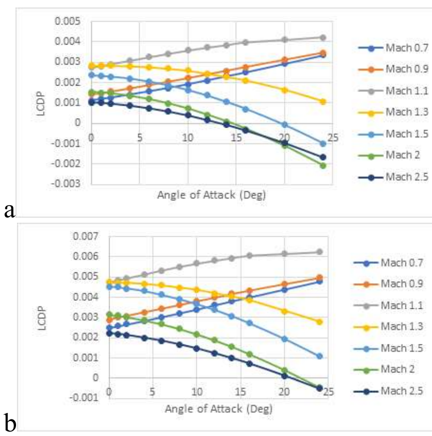


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FIGURE 39 - LCDP vs $\alpha$ (Top Original, Bottom Large Vertical) [76]

## IX. Would History Have Been Different If Ezra Kotcher Remained Actively Involved?

The review of Ezra Kotcher's personal notes from those fateful days in 1945 and 1946 reveal the mind of a technical leader who strove for rapid progress but was always interested in "form following function." In hindsight, his advocacy of rocket propulsion was prescient – as the first sustained turbine propelled supersonic flight did not occur until December 1951.[78]

Kotcher's notes indicate a keen sense of risk, and a lack of foolhardiness. While both the X-1 and X-2 were revolutionary aircraft, the preserved meeting notes reflect a design based on a broad consensus among the experts – balancing lift, drag, weight, and thrust – to achieve a prototype that could actually perform its intended mission. The demand for *Nz*=12+ gee structural strength was a concession to an understanding that the aircraft might not exhibit satisfactory stability and control; it might "spin out" in its attempt to reach its ultimate speed and altitude limits. At the same time, these 1945-era discussion reflect a "classically modern" sense of the stability & control requirements that reflect a well-flying aircraft: attention to the rigid body modes (Short Period, Dutch Roll, Spiral Modes), an understanding of the perils of adverse yaw and a desire to have strong positive directional stability. They also reveal, through the advocacy of R.T. Jones the emergent "postmodern" sensibility; to let the detail design of the flight control system "fix" fundamental aerodynamic problems.

Historical evidence indicates that Ezra Kotcher was cognizant of the need for substantial directional stability. Had he been actively involved in the X-2 program as it progressed, it seems likely that he would have insisted on a further redesign to address the emergent issues. While early supersonic sideslip data from the wind tunnel was limited to a simple rolled-model test (i.e., sideslip data only at $\alpha$=0$^o$), it indicated marginal static directional stability. The lack of hard higher-speed data (i.e., Mach 3) earlier in the design process led to a situation where an "absence of evidence" was taken as evidence of an absent issue (i.e., loss of directional stability with increasing Mach number). Had the tail been enlarged earlier, captive carry fitment for the X-2 under its B-50 mothership could have accommodated a solution.

Kotcher's departure from both programs in 1946 seems to have closed the door to the "form follows function" approach.

In hindsight, the original X-1 was configured to have satisfactory flying qualities through its top speed of Mach ~ 1.5. The innate balance and poise of the X-1, plus its sturdy construction, made it famous.

Yeager's near tragedy in his 1953 X-1A near crash should have served as a wake-up call. While the Air Force placed a hard. Mach 2 speed limit on the X-1A after that, Major Arthur Murray similarly lost control of X-1A at high altitudes near Mach 2.[20] Both departures from controlled flight are related to control coupling, inertia coupling, and a lack of positive static directional stability inherent in the aerodynamic design.

FIGURE 40 – Retrofitted Bell X-1E airframe with enlarged vertical tail surfaces (note a pair of Ventral fins) [79]

The "second phase" X-1A, with its higher thrust and longer endurance propulsion system, but no change to its empennage, was capable of speeds beyond its ability to control. Ironically, after the crash of the Bell X-2, the X-1E was retrofitted with enlarged vertical tail areas through a pair of ventral fins; see FIGURE 40.[79] While the X-1E will forever be in our minds as a backdrop to "I Dream of Jeannie," aviation historians have not immortalized the X-1A,B,D or E like the original series.

The X-2, with its tail size frozen after initial wind tunnel tests in 1946, proved even more discouraging. On the bright side, Bell and the Air Force undertook considerable effort to prove out its "circular arc" wing. They built, flew and developing the L-39-2 prototype; return to FIGUREs 27 and 28. With the help of the NACA, they refined the low-speed configuration to include outer part-span leading-edge slats to complement the inner part-span split flaps. At the same time, certain lessons learned on the L-39-2 went unheeded; specifically, the need to further enlarge the vertical tail.

With wind tunnel data trickling in throughout 1946, the emerging aerodynamic database indicated that the X-2 would see the same sorts of decline in static directional at higher Mach numbers that bedeviled the X-1A.[68] Yet no further effort was made to enlarge the vertical fin. Thus, the X-2 had a documented expectation for weak lateral-directional stability long before it arrived at Edwards. In hindsight, despite all of its programmatic delays, the Air Force should have approached the Bell X-2 with a more cautious envelope expansion flight series. History finds Air Force management reckless when scheduling Mel Apt on a Mach 3 mission for his "pilot familiarization" flight.

I end where I began: reminding us that "those who cannot remember the past are condemned to repeat it." With today's renewed interest in high-speed systems, we must never forget the lessons learned – both the good and the bad – from Ezra Kotcher and the Bell X-1 and X-2.

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