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ANALYSIS OF AN EMERGENCY DECELERATION AND DESCENT OF THE XB-70-1 AIRPLANE DUE TO ENGINE DAMAGE RESULTING FROM STRUCTURAL FAILURE

by Chester H. Wolowicz

Flight Research Center
Edwards, Calif.

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SUMMARY

An emergency on flight 12 of the XB-70-1 airplane at a Mach number of 2.6 and a pressure altitude of 63,000 feet provided unusual operational, handling qualities, and stability and control data of interest to the supersonic-transport designer. Failure of the wing apex, its ingestion into the right inlet duct, and subsequent damage to the engines produced a steadily deteriorating propulsion situation, which led to resonant vibrations in the relatively flexible fuselage and subsequent stability and control problems in attempting to deal with the vibrations.

The results of an analysis of this emergency may be useful in developing adequate operational margins and procedures in the design of the supersonic transport.

INTRODUCTION

The supersonic transport, not having a military counterpart as did the subsonic transport, will not be able to amass the flight hours and operational experience accumulated by the subsonic jet prior to regular commercial operation. Fortunately, the XB-70 aircraft (fig. 1) is the same class of vehicle as the supersonic transport and operates in a similar environment for approximately the same length of time per flight; thus, it is an excellent vehicle with which to obtain operational experience applicable to the supersonic transport. As part of its supersonic-transport research program, the National Aeronautics and Space Administration is taking an active interest in the flight testing of the XB-70 aircraft in order to accumulate operational, handling qualities, and stability and control data which may be of value to the supersonic-transport development program.

During the course of its envelope-expansion program, the XB-70A (S/N 62-001) --referred to as the XB-70-1--experienced an emergency on its twelfth flight which provided unusual operational, propulsion, and handling-qualities data of interest to designers, flight-safety engineers, and pilots concerned with the evolution of the supersonic transport. Flight 12 of the XB-70-1 program required an emergency deceleration and descent when a small portion of the wing apex failed and was ingested into the right-hand duct at a Mach number of 2.6 and a pressure altitude of 63,000 feet.

The ensuing sequence of events included compressor stalls, inlet unstarts, and duct buzz with accompanying severe transverse vibrations. The emergency situations were eventually brought under control and the aircraft was landed safely. A postflight inspection of the aircraft revealed considerable damage to the right-hand duct and extensive damage on all three engines in the duct.

This paper presents a cursory analysis of the time-history record of this event and describes the resulting pilot action, control inputs, and airplane response. Of particular interest is the portion of the deceleration in which "hard" duct buzz was experienced. The data and sequence of events were deduced from flight-monitoring notes compiled by North American Aviation (NAA), U.S. Air Force, and NASA personnel, reduced flight data, manufacturer's data, and pilot comments.

The symbols used herein are defined in appendix A.

THE AIRPLANE

The XB-70-1 airplane (fig. 1) was originally designed as a weapons system to provide long-range supersonic-cruise capabilities. The aircraft has a design gross weight in excess of 500,000 pounds, design cruising speed of Mach 3.0 at 70,000 to 80,000 feet, and intercontinental ranging capability. It features a thin, low-aspect-ratio, 65.6°-leading-edge delta wing with folding wing tips, twin vertical stabilizers with rudders, elevon surfaces for pitch and roll control, and a movable canard with trailing-edge flaps. The flight control system is irreversible.

The wing tips, in normal operation, are undeflected up to high subsonic speeds; deflected 25° tips down in the high subsonic, transonic, and supersonic region up to $M \approx 1.4$; and deflected 65° tips down at high Mach numbers. In their various folded positions, the wing tips enhance the directional stability.

In the normal flight configuration, the canard is geared to the elevator action of the elevons. The coordinated movement of the two surfaces is provided by the control column. Full elevator travel of the elevons is 15° to -25°. Full travel of the canard is from 0° to 6°. For takeoffs and landings, the forepart of the canard is fixed at 0° incidence and the canard flap is full down at 20°.

The XB-70-1 airplane, built with zero geometric dihedral, has less than the required geometric dihedral to provide positive effective dihedral at high Mach numbers with the flight augmentation control system (FACS) off and the wing tips in the 65° deflected position and is very sensitive in roll and yaw to aileron inputs; as a result, the manufacturer incorporated a lateral bobweight to improve the lateral handling characteristics. The bobweight was locked and thus not used on this flight. (On the XB-70-2 airplane, the lateral characteristics were improved by incorporating 5° geometric dihedral in the wing.)

The elevons are segmented--six segments to a surface--to prevent binding of each elevon surface due to bending of the wing. When the wing tips are in a deflected position, the two outboard segments of the elevons on each wing tip are faired at zero setting and become part of the folded tip.

Full rudder travel is ±3° when the landing gear is up, and ±12° when the gear is down.

The airplane is equipped with a flight augmentation control system to augment the stability of the vehicle in pitch, roll, and yaw. In the pitch mode, the system actuates only the elevator mode of the elevons; it does not affect the canard. The geared movement of the canard-elevator combination comes through the control column.

Propulsion is provided by six YJ93-GE-3 engines; each engine has a 30,000-pound-thrust classification at sea level. Each engine has an 11-stage axial-flow compressor, an annular combustion section, a two-stage turbine, and a variable-area converging-diverging exhaust nozzle. With the rpm lockup switch in AUTO, the rpm of all the engines will be locked automatically at 100 percent to maintain stable airflow, regardless of throttle settings, at increasing speeds above $M = 1.5$. This lockup is automatically disengaged below $M = 1.3$ with decreasing Mach number, and the rpm of each engine reverts to throttle control. Below military thrust, throttle movement with lockup engaged varies exhaust-nozzle area which, in turn, varies engine thrust.

The six engines are mounted side by side in the rear of the fuselage in a single nacelle under the center section of the wing. The nacelle is divided into twin, two-dimensional, mixed-compression inlets incorporating variable ramp positions and throat areas for optimum operation throughout the Mach number range.

The left- and right-hand air-intake ducts are each equipped with six inlet-air bypass doors on top of each duct just forward and inboard of the leading edge of the rudder (fig. 1). These doors are used in conjunction with the controlled width of the two-dimensional throats to control the position of the normal shock in each of the ducts and to match engine-airflow requirements. Operating limits of bypass doors and throat are shown in figure 2. As shown in figure 2(a), engine stall, inlet unstart, and buzz can be encountered by exceeding these operating limits. Start and unstart conditions of the duct are illustrated in figure 2(b). Maximum bypass setting takes place at $M = 2.0$; zero or near zero bypass setting takes place at $M = 3.0$. At stable subcritical operating conditions (below $M = 2.0$ on the XB-70), the normal inlet shock is located upstream of the cowl lip. Above $M = 2.0$, the normal shock is located in the inlet duct as shown in figure 2(b). The position of the shock is controlled by the bypass doors and throat width. Opening the bypass doors causes the normal shock to move rearward; closing the bypass doors moves it forward. Deviations from a scheduled positioning of the bypass doors and throat can result either in an aft displacement of the normal shock--causing stall--or expelling the shock (the unstart condition), as shown in figure 2(b). The unstart condition causes increased spillover of airflow, reduced inlet recovery, and increased drag. When the shock pattern of the unstart condition is unstable, a buzz situation is possible. During the buzz, the shock pattern vibrates rapidly about the stable position. The alternate swallowing and expelling of the normal shock creates an intermittent flow of air to the engine, resulting in severely degraded engine performance, intermittent additive drag, and--as in the case of the XB-70-1--structural vibrations.

The XB-70-1 is equipped with a manual and semiautomatic air induction control system (AICS). Control of the propulsion system is a team effort, involving both the pilot and the copilot. The pilot controls the engines; the copilot controls the air induction system. In the manual mode of operation of the air induction system, the copilot positions both the throat and the bypass doors using control wheels located under the control column. The throat can be controlled automatically to follow a Mach schedule. This automatic throat movement, along with the manual positioning of the bypass doors, comprises the semiautomatic AICS mode. The XB-70-2 airplane has a fully automatic AICS (throat and bypass) with a manual backup system.

Some of the more pertinent geometric characteristics of the airplane are listed in the following table:

	Wing	Canard	Vertical tail (1 of 2)
Area, sq ft	6298	415.6	225
Aspect ratio	1.75	2	1
Root chord, ft	117.76	20.79	23
Mean aerodynamic chord, in.	942.4	184.3	197.4
Fuselage station of 0.25 mean aerodynamic chord	1621.2	553.7	2188.5
Leading-edge sweepback, deg	65.6	31.7	51.8

DISCUSSION

As deduced from postflight inspections of the aircraft, analysis of flight data, study of flight-monitoring notes, and information supplied by the manufacturer (ref. 1), the initial duct unstart of the emergency portion of the flight was caused by a stall of the No. 5 engine (in the right duct) resulting from ingestion of pieces of the wing apex into the right duct. Figure 3 is a postflight photograph of the damaged apex section of the wing.

The damage done to the right duct and its engines is shown in figures 4(a) to (c) and 5(a) to (c). Fortunately, time histories of propulsion and aerodynamic parameters were obtained for the entire duration of the ensuing emergency. Time histories of the pertinent propulsion parameters for both ducts are shown in figure 6. The more pertinent portions of the aerodynamic time histories obtained from the manufacturer's tabulated data are shown in figures 7(a) and 7(b).

The following sections discuss briefly the effects of this failure on the propulsion system and on the airplane handling and operating characteristics. The chronological sequence of emergency deceleration events, which started with a pronounced right-duct unstart (throat shock moving out of the intake duct) at $M = 2.6$ and 63,000 feet pressure altitude and terminated with the elimination of severe right-duct buzz and lateral accelerations at $M = 1.75$ and 45,000 feet pressure altitude, is presented in appendix B. Subsequent emergency events which occurred at $M = 1.3$, although not included in the appendix, are also discussed.

Propulsion System

As stated previously, the intake-air bypass doors in each of the two ducts are used in conjunction with the controlled width of the two-dimensional throats to control the position of the normal shock in each of the ducts (fig. 2). The throat is normally at maximum opening below $M = 1.7$, and the bypass doors are normally closed below $M = 1.0$. Both the throat and the bypass doors have, respectively, schedules of width and opening as shown in figure 2(a) to provide optimum inlet operation. Below $M = 2.0$, the inlet ducts operate in the unstarted condition. Incorrect scheduling of the throat width and the bypass opening can result in engine stall at any Mach number, buzz above $M = 1.5$, and unstart conditions above $M = 2.0$.

Initial indication of wing-apex failure and its ingestion into the right duct at the time the aircraft was flying at $M = 2.6$ at 63,000 feet pressure altitude was evidenced by a local Mach disturbance at the duct and was also reflected in the shock-position pressure ratio. The copilot, observing the disturbance to the normal shock position in the right duct as noted on the shock-position indicator, but unaware of its cause, proceeded through normal corrective action to open the right-duct bypass doors to reposition the shock. At this time, on the basis of the pattern of damage done to the duct and its engines, a portion of the disintegrated apex struck engine No. 5, causing a momentary stall and a pronounced unstart signal from the right duct--as evidenced in figure 6 at time 1:06:21. The left duct shows normal operation at this time. The copilot apparently reacted to the unstart signal, to regain a started inlet condition, by continuing to open the bypass doors in the right duct. Less than a second later, he switched the throat to manual mode, which caused the throat to open and the inlet to start, since the manual control had been prepositioned to the restart position. The actions caused the normal shock to return to its throat position (start condition). Transverse resonant fuselage vibrations which were initiated by the unstart pulse (fig. 7(a)) damped out.

After succeeding in returning the shock to its started position, the pilot closed the right bypass doors toward their original position (fig. 6) and returned the throat control to AUTO mode; however, because of the damage to the engines and the consequent reduction in the engine airflow, it became necessary to set the doors to 11°, rather than the original 4°, to bring the shock to its proper operating position. The subsequent opening of the right bypass doors from 11° to 21° to keep the normal shock in proper position was, to a large extent, dictated by the gradual deterioration in airflow through the damaged engines as well as a deceleration from $M = 2.5$ to 2.2 in the time interval 1:07:20 to 1:09:03. (Within this interval, engine No. 5 was throttled to military power because of persistent vibration; all other engines were cut to minimum afterburner and began to show minimum afterburner instability. The minimum afterburner instability is not related to the problem generated by the damage to the engines. This instability is a problem related to the engines installed in the XB-70 and has been encountered numerous times. At time 1:08:16 to 1:08:20, because of the persistence of the instability (not illustrated in fig. 6), all engines except No. 5 were momentarily advanced in power and then retarded to military power for deceleration and descent to terminate the flight.)

At $M = 2.2$ (time 1:09:03) with the airplane decelerating and descending, engine No. 6 went into a steady-state stall, followed immediately by an unstart of the right duct. The copilot opened the bypass doors to 28° and 11 seconds later opened the throat. Because of the deteriorated condition of the damaged engines and the consequent reduced airflow conditions, as well as the reduction of aircraft speed, this bypass angle did not provide sufficient opening to restart the inlet. At M = 2.17 (time 1:09:18) the unstart signal light went out, possibly leading the copilot to believe that the right-duct inlet had started. However, the light went out because of an automatic disarming of this warning system at M = 2.17, even though inlet start conditions prevail down to M = 2.0, as shown in figure 2(a). Inability to recover engine No. 6 from the stalled condition subsequently resulted in it being shut down at time 1:09:38 at M = 2.08. This was followed by a closing of the right bypass doors to 11°.

With the airplane decelerating, right-duct throat opening increasing in AUTO mode, and right-duct inlet unstarted, the copilot began to follow standard checklist procedures and closed the right bypass doors to 4 1/2° at M = 1.91 (time 1:10:36). This is the normal bypass setting for the Mach range from 1.4 to 2.0, providing engines 4, 5, and 6 are operating normally at 100-percent rpm (actually, No. 6 was shut down and No. 4 and No. 5 were operating in a damaged condition). Standard emergency procedures, which are memorized by the crew, call for the following bypass settings in the event one or more engines have been shut down or are at idle rpm in the speed range from M = 1.4 to 2.0:[a]

Bypass door setting	Engine condition
400 square inches (3.6°)	All engines operating normally
700 square inches (7°)	One engine shut down
1100 square inches (13.2°)	Two engines shut down
1800 square inches (25.5°)	Three engines shut down

As the doors were reaching the 4 1/2° setting, an incipient buzz was encountered which, in turn, induced heavy transverse resonant acceleration vibrations at the pilot's station that built up in amplitude (fig. 7(b)). At time 1:10:44 when the resonant acceleration had built up to ±0.45g, the copilot opened the right bypass from 4 1/2° to 6°. This action appeared to have alleviated the magnitude of the vibrations which started to subside and decreased to ±0.1g amplitude at time 1:10:48. At time 1:10:48 the FACS was shut off in an attempt to ascertain if the system were contributing to the vibration.

At time 1:11:05, M = 1.89, the copilot (aware that some engine damage had probably occurred but not aware of the magnitude) was not completely satisfied with the response to the bypass-door opening and started closing the bypass doors from 6° to about 4 3/4° to determine if it would help to eliminate the vibration. This action

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[a]As a result of the problems encountered on flight 12, the normal operating procedures have been simplified. When a Mach number of 2.1 is reached on deceleration, the copilot sets 700 square inches (7°) rather than 400 square inches (3.6°) on the cockpit bypass area indicators. The 700 square inches of bypass area are considered sufficient by the manufacturer to permit one engine to be shut down and the other two to be operated at reduced flow (similar to flight 12) without instigating a buzz condition. Previously, 400 square inches was recommended for normal engine operation and 700 square inches for one engine inoperative. The manufacturer is considering an alternative procedure whereby the copilot sets a given value of shock pressure ratio when at M = 2.1 during deceleration to automatically compensate for engine shutdown and/or reduced flow.

appears to have contributed to the steady-state stall of engine No. 4, which occurred at time 1:11:08. At time 1:11:09, the FACS was turned back on. The closing of the right bypass doors to 4 3/4° and the steady stall of engine No. 4 forced the inlet into a full buzz situation at about the same time the FACS was turned on, and the mild resonant transverse vibration which was present during FACS-off increased to a peak magnitude of ±0.7g (fig. 7(b)). Figure 7(b) shows an irregular beat-frequency pattern in the transverse accelerations. The cause of the irregular beat frequency of approximately 3 seconds is not known. Whether or not this vibration would have built up to the maximum of ±0.7g in beat-frequency fashion at the pilot station had FACS been left off is unknown.

During the vibration at time 1:11:24, M = 1.87, engines No. 4 and No. 5 were shut down because of the continued stall condition of No. 4 and overtemperature of the exhaust gas on No. 5. At the same time, the throttles for engines 1, 2, and 3 in the left duct were retarded to idle. At time 1:11:27, the crew noticed that the right buzz light was on, and the copilot opened the right bypass doors to 7°. This appears to have caused the amplitude of the transverse vibrations to decrease to approximately ±0.2g. At time 1:11:45, M = 1.8, the bypass doors were closed down from 7° to 4 1/2° without causing any significant increase in the amplitude of the vibration, probably due to the decreasing Mach number. At 1:11:52, M = 1.75, the bypass doors were opened to 16 1/2°, causing the buzz and resonant oscillation to cease.

As can be observed from the preceding sequence of events, the XB-70-1 airplane does not have an automatic AICS which would have provided an automatic buzz control. With the manual AICS, a buzz warning system is provided to warn the copilot of buzz conditions and thereby require him to eliminate the buzz by opening the bypass doors. It should be pointed out that if the same sequence of events was to occur on the XB-70-2 airplane, which is equipped with an automatic AICS, the buzz, in all likelihood, would have been automatically eliminated. However, the sequence of events does point out what could happen during an emergency after failure of an automatic AICS and subsequent recourse to manual air induction control.

As the airplane decelerated through M = 1.3, the rpm of the three idling engines in the left duct suddenly unwound as a result of the automatic release of the engine rpm lockup. The pilot thought it was a flameout. Laboring under the impression that all engines were out, he attempted to airstart No. 3 engine which is critical, inasmuch as it drives the left primary electrical generator supplying power for such items as engine ignition, throttle control, communications, and radar beacon.

In attempting to restart No. 3 engine, the engine was inadvertently shut down, causing loss of ground-air communications, telemetry, and onboard instrumentation records. Realizing what had happened, the crew advanced power on the remaining two engines (No. 1 and No. 2). At the end of 1 minute 40 seconds from shutdown of No. 3 engine, the copilot succeeded in airstarting No. 5 and then No. 3 engine. Because of the loss of the total-temperature probe on the engine splitters and, therefore, the rpm control function, the No. 5 engine rpm would not exceed 90 percent.

It is worthy of note that despite the proximity of the two inlets, the disturbances in the right duct did not significantly affect the performance in the left duct.

Handling Characteristics

Up to the time of the unstart of the right duct at time 1:06:21, the airplane behaved normally and the pilot had no stability or control problems. From the time of the unstart to landing, several stability and control problems did arise; however, even though the pressures of the emergencies were demanding of the pilot's attention, he was able to bring the airplane safely to its home base.

At the time, and as a result of the unstart, the pilot took counteractions to anticipated pitch and yaw resulting from the unstart (fig. 7(a), time 1:06:21). The disturbances resulting from the unstart, the control inputs, and the change in longitudinal and lateral-directional trim, due to the abrupt opening of the right-duct bypass doors, were brought under control in the following 11 seconds. The trim changes in elevon, rudder, and aileron due to the opening of the right bypass doors can be seen in figure 7(a) by comparing the trim setting prior to time 1:06:21 to that following time 1:06:32. The continuous movement of the control surfaces up to time 1:06:57 is due to the pilot's attempt to manually maintain the vehicle in trim. At time 1:06:57, rudder trim was initiated, as evidenced by decreasing pedal force to maintain rudder deflections required (with $F_p = 0$ lb) to counter yaw moments caused by the overall engine-duct-bypass situation.

One of the most interesting insights into the handling characteristics of the vehicle under the pressures of the emergency occurred during the period of the buzz and severe transverse-acceleration vibrations at the pilot's station which started at time 1:10:38 (fig. 7(b)). At the time the vibration started, the pilot had been holding a 25-pound left-pedal force to maintain trim condition. About 2 to 4 seconds after the vibrations started, the pilot applied right-pedal force to eliminate a left-yaw trend. By maintaining a right-pedal force of approximately 35 pounds, he was able to hold the vehicle in directional trim. Shortly thereafter, at time 1:10:48, the FACS was shut off in an attempt to eliminate the vibrations; however, in doing this, a sideslip was initiated. In attempting to counter this sideslip, the pilot found himself contending with a mildly divergent, 6-second-period Dutch roll oscillation which was primarily a yawing or "wallowing" motion due to the very small value of C_{l_β} as evidenced by the low $\frac{|p|}{|r|}$ amplitude ratio of approximately 0.50 (fig. 7(b)).

The time history for this oscillation shows considerable aileron inputs but very little variation in rudder inputs, thus indicating what amounts to an essentially aileron-only control being applied in attempting to maintain control of the vehicle. Although the lateral acceleration at the center of gravity shows appreciable response to the oscillation, the pilot's station is apparently far enough forward to provide cancellation of this acceleration at the pilot's station by the yawing motion; this could possibly have contributed to the lack of use of rudder for damping the oscillation. To obtain an objective insight into the factors which affected the handling qualities adversely during the divergent oscillation, recourse was made to the following handling-qualities parameter (from ref. 2) applicable for aileron-only control:

$$\left(\frac{\omega_\varphi}{\omega_d}\right)^2 = 1 - \frac{\left(\frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} + \frac{I_{XZ}}{I_X}\right)\left(\frac{C_{l_\beta}}{C_{n_\beta}} + \frac{I_{XZ}}{I_Z}\right)}{1 + \frac{I_{XZ}}{I_X}\frac{C_{l_\beta}}{C_{n_\beta}}} \qquad (1)$$

It has been shown by various investigators (refs. 2 to 4, for example) that when $\left(\frac{\omega_\varphi}{\omega_d}\right) \neq 1$ and $\zeta_\varphi \neq \zeta_d$, the rolling induced by aileron input contains not only a pure roll-subsidence component but also an additional oscillatory component whose magnitude depends largely on $\left(\frac{\omega_\varphi}{\omega_d}\right)$. When $\left(\frac{\omega_\varphi}{\omega_d}\right) < 1$, an aileron-only tracking task will indicate a closed-loop (pilot-airplane) trend of increasing stability; when $\left(\frac{\omega_\varphi}{\omega_d}\right) > 1$, a trend toward decreasing stability in the task will be evidenced. The extent of the destabilization is dependent upon ω_φ, ω_d, ζ_φ, ζ_d, and T_R as well as upon $\left(\frac{\omega_\varphi}{\omega_d}\right)$.

Limited results have shown some serious differences between predicted and flight-determined (analog matching of flight data) values of C_{l_β} and $C_{n_{\delta_a}}$ (fig. 8). With due consideration to the weight and altitude of the aircraft for the data shown in figure 8, the values of the derivatives pertinent to equation (1) for the divergent oscillation (M = 1.9) were estimated--on the basis of the flight data--to be of the order shown in the figure by the crosses. Pertinent values of the moments and products of inertia were supplied by the manufacturer. Substituting all pertinent values into equation (1)

$$\left(\frac{\omega_\varphi}{\omega_d}\right)^2 = 1 - \frac{\left(\frac{-.00004}{.00006} + \frac{-.665 \times 10^6}{1.53 \times 10^6}\right)\left(\frac{.00021}{.0011} + \frac{-.665 \times 10^6}{18.2 \times 10^6}\right)}{1 + \frac{-.665 \times 10^6}{1.53 \times 10^6}\frac{.00021}{.0011}} = 1.187 \qquad (2)$$

Inasmuch as the ratio is greater than 1, it appears that the aileron-alone control tended toward a destabilizing trend in this instance. Additional analysis of the time history of the oscillations showed a closed-loop damping ratio of the order of -0.016 compared to a calculated controls-fixed damping ratio of the order of 0.17, thus tending to substantiate the destabilizing tendency of the essentially aileron-alone attempts to regain control of the aircraft.

It should be noticed that the combination of the negative effective dihedral (C_{l_β} = +) and the adverse yaw due to aileron ($C_{n_{\delta_a}}$ = -), augmented by the relatively large magnitude of $\frac{I_{XZ}}{I_X}$ resulting from the relatively large negative product of inertia and small rolling moments of inertia, affected the handling qualities adversely.

Reverting to the actual divergent oscillations, it should be noted that upon reactivating the FACS at time 1:11:09, the augmented control system appears to have put in primarily rudder control to recover from the divergent oscillations.

Operations Problems

When viewed in terms of the supersonic transport, the emergency portion of the flight, which started with the failure of the wing apex at time 1:06:21, gives some insight into:

1. The considerable amount of training required of the crew member charged with monitoring and operating a manual inlet control system to enable him to recognize any unusual behavior of the propulsion system and to apply corrective measures.

2. The ability of the flight crew to deal with a deteriorating propulsion and controllability situation.

3. The seriousness of the interaction between the duct-inlet conditions and the airplane handling characteristics.

4. The need for simple straightforward emergency procedures to minimize the emergency procedural problems encountered with many controls and complex operational steps.

5. The rates and decelerations that might be expected during an emergency descent for a commercial vehicle.

As discussed previously, the crew of two on the XB-70-1 airplane equipped with a manual AICS was able to apply corrective measures to the propulsion system and the stability and control problems encountered. The pressures of the sequence of events, and the automatic disarming of the unstart light, undoubtedly resulted in some confusion. This situation emphasizes the importance of close coordination between the pilot and copilot and the need for development of interrelated engine and inlet control systems.

The seriousness of the interaction of the inlet conditions with the vehicle performance and handling characteristics tends to be accentuated for high-supersonic aircraft. Bypass-door settings are critical on mixed-compression inlets to maintain efficient inlet conditions. Considering the complexity of the shock patterns at and near the inlet, more sophisticated wind-tunnel testing may be required to ascertain the aerodynamic loads on the structure near the inlets (as on the XB-70 wing apex) to determine the adequacy or inadequacy of aerodynamic theory in predicting loads.

An unstart signal and a shock-position indicator may well compliment each other in the monitoring of inlet duct conditions; however, the early automatic disarming of the unstart signal light at $M = 2.17$--with unstart conditions attainable down to $M = 2.0$--may have resulted in confusion during the pressure of the emergency events. Undoubtedly, the complexity of power and control systems on high-supersonic transports will require considerable thought to provide simple straightforward indicators and emergency procedures to minimize emergency procedural problems.

Insofar as the emergency descent is concerned, the pilot--upon realizing that the No. 3 engine was accidentally shut down (shutdown occurred at 1:13:45)--placed the airplane into a rapid rate of descent to maintain windmill rpm in order to maintain electrical and hydraulic power. With No. 1 and 2 engines operating, the airplane was subjected to a 24,000-foot decrease in altitude from 44,000 feet in the 1 minute 40 seconds that followed and before the restart of engines No. 5 and No. 3 (fig. 9). In this same time period, Mach number decreased from 1.07 to 0.87 and the airplane traveled approximately 18 nautical miles (fig. 9). This represents an average rate of descent of 14,400 feet per minute or an average glide angle of 12.3°. The crew believes that, had a restart of No. 5 and No. 3 engines not been successful, they could possibly have reached their home base (Edwards) on the two remaining engines at the time they pulled out of the descent.

Slight discrepancies in the time history of the pressure altitude in figure 7 exist in comparison with the altitude time history shown in figure 9, obtained from NASA radar data. The discrepancy is not considered important for the purposes of this analysis.

CONCLUDING REMARKS

The emergency situation of the XB-70-1 airplane on flight 12 revealed some of the problem areas that designers of a Mach 3 supersonic transport will have to consider.

This emergency was centered around a steadily deteriorating propulsion situation which resulted in resonant vibrations of the relatively flexible fuselage. The flight augmentation control system (FACS) was shut off in an attempt to minimize the vibrations, and, in the resulting essentially aileron-only control of the lightly damped airplane, a divergent Dutch roll oscillation was experienced. This unstable trend appears to be due to the characteristics of the vehicle in aileron-only control (FACS off) at the aerodynamic conditions prevailing at the time. The seriousness of the interaction of the inlet conditions with vehicle performance and handling characteristics tends to be accentuated for high-supersonic aircraft. Bypass-door settings are critical on mixed-compression inlets to maintain efficient inlet conditions.

Designers, in considering the overall aerodynamic aspects of a design, may well weigh the advisability of placing half of the propulsion capability in one pod or duct. Any consideration of this aspect will undoubtedly involve a trade-off between increased propulsion safety and airplane response. On flight 12, the XB-70-1 lost almost one-half of its propulsion capability as a result of the ingestion of a foreign object into its right duct and consequent damage to all three engines in the duct. However, good control was maintained.

There is undoubtedly a need for simple, straightforward procedures to minimize emergency procedural problems encountered with many controls and operational steps. On flight 12, the crew was under considerable pressure because of the rapidity of the events, which caused them to misinterpret the cockpit display. Subsequently, the situation was properly assessed and the aircraft was returned safely to its base.

The situations encountered emphasize the importance of close coordination between the pilot and copilot and the need for development of interrelated engine and inlet control systems.

Flight Research Center,
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APPENDIX A

NOMENCLATURE

$a_{n(cg)}, a_{t(cg)}, a_{x(cg)}$	normal, transverse, and longitudinal accelerations, respectively, at the center of gravity, g
$a_{n(ps)}, a_{t(ps)}$	normal and transverse accelerations, respectively, at the pilot's station, g
b	wing span, feet
C_l	rolling-moment coefficient, $\frac{\text{Rolling moment}}{\bar{q}Sb}$
C_n	yawing-moment coefficient, $\frac{\text{Yawing moment}}{\bar{q}Sb}$
C_{l_β}	effective dihedral parameter, $\frac{\partial C_l}{\partial \beta}$, per degree
$C_{l_{\delta_a}}$	aileron effectiveness derivative, $\frac{\partial C_l}{\partial \delta_a}$, per degree
C_{n_β}	static directional-stability parameter, $\frac{\partial C_n}{\partial \beta}$, per degree
$C_{n_{\delta_a}}$	variation of yawing-moment coefficient with aileron deflection, $\frac{\partial C_n}{\partial \delta_a}$, per degree
F_p	pedal force, pounds
g	acceleration due to gravity, feet/second^2
h	altitude, feet
h_p	pressure altitude, feet
I_X, I_Z	moments of inertia about X and Z body axes, respectively, slug-foot^2
I_{XZ}	product of inertia, $\frac{1}{2}(I_Z - I_X) \sin 2\epsilon$, slug-foot^2
M	Mach number

p, q, r	rolling, pitching, and yawing rates, respectively, about the body axes, degrees per second
$\bar{q}$	dynamic pressure, $\frac{1}{2}\rho V^2$, pounds per square foot
S	wing area, square feet
T_R	roll subsidence root of the characteristic equation
V	true airspeed, feet per second
W	weight of airplane, pounds
α, β	angle of attack and angle of sideslip, degrees
δ_a	total aileron deflection, degrees
δ_c	deflection of canard surface, degrees
δ_e	elevator deflection, degrees
δ_r	rudder deflection, degrees
ϵ	inclination of principal X-axis to the body X-axis, positive when principal axis is below body axis at nose of airplane, degrees
ζ_d	damping ratio of Dutch roll mode
ζ_φ	damping ratio of second-order expression in numerator of frequency-response expression $\frac{\lvert p \rvert}{\lvert \delta_a \rvert}$
Θ	pitch attitude, degrees
ρ	mass density of air, slugs per cubic foot
ω_d	Dutch roll frequency, radians per second
ω_φ	natural frequency of second-order expression in the numerator of the frequency-response expression $\frac{\lvert p \rvert}{\lvert \delta_a \rvert}$, radians per second

APPENDIX B

CHRONOLOGICAL SEQUENCE OF EMERGENCY DECELERATION EVENTS

Time	Event	Comments
1:06:20	The aircraft stabilized at M = 2.6 at 63,000 feet pressure altitude for duct-performance runs. FACS on. Right-duct bypass doors set at 4°.	
1:06:21	High vibrations on No. 5 engine followed almost simultaneously by right-duct unstart.	Accompanied by a loud bang, right-duct unstart light "on," a 0.06g change in longitudinal acceleration, and aircraft shaking at approximately 2 1/2 cps (natural frequency of the fuselage).
	The copilot opened the right-duct bypass doors to 13° and in a time span of 13 seconds to 19°.	At the time the unstart light went on, the shock-position indicator moved to high red and showed a need to open the right-duct bypass doors. Approximately 4 seconds after the unstart, the light went off as a result of opening the bypass to 13° and of opening the throat; inlet start condition regained.
	The unstart caused the pilot to apply corrective control to counter the pitch and yaw due to the unstart.	The elevon input was pilot-induced, as evidenced by the correlated canard surface movement; an FACS input in pitch affects elevon only.
1:06:32	Structural vibration ceased.	Vibrations in No. 5 engine persisting.
1:06:57	Rudder trim initiated to counter bypass-door yaw.	
1:07:05	Started closing right-duct bypass doors from 18° to 11°.	Vibrations in No. 5 engine persisting.
1:07:17	Started gradual opening of right-duct bypass doors from 11°. Pedal inputs coordinated to compensate for yaw due to bypass-door positioning.	Right-duct bypass-door opening required to keep shock wave in intake at proper position. Vibrations in No. 5 engine persisting.

Time	Event	Comments
1:07:48-50	Engine No. 5 throttled to military power--all others to minimum afterburner.	M = 2.42. Engines in minimum afterburner began to show instability. Right-duct bypass doors were at 13° and still opening to keep normal shock in proper position.
1:08:16	Minimum afterburner instability persisting as evidenced by exhaust-gas-temperature fluctuations. All engines throttled to military power.	M = 2.36. Bypass doors at 16° and still opening in attempt to keep normal shock in proper position; however, shock moving forward. Aircraft descending.
1:09:03	Right duct unstarted. (Records showed that No. 6 engine had stalled.)	M = 2.2. Noise sounded like compressor stall. Exhaust-gas temperature of engine No. 6 went to 1100° to 1200° F.
		M = 2.2. An abrupt opening of the right-duct bypass doors from 21° to 28° failed to restart the duct.
1:09:18	Unstart signal light went out at M = 2.17.	Unstart signal light disarms automatically at M = 2.17. Shock-position indicator remains operational. Pressure of events may have caused copilot to misinterpret outage of unstart light.
1:09:38	Engine No. 6 shut down.	M = 2.06. Right duct still unstarted. Bypass doors at 24°.
1:09:44	Right-duct bypass doors opened abruptly from 24° to 29°.	M = 2.05. Right duct remained unstarted.
1:09:48	Right-duct bypass doors closed rapidly from 29° to 11°.	Right duct remained unstarted.
1:10:00	Light aircraft vibration reported.	Initially attributed to turbulence, damped out by 1:10:13. Bypass doors reached 11° at 1:10:00.
1:10:25	Mild divergent Dutch roll oscillation.	Record indicates that light pilot input into wheel is exciting a Dutch roll oscillation. FACS trying to rectify situation.
1:10:36	Right-duct bypass doors closed to 4 1/2°.	M = 1.91.

Time	Event	Comments
1:10:38	Right-duct incipient buzz started.	Duct buzz accompanied by high-frequency oscillatory accelerations of the aircraft which reached approximately 0.4g at fuselage resonant frequency within an irregular beat frequency envelope. Pilot initially attributed oscillations to turbulence. Seconds later, he realized that turbulence was not the cause and suspected that FACS might be feeding the disturbance. (Disturbance was of sufficient severity to be reflected in the β, yaw rate, and yaw control records.) Buzz appears to have actually started because of closing of right bypass to 4 1/2°.
1:10:44	Right-duct bypass doors opened abruptly from 4 1/2° to 6°.	M = 1.9. Severe transverse high-frequency oscillations and duct buzz persisting.
1:10:48	FACS turned off. Mildly divergent Dutch roll oscillation started.	Buzz persisting. Transverse oscillations minimized in amplitude but still present. Divergent, 6-second-period Dutch roll oscillation started when FACS turned off. Pilot's attempts to maintain control involved essentially aileron-only inputs. Analysis of flight data showed the combination of adverse yaw due to aileron, negative product of inertia, and negative effective dihedral prevailing at the time resulted in a closed-loop destabilizing trend in the aileron-only tracking task.
1:11:08	Engine No. 4 went into steady-state stall.	

Time	Event	Comments
1:11:09	FACS turned on. At about the same time, the right-duct bypass doors were closed from 6° to 4 3/4° and the incipient buzz became "hard" buzz.	Turning on FACS rectified the divergent Dutch roll oscillation in two cycles and reestablished the transverse frequency of the body which reached a maximum amplitude of ±0.7g at the pilot station. These oscillations are evident not only in the yaw rate and yaw control records but also in the unstart signal pressure records of the right duct. At about the time FACS was turned on, it was noticed that No. 4 and No. 5 engines were overtemperature.
1:11:24	Engines No. 4 and No. 5 shut down because of overtemperature.	M = 1.87. Violent transverse resonant-frequency oscillations persisting.
1:11:27	Right-duct bypass doors opened from 5° to 7°.	Transverse oscillations diminished in intensity but still strong. (The oscillation is still evident in the right-duct unstart signal records.)
1:11:36-37	Engines on left side were increased in power and left rudder was applied to balance the asymmetric thrust.	M = 1.81.
1:11:45	Right-duct bypass doors closed from 7° to 5°.	Transverse oscillation persisting within beat frequency.
1:11:52	Right-duct bypass doors opened rapidly from 5° to 16 1/2°.	M = 1.75. Buzz and resonant oscillations ceased immediately and did not recur for the remainder of the flight.

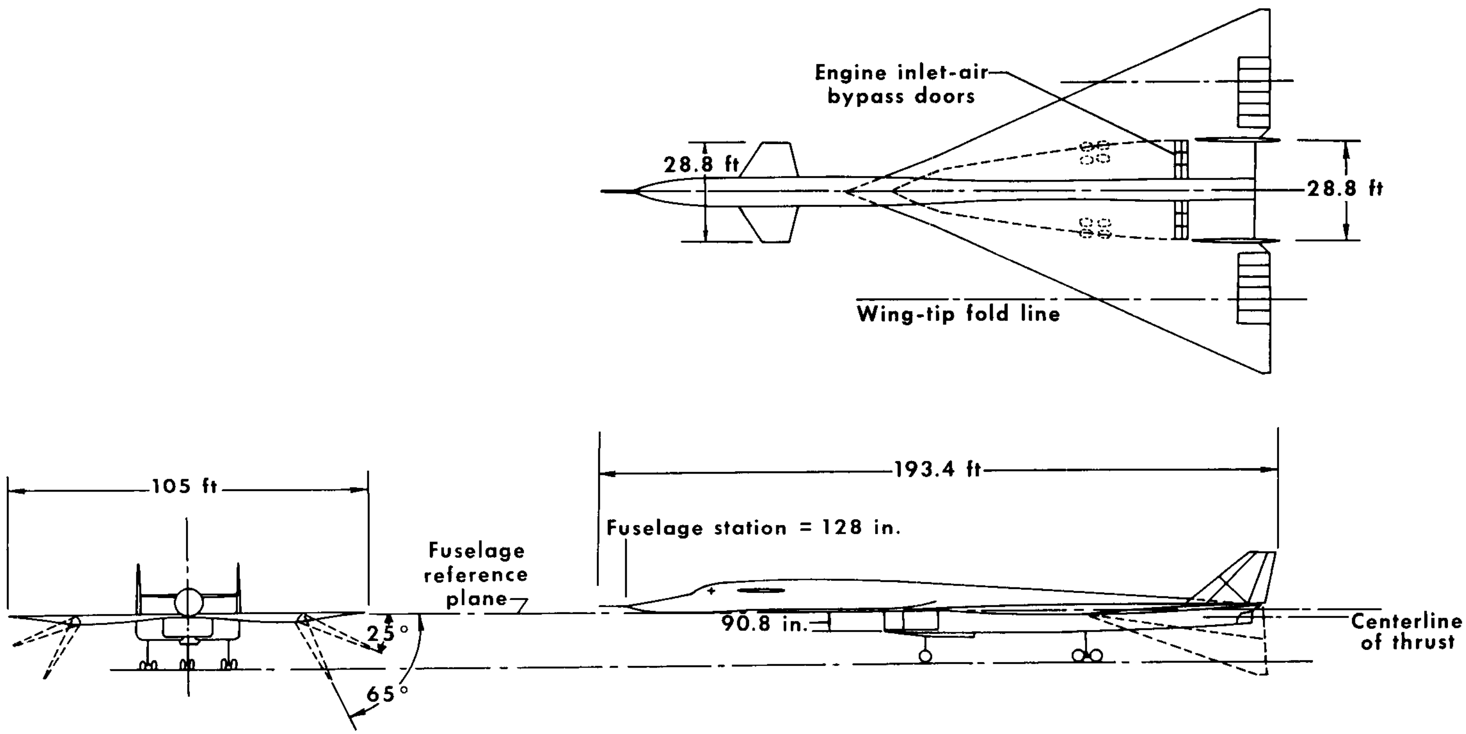
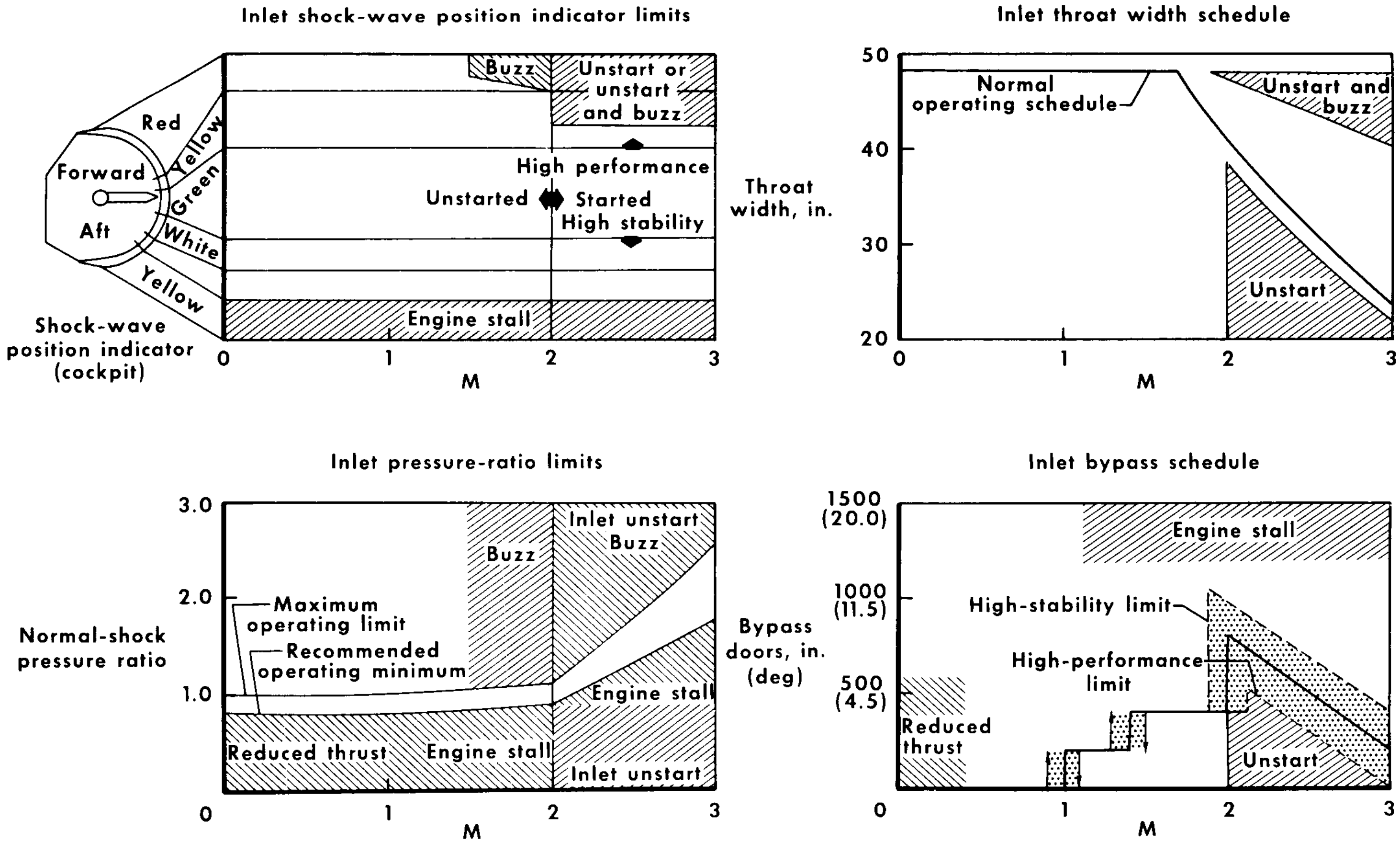
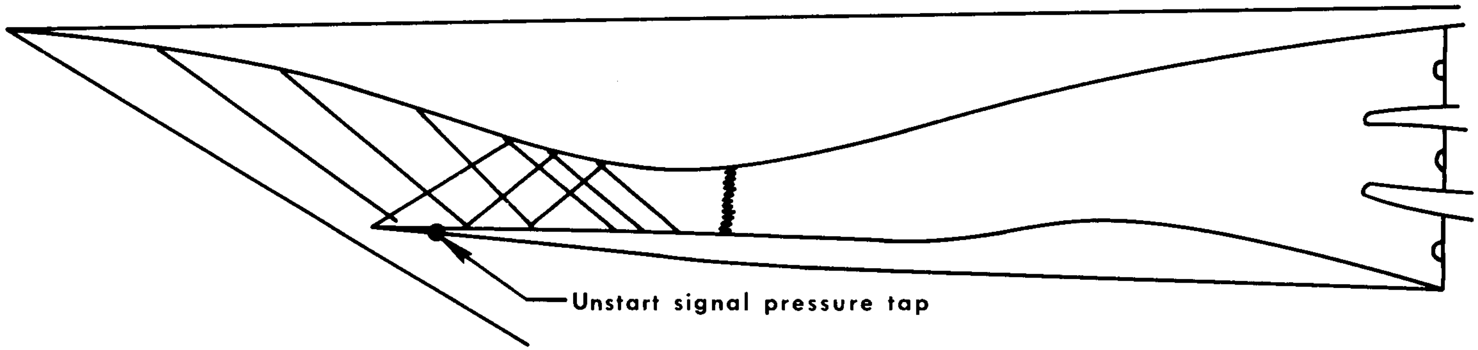


Figure 1. – Three-view drawing of the XB-70-1 airplane.

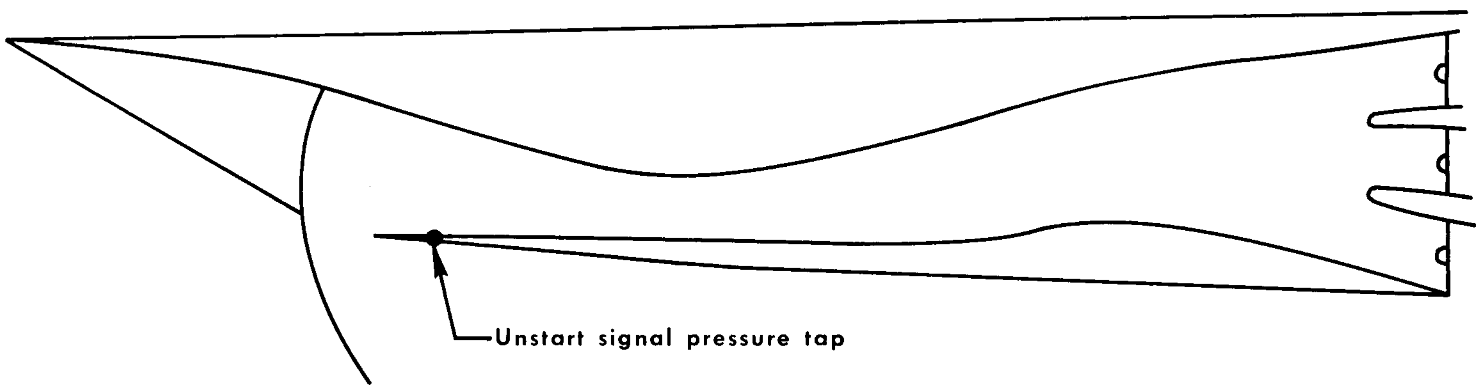


(a) Operating limits of inlet bypass doors and throat width.

Figure 2. – Propulsion-system inlet operating limitations.



Normal "started" position of normal shock



Shock pattern for inlet unstart condition

(b) Start and unstart positions of normal shock.

Figure 2. – Concluded.

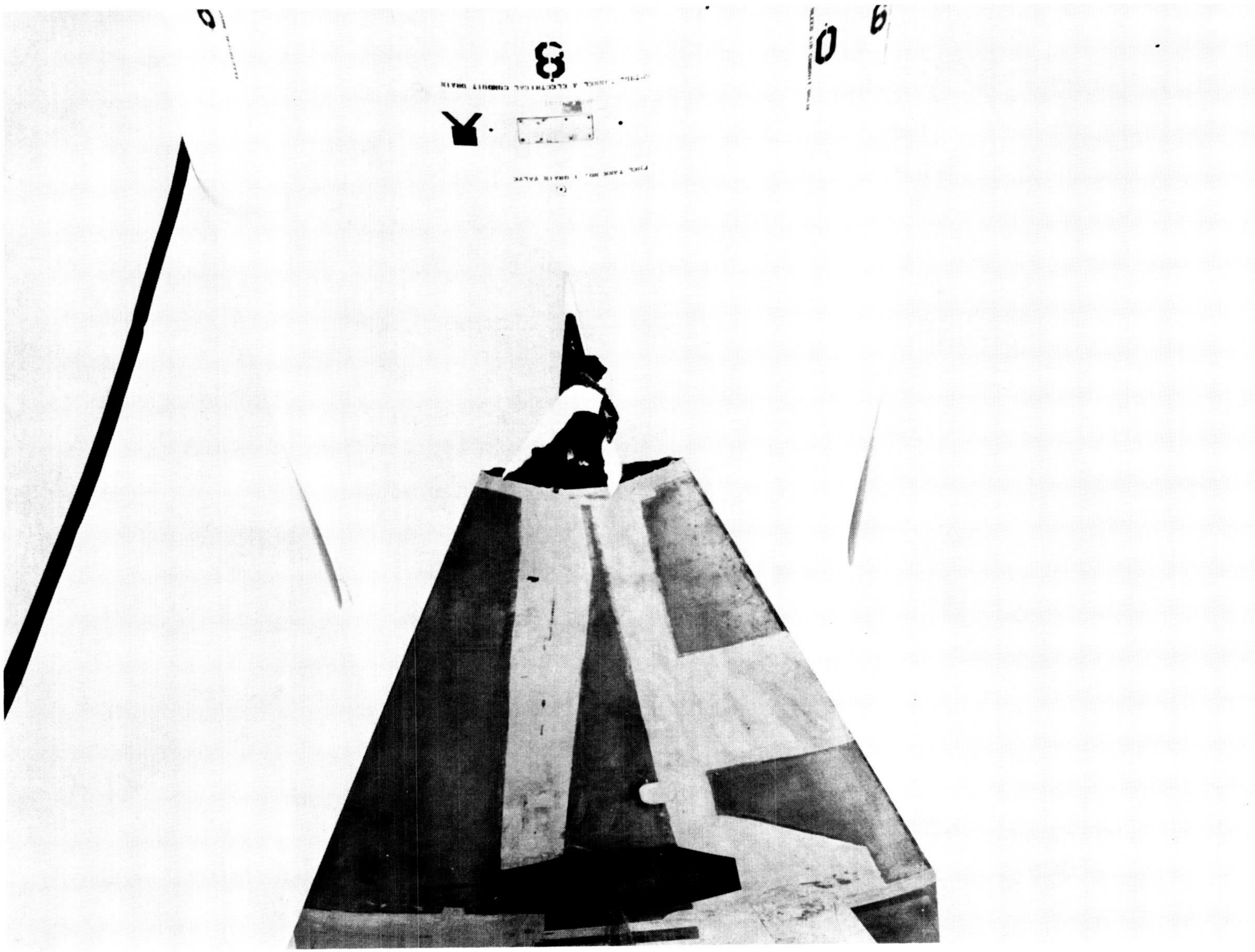
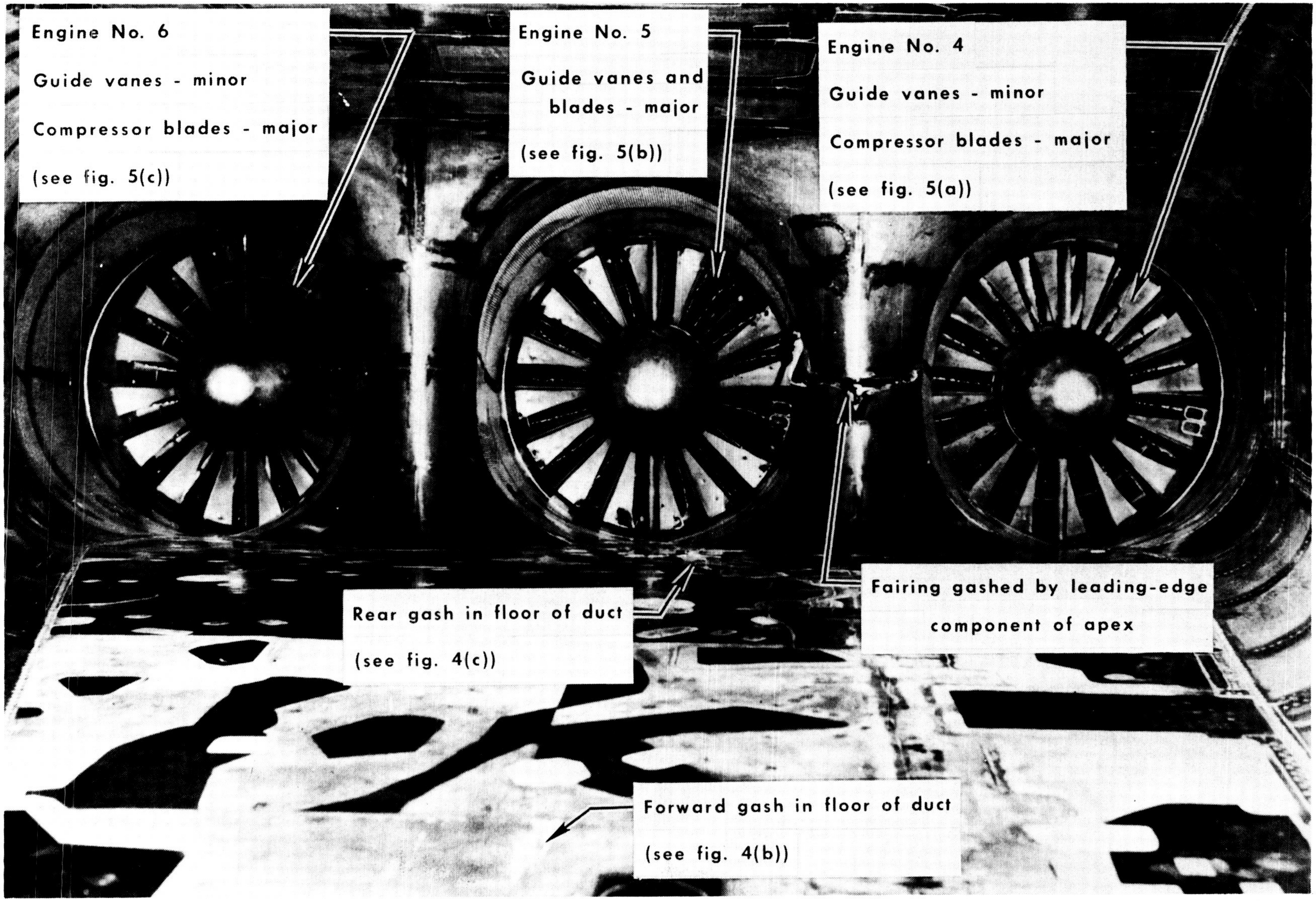
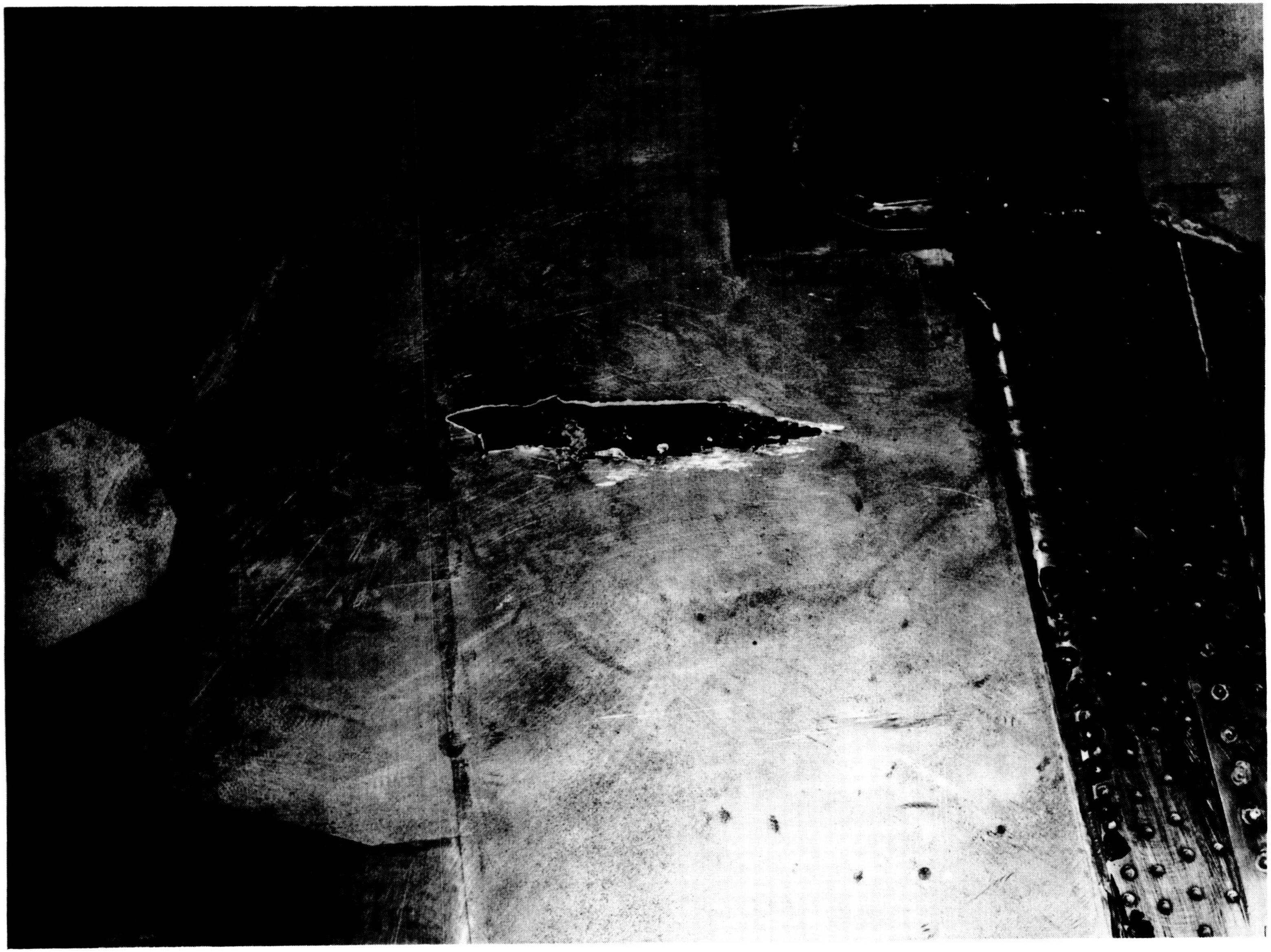


Figure 3. – Postflight photograph of disintegrated apex of wing. XB-70-1; flight 12.



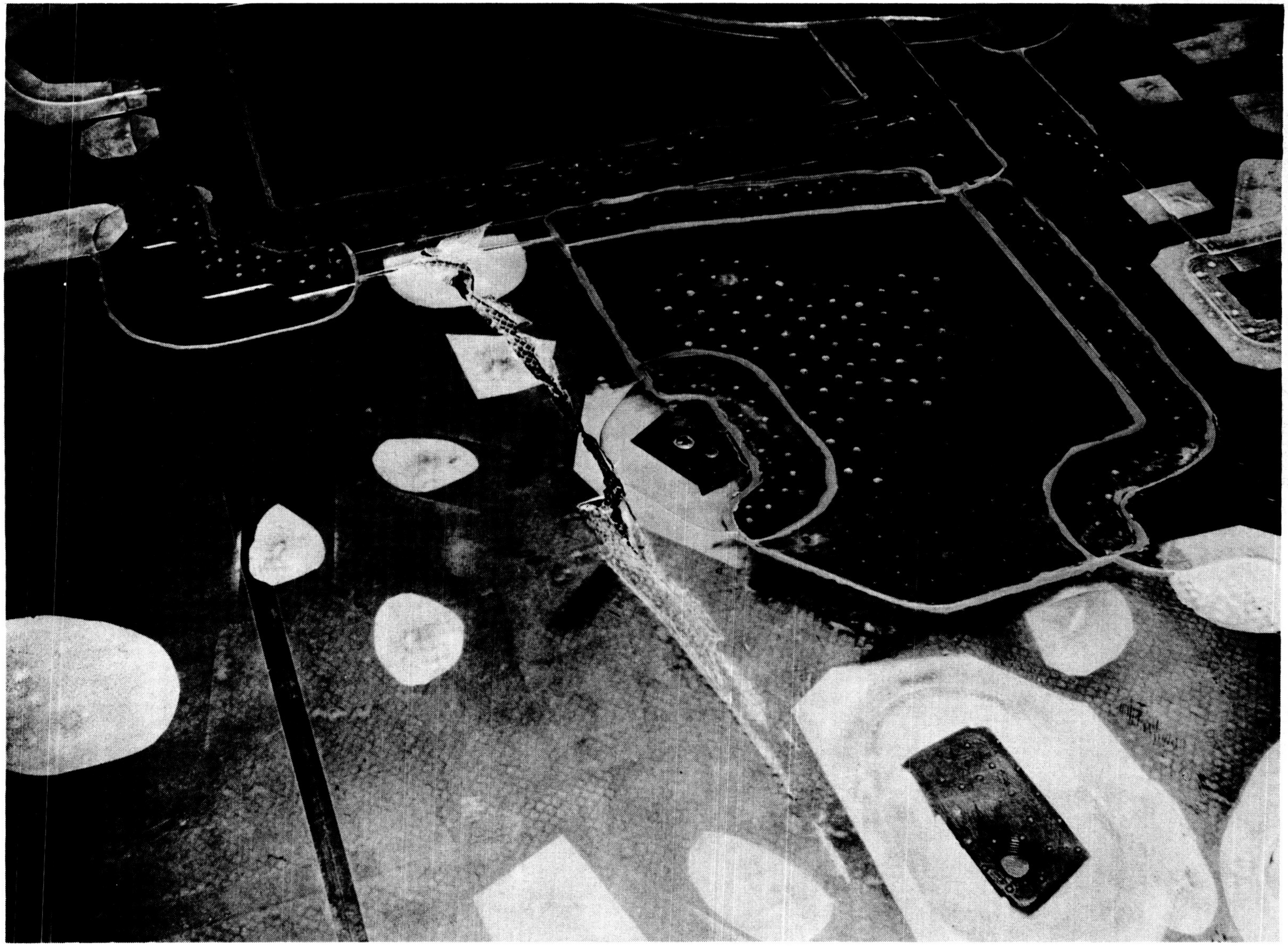
(a) Overall view encompassing areas damaged by disintegrated wing apex.

Figure 4. – Right-hand-duct damage.



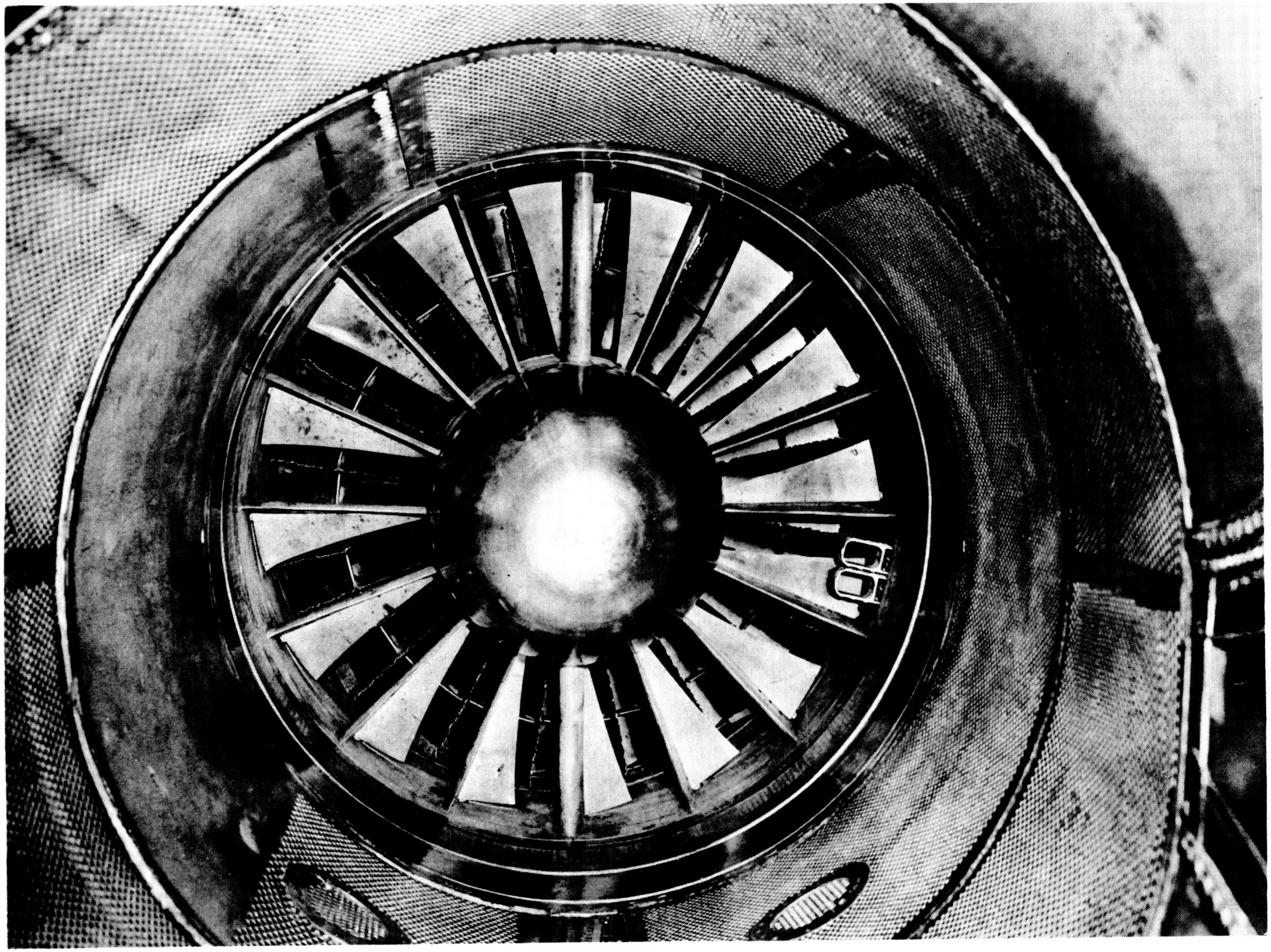
(b) Detailed view of forward gash in floor.

Figure 4. – Continued.



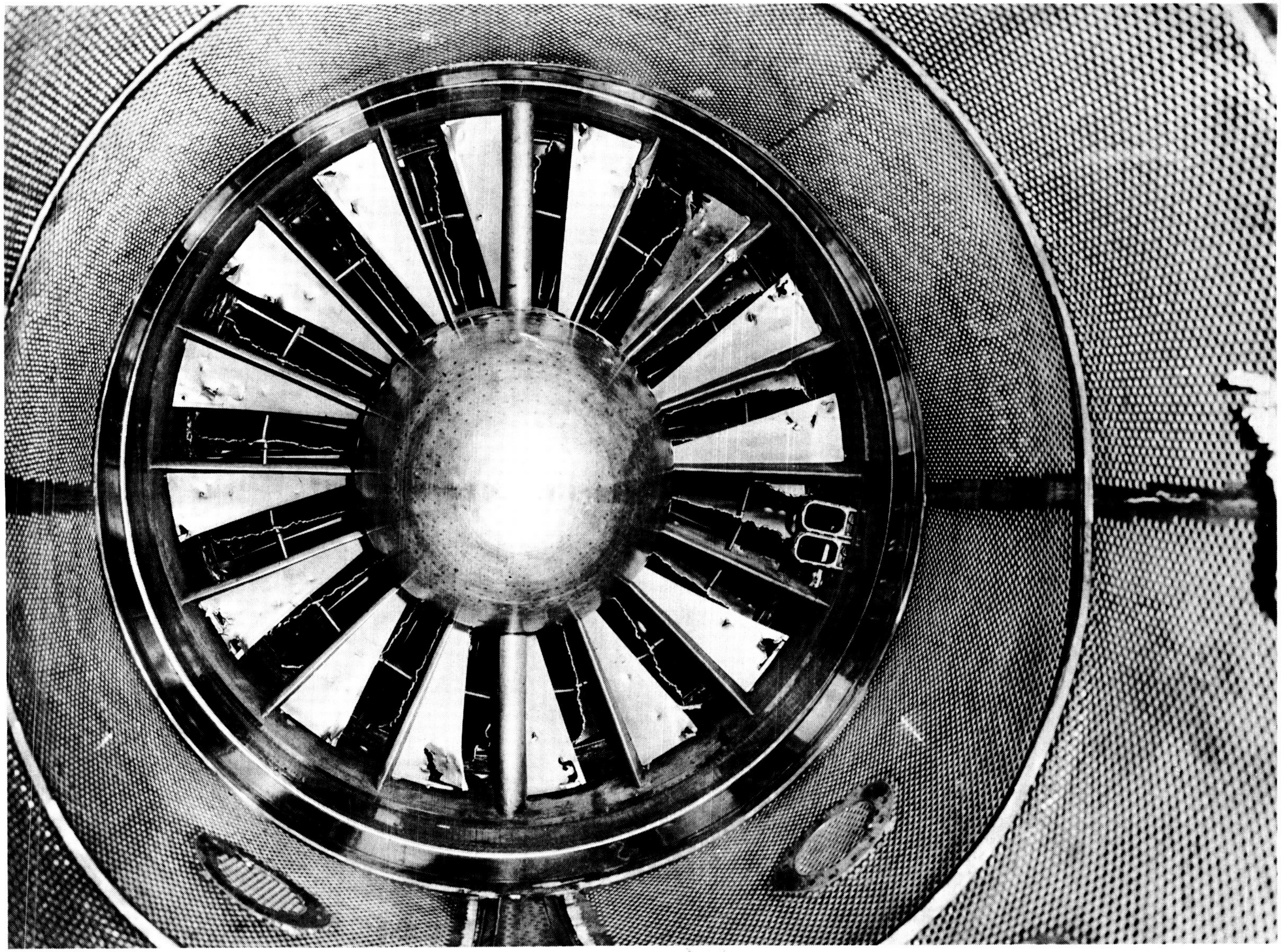
(c) Detailed view of rear gash in floor.

Figure 4. – Concluded.



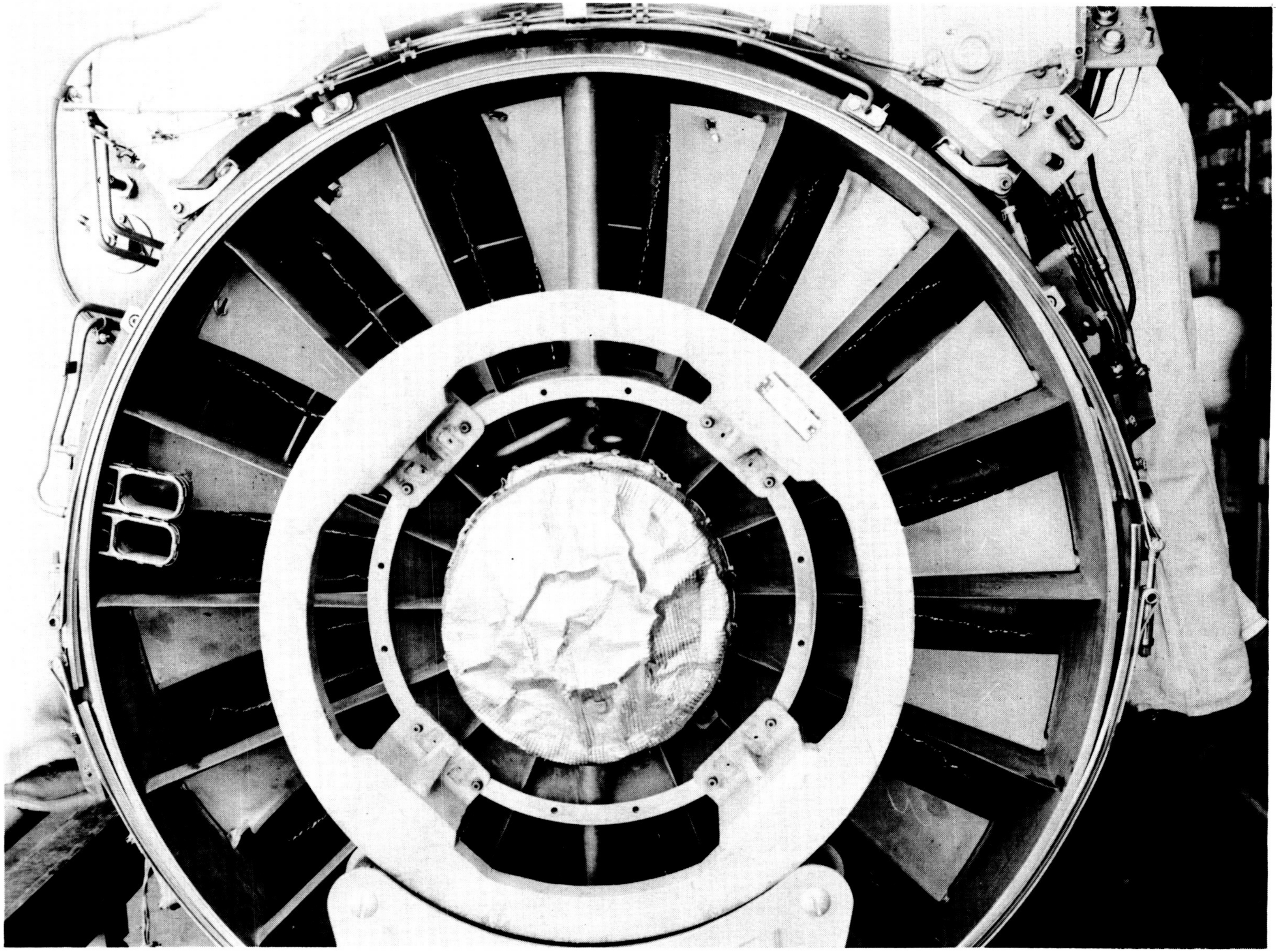
(a) No. 4 engine.

Figure 5.- Detailed views of engine damage.



(b) No. 5 engine.

Figure 5. – Continued.



(c) No. 6 engine removed from the aircraft installation. Center fairing dome and other fairings removed.

Figure 5. – Concluded.

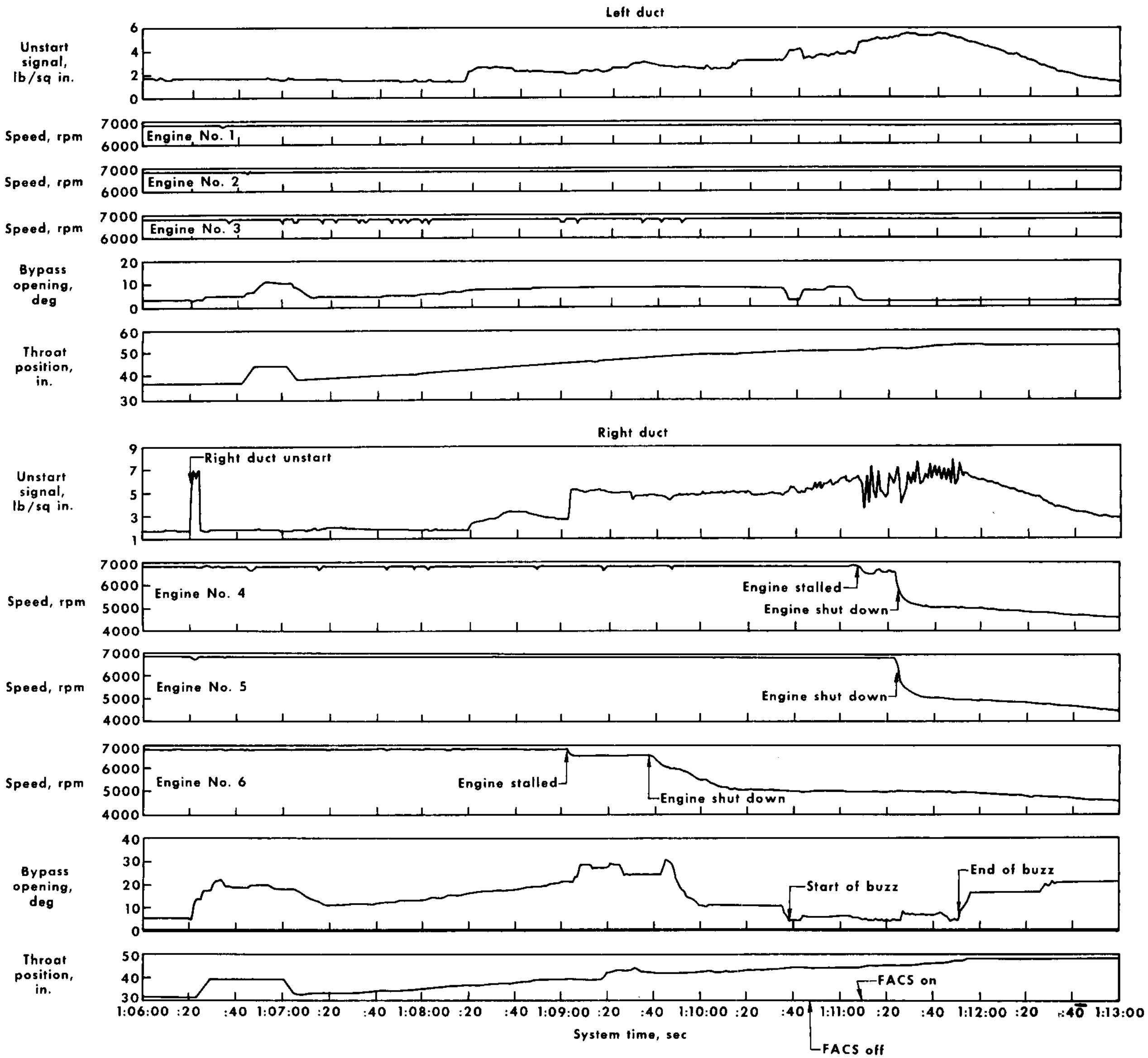
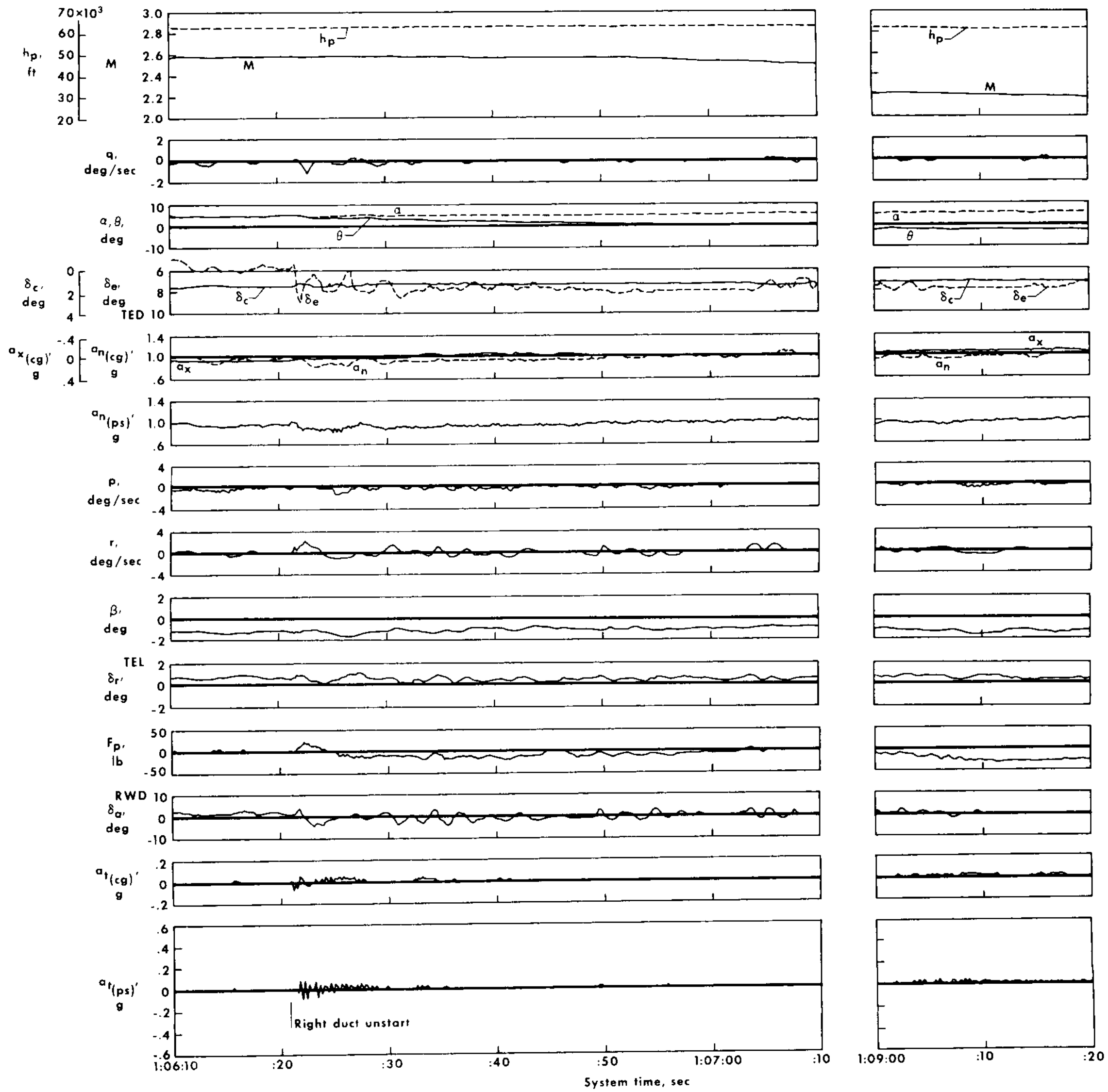
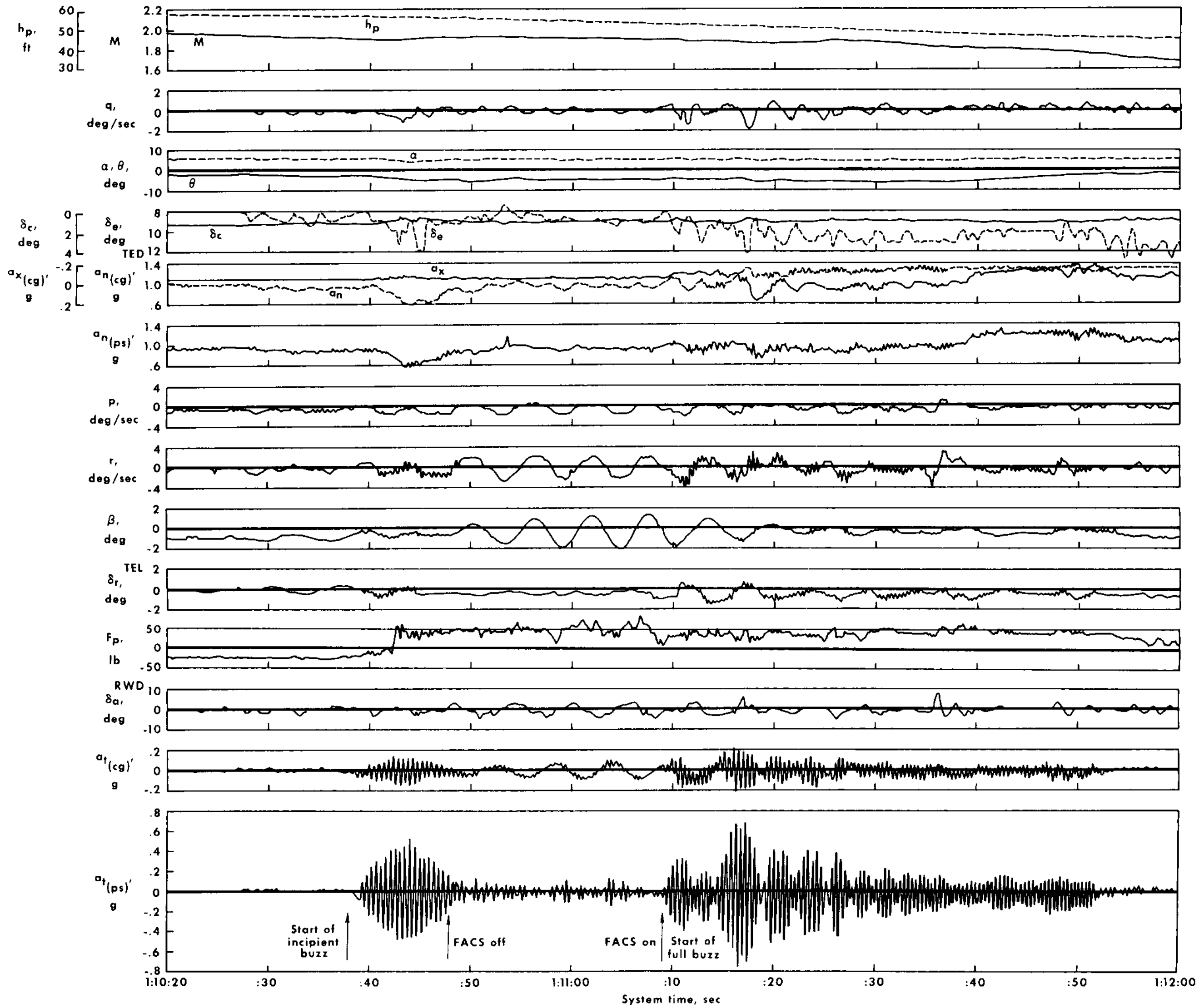


Figure 6. – Time history of propulsion-system performance. XB-70-1; flight 12.



(a) System time = 1: 06: 10 to 1: 09: 20.

Figure 7. – Time history of aerodynamic aspects. XB-70-1; flight 12.



(b) System time = 1: 10: 20 to 1: 12: 00.

Figure 7. – Concluded.

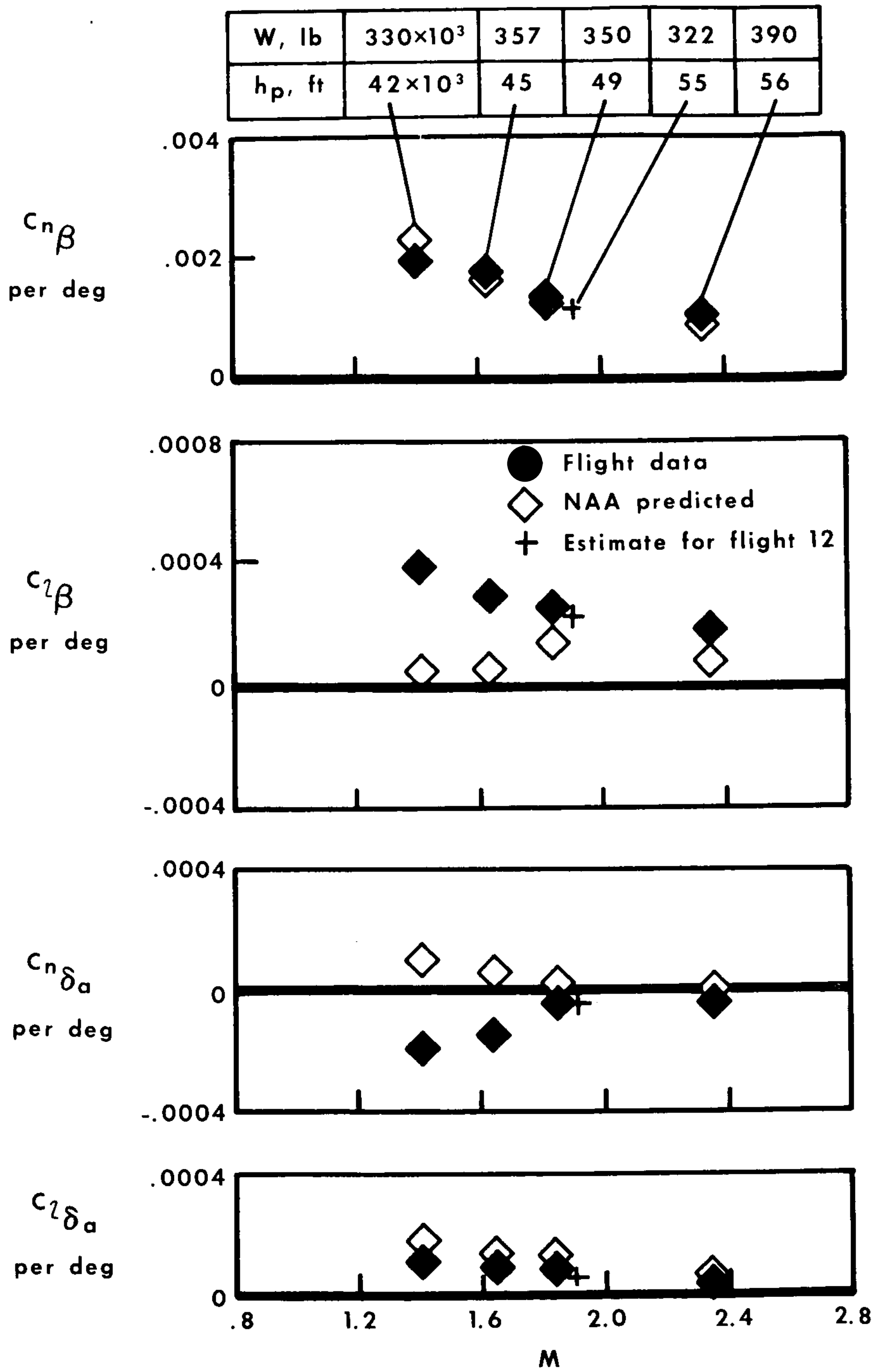


Figure 8.— Comparison of predicted derivatives with derivatives determined by analog-matching of flight data from various flights.

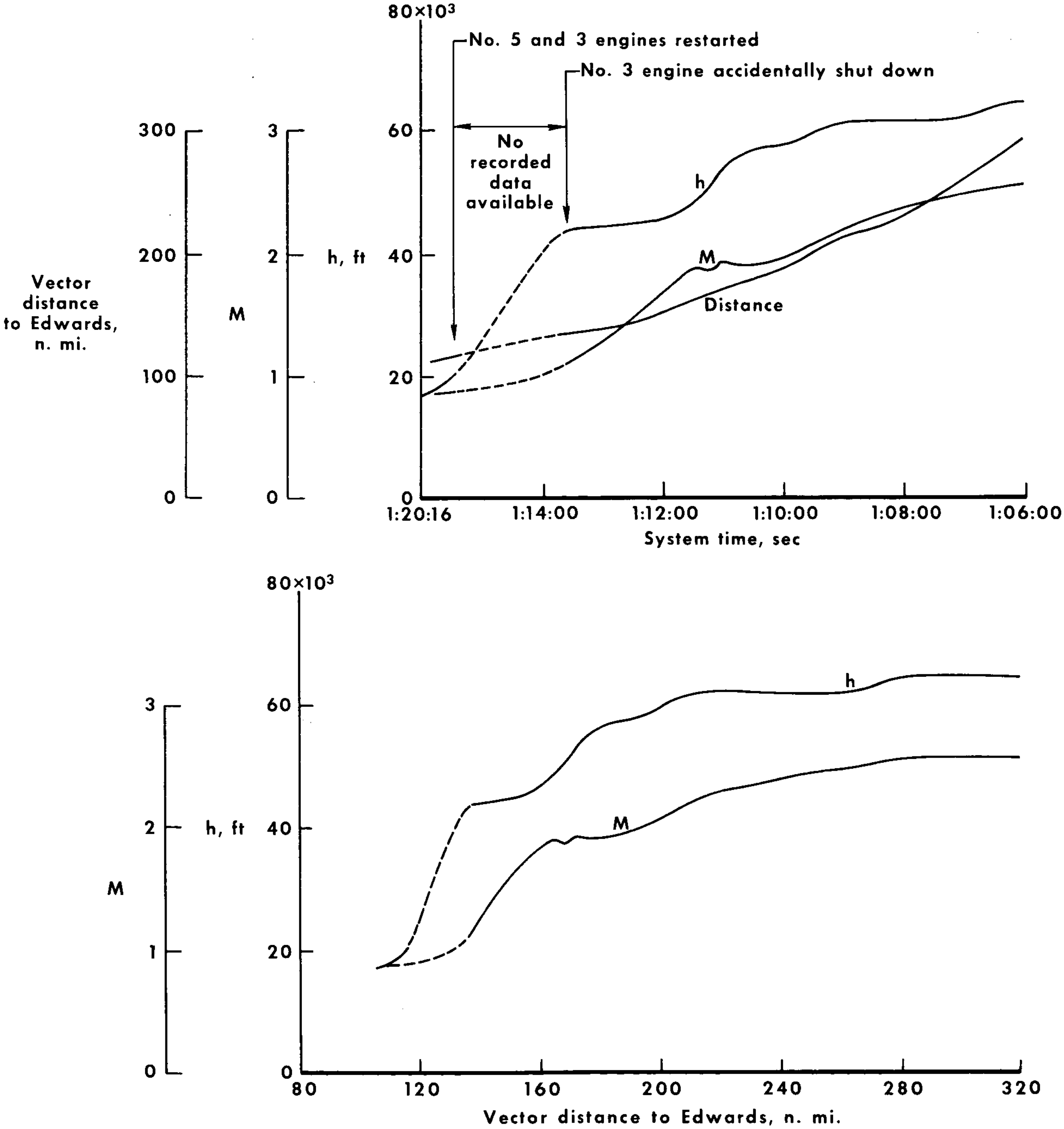


Figure 9. – Time and distance histories of altitude and Mach number for emergency portion of flight. Data based on NASA radar.