NASA Technical Memorandum 4137

A Smoke Generator System for Aerodynamic Flight Research

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SEPTEMBER 1989

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National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division
1989

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SUMMARY

A smoke generator system has been developed for in-flight vortex flow studies on the F-18 high alpha research vehicle (HARV). The development process has included conceptual design, a survey of existing systems, component testing, detailed design, fabrication, and functional flight testing. Housed in the forebody of the aircraft, the final system consists of multiple pyrotechnic smoke cartridges which can be fired simultaneously or in sequence. The smoke produced is ducted to desired locations on the aircraft surface. The smoke generator system (SGS) has been used successfully to identify vortex core and core breakdown locations as functions of flight condition. Although developed for a specific vehicle, this concept may be useful for other aerodynamic flight research which requires the visualization of local flows.

This paper describes the design and flight qualification of the system and includes examples of flight test results from this system on the F-18 HARV. Operational limitations and practical considerations obtained from the functional flight testing of this system are also discussed.

NOMENCLATURE

a_N	normal acceleration, g
HARV	high alpha research vehicle
LEX	leading-edge extension
M	Mach number
p	roll rate, deg/sec
SGS	smoke generator system
α	angle of attack, deg
β	angle of sideslip, deg
ϕ	roll attitude, deg

INTRODUCTION

To achieve improved performance or flying qualities, some modern aircraft configurations have been designed to promote vortex flows at high angles of attack. This approach makes use of the low pressure fields of separated vortexes, generated by sharp, highly-swept leading edges, to augment lift. The location and strength of the vortexes also have a profound effect on the stability and control characteristics of the vehicle. These effects can be sensitive to details such as noseboom geometry and even minor surface imperfections in the forebody. In addition, the vortexes may impinge on other vehicle components causing structural buffeting concerns. To develop aircraft with confidence that utilize vortex flows, it is critical to have reliable design tools which have been validated with flight data.

Design tools such as wind tunnels, water tunnels, and numerical methods predict detailed vortex characteristics in the form of off-surface flow field quantities. Obtaining flow field measurements in-flight using conventional instrumentation is complicated by the distance of the vortexes from the vehicle surface. Consequently, flight data is generally limited to surface properties or total vehicle forces and moments which can only imply the strength and location of the vortex flow. Smoke inserted into the flow field can allow for direct in-flight observation of the strength and location of the vortex flow.

Other potential applications of in-flight smoke include identification of flow field streamlines, regions of separated flow, and aerodynamic interactions of vehicle components. Although commonly used in wind-tunnels, (Goldstein, 1983; Maltby, 1962; and Nelson, 1986) smoke has rarely been used for in-flight aerodynamic research. The majority of airborne smoke generators have been developed for flightpath identification purposes (such as trajectory analysis, tracking, skywriting, or airshow performances) and are not suitable for analysis of the local flow field.

A research program to study the high angle of attack (alpha) flight regime is being conducted by the National Aeronautics and Space Administration (NASA) using a modified F-18 fighter airplane. The airplane is referred to as the high alpha research vehicle (HARV). One objective of the NASA program is to obtain a flight database of the off-surface vortex characteristics for direct comparison with experimental and computational vortex flow prediction methods.

A unique in-flight smoke generator system (SGS) was developed to support the F-18 HARV program. A survey of existing smoke generating systems identified many candidate approaches, but only the most promising approach was pursued further. A detailed design was generated and system components were tested on the ground and in preliminary flight tests on the pylon of an F-104 airplane. The complete system was then fabricated, flight-qualified, and flight-tested onboard the F-18 HARV.

This paper describes the development of the smoke generator, flight test operation, examples of results, and operational limitations and considerations. Although this system was designed specifically to support the F-18 HARV project, it may be useful for other in-flight flow visualization studies.

VEHICLE DESCRIPTION

The HARV is a single-place F-18 aircraft and is powered by two F404-GE-400 turbofan engines with afterburner. As shown in figure 1, the aircraft features a variable-camber wing with leading-edge extensions (LEX) mounted on each side of the fuselage extending forward of the wing roots to just forward of the windshield. The F-18 HARV is flown by NASA without stores.

External modifications to the basic F-18 configuration consist of unique wingtip pods used to house cameras and to support air data probes, a camera housing on the upper fuselage centerline just aft of the cockpit, and ducts from the SGS.

SMOKE GENERATOR SYSTEM DEVELOPMENT

Conceptual Design

The development of an effective in-flight SGS required some basic considerations in order to meet local aerodynamics research objectives. Any in-flight SGS must provide a large amount of smoke and deliver this smoke to specific locations. The system must also be able to operate over a wide flight envelope. At $\alpha > 35°$, the F-18 HARV is limited to altitudes above 18,000 ft in order to provide a recovery margin in case of a departure; the service ceiling limit on the F-18 is 52,000 ft. Although the majority of high-α flight testing is expected to occur at about 120 kn indicated airspeed and 20,000 ft, it is desirable for the SGS to operate effectively at transonic speeds and altitudes up to the service ceiling limit of the F-18 HARV.

An in-flight SGS must be incorporated into an existing vehicle, in this case, the F-18 HARV. Therefore, compactness and versatility are important features for aircraft integration while retaining system independence. With system independence, the system does not require extensive integration with the aircraft power or control systems. Finally, any in-flight SGS must be compatible with the flight test environment and meet all flight safety considerations.

A survey was conducted to determine the most promising design concept which would meet the system requirements. This survey included the use of natural condensation (Campbell and others, 1988), heat exchanger based systems (Lamar and others, 1987 and Smith, 1975), cryogenic systems (Lamar and others, 1987), solid particulates, chemical reactions, spray from another airplane (such as a tanker), and pyrotechnic smoke cartridges (Fennell, 1971). Most of these techniques have been used in previous flight test applications. The potential approaches were considered not only for their suitability to the F-18 HARV requirements, but also for their suitability as a basic tool for other flight research applications.

A pyrotechnic smoke cartridge-based system, using a unique chemical formulation, was selected for the current application. The conceptual design consists of two housings, each containing six cartridges, installed internally to the airframe of the F-18 HARV. The cartridges can be ignited independently or in any combination. Smoke from each housing is ducted to the desired flow field location.

The selection was supported by the following features:

1. Demonstrations of the smoke cartridges indicated rapid and dense smoke production relative to other concepts.
2. Multiple packaging allows from one to six cartridges to be ignited simultaneously, offering a wide variation in smoke production rate to match particular flight conditions.
3. Ducting allows the housing to be in a convenient airframe location for installation and servicing.
4. Minimal integration is required with the cockpit and aircraft electrical power systems.
5. The cartridges can be stored, loaded, and unloaded in a similar manner as other pyrotechnic devices commonly used in high performance aircraft systems (such as ejection seat and bomb racks).

Smoke Cartridges

The F-18 HARV SGS cartridges consist of a steel cannister, pyrotechnic chemical mixture, and an electric ignitor unit. This assembly, shown in figure 2, was specially designed for the HARV application by the U.S. Army Chemical Research, Development and Engineering Center, Aberdeen, Md. The safety and performance of the cartridges are dependent on the design and assembly details which are not included in this report.

The chemical formulation, which contains its own oxidizer, is described under U.S. Statutory Invention Registration Patent No. H233, issued on March 3, 1987. It was developed to produce nontoxic smoke at a high rate while minimizing fire, detonation, and handling hazards. After blending, the chemical mixture is pressed into the cannister at 2000 lb/in.^{2} in three increments. A thin layer of starter mix is added on the last increment. The completed cannisters contain about 330 grams of the chemical mixture.

The smoke cartridge cannister is 2.4 in. in diameter and 4.7 in. long. The lid is seamed onto the cannister and has four evenly spaced 0.31 in. diameter holes covered with aluminum tape. The tape is removed by the slight buildup of internal pressure when the cannister is ignited.

The cartridge lid has a threaded fitting which allows an electric ignitor assembly to be screwed into place. When actuated by a 28 V, 1.3 A current, the ignitor assembly produces a small flame onto the surface of the starter composition, starting the reaction. The ignitor assembly uses a standard electric match with 24-in. leads.

During developmental testing at the Chemical Research, Development and Engineering Center, the smoke cartridges burned an average of 42 sec. There was no visible flame and the cartridge cannisters showed little effect from the burn. At the completion of the burn, the cannisters contained less than 50 grams of residue.

Housing

The smoke cartridges are contained inside individual cylinders. The cylinders are grouped into a housing in a 3 × 2 arrangement as shown in figure 3. Two smoke generator housings are mounted on a rack in the gun bay of the aircraft, see figure 4. Smoke from each housing feeds a plenum chamber.

The 4-in. diameter cylinders feature coupler latches for rapid loading or unloading of cartridges. Cartridges are placed into a retainer within each cylinder which holds the smoke cartridge in place. To monitor its temperature, each cylinder also has a sensor installed on the inside wall where smoke exits the cartridge. Independent temperature-controlled 5 A heater blankets were installed around each cylinder to maintain temperatures between 50 and 130°F at flight altitudes before cartridge ignition. This temperature range was found to provide the most consistent environment for ignition of the smoke cartridges.

During nominal operation, smoke exits from the top of the cylinder through a 0.93 in. inside diameter duct at differential pressures ranging from 2 to 10 lb/in.^2 The ducts from all cylinders of a housing are connected to a common plenum chamber. A pressure transducer is installed in each plenum chamber.

If a system overpressure occurs due to a duct blockage or an excessive cartridge burn rate, rupture discs in each cylinder provide an alternate flow path. The smoke exits the bottom of the cylinder by passing around the retainer and through the opening left by the rupture disc. The 2.5-in. diameter brass rupture disc has an area of 4.9 in^2 and is designed for rupture at differential pressures between 55 and 75 lb/in.^2 If a rupture disc bursts, the smoke vents into a common chamber for each housing and then exhausts through louvers on the lower surface of the aircraft.

Ignitor wires are fed through a fitting on each cartridge cylinder and are connected to a squib terminal strip on the aft end of each housing. The squib terminal strip is terminated at a single connector. For ground handling safety, a shorting device is installed on this connector to protect against inadvertent ignition of the cartridges.

The gun bay was chosen as the housing site because it was close to the apex of the LEX, minimizing ducting lengths, and for flight safety considerations. Since the gun bay was originally designed for high temperatures created during gun operation, it offered an additional margin of safety in the event that unexpected high temperatures were produced by the SGS. No flight-critical wiring or control systems were located in the gun bay. The existing louvers at the bottom of the gun bay which were originally intended for venting gun gasses are also used by the SGS.

Ducting

Smoke from each housing plenum chamber is ducted through flexible hose inside the airframe connected to a rigid external duct at the aircraft skin. All ducts are 0.93 in. inside diameter with a relatively smooth flow path of about 2 ft in length.

Internal ducts from the plenum chamber are flexible in order to structurally decouple the smoke generator housings from the aircraft skin and for ease in installation. The flexible ducts are teflon-lined internally to prevent heat damage.

The external ducts (fig. 5) are located on the aircraft forebody below the LEX and exhausts on the LEX upper surface about 4 in. aft of the apex. The external stainless steel LEX ducts are removable and attach to the forebody and LEX. This allows for a relatively simple ducting reconfiguration if needed. The mounting provides structural decoupling of the duct from vertical deflections of the LEX.

Cockpit Controls

Figure 6 shows the smoke generator cockpit controls which consist of two toggle switches on the instrument panel, a trigger on the stick, and a control panel at the upper right corner of the cockpit panel. One instrument panel switch activates the heater blankets. The other activates the smoke generator control panel. The seven-position smoke select switch (off and six ignition positions) is used to select the desired cartridge ignitions for a particular maneuver. Programmed prior to flight, each ignition position of this switch can command from one to six simultaneous cartridge ignitions. The two-position smoke generator arming switch arms the trigger switch on the stick, which is then used to ignite the selected smoke cartridges.

Flight Qualification

Safety and research-related concerns were identified and resolved prior to flight of the F-18 HARV SGS. Concerns related to the research mission included the overall quantity of visible smoke and the ability to document this smoke using video and photographic systems. The primary safety concerns included ground handling, potential sources of fire and heat, system overpressure, and the overall strength and durability of the system. This section provides an overview of the tests that were performed to address these concerns.

To minimize the initial risks of building the F-18 HARV SGS, a preliminary test fixture was built for ground and flight testing. This fixture, as shown in figure 7, was mounted on the right wing pylon of an F-104. It resembled a single cylinder of the F-18 HARV SGS and operated one smoke cartridge per flight. Several ground tests of this fixture were required to demonstrate the normal operation and to verify the pressure relief rupture disc mechanism prior to flight. In addition, checklist procedures for stray voltage checks, loading, ignition, unloading, and cartridge disposal were developed during these tests. Documentation of the smoke using video cameras was also verified.

The first phase of flight testing with the F-104 SGS indicated that smoke production rate and smoke density were marginally acceptable at 20,000 ft and ignition could not be achieved at 40,000 ft. The second phase included a temperature-controlled heater blanket and showed that smoke cartridge performance increased with higher cartridge temperatures. With the heater blanket, one smoke cartridge ignition was achieved as high as 40,000 ft, although smoke production rate and smoke density were poor. Although not tested on the F-104, multiple or sequential ignitions of cartridges appeared to be required in order to increase smoke production significantly over a useful test time. The average duration of useful smoke production from a single cartridge during flight test was approximately 35 sec.

Several components of the F-18 HARV SGS were tested on the ground to verify operation and to qualify the system for flight. Ground vibration tests were performed on the LEX ducts and the smoke generator housings. The housings with heater blankets were tested in an environmental chamber at temperatures as low as −40 °F. Heater blankets around each cylinder were able to maintain a minimum cylinder temperature of 80 °F.

The complete F-18 HARV SGS was tested on the ground for system validation before installation into the aircraft. All system procedures and hardware were verified for proper operation. Sequential and multiple ignition techniques, with up to six cartridges within a housing being ignited at one time, were successfully demonstrated. Figure 8 shows an example of two cartridges fired simultaneously during ground testing. Smoke cartridge burn times averaged about 40 sec with maximum burn temperatures of about 230 °F within the housing cylinders.

A defective cartridge was simulated by a cartridge in which the grain was not pressed. This "loose grain" cartridge was felt to represent the fastest possible burn rate of a cartridge. Two of these loose grain cartridges were ignited simultaneously inside of the SGS without a system overpressure.

The proper operation of the rupture disc pressure relief system was tested by closing off the normal smoke path. This was performed by manually closing a valve at the smoke outlet during the most rapid burn of the smoke cartridge.

After installation of the F-18 SGS into the F-18 HARV, further ground tests were conducted. Electromagnetic interference tests were conducted to verify that the system could not be electrically activated by other aircraft systems and vice versa. Normal cartridge ignitions and a simulated blocked ducting were also performed. No significant increase in gun bay temperatures were recorded during ground testing.

INSTRUMENTATION

The complete F-18 HARV research instrumentation system is designed to monitor 544 channels of 10-bit data utilizing two airborne pulse code modulation (PCM) systems. The SGS instrumentation data stream is processed at

50 samples/sec, telemetered to a ground station during flight, displayed for real-time monitoring, and then stored for post-flight analysis.

Each cartridge cylinder temperature (12 total) is measured using a resistance thermometer ranged from 0 to 400 °F. The plenum chamber pressure for each housing (two total) is measured using a pressure transducer ranged from 0 to 200 psia. When the stick trigger is pulled, a trigger event discrete is signaled. These channels are monitored in real time on two stripcharts during flight testing of the SGS.

As shown in figure 1, the F-18 HARV video system consists of four video cameras and one 35 mm still camera. The vertical tail cameras are black and white video cameras with an 8.5 mm, wide angle, auto-iris lens. Because of the severe vibrational environment of the vertical tails, these cameras were specially modified into two components, a video amplifier–power supply assembly and a sensor–lens assembly. The sensor–lens assemblies and mounting hardware weigh 17 oz each and are located on the inboard surfaces of the vertical tails. The color video cameras, which are mounted on the left wingtip and fuselage have 4.8-mm and 8-mm, wide angle, auto iris lenses, respectively. The right wingtip 35 mm still camera is an automatic exposure 35 mm camera operated in shutter priority mode with a specially modified remote shutter control. The shutter control is wired into the thumb switch on the stick for operation by the pilot as required during flight. All cameras are heated by heater blankets or heater plates.

The operation of the F-18 HARV camera system is controlled by the video control unit (VCU). The VCU also controls all heater blankets, video camera recorders (2) and transmitters (2), and interfaces with the TV control panel located in the cockpit. The TV control panel is used by the pilot to select which cameras are transmitted or recorded onboard. The two transmitted video signals are displayed in the control room during all F-18 HARV SGS flight testing.

F-18 HIGH ALPHA RESEARCH VEHICLE SMOKE GENERATOR SYSTEM FLIGHT TESTING

A series of three functional test flights were conducted to evaluate the F-18 SGS (table 1). A total of 16 maneuvers were performed with a variety of smoke cartridge firing combinations. Operation of the SGS was attempted over an altitude range from approximately 18,000 to 46,000 ft. The indicated airspeed varied from 100 to 140 kn during the maneuvers. The flight test maneuvers included steady-state flight at high angle of attack, windup g turns, angle of attack sweeps, and sideslip sweeps.

The steady-state maneuvers consisted of trimming the airplane at $\alpha = 20°$, activating the SGS ignitor assembly, and holding the flight condition for the duration of smoke production (about 30 sec).

The windup g turns were initiated by stabilizing at a predetermined 1-g flight condition and activating the SGS. When visible smoke was observed (approximately 15 sec after ignition), a coordinated turn with slowly increasing normal acceleration and turn rate was conducted. As shown in a typical time history (fig. 9(a)), this maneuver provides a relatively smooth increase in angle of attack from about 6 to 35°. As angle of attack increases beyond about 25°, normal acceleration levels off at about 2 g, and Mach number (M) and altitude begin to decrease. Also, in this range there are some excursions in sideslip and roll rate.

Angle of attack sweeps were initiated by stabilizing at $\alpha = 25°$ and activating the SGS. When visible smoke was observed, a slow pushover to $\alpha = 15°$ and a pullup to $\alpha = 35°$ was commenced. If visible smoke was still present at $\alpha = 35°$, the maneuver was repeated. An example of this maneuver is shown in figure 9(b). This maneuver provides more test time at angles of attack above 15° than the windup turn maneuver. Again, some deviations in sideslip and roll rate are most significant as angle of attack exceeds about 25°.

Sideslip sweeps were conducted at a stabilized $\alpha = 20°$. The SGS was activated at $\beta = 0°$ and when visible smoke was observed, the pilot used aileron and rudder controls to sweep sideslip nose left and then nose right slowly with wings level. If visible smoke was still present, the maneuver was repeated. Two sideslip sweeps were accomplished as shown in a typical time history, figure 9(c). Angle of attack, Mach, and altitude are held constant during these maneuvers.

During all maneuvers, the pilot operated the 35 mm still camera on the right wingtip according to a predetermined schedule. Additional photos were also requested from the control room based on observations of the video displays. All three functional test flights included a chase airplane for air-to-air still photos, movies, or video.

RESULTS AND DISCUSSION

Results from the functional flight tests include an evaluation of SGS operational envelope, smoke production rate and density, flight maneuver techniques, documentation, and data extraction capability. In addition, some observations regarding the practicality of the system in the flight test environment were obtained.

Operational Envelope

During the functional flight testing, all cartridge ignition attempts at altitudes up to 33,000 ft were successful. An unsuccessful attempt was made to ignite two cartridges at 46,000 ft.

Based on the nature of the smoke cartridge and ignitor mix formulation, and on previous experience from the F-104 flight tests, low ambient pressures, low oxygen content, or both are expected to contribute to the unreliable ignition characteristics at high altitudes. These factors cannot be easily controlled through the design of the SGS. The operational envelope of the SGS has been limited to 30,000 ft for future reliable operation.

Smoke Production Rate and Density

The effect of multiple-cartridge ignition on smoke visibility was assessed during a series of consecutive maneuvers, all at the same flight condition. The number of cartridges was systematically increased from one to three. When a single cartridge was used, only short periods of useful smoke were observed. The use of two cartridges not only increased the density of the smoke produced, but also resulted in a more consistent stream of visible smoke. Using three cartridges further increased the smoke density a small amount. The additional density was not necessary at this flight condition, but could be useful if testing at higher airspeeds is required. In conclusion, a combination of two cartridges provided the most effective and efficient use of the system at this flight condition.

For all cartridge combinations, there was a delay of 10 to 30 sec between cartridge ignition and useful smoke production. Once initiated, a steady stream of useful smoke could be expected for 30 sec when using two or more cartridges.

Flight Test Maneuver Evaluations

The steady-state high-angle-of-attack flight maneuvers were successful in obtaining high-quality data at a constant angle of attack. This technique was not an efficient use of the SGS since only one flight condition could be observed each operation. Also, it is not as desirable at angles of attack above about 35° because of the difficulty of piloting the aircraft for long periods at these conditions. The delay between ignition and visible smoke production increases the duration of this maneuver.

The windup turn, angle of attack sweep, and sideslip sweep maneuvers were also complicated by the delay between cartridge ignition and visible smoke production. It was necessary to coordinate the operation of the SGS in order to insure that visible smoke was present when the airplane passed through desired test conditions. The pilot started a maneuver based on direct observation of the smoke visibility, and control room observers identified useful smoke production from the telemetered video images and cartridge temperatures. In future applications in which the pilot may not be able to observe the smoke directly, ground commands could be used to coordinate these maneuvers.

To summarize, functional flight tests of the SGS have shown that the duration and density of smoke was sufficient for all maneuvers used in this study.

Documentation and Data Analysis

An example of the smoke flow visualization taken from the right wingtip 35 mm camera is shown in figure 10. The smoke pattern is clearly evident against the blue sky background. Although offering less contrast, the smoke can also be identified against the white surface of the fuselage. As shown in the figure, the rapid dispersal of the dense smoke filament indicates the vortex core burst point.

The onboard video systems were also successful in documenting the smoke patterns. Photographs of video screen images during an angle-of-attack sweep maneuver by the F-18 HARV are shown in figure 11.

For best results, it was necessary to coordinate the airplane heading with respect to sun angle. Smoke was visible when illuminated by forward or back lighting, however, it was important that the sun was not in the field of view as this would cause the auto-iris feature of the cameras to decrease light sensitivity and reduce the smoke's contrast against the background. Because of the multiple cameras on the vehicle, several views were suitable for good documentation. On constant heading maneuvers, the pilot could obtain good results from all cameras by heading toward the sun. However, during the windup turns, the sun angle varied and resulted in some loss of data.

A video screen photograph of the F-18 HARV taken from a chase aircraft is shown in figure 12. The SGS was providing smoke over both the left and right LEXs, as noted in the photograph. Glare from the sun's reflection on the canopy and fuselage crown can also be seen.

To improve the contrast of the smoke against the airplane and to reduce the glare from the sun's reflection, the airplane was painted with a flat black finish for future flight testing.

Operational Observations

After flight, a powdery noncorrosive residue from the smoke cartridges remained in the SGS housings, ducting, and on the airplane surfaces. The airplane surfaces were cleaned with alcohol and rags, and the housings and ducts were cleaned with wire brushes and washed with water when possible. The rupture discs were inspected after each flight. Some indications of degradation of the rupture discs were noted, possibly due to repeated exposure to heat, residue, or vibration. Replacement of the discs after all future flights was decided to insure proper performance. Unloading, cleaning, and reloading the SGS was completed in a matter of hours.

CONCLUDING REMARKS

Functional flight tests of the F-18 HARV SGS have shown that the system meets the conceptual system requirements and satisfactory operational performance can be achieved within the constraints of the flight research environment. Visible smoke patterns, revealing the LEX vortex cores and core breakdown locations, have been documented using video and photographic techniques. These patterns have been correlated with flight conditions and can be used for comparison with theoretical and other experimental data.

The F-18 HARV SGS will allow up to six flow visualization maneuvers each flight (when using two cartridges for each operation), each lasting about 30 sec. Smoke generator system operation can be coordinated with airplane maneuvers to provide data at specific flight conditions. Reliable operation of the system is limited to altitudes of 30,000 ft or less. The SGS can be cleaned and readied for a subsequent flight in several hours.

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Table 1. Summary of F-18 HARV SGS functional flight testing.

Flight	Test point	α, deg	Altitude, ft	Maneuver	Smoke generator system operation, number of cartridges (side of aircraft)
29	1	20	26×10^3	Steady-state	1 (right)
29	2	20	26	Steady-state	2 (right)
29	3	20	23	Steady-state	3 (right)
29	4	Up to 40	26	Windup turn	2 (left)
29	5	Up to 40	33	Windup turn	2 (left)
29	6	Up to 40	46	Windup turn	2 (left)
30	1	15 to 35	21	α sweep	2 (left)
30	2	15 to 35	18	α sweep	2 (left)
30	3	Up to 40	25	Windup turn	2 (left)
30	4	Up to 40	25	Windup turn	2 (right)
30	5	Up to 40	30	Windup turn	2 (right)
30	6	15 to 35	20	α sweep	2 (right)
33	1	20	19	Sideslip sweep	2 (left)
33	2	20	20	Sideslip sweep	4 (2 each side)
33	3	15 to 35	19	α sweep	2 (left)
33	4	15 to 35	20	α sweep	4 (2 each side)

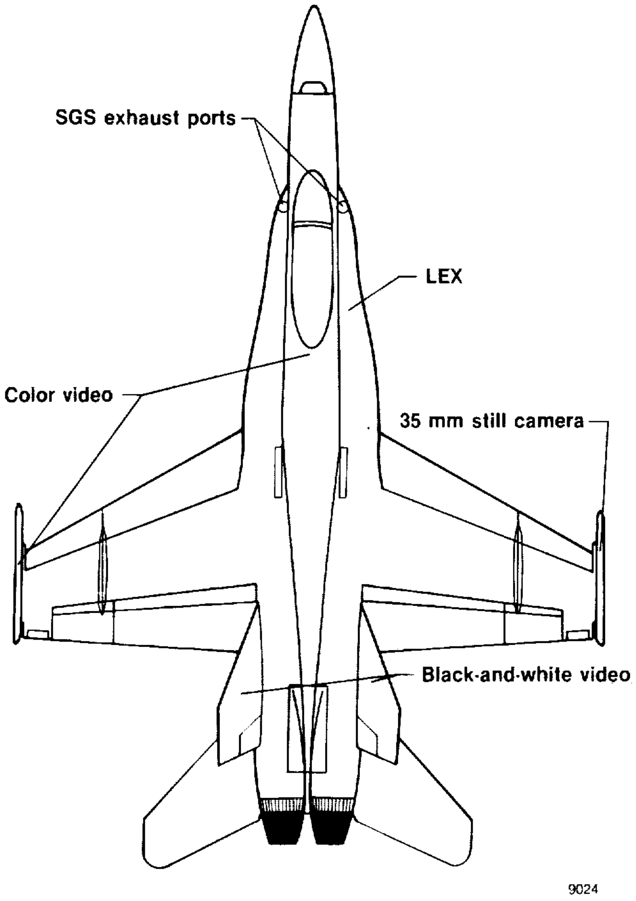

Figure 1. Plan view of F-18 HARV.

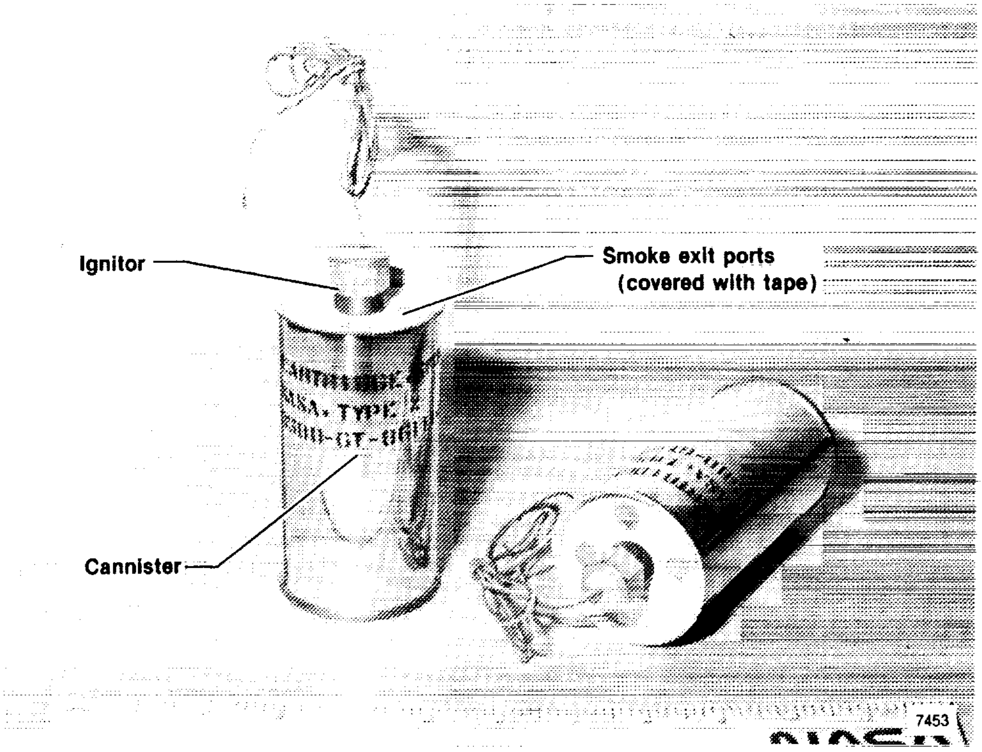

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Figure 2. Smoke cartridges.

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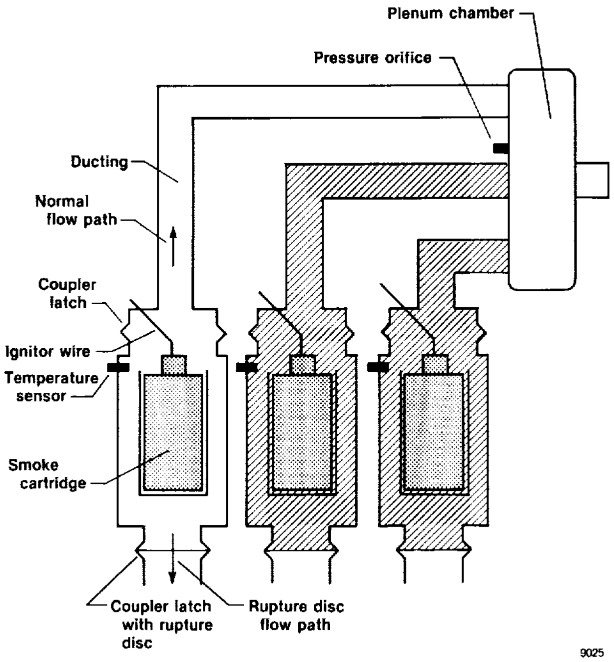
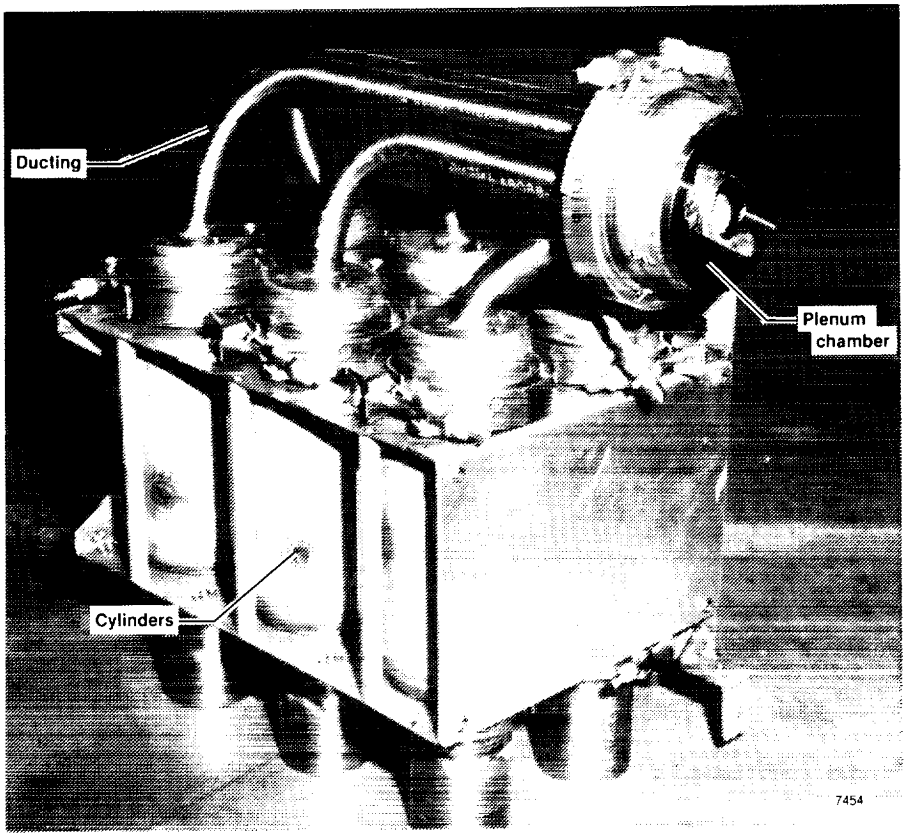


(a) Schematic.



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(b) Assembly with heater blankets removed.

Figure 3. SGS cartridge housing.

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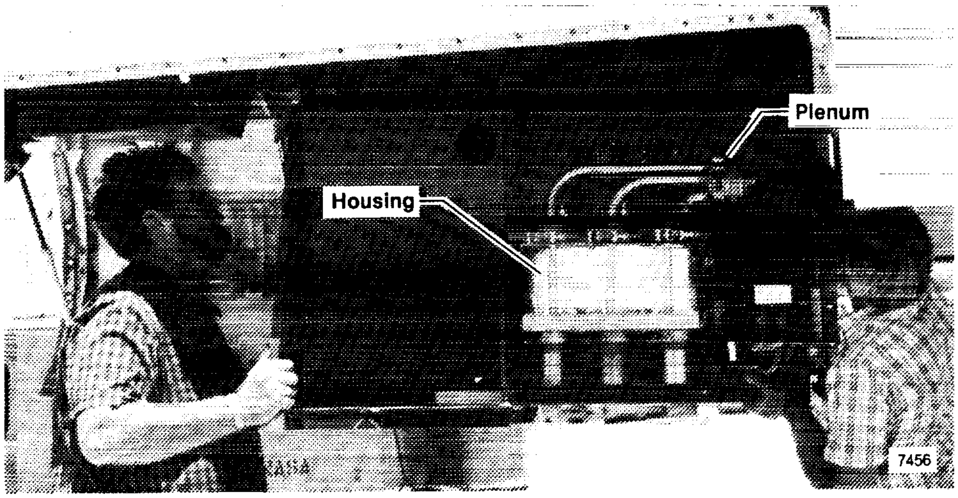

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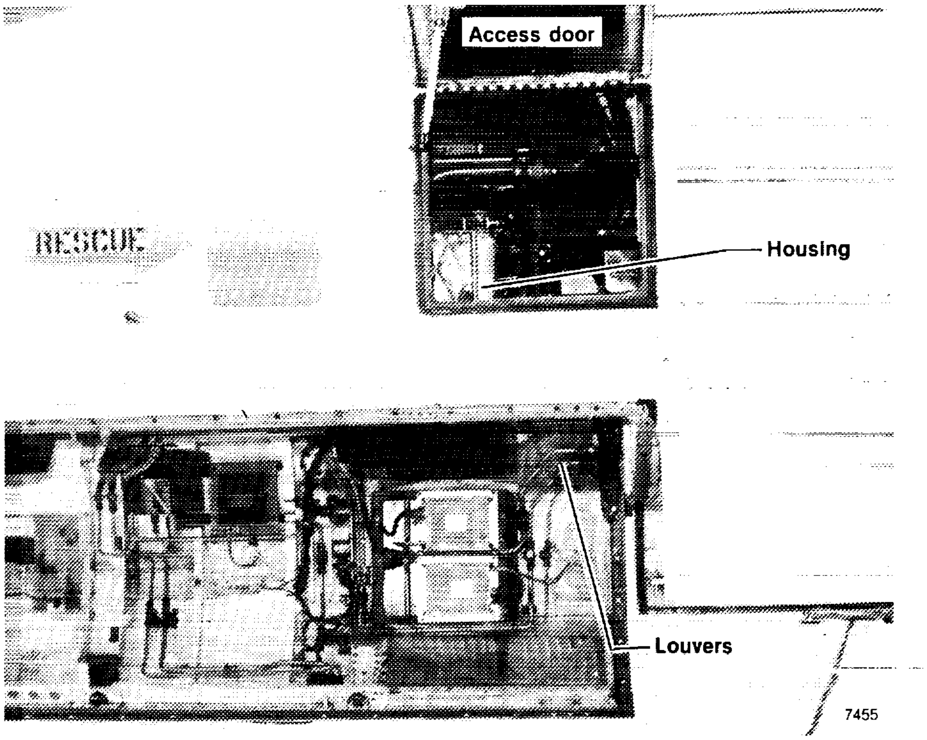
(a) System disconnected and lowered on gun bay rack.



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(b) Installed system.

Figure 4. SGS housing installation in F-18 HARV gun bay.

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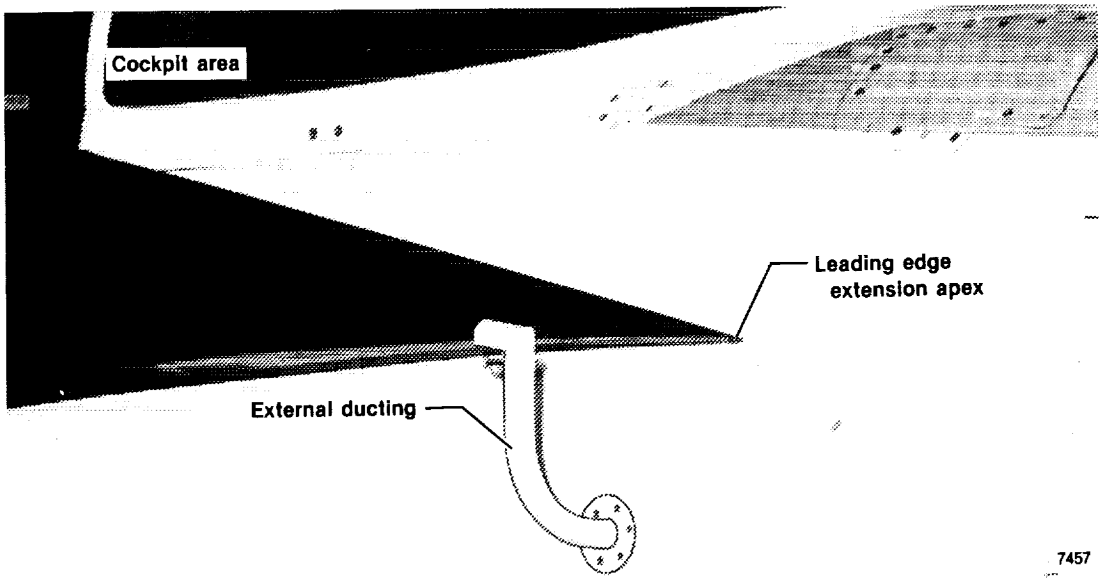
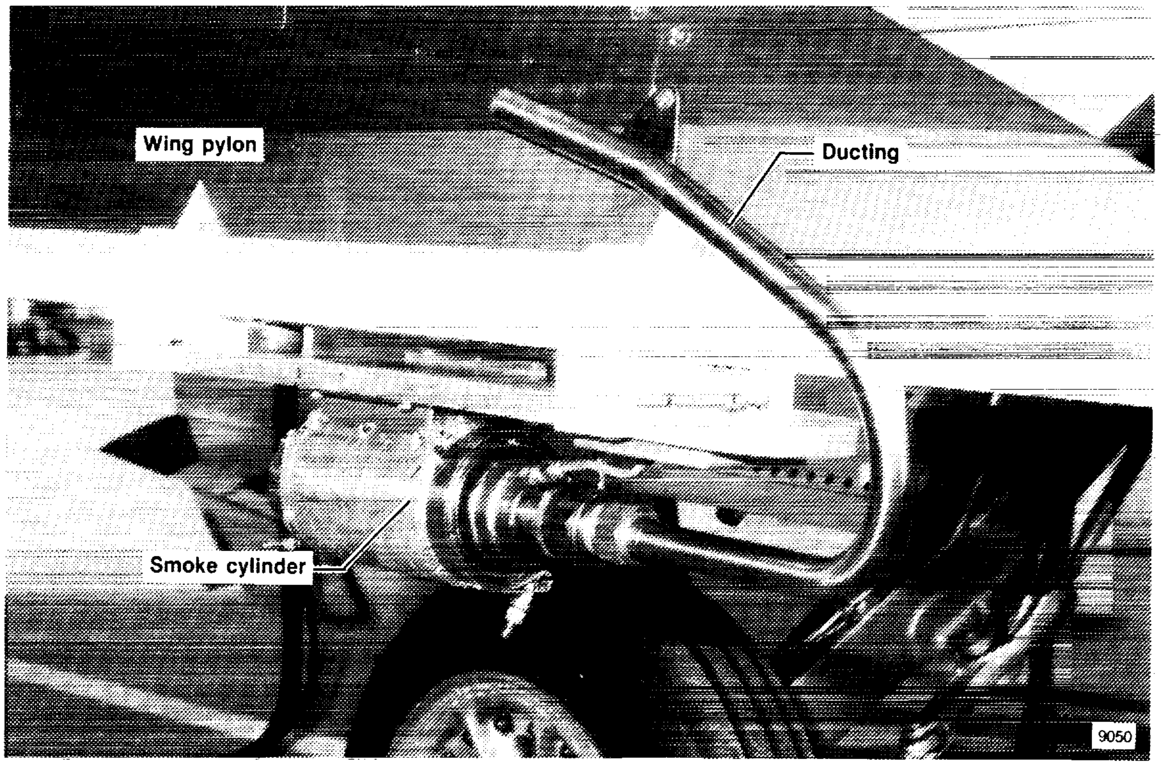


EC 88-0091-006

Figure 5. External ducting installation.

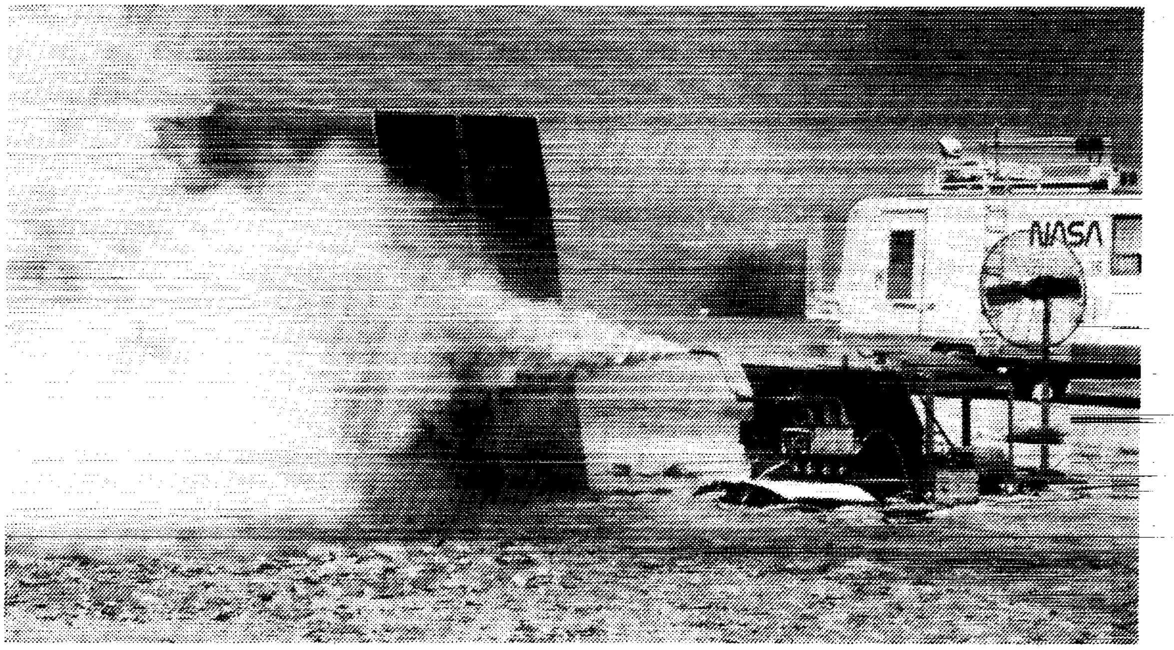
EC 88-0091-007

Figure 6. SGS cockpit controls.



EC 86-33564-002

Figure 7. Developmental SGS installed on F-104 wing pylon for flight testing.



EC 87-0248-008

Figure 8. Ground test of the F-18 HARV SGS, prior to aircraft installation.

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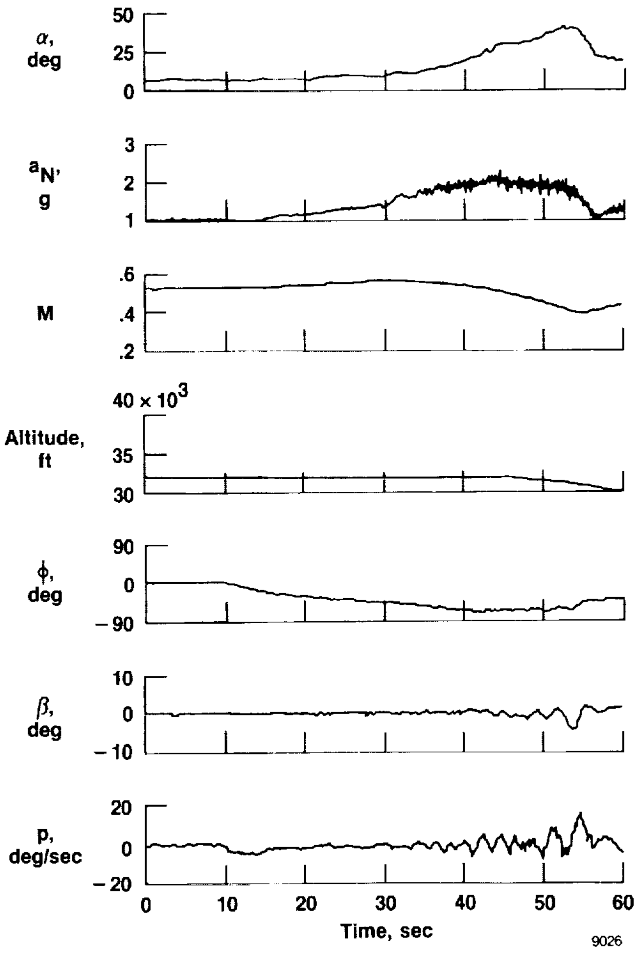
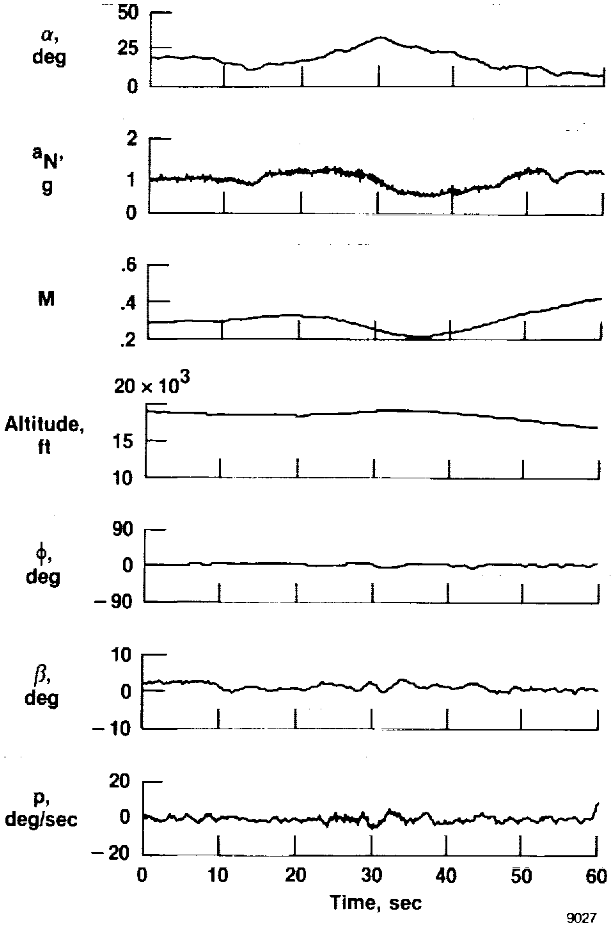


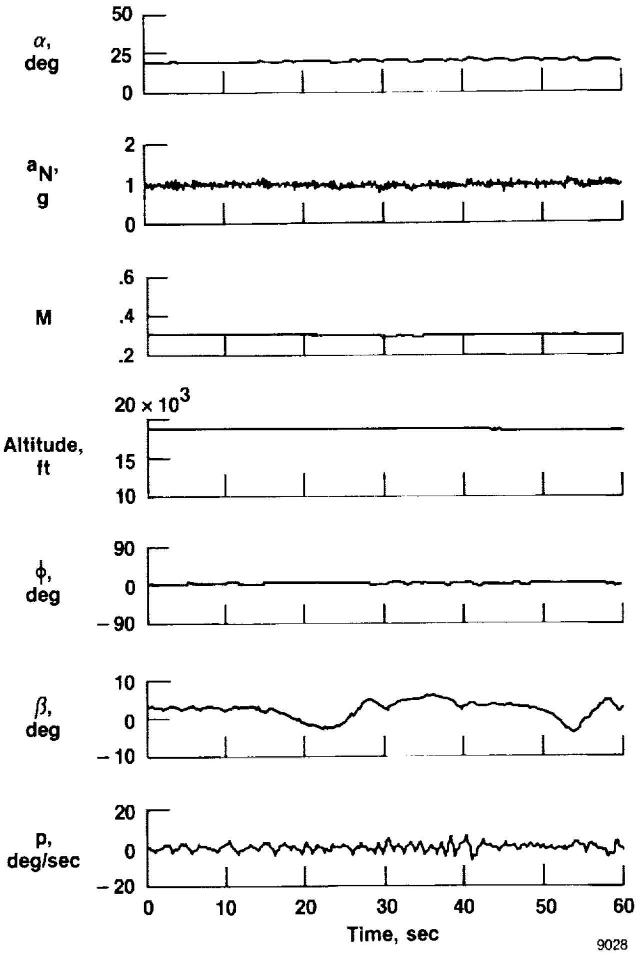
(a) Windup turn.

Figure 9. Time histories of representative flight test maneuvers.



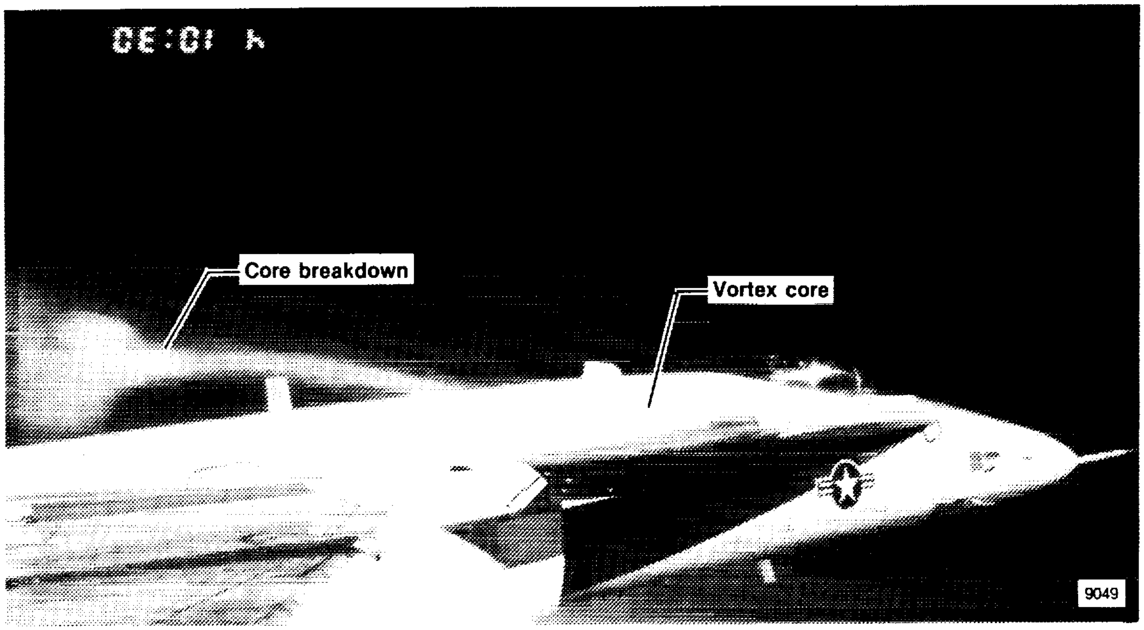
(b) Angle of attack sweep.

Figure 9. Continued.



(c) Sideslip sweep.

Figure 9. Concluded.



EC 88-0024-002

Figure 10. Smoke flow visualization photograph taken from right wingtip 35 mm camera; $\alpha = 21°$, $M = 0.31$, altitude = 23,000 ft.

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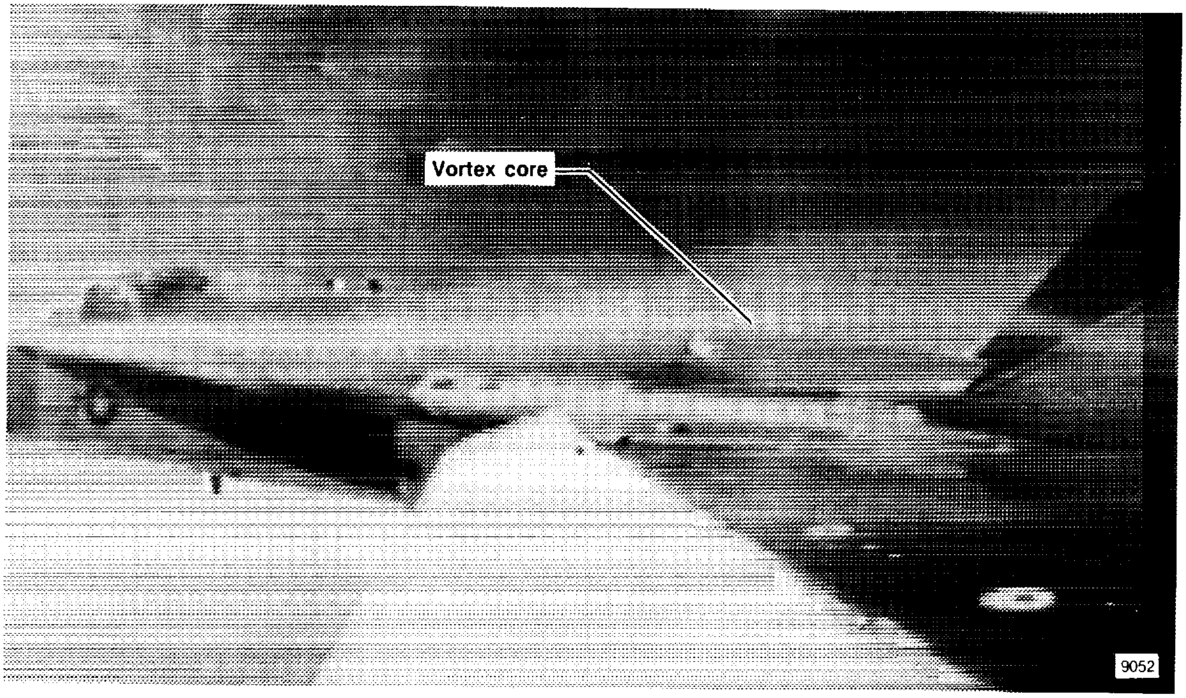
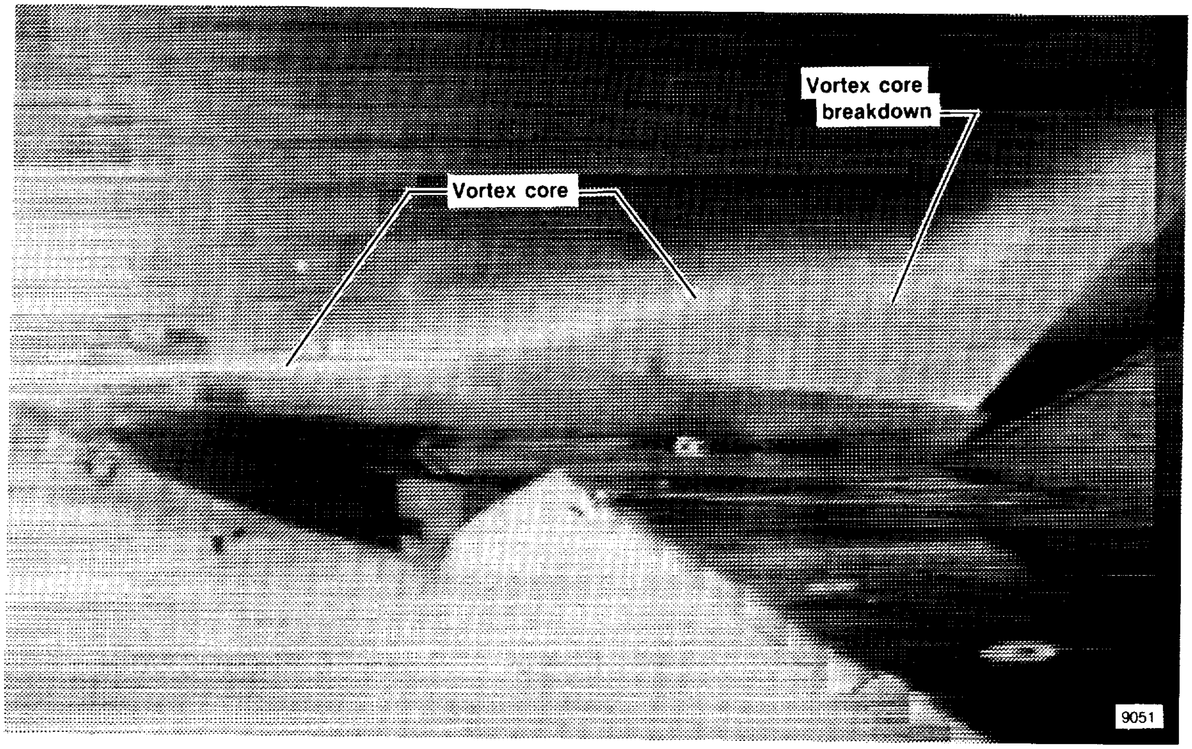


EC 88-0069-004

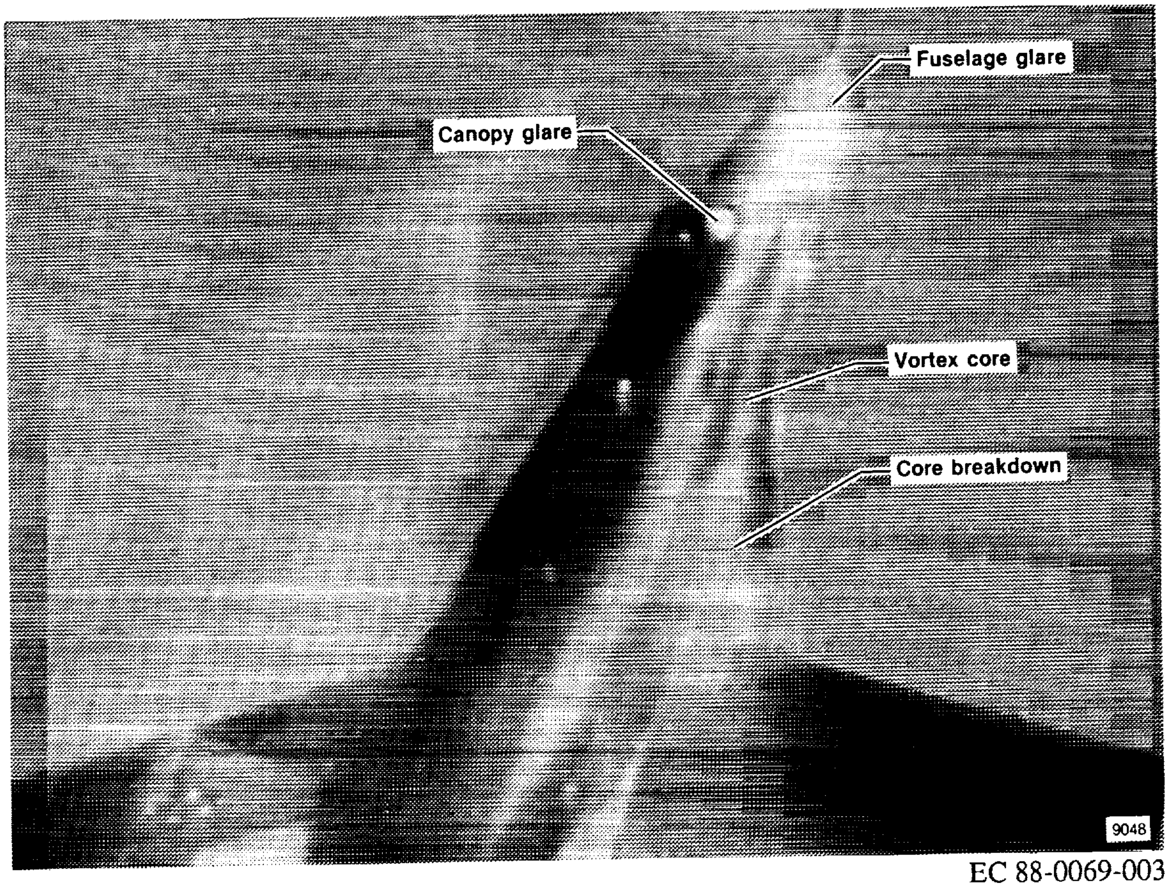
(a) $\alpha = 13°$.



EC 88-0069-006

(b) $\alpha = 26°$.

Figure 11. Photographs of smoke flow visualization from video images taken from onboard cameras; $M = 0.30$, altitude = 21,000 ft.



EC 88-0069-003

Figure 12. Photograph of smoke flow visualization from video image taken from chase aircraft.

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National Aeronautics and
Space Administration

Report Documentation Page

1. Report No.
NASA TM-4137

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
A Smoke Generator System for Aerodynamic Flight Research

5. Report Date
September 1989

6. Performing Organization Code

7. Author(s)
David M. Richwine, Robert E. Curry, and Gene V. Tracy

8. Performing Organization Report No.
H-1515

10. Work Unit No.
RTOP 505-68-71

9. Performing Organization Name and Address
NASA Ames Research Center
Dryden Flight Research Facility
P.O. Box 273, Edwards, CA 93523-5000

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A smoke generator system has been developed for in-flight vortex flow studies on the F-18 high alpha research vehicle (HARV). The development process has included conceptual design, a survey of existing systems, component testing, detailed design, fabrication, and functional flight testing. Housed in the forebody of the aircraft, the final system consists of multiple pyrotechnic smoke cartridges which can be fired simultaneously or in sequence. The smoke produced is ducted to desired locations on the aircraft surface. The smoke generator system (SGS) has been used successfully to identify vortex core and core breakdown locations as functions of flight condition. Although developed for a specific vehicle, this concept may be useful for other aerodynamic flight research which requires the visualization of local flows.

17. Key Words (Suggested by Author(s))
Flow visualization
F-18
High angle of attack
Smoke generator

18. Distribution Statement
Unclassified — Unlimited

Subject category 05

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of pages**	**22. Price**
Unclassified	Unclassified	28	A02

NASA FORM 1626 OCT 86

For sale by the National Technical Information Service, Springfield, VA 22161-2171.

NASA-Langley, 1989