INTERFACE CONCERNS OF EJECTOR INTEGRATION IN V/STOL AIRCRAFT

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The development of ejector technology has historically been concerned with achieving higher augmentation ratios through improved nozzle development, better mixing and overall ejector design. Most efforts have been successful with augmentation ratios in excess of 2.0 being achieved in the laboratory. However, the two experimental military aircraft, the XV-4A in the 1961-1964 time period and the XFV-12 in the 1971-1978 time period, have been developed using ejector systems for vertical thrust; both have been rated at best only marginally successful. In spite of the modest design augmentation ratios, 1.41 for the XV-4A and 1.55 for the XFV-12, neither aircraft achieved these levels. The reasons for not achieving the design level of augmentation and the lack of success of these aircraft can largely be attributed to the interface of the ejector with the aircraft, ejector characteristics, and the additional requirements (other than vertical thrust production) imposed on the ejector. The compromises required to interface the ejector into the V/STOL aircraft result in systems losses, weight increases, volume requirements and additional complexity. These interface areas include the engine/ejector, ducting system, force vector control, flight control, ground effects and VTOL translation/transition characteristics.

ENGINE/EJECTOR INTERFACE

In ejector-equipped aircraft, the engine(s) must perform the dual function of providing primary gas to the ejector system and of providing thrust for conventional flight. When operating in the ejector-powered mode, the engine exhaust gases are directed into the ejector system through a diverter valve scheme. The XV-4A incorporated a two-door block and turn diverter and the XFV-12 a sliding sleeve arrangement. The compromises associated with installation of the diverter valve include (fig. 1): exhaust gas pressure losses in the order of 3%, exhaust gas leakage losses in the order of 1%, weight increase in the order of 200 lb (generally aft of the C.G.). The XFV-12 diverter valve weighs approximately 400 lb. Depending on the diverter valve scheme, a possible increase in engine tail pipe length and to date no diverter valve has been flown that is compatible with afterburner operation. Another engine/ejector interface is the engine tailpipe area/ejector primary nozzle area matching. In the ejector mode, for proper engine operation, the engine must feel an exhaust area equivalent to the trim design tail pipe area. In the case of the XFV-12, F401 engine, this is approximately 8.3 ft^2. The ejector system must be designed and the nozzles sized for this equivalent area. Figure 2 shows that too little equivalent area can back pressure the engine and reduce thrust; too much area, depending upon the engine control system, can reduce stall margin. The ejector system must be designed to allow matching of the engine operating line or complications such as reduced thrust or reduced stall margin may result.

DUCTING SYSTEM

The propulsion system is connected to the ejector through a ducting system. The ducting system is comprised of duct runs, expansion bellows, integral turning vanes, attachments for mounting and insulation. In addition to being a potential source of problems ranging from intolerable internal airframe temperatures to catastrophic loss of augmentation, the ducting system compromises the vehicle through increased weight and large volume requirements, and reduces primary nozzle thrust through system pressure losses. In general, the ducting design parameters (i.e., temperature, pressure and flow Mach number) are conducive to relatively large cross-section ducts of thin gage material. Figure 3 shows some typical duct characteristics. These in turn present areas for potential problems in manufacturing such as duct joining, mismatch and welding difficulties leading to stress concentrations and hot spots which can result in duct ruptures as shown in figure 4. In addition, maintenance problems can be encountered in handling and inspection. Typical ducting systems can add 200 to 300 lb to the vehicle weight (the XFV-12 ducting system weighs approximately 900 lb) and exact a thrust loss, before augmentation, of approximately 8%. Example pressure losses are shown in figure 5. The duct pressure losses in the XFV-12 were initially estimated to be approximately 12% and the XV-4A at 10%. A rule of thumb converts 2% pressure losses into 1% thrust loss.

FORCE VECTOR CONTROL

When operating in the vertical mode, a VTOL aircraft requires some method of providing a horizontal thrust component for translation acceleration to wingborne flight. In the XV-4A, the ejector nozzles were canted 12° aft and acceleration was accomplished by assuming a nosedown attitude. Due to the limited augmentation of the XV-4A this resulted in a bouncing leapfrog translation until sufficient speed was obtained to eliminate all hot gas reingestion and to develop sufficient augmentation to maintain altitude. In the XFV-12, the horizontal thrust component is generated by rotation of the augmentor flaps to an aft position. These schemes are shown in figure 6. If sufficient augmentation can be achieved, such a scheme is more desirable and comes with relatively little penalty except complexity since the augmentor flaps are stowed in a rotated position for conventional flight. However, if accomplished by doors or louvers, the system can be back pressured resulting in loss of thrust and, if not efficient, can add to ram drag.

FLIGHT CONTROL

A VTOL vehicle must incorporate supplemental control power to hover and low-speed flight where aerodynamic controls are ineffectual. The XV-4A utilized continuous flow exhaust gas for pitch and yaw and compressor bleed air (on demand) for roll control. The pitch/yaw system required 450-lb engine thrust and at a 5% bleed rate the roll system extracted the equivalent of 216 lb of thrust (108 lb per valve). In addition to the extra weight and volume, the reaction control system extracted a total of 666 lb of thrust before augmentation (a 10% thrust loss). The XFV-12 utilizes a total force management system in which the ejector provides functions of pitch, roll, yaw, height control and force vector control. These control functions are shown in figure 7. Such a force management system imposed on the ejector requires that a certain amount of lift be retained (unusable) for control purposes, for example, with full-up height control the system must allow for further open modulation (additional lift) if a lateral or pitch control moment is demanded. Also, such a system usually suffers from a marginal lateral control capability during transition speeds before aerodynamic control is effective. Figure 8 depicts the relationship. With the ejector rotated aft and a lateral control moment demanded, the resultant effective lateral control force is equal to the delta force times the cosine of the rotational angle. In addition an unbalanced horizontal force equal to the delta force times the sine of the rotational angle induces a yaw moment; that is, as rotational angle is increased lateral control is reduced in effectiveness and is coupled with yaw. This type control system requires that either mechanical or electronic control mixing and aerodynamic/reaction control blending for smooth transition. This adds both weight and complexity to the vehicle.

GROUND EFFECTS

The ground effects generated by a VTOL aircraft have been proven to be very configuration oriented. Ground effects are characterized in four forms: hot gas reingestion into the engine, suckdown or positive lift, temperature effects and ground erosion. Ejectors generally have good velocity and temperature profiles. The mixed exhaust gas temperature at the ejector exit approaches 300° F and the velocity is approximately 600 ft/sec. This advantage gives good erosion characteristics and little temperature effect on the vehicle or surrounding equipment. However, due to the large mass of airflow through the ejector (fig. 9), five to six times the primary engine exhaust and the flow field around the vehicle, hot gas reingestion and suckdown/positive lift effects are pronounced. Reingestion of hot gases can cause two detrimental effects. Operation of the engine in a uniform elevated temperature environment causes a loss of thrust equal to about 1% for 5° F temperature rise. Both the XV-4A and the XFV-12 experienced compressor inlet temperature increases of 25° F after short periods of operation in ground effect. The second detrimental effect of reingestion occurs when the engine ingests a spike of high temperature air causing compressor stall. This is a function of temperature rate of change and not necessarily only high temperature; a 20°F temperature increase in 0.1 sec gives a 200° F/sec spike and can cause compressor stall. Compressor stall can be catastrophic if it results in engine flameout. Insofar as suckdown/positive lift is concerned, the vehicle/ejector configuration is the determiner. The XFV-12 claims positive ground effect, but testing is required to verify this claim. The XV-4A suffered from suckdown while in a three-point landing attitude; but upon raising the nose to 12° (hover attitude due to the canted ejector nozzles) the vehicle experienced positive ground effect as shown in figure 10. In any case, ground effects are clearly a design consideration for an ejector V/STOL aircraft and can attribute greatly to lift losses. In some cases, special provisions to increase the engine stall margin, such as upstaging the inlet guide vanes or increasing the turbine nozzle area have been necessary. This results in additional thrust losses before augmentation.

VTOL TRANSITION/TRANSLATION CHARACTERISTICS

For the VTOL aircraft, the transition from vertical-powered to wingborne flight (and vice versa) is the most demanding and critical phase of flight. Below about 60 knots airspeed, the power-induced effects upon the vehicle are predominant and are particularly so on the ejector vehicle because of the large amount of secondary airflow taken through the ejector system. The vehicle design configuration is clearly a driving factor on the transition characteristics. A configuration such as the XFV-12 (four poster arrangement) should exhibit good stability characteristics relative to induced pitching and rolling moments; but the single-ejector configuration such as the XV-4A develops severe low-speed pitch and roll characteristics due to the ejector-induced mass flow. Figure 11 depicts the upset moments that are induced by forward translation, sideslip or a combination of the two. These large mass flow effects were very pronounced on the XV-4A and on the XV-5A, fan-in-wing vehicle, which also induced large mass flows. To obtain adequate pitch control for transition, both vehicles required special longitudinal control design. The XV-4A required installation of a down spring to offset the high elevator hinge moments, a 30° elevator droop mechanism and boundary layer blowing on the elevator to prevent separation. With these controls the angle of attack was limited to 10° to prevent pitchup. The XV-5A required the complete horizontal tail to be positioned at an 11° leading-edge-up incidence angle and a nose-mounted pitch fan when operating in the transition regime. The moments generated in sideslip required that the XV-4A be limited to 5° and that the XV-5A limited to winds of 6 knots while in the vertical mode of operation. In addition, the large mass of air being turned through the ejector system causes high ram drag which limits forward speed while operating in the vertical transition mode. This characteristic can require special transition techniques. For example, to achieve wingborne flight speed above stall, it was necessary for the XV-4A to accomplish sequential diversion of the engine exhaust from the ejector to the thrusting mode. The XV-4A transition shown in figure 12 is undesirable from an operational standpoint. The ejector vehicle configuration should be designed to provide for a smooth continuous transition and conversion, however the requirements of transition and conversion add weight and complexity to the ejector V/STOL aircraft.

SUMMARY

A number of areas have been identified which have in the past contributed to weight, complexity, and thrust losses in the ejector-powered V/STOL vehicle. A summary of the area is shown in figure 13. Most of these interfaces taken singly do not represent a severe compromise to the vehicle; however, the bottom line is that the sum of compromises and the subsequent effects on performance, flight operations and maintenance have rendered the ejector V/STOL aircraft unattractive. In addition to some of the unique ejector/aircraft integration problems, the vehicle by virtue of having a V/STOL capability is compromised in other areas such as inlets for low speed (blow-in doors, sliding inlets, auxiliary inlets, rounded lips) and high speed compatibility, zero-zero/bad attitude ejection capability, additional controls and displays, stability augmentation, and weapons compatibility. To be successful and acceptable, the advantages must outweigh the disadvantages and simplicity with minimum penalties must be the rule. Figure 14 lists the advantages and disadvantages of the V/STOL ejector-aircraft. It is clear that more emphasis must be placed on the ejector/aircraft interface for the concept to be successful.

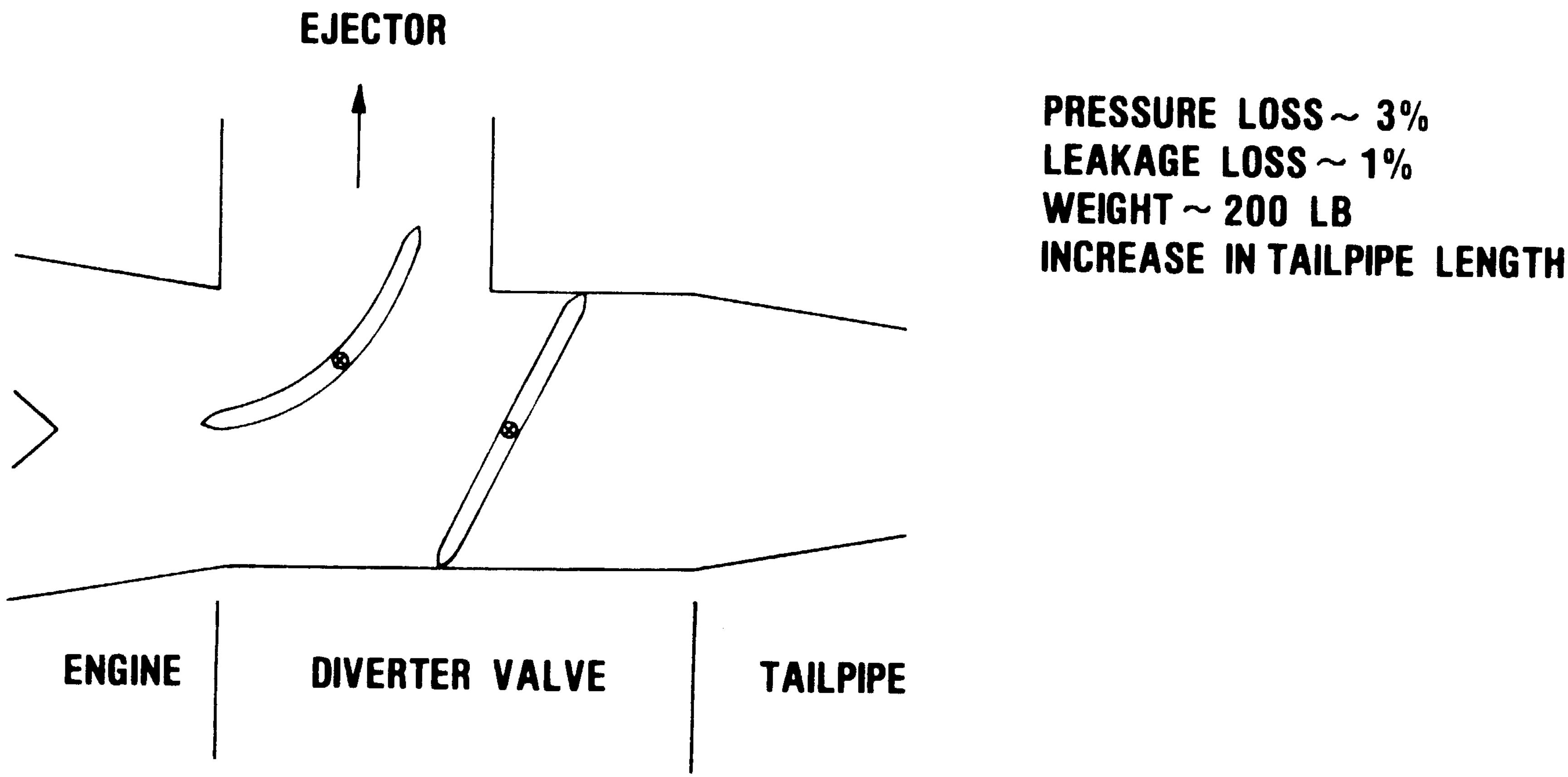

Figure 1.- Diverter valve.

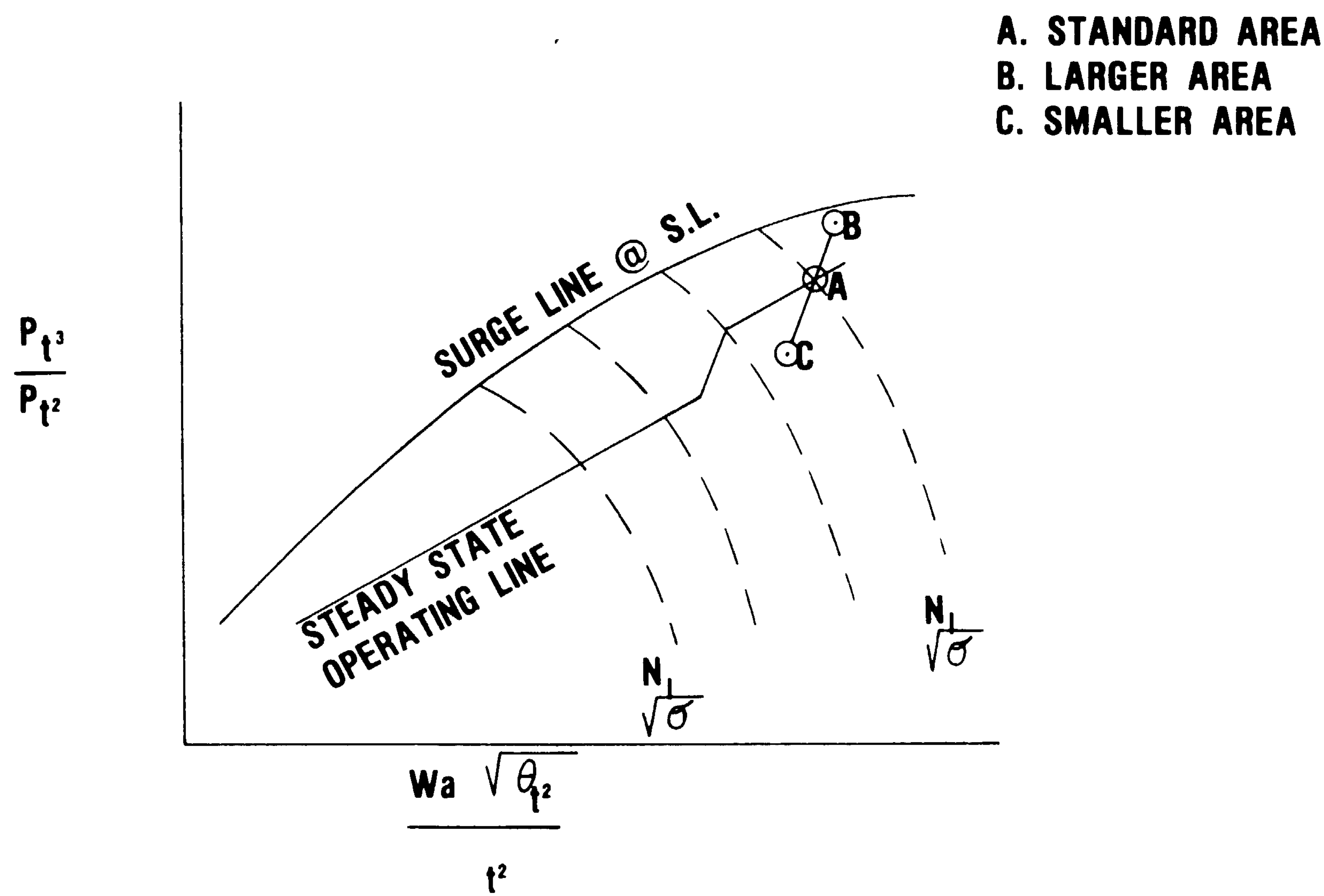

Figure 2.- Area matching.

XV-4B

	MANIFOLD	COLLECTOR	REACTION CONTROL	DIVERTER
TEMPERATURE	540°F	540°F	540°F	1000°F
PRESSURE	102 PSI	153 PSI (PROOF)	153 PSI (PROOF)	30.8 PSI (PROOF)
MATERIAL	INCONEL X-750	SS 321/347	INCONEL X-750	INCONEL 718
THICKNESS	.016	.016	.016	.025

Figure 3.- Ducting characteristics.

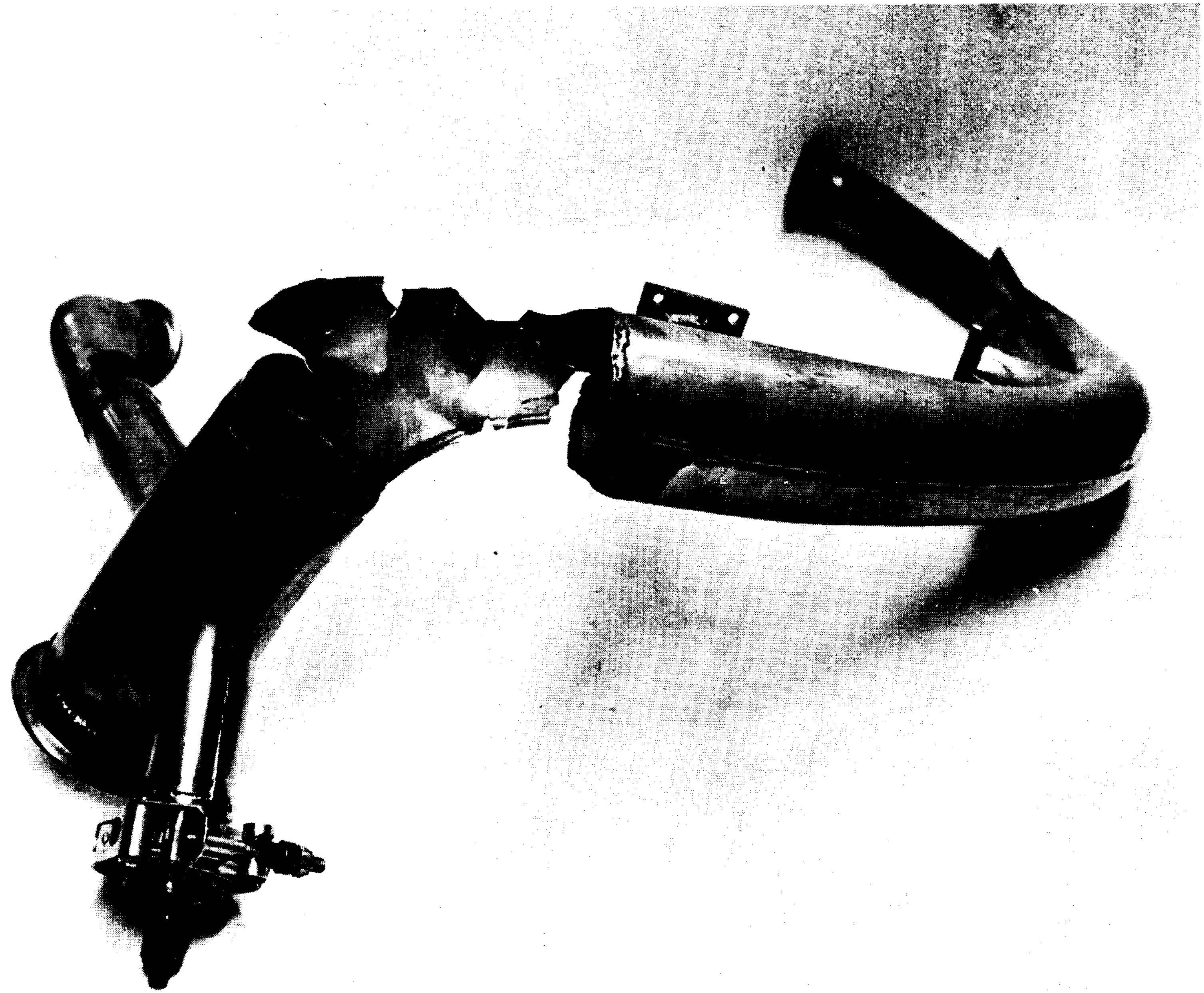

Figure 4.- Example of rupture due to hot spot.

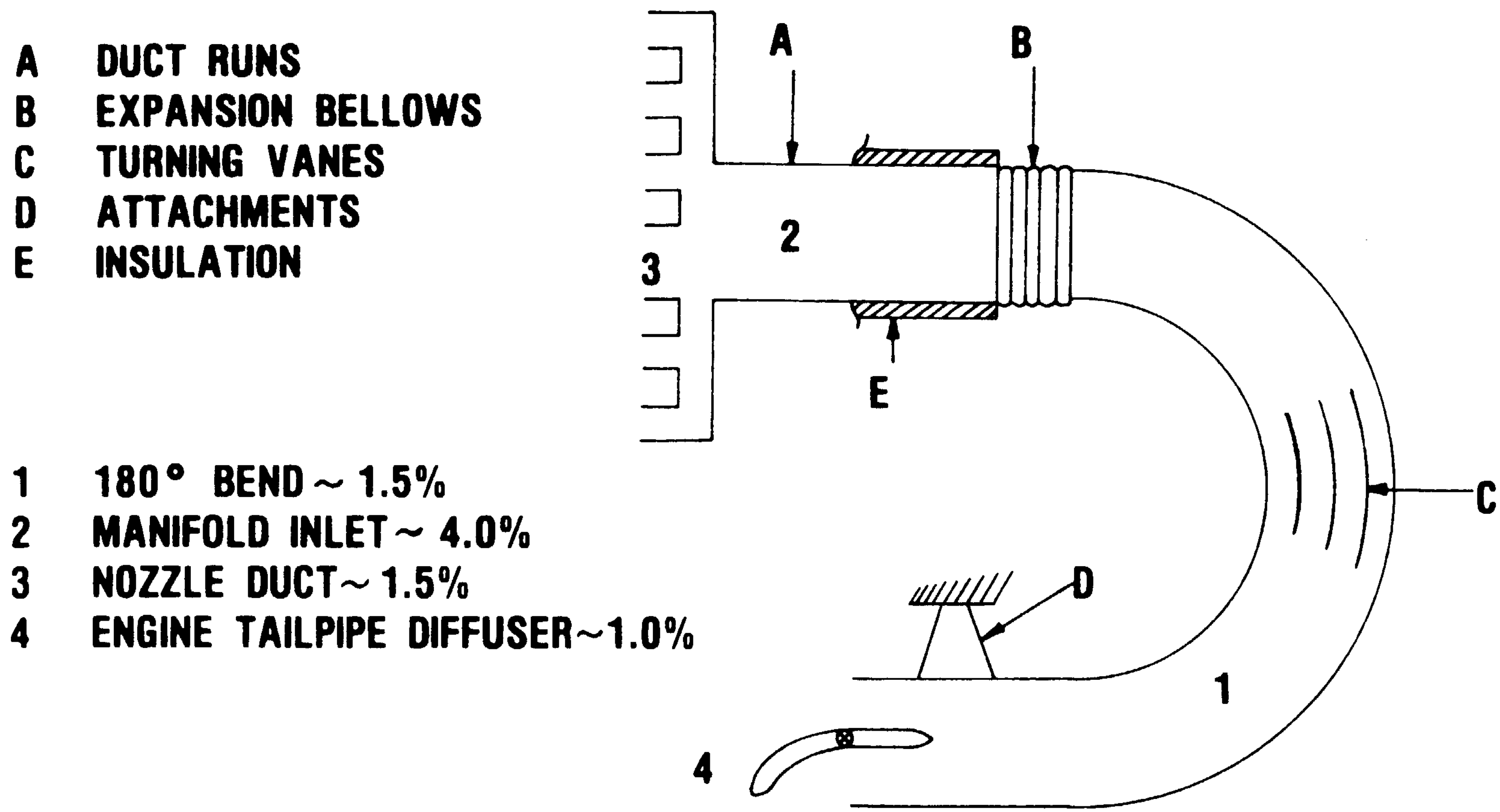

Figure 5.- Ducting system.

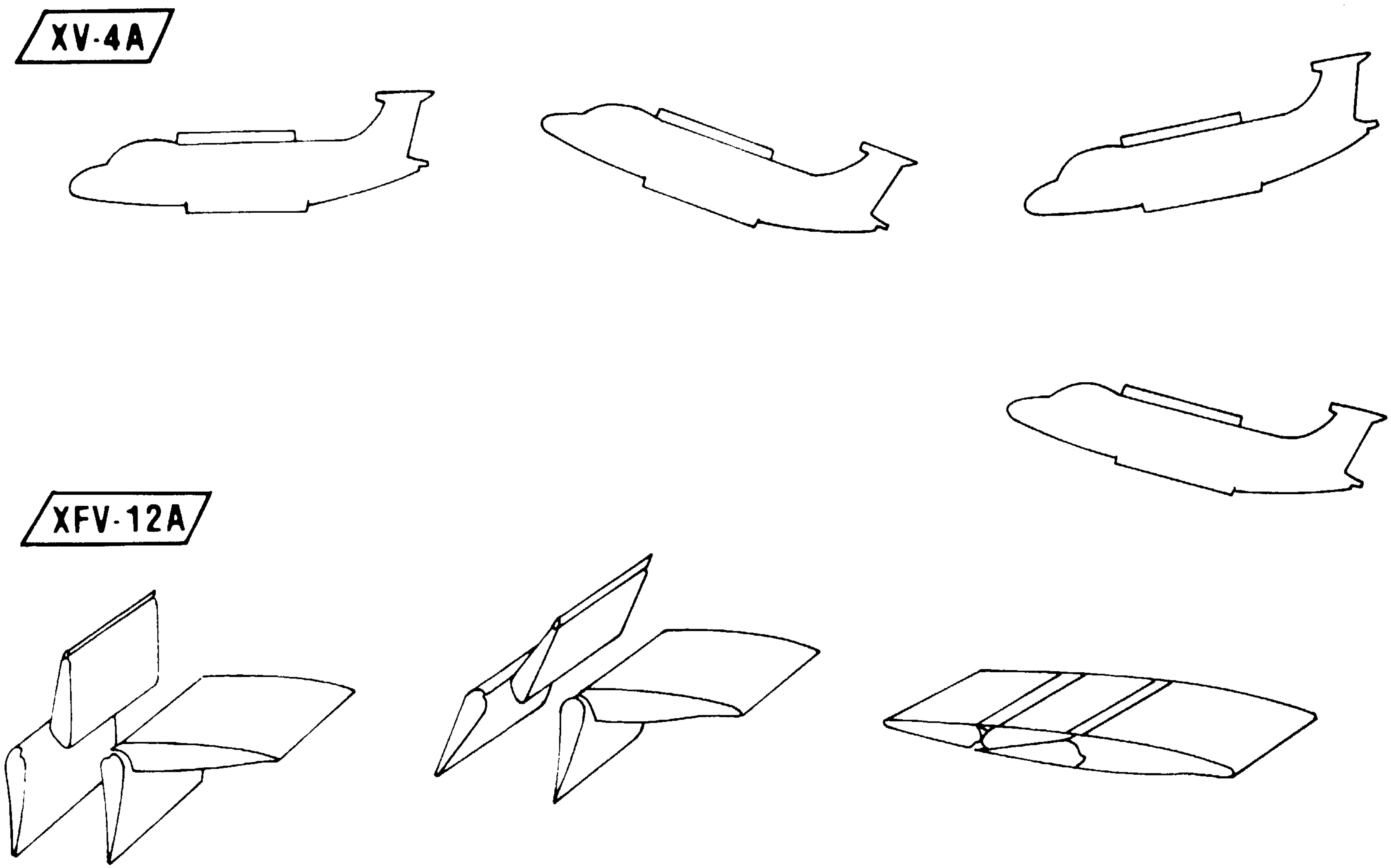

Figure 6.- Force vector control.

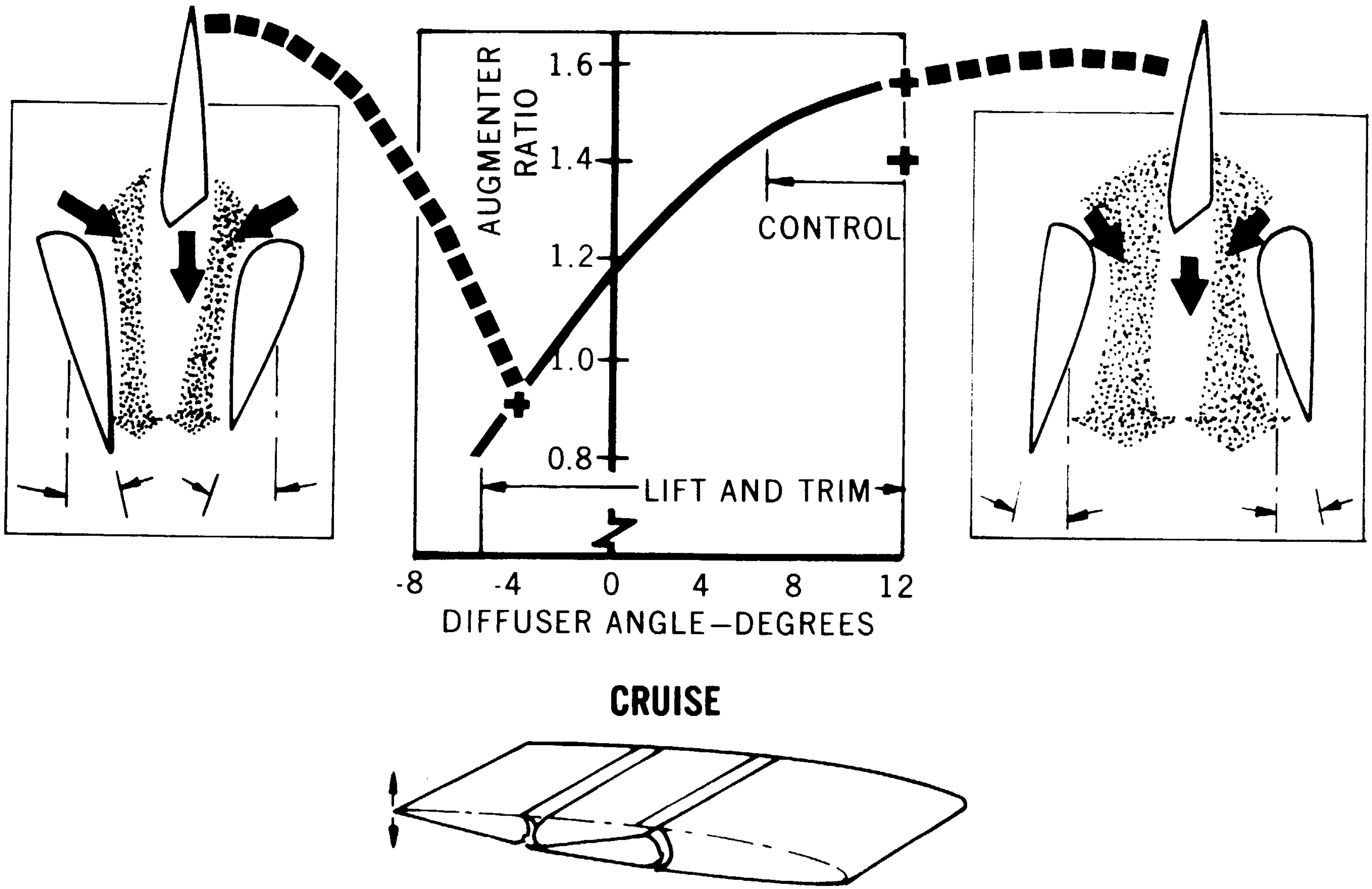

Figure 7.- V/STOL technology Rockwell TAW.

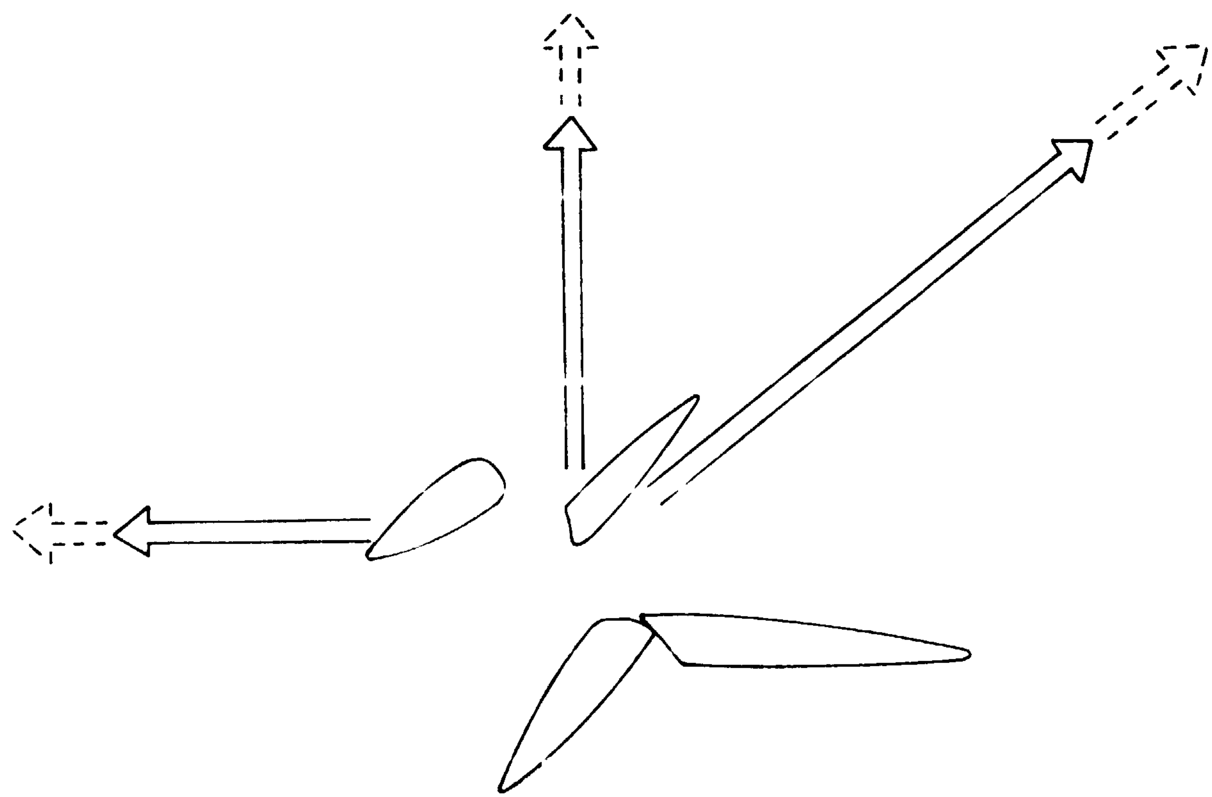

Figure 8.- Flight-control effectiveness.

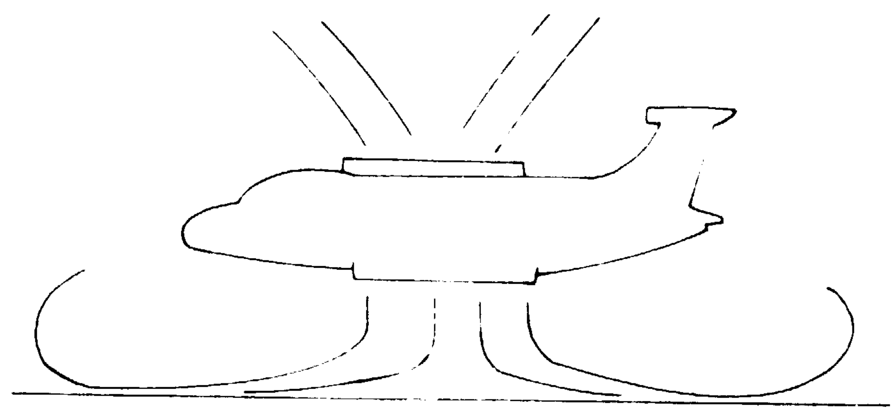

Figure 9.- Ground effects.

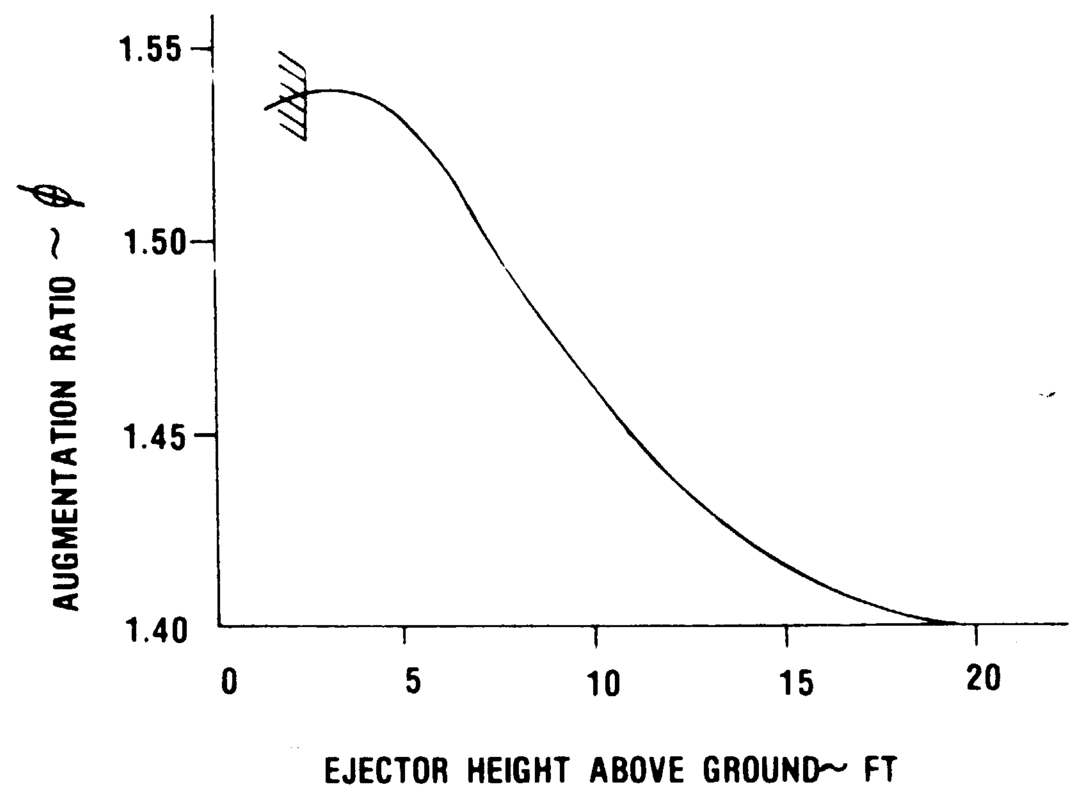

Figure 10.- XV-4A positive ground effect.

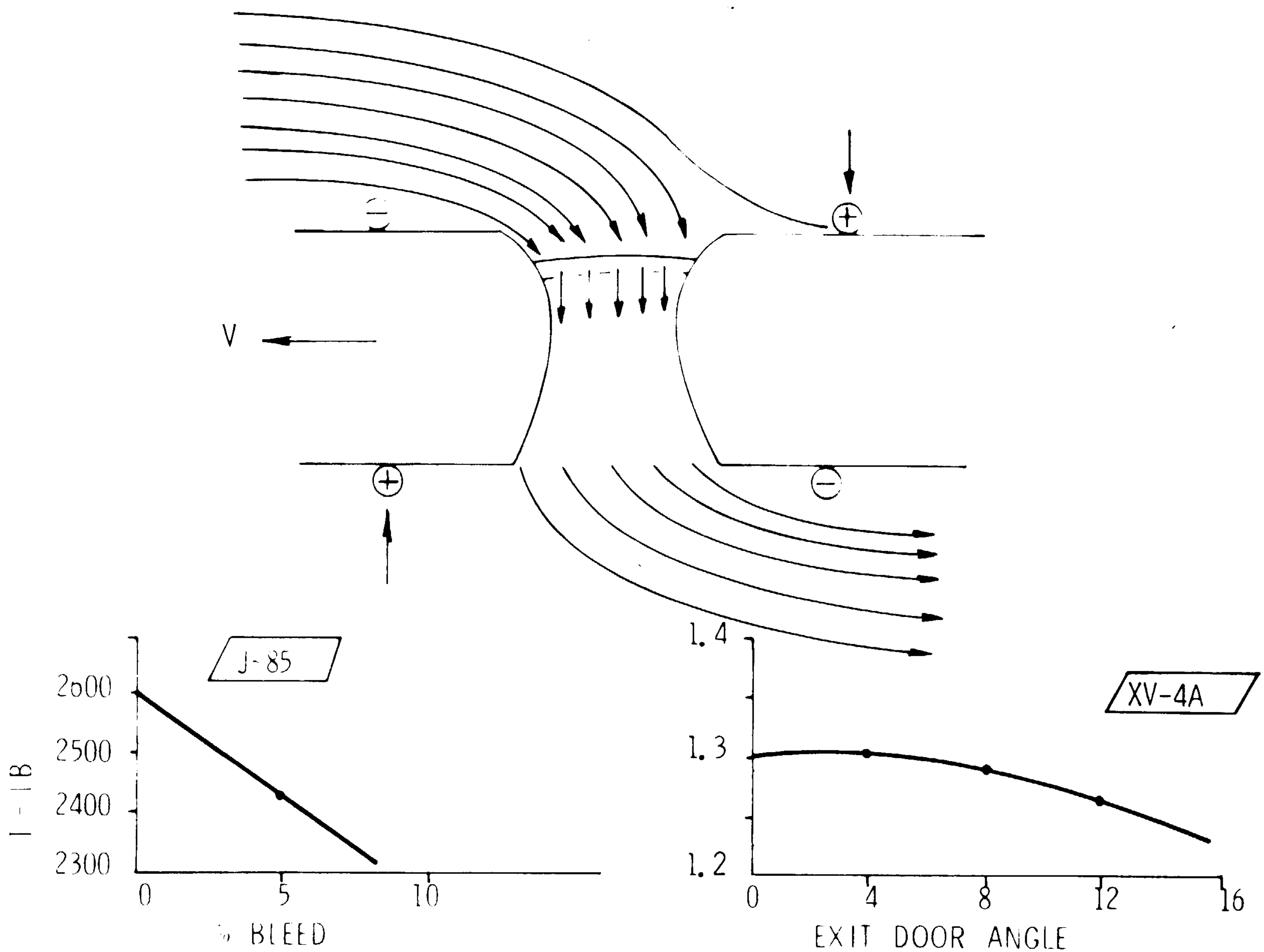

Figure 11.- Control considerations.

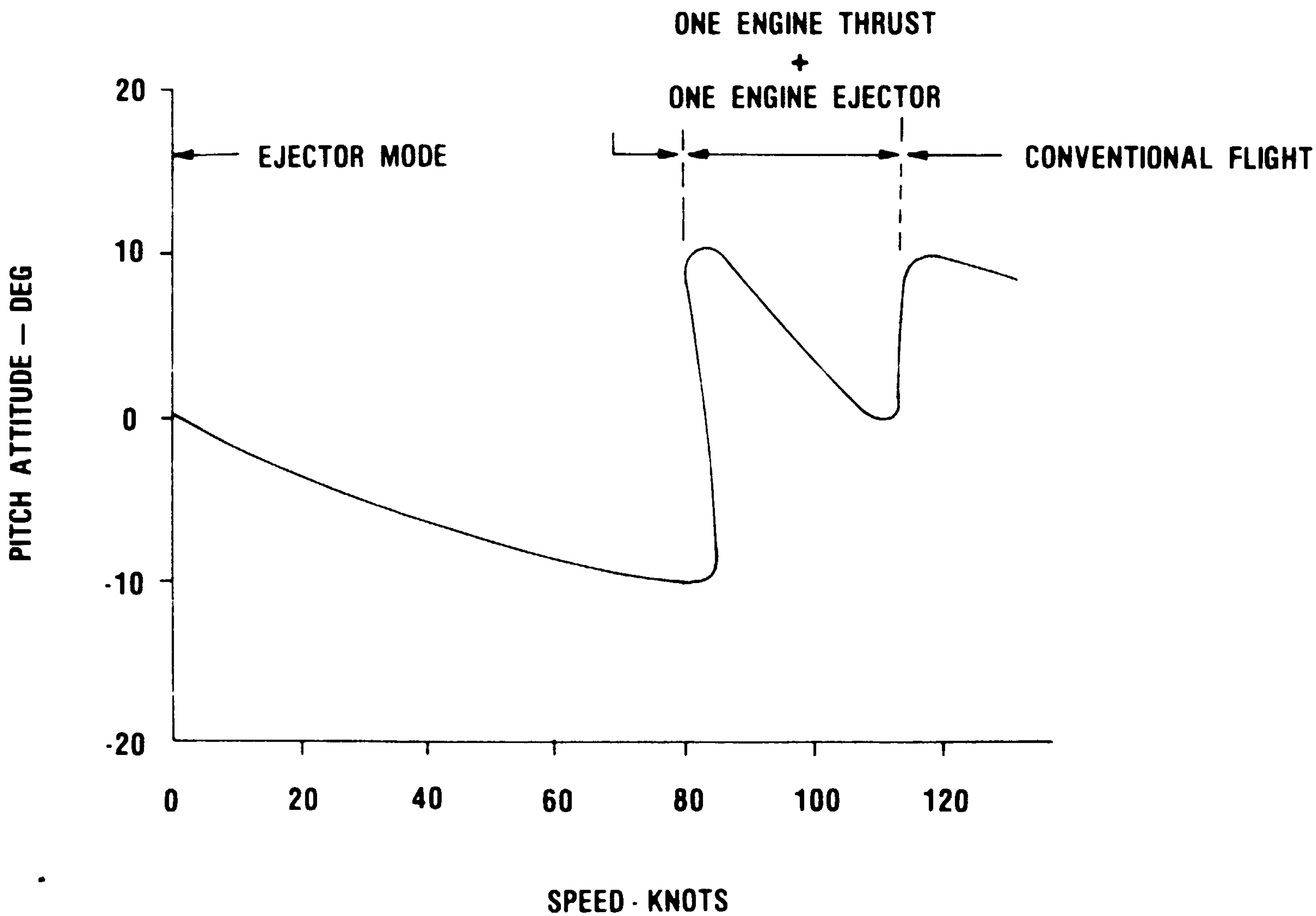

Figure 12.- Transition sequence (XV-4A).

INTERFACE AREA	WEIGHT	VOLUME	COMPLEXITY	THRUST LOSS
ENGINE INLET	X		X	
DIVERTER VALVE	X	X	X	X
TAILPIPE/NOZZLE TRIM				X
DUCTING SYSTEM	X	X	X	X
FORCE VECTOR CONTROL	X		X	
FLIGHT CONTROL	X	X	X	X
REINGESTION				X
SUCKDOWN				X
TRANSLATION			X	

Figure 13.- Summary.

ADVANTAGES

LOW-TO-MEDIUM DOWNWASH VELOCITY
LOW-TO-MEDIUM DOWNWASH TEMPERATURE
SINGLE PROPULSION SYSTEM FOR HOVER AND CRUISE
GOOD HOVER/CRUISE THRUST MATCH
INHERENT STOL CAPABILITY

DISADVANTAGES

LARGE VOLUME INSTALLATION REQUIRED
INTERNAL HOT GAS DUCTING REQUIRED
HIGH VTOL DRAG AND MOMENTUM MOMENTS
CONTROL CONSIDERATIONS COMPROMISE THRUST AUGMENTATION
COMPROMISES EXTERNAL/INTERNAL STORES CARRIAGE

Figure 14.- V/STOL ejector configurations.