N72-29916

STRUCTURAL TESTING OF CONCORDE AIRCRAFT – FURTHER REPORT ON UNITED KINGDOM TESTS

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SUMMARY

This section of the United Kingdom review of structural testing for the period 1969 to 1971 gives a summary of the tests being carried out on Concorde nacelle structure as part of the structural development and certification programme. It attempts to complete the overall picture provided by other papers which primarily deal with testing of the remainder of the Concorde airframe.

INTRODUCTION

During this symposium, much information has been presented on the structural testing of Concorde. In particular, paper no. 1 by E. L. Ripley, given as the Third Frederick J. Plantema Memorial Lecture, deals extensively with the Concorde airframe major fatigue test and similar development tests on fuselage components. Paper no. 20 by V. P. N'Guyen and J. P. Perrais gives a summary of the Concorde major airframe static test and other large fuselage-wing component tests at the Centre d'Essais Aéronautiques de Toulouse (C.E.A.T.) in France.

To complete the picture, the present paper gives an account in general terms of a series of tests being carried out in the United Kingdom (U.K.) on Concorde nacelle components. These components are relatively large structural elements (e.g., the intake is 3.5 by 7 by 17 feet) subject to unique types of loading and involving novel forms of design and construction. They are designed to meet the full static strength, fail-safe, and fatigue requirements of the basic airframe and, thus, have to be the subject of a complete certification test programme. In this sense, they must be considered as a complementary part of the major static and major fatigue test programmes.

SYMBOLS

M Mach number

n manoeuvering load factor

V_C design cruising speed

V_D design diving speed

DESCRIPTION OF NACELLE STRUCTURAL SPECIMENS

A supersonic aircraft, such as Concorde, requires a sophisticated power-plant installation, including a variable-geometry intake with its own automatic-control system, an engine bay providing full accessibility, and a variable-geometry nozzle incorporating thrust reversers. A general view of the complete Concorde nacelle is shown in figure 1, and a more detailed description of the specimens is given in the appendix.

Part of the basic philosophy for the production nacelle structure has been to design the three main components – intake, engine bay, and nozzle – as separate units linked together in a statically determinate manner to minimise redundant interaction forces arising because of wing distortions. For the same reason, the engine bay itself has been designed in two halves – a forward bay and a rear bay – simply spigoted together at the joint.

Advantage has been taken of this design philosophy to reduce the complexity of testing; thus, the air intake was tested separately from the engine bay and nozzle, and the forward engine bay was tested independently of the rear engine bay.

A summary of the nacelle structural test specimens either tested or to be tested as part of the Concorde development and certification programme is given in table 1 for the intake and in table 2 for the engine bay and nozzle.

An additional production nozzle specimen is also being provided, and will be tested under operating environmental conditions behind a pair of Olympus engines installed in a test bed at Société Nationale d'Etude et de Construction de Moteur d'Aviation (SNECMA) in France.

PROBLEMS ASSOCIATED WITH INTAKE TESTING

Summary of Loading Actions

The primary loading action on the intake results from internal pressures due to the airflow through the ducts. The internal pressures due to two typical operating conditions are shown in figure 2. Since part of the top of the intake is closed by the lower surface of the wing, these pressures produce significant loads in the wing-nacelle attachment links, as well as designing the intake shell. Additional loading in intake and links is due to the interaction forces at the links due to wing distortions.

During supersonic cruise conditions, the intake is also subjected to elevated temperatures with the internal temperature reaching a maximum of 125^{o} to 130^{o} C and the external temperature a value of 100^{o} C. Because both inside and outside surfaces are subjected to similar forcing conditions, thermal stresses during acceleration and deceleration are, in general, less than those produced by the cruise temperature gradients quoted previously.

Test Realisation

For all three intake test specimens, the approach to the problem of simulating wing interaction loads and pressure loads is the same. To represent wing-nacelle interaction loads, the specimens are mounted from a rigid test frame by links at the points A, C, E, and G shown in figure 1. Each link is then calibrated to enable the link-reaction load to be measured. Three remaining links (points B, D, and F) are attached to hydraulic jacks which are controlled to apply specified displacements.

The representation of the varying pressure distributions within the ducts has been a major difficulty. The interior of the specimen was divided into four main zones, with a fifth zone representing the boundary-layer bleed between the wing and the forward part of the intake. (See fig. 2.). Between adjacent zones a pressure seal has had to be developed in such a way that while maintaining the interzone pressure differentials, local loading and restraint to specimen movement have been avoided. The final solution, following extensive development, has led to the design of flexible suction seals mounted off a central core rigidly supported by the test frame. The assembly of one such core for the room-temperature tests on specimen 2.9B is shown in figure 3.

For the thermal testing on specimen 2.9.4, the specimen has to be heated cyclically inside and outside. Each internal zone is thus supplied with pressurized air through a separate closed-circuit system of ducts with outlets into the specimen through the central core. The heating of this air is controlled through a heat exchanger. For cooling, the circuit is depressurized and switched to open circuit; ambient air is then blown through the specimen. The exterior of the specimen is surrounded by a duct through which unpressurized air is blown at the requisite temperatures. This system, which is duplicated for each intake duct, results in an extremely complex facility. A scale model of this facility is shown in figure 4.

With this facility it is possible to simulate adequately the major loading actions. In the fatigue test, advantage is taken of the absence of significant climb and descent thermal stresses by shortening the thermal cycle to simulate only cruise gradients and imposing a test cruise time of 12 minutes compared with an average aircraft cruise time of 75 minutes. To compensate for this shorter test time at temperature, creep rate is increased by a factor of approximately 5 by increasing maximum test temperatures 15^{o} C. The proposed test cycle is shown in figure 5. The aim is to achieve a rate of testing comparable with the major airframe fatigue test (where each 1-hour test cycle simulates the damage done in two typical aircraft supersonic flights).

PROBLEMS ASSOCIATED WITH ENGINE-BAY AND NOZZLE TESTING

Summary of Loading Actions

The loading actions on the engine bay and nozzle are similar to those on the intake, but there are some significant differences which are summarized below:

(1) The distribution of pressure in the engine bay and nozzle is essentially constant; thus, only one internal-pressure zone is required in each duct.

(2) The concentrated system of hydraulic jacks required to represent reverse-thrust bucket loads, bucket operating jack loads, and engine jet pipes leads to local complications in the heating, cooling, and pressurisation system.

(3) The maximum operating temperatures in the rear engine bay and nozzle are high, reaching about 240° C in the engine bay and between 320° and 410° C in the nozzle; as in the intake, a steady gradient is present during cruise causing significant thermal stresses. In addition, large transient thermal gradients arise in the nozzle centre-wall structure during descent and due to reheat in the climb and result in another thermal-stress cycle. These temperatures are shown diagrammatically in figure 6.

Test Realisation

Two of the engine-bay specimens (specimen 1.11.2.2 and specimen 2.9.4.2) are relatively simple; tests on these specimens involve static pressure and mechanical loading at room temperature. Specimen 2.9.4.3 is subjected to a pressure fatigue test at elevated temperature. This test poses no serious problems apart from the control and monitoring of temperature and the timing of the pressure cycle to ensure a consistent accumulation of creep and fatigue damage.

The fourth specimen, specimen 2.9.6, is subjected to both static and fatigue testing with representation of thermal conditions. This testing requires a complex test facility similar to that for the intake shown in figure 4. The simulation of wing distortions and bay pressures is done in a similar manner to that for the intake; the number of pressure zones is less, but seal design is complicated by the higher temperatures required.

In order to limit the test temperatures, advantage is taken of the fact that thermal stress due to temperature gradient is the most significant requirement since creep and material degradation at the aircraft temperature levels are unimportant for the stainless steel materials of the nozzle bay and the titanium and inconel alloys of the engine bay.

The required temper gradients of about 250° C maximum through the nozzle side-walls are therefore o by blowing air at room temperature over the outside of the specimen and blowing hot from the rear to the front through the inside. A special problem arises in simulati t temperature gradients through the centre wall of the nozzle during descent and due reheat in the climb.

To achieve these in as short a time as possible, a special system is provided to blow alternately hot and cold air into the centre wall void. This system is switched on at appropriate times in the cycle, thus enabling the required cruise and recovery equilibrium conditions to be rapidly achieved. (See fig. 7.) A diagram of the fatigue cycle achieved with this forcing system is shown in figure 8; the target, as in the case of the intake, is to achieve a rate of testing comparable with the major airframe fatigue test.

TEST CONTROL

Both the intake (specimen 2.9.4) fatigue test and the engine-bay and nozzle (specimen 2.9.6) fatigue test are to be controlled and monitored by a single IBM 1800 computer, which will also provide data logging and both on-line and off-line data analysis and display.

The monitoring facility checks the applied values of all control variables with the required values against a set of inner and outer limits; the inner limit exceedances are printed-out and the outer limit exceedances cause shutdown of the test.

A general view of this installation is shown in figure 9, and a flow diagram illustrating the control logic of the test facility is shown in figure 10.

APPENDIX

DESCRIPTION OF PRODUCTION NACELLE STRUCTURE

Air-Intake Structure

A structural breakdown of the intake is shown in figure 11. The operating temperature during Mach 2.0 cruise is approximately 120° C, and aluminium alloy is used for all the structure with the exception of the rear frame (frame 204), which is made from titanium alloy to provide a fireproof bulkhead. The forward lip, the forward- and centre-duct skins, and the intake frames are mostly machined from thick plate. The moveable ramps are made from aluminium alloy honeycomb.

The intake is suspended from the wing at six points, with a forward and rear attachment on each of the three walls. Five of the attachments are simple links taking vertical loads only; the sixth, at the centre of the rear frame, is a fixed-point attachment taking loads in all planes. A secondary horizontal link is also provided on the forward centre wall to provide yawing restraints.

Engine-Bay Structure

The general arrangement of the engine bay can be seen from figure 1. Since the engines are mounted directly from the wing, engine-bay loads derive predominantly from internal pressures. The bay consists of a forward and rear section, simply spigotted together; each section consists of a fixed centre wall with an L-shaped door forming the side and bottom walls of each bay. The front and rear bulkheads of the bay are formed by the rear frame of the intake and the front frame of the nozzle-fixed structure, respectively.

The centre wall (see fig. 12) has a maximum operating temperature of 250° C and must resist flame temperatures of up to 1100° C for 5 minutes. Thus, both front and rear sections are made from a nickel alloy (Inconel 718) honeycomb-sandwich panel.

The forward doors (see fig. 13) have a maximum operating temperature of 150° C and are made from aluminium alloy. Inner and outer skins are riveted and spot-welded, respectively, to close-pitched frames of the extruded I-section. The rear doors (shown in fig. 14), where maximum operating temperatures are about 200° C, are of similar construction but made of titanium alloy with the frames either machined from bar or fabricated from welded plate. Both sets of doors are provided with fore and aft sliding freedom of about 30 mm along a line near the door corner. This freedom has been provided to eliminate large interaction forces between the wing and door which would otherwise arise because of wing distortions in flight. The slide also incorporates a hinge, so that it is possible to open the bottom part of the door independently for simple servicing. Also to avoid interaction forces due to distortion, the doors are supported from two hinges, at the front and rear of the top edge only. Intermediate hinges are provided but are designed to only restrain the door against lateral pressure forces.

Nozzle Structure

The general arrangement of the nozzle fixed structure is shown in figure 15. The maximum operating temperature of the structure is in the region of 450° C, and for this region stainless steel is the basic structural material.

The basic structure is made up of a pair of barrels forming the main ducts, supported by spectacle frames and enclosed by an outer fairing. These components are mainly fabricated from stainless steel stresskin honeycomb. Upper and lower fore and aft longerons run between the inner barrels and outer fairings in the sidewalls and centre walls. These form the primary load path for the reverser bucket loads; these buckets are attached to hinge fittings which connect with the aft end of these longerons.

This fixed structure is attached to the engine-bay—wing interface at three non-redundant fittings, one on each sidewall and one on the centre wall. A fourth attachment at the centre wall is provided as a fail-safe standby. The main centre-wall attachment connects with the engine-bay centre wall, the two sidewall attachments connecting with a pair of triangulated frames attached to the wing undersurface.

Provision in the fixed structure is made for attaching the engine primary nozzle by means of three spigot fittings projecting into the main ducts. Additional attachments are provided for the reverser-bucket operating jacks, four in each duct.

TABLE 1.- INTAKE MAJOR STRUCTURAL TEST SPECIMENS

Description	Remarks	Summary of test requirements		
		Static	Fail-safe	Fatigue
Specimen 2.9B (prototype air intake)	A twin left-hand intake to prototype standard. Rig applies internal pressure in four zones per duct with wing distortions.	Static design cases at room temperature up to 85% ultimate load to clear prototype flying. Test cases include (1) Symmetric and asymmetric surge cases (2) Ground running manoeuvre cases at V_D.		
Specimen 2.9.4 (production air-intake fatigue specimen)	A twin right-hand intake to preproduction standard. Rig applies internal and external heating in association with internal pressure in four internal zones. Wing distortion can be simulated. Static-strength certification of the intake is based on hot tests to limited loads	Static design cases for certification at elevated temperature as appropriate up to 50% ultimate load in order not to invalidate fatigue test. Test cases include (1) Ground running single engine surge (2) Single engine surges at V_C, $M = 0.66$ (3) Double engine surges at V_C, $M = 2.0$ (4) Supersonic wing distortion, $M = 2.13$ at V_D, $n = 2.5$.		Certification fatigue test. Cyclic temperature, pressures, and wing distortions. Temperatures increased by 15° C to give a factor of 5 on creep, resulting in a shorter test cycle.
Specimen 2.9.5 (production air-intake fail-safe and static-strength specimen)	Basically a twin right-hand intake to production standard. Rig similar to that for specimen 2.9.4 but at room temperature only. Static-strength certification of the intake is based on cold tests to 100% ultimate load.	Static design cases for certification up to 100% ultimate load. All tests were at room temperature; for hot cases, loads and pressures are adjusted to allow for thermal stresses, adjustment based on results from specimen 2.9.4. Test cases were the same as those for specimen 2.9.4.	Crack propagation and residual tests to meet FAA fail-safe requirements for intake structure. All tests will be done at room temperature.	

TABLE 2.- ENGINE-BAY AND NOZZLE MAJOR STRUCTURAL TEST SPECIMENS

Description	Remarks	Summary of test requirements		
		Static	Fail-safe	Fatigue
Specimen 1.11.2.2 (prototype engine-bay centre-wall specimen)	Rig applies lateral pressures, engine mounting loads, and nozzle loads.	Static design cases at room temperature to clear prototype flying. Design cases include (1) Ground running (2) Symmetric reverse thrust (3) One engine windmilling (4) Manoeuvre at V_D (with and without nacelle twist)		
Specimen 2.9.4.2 (preproduction engine-bay centre-wall specimen)	Test to provide Mach 2.0 flight clearance for 01 aircraft flying. Test at room temperature since temperature not critical for this component.	A single design case to 100% ultimate load. Outboard engine, windmilling at V_C, M = 2.0 (inboard engine, normal running).		
Specimen 2.9.4.3 (forward engine-bay door)	Fatigue and creep test for certification. Static certification of this component is being based on calculation plus detail tests.			Certification fatigue test: cyclic pressure and wing distortion, at constant elevated temperature. A temperature gradient is maintained through the door, temperature levels being increased to accelerate creep.
Specimen 2.9.6 (rear engine bay and type 28 nozzle)	A twin left-hand rear engine bay and type 28 nozzle to production standard. Rig applies internal heating and pressurisation in association with primary nozzle and reverser bucket loads. Heating represents internal to external temperature gradients only; absolute temperature judged to be not critical.	Static design cases for certification with thermal stresses. Where appropriate, loads and pressures are limited in the right-hand duct in order not to invalidate fatigue test; thus, symmetric cases are taken to 50% ultimate load; asymmetric cases to 85% ultimate load in the left-hand duct. Design cases include (1) Reverse thrust on ground (2) Ground running, maximum take-off power (3) Manoeuvre at V_D, M = 2.2 (4) One engine windmilling, V_C, M = 2.0 (5) Single-engine surge, V_C, M = 2.0	Nozzle loads only applied with various members disconnected in turn. Redistribution of stresses measured. Load levels limited to avoid invalidation of fatigue test.	Certification fatigue test: cyclic temperatures and pressures with distortions and nozzle loads.

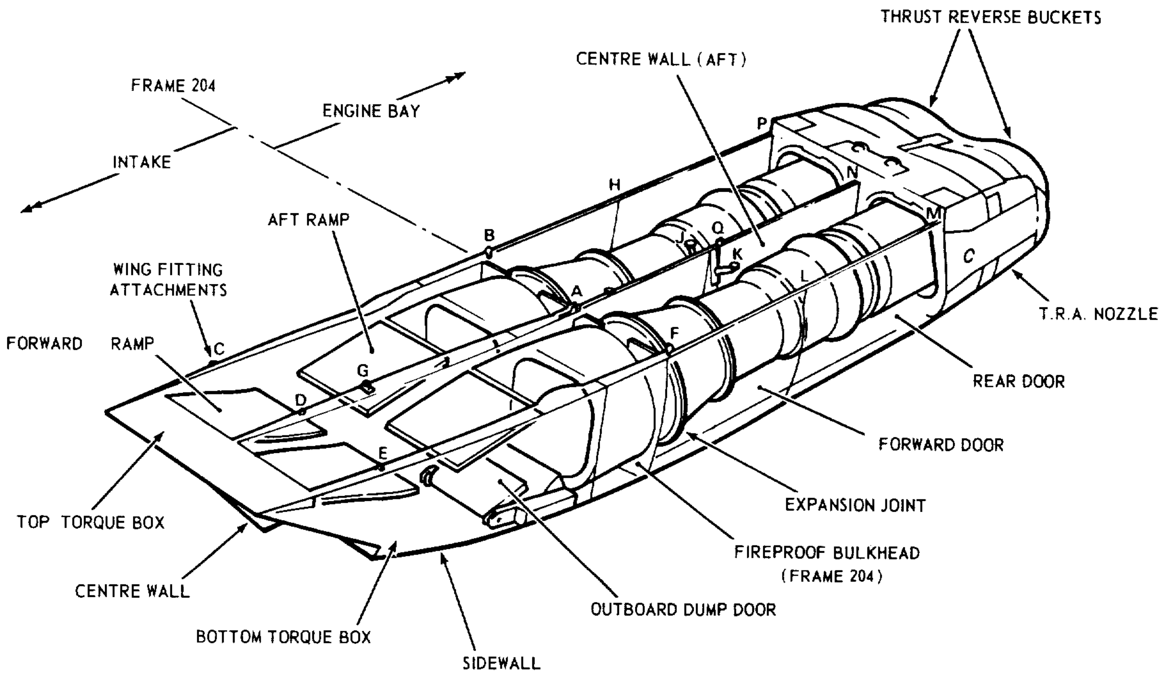

Figure 1.- General view of complete nacelle.

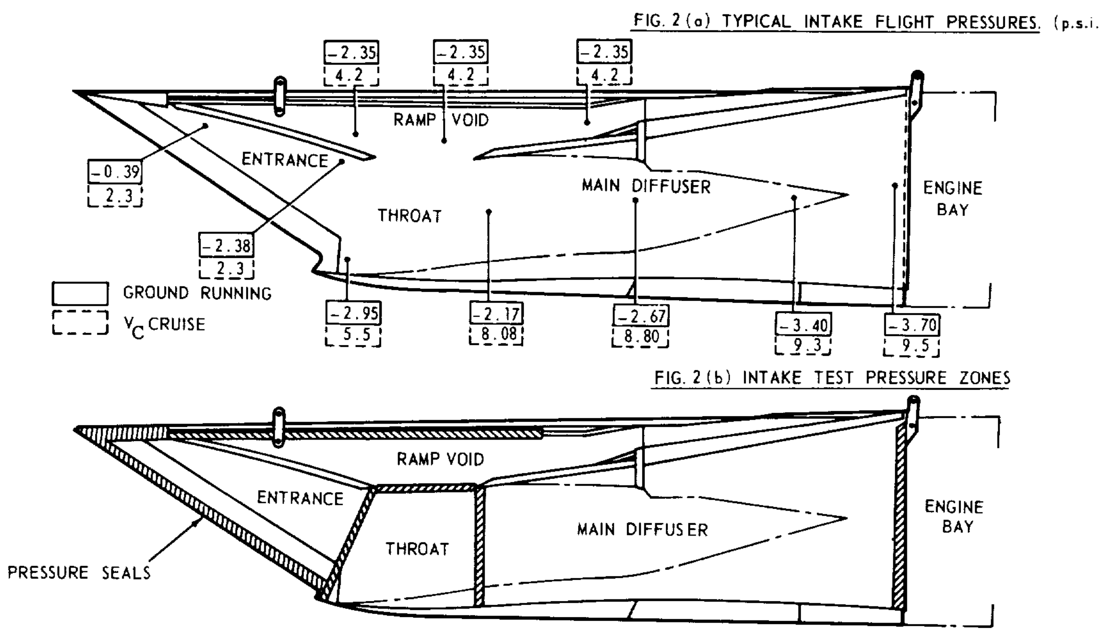

Figure 2.- Intake pressures and pressure test zones.

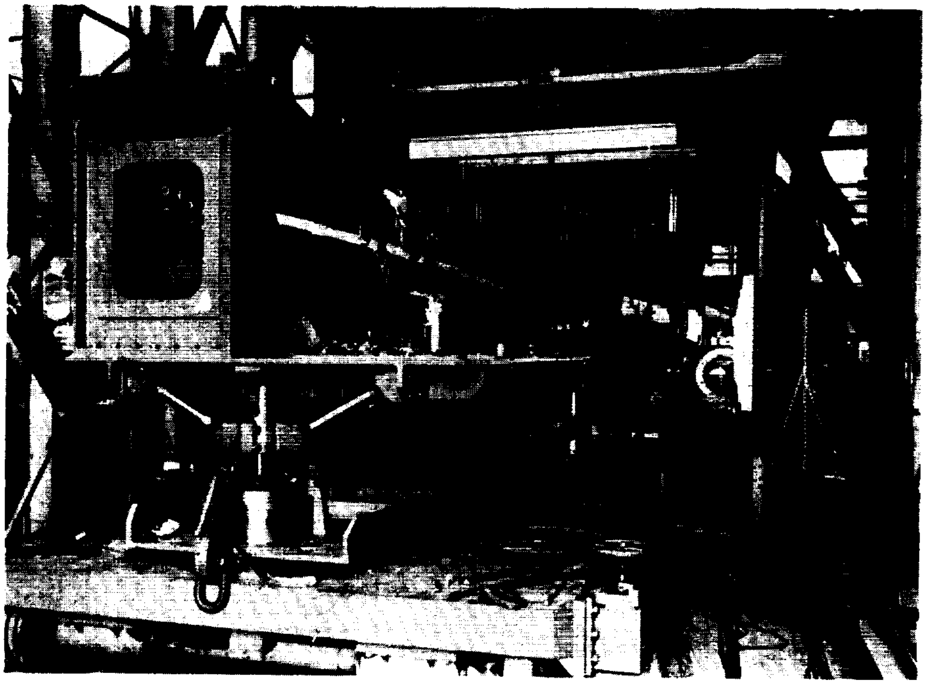

Figure 3.- Internal core for one intake duct (specimen 2.9B).

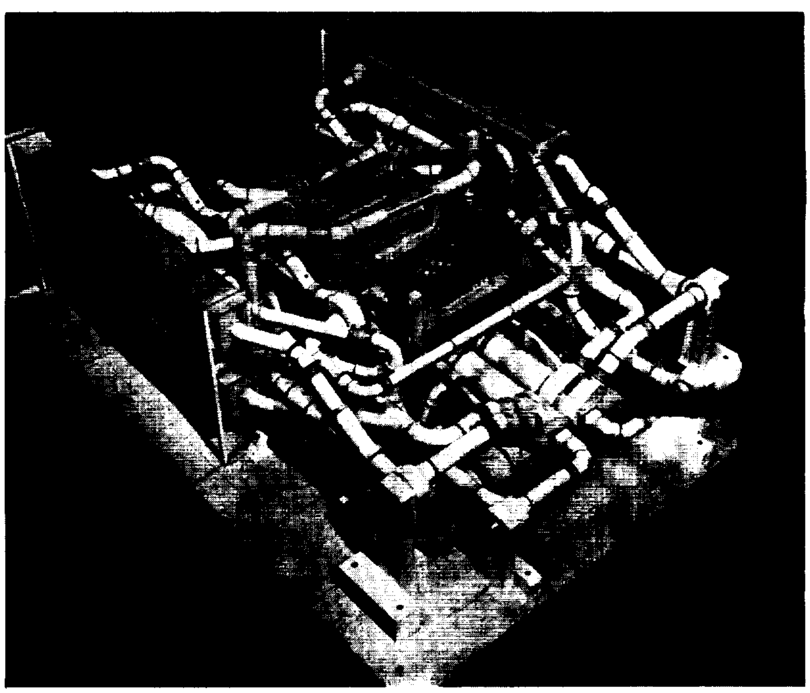

Figure 4.- Model of intake test rig.

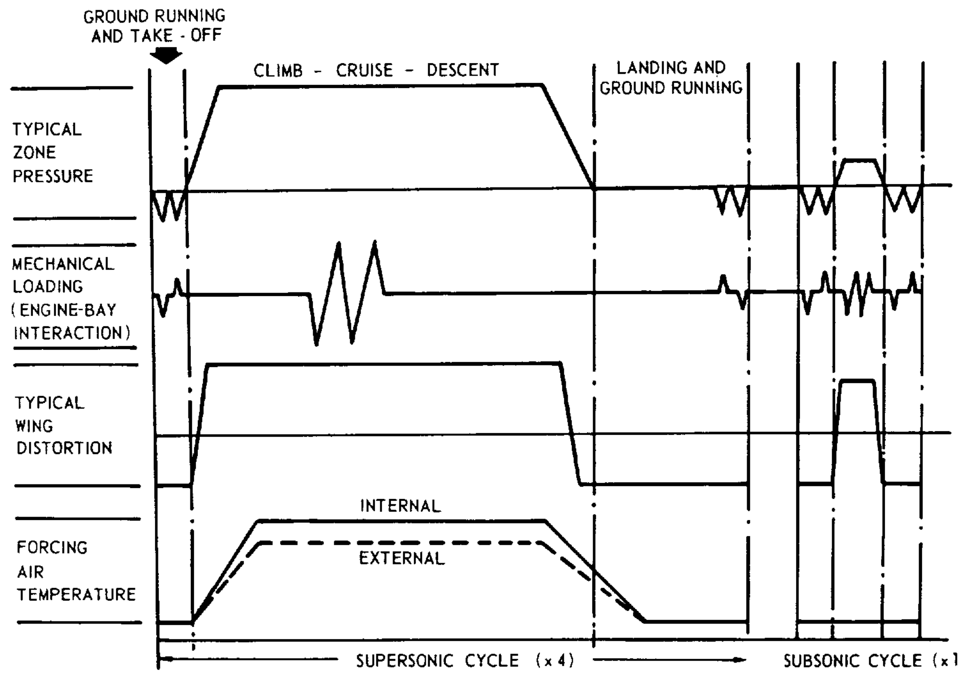

Figure 5.- Diagrammatic representation of intake fatigue cycle.

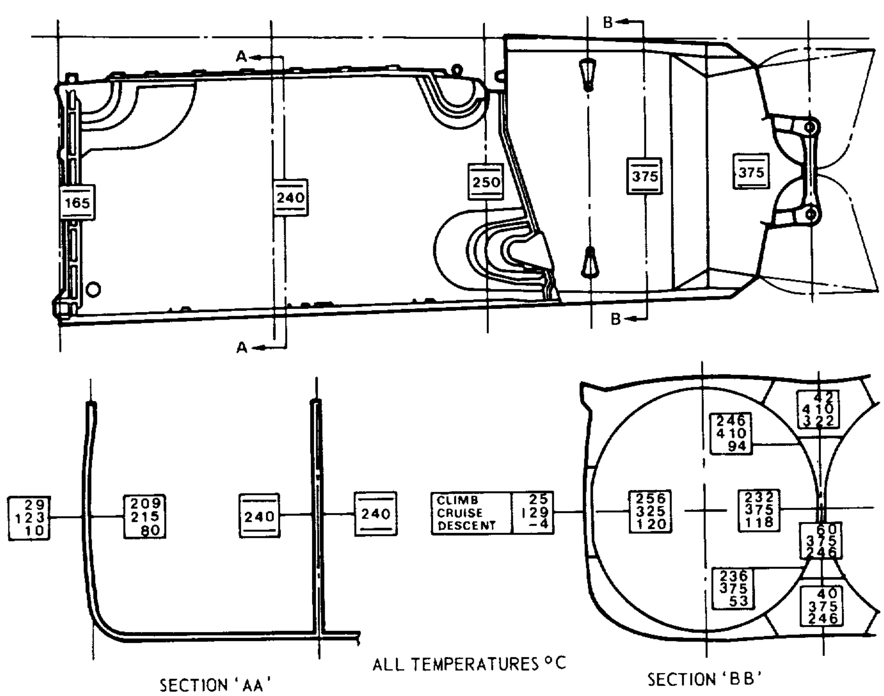

Figure 6.- Engine-bay and nozzle temperature distribution.

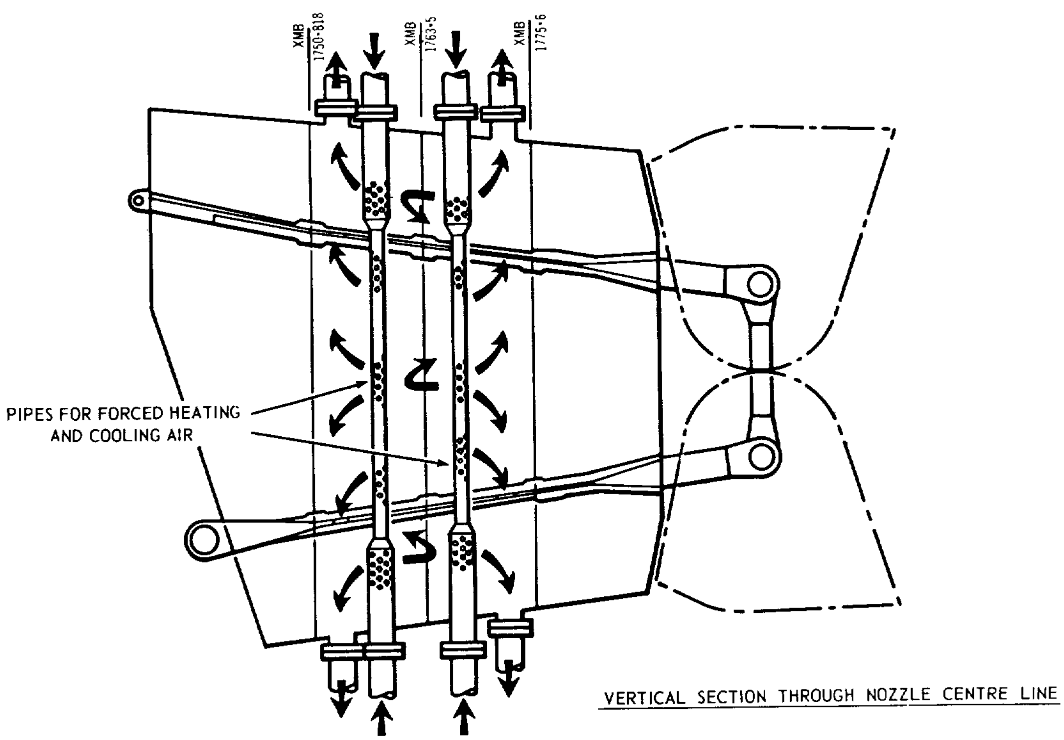

Figure 7.- Internal forced heating and cooling of nozzle centre wall.

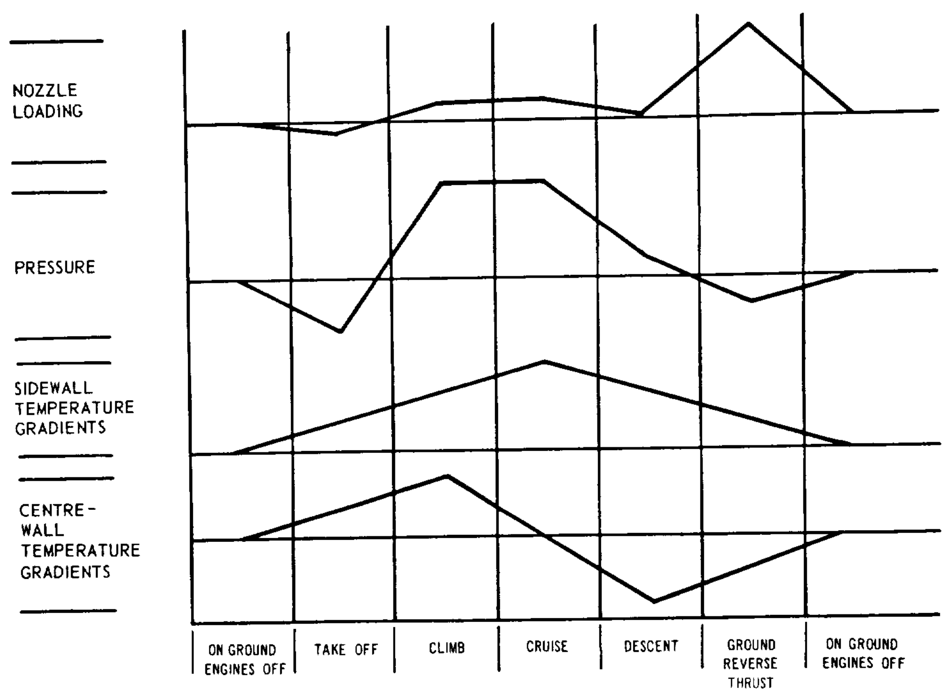

Figure 8.- Diagrammatic representation of engine-bay and nozzle fatigue cycle.

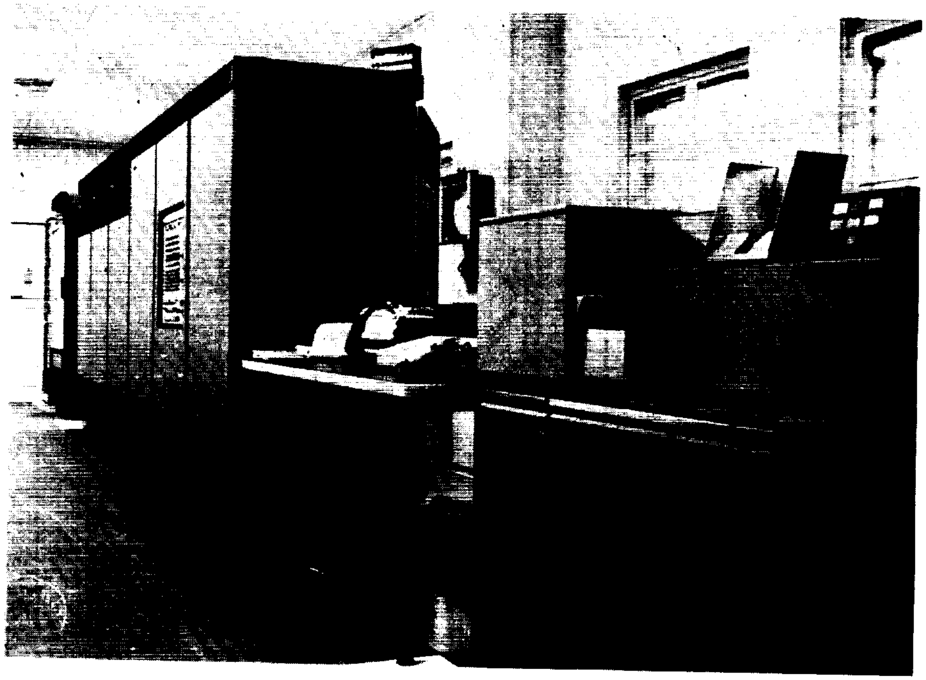

Figure 9.- IBM 1800 computer installation.

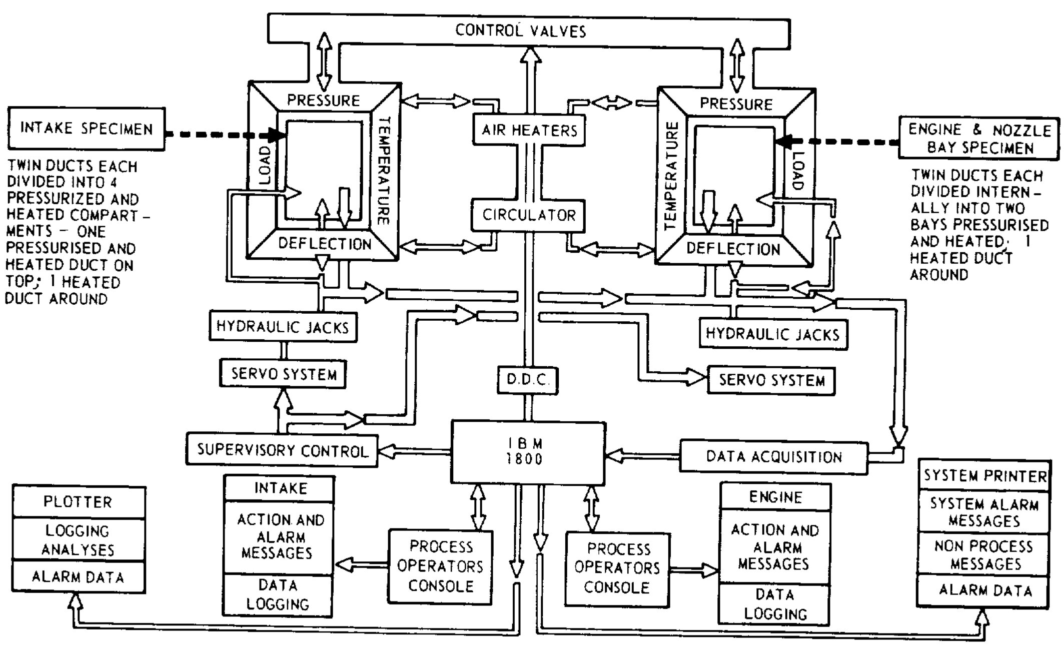

Figure 10.- Nacelle test-control flow diagram.

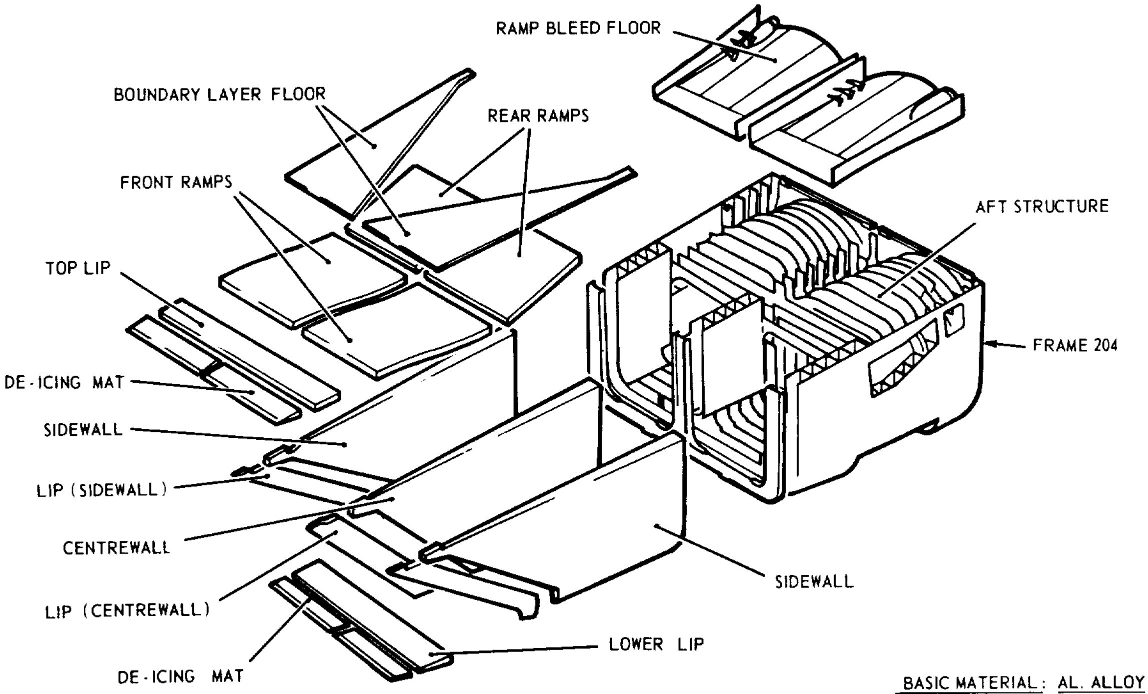

Figure 11.- Structural breakdown of the intake.

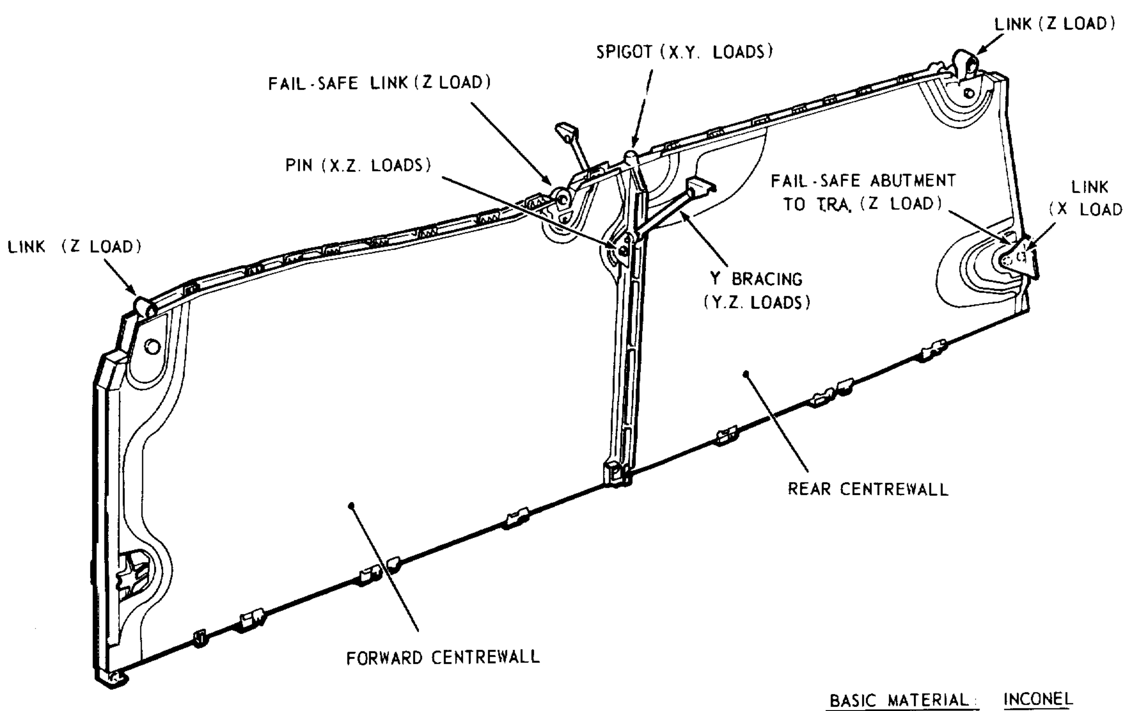

Figure 12.- Engine-bay centre wall.

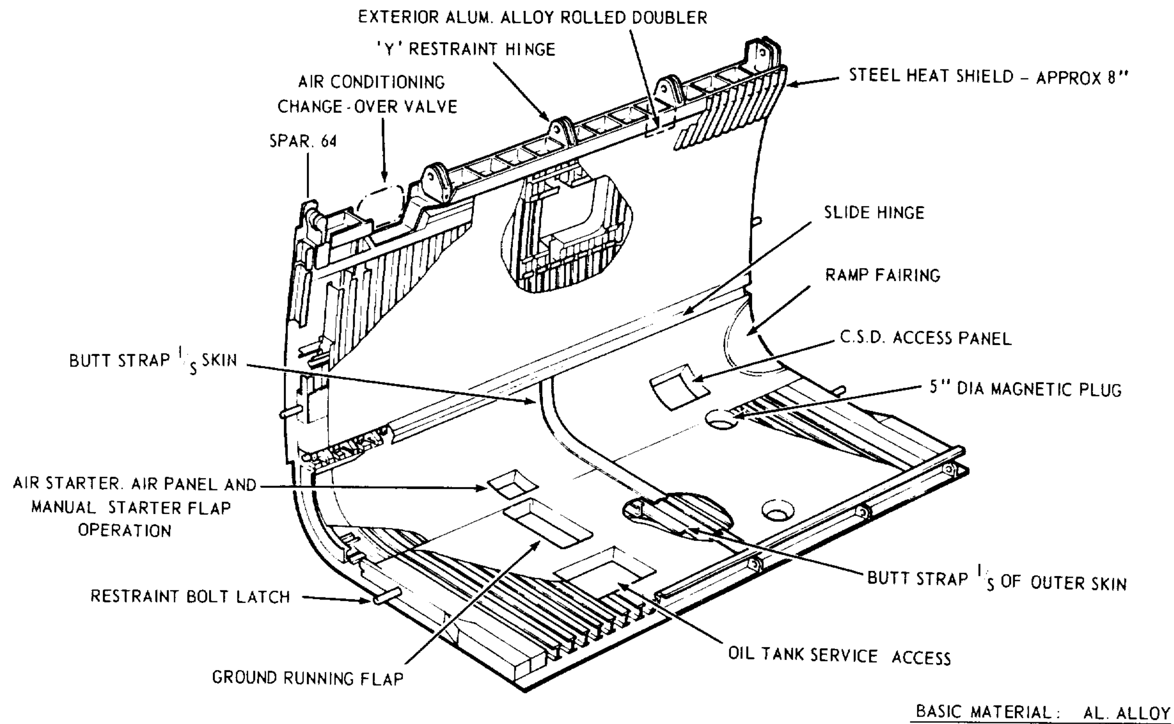

Figure 13.- Engine-bay forward door(s).

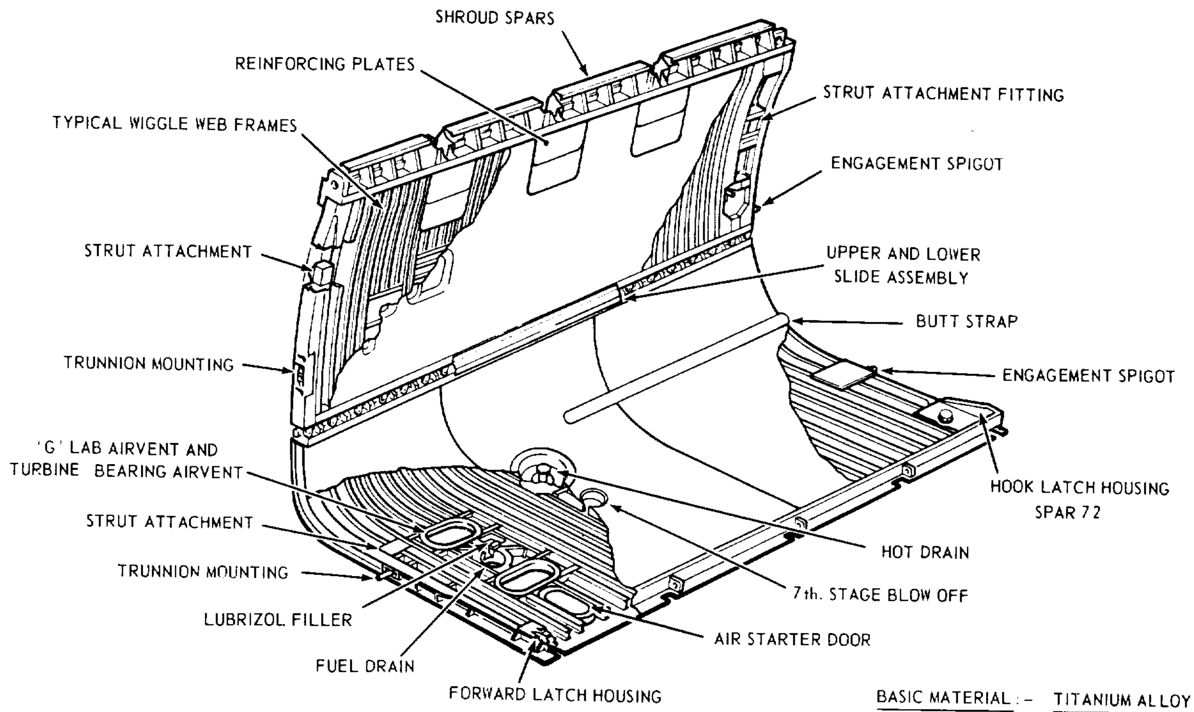

Figure 14.- Engine-bay rear door(s).

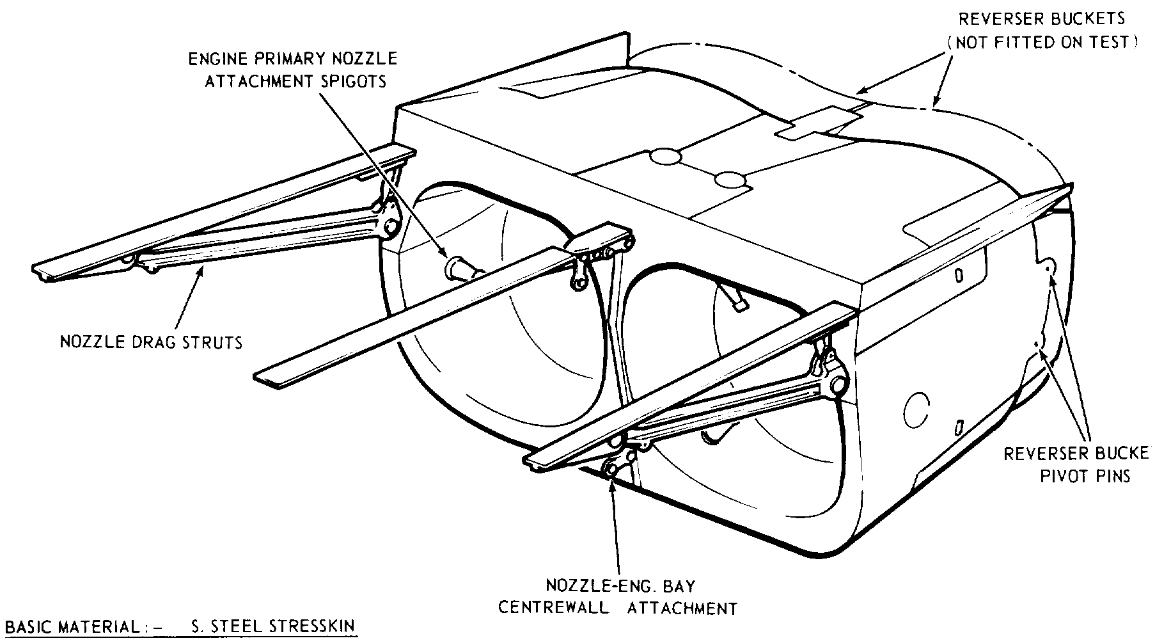

Figure 15.- General arrangement of nozzle structure.