APPLICATION OF ADVANCED TECHNOLOGY FOR IMPROVING THE INTEGRATION OF ENGINE AND AIRFRAME FOR FUTURE TRANSPORT AIRCRAFT

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Abstract

Future transport aircraft using new concepts for the integration of engine and airframe on the basis of advanced technology will achieve substantial improvements in performance and energy efficiency and also fulfill expected noise limitations. The investigation of different possibilities for the combination of engine and airframe taking into account existing experience with the propulsion-system integration of modern high-bypass ratio engines and the benefits of positive engine-airframe interference show a potential for further improvements.

One of these configurations is the engine-over-wing installation making optimum use of jet-interference with the wing. Theoretical and experimental investigations show that this configuration shows a very promising potential for further improving the overall performance of future transport aircraft. For prediction and testing the application of partly new theoretical and experimental methods are necessary. Jet/body interference problems can be treated by potential theory. Panel methods can handle subsonic flow including jet-effects. For transonic flow a Difference Method based on streamline coordinates can be used. Wind-tunnel testing of the highly integrated engine/airframe configuration with strong jet-effects demands careful attention of the simulation of the propulsion system inlet and jet flow.

The evaluation of noise characteristics includes airframe shielding effects. Measurements with realistic configurations already show the possibilities of a significant noise reduction to meet or even overfulfill future more stringent noise requirements.

1. Introduction

Future transport aircraft will be expected to offer significant improvements in efficiency with respect to energy conservation, better performance and economic considerations such as operating costs. This requires the application of advancing technology particulary in the areas shown in fig. 1. The integration of engine and airframe on this basis of modern high bypass-ratio engine technology and advanced engine/airframe configurations offer a potential for substantial improvements. This demands the application of configuration oriented technology making best use of individual highly advanced components.

New concepts for engine/airframe configurations can lead to significant improvements in the overall aerodynamic characteristics of an aircraft with respect to higher lift over drag L/D, lower drag coefficient C_D and higher lift $C_{L_{max}}$, thus making it more efficient.

This paper is mainly concerned with impact of configuration-oriented technology for improving the overall performance of future transport aircraft by making optimum use of positive interference effects between engine and airframe. The evolution of such propulsion-system-integration concepts is the result of experience gained with aircraft having a high degree of interference between engine and airframe and of systematic theoretical and experimental investigations. Reliability and low costs of operation call for technology concepts employing a minimum of complexity and making maximum use of proven components.

Present-day transport aircraft are characterized by engine locations in specific positions relative to the wing as shown in figs. 2 and 3. The development of engine and airframe for this generation of aircraft has mainly been component oriented. The integration task has mainly been to install an engine with proven non-installed performance (testbed, altitude facility) in a position of minimum interference taking into account the constraints of weight, stability and costs.

Fig. 4 summarizes the engine locations and shows clearly that the underwing location with a forward swept pylon is most commonly used. Increasing dimensions of future advanced bypassengines and higher sensitivity of supercritical wing profiles at high speed flight. require the consideration of other locations.

There have been several attempts at making use of interference effects generated by the propulsion system to improve the aerodynamic characteristics of the overall aircraft. These have mainly been concentrated on the use of high-pressure bleed air and the energy of the engine exit airflow for lift augmentation. All these concepts for Powered Lift have different grades of complexity. The most recent applications using present-day turbofan engines have been demonstrated by the YC-14 and YC-15 shown in fig. 5. Both use different interference concepts. A general summary of the aerodynamic improvements achieved by means of propulsion system interference effects and configurations already proposed is shown in fig. 6. These results show that the engine location above the wing offers the biggest aerodynamic improvements. It is thus concluded that further development should proceed in this direction.

Theoretical and experimental investigations of VFW-Fokker lead to the same general result and indicate a number of variations to obtain further improvements. The VFW-Fokker approach philosophy is shown in fig. 7. Wing and propulsion technologies and interference effects will be analysed. An advanced concept for propulsion system integration will be defined and the results of a test program presented.

2. Component Technologies

2.1 Wing Technology

Advanced airfoil research shows that there is still a potential for improvement in aerodynamic characteristics. Supercritical airfoil aerodynamics offers this potential for improving the fuel efficiency over today's transport aircraft. This technology can be used either to increase flight Mach number for a given wing geometry or to increase airfoil thickness for the same cruise Mach number. Fig. 8 shows the differences in aerodynamic profile for the same cruise Mach number.

Supercritical wing profiles are sensitive to flow disturbances caused by the engine pylon and due to jet effects. The upper surface of the wing is sensitive in the supersonic region. Disturbances due to the presence of a pylon can lead to lift loss and drag rise. The lower surface has a pressure distribution nearly conventional in the forward part and a distinct rear loading at the rear. Jet effects and pylon design can lead to lift losses especially by disturbing the rear-loading area. Modern wing design can compensate for local flow disturbances to a limited extent. Typical pressure distributions for a Mach number of 0,785 at C_L = 0,5 are shown in fig. 9.

2.2 Propulsion Systems

The use of highly efficient large bypass-ratio engines represents the advanced state of the art of today's propulsion technology for subsonic transport aircraft (see fig. 10). Compared to the first generation of low bypass-ratio turbofans and simple turbojets two outstanding characteristics must be taken into account:

- cooler exhaust flow due to larger proportion of bypass-air at lower exit velocities. This reduces structure loads in cases of jet-impingement.

- greater mass flow of engine for the same thrust. Thus greater possibility of influencing larger portions of the wing. Bypass-ratio of present engines is between 5 and 6 : 1. Future more efficient engines will be based on a bypass-ratio of about 8 : 1 with an engine cycle as shown in fig. 11 compared to present-day turbofan engines. The relative increase in engine external dimensions with increasing bypass-ratio is given in fig. 12. From this it can be seen that future more efficient engines will also have greater external dimensions.

Basically the trend in engine dimensions is such that going from a bypass-ratio of 1 to 8 the external engine diameter is doubled for the same take-off thrust. The reduction in fuel consumption is in the order of 25 %. The NASA is investigating a future engine with a bypass-ratio of even 10 : 1 in its QCEE (Quiet Clean Efficient Engine) program.

Installation of engines with these large dimensions and in connection with thicker supercritical wing sections require a revision of engine position relative to the wing. The conventional engine location below the wing with the constraints of ground clearance and minimum interference drag between propulsion system and wing offers a very limited potential for future powerplant growth. Unconventional engine locations will have to be considered. One of these is the engine location above the wing as already demonstrated in the VFW 614 and the YC-14.

3. Interference Effects

3.1 Definition of Interference and Past Experience

The installation of high bypass-ratio engine nacelles will modify the local flow field in high and low speed flight with respect to the following effects:
- flow around nacelle cowling
- changes of inlet mass flow ratio (spillage effects)
- jet effects
- flow disturbance due to pylon for engine mounting.

Depending upon the configuration these effects will lead to distinct changes in the aerodynamic characteristics of an aircraft.

The general definition of aerodynamic interference due to the propulsion system has mainly been the classical problem of designing to keep interference drag at a minimum unter specified flight conditions.

The main subject of interest for future transport aircraft consists of configuration-oriented effects taking into account design requirements of individual components (e.g. sensitivity of advanced airfoils, dimensions of high bypass-ratio engines). Development of aircraft with strong engine/airframe interference and extensive research work at VFW-Fokker show that jet interference is a parameter which can cause substantial changes in aerodynamic performance. Under certain conditions however this interference effect can even be favourable.

The large mass flows of high bypass engines influence greater portions of the airframe than early turbojets and first-generation turbofans. This usually is the wing, the main lift producing component. For the final evaluation of a given engine/airframe configuration the effect of inlet mass flow must also be considered.

Typical examples of aircraft with strong interference are the VFW 614 transporter (fig. 2) and the V/STOL fighter aircraft VAK 191 B (see fig. 13). Jet interference can be predicted by theory. The comparison of theory and experiment as well as actual flight results with the above aircraft showed good agreement.

3.2 Systematic Investigations

Over the past a systematic investigation of engine nacelle effects at different wing positions has been investigated. Fig. 14 gives a summary of this work.

An experimental programm has also been conducted to obtain basic results of jet interference at different positions. These tests were done in the VFW-Fokker Low Speed Tunnel of the open return type with a closed test section of about 2 m x 2 m at a maximum speed of 70 m/s. The variations tested are shown in fig. 15.

The main results of these systematic investigations are presented in fig. 16 and 17 and can be summarized as follows:

- engine blowing over the wing has the highest lift capacity
- drag is decreased for the over-wing location especially at high lift and increased by nearly a constant value for the under-wing location
- jet effects a more pronounced at high velocity ratios V_j/V_∞ .

3.3 Methods of Calculation

VFW-Fokker has investigated the application of panel-methods for the solution of different flow problems. Panel methods can be used for jet-body interference in subcritical flow.

The singularity method of Hess and Smith forms the basis of the computational method for these problems. The surface of the investigated configuration is panelled, alloting a constant source distribution to each panel. The source strength is so calculated that the normal velocity on the body surface vanishes (see fig. 18).

To simulate the suction and the displacement effects of jet the jet can be panelled as a solid body with the exception that the source strength is obtained from prescribed non-vanishing normal velocities.

To calculate lift a system of horse-show vortices is placed on the wing camber surface. The vortex distribution in chord direction is prescribed and the Kutta-Condition is used to calculate the spanwise distribution. This is controlled in a point near the trailing edge (Kutta-point, see fig. 18).

For the calculation of a jet-powered high aspect ratio STOL aircraft as shown in fig. 19 a half-panel model with 200 and 322 panels for the fuselage and wing is required. The engine nacelle is represented by an axially symmetric cylinder consisting of 132 panels.

The jet can be represented by a straight cylinder of constant circular section. The normal velocity on the cylinder surface however must be prescribed. For a jet length of about 14 exit diameters 84 panels are necessary.

Fig. 19 shows an over-wing nacelle configuration with a velocity ratio of jet to free stream of 7 : 1. A panel model with a faired inlet was used corresponding to a known experimental model. Comparison of test and calculation shown in fig. 20 shows good agreement. These results show that a propulsive jet over the wing causes a considerable lift augmentation at the engine station of the wing. Thus this type of calculation model can be used to predict jet interference.

The accuracy of this rather simple model increases as the distance of the jet from the airframe increases. This is due to the fact that the jet geometry is deformed by the airframe and this leads to an alteration of the jet entrainment velocities.

At small distances between jet and airframe an attachment of the jet is possible. Potential-theoretical methods cannot be applied in these cases.

Experience shows that this type of jet model yields satisfactory results as long as the distance between jet and airframe is not less than one jet exit diameter.

The same method of calculation can also be applied to more complex jet interference problems, e.g. mult-jet V/STOL aircraft. A half-panel model of the VAK 191 B with panelling of the main engine nozzles is shown in fig. 21. This model can be used to calculate suck-down effects due to jet entrainment.

4. Advanced Concept for Propulsion System Integration

4.1 Definition of Advanced Concept (Over-the-Wing Blowing)

Experience with propulsion system integration of modern high bypass-ratio engines and systematic investigations of jet interference show that the location of a jet above the wing can significatly improve the aerodynamic characteristics of an aircraft with respect to lift over drag and maximum lift.

Based on this result and taking account of the requirements that an advanced concept must furthermore be based more on efficient "flow physics" than on "complexity" and make use of proven components the basic engine/airframe configuration shown in fig. 22 offers a potential for future transport aircraft.

This novel concept of "Over-the-Wing Blowing" uses a wing stub called the "Nacelle Wing" above and ahead of the main wing for attachment of the engine nacelle. The engine jet blows between both wings creating favourable interference effects.

Separating the main wing from the engine mounting pylon offers the possibility of making optimum use of a given wing area. Wing design is not disturbed by the pylon-junction.

4.2 Experimental Investigations

a) Wind Tunnel Program

An experimental investigation in a low-speed wind tunnel tunnel program has been conducted in order to identify main parameters of the above configuration and to obtain basic effects. This program used an already existing semi-span model of the VFW 614 transport aircraft with a known wing. Model scale was 12 %. Reynolds numbers were in the order of 1.2 x 10^6 based on aerodynamic mean chord.

An externally mounted ejector-powered engine simulator was used at a spanwise engine location similar to the VFW 614.

The following configuration variations were tested:

- 3 nacelle wings as shown in fig. 23. Axial positioning of nacelle wing and engine nacelle remained constant for these tests. Fan-nozzle exit was always at the trailing edge of the nacelle wing.
- different axial and vertical positions of the engine relative to the main wing are shown in fig. 24 (a). "*Axial location*" of the *nacelle was based on distance* of fan-nozzle exit from wing leading edge referred to wing chord.
- "*Vertical location*" was based on the distance between engine centreline and wind chordline referred to the gap between nacelle wing and main wing.
- velocity ratio of jet to free stram V_j/V_∞ from 1 to 7.
- angle of attack α .
- flap deflection.

Forces and moments were measured on the whole airframe with the exception of the engine nacelle which was externally mounted.

For reference the following additional configurations were also tested:
- clean wing
- nacelle wing without engines
- under-wing engine location.

Figs. 24 (b) to 24 (d) show the configurations tested.

b) Engine Simulation

The propulsion system was based on a high bypass-ratio engine of the type already shown in fig. 10.

Various types of engine simulators currently in use for model testing are shown in fig. 25. For windtunnel testing of the Over-the-Wing Blowing concept an ejector-powered simulator was constructed as shown in fig. 26. Both inlet and nozzle flow were simulated.

Purpose of the simulation was to obtain mean nozzle to free stream velocity ratios corresponding to cruise, take-off and climb and approach.

Conditions	velocity ratio V_j/V_∞
cruise	1
approach	4
take-off and climb	7

For the purpose of these tests in the low-speed regime an idealised velocity ratio of 1 has been assumed for cruise conditions.

Forces and pitching moment (excluding the engine nacelle) were measured.

Data analysis shows the following tendencies (*see also Fig. 27 to 31*):

- the nacelle wing without a powered nacelle increases the maximum lift of the basic configuration *proportional to the increase in total wing area.* Lift over drag is slightly reduced.
- a powered nacelle blowing over the wing with an idealised velocity ratio of V_j/V_∞ = 1,0 has little influence on maximum lift but improves lift over drag considerably. There is a strong nose-up pitching moment tendency.
- increasing the main nozzle velocity V_j relative to free stream V_∞ further augments the lift over drag ratio by nearly 80 % and also leads to higher lift. In general the effects of favourable jet interference are further increased. There is also an increase in pitch-up tendency.

The results also show that the vertical position of the engine above the wing has a stronger influence on the aerodynamic characteristics than the axial location. However an axial position at 30 % chord depth appears to be an optimum for the low-speed flight cases tested.

Postions of the engine under the wing do not show any favourable interference. The measured results are worse than for the basic configuration without jet-effects.

These results clearly indicate the superior performance of the Over-the-Wing Blowing concept.

4.3 Noise Shielding

Noise evaluation of the VFW 614 transport aircraft with engines above the wing and other investigations show that over-wing engine locations experience good wing shielding of engine noise. This shielding effect is shown in fig. 32 with data obtained from tests conducted by NASA Lewis Research Center.

5. Conclusions

Theoretical and experimental investigations supported by experience gained with propulsion system interference show that the concept of Engine Over-the-Wing Blowing offers a substantial potential of advanced technology for future transport aircraft. The introduction of a small "nacelle wing" to support the engine nacelle is a solution which keeps the wing free of pylon disturbances. This approach demands a minimum of complexity and makes use of proven components. Measurements show a potential for 25 % improvement in maximum lift and up to 80 % for lift over drag.

The engine location above the wing eliminates problems associated with ground clearance and classical high-speed interference drag problems of high bypass-ratio engines with the main wing.

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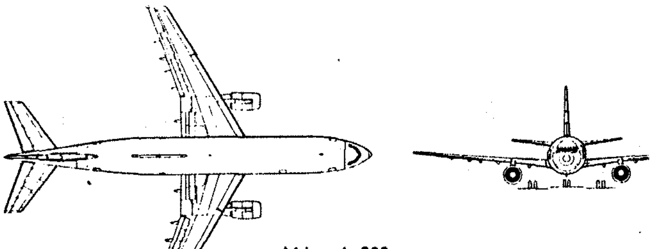
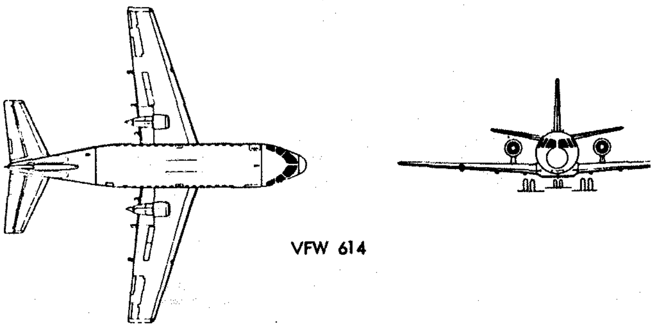
- *supercritical aerodynamics*
- reduction of friction and induced drag
- *improved engine efficiency with respect to weight, fuel consumption and maintenance costs*
- integration of engine and airframe
- reduction of structural weight and use of composite materials
- active controls

Fig. 1 Advanced Technology For Future Transport Aircraft

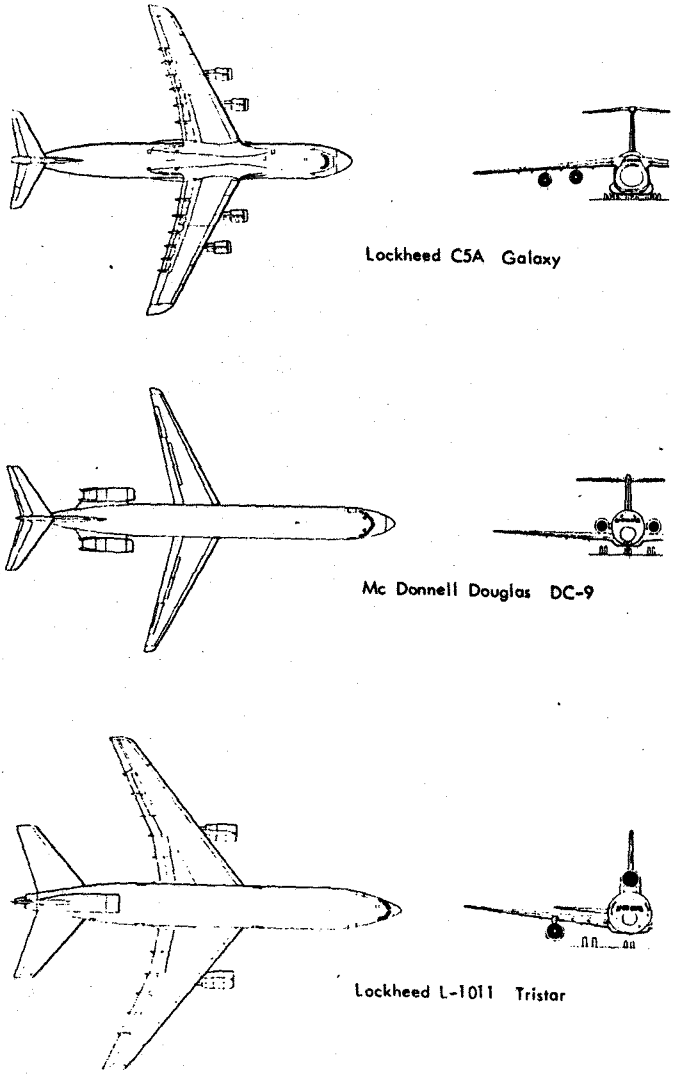


Airbus A 300



VFW 614

Fig. 2 Present Day Transport Aircraft In Service


Lockheed C5A Galaxy

Mc Donnell Douglas DC-9

Lockheed L-1011 Tristar

Fig. 3 Present Day Transport Aircraft In Service

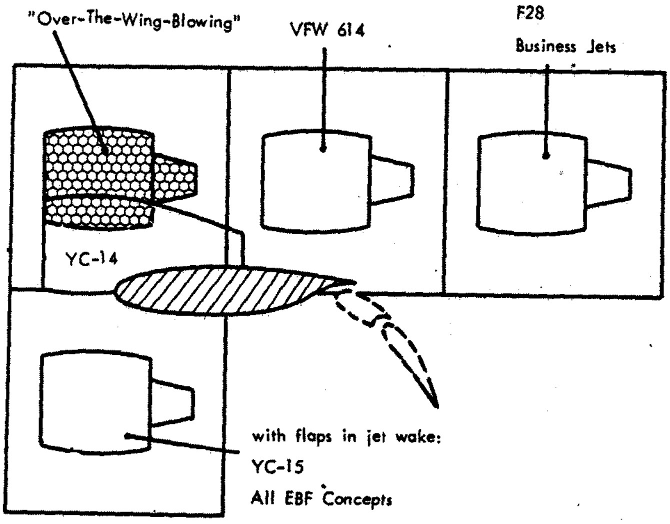
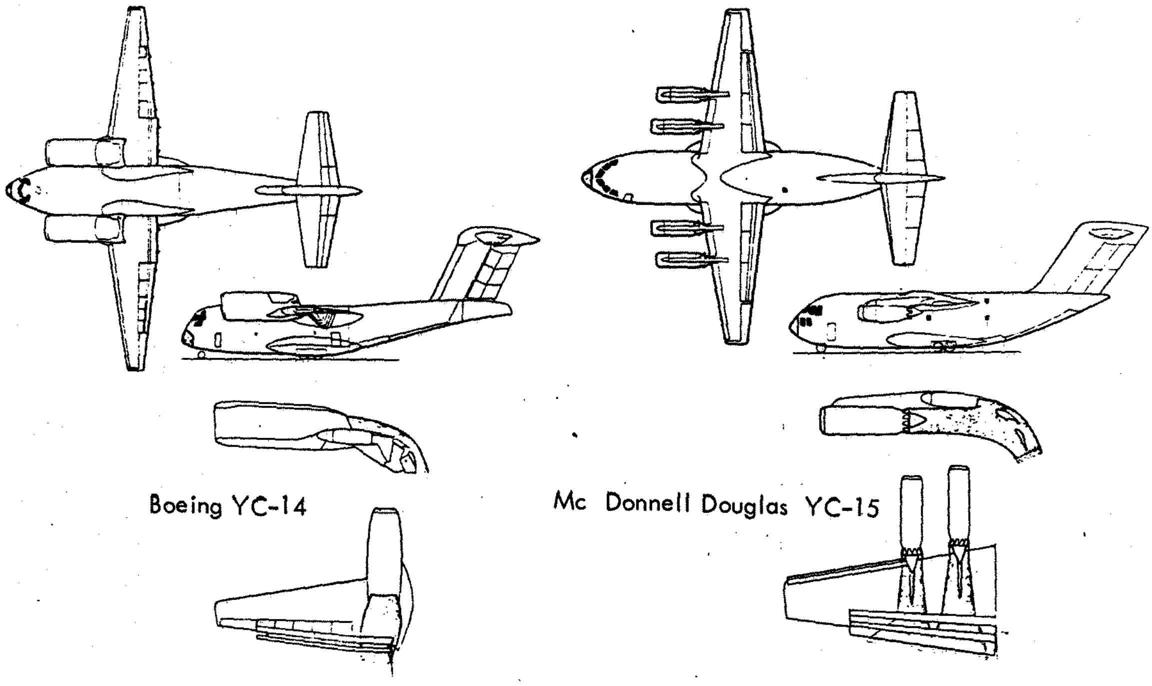


Fig. 4 Engine Position Relative To Wing And Powered Lift Concepts


Boeing YC-14

Mc Donnell Douglas YC-15

Fig. 5 Usage Of Jet Interference Today

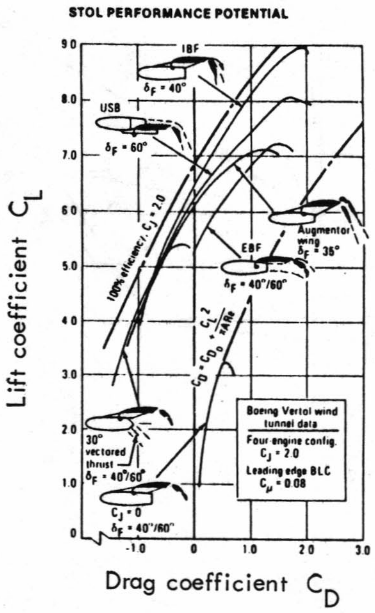
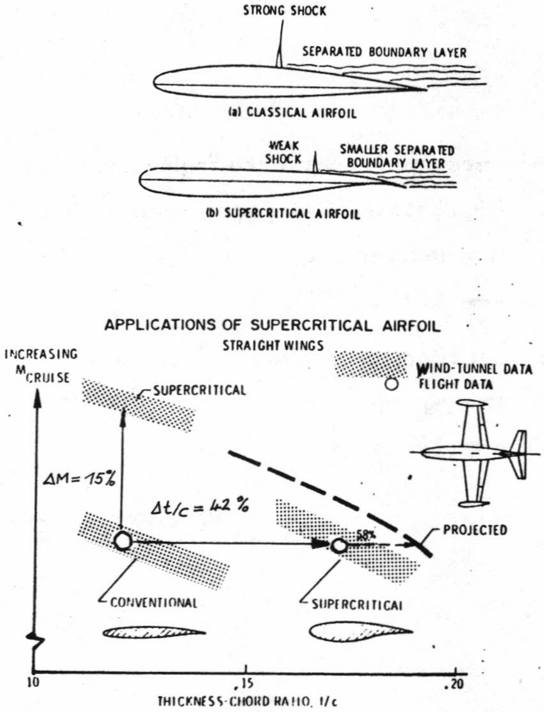


Fig. 6 Drag Polars For Various Powered-Lift Concepts



Advantages of application of supercritical airfoils

Fig. 8 Supercritical Airfoils

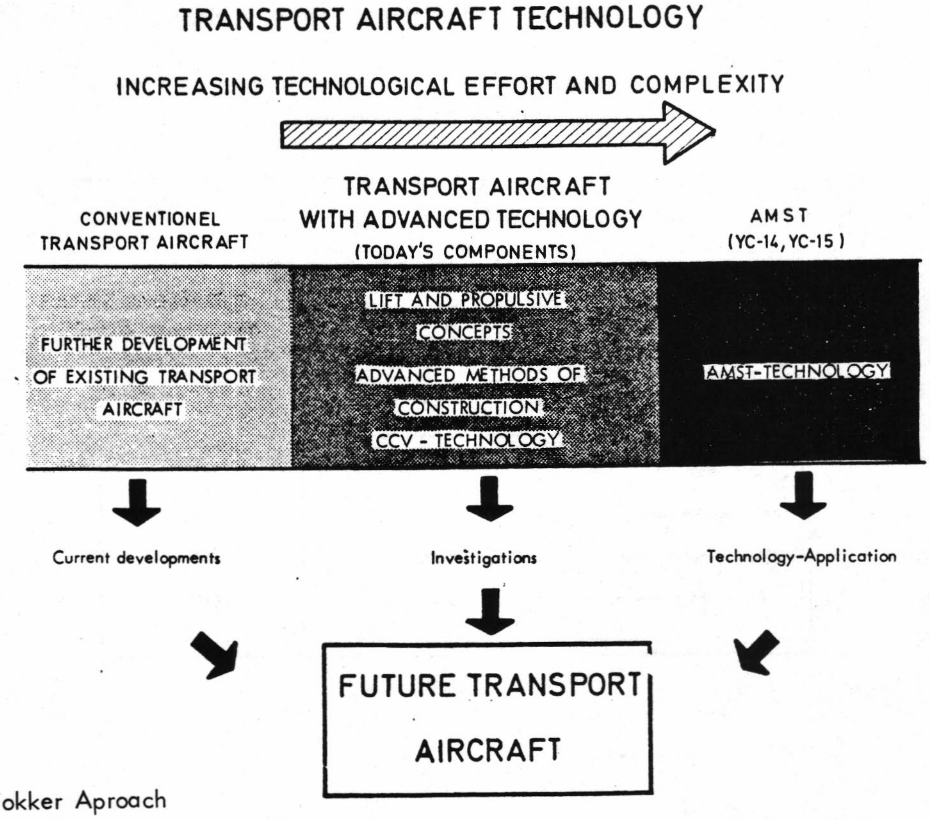


Fig. 7 VFW-Fokker Aproach

Increased Interference of the Engine and Pylon

- o High Loading of wing upper surface, sensitive flow in supersonic region
  - ➞ Lift loss, Drag rise
- o Jet effect on wing lower surface in rear loading region
  - ➞ Lift loss

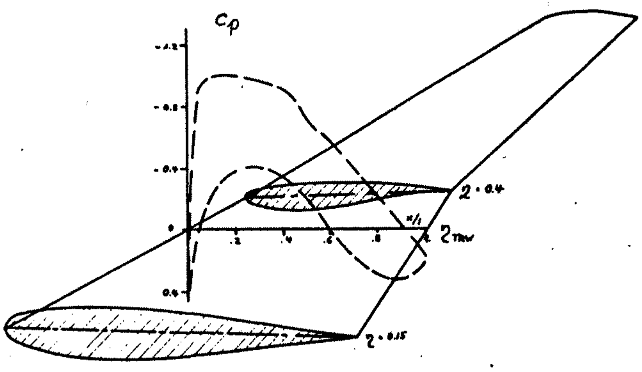
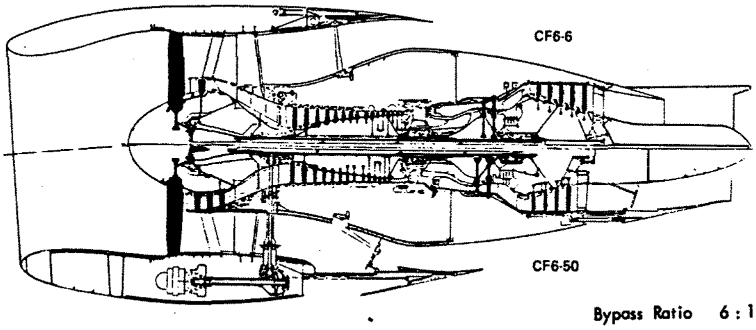


Fig. 9 Interference Effects Of Transonic Wings



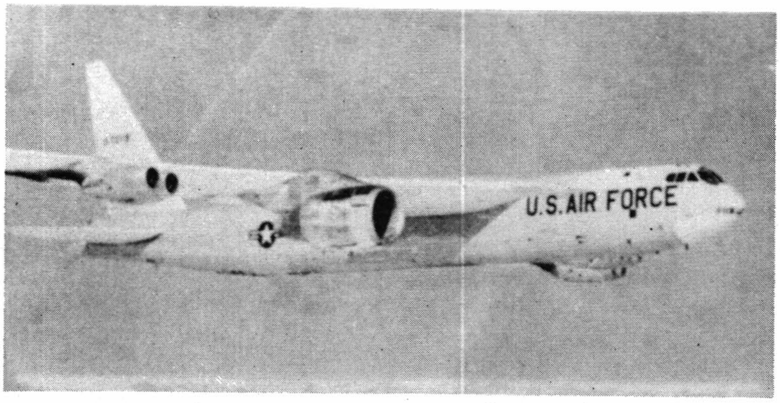
CF6-50/CF6-6 Comparison

Bypass Ratio 6 : 1
Technology 1970 - 80

Fig. 10 High-Bypass Ratio Engine

	Second generation turbofan (1970 - 1985)	Advanced turbofan (1985 - 2000)
Bypass ratio	6	7-8
Fan pressure ratio	1,45	1,6-1,7
Cycle pressure ratio	25 : 1	35-45 : 1
Turbine inlet temperature	1530°K	1675°K

Fig. 11 Comparison Of Engine Cycles



Comparison of Dimensions

2 X J57-P43W	28.000 lb	thrust	bypass-ratio 1,0
1 X CF6	42.000 lb	thrust	bypass-ratio 6,0

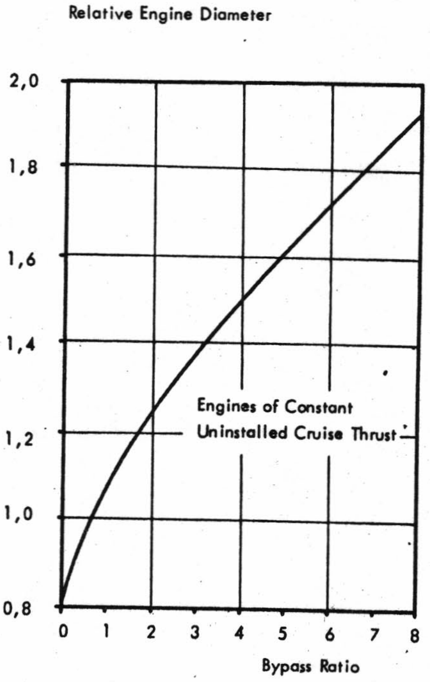


Fig. 12 Engine Dimensions

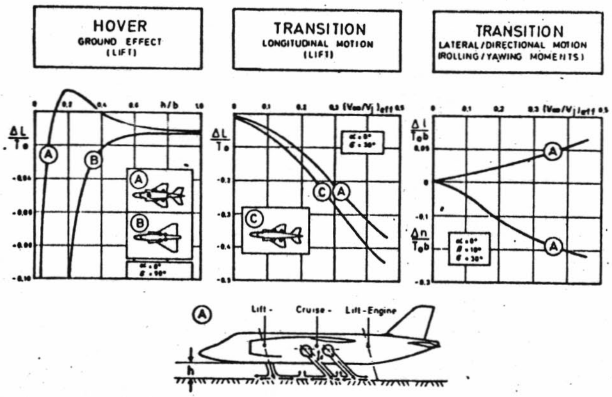
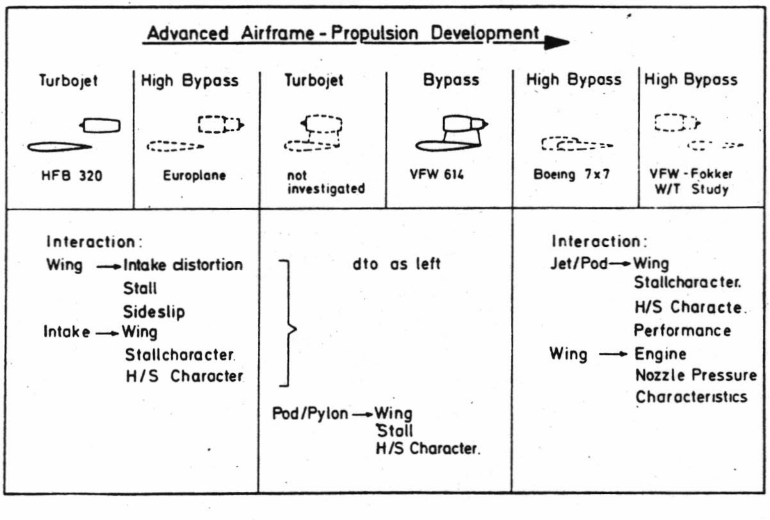


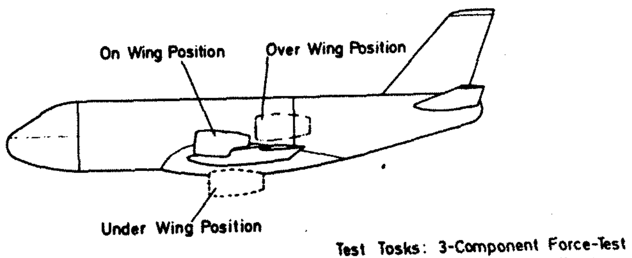
Fig. 13 Jet Influence On VAK 191 B



Advanced Airframe - Propulsion Development

Turbojet	High Bypass	Turbojet	Bypass	High Bypass	High Bypass
HFB 320	Europlane	not investigated	VFW 614	Boeing 7x7	VFW-Fokker W/T Study
Interaction: Wing → Intake distortion Stall Sideslip Intake → Wing Stallcharacter. H/S Character		dto as left Pod/Pylon → Wing Stall H/S Character.		Interaction: Jet/Pod → Wing Stallcharacter. H/S Characte. Performance Wing → Engine Nozzle Pressure Characteristics	

Fig. 14 Wing Engine Interaction



Test Tasks: 3-Component Force-Test
Pressure Distribution

Fig. 15 Jet Influence For Different Engine Locations

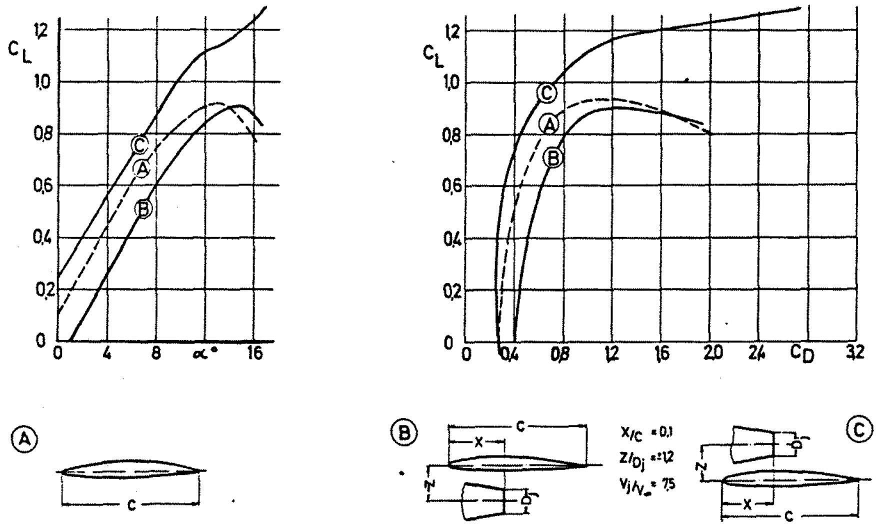


Fig. 16 Jet Influence On Lift And Drag

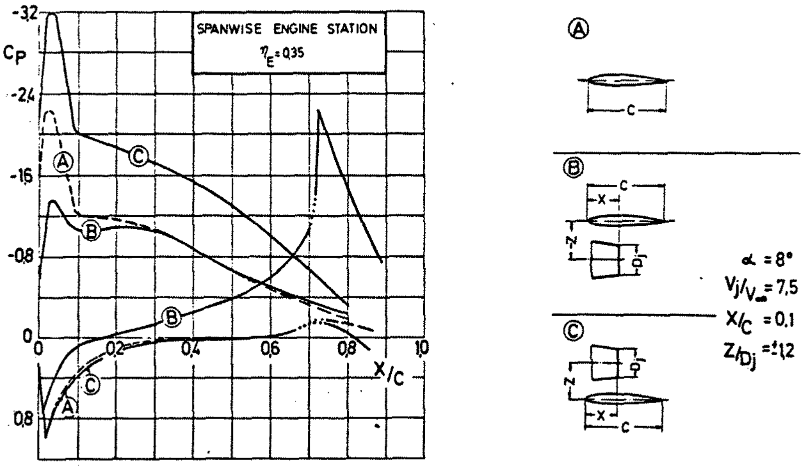


Fig. 17 Wing Pressure At Engine Position

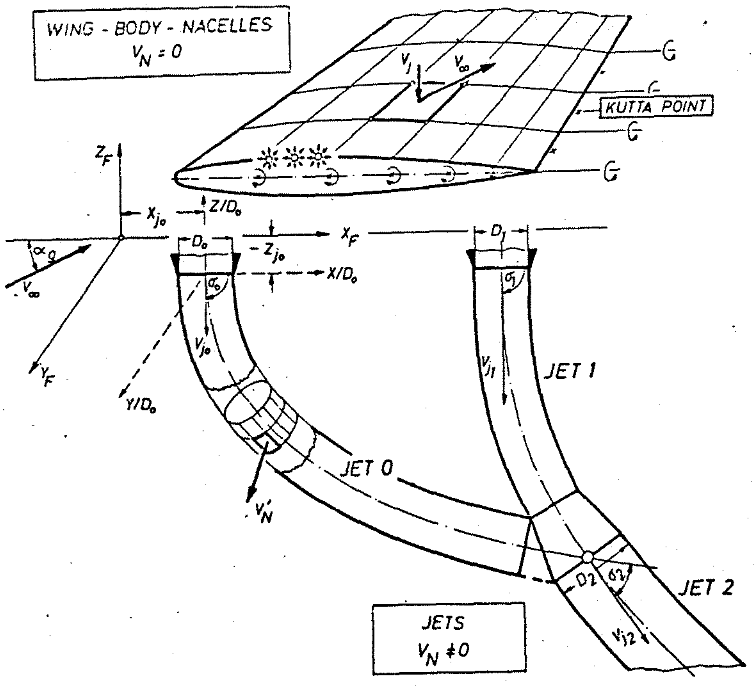


Fig. 18 Panel Method For Interference Flow Fields

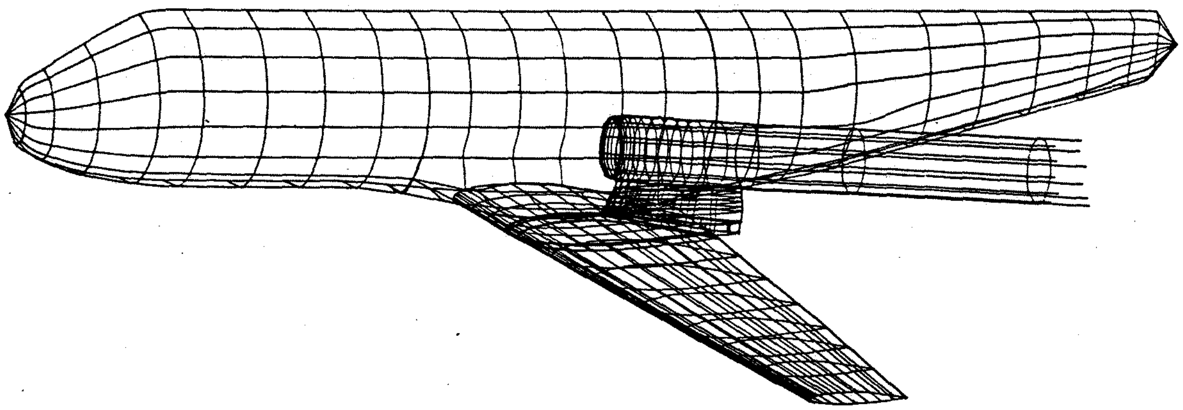
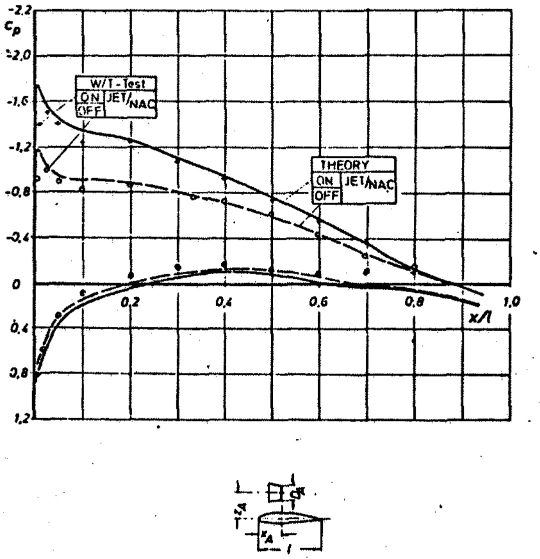
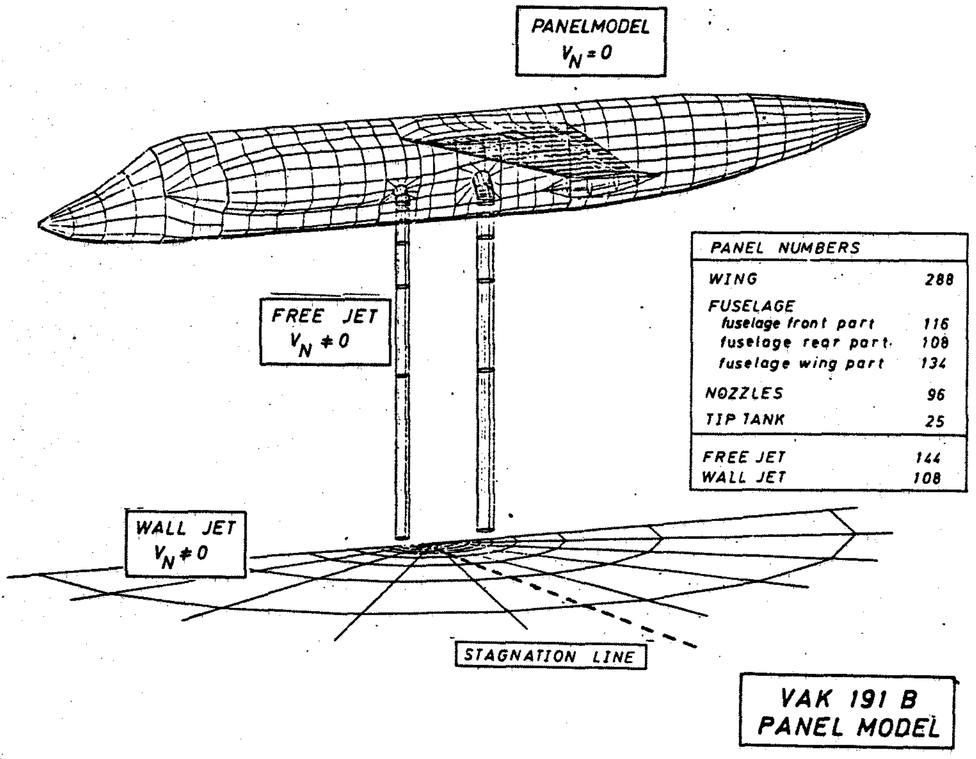


Fig. 19 Panel Model VFW 614



$V_\infty / V_j = 0{,}133$
$x_A / l = 0{,}25$
$z_A / D_A = 1{,}86$
$\alpha = 6°$
$\eta = \eta_E = 0{,}35$

Fig. 20 Model Results



PANEL NUMBERS	
WING	288
FUSELAGE	
fuselage front part	116
fuselage rear part	108
fuselage wing part	134
NOZZLES	96
TIP TANK	25
FREE JET	144
WALL JET	108

Fig. 21 Panel Model VAK 191 B

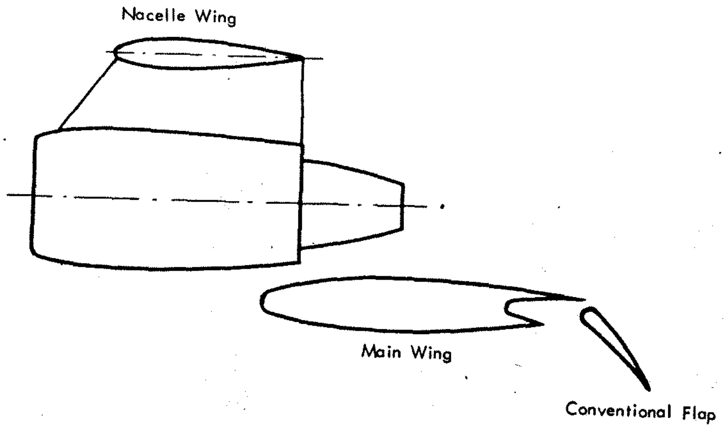


Fig. 22 Over-The-Wing-Blowing Concept

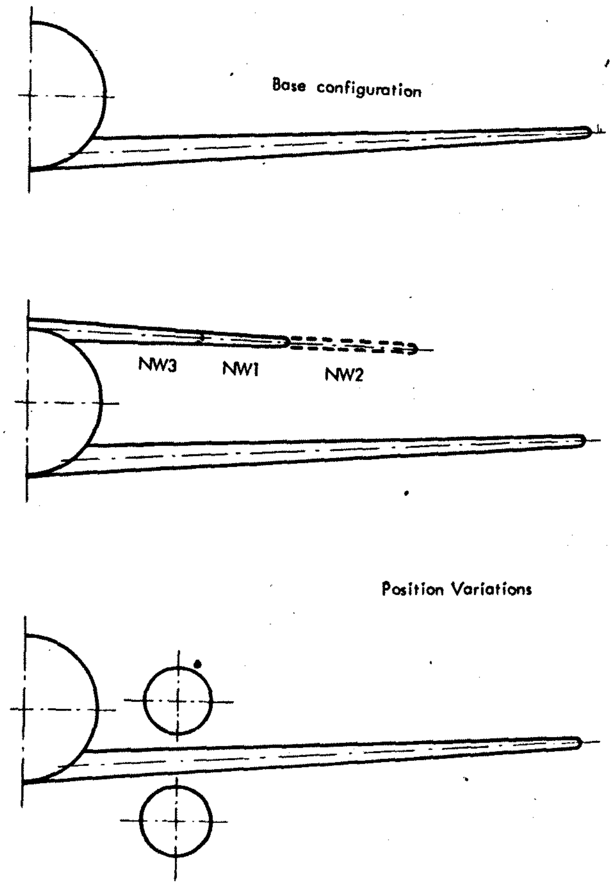


Fig. 23 Configuration Variations (front view)

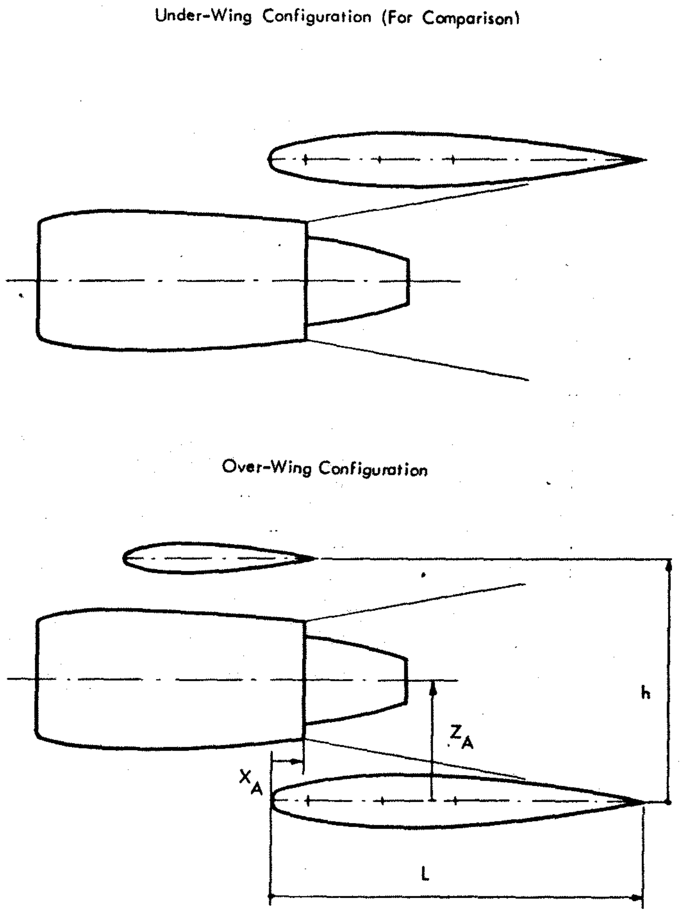


Fig. 24 (a) Configuration Variations (side view)

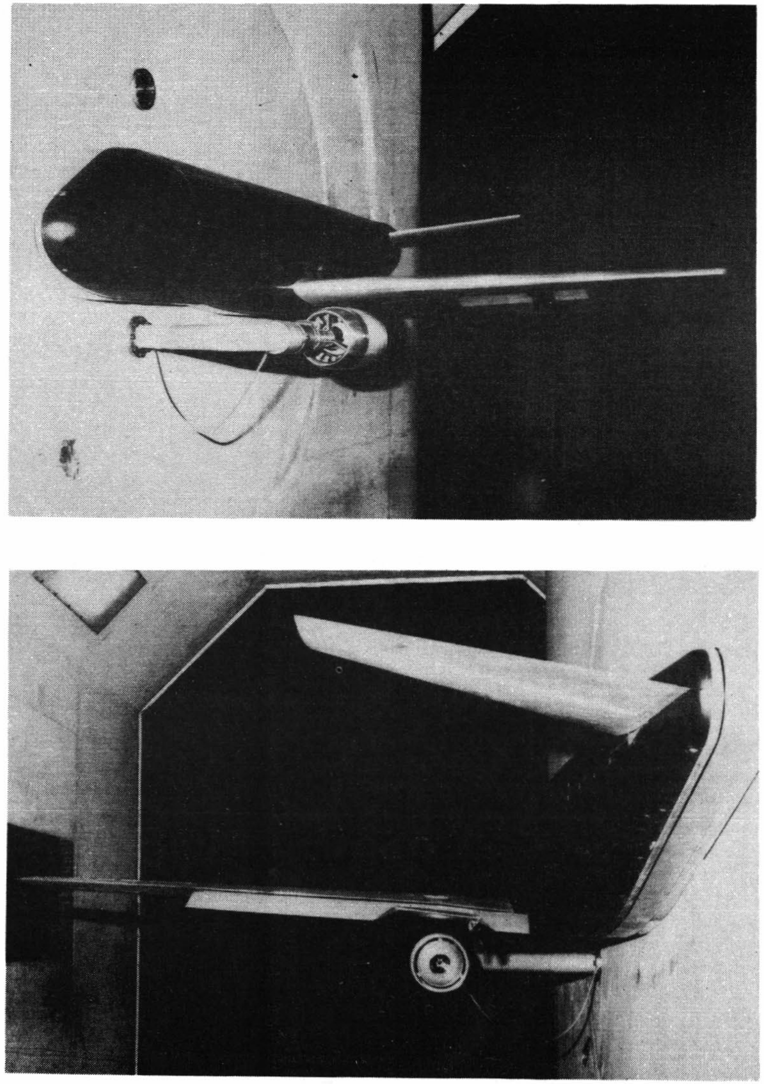


Fig. 24 (b) Wind Tunnel Model

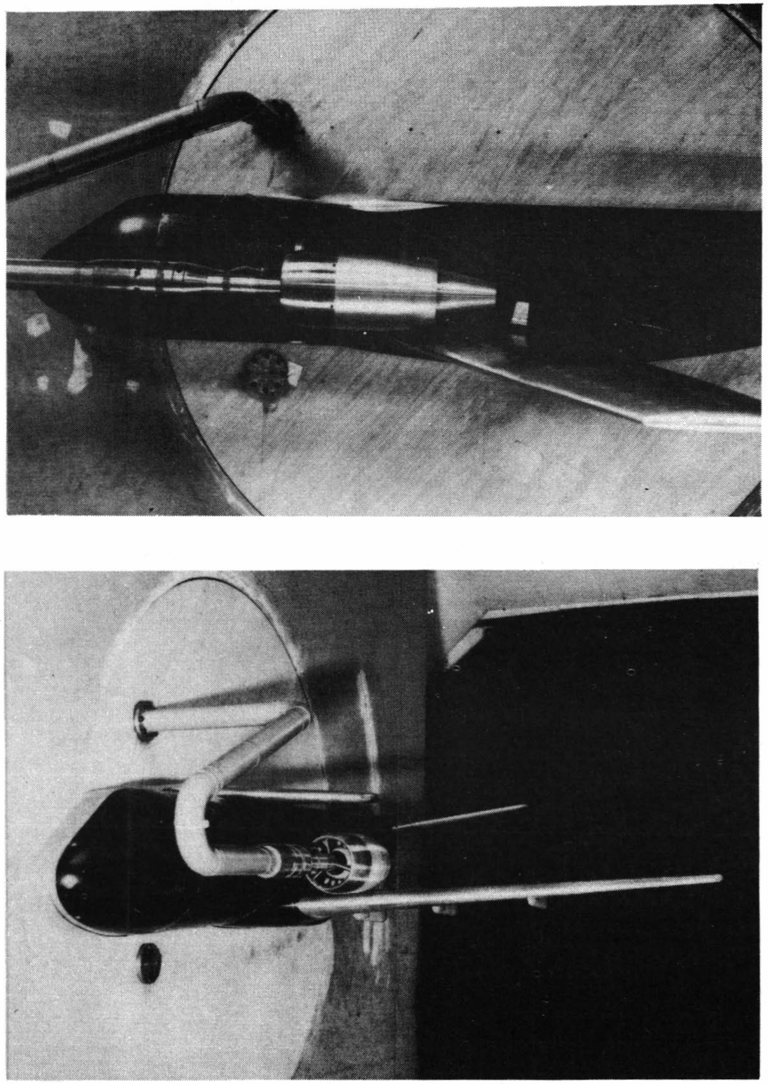


Fig. 24(c) Wind Tunnel Model

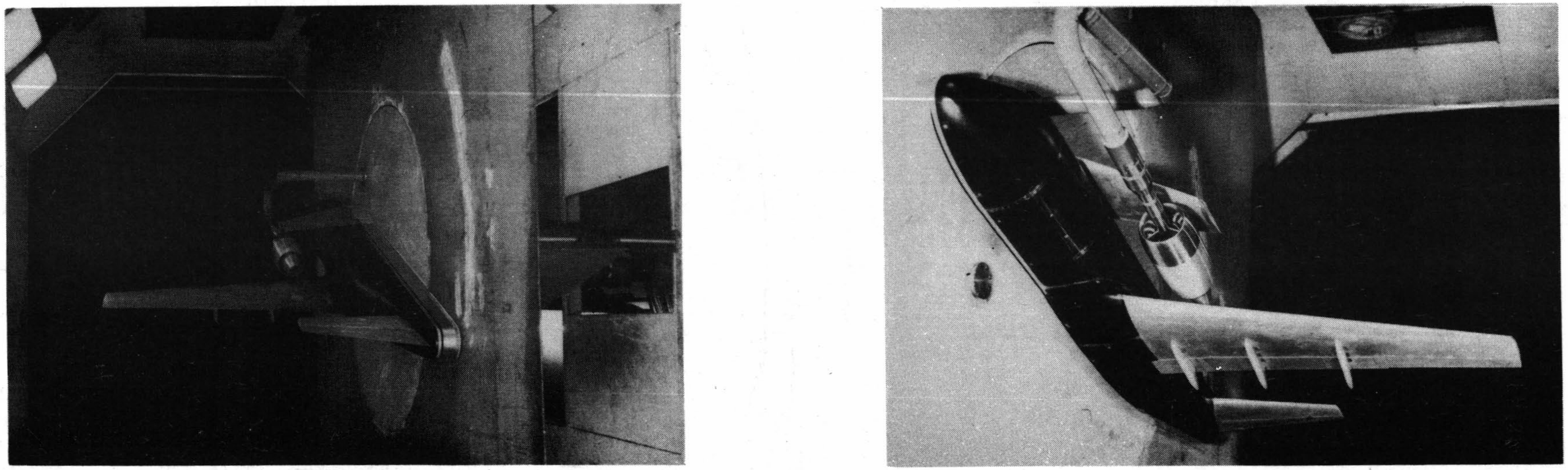
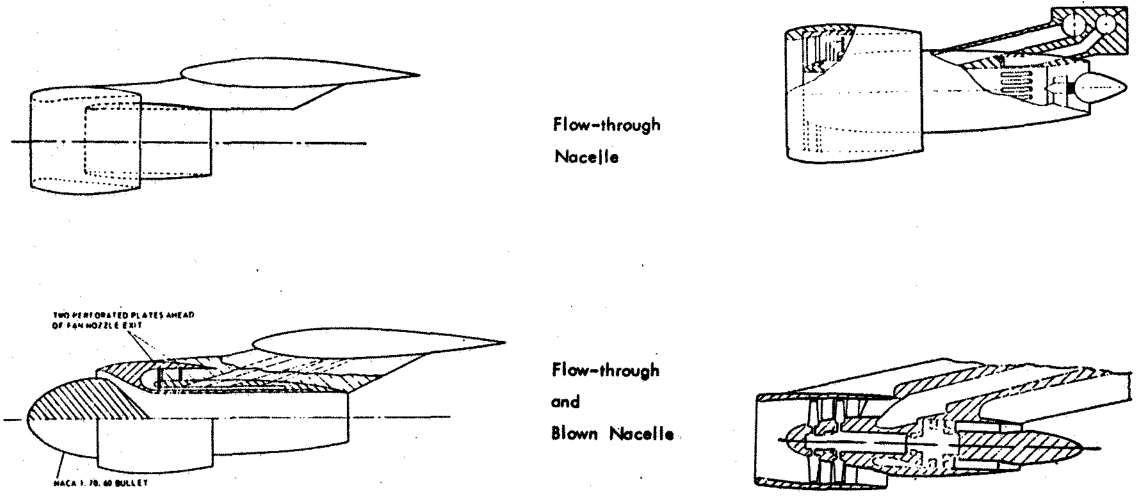


Fig. 24 (d) Wind Tunnel Model



Flow-through Nacelle

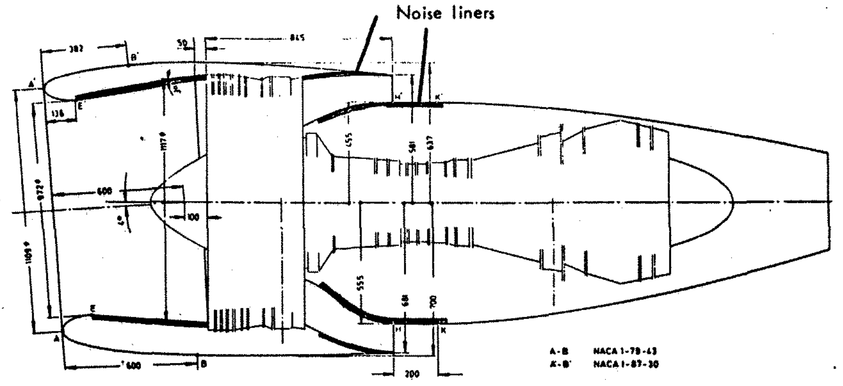
Ejector-powered Engine Simulator

Flow-through and Blown Nacelle

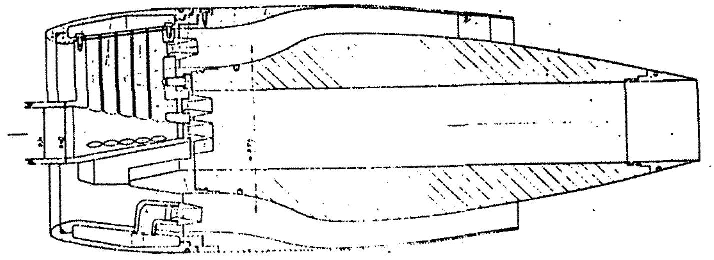
Turbine-powered Engine Simulator

Fig. 25 Engine Simulators

Bypass Ratio	6.2
Engine Pressure Ratio	21.9
Fan Pressure Ratio	1.51
Cruise Consumption	0.643 kg/daN · h
Pressure Ratio, cold nozzle	1.51
Pressure Ratio, hot nozzle	1.30

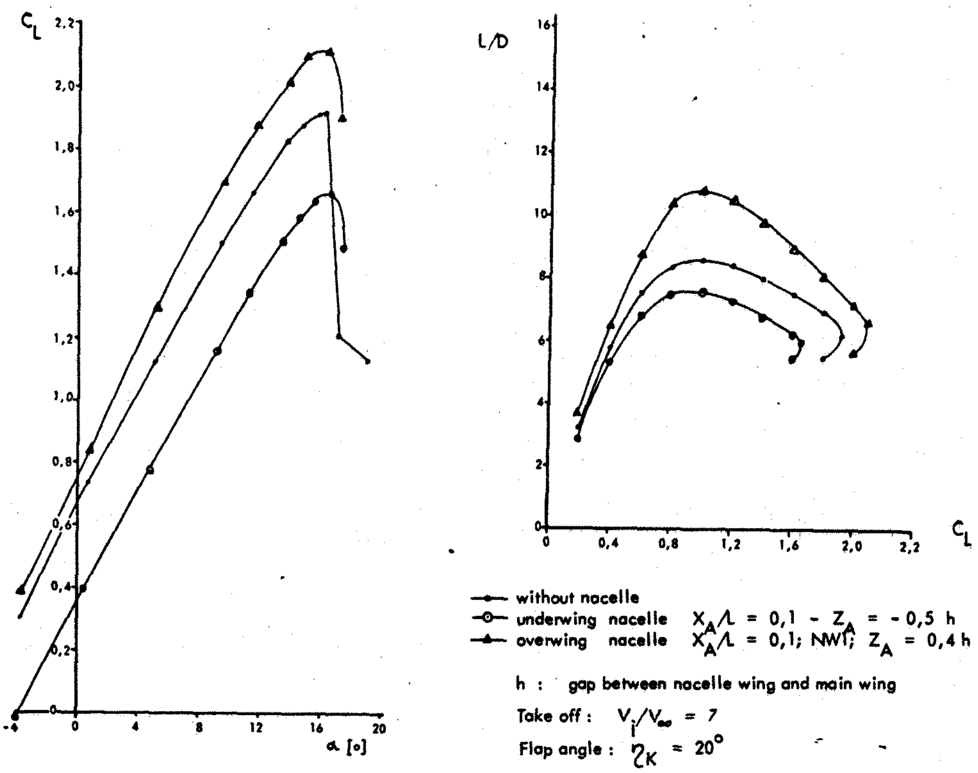


Turbofan with Bypass Ratio 6 : 1



Ejector-powered Engine Simulator

Fig. 26 Engine Simulator for Model Tests

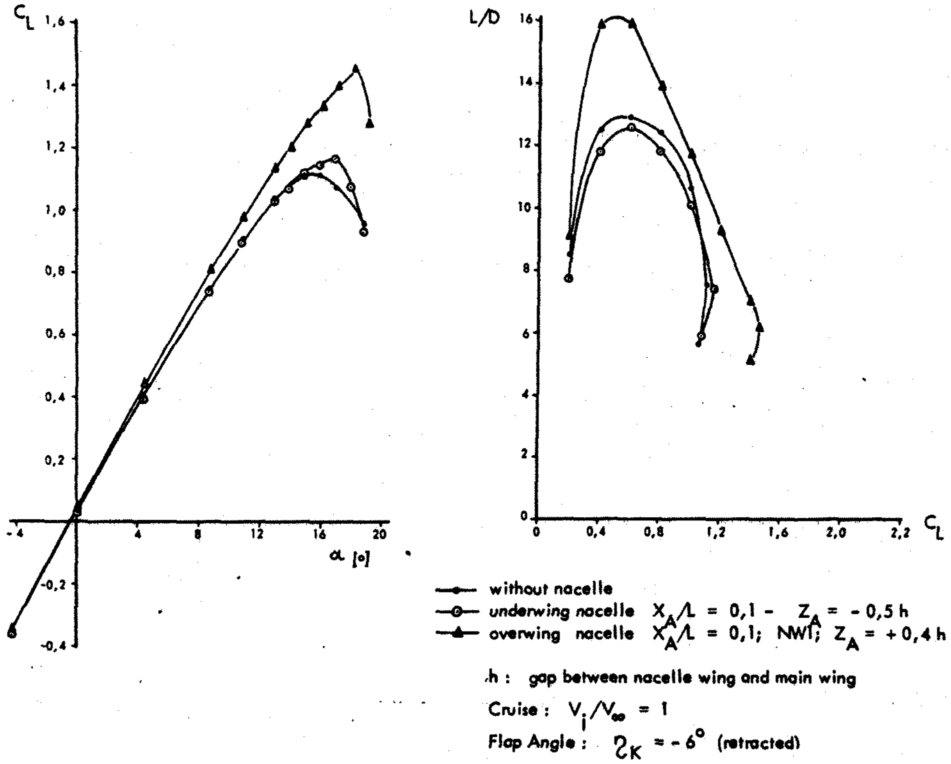


h : gap between nacelle wing and main wing

Take off : $V_i/V_\infty = 7$

Flap angle : $\eta_K = 20°$

Fig. 27 Model Results



h : gap between nacelle wing and main wing

Cruise : $V_i/V_\infty = 1$

Flap Angle : $\eta_K = -6°$ (retracted)

Fig. 28 Model Results

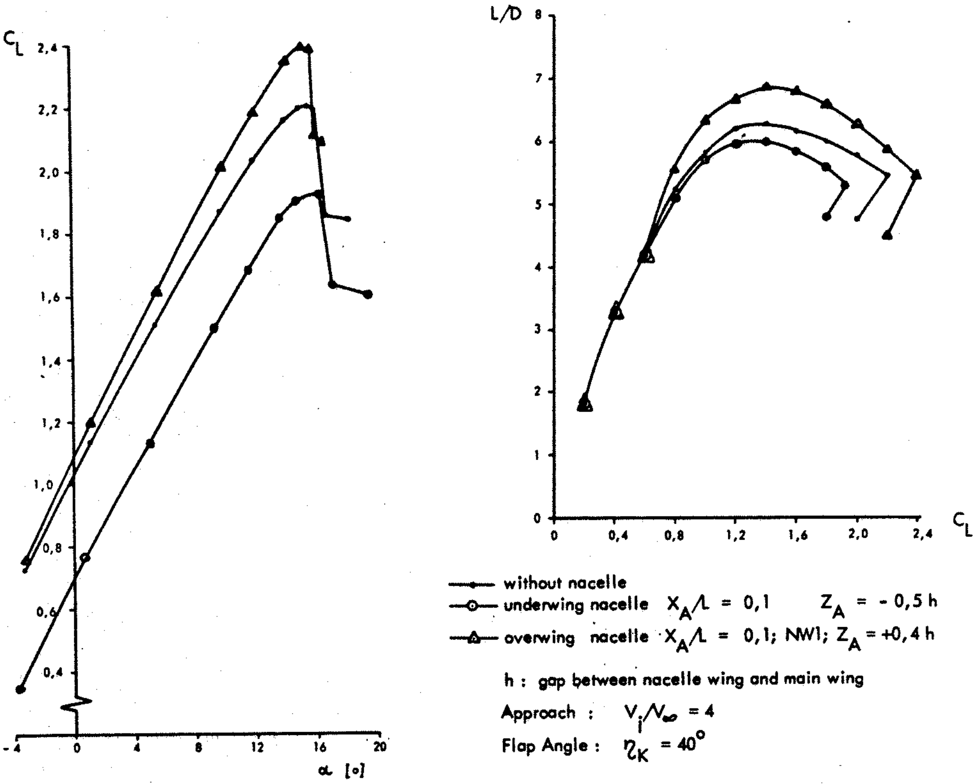


Fig. 29 Model Results

Symbol	Engine Height
----	Without Engine (base configuration B1)
●	- 50 %
☐	40 %
○	60 %

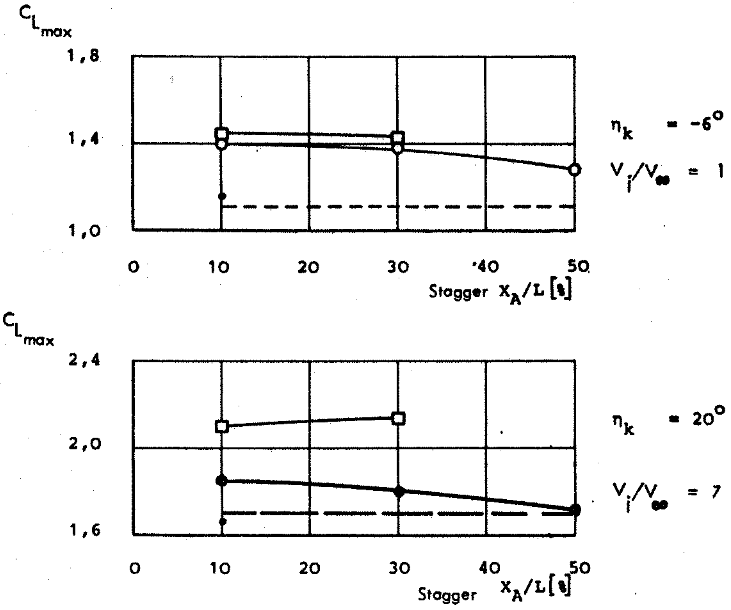


Fig. 30 Maximum - Lift Comparison

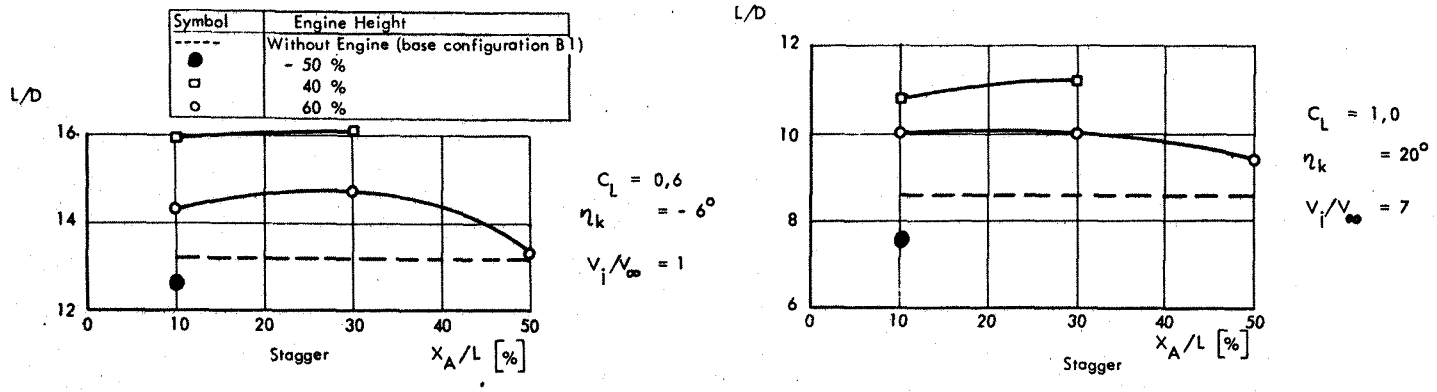
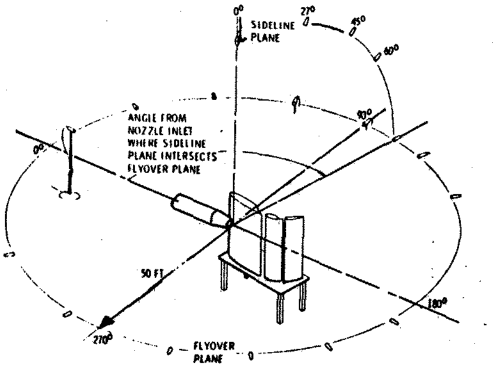
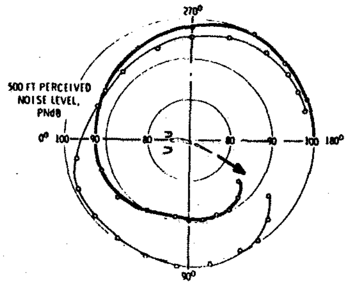


Fig. 31 L/D - Comparison



Microphone layout



(a) TRAILING FLAP ANGLE, 20°; NOZZLE EXHAUST VELOCITY, 765 FT/SEC

Noise radiation comparison of the engine over the wing and under the wing models with powered lift. PNL at 500 ft.

▬ NOZZLE OVER WING
— NOZZLE UNDER WING

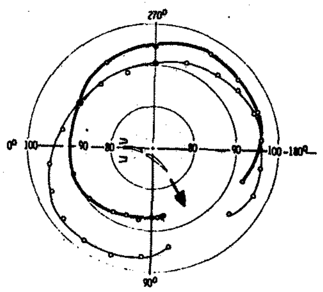


Fig. 32 Noise Measurements (Ref. 3)

(b) TRAILING FLAP ANGLE, 60°; NOZZLE EXHAUST VELOCITY, 680 FT/SEC