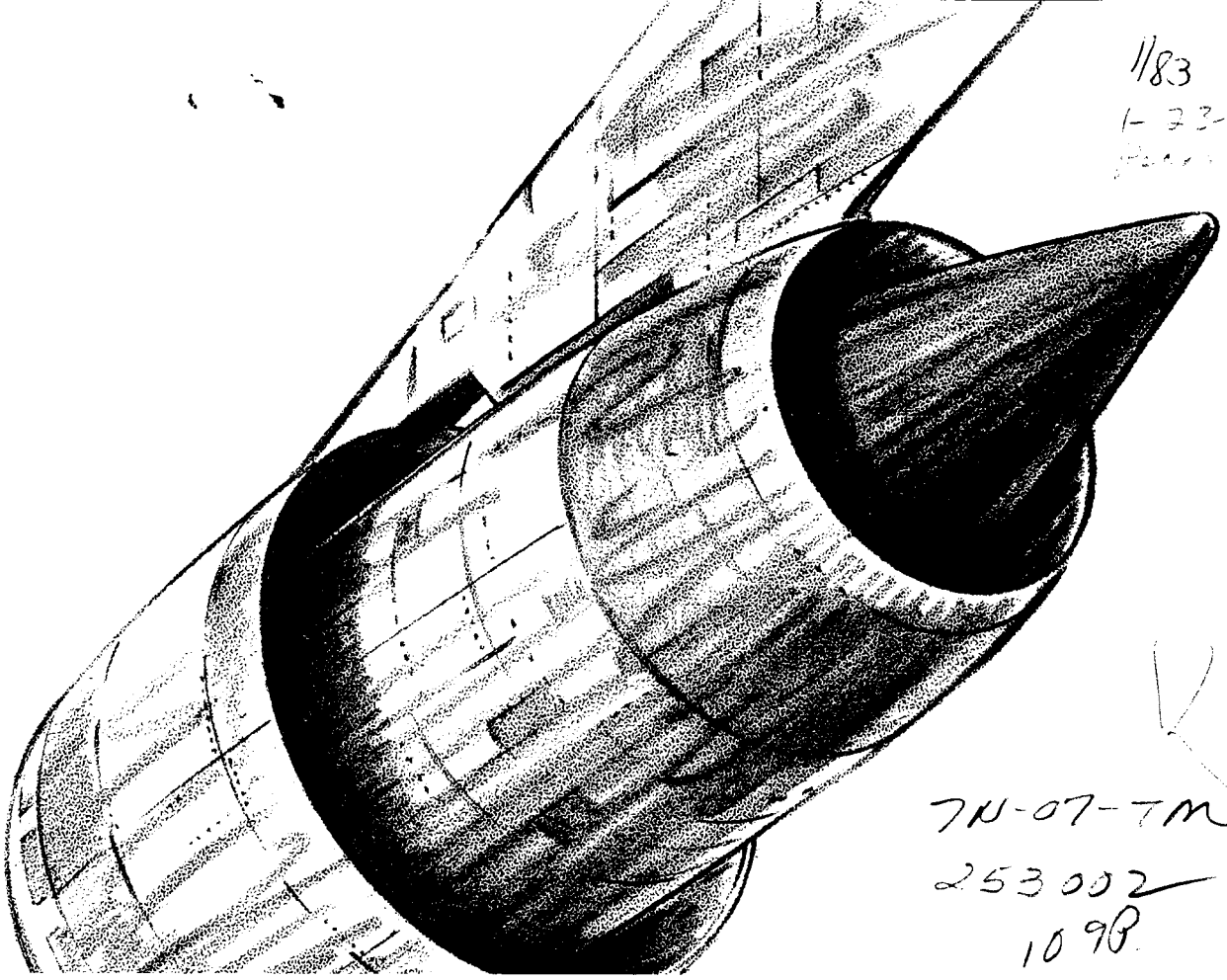

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AERONAUTICAL PROPULSION CONFERENCE

MAY 13-14, 1975

LEWIS RESEARCH CENTER
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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AERONAUTICAL PROPULSION

Conference

Lewis Research Center
Cleveland, Ohio
May 13-14, 1975

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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INTRODUCTION

Warner L. Stewart

CONFERENCE OUTLINE

- NOISE REDUCTION
- ENGINE EMISSIONS
- ENERGY CONSERVATIVE ENGINES
- ENGINE MATERIALS TECHNOLOGY

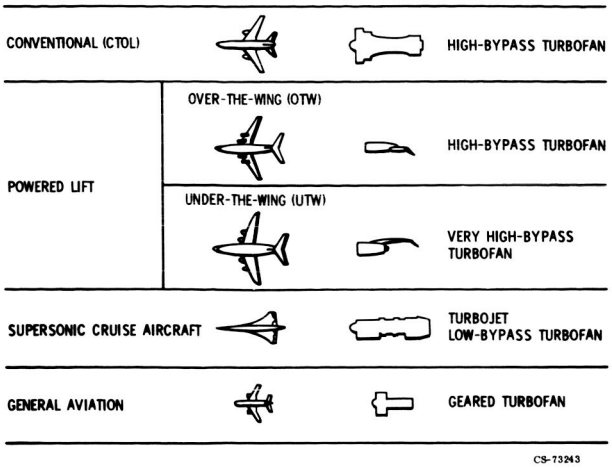
- TURBOMACHINERY TECHNOLOGY
- MECHANICAL SUBSYSTEMS
- ENGINE & SYSTEM TECHNOLOGY
- SUPERSONIC & HYPERSONIC PROPULSION

CS-73478

I. NOISE REDUCTION TECHNOLOGY

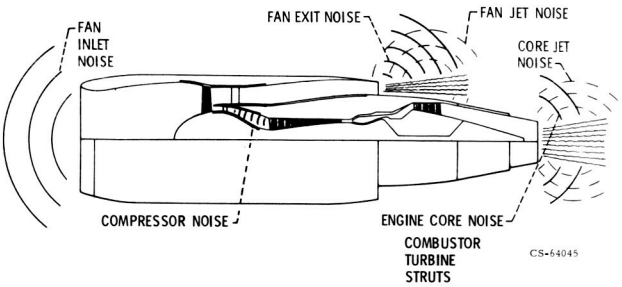
Charles E. Feiler, Chairman
Laurence J. Heidelberg
Allen M. Karchmer
Donald L. Lansing
Brent A. Miller
Edward J. Rice

TYPES OF AIRCRAFT AND ENGINES FOR NOISE REDUCTION TECHNOLOGY



I-1

TURBOFAN ENGINE NOISE SOURCES



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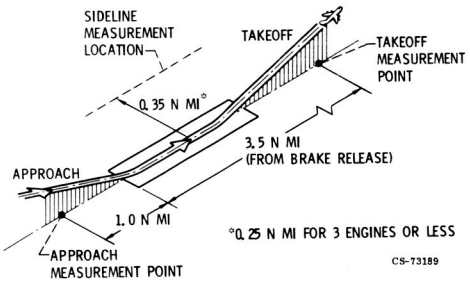
FAA NOISE MEASUREMENT LOCATIONS



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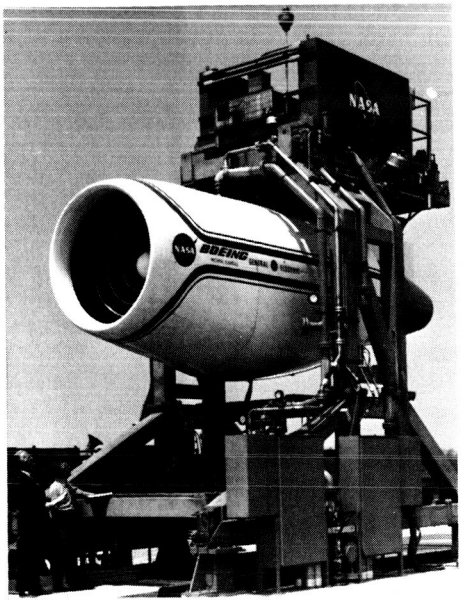
QUIET ENGINE IN BOEING NACELLE



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QUIET ENGINE IN BASELINE CONFIGURATION

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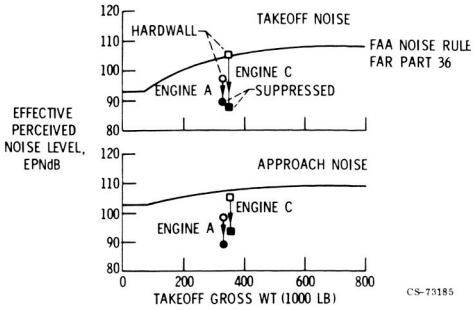
QUIET ENGINE NOISE PERFORMANCE



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TECHNOLOGY AREAS

FAN NOISE

ADVANCES IN SUPPRESSION
- CONVENTIONAL ACOUSTIC TREATMENT
- HIGH MACH NO. INLETS
- WING SHIELDING

ENGINE CORE NOISE

POWERED LIFT FLAP NOISE

SUPERSONIC JET NOISE SUPPRESSION

NOISE PREDICTION

CS-73174

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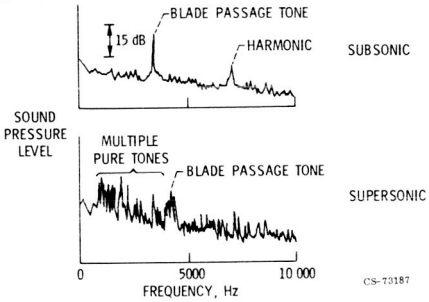
FAN NOISE SPECTRA AT LOW AND HIGH TIP SPEEDS



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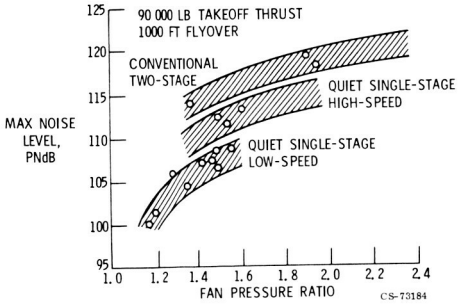
FAN NOISE



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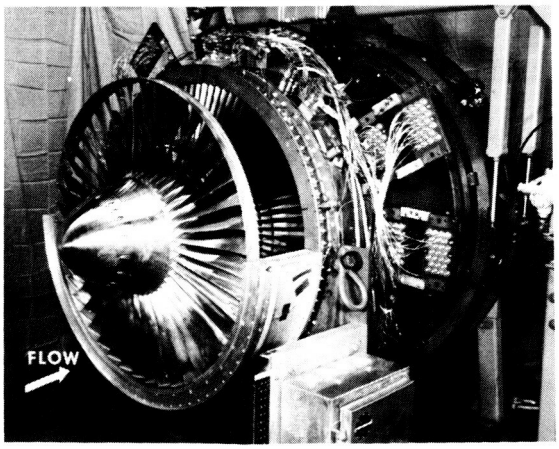
SINGLE STAGE FAN



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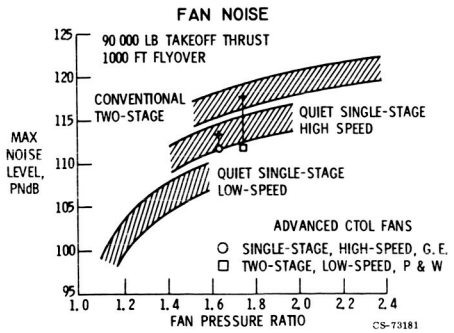

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FAN NOISE REDUCTION CONCEPTS

SERRATED ROTOR BLADES

LEANED STATORS

LONG CHORD STATORS

ROTOR STATOR SPACING

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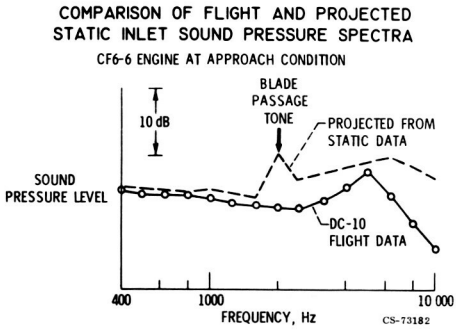

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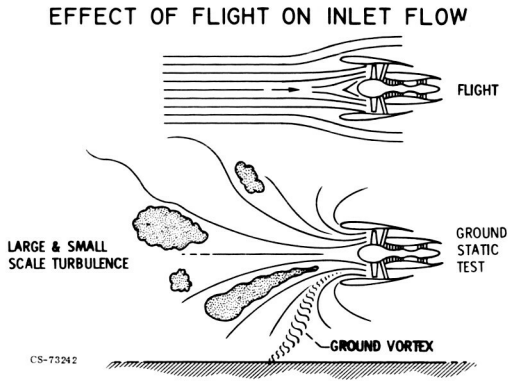

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TECHNOLOGY AREAS

FAN NOISE

→ ADVANCES IN SUPPRESSION
- CONVENTIONAL ACOUSTIC TREATMENT
- HIGH MACH NO. INLETS
- WING SHIELDING

ENGINE CORE NOISE

POWERED LIFT FLAP NOISE

SUPERSONIC JET NOISE SUPPRESSION

NOISE PREDICTION

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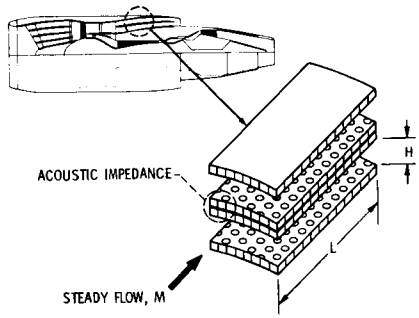
SUPPRESSION PARAMETERS



FREQUENCY PARAMETER: $fH/C \approx H/\lambda$ OR $fD/C \approx D/\lambda$

CS-63332

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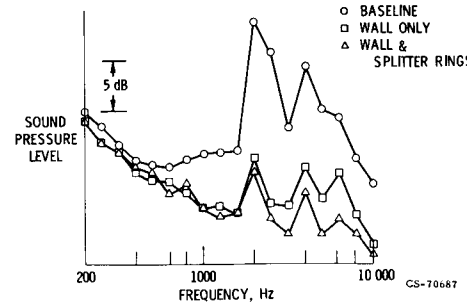
EFFECT OF INLET CONFIGURATION ON SPL SPECTRUM

ENGINE A, TAKEOFF POWER



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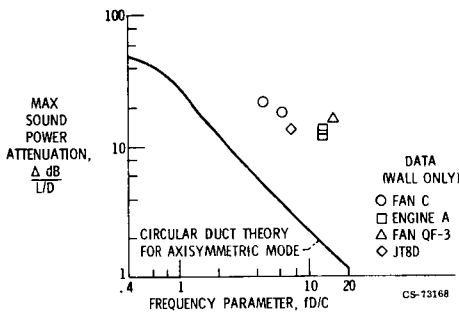
COMPARISON OF SUPPRESSOR THEORY WITH DATA



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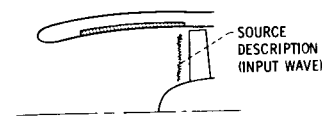
NOISE SOURCE DESCRIPTION



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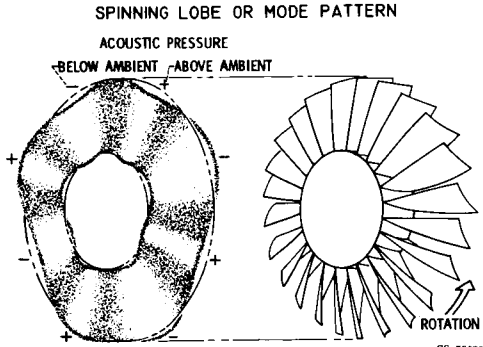
SPINNING LOBE OR MODE PATTERN



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FOUR LOBE PATTERN, m = 4

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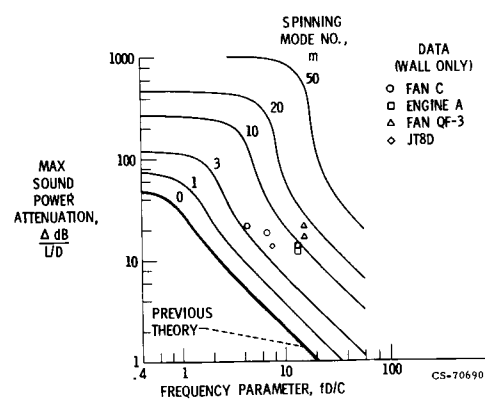
EFFECT OF SPINNING MODE NUMBER ON THEORETICAL MAXIMUM SOUND ATTENUATION



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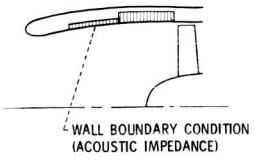
INCREASED ATTENUATION BY WALL IMPEDANCE VARIATION



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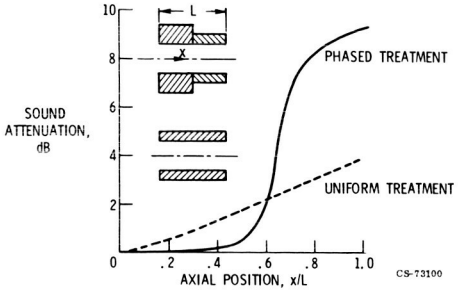
THEORETICAL ATTENUATION FOR OPTIMIZED PHASED AND UNIFORM ACOUSTIC TREATMENTS



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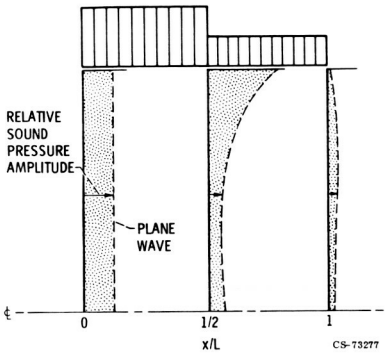
SOUND PRESSURE PROFILES IN DUCT WITH OPTIMUM PHASED TREATMENT



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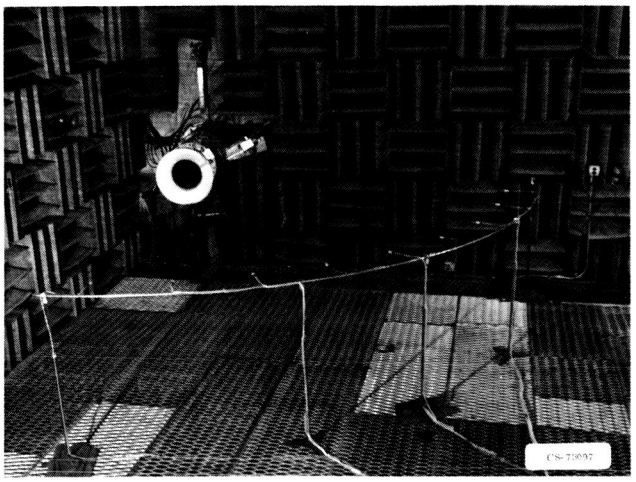
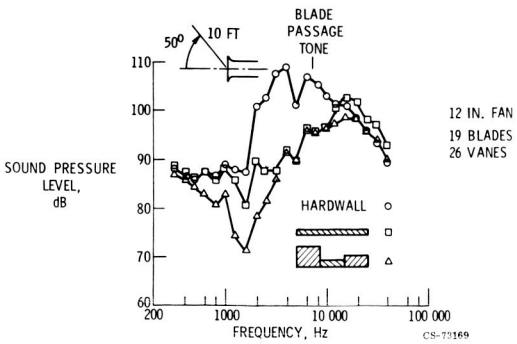
MODEL FAN IN LANGLEY ANECHOIC CHAMBER



I-26

COMPARISON OF NOISE SPECTRA FOR SAMPLE UNIFORM AND PHASED TREATMENTS



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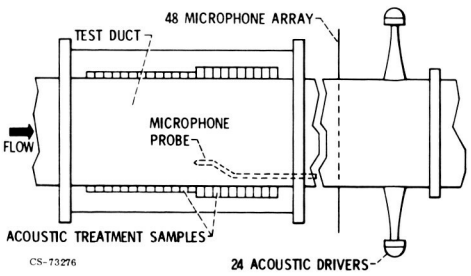
TEST AND SOURCE SECTIONS



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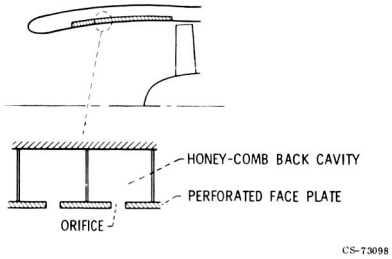
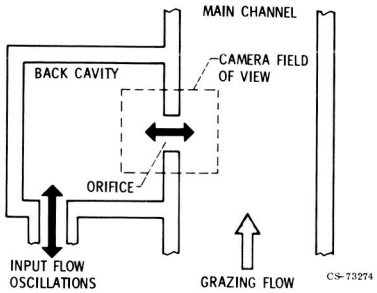
I-28

STUDY OF ACOUSTIC IMPEDANCE



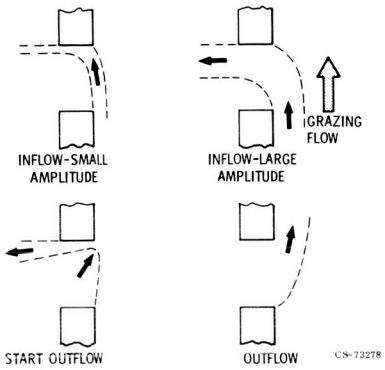
I-29

OSCILLATORY FLOW VISUALIZATION APPARATUS



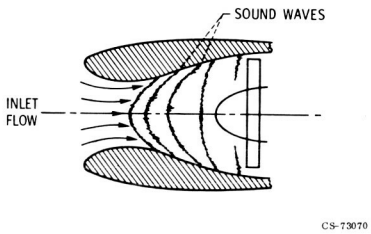
I-30

OSCILLATORY ORIFICE FLOW WITH GRAZING FLOW



I-31

SONIC INLET PRINCIPLE



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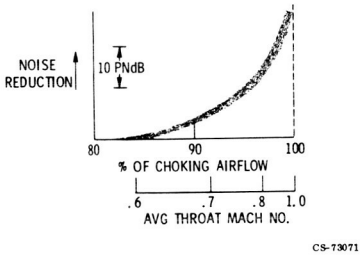
SONIC INLET NOISE REDUCTION



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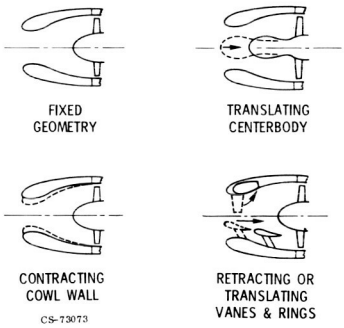
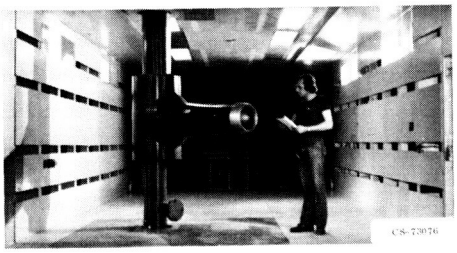
SONIC INLET CONFIGURATIONS TESTED



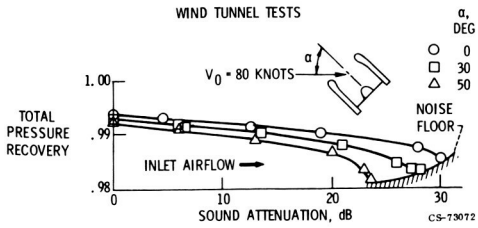
I-34

SONIC INLET WIND TUNNEL TEST



I-35

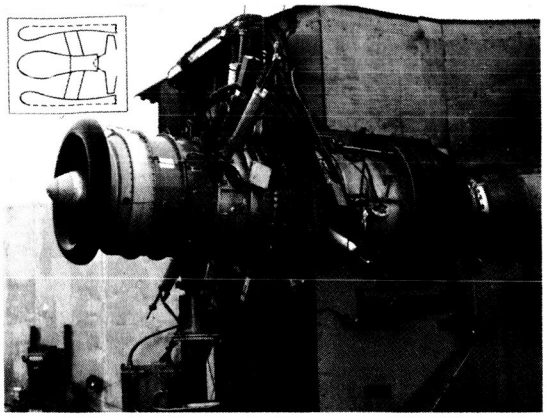
SONIC INLET PERFORMANCE



I-36

TRANSLATING CENTERBODY SONIC INLET

P & WA ADVANCED CTOL TWO STAGE FAN



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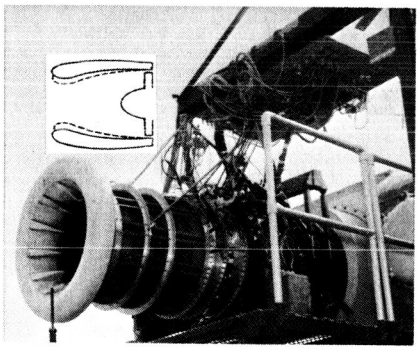
CONTRACTING COWL WALL SONIC INLET

G.E. ADVANCED CTOL SINGLE STAGE FAN



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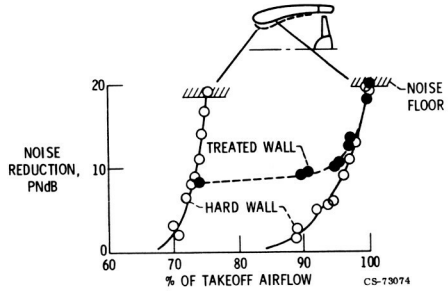
PERFORMANCE OF CONTRACTING COWL WALL INLET



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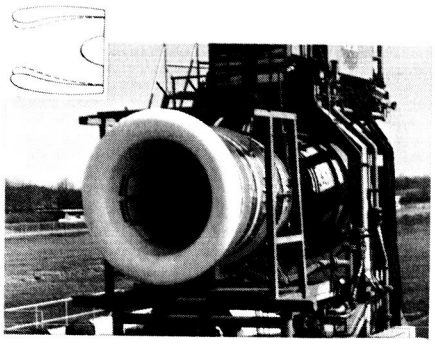
ENGINE "C" WITH SONIC INLET



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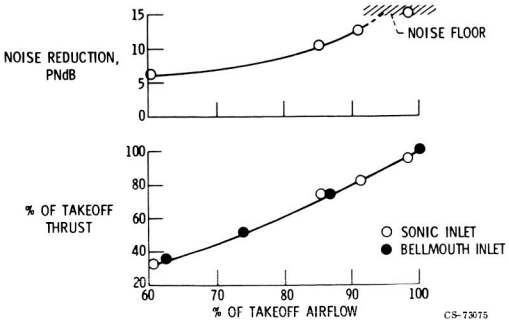
TURBOFAN ENGINE PERFORMANCE

CONTRACTING COWL WALL INLET



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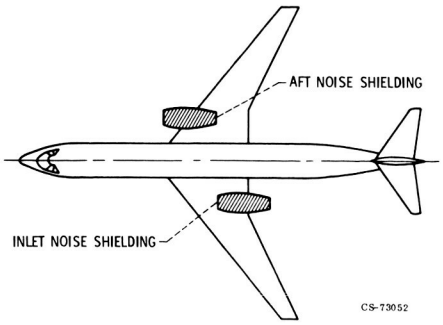
WING SHIELDING CONCEPTS



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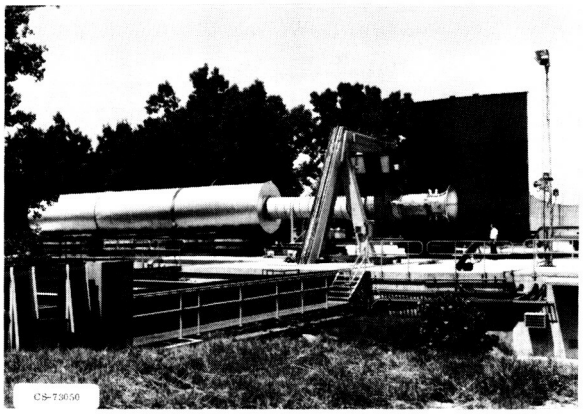
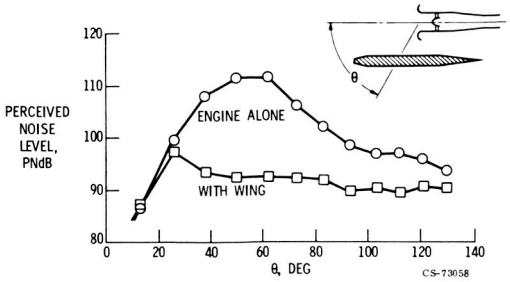
INLET NOISE SHIELDING TESTS USING A TF34 ENGINE AND MUFFLER



I-43

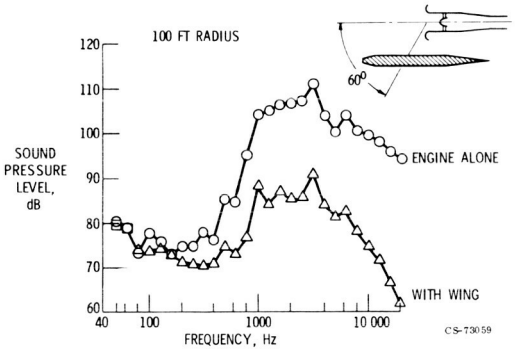
EFFECT OF INLET SHIELDING ON NOISE DIRECTIVITY

500 FT FLYOVER



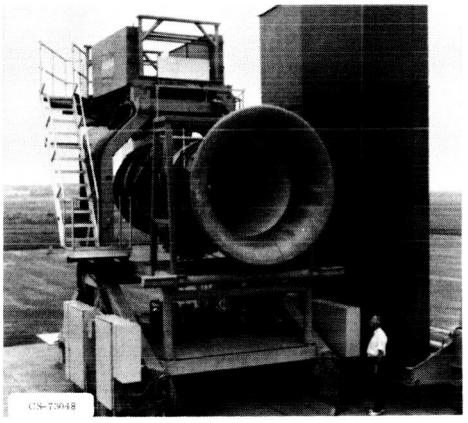
I-44

EFFECT OF INLET SHIELDING ON NOISE SPECTRA



I-45

AFT NOISE SHIELDING TESTS WITH QUIET ENGINE "C"



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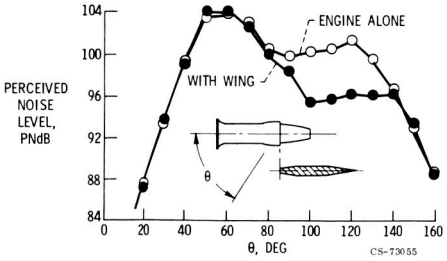
EFFECT OF AFT SHIELDING ON NOISE DIRECTIVITY

UNSUPPRESSED ENGINE, 1000 FT FLYOVER



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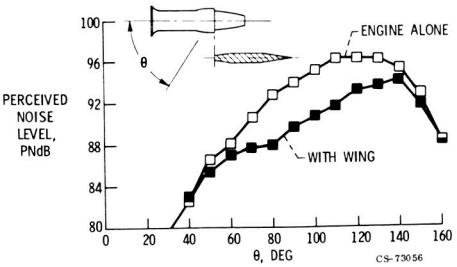
EFFECT OF AFT SHIELDING ON NOISE DIRECTIVITY

SUPPRESSED ENGINE, 1000 FT FLYOVER



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TECHNOLOGY AREAS

FAN NOISE

ADVANCES IN SUPPRESSION
- CONVENTIONAL ACOUSTIC TREATMENT
- HIGH MACH NO. INLETS
- WING SHIELDING

→ ENGINE CORE NOISE

POWERED LIFT FLAP NOISE

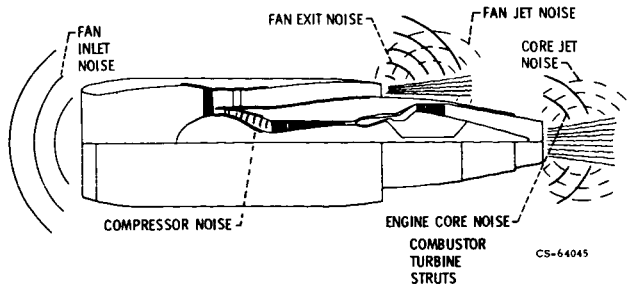
SUPERSONIC JET NOISE SUPPRESSION

NOISE PREDICTION

CS-73179

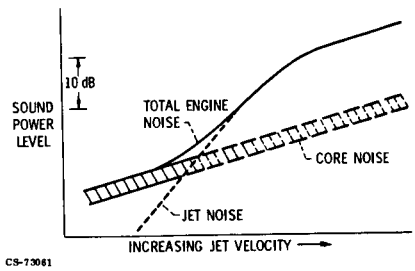
I-49

TURBOFAN ENGINE NOISE SOURCES



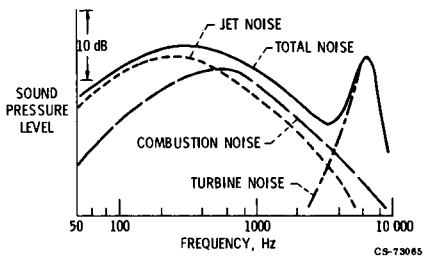
I-50

ENGINE NOISE
FAN NOISE SUPPRESSED



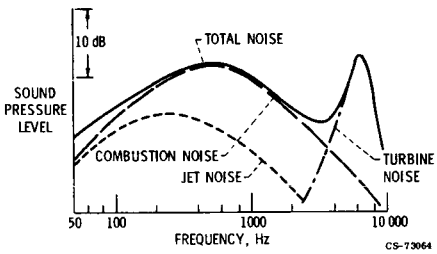
I-51

STATIC ENGINE SPECTRUM
APPROACH POWER



I-52

"IN-FLIGHT" ENGINE SPECTRUM
APPROACH CONDITIONS



I-53

APPROACH TO COMBUSTOR NOISE STUDIES

ESTABLISH

NOISE GENERATION LEVEL

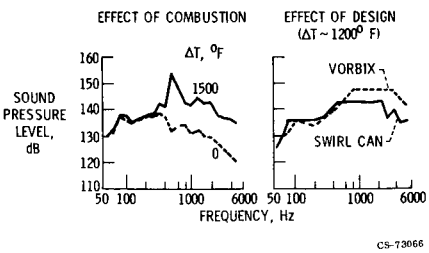
TRANSMISSION ACROSS TURBINE

FAR-FIELD RADIATION EFFICIENCY

CS-73060

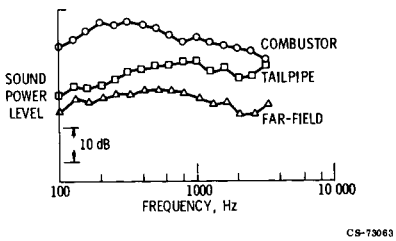
I-54

IN-DUCT COMBUSTOR NOISE DATA



I-55

COMPARISON OF INTERNAL AND FAR-FIELD DATA FOR CORE NOISE STUDIES



I-56

TECHNOLOGY AREAS

FAN NOISE

ADVANCES IN SUPPRESSION
- CONVENTIONAL ACOUSTIC TREATMENT
- HIGH MACH NO. INLETS
- WING SHIELDING

ENGINE CORE NOISE

→ POWERED LIFT FLAP NOISE

SUPERSONIC JET NOISE SUPPRESSION

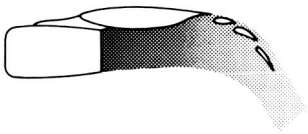
NOISE PREDICTION

CS-73180

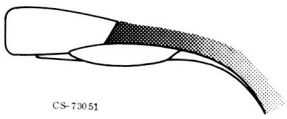
I-57

POWERED LIFT CONCEPTS

ENGINE UNDER THE WING - UTW



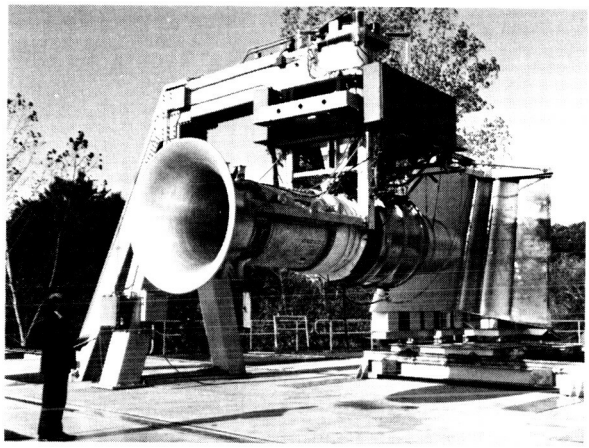
ENGINE OVER THE WING - OTW



CS-73051

I-58

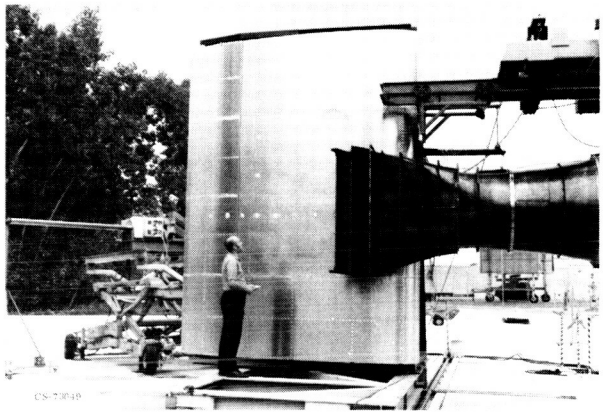
SUPPRESSED TF34 IN UTW TEST CONFIGURATION



CS-73068

I-59

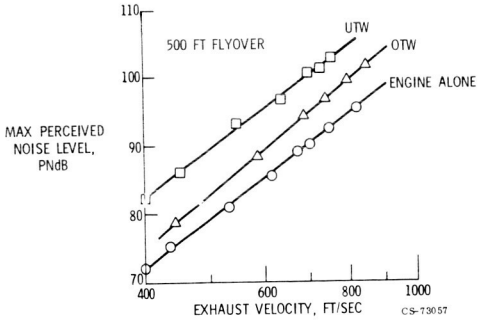
OTW TEST CONFIGURATION WITH SLOT NOZZLE



CS-73049

I-60

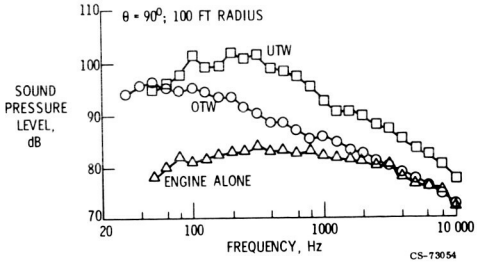
NOISE COMPARISON OF THE OTW AND UTW CONCEPTS



CS-73057

I-61

SPECTRAL COMPARISON OF OTW AND UTW NOISE



CS-73054

I-62

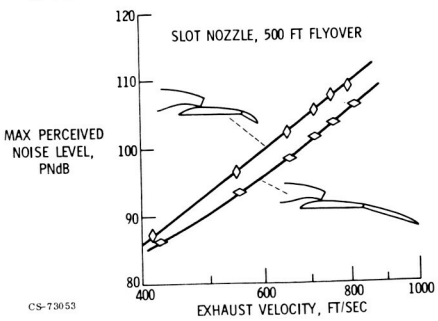
APPROACHES TO UTW NOISE REDUCTION

POROUS FLAPS
COMPLIANT FLAP SURFACES
TRAILING EDGE BLOWING
TRAILING EDGE GEOMETRY VARIATION
FLAP GAP SPACING
WING-NOZZLE SPACING
VELOCITY DECAYER NOZZLE WITH TREATED SHROUD

CS-73646

I-63

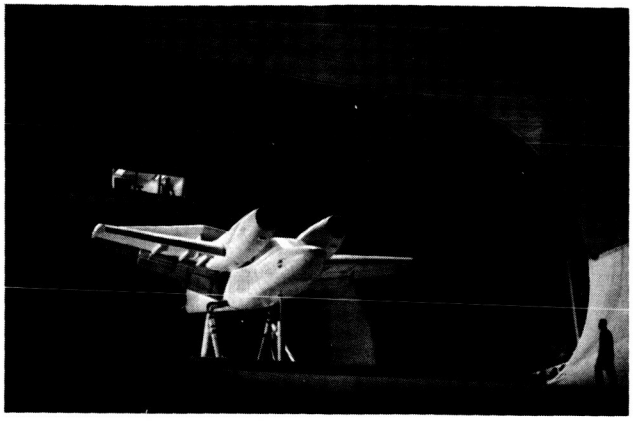
EFFECT OF FLAP LENGTH ON OTW NOISE



CS-73053

I-64

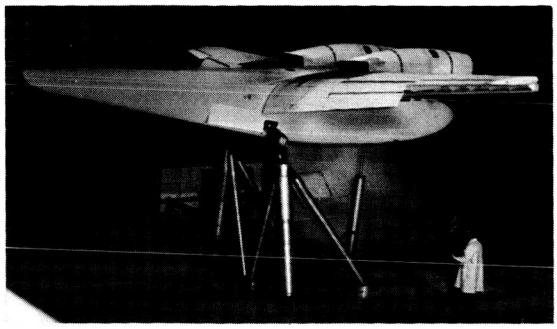
LARGE SCALE OTW CONFIGURATION AT LANGLEY



CS-73046

I-65

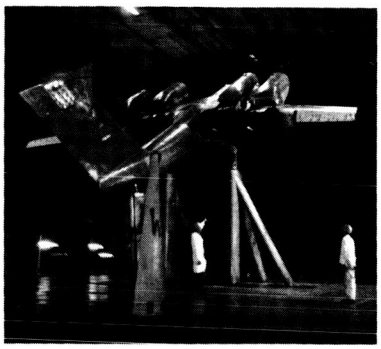
LARGE SCALE OTW CONFIGURATION AT LANGLEY



CS-73047

I-66

FOUR ENGINE OTW CONFIGURATION AT AMES



CS-73045

I-67

TECHNOLOGY AREAS

FAN NOISE

ADVANCES IN SUPPRESSION
- CONVENTIONAL ACOUSTIC TREATMENT
- HIGH MACH NO. INLETS
- WING SHIELDING

ENGINE CORE NOISE

POWERED LIFT FLAP NOISE

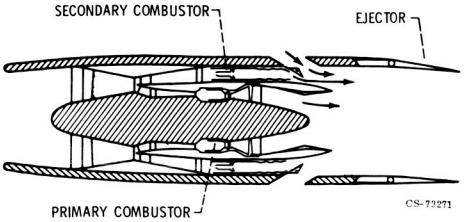
→ SUPERSONIC JET NOISE SUPPRESSION

NOISE PREDICTION

CS-73176

I-68

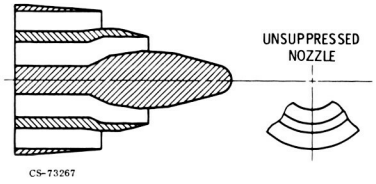
DUCT BURNING TURBOFAN (DBTF) ENGINE FOR SUPERSONIC CRUISE AIRCRAFT



CS-73271

I-69

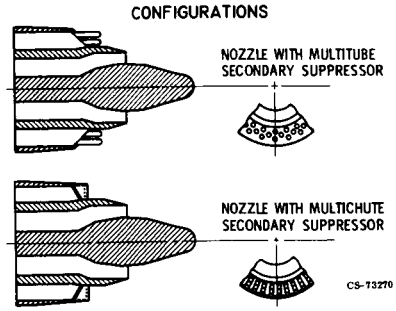
G.E. DUCT-BURNING TURBOFAN NOZZLE CONFIGURATIONS



CS-73267

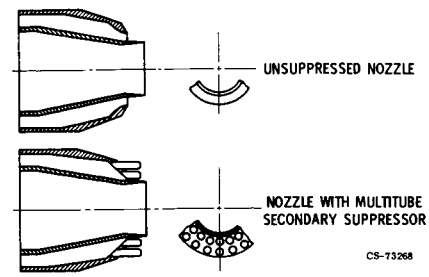
I-70

G.E. DUCT-BURNING TURBOFAN NOZZLE CONFIGURATIONS



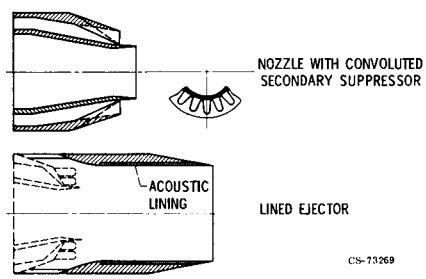
I-71

P&W DUCT-BURNING TURBOFAN NOZZLE CONFIGURATIONS



I-72

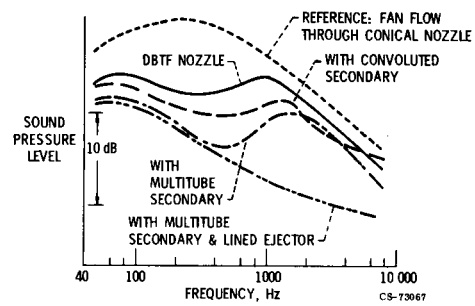
P&W DUCT-BURNING TURBOFAN NOZZLE CONFIGURATIONS



I-73

SPECTRA FOR DBTF CONFIGURATIONS

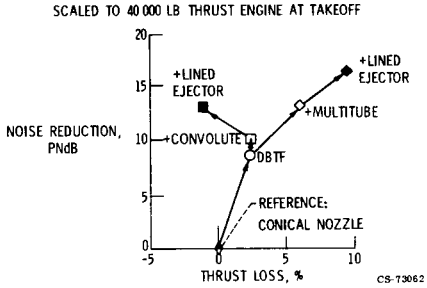
PEAK SIDELINE NOISE



I-74

STATIC PERFORMANCE OF DBTF NOZZLES

SCALED TO 40 000 LB THRUST ENGINE AT TAKEOFF



I-75

TECHNOLOGY AREAS

FAN NOISE

ADVANCES IN SUPPRESSION
- CONVENTIONAL ACOUSTIC TREATMENT
- HIGH MACH NO. INLETS
- WING SHIELDING

ENGINE CORE NOISE

POWERED LIFT FLAP NOISE

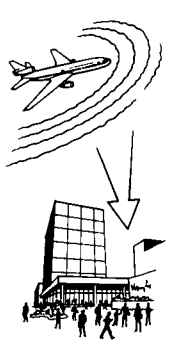
SUPERSONIC JET NOISE SUPPRESSION

→ NOISE PREDICTION

CS-73175

I-76

AIRCRAFT NOISE PREDICTION – ANOP



KEY TECHNOLOGY AREAS

SOURCE NOISE
- TURBOMACHINERY
- JET
- COMBUSTION
- FLAP
- DUCT ACOUSTICS
- AIRFRAME
- SHIELDING/REFLECTION

PATH
- ATMOSPHERIC ATTENUATION
- EXTRA GROUND ATTENUATION

RECEIVER
- HUMAN FACTORS
- COMMUNITY EXPOSURE

CS-73043

I-77

PROGRAM PLAN

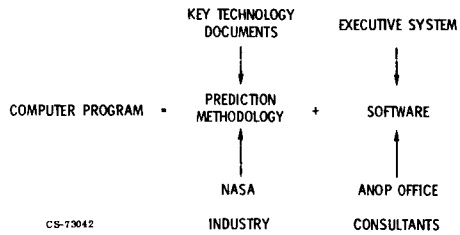
ACQUIRE & EVALUATE EXISTING PROGRAMS → INTERIM COMPUTER PROGRAM CAPABILITY

IDENTIFY CRITICAL RESEARCH NEEDS → PREPARE KEY TECHNOLOGY DOCUMENTS → ANOP COMPUTER PROGRAM

CS-73041

I-78

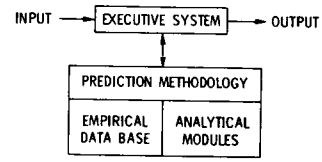
ANOP COMPUTER PROGRAM



CS-73042

I-79

ANOP COMPUTER PROGRAM STRUCTURE



CS-73039

I-80

STATUS

INTERIM COMPUTER PROGRAM CAPABILITY	EXISTS
KEY TECHNOLOGY DOCUMENTS	MOST FIRST VERSIONS COMPLETE
EXECUTIVE SYSTEM	CONTRACT IN PROCUREMENT CYCLE

CS-73040

I-81

TECHNOLOGY AREAS

FAN NOISE

ADVANCES IN SUPPRESSION
- CONVENTIONAL ACOUSTIC TREATMENT
- HIGH MACH NO. INLETS
- WING SHIELDING

ENGINE CORE NOISE

POWERED LIFT FLAP NOISE

SUPERSONIC JET NOISE SUPPRESSION

NOISE PREDICTION

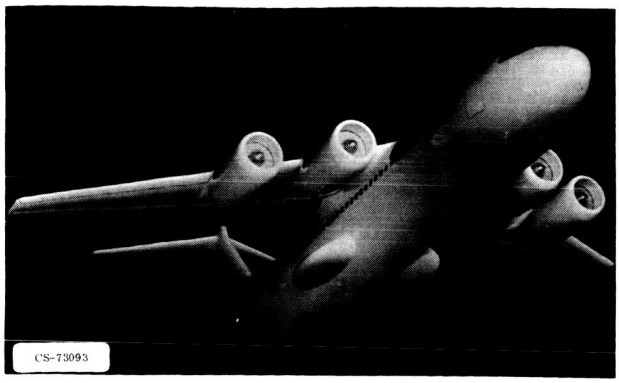
CS-73177

I-82

II. QCSEE PROGRAM

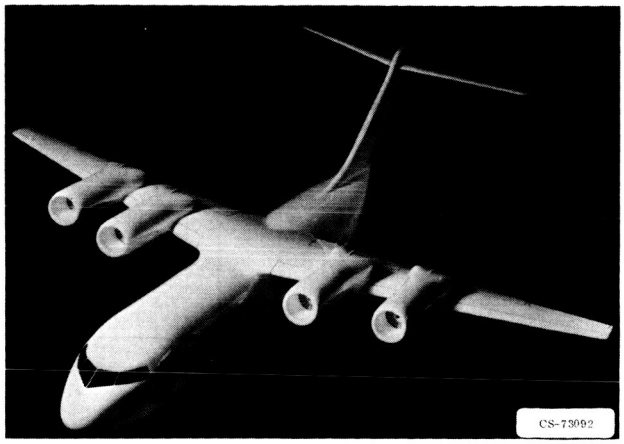
Carl C. Ciepluch

UTW SHORT-HAUL AIRCRAFT



II-1

OTW SHORT-HAUL AIRCRAFT



II-2

SHORT HAUL AIRCRAFT CHARACTERISTICS

PASSENGERS	150
AIRCRAFT TAKEOFF WEIGHT, LB	150 000
RANGE, N MI	500
FIELD LENGTH, FT	3000
CRUISE MACH NO.	0.7

CS-73083

II-3

QCSEE PROGRAM OBJECTIVES

DEVELOP SHORT-HAUL PROPULSION TECHNOLOGY
- ENVIRONMENTALLY ACCEPTABLE
- ECONOMICALLY FEASIBLE
- POWERED LIFT
- USING FULL-SCALE HARDWARE

PROVIDE GOVERNMENT WITH DATA
- CONFIRM ENVIRONMENTAL ACCEPTABILITY
- BASIS FOR RULEMAKING

PROVIDE INDUSTRY WITH DATA
- VERIFY CONCEPTS
- MINIMIZE DEVELOPMENT RISKS

CS-73081

II-4

QCSEE TECHNICAL REQUIREMENTS

NOISE, 500 FT SIDELINE	
TAKEOFF & APPROACH, EPNdB	95
REVERSE, PNdB	100
FOOTPRINT AREA, SQ MI	<0.5
POLLUTION	EPA 1979 EMISSION LEVELS
INSTALLED THRUST	
FORWARD UTW, LB	17 400
FORWARD OTW, LB	20 300
REVERSE	35% OF FORWARD THRUST
INSTALLED THRUST/WEIGHT	
UTW	4.3
OTW	4.7
DYNAMIC RESPONSE	
APPROACH TO TAKEOFF THRUST, SEC	1.0
REVERSE THRUST, SEC	1.5

CS-73086

II-5

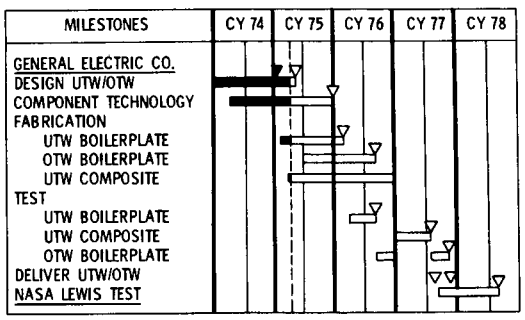
ADVANCE QCSEE TECHNOLOGY

- HIGH BYPASS RATIOS ENGINES
- VARIABLE PITCH FAN
- VARIABLE AREA FAN NOZZLE
- ADVANCED ACOUSTIC SUPPRESSION
  - HIGH MACH INLET
  - ACOUSTIC LININGS
- DIGITAL ELECTRONIC CONTROLS
- REDUCTION GEARING
- COMPOSITE COMPONENTS
  - FAN BLADES
  - FAN FRAME
  - NACELLE

CS-73477

II-6

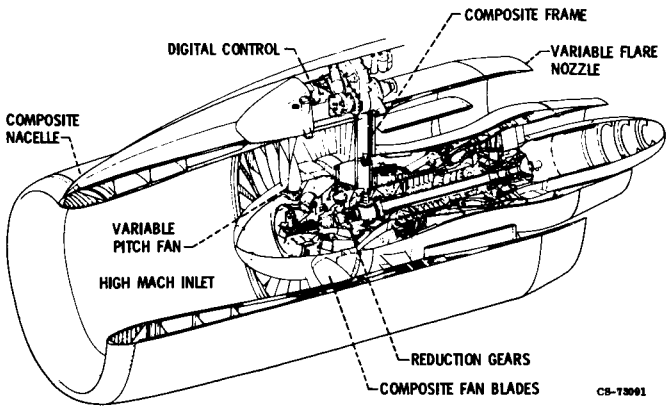
QCSEE PROJECT OVERALL SCHEDULE



CS-73087

II-7

QCSEE UTW ENGINE



CS-73091

II-8

UTW PROPULSION SYSTEM ACOUSTIC DESIGN

DESIGN POINT, TAKEOFF

NOISE SOURCES	METHOD OF REDUCTION
JET/FLAP INTERACTION	REDUCED FAN PRESSURE RATIO, 1.27
FAN NOISE	LOW FAN TIP SPEED LARGE ROTOR/STATOR SPACING BLADE/VANE RATIO ACOUSTIC SUPPRESSION
CORE NOISE	ACOUSTIC SUPPRESSION

CS-73079

II-9

UTW ENGINE CHARACTERISTICS

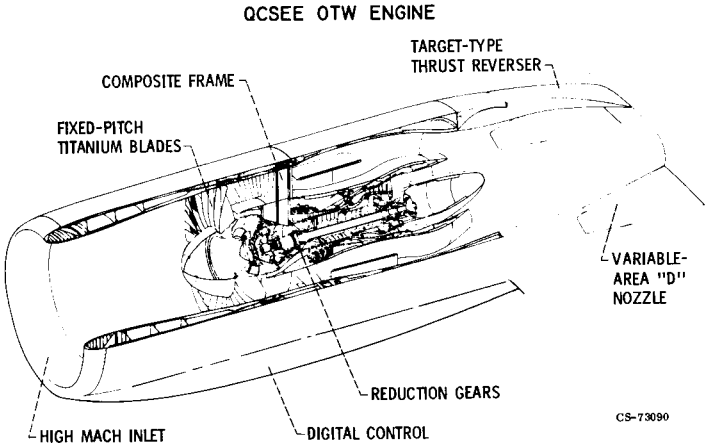
TAKEOFF

BYPASS RATIO	12.1
FAN PRESSURE RATIO	1.27
FAN TIP SPEED, FT/SEC	950
OVERALL PRESSURE RATIO	14.3
THRUST, LB	17 400

II-10

CS-73080

QCSEE OTW ENGINE



CS-73090

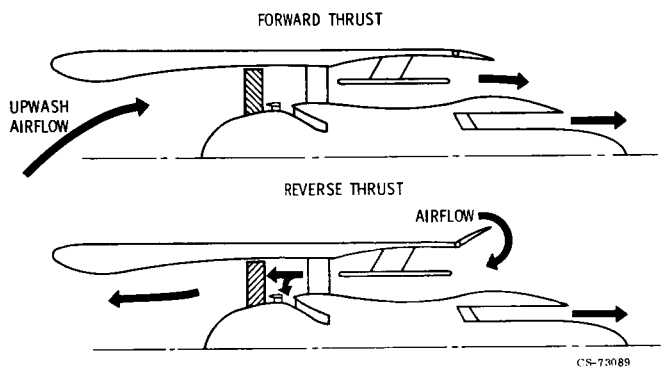
II-11

ENGINE CHARACTERISTICS
TAKEOFF

	UTW	OTW
BYPASS RATIO	12.1	10.1
FAN PRESSURE RATIO	1.27	1.34
FAN TIP SPEED, FT/SEC	950	1162
OVERALL PRESSURE RATIO	14.3	17.3
THRUST, LB	17 400	20 300

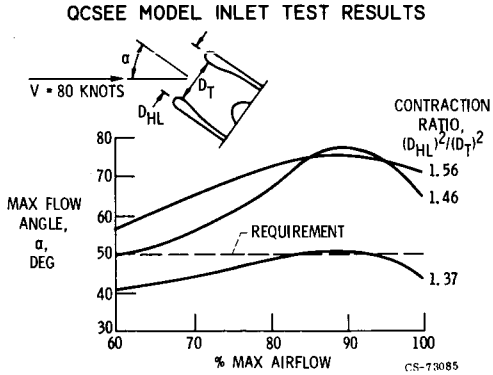
II-12 CS-73078

QCSEE UTW NACELLE AERODYNAMIC FLOWPATH



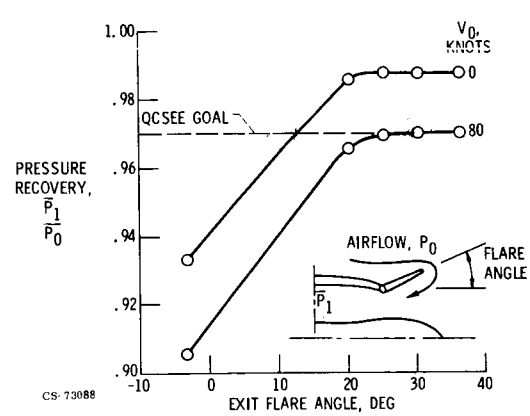
II-13

QCSEE MODEL INLET TEST RESULTS



II-14

QCSEE EXLET AERODYNAMIC PERFORMANCE



II-15

III. REFAN PROGRAM

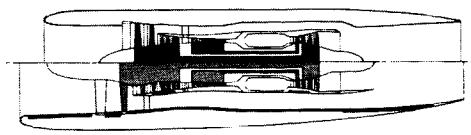
Robert W. Schroeder

REFAN CONCEPT FOR AIRCRAFT NOISE REDUCTION

REDUCE JET NOISE (TAKEOFF)

- DECREASE CORE JET VELOCITY (INCREASED TURBINE WORK)
- DECREASE FAN DUCT JET VELOCITY (REDUCED FAN PRESSURE RATIO)

BASELINE ENGINE



REFAN ENGINE

CS-72961

REDUCE FAN NOISE (LANDING APPROACH)

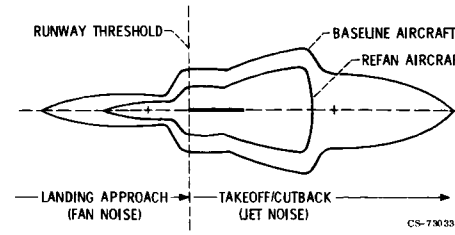
- USE SINGLE-STAGE FAN (REPLACES TWO-STAGE)
- ACOUSTICALLY-TREAT ENGINE & NACELLE

III-1

AIRCRAFT NOISE REDUCTION GOALS

SIGNIFICANT REDUCTION IN NOISE EXPOSURE CONTOUR AREA

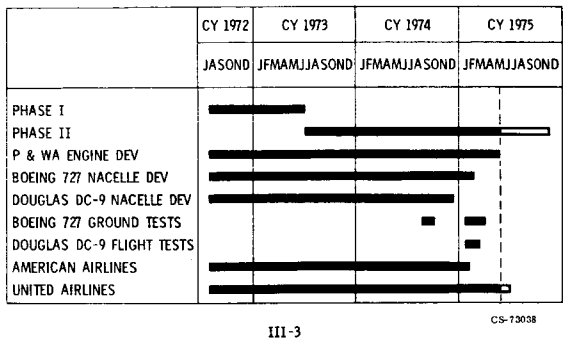
REDUCTION IN LANDING APPROACH & TAKEOFF NOISE AT FAR PART-36 MEASURING STATIONS BY ABOUT 6-10 EPNdB



CS-73033

III-2

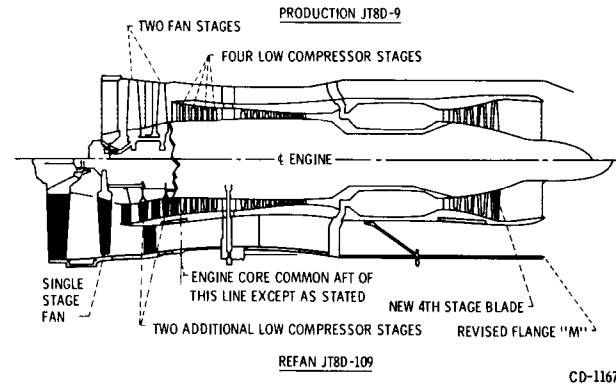
JT8D REFAN PROGRAM ELEMENTS



CS-73038

III-3

PRODUCTION AND REFAN ENGINE COMPARISON



CD-11670

CS-69528

III-4

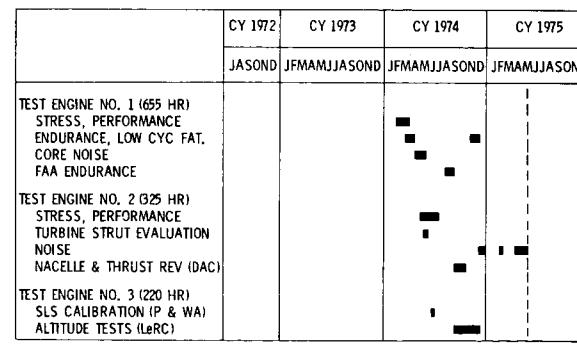
COMPARISON OF BASELINE JT8D-9 AND REFAN JT8D-109 ENGINES

	BASELINE	REFAN
THRUST, SLS, LB	14 500	16 600
FAN	2-STAGE	1-STAGE
INLET GUIDE VANES	YES	YES
FAN DIAM, IN.	40.5	49.2
INLET DIAM, IN.	42.5	54.5
LENGTH, IN.	120	134
ENGINE WEIGHT (DRY), LB	3218	3780
TOTAL AIRFLOW, SLS, LB/SEC	319	467
FAN PRESSURE RATIO	1.97	1.67
FAN TIP SPEED AT TO, FT/SEC	1420	1600
BYPASS RATIO	1.05	2.03
TURBINE INLET TEMP, °F	1766	1766
PRIMARY JET VELOCITY, FT/SEC	1766	1445
MIXED JET VELOCITY, FT/SEC	1470	1140

III-5

CS-73027

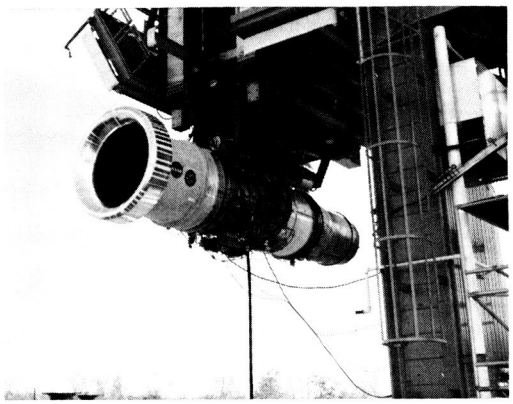
ENGINE TEST PROGRAMS (P & WA & LeRC)



CS-73037

III-6

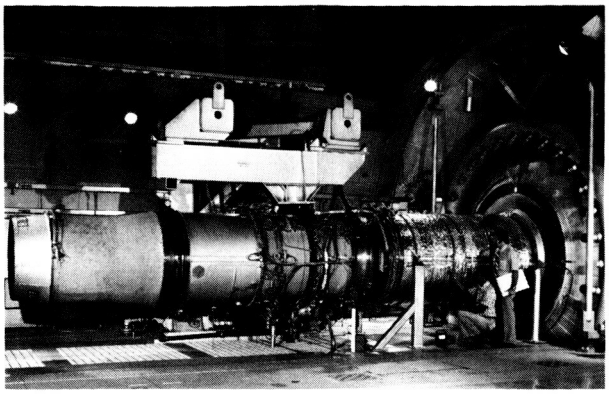
REFAN ENGINE NO. 1 AT P&WA



CS-73026

III-7

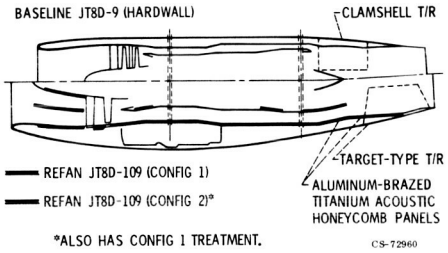
REFAN ENGINE NO. 3 IN ALTITUDE TEST FACILITY AT LeRC



C-74-3152
CS-73025

III-8

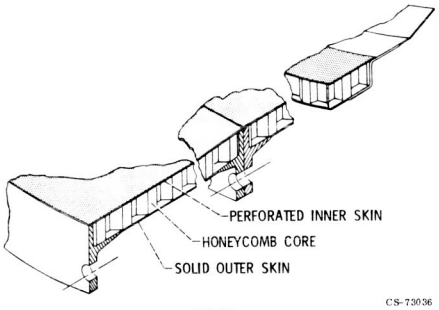
727 SIDE-ENGINE NACELLE COMPARISON



CS-72960

III-9

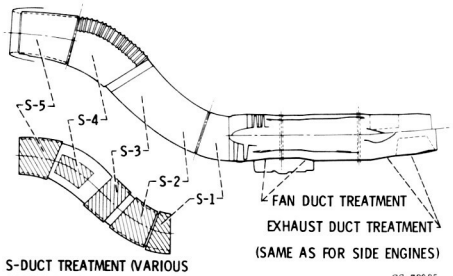
727 EXHAUST DUCT ACOUSTIC TREATMENT
ALUMINUM-BRAZED TITANIUM HONEYCOMB PANELS



CS-73036

III-10

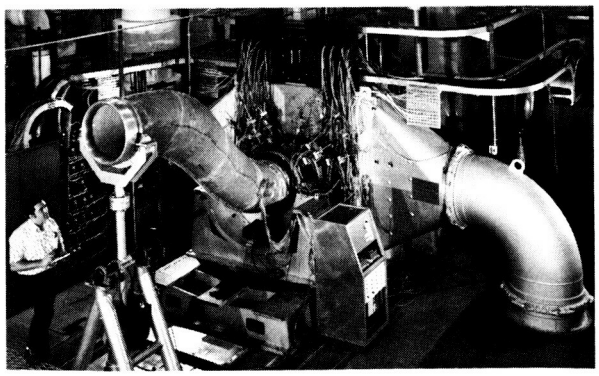
727 CENTER ENGINE & S-DUCT INLET
REFAN ACOUSTIC TREATMENT CONFIGURATION



CS-73035

III-11

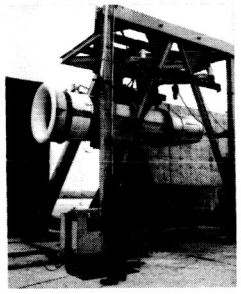
S-DUCT MODEL IN 20-INCH FAN RIG AT LeRC



C-74-2270
CS-73022

III-12

REFAN 727 SIDE-ENGINE NACELLE
AT BOARDMAN TEST SITE



CS-73023

III-13

727-200 ACOUSTIC PERFORMANCE COMPARISON
GROSS WEIGHT, 172 500 LB

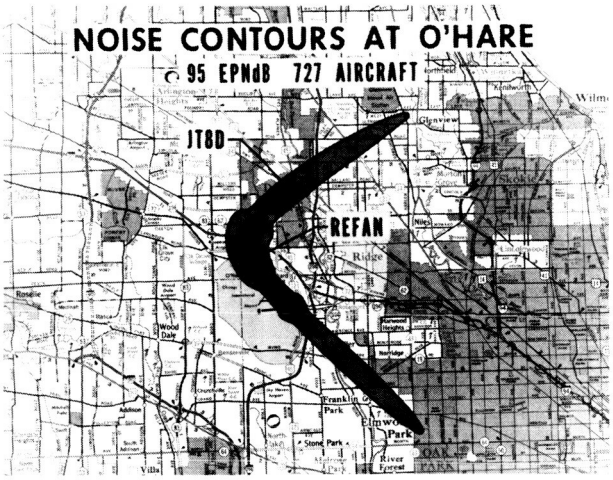
POSITION	FAR 36, EPNdB	BASELINE, EPNdB	REFAN #1, EPNdB	BASELINE -REFAN, ΔEPNdB
SIDELINE	104.4	99.9	92.8	7.1
TAKEOFF/5° FLAPS	99.0	107.4	98.9	8.5
CUTBACK	99.0	100.0	92.4	7.6
APPROACH/40° FLAPS	104.4	109.5	102.5	7.0
APPROACH/30° FLAPS	104.4	108.2	100.9	7.3

NOISE LEVEL, EPNdB	NOISE EXPOSURE CONTOUR AREA*, SQ MI		
	BASELINE	REFAN	AREA REDUCTION, %
95	9.1	3.0	67
90	27.6	7.2	74

*40° APPROACH FLAPS.

CS-73031

III-14



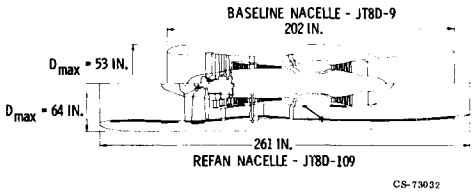
III-15

FIRST FLIGHT OF DC-9 REFAN AIRPLANE

CS-73024

III-16

DC-9 NACELLE COMPARISON



III-17

DC-9 ACOUSTIC PERFORMANCE COMPARISON

GROSS WEIGHT = 108 000 LB

POSITION	FAR 36, EPNdB	BASELINE, EPNdB	REFAN, EPNdB	BASELINE -REFAN, ΔEPNdB
SIDELINE	103.1	100	93	7
TAKEOFF	95.6	103	93	10
TAKEOFF/CUTBACK	95.6	97	87	10
APPROACH/50° FLAPS	103.1	103	97	6
APPROACH/35° FLAPS	103.1	101	96	5

90 EPNdB NOISE EXPOSURE CONTOUR AREA*, SQ MI		
BASELINE	REFAN	AREA REDUCTION, %
7.7	3.0	61

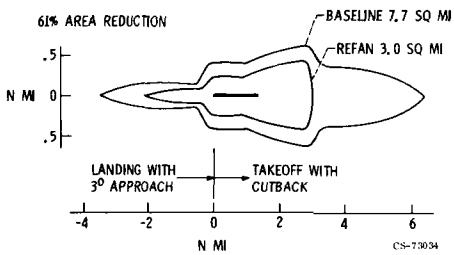
*50° APPROACH FLAPS.

CS-73030

III-18

90 EPNdB NOISE EXPOSURE CONTOURS FOR DC-9

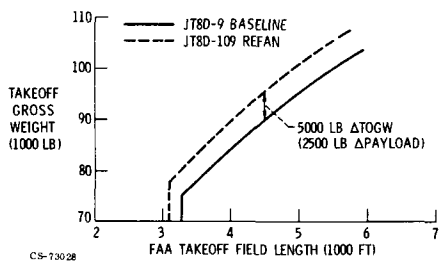
50° APPROACH FLAPS



III-19

FAA TAKEOFF FIELD LENGTH COMPARISON

DC-9 BASELINE VS REFAN



III-20

IV. COMBUSTION AND EMISSION TECHNOLOGY

Jack Grobman, Chairman
David N. Anderson
Larry A. Diehl
Richard W. Niedzwiecki

SCOPE

WHAT IS AIRCRAFT POLLUTION PROBLEM?

WHAT ARE AIRCRAFT POLLUTION STANDARDS?

WHAT IS EFFECT OF ENGINE OPERATING CONDITIONS ON AIRCRAFT POLLUTANTS?

HOW CLOSE ARE PRESENT-DAY ENGINES TO MEETING STANDARDS?

WHAT PROGRESS HAS BEEN MADE IN EMISSION REDUCTION TECHNOLOGY?

CS-73136

IV-1

AIRCRAFT ENGINE POLLUTION
LOW ALTITUDE, <3000 FT

ENGINE EMISSION	ENVIRONMENTAL EFFECT
CO	TOXIC GAS
THC (TOTAL HYDROCARBONS)	ODORS PHOTOCHEMICAL SMOG
NO_x	TOXIC GAS PHOTOCHEMICAL SMOG
SMOKE	VISIBLE PARTICLE DEPOSITION

CS-73135

IV-2

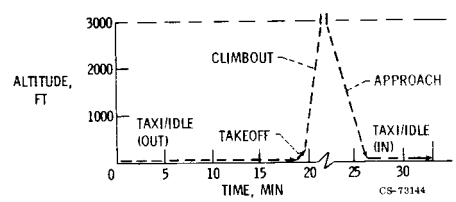
EPA ENGINE EMISSION STANDARDS

ENGINE CLASS	DEFINITION	APPLICATION
T1	TURBOFAN/TURBOJET < 8000 LB THRUST	GENERAL AVIATION
T2	TURBOFAN/TURBOJET > 8000 LB THRUST	WIDE-BODY TRANSPORT
T3	JT3D MODELS	B707, DC-8
T4	JT8D MODELS	B727, B737, DC-9
T5	SUPERSONIC CRUISE ENGINE	SUPERSONIC TRANSPORTS
P2	TURBOPROPS	GENERAL AVIATION

CS-73146

IV-3

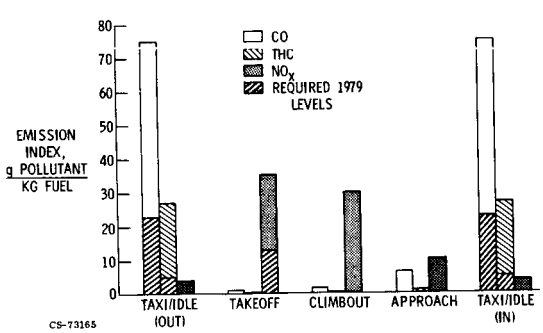
EPA LANDING–TAKEOFF CYCLE



CS-73144

IV-4

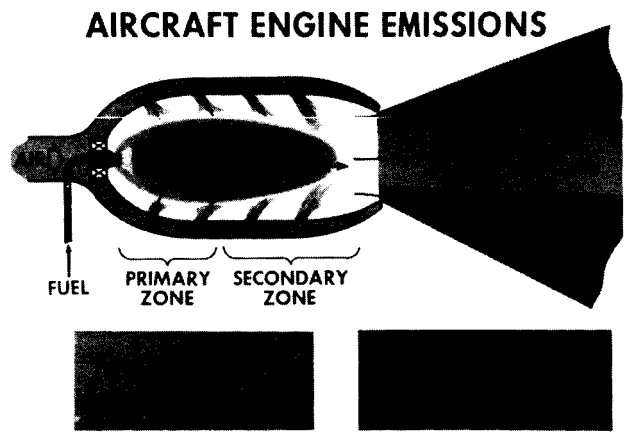
TYPICAL T2 CLASS ENGINE EMISSIONS



CS-73165

IV-5

AIRCRAFT ENGINE EMISSIONS



IV-6

IDLE POLLUTION CONSIDERATIONS

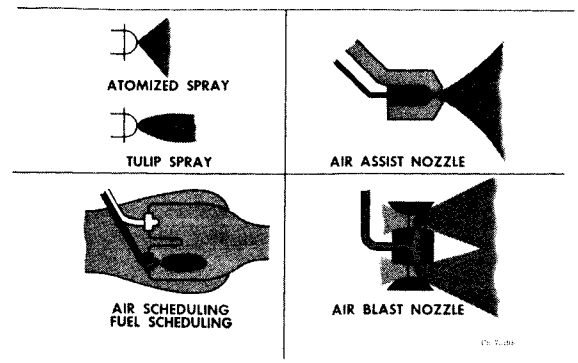
PRINCIPAL IDLE POLLUTANTS: CO & THC
PRINCIPAL CAUSES: LOW VALUES OF FUEL NOZZLE PRESSURE DROP, FUEL/AIR RATIO, COMBUSTOR INLET TEMP & PRESSURE

POLLUTION MECHANISM	CORRECTION
POOR ATOMIZATION & DISTRIBUTION	IMPROVE ATOMIZATION & DISTRIBUTION
POOR COMBUSTION STABILITY	INCREASE EQUIVALENCE RATIO TO 1
QUENCHING	INCREASE RESIDENCE TIME REDUCE VELOCITY DELAY MIXING

CS-73148

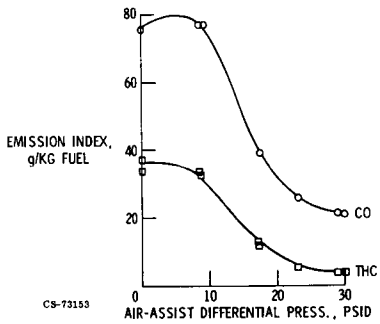
IV-7

EMISSIONS REDUCTION AT IDLE



IV-8

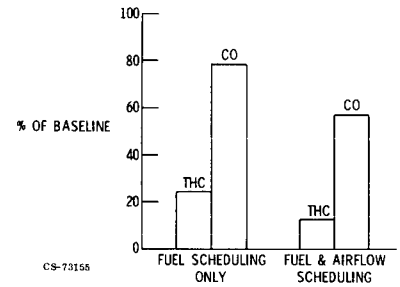
EFFECT OF IMPROVING FUEL ATOMIZATION



CS-73153

IV-9

EFFECT OF FUEL AND AIRFLOW SCHEDULING ON IDLE EMISSIONS



CS-73155

IV-10

FULL POWER POLLUTION CONSIDERATIONS

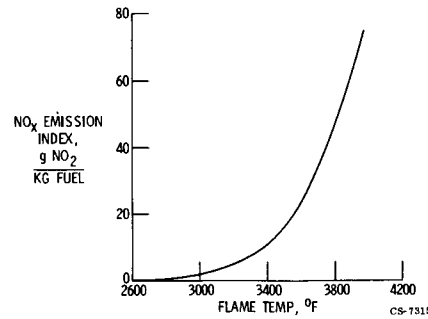
PRINCIPAL POLLUTANT: NO_x
PRINCIPAL CAUSES: HIGH VALUES OF COMBUSTOR INLET TEMP, PRESSURE, & FUEL/AIR RATIO

POLLUTION MECHANISM	CORRECTION
HIGH FLAME TEMP	LOWER FLAME TEMP BY ADDING DILUENTS (WATER) BURNING LEANER MIXTURES PREMIXING FUEL & AIR PREVAPORIZING FUEL
EXCESSIVE RESIDENCE TIME	REDUCE RESIDENCE TIME BY INCREASING VELOCITY RAPID QUENCHING

CS-73149

IV-11

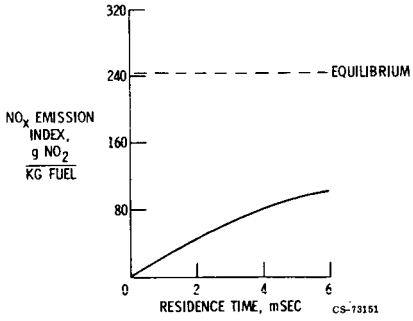
EFFECT OF FLAME TEMPERATURE ON NO_x



CS-73152

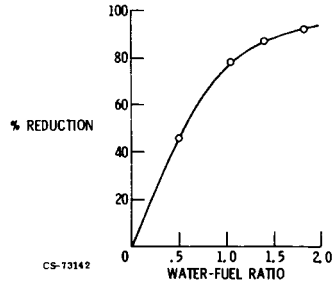
IV-12

EFFECT OF RESIDENCE TIME ON NO_x



IV-13

EFFECT OF WATER INJECTION ON NO_x



IV-14

WATER INJECTION ASSOCIATED PROBLEMS

DEMINERALIZED WATER REQUIRED

ANTIFREEZE PROTECTION

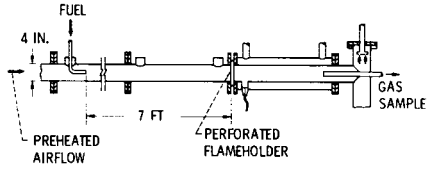
AIRPORT LOGISTICS

NOT A SOLUTION FOR CRUISE NO_x EMISSION

IV-15

CS-73520

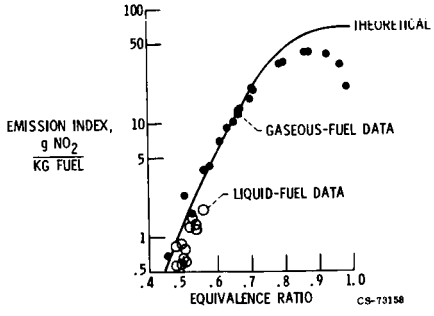
PREMIXED PRIMARY ZONE TEST SECTION



IV-16

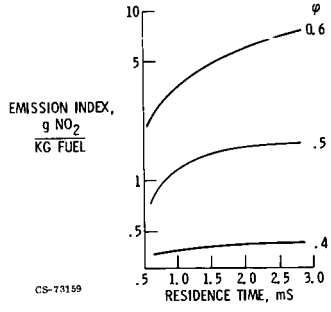
CS-73137

PREMIXED NITROGEN OXIDES EMISSIONS



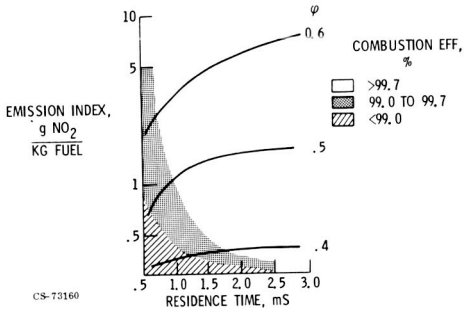
IV-17

EFFECT OF RESIDENCE TIME ON NITROGEN OXIDES EMISSIONS



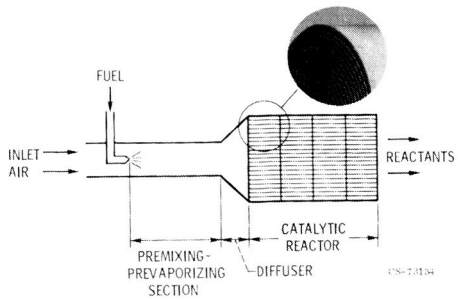
IV-18

COMBUSTION EFFICIENCY AND NO_x EMISSIONS



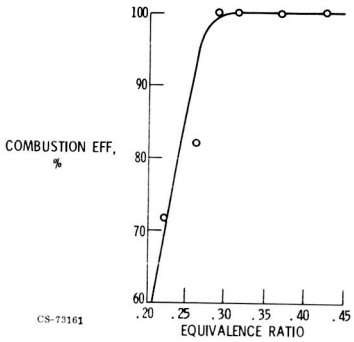
IV-19

SCHEMATIC OF CATALYTIC COMBUSTOR



IV-20

CATALYTIC REACTOR COMBUSTION EFFICIENCY



IV-21

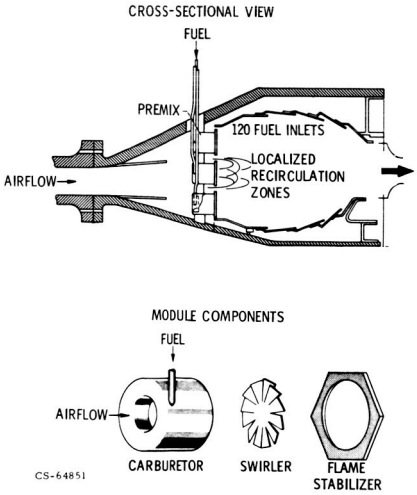
CATALYTIC COMBUSTOR DEVELOPMENTAL PROBLEMS

- OPERATING RANGE
- DURABILITY
- POISONS
- FOREIGN OBJECT DAMAGE
- COLD START
- IDLE
- FUEL PREPARATION

IV-22

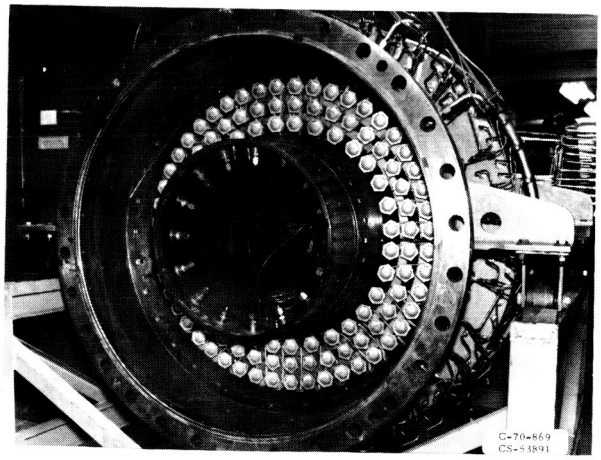
CS-73519

EXPERIMENTAL MODULAR COMBUSTOR



IV-23

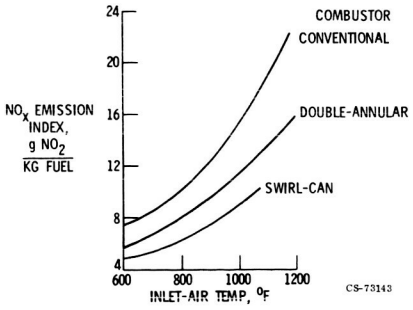
HIGH TEMPERATURE SWIRL CAN COMBUSTOR



IV-24

NO_x EMISSIONS WITH COMBUSTOR–INLET TEMPERATURE

6 ATM COMBUSTOR PRESSURE



CS-73143

IV-25

OVERALL POLLUTION CONSIDERATIONS

POLLUTANT REDUCTION APPROACH	
CO & THC	NO_x
BURN STOICHIOMETRIC MIXTURE	BURN LEAN MIXTURE
MAXIMIZE RESIDENCE TIME	MINIMIZE RESIDENCE TIME
IMPROVE FUEL ATOMIZATION & DISTRIBUTION	

CS-73138

IV-26

EMISSIONS REDUCTION TECHNOLOGY PROGRAMS

OBJECTIVES

- TO INVESTIGATE & DEVELOP NEW COMBUSTOR CONCEPTS WITH POTENTIAL FOR SIGNIFICANTLY LOWER EMISSION LEVELS
- TO DEMONSTRATE THE EMISSIONS REDUCTION BY ENGINE TEST

PROGRAM PLAN

- CONTRACTED PROGRAM
- MULTIPHASE PROGRAM
- PHASE I - SCREENING
- PHASE II - REFINEMENT
- PHASE III - ENGINE DEMONSTRATION

CS-73140

IV-27

EMISSIONS REDUCTION TECHNOLOGY PROGRAMS

ENGINE CLASS	ENGINE DEMONSTRATION	STATUS
T1	AIRESEARCH TFE 731	PHASE I INITIATED
T2	GENERAL ELECTRIC CF6-50 PRATT & WHITNEY JT9D-7	PHASE I COMPLETE, PHASE II INITIATED
T4	PRATT & WHITNEY JT8D-17	PHASE I INITIATED
P2	ALLISON 501D22	PHASE I INITIATED

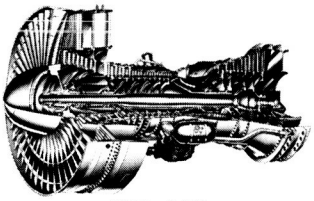
IV-28

CS-73145

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM

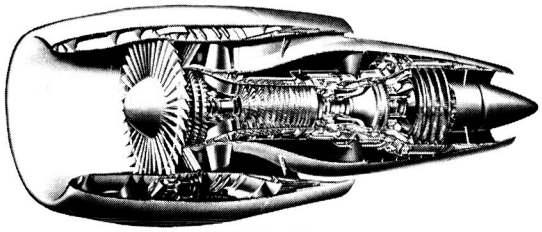
T-2 CLASS ENGINE

THRUST - 43 500 LB MAX
PRESSURE RATIO - 22:1



JT9D P&W

THRUST - 50 000 LB MAX
PRESSURE RATIO - 30:1



CF6-50 G.E.

CS-73592

IV - 29

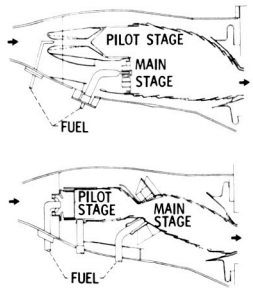
POLLUTION GOALS
T-2 CLASS ENGINES

POLLUTANT	ENGINE MODE	1979 REQD VALUE	JT9D-7 ENGINE CURRENT VALUE	CF6-50 ENGINE CURRENT VALUE
NO_x, g/KG	TAKEOFF	13	32	36
CO, g/KG	IDLE	22.5	75	67
THC, g/KG	IDLE	4.5	27	27
SMOKE, SAE NO.	TAKEOFF	<25	12	15

CS-73147

IV-30

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM
JT9D ENGINE



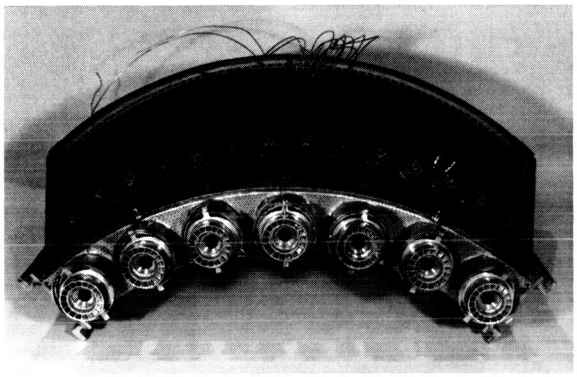
HYBRID COMBUSTOR

VORBIX COMBUSTOR

CS-73150

IV-31

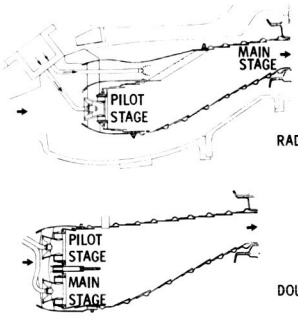
VORBIX COMBUSTOR



CS-73117

IV-32

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM
CF 6-50 ENGINE



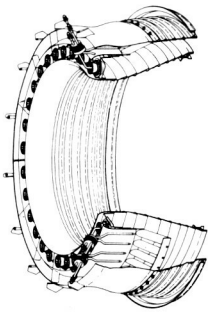
RADIAL/AXIAL STAGED COMBUSTOR

DOUBLE ANNULAR COMBUSTOR

CS-73157

IV-33

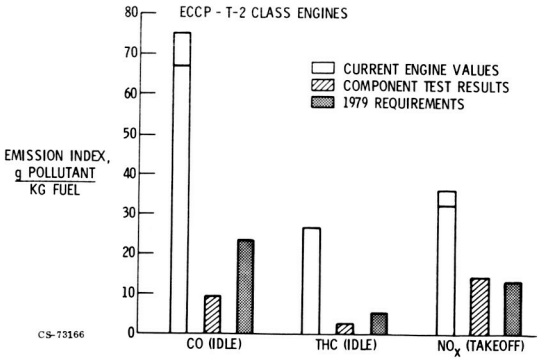
RADIAL/AXIAL STAGED COMBUSTOR



CS-73141

IV-34

POLLUTION REDUCTION STATUS



CS-73166

IV-35

TECHNOLOGY CHALLENGES FOR PHASE II -
CURRENT EFFORT
T-2 CLASS ENGINES

POLLUTION:
- ADDITIONAL IDLE & TAKEOFF REDUCTIONS
- FUEL STAGING AT PART POWER
- EPA CYCLE DATA

PERFORMANCE:
- EXIT TEMP
- ALTITUDE RELIGHT
- DURABILITY

DESIGN:
- SIMULATED ENGINE FUEL CONTROL SYSTEM

CS-73517

IV-36

TECHNOLOGY CHALLENGES FOR PHASE III -
FUTURE EFFORT
ENGINE TESTS

DESIGN:
- COMBUSTOR/ENGINE INTERFACE

POLLUTION:
- AUTHENTICATE POLLUTION REDUCTIONS FOR EPA CYCLE
- INVESTIGATE SAMPLING TECHNIQUES

PERFORMANCE:
- ACCELERATION/DECELERATION CHARACTERISTICS
- FUEL STAGING THRUST TRANSIENTS

POLLUTION & PERFORMANCE:
- DETERMINE TRADEOFFS

IV-37

CS-73518

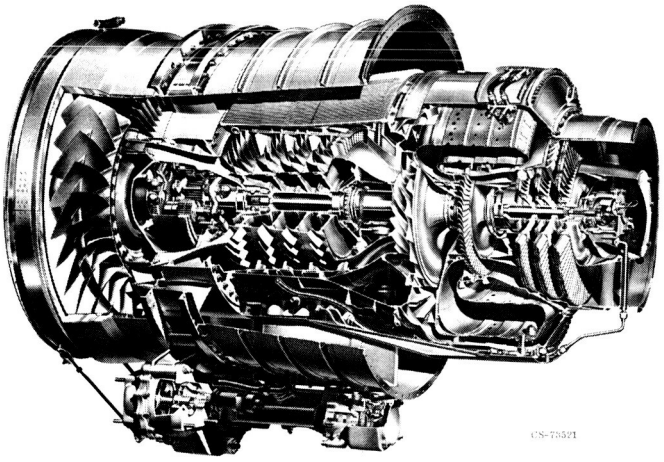
EXHAUST EMISSION POLLUTION REDUCTION
PROGRAM GOALS
T4, T1, & P2 CLASS ENGINES

PHASE III ENGINE	THC, g/KG (IDLE)		CO, g/KG (IDLE)		NO_x, g/KG (TAKEOFF)		SMOKE, SAE (TAKEOFF)	
	PRES.	1979 REQD	PRES.	1979 REQD	PRES.	1979 REQD	PRES.	1979 REQD
JT8D-17	8	2.1	35	12.2	27	5	25-30	<25
TFE731	23	5	62	25	21	12	32-44	40
501D22	13	6	27	33	10	16	55	29

CS-73164

IV-38

TFE-731 COMBUSTOR

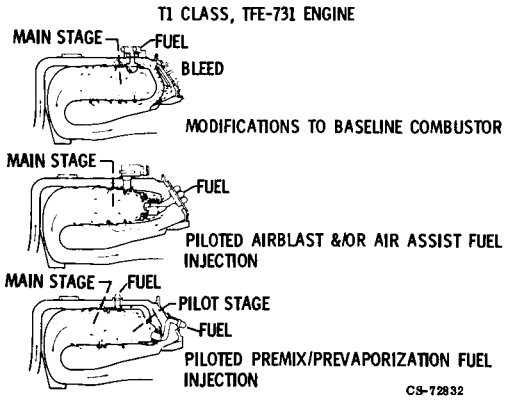


CS-73521

IV-39

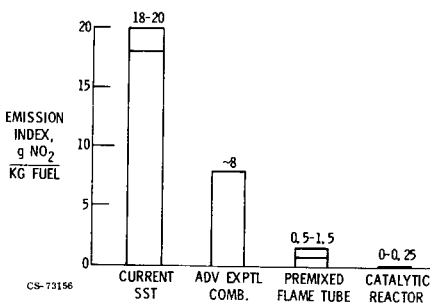
POLLUTION REDUCTION TECHNOLOGY PROGRAM

T1 CLASS, TFE-731 ENGINE



IV-40

ALTITUDE CRUISE NO_x REDUCTION



IV-41

ASSESSMENT OF EMISSIONS REDUCTION TECHNOLOGY

TECHNIQUES		REQD ENGINE MODIFICATION
LOW POWER:		
FUEL PREPARATION	AIR-ASSIST	MODERATE
	AIR-BLAST	MODERATE
	FUEL SCHEDULING	MODERATE
FULL POWER:		
WATER INJECTION		MODERATE
LEANER FUEL-AIR MIXTURES	MODULAR	MAJOR
	PREMIX-PREVAPOR.	VERY MAJOR
CATALYTIC REACTOR		EXTREME
ALL POWER LEVELS:		
MULTIPLE BURNING ZONES		MAJOR
VARIABLE GEOMETRY		VERY MAJOR

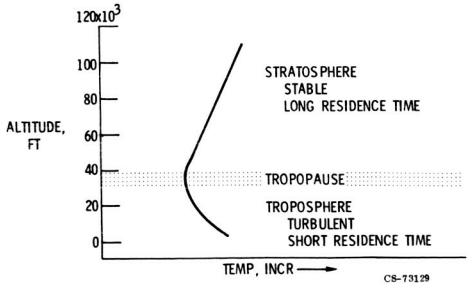
CS-72976

IV-42

V. UPPER ATMOSPHERE POLLUTION MEASUREMENTS (GASP)

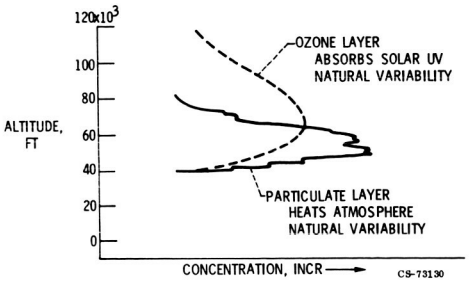
Richard A. Rudey

PROPERTIES OF EARTH'S ATMOSPHERE



V-1a

PROPERTIES OF EARTH'S ATMOSPHERE



V-1b

UPPER ATMOSPHERE EMISSIONS

ENGINE EFFLUENT	POTENTIAL ENVIRONMENTAL EFFECT
NO_x	REDUCTION IN OZONE
SO_2	INCREASE IN SULFATES
WATER VAPOR	INCREASE IN CLOUDS
PARTICULATES	INCREASE IN PARTICLES

CS-73128

V-2

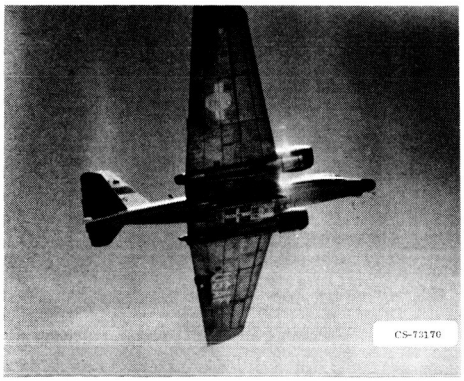
U2 AIRCRAFT USED FOR ATMOSPHERIC AIR QUALITY MEASUREMENTS

AMES RESEARCH CENTER

V-3a

WB-57F AIRCRAFT USED FOR ATMOSPHERIC AIR QUALITY MEASUREMENTS

JOHNSON SPACE CENTER



V-3b

GLOBAL ATMOSPHERIC SAMPLING PROGRAM (GASP)

OBJECTIVES

- OBTAIN UPPER ATMOSPHERE BASELINE DATA
- ASSESS POTENTIAL ADVERSE EFFECTS OF EXHAUST EMISSIONS

APPROACH

- INSTALL & OPERATE AUTOMATED INSTRUMENT SYSTEMS ON COMMERCIAL 747 AIRCRAFT
- ACQUIRE GLOBAL AIR QUALITY DATA DURING ROUTINE AIRLINE OPERATION
- DOCUMENT & ANALYZE DATA FOR A PERIOD OF 5 TO 10 YR

CS-73127

V-4

GASP MEASUREMENTS

PARTICULATES	GASES
NUMBER DENSITY	OZONE
SIZE DISTRIBUTION	WATER VAPOR
MASS CONCENTRATION	OXIDES OF NITROGEN
CHEMICAL COMPOSITION	CARBON MONOXIDE
SULFATES	CARBON DIOXIDE
NITRATES	CHLOROFLUOROMETHANES
CARBON	

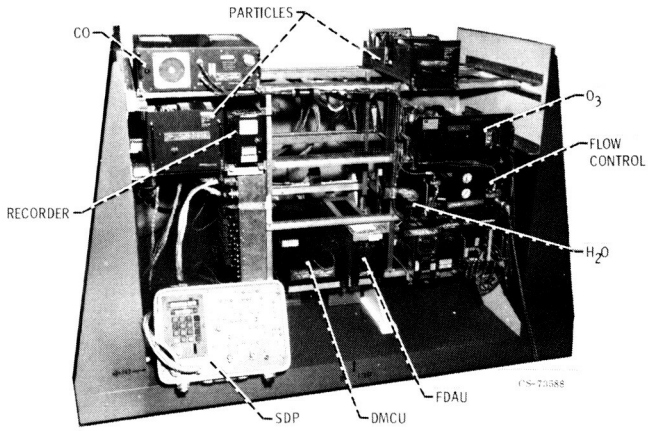
RELATED INFORMATION

GEOGRAPHICAL LOCATION
METEOROLOGICAL CONDITIONS
AIRCRAFT OPERATING CONDITIONS

CS-73126

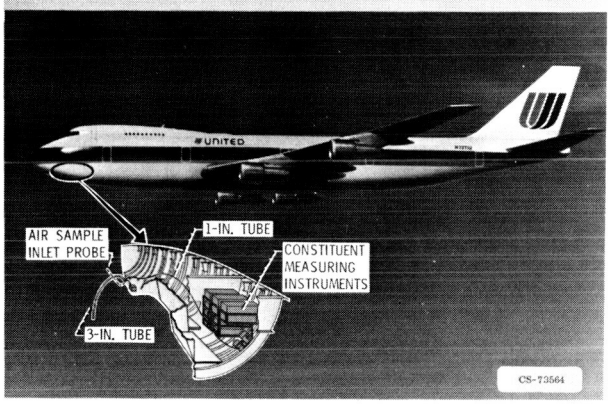
V-5

GASP CONSTITUENT MEASURING SYSTEM



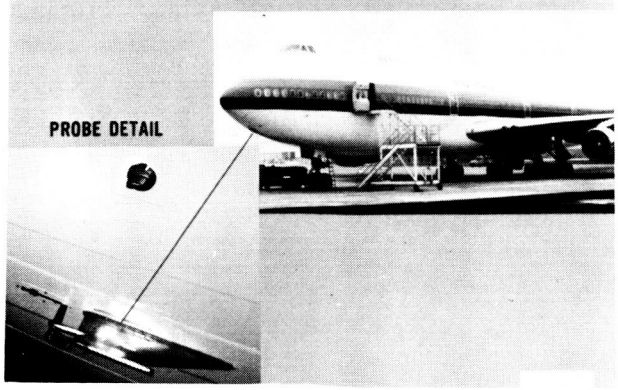
V-6

GASP SYSTEM INSTALLATION



V-7a

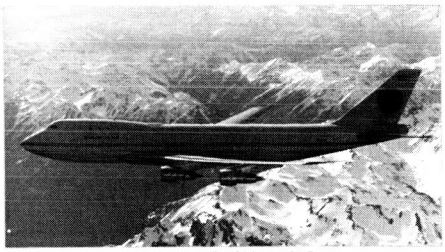
FIRST OPERATIONAL GASP AIRCRAFT ROLLOUT AT UNITED AIRLINES (DEC 10, 1974)



V-7b

GASP PARTICIPATING AIRLINES

IN SERVICE, DEC 1974



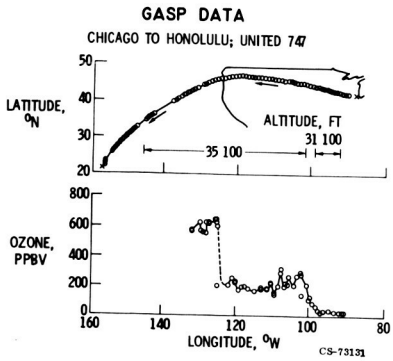
IN SERVICE, MAR 1975

INSTALLATION, LATE 1975

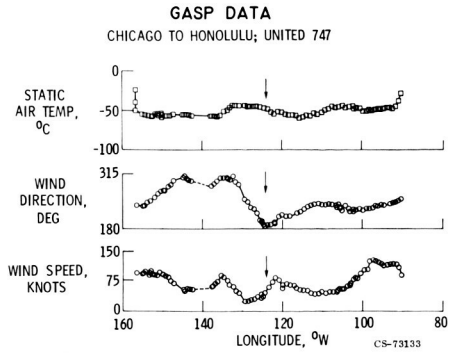
CS-75563

GASP ROUTE STRUCTURE

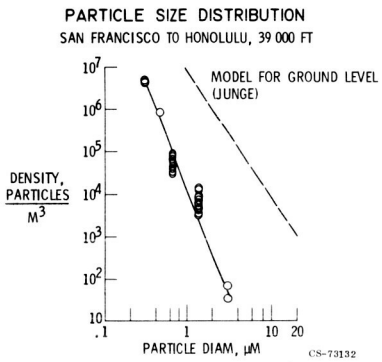
CS-75565



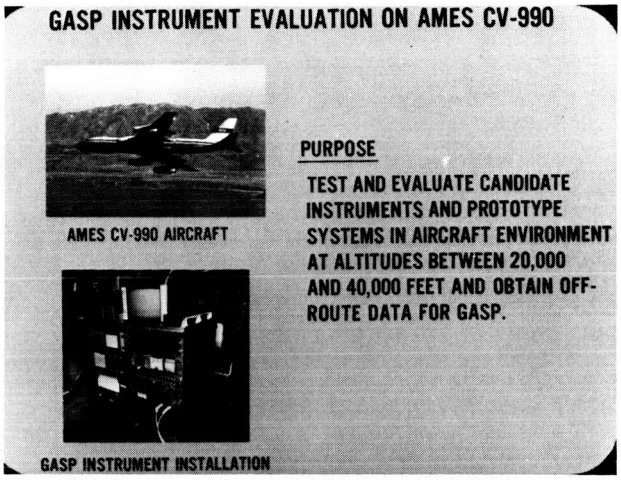
V-10a



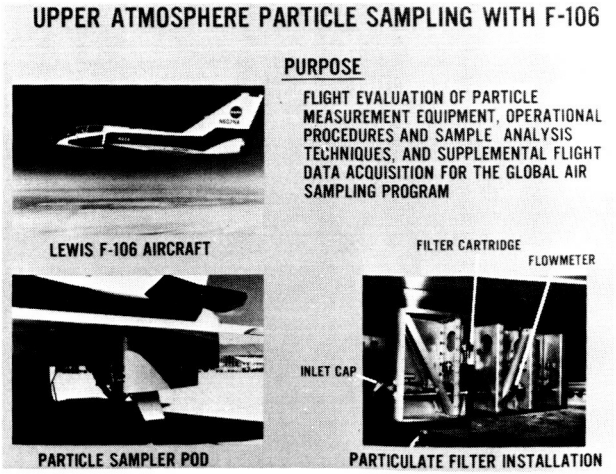
V-10b



V-11

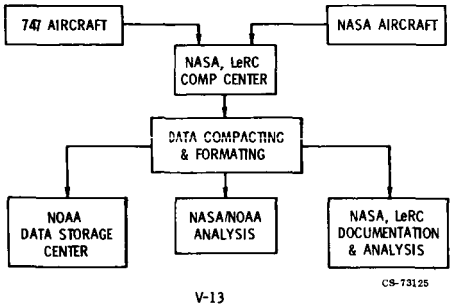


V-12a



V-12b

GASP DATA FLOW CHART



CS-73125

V-13

IMPACT OF AIRCRAFT EMISSIONS IN UPPER ATMOSPHERE IS UNCERTAIN

GLOBAL DATA BANK OF UPPER ATMOSPHERE DATA IS NEEDED

LEWIS GASP WILL PROVIDE SIGNIFICANT INPUT

AEROSPACE INDUSTRY INTEREST & ASSISTANCE INVALUABLE

V-14

CS-73124

VI. FUEL-CONSERVATIVE ENGINE TECHNOLOGY

James F. Dugan, Jr., Chairman
John E. McAulay
Thaine W. Reynolds
William C. Strack

FUEL CONSERVATION

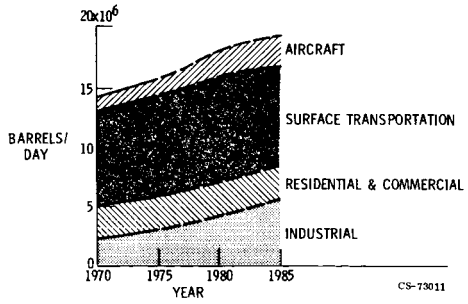
PROBLEM
- DWINDLING OIL SUPPLY
- RISING COST OF FUEL

SOLUTIONS
- INCREASE FUEL SUPPLY
- USE FUEL MORE EFFICIENTLY

CS-73005

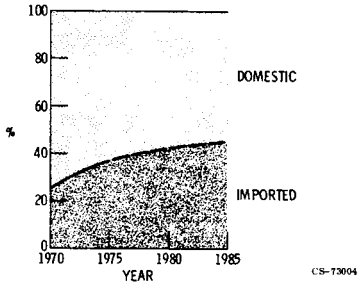
VI-1

OIL USAGE



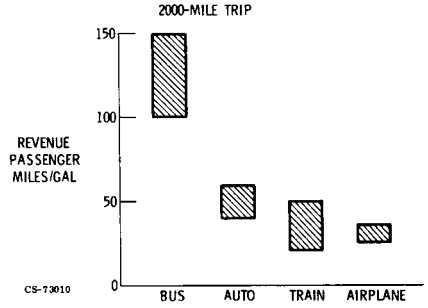
VI-2

OIL SUPPLY



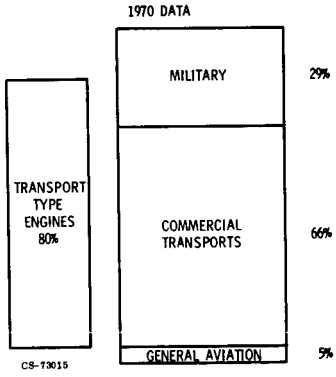
VI-3

ARE AIRCRAFT INEFFICIENT?



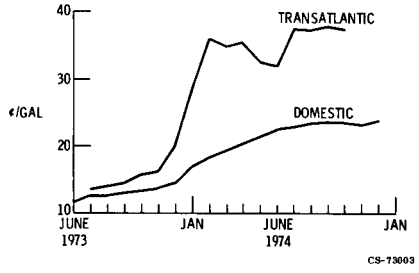
VI-4

WHICH AIRCRAFT USE THE FUEL?



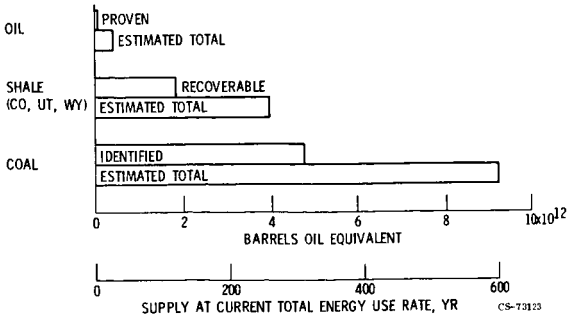
VI-5

U.S. AIRLINE AVERAGE FUEL PRICES



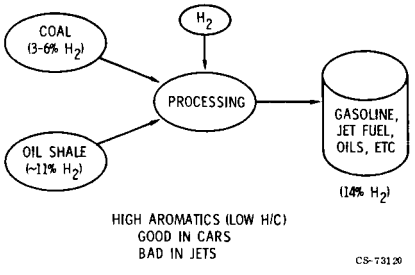
VI-6

COMPARISON OF U.S. RESOURCES



VI-7

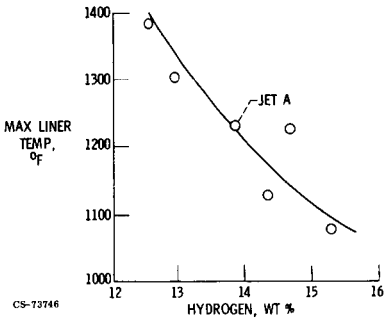
HYDROGEN REQUIREMENT FOR PROCESSING



VI-8

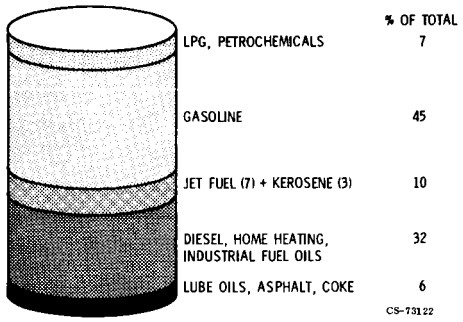
EFFECT OF HYDROGEN CONTENT OF FUEL

JT8D COMBUSTOR; SIMULATED CRUISE CONDITIONS



VI-9

DISTRIBUTION OF PETROLEUM TO FINISHED PRODUCTS



VI-10

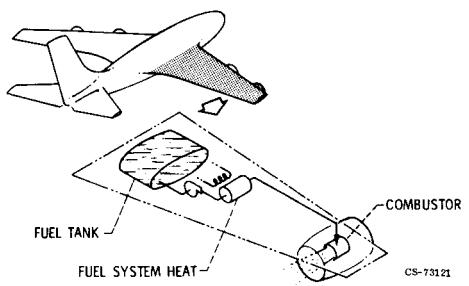
ALTERNATE FUELS EVALUATION PROGRAM

- PERFORMANCE EVALUATION
  - VOLATILITY
  - H/C RATIO
  - FREEZING POINT
- COMPONENT TECHNOLOGY DEVELOPMENT
  - COMBUSTORS
  - FUEL SYSTEMS
  - MATERIALS
- CHARACTERIZATION & PROCESSING
  - PHYSICAL PROPERTIES
  - CHEMICAL ANALYSES
  - THERMAL STABILITY

CS-73119

VI-11

COMPONENT DEVELOPMENT AREAS



VI-12

USE FUEL MORE EFFICIENTLY

CURRENT ENGINES

- RESTORE LOST PERFORMANCE
- USE ADVANCED TECHNOLOGY IN DERIVATIVE ENGINES

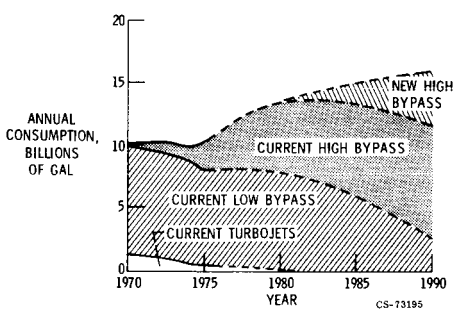
FUTURE ENGINES

- THIRD GENERATION TURBOFAN
- UNCONVENTIONAL ENGINES

CS-73006

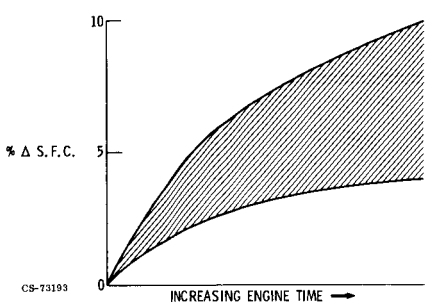
VI-13

U.S. AIRLINE FUEL CONSUMPTION BY ENGINE TYPE



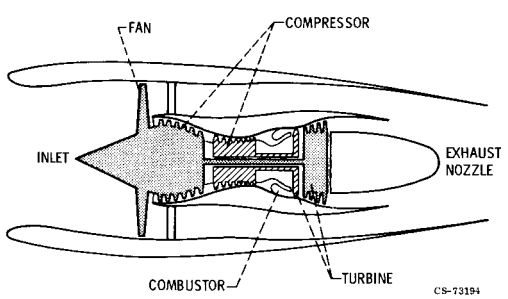
VI-14

ENGINE PERFORMANCE DETERIORATION



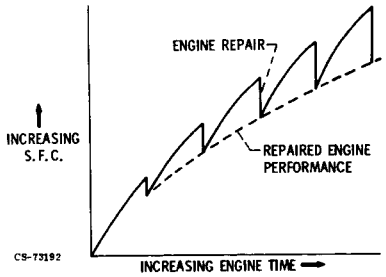
VI-15

MODERN TURBOFAN ENGINE



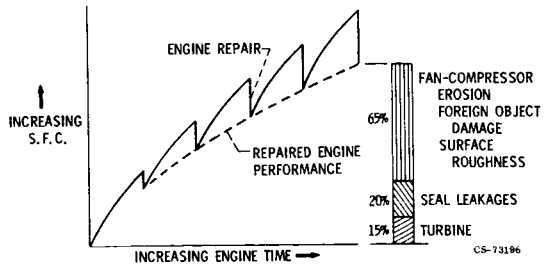
VI-16

PERFORMANCE DETERIORATION



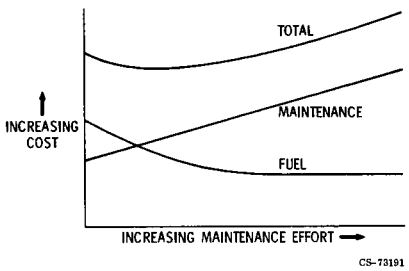
VI-17

PERFORMANCE DETERIORATION CAUSES



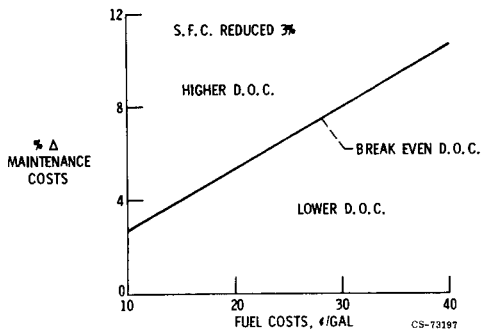
VI-18

FUEL–MAINTENANCE TRADE–OFF



VI-19

FUEL–MAINTENANCE TRADE–OFF



VI-20

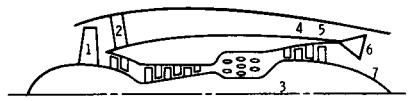
DERIVATIVE ENGINES
MODERN HIGH BPR TURBOFAN

DESIGN CHANGE	ΔFUEL, %	ΔDOC, %
IMPROVED FAN AERO	-0.28	-0.11
COMPOSITE BLADES	-.60	-.53
COMPOSITE FRAME	-.17	-.19
HYDRODYNAMIC SEALS	-.50	+.10
ADV HPT BLADE MATERIAL	-.62	+.13
ADV SHROUD MATERIAL	-.19	-.08
HPT CLEARANCE CONTROL	-.45	-.16
MIXED FLOW COMPOSITE NACELLE	-3.9	-1.47

CS-73718

VI-21

FUEL SAVINGS OF DERIVATIVE ENGINES

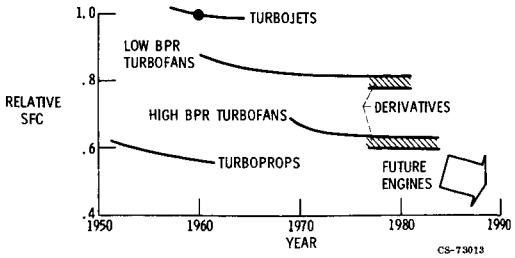


	MODIFICATION	MAX ΔSFC, %
1-5	AERODYNAMICS, SEALS, CLEARANCES	4
6	MIXED EXHAUST OR	3
7	NOZZLE REDESIGN & REMOVE PRIMARY REVERSER	2

CS-73008

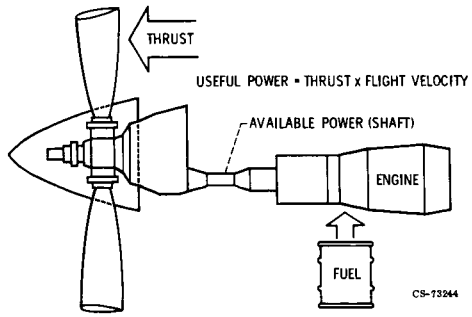
VI-22

TRENDS IN AIRCRAFT ENGINE FUEL CONSUMPTION



VI-23

FROM FUEL TO USEFUL POWER



VI-24

OVERALL POWERPLANT EFFICIENCY (η_{OA})

$$\eta_{OA} = \left(\frac{\text{AVAILABLE POWER}}{\text{FUEL POWER}}\right) \times \left(\frac{\text{USEFUL POWER}}{\text{AVAILABLE POWER}}\right)$$

= (THERMAL EFFICIENCY) x (PROPULSIVE EFFICIENCY)

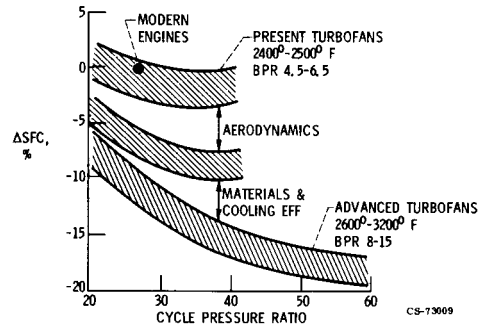
IMPROVE COMPONENTS
RAISE CYCLE TEMP
RAISE CYCLE PRESSURE RATIO
USE REGENERATOR

REDUCE JET VELOCITY
1. HIGH BPR TURBOFANS
2. LOW F.P.R.
3. TURBOPROPS

CS-73012

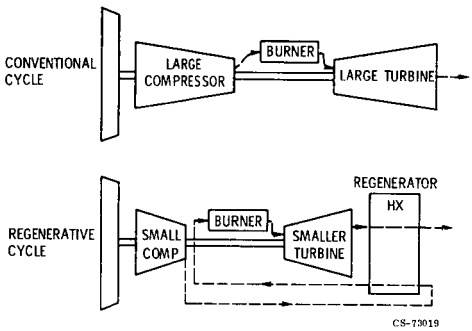
VI-25

ADVANCED TECHNOLOGY BENEFITS FOR TURBOFANS



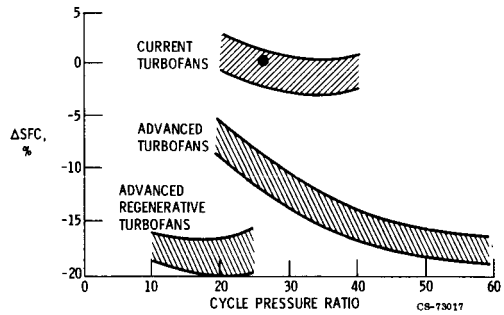
VI-26

REGENERATIVE CYCLE HAS SMALLER COMPRESSOR AND TURBINE



VI-27

REGENERATIVE TURBOFANS NEED LOWER CYCLE PRESSURE RATIO



VI-28

OVERALL POWERPLANT EFFICIENCY (η_{OA})

$$\eta_{OA} = \left(\frac{\text{AVAILABLE POWER}}{\text{FUEL POWER}}\right) \times \left(\frac{\text{USEFUL POWER}}{\text{AVAILABLE POWER}}\right)$$

= (THERMAL EFFICIENCY) x (PROPULSIVE EFFICIENCY)

IMPROVE COMPONENTS
RAISE CYCLE TEMP
RAISE CYCLE PRESSURE RATIO
USE REGENERATOR

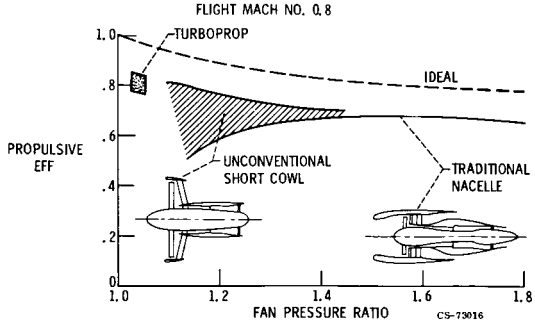
REDUCE JET VELOCITY
1. HIGH BPR TURBOFANS
2. LOW F.P.R.
3. TURBOPROPS

CS-73012

VI-29

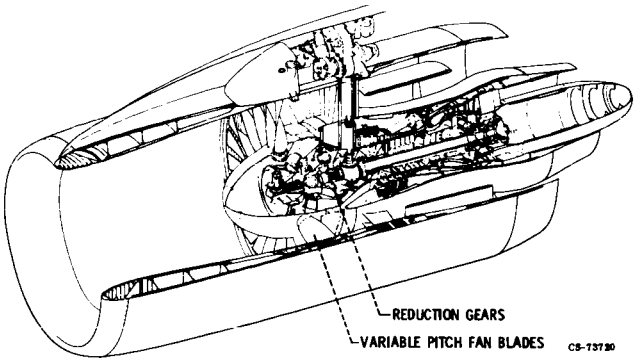
THE POTENTIAL OF LOW FAN PRESSURE RATIOS

FLIGHT MACH NO. 0.8



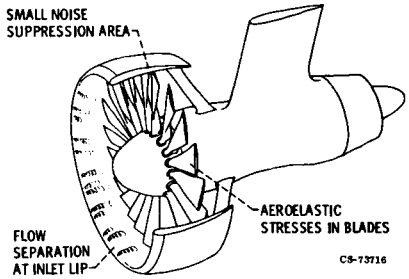
VI-30

QCSEE UTW ENGINE



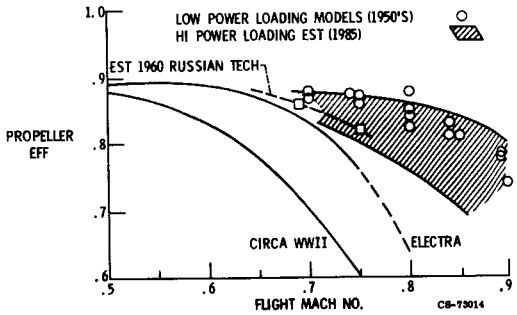
VI-31

SHORT COWL TURBOFAN



VI-32

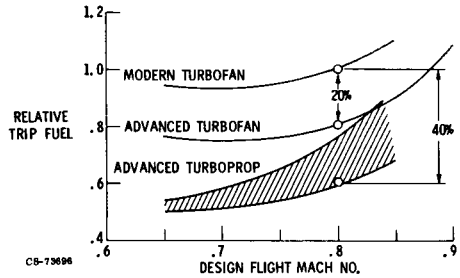
PROPELLER EFFICIENCY TRENDS



VI-33

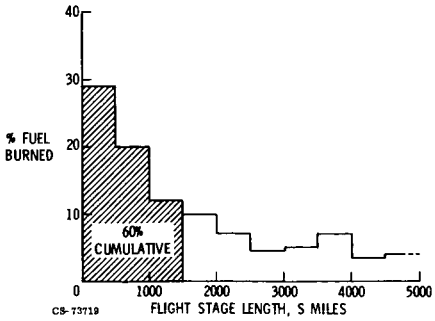
POTENTIAL FUEL SAVINGS OF FUTURE AIRCRAFT POWERPLANTS

200 PASSENGER AIRLINER, 3000 N MI RANGE, 36 000 FT ALTITUDE



VI-34

WORLD JET FUEL CONSUMPTION



VI-35

FUEL REDUCTION POTENTIAL

CURRENT ENGINES	
RESTORE LOST PERFORMANCE	3%
USE ADVANCED TECHNOLOGY IN DERIVATIVE ENGINES	5%
FUTURE ENGINES	
THIRD GENERATION TURBOFAN	10 TO 20%
UNCONVENTIONAL ENGINES	20 TO 40%

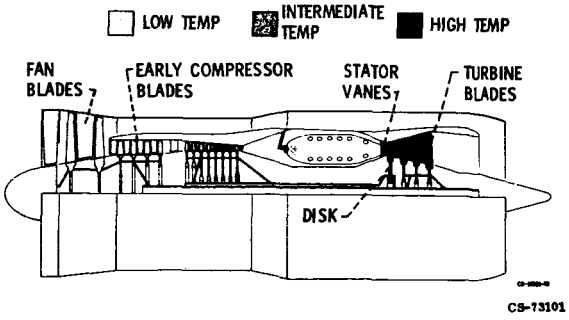
CS-73007

VI-36

VII. COMPOSITES FOR FANS AND COMPRESSORS

Tito T. Serafini

SCHEMATIC DIAGRAM OF TURBOFAN ENGINE



VII-1

BENEFITS FROM COMPOSITE MATERIALS

COMPONENTS	MATERIALS	BENEFITS
FAN BLADES	RESIN MATRIX METAL MATRIX	REDUCED ENGINE WT REDUCED FUEL CONSUMPTION REDUCED OPERATING COSTS INCREASED RETURN ON INVESTMENT
FAN FRAME	RESIN MATRIX	
FAN CONTAINMENT RING	RESIN MATRIX	

CS-73467

VII-2

BENEFITS FROM COMPOSITE MATERIALS

WEIGHT SAVINGS
- 24 TO 30% (FAN ROTOR ASSEMBLY)
- 24 TO 46% (FAN FRAME)

FUEL SAVINGS
- 1.91 TO 3.53%
- (80 TO 120 MILLION GAL/YR)

REDUCED OPERATING COSTS
- 2.82 TO 4.64%
- (55 TO 95 MILLION $/YR)

CS-73458

VII-3

MAJOR THRUSTS OF COMPOSITES RESEARCH

IMPROVED MATERIALS & FABRICATION METHODS

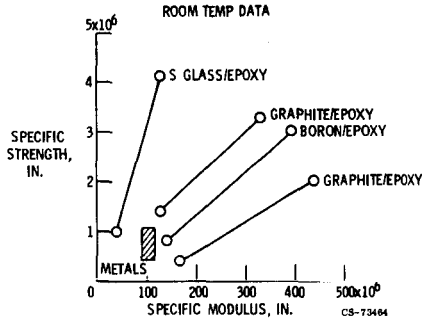
PROVIDE FOD RESISTANCE TO MEET FAA REQUIREMENTS

DEVELOP DESIGN & ANALYSIS PROCEDURES

CS-73456

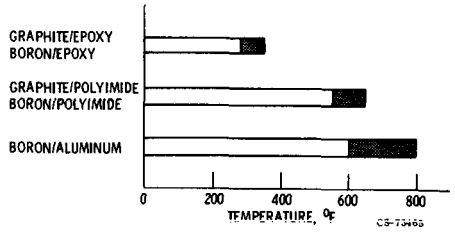
VII-4

ADVANTAGES OF COMPOSITES OVER METALS



VII-5

USE TEMPERATURES OF COMPOSITE SYSTEMS UNDER CONSIDERATION



VII-6

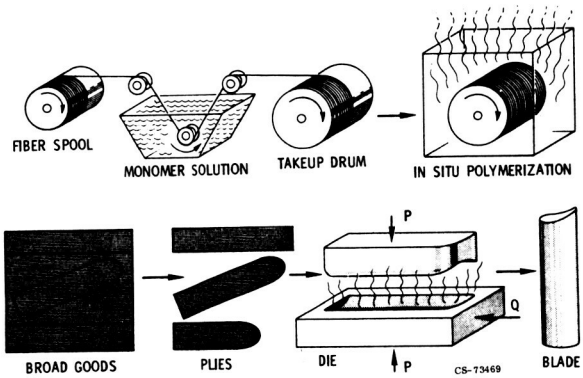
COMPARISON OF CONVENTIONAL AND IN SITU PMR FABRICATION PROCESSES

CONVENTIONAL FABRICATION PROCESS	IN SITU PMR PROCESS
MONOMERS POLYMERIZATION PACKAGING SHIPMENT STORAGE	MONOMERS MIXING VESSEL
PREPREG FAB PACKAGING SHIPMENT STORAGE	PREPREG FAB
ASSEMBLY	ASSEMBLY
MOLD	MOLD

CS-69020

VII-7

PMR POLYIMIDE PROCESS



VII-8

ADVANTAGES OF PMR POLYIMIDES

IMPROVED PERFORMANCE

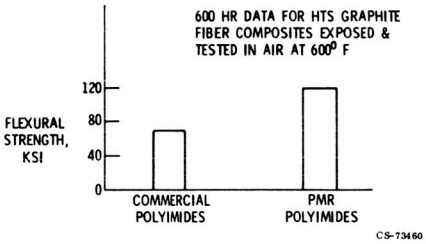
GREATER SAFETY

LOWER COST

CS-73457

VII-9

IMPROVED PROPERTIES OF PMR POLYIMIDE GRAPHITE FIBER COMPOSITES



VII-10

PMR POLYIMIDE/GRAPHITE FIBER FAN BLADE

VII-11

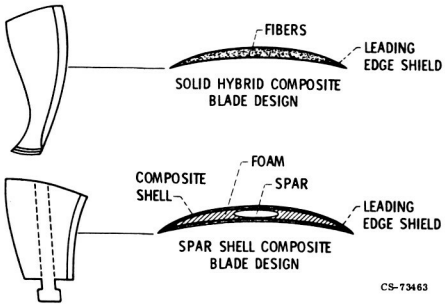
FAA FOREIGN OBJECT INGESTION REQUIREMENTS

GROUP	OBJECTS	REQUIREMENT
I	TOOLS TIRE TREAD CLEANING CLOTH BIRDS 4 LB	SAFE SHUTDOWN OF ENGINE
II	GRAVEL SAND ICE BIRDS UP TO 2 LB	POWER RECOVERY TO 75% LEVEL

CS-73466

VII-12

COMPOSITE FAN BLADE DESIGN CONCEPTS



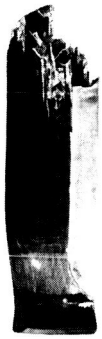
VII-13

NASA-IMPACT IMPROVEMENT PROGRAM

TF39 COMPOSITE BLADE

GRAPHITE/
EPOXY
$1\frac{3}{4}$ LB BIRD
12 OZ SLICE

HYBRID/
EPOXY
$2\frac{1}{2}$ LB BIRD
24 OZ SLICE



CS-73472

VII-14

METHODS TO IMPROVE FOD RESISTANCE OF B/AI COMPOSITES

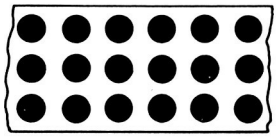
- LARGER DIAM FIBERS
- MORE DUCTILE MATRIX
- HYBRID MATRIX
- LOWER TEMP PROCESSING
- OPTIMIZED PLY CONFIGURATION

CS-73462

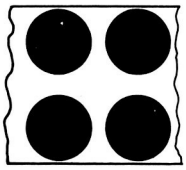
VII-15

LARGER DIAMETER FIBERS INCREASE INTERFIBER SEPARATION

50 VOL % FIBERS



4 MIL FIBERS



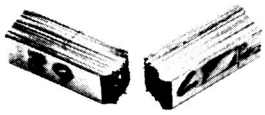
8 MIL FIBERS

CS-73468

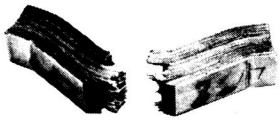
VII-16

IMPROVED B/AL IMPACT RESISTANCE

50 VOL % FIBER



13 FT-LB
5.6 MIL B IN BRITTLE MATRIX



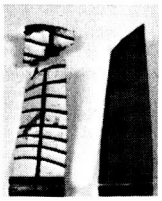
47 FT-LB
5.6 MIL B IN DUCTILE MATRIX

68 FT-LB
8 MIL B IN DUCTILE MATRIX

CS-73473

VII-17

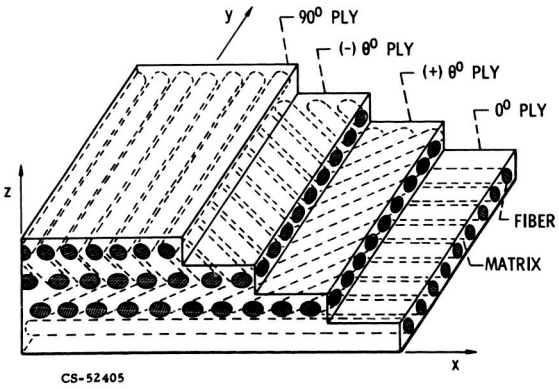
IMPROVED IMPACT RESISTANCE OF J79 B/AL COMPRESSOR BLADES



CS-73475

VII-18

FIBER COMPOSITE



CS-52405

VII-19

NASTRAN

NASA STRUCTURAL ANALYSIS

GENERAL PURPOSE DIGITAL COMPUTER PROGRAM

USES THE FINITE ELEMENT METHOD

CAN BE USED TO SOLVE THE FOLLOWING GENERAL CLASSES OF PROBLEMS:

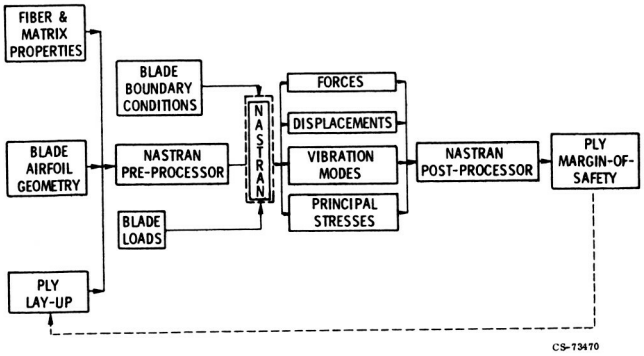
- STATIC STRUCTURAL
- ELASTIC STABILITY
- DYNAMIC STRUCTURAL
- GENERAL MATRIX

CS-73458

VII-20

STRUCTURAL ANALYSIS AND DESIGN OF FIBER COMPOSITE BLADES

NASTRAN PRE- & POST-PROCESSOR COMPUTER PROGRAM

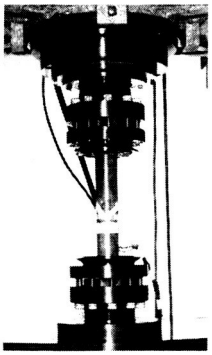


CS-73470

VII-21

COMBINED LOADING SPECIMEN

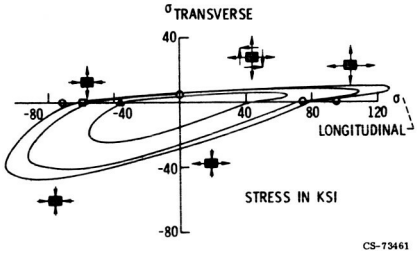
AXIAL-TORSION-PRESSURE



CS-73476

VII-22

COMBINED STRESS FAILURE ENVELOPES



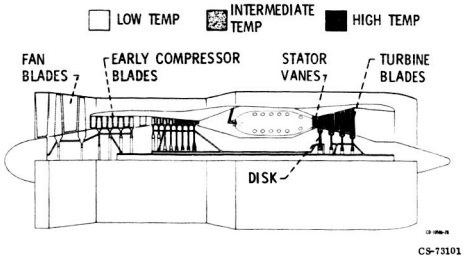
CS-73461

VII-23

VIII. TURBINE MATERIALS AND LIFE PREDICTION

Hugh R. Gray

SCHEMATIC DIAGRAM OF TURBOFAN ENGINE



VIII-1

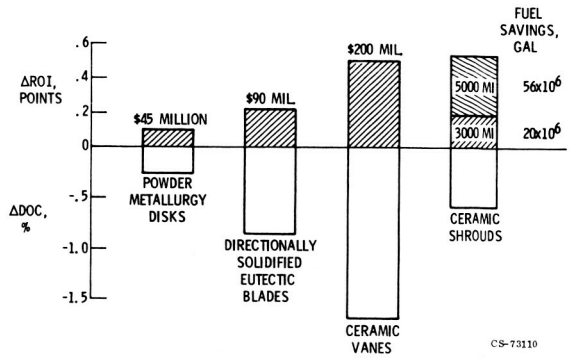
MAJOR CHALLENGES OF TURBINE MATERIALS RESEARCH

CHALLENGES	RESULTS	BENEFITS
INCREASE MATERIAL USE TEMP	→ HIGHER TURBINE INLET TEMP REDUCED COOLING	→ DECREASED FUEL CONSUMPTION INCREASED THRUST
INCREASE MATERIAL STRENGTH	→ INCREASED ROTOR SPEED DECREASED WT	→ FEWER STAGES REDUCED ENGINE WT REDUCED COST
INCREASE COMPONENT LIFE	→ INCREASED TIME BETWEEN OVERHAUL	→ DECREASED MAINTENANCE COST INCREASED RELIABILITY

CS-73102

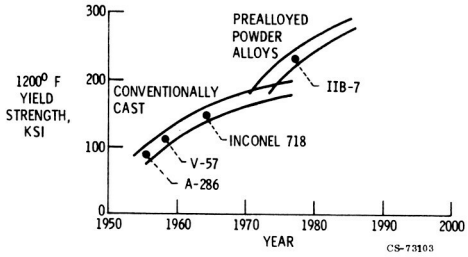
VIII-2

POTENTIAL ECONOMIC BENEFITS FROM ADVANCED TURBINE COMPONENTS



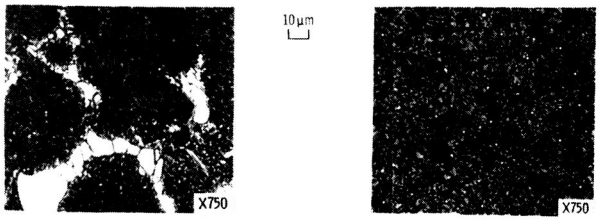
VIII-3

PROJECTED STRENGTH OF TURBINE DISK ALLOYS



VIII-4

MICROSTRUCTURE OF NASA-TRW VI A ALLOY



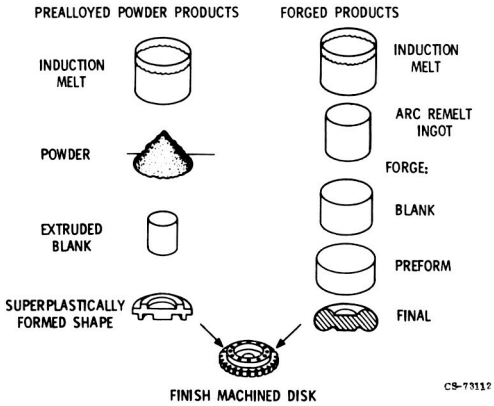
AS CAST VI-A

VI-A POWDER PRODUCT

CS-66862

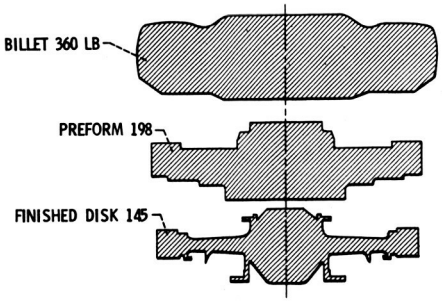
VIII-5

PREALLOYED POWDER PROCESS SAVES MATERIALS AND PROCESSING STEPS



VIII-6

PREALLOYED POWDER PROCESS REDUCES COST OF DISK

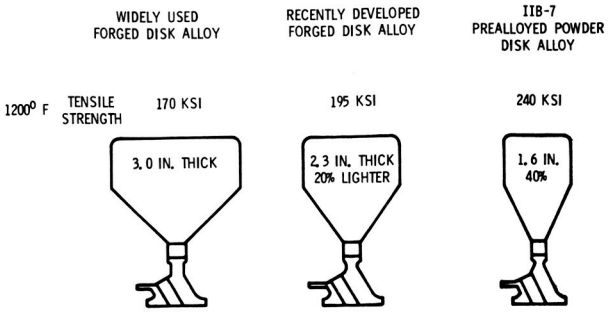


MATERIAL SAVED BY POWDER PROCESS	162 LB OR 45%
TOTAL MACHINING REQUIRED	
BY POWDER PROCESS	53 LB OR 27%
BY FORGING PROCESS	215 LB OR 60%

CS-72316

VIII-7

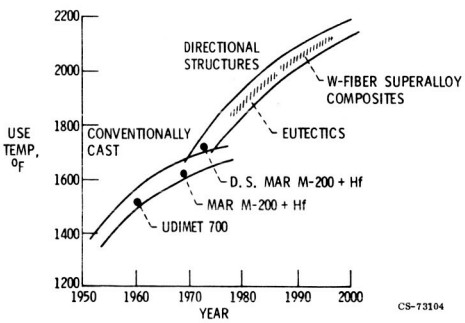
PREALLOYED POWDER PROCESS PERMITS ADVANCES IN DISK TECHNOLOGY



CS-73111

VIII-8

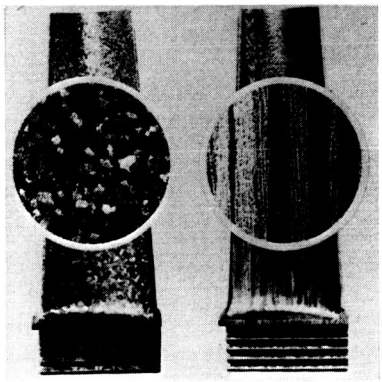
PROJECTED USE TEMPERATURE OF TURBINE BLADE ALLOYS



CS-73104

VIII-9

CONTROLLED GRAIN STRUCTURE IN CAST BLADES



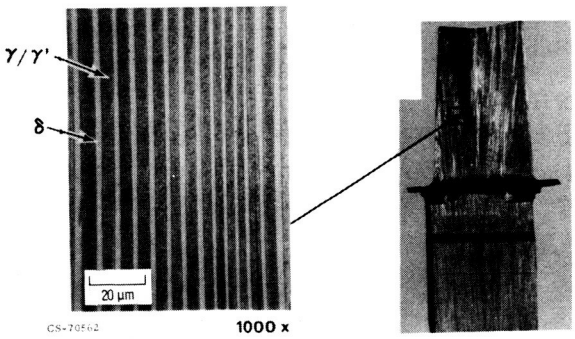
CONVENTIONALLY CAST DIRECTIONALLY SOLIDIFIED

COURTESY PRATT & WHITNEY AIRCRAFT

CS-73114

VIII-10

TURBINE BLADE OF $\gamma/\gamma' - \delta$ D.S. EUTECTIC ALLOY

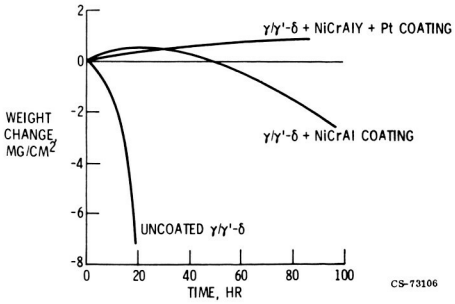


CS-70562 1000 x

VIII-11

ADVANCED TURBINE BLADE ALLOYS REQUIRE PROTECTIVE COATINGS

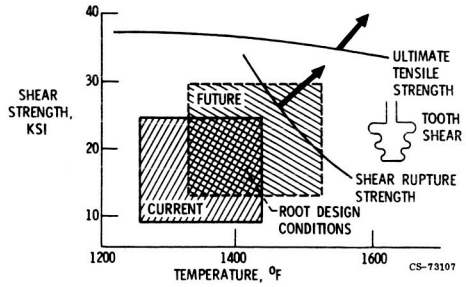
2200° F, STATIC AIR



CS-73106

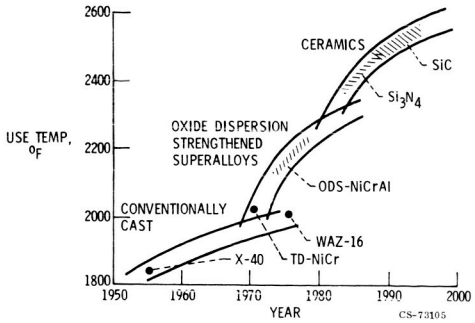
VIII-12

IMPROVED SHEAR STRENGTH FOR $\gamma/\gamma' - \delta$ EUTECTICS



VIII-13

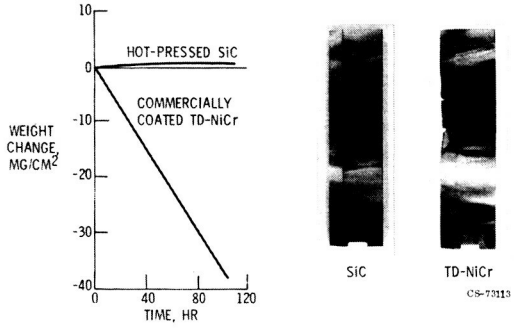
PROJECTED USE TEMPERATURE OF TURBINE VANE MATERIALS



VIII-14

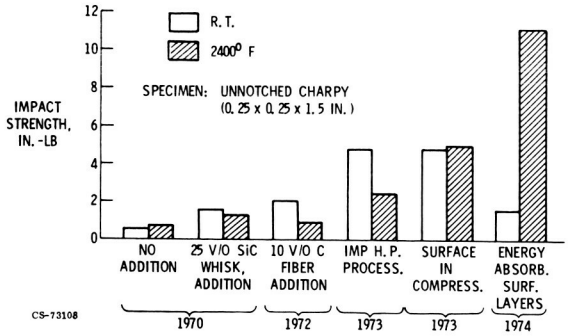
OXIDATION RESISTANCE OF CERAMICS

MACH 1, 2200° F, 1 HR CYCLES



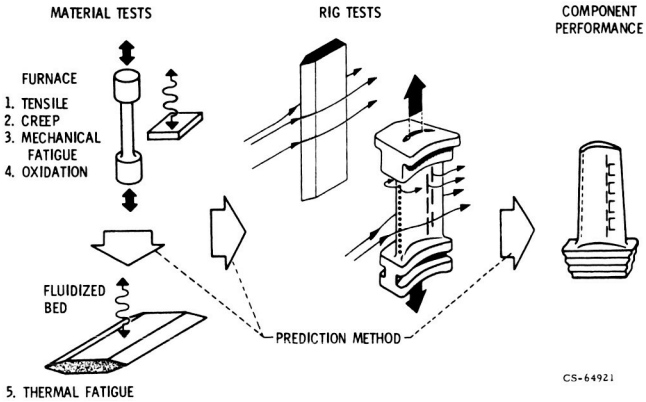
VIII-15

BEST IMPACT STRENGTH VALUES FOR SiC



VIII-16

TURBINE COMPONENT LIFE PREDICTION PROGRAM



VIII-17

VIII-18

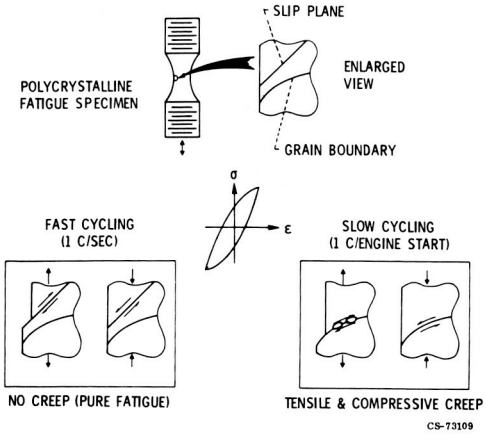
NASA - LEWIS DEVELOPMENTS FOR FATIGUE LIFE PREDICTION

1964 - UNIVERSAL SLOPES	LOW & INTERMEDIATE TEMPS
1966 - 10% RULE	HIGH TEMPS
1971 - STRAINRANGE PARTITIONING	HIGH TEMPS

CS-72379

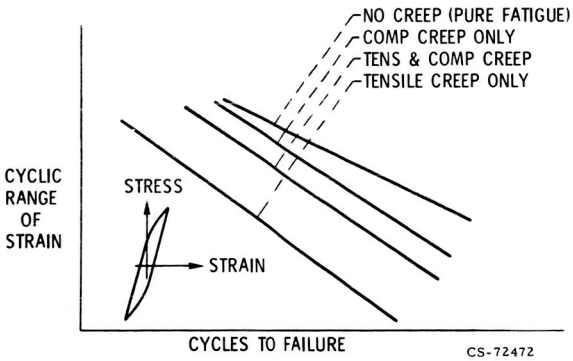
VIII-19

SIMPLE CYCLIC DEFORMATION MODELS FOR STRAINRANGE PARTITIONING



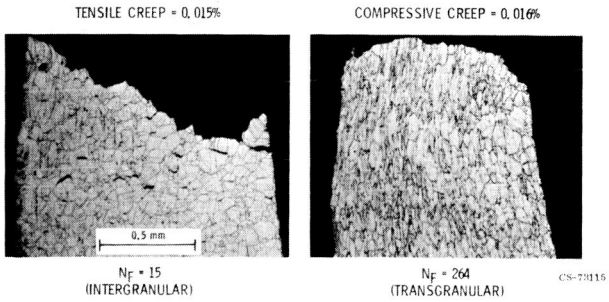
VIII-20

CHARACTERIZATION OF MATERIAL BEHAVIOR BY STRAINRANGE PARTITIONING



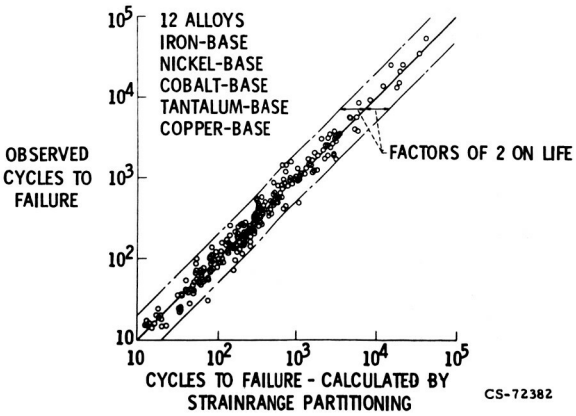
VIII-21

FATIGUE FRACTURES OF 316 STAINLESS STEEL AT 1300° F



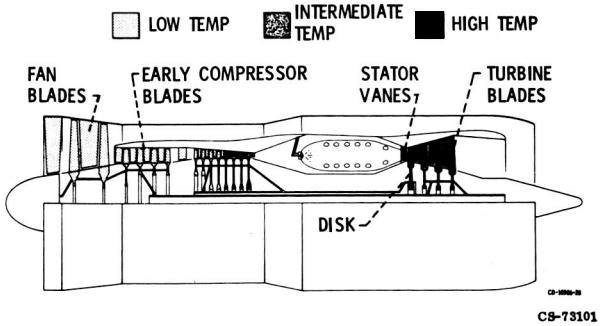
VIII-22

STRAINRANGE PARTITIONING PREDICTS CYCLIC LIVES



VIII-23

SCHEMATIC DIAGRAM OF TURBOFAN ENGINE

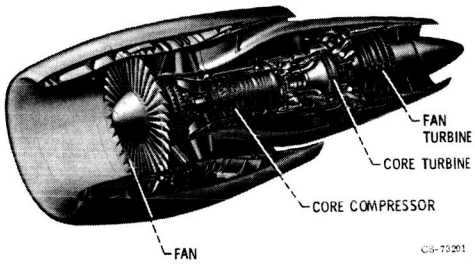


VIII-24

IX. COMPRESSOR AND TURBINE TECHNOLOGY

Cavour H. Hauser, Chairman
Calvin L. Ball
Raymond S. Colladay
William D. McNally
Thomas P. Moffitt

TURBOFAN ENGINE



IX-1

DESIRED ENGINE CHARACTERISTICS

LOW SPECIFIC FUEL CONSUMPTION

LOW NOISE

LOW WEIGHT

LOW COST

CS-73212

IX-2

COMPRESSOR AND TURBINE TECHNOLOGY

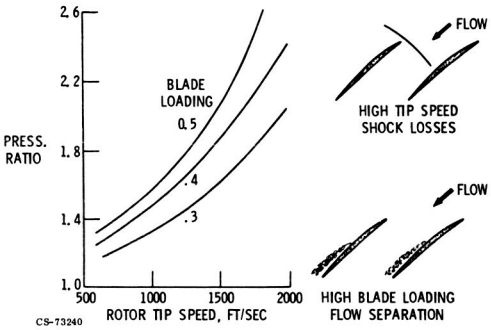
FANS & COMPRESSORS
- → STAGE PERFORMANCE TRENDS
- COMBINING HIGH PRESSURE RATIO STAGES
- ANALYTICAL & EXPERIMENTAL METHODS
- FANS FOR LOW NOISE
- CORE COMPRESSORS

TURBINES
- CORE TURBINE
  - HEAT TRANSFER
  - AERODYNAMICS
- FAN TURBINE
  - LOW SPEED, HIGH WORK FACTOR STAGES

CS-73258

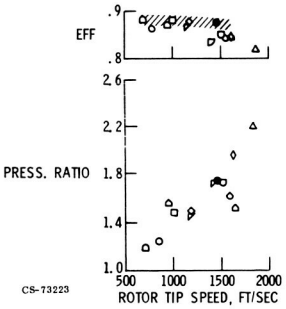
IX-3

FACTORS AFFECTING STAGE PRESSURE RATIO



IX-4

STAGE PERFORMANCE TRENDS



IX-5

COMPRESSOR AND TURBINE TECHNOLOGY

FANS & COMPRESSORS
- STAGE PERFORMANCE TRENDS
- → COMBINING HIGH PRESSURE RATIO STAGES
- ANALYTICAL & EXPERIMENTAL METHODS
- FANS FOR LOW NOISE
- CORE COMPRESSORS

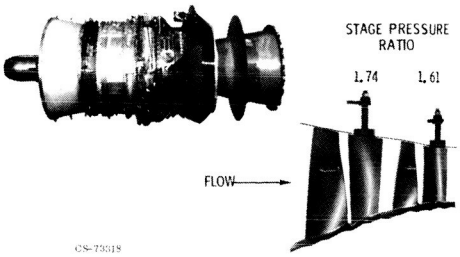
TURBINES
- CORE TURBINE
  - HEAT TRANSFER
  - AERODYNAMICS
- FAN TURBINE
  - LOW SPEED, HIGH WORK FACTOR STAGES

CS-73254

IX-6

HIGH PRESSURE RATIO TWO STAGE FAN

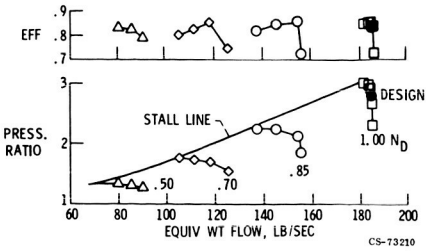
TIP SPEED, 1450 FT/SEC; PRESSURE RATIO, 2.8



IX-7

HIGH PRESSURE RATIO TWO STAGE FAN PERFORMANCE

DESIGN TIP SPEED, 1450 FT/SEC



IX-8

COMPRESSOR AND TURBINE TECHNOLOGY

- FANS & COMPRESSORS
  - STAGE PERFORMANCE TRENDS
  - COMBINING HIGH PRESSURE RATIO STAGES
  - → ANALYTICAL & EXPERIMENTAL METHODS
  - FANS FOR LOW NOISE
  - CORE COMPRESSORS
- TURBINES
  - CORE TURBINE
    - HEAT TRANSFER
    - AERODYNAMICS
  - FAN TURBINE
    - LOW SPEED, HIGH WORK FACTOR STAGES

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IX-9

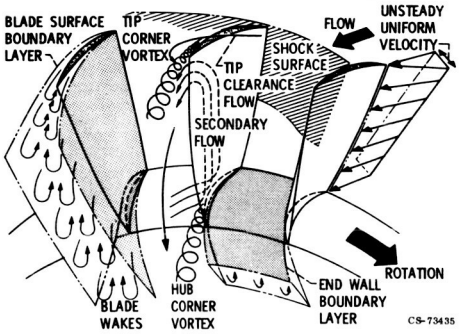
ROTOR BLADE ROW FLOW PHENOMENA

- BLADE SURFACE BOUNDARY LAYERS
- BLADE WAKES
- END WALL BOUNDARY LAYERS
- TIP CLEARANCE FLOWS
- CORNER VORTICES
- SECONDARY FLOWS
- SHOCKS
- UNSTEADY FLOWS

CS-73213

IX-10

ROTOR BLADE ROW FLOW PHENOMENA



CS-73435

IX-11

FLOW ANALYSIS METHODS

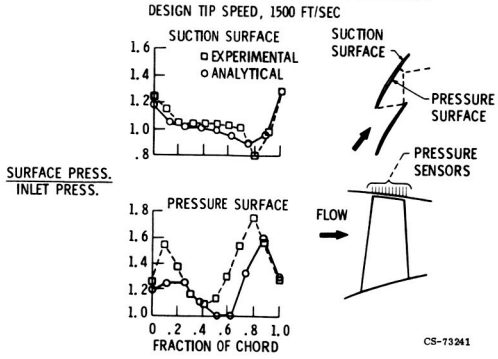
ANALYTICAL	EXPERIMENTAL
2- OR 3-DIMENSIONAL	DYNAMIC PRESSURE SENSORS
INVISCID OR VISCOUS	HOT WIRE PROBES
SUBSONIC OR TRANSONIC	LASER VELOCIMETER
STEADY OR UNSTEADY	LASER HOLOGRAPHY

CS-73261

IX-12

TRANSONIC ROTOR TIP STATIC PRESSURES

DESIGN TIP SPEED, 1500 FT/SEC

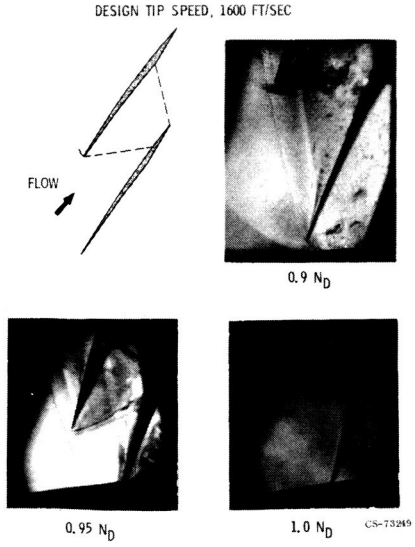


CS-73241

IX-13

HOLOGRAPHIC VIEW OF ROTOR BLADE SHOCKS

DESIGN TIP SPEED, 1600 FT/SEC

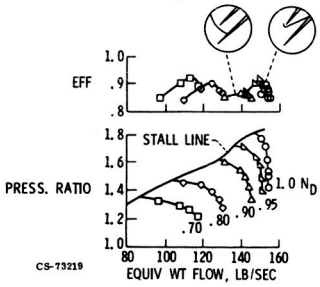


CS-73249

IX-14

ROTOR PERFORMANCE

DESIGN TIP SPEED, 1600 FT/SEC



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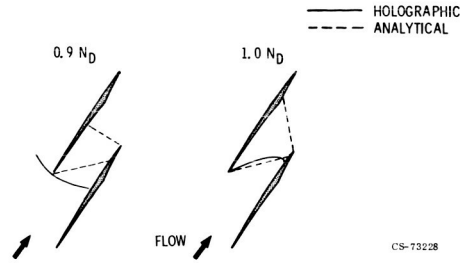
IX-15

ROTOR TIP SHOCK PATTERNS

DESIGN TIP SPEED, 1600 FT/SEC



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IX-16

COMPRESSOR AND TURBINE TECHNOLOGY

- FANS & COMPRESSORS
  - STAGE PERFORMANCE TRENDS
  - COMBINING HIGH PRESSURE RATIO STAGES
  - ANALYTICAL & EXPERIMENTAL METHODS
  - → FANS FOR LOW NOISE
  - CORE COMPRESSORS
- TURBINES
  - CORE TURBINE
    - HEAT TRANSFER
    - AERODYNAMICS
  - FAN TURBINE
    - LOW SPEED, HIGH WORK FACTOR STAGES

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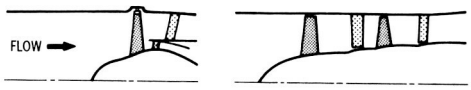
IX-17

FANS FOR LOW NOISE

HIGH TIP SPEED SINGLE STAGE FAN		LOW TIP SPEED TWO STAGE FAN	
PRESS. RATIO	1.8	PRESS. RATIO	1.9
TIP SPEED	1650 FT/SEC	TIP SPEED	1200 FT/SEC
SPECIFIC FLOW	44.0 LB/SEC/FT^2	SPECIFIC FLOW	42.9 LB/SEC/FT^2



CS-73225

IX-18

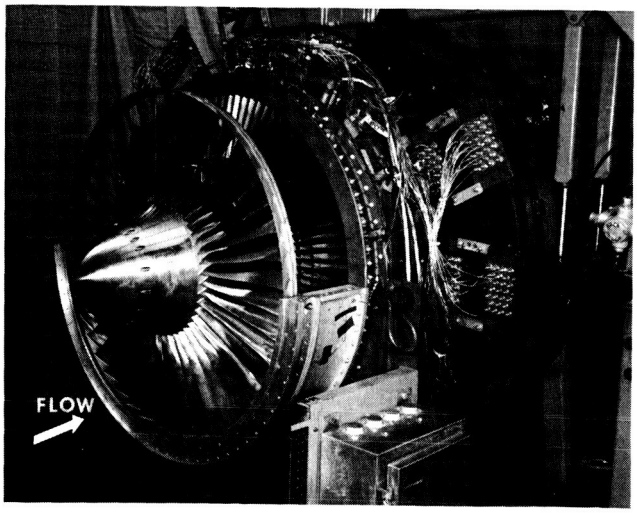
LOW NOISE COMPROMISES

	HIGH SPEED SINGLE STAGE FAN	LOW SPEED TWO STAGE FAN
HIGH SPECIFIC FLOW	X	X
BLADE ROWS SPACED	X	X
STATOR/ROTOR BLADE NO. RATIO	X	X
STAGING		X
LARGE ROTOR BLADE THROAT AREA	X	

CS-73381

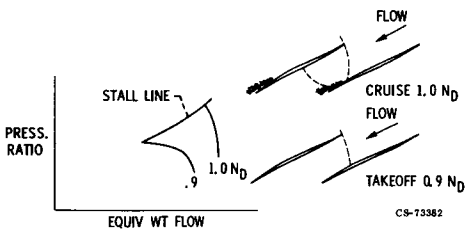
IX-19

SINGLE STAGE FAN



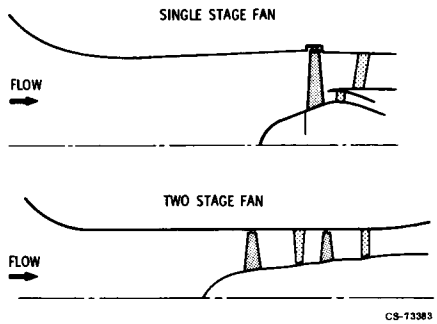
IX-20

EFFECT OF ROTOR BLADE THROAT AREA



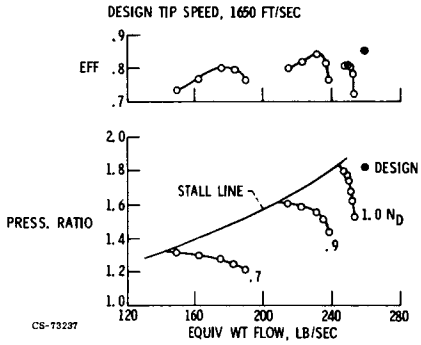
IX-21

LOW NOISE FANS
BELLMOUTH INLET



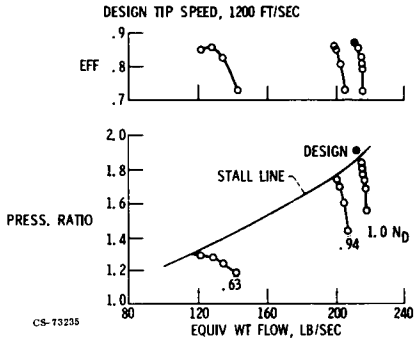
IX-22

SINGLE STAGE FAN PERFORMANCE
DESIGN TIP SPEED, 1650 FT/SEC



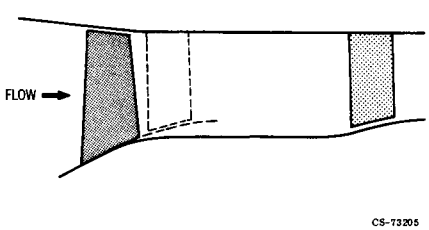
IX-23

TWO STAGE FAN PERFORMANCE
DESIGN TIP SPEED, 1200 FT/SEC



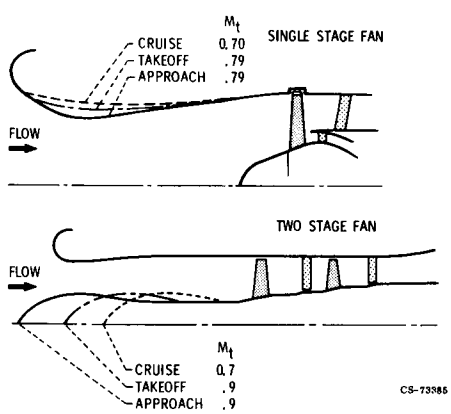
IX-24

FLOW PATH GEOMETRY



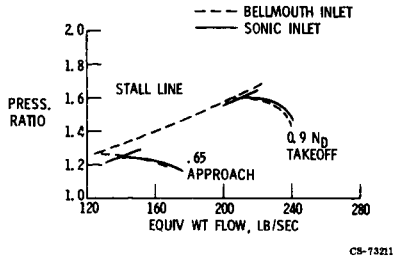
IX-25

LOW NOISE FANS
SONIC INLET



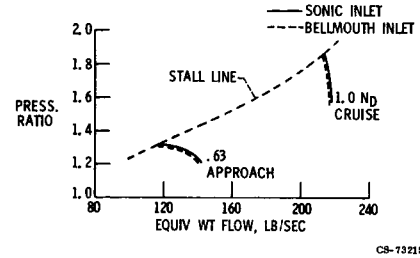
IX-26

SINGLE STAGE FAN PERFORMANCE



IX-27

TWO STAGE FAN PERFORMANCE



IX-28

COMPRESSOR AND TURBINE TECHNOLOGY

FANS & COMPRESSORS
- STAGE PERFORMANCE TRENDS
- COMBINING HIGH PRESSURE RATIO STAGES
- ANALYTICAL & EXPERIMENTAL METHODS
- FANS FOR LOW NOISE
- → CORE COMPRESSORS

TURBINES
- CORE TURBINE
  - HEAT TRANSFER
  - AERODYNAMICS
- FAN TURBINE
  - LOW SPEED, HIGH WORK FACTOR STAGES

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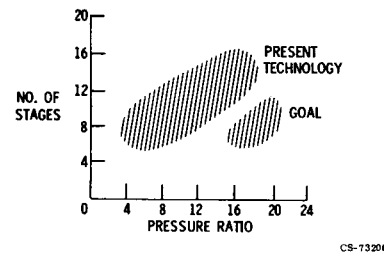
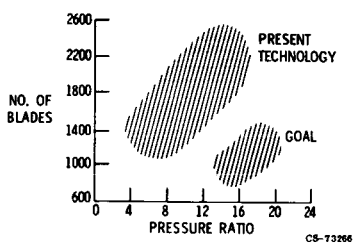
IX-29

NUMBER OF STAGES FOR CORE COMPRESSORS



IX-30

NUMBER OF BLADES FOR CORE COMPRESSORS



IX-31

ADVANCED CORE COMPRESSOR REQUIREMENTS

HIGH STAGE PRESSURE RATIO
- HIGH TIP SPEED
- HIGH BLADE LOADING

REDUCED NO. OF BLADES
- HIGH STAGE PRESSURE RATIO
- LOW BLADE ASPECT RATIO

HIGH HUB TIP RATIO

STAGE MATCHING

ADVANCED MATERIALS

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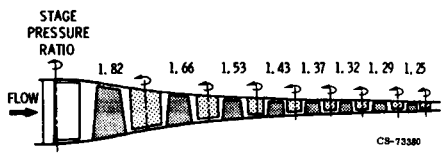
IX-32

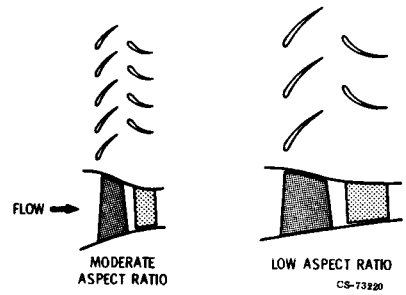
EXAMPLE ADVANCED CORE COMPRESSOR

PRESSURE RATIO	20
NO. OF STAGES	8
TIP SPEED	1500 FT/SEC
HUB TIP RATIO	0.70 TO 0.95



IX-33

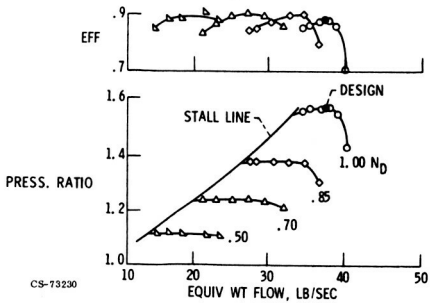
EFFECT OF REDUCED ASPECT RATIO



IX-34

LOW ASPECT RATIO HIGHLY LOADED COMPRESSOR STAGE

DESIGN TIP SPEED, 933 FT/SEC



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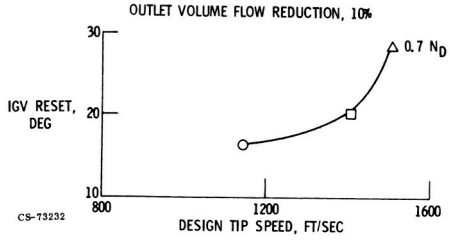
IX-35

EFFECT OF TIP SPEED ON REQUIRED INLET GUIDE VANE RESET

OUTLET VOLUME FLOW REDUCTION, 10%



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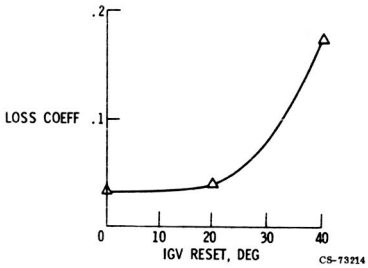
IX-36

EFFECT OF RESET ON INLET GUIDE VANE LOSS

RELATIVE INLET MACH NO. 0.3; MEAN RADIUS



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IX-37

COMPRESSOR AND TURBINE TECHNOLOGY

FANS & COMPRESSORS
- STAGE PERFORMANCE TRENDS
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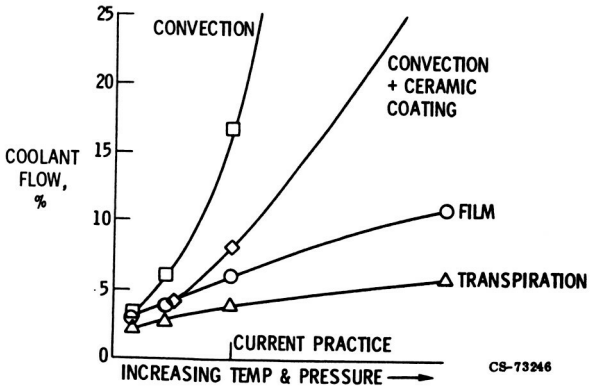
- FANS FOR LOW NOISE
- CORE COMPRESSORS

TURBINES
- → CORE TURBINE
  - HEAT TRANSFER
  - AERODYNAMICS
- FAN TURBINE
  - LOW SPEED, HIGH WORK FACTOR STAGES

CS-73379

IX-38

TURBINE COOLING REQUIREMENTS



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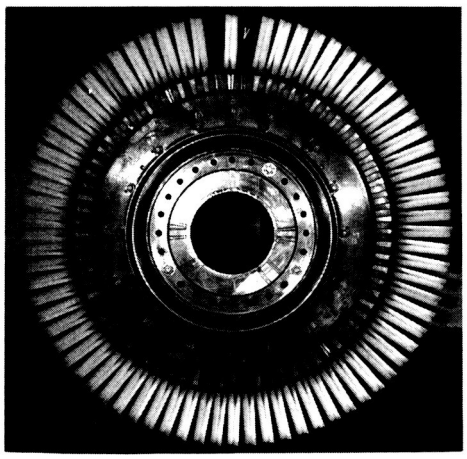
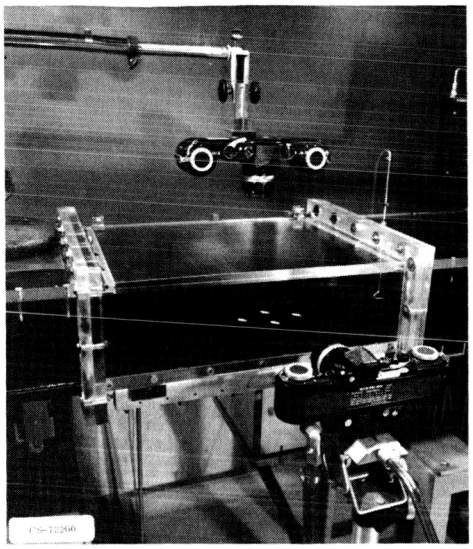
IX-39

CERAMIC COATED TURBINE BLADES



IX-40

FLOW VISUALIZATION TEST SECTION



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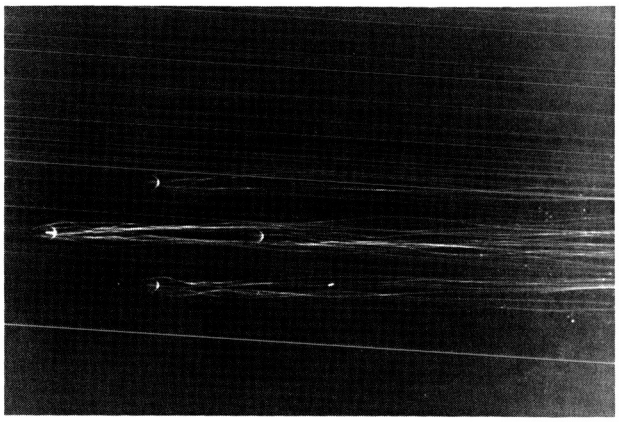
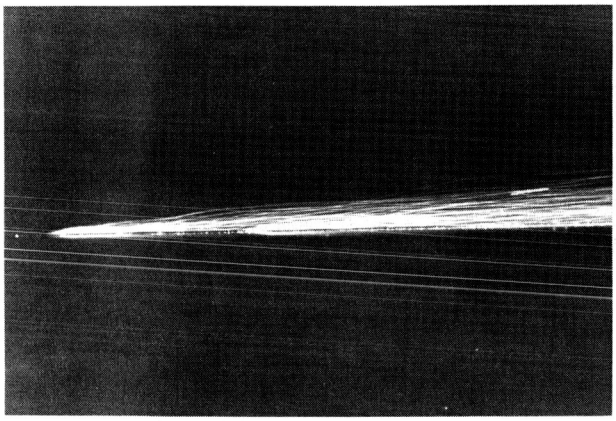


IX-42



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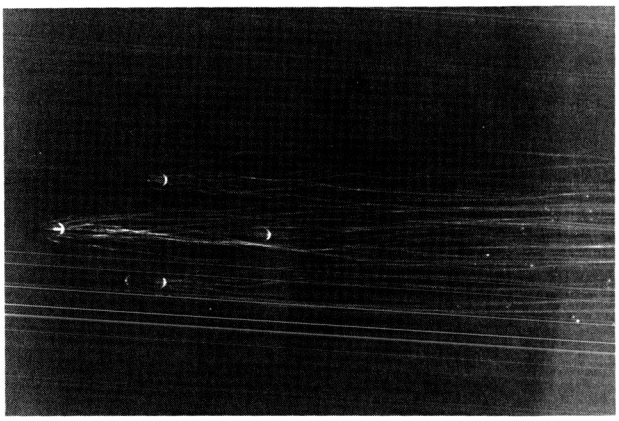
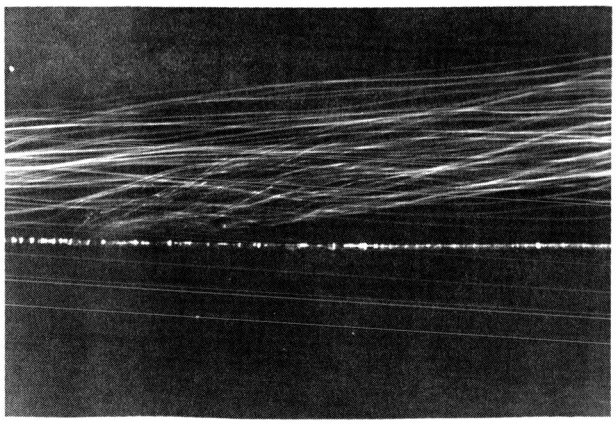
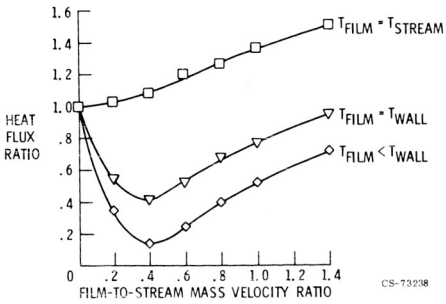


IX-44



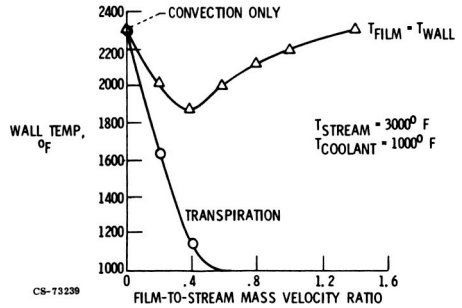
IX-46

EFFECT OF BLOWING RATE ON FILM COOLING HEAT TRANSFER



IX-47

EFFECT OF FILM COOLING ON WALL TEMPERATURE



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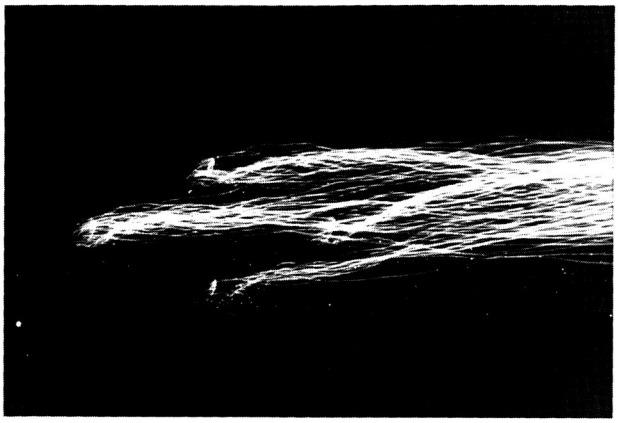

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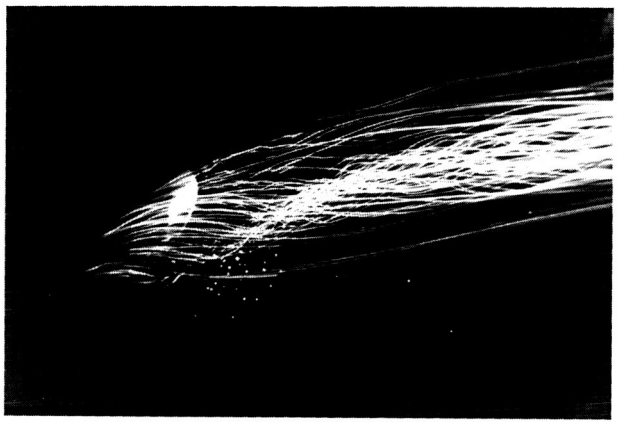
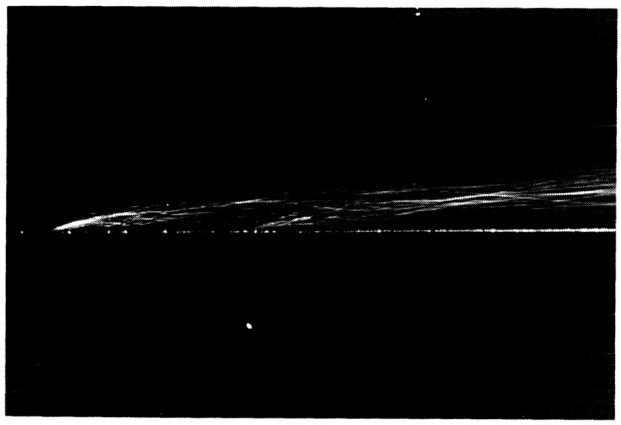


IX-50



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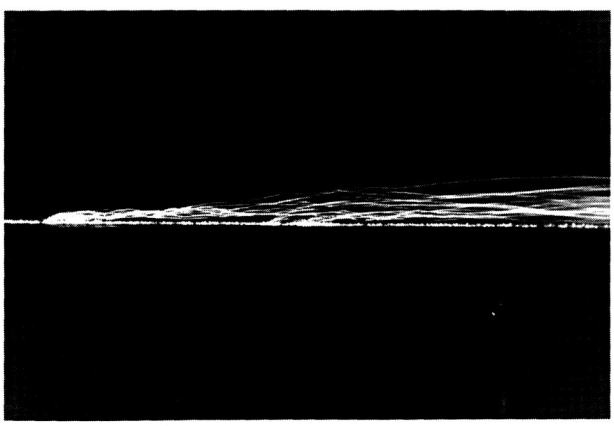
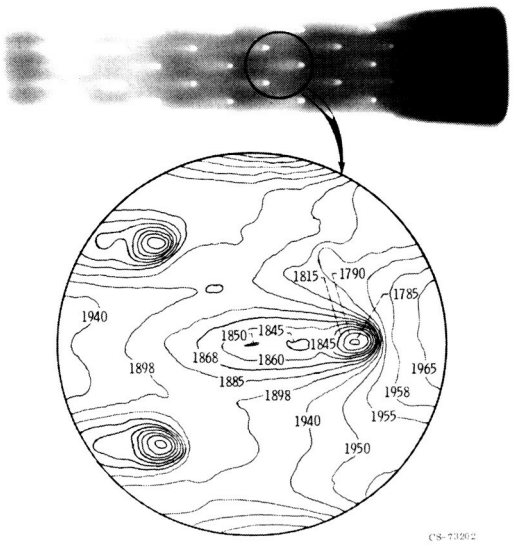


IX-52

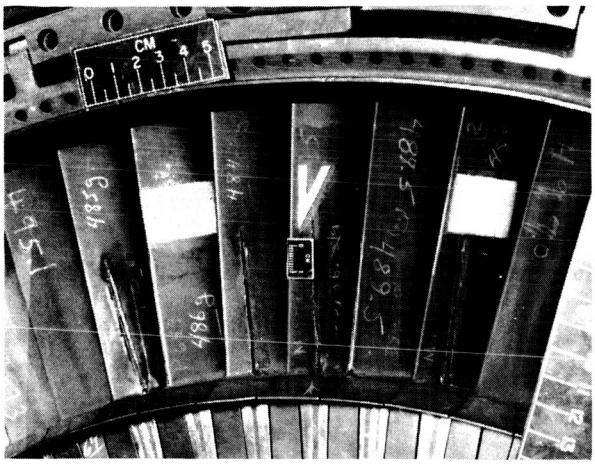
INFRARED IMAGE OF A FILM COOLED WALL



TEMP DISTRIBUTION

IX-53

TURBINE ROTOR



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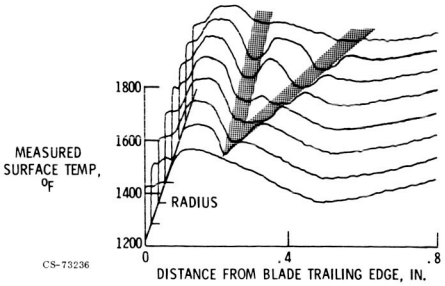
IX-54

RADIATION PYROMETER SCANS



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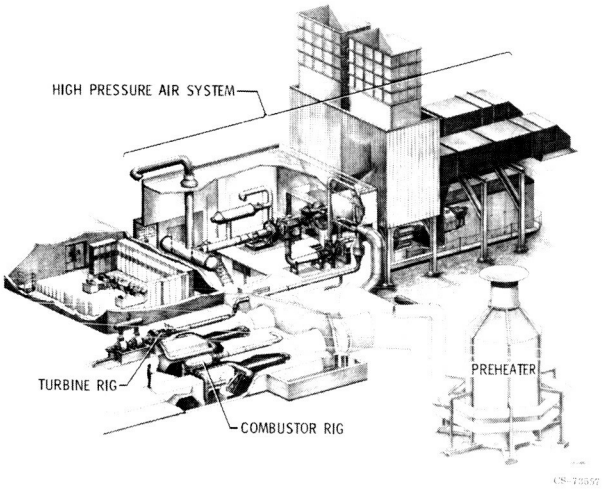
IX-55

HIGH PRESSURE–HIGH TEMPERATURE TURBINE FACILITY



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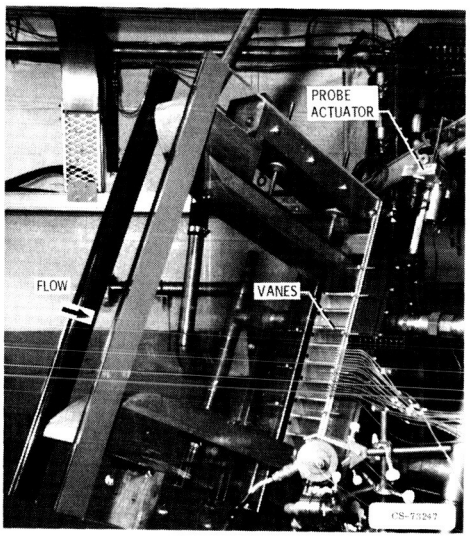
IX-56

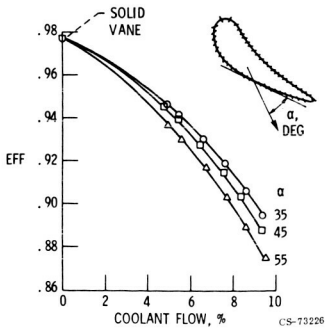
CORE TURBINE VANE 2-DIMENSIONAL CASCADE



CS-73247

IX-57

EFFECT OF IN–LINE EJECTION ANGLE ON VANE EFFICIENCY

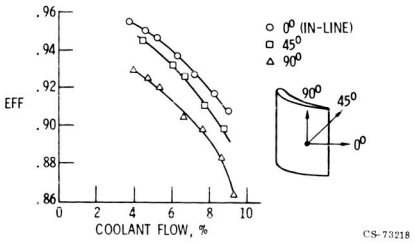


CS-73226

IX-58

EFFECT OF COMPOUND EJECTION ANGLE ON VANE EFFICIENCY

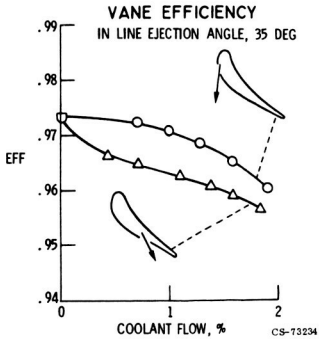
ALL HOLES ORIENTED 35 DEG TO LOCAL SURFACE



CS-73218

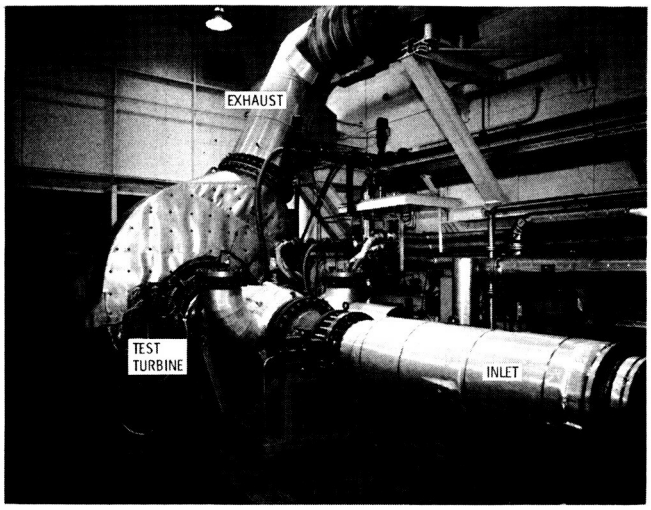
IX-59

EFFECT OF HOLE LOCATION ON VANE EFFICIENCY



IX-60

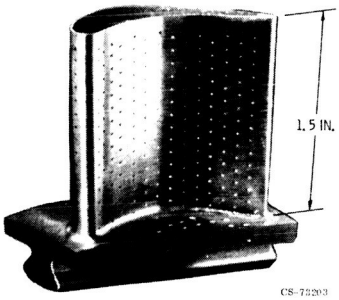
CORE TURBINE TEST FACILITY



CS-73430

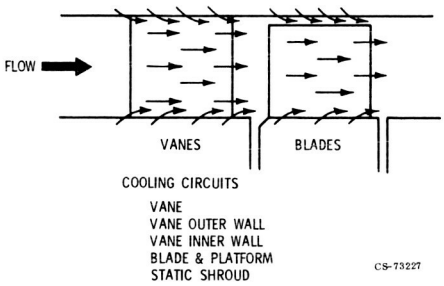
IX-61

CORE TURBINE BLADE



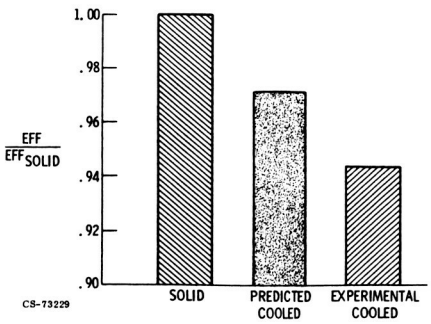
IX-62

20 INCH CORE TURBINE COOLING CIRCUITS



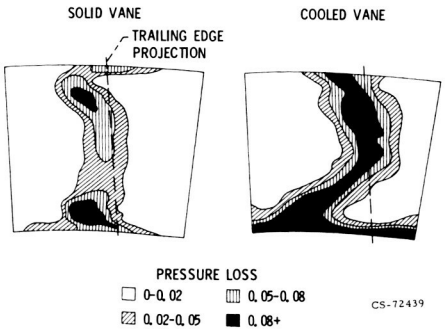
IX-63

CORE TURBINE PERFORMANCE



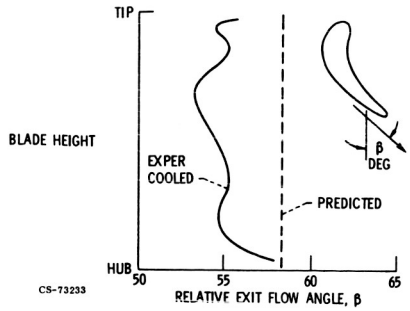
IX-64

VANE EXIT SURVEYS



IX-65

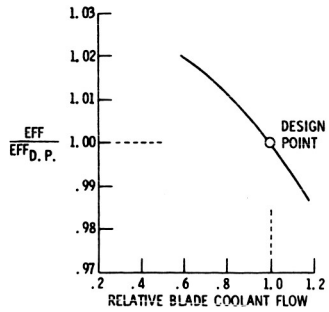
CORE BLADE UNDERTURNING



CS-73233

IX-66

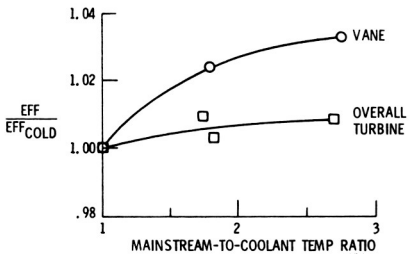
EFFECT OF BLADE COOLANT ON TURBINE EFFICIENCY



CS-73265

IX-67

EFFECT OF TEMPERATURE RATIO ON TURBINE EFFICIENCY



CS-73209

IX-68

COMPRESSOR AND TURBINE TECHNOLOGY

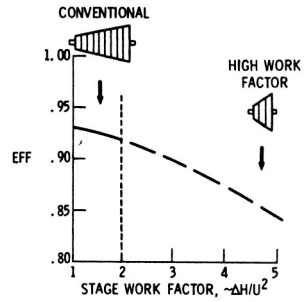
FANS & COMPRESSORS
- STAGE PERFORMANCE TRENDS
- COMBINING HIGH PRESSURE RATIO STAGES
- ANALYTICAL & EXPERIMENTAL METHODS
- FANS FOR LOW NOISE
- CORE COMPRESSORS

TURBINES
- CORE TURBINE
  - HEAT TRANSFER
  - AERODYNAMICS
- → FAN TURBINE
  - LOW SPEED, HIGH WORK FACTOR STAGES

CS-73377

IX-69

PREDICTED TURBINE EFFICIENCY



CS-73207

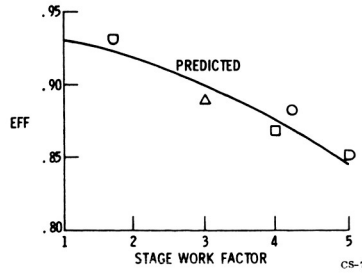
IX-70

FAN TURBINE ROTOR

CS-73248

IX-71

PERFORMANCE OF FAN TURBINES



CS-73250

IX-72

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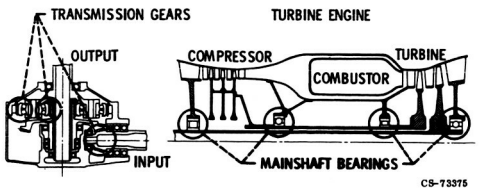
IX. COMPRESSOR AND TURBINE TECHNOLOGY

Cavour H. Hauser, Chairman
Calvin L. Ball
Raymond S. Colladay
William D. McNally
Thomas P. Moffitt

X. BEARINGS AND GEARS FOR ADVANCED TURBINE ENGINES AND TRANSMISSIONS

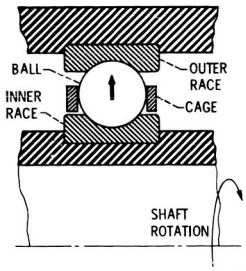
Richard J. Parker

BEARING AND GEAR LOCATIONS



X-1

BALL BEARINGS AT HIGH SPEEDS



CAUSE:
- CENTRIFUGAL FORCES
- HIGH CYCLING RATE

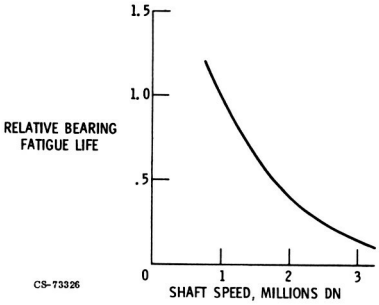
EFFECT:
- MORE DIFFICULT LUBRICATION
- MORE COOLING REQUIRED
- REDUCED FATIGUE LIFE

APPROACH:
- NEW LUBRICATION TECHS
- IMPROVED MATERIALS
- IMPROVED BEARING DESIGN

CS-73324

X-2

HIGH SPEED REDUCES FATIGUE LIFE

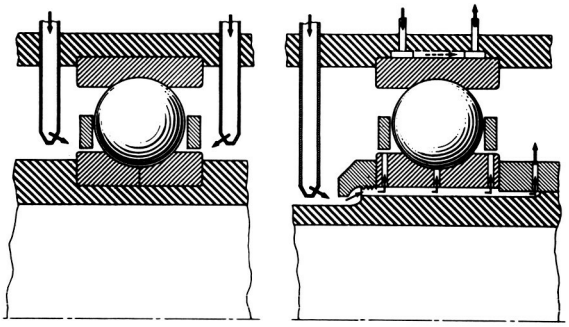


X-3

LUBRICATION AT HIGH SPEEDS

JET LUBRICATION

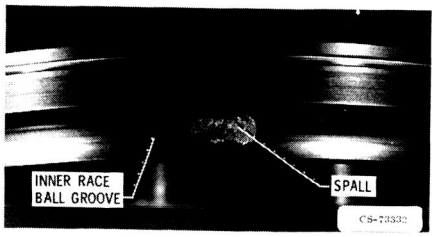
UNDER-RACE LUBRICATION



CS-73325

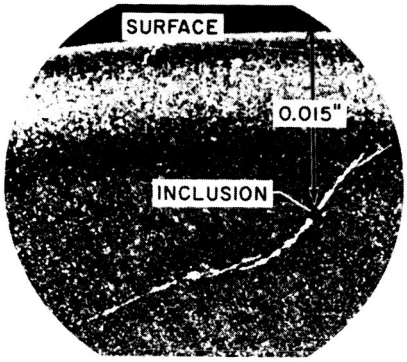
X-4

TYPICAL FATIGUE SPALL



X-5

FATIGUE CRACK ORIGINATING AT AN INCLUSION



X-6

COMPUTER PROGRAMS FOR ROLLING-ELEMENT BEARING ANALYSIS

TO PREDICT:
- PERFORMANCE
- FATIGUE LIFE

ACCOUNT FOR:
- APPLIED LOADS
- HIGH SPEED EFFECTS
- TEMP EFFECTS

DETERMINE:
- CONTACT STRESSES
- LUBRICANT FILM THICKNESS
- BALL OR ROLLER MOTION
- BEARING FATIGUE LIFE
- TEMP DISTRIBUTION

VALUE:
- OPTIMIZE BEARING DESIGN FOR SPECIFIC APPLICATION

CS-73323

X-7

120-MM BORE HIGH-SPEED BALL BEARINGS

CS-73331

X-8

TEST CONDITIONS

SHAFT SPEED, 25 000 RPM (3 MILLION DN)

THRUST LOAD, 5000 LB

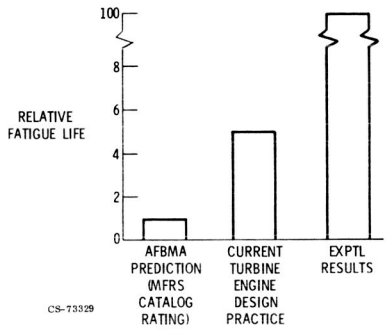
BEARING TEMP, 425° F

LUBRICANT, TYPE II ESTER

CS-73322

X-9

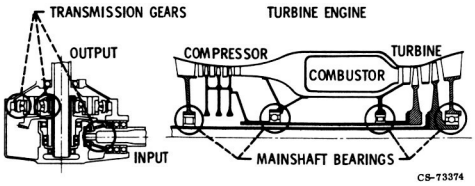
FATIGUE LIFE AT 3 MILLION DN



CS-73329

X-10

BEARING AND GEAR LOCATIONS



CS-73374

X-11

AREAS OF ADVANCEMENT OF GEAR TECHNOLOGY

LONGER FATIGUE LIFE

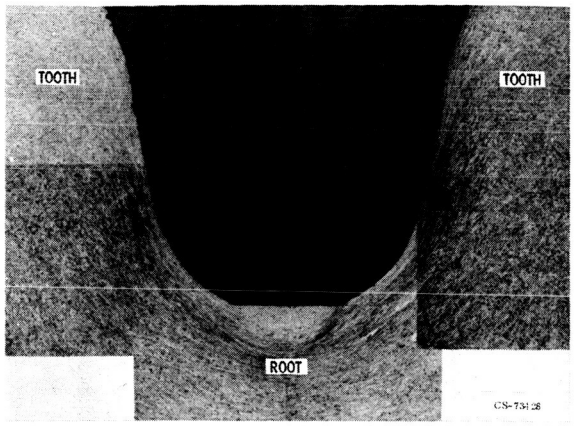
HIGHER TEMP CAPABILITY

APPROACHES:
- IMPROVED MATERIALS
- IMPROVED DESIGN
- IMPROVED LUBRICATION

CS-73319

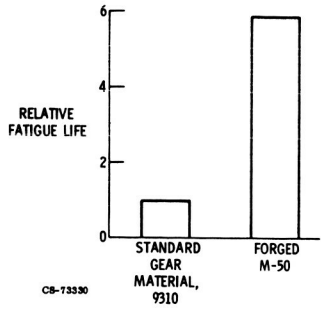
X-12

FORGED M-50 GEAR



X-13

EXPERIMENTAL FATIGUE LIFE OF 3.5 INCH SPUR GEARS



X-14

SPUR GEAR FATIGUE LIFE PREDICTION

TOOTH MESH CAPACITY

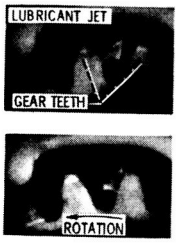
BASED ON TOOTH GEOMETRY

LOAD THE MESH CAN TRANSMIT FOR ONE MILLION CYCLES WITH 90% SURVIVAL

$$\text{FATIGUE LIFE (IN MILLIONS OF CYCLES)} = \left(\frac{\text{TOOTH MESH CAPACITY}}{\text{TRANSMITTED LOAD}}\right)^{1.6}$$

X-15 CS-73328

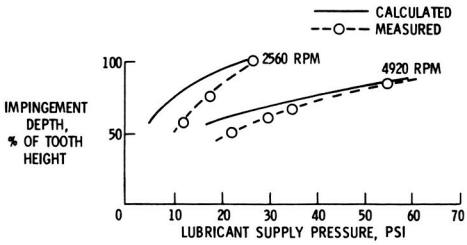
LUBRICANT JET PENETRATION



CS-73333

X-16

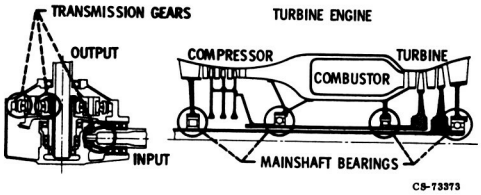
LUBRICANT IMPINGEMENT DEPTH



CS-73327

X-17

BEARING AND GEAR LOCATIONS



X-18

SUMMARY

BEARING FATIGUE LIFE PROVEN TO BE 20 TIMES CURRENT DESIGN PRACTICE

3 MILLION DN OPERATIONAL CAPABILITY DEMONSTRATED EXPERIMENTALLY

SIGNIFICANTLY IMPROVED GEAR LIFE DEMONSTRATED EXPERIMENTALLY

X-19

CS-73321

XI. ENGINE SEALING AND LUBRICATION SYSTEMS

John Zuk

ENGINE SEALING AND LUBRICATION

SHAFT SEALS

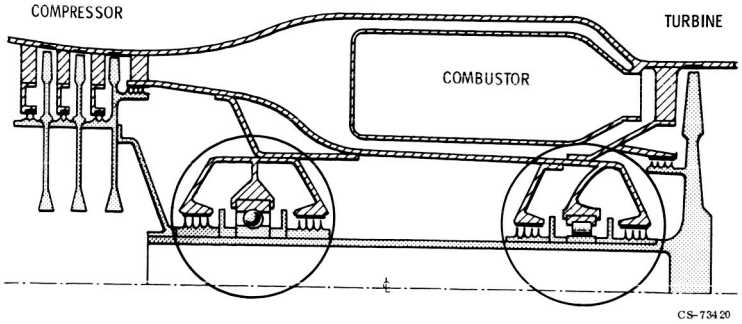
PRIMARY GAS PATH SEALS

LUBRICATION

XI-1

CS-73402

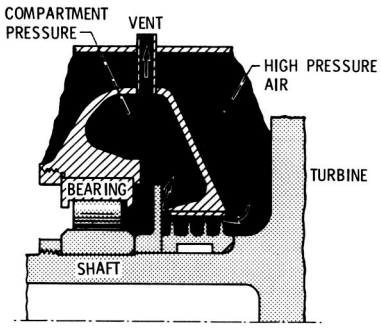
SHAFT SEALS



CS-73420

XI-2

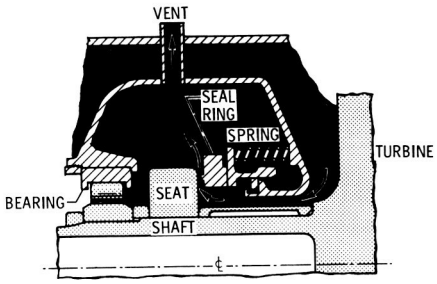
LABYRINTH SEAL



CS-73407

XI-3

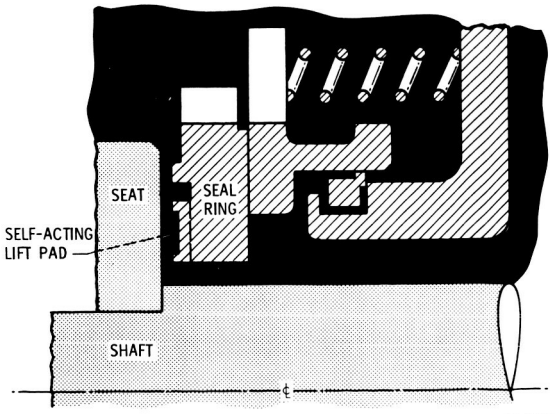
FACE CONTACT SEAL



CS-73406

XI-4

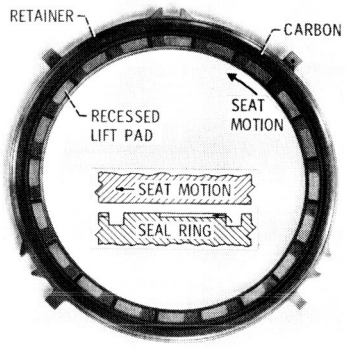
NASA SELF-ACTING LIFT PAD SEAL



CS-73415

XI-5

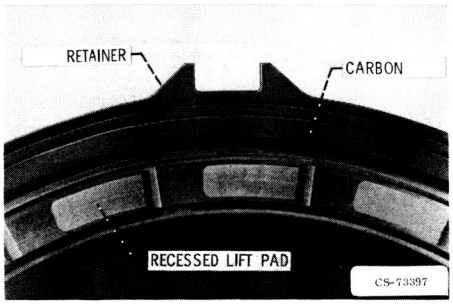
SEAL RING



CS-73516

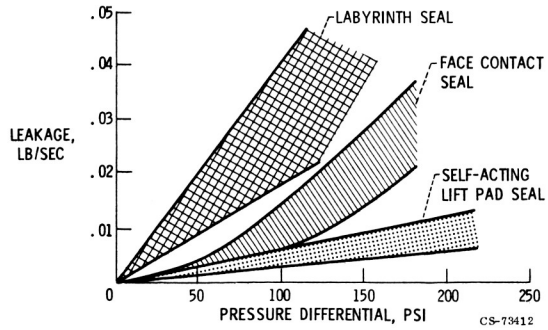
XI-6

SECTION OF SEAL RING



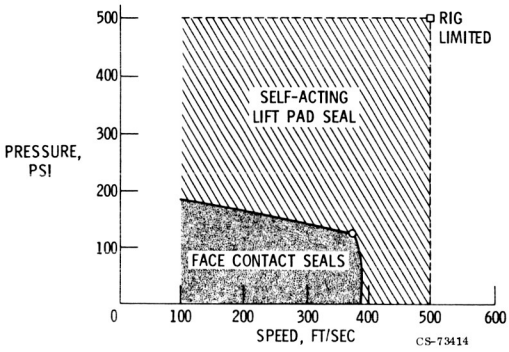
XI-7

SEAL LEAKAGE COMPARISON



XI-8

SEAL PERFORMANCE COMPARISON



XI-9

ENGINE SEALING AND LUBRICATION

SHAFT SEALS

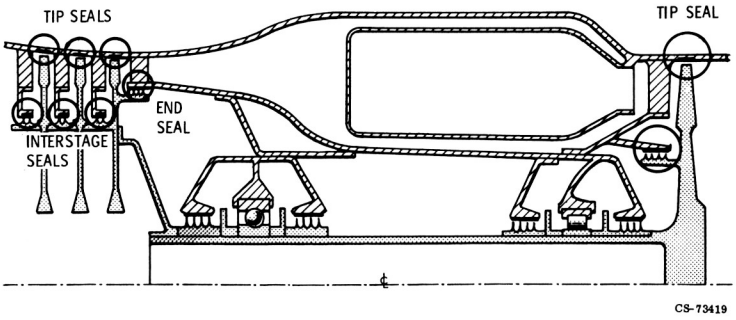
➡ PRIMARY GAS PATH SEALS

LUBRICATION

CS-73404

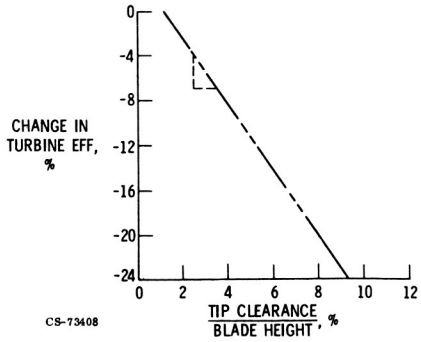
XI-10

PRIMARY GAS PATH SEALS



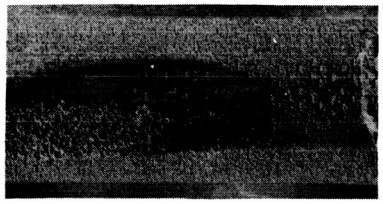
XI-11

TURBINE PERFORMANCE DEGRADATION



XI-12

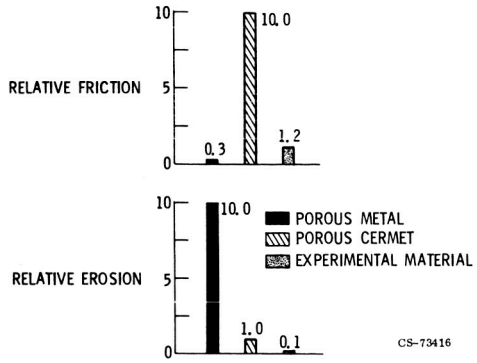
SHROUD SEAL RUB



CS-73399

XI-13

FRICTION AND EROSION OF SHROUD SEAL MATERIALS

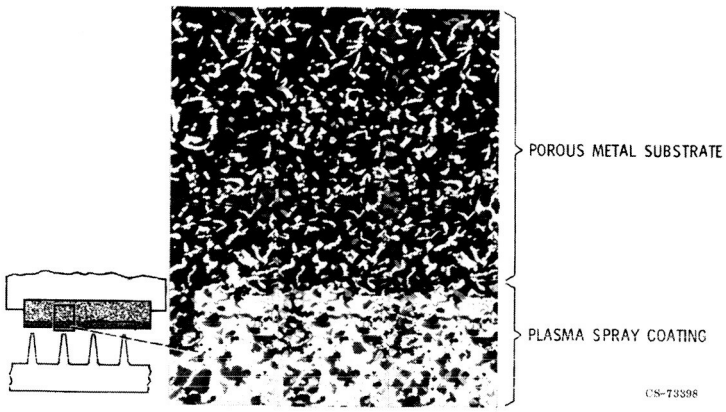


CS-73416

XI-14

NASA EXPERIMENTAL SEAL MATERIAL CONCEPT

PHOTOMICROGRAPH



CS-73398

XI-15

PHOTOMICROGRAPH OF RUB GROOVE

CS-73455

XI-16

ENGINE SEALING AND LUBRICATION

SHAFT SEALS

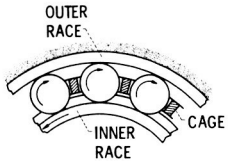
PRIMARY GAS PATH SEALS

→ LUBRICATION

CS-73405

XI-17

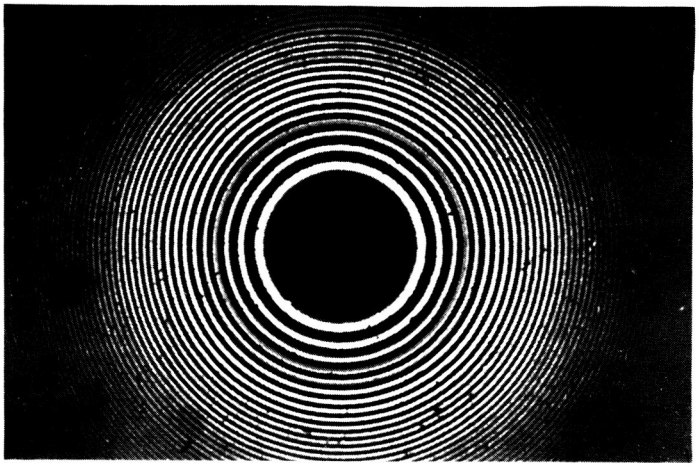
BALL BEARING SECTION



CS-73403

XI-18

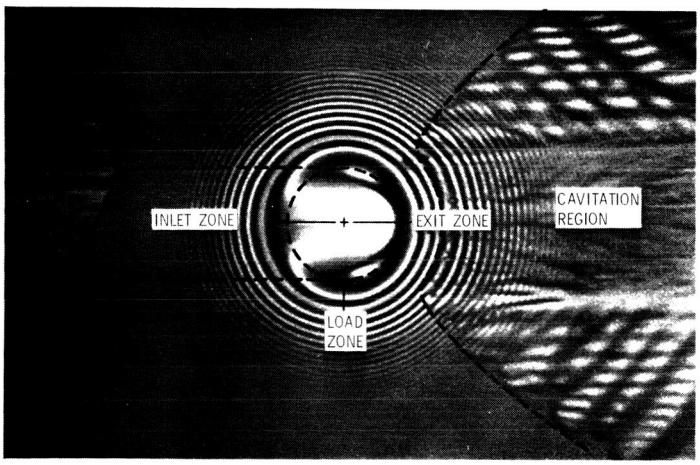
PHOTOMICROGRAPH OF LOAD ZONE
STATIC



XI-19

CS-73591

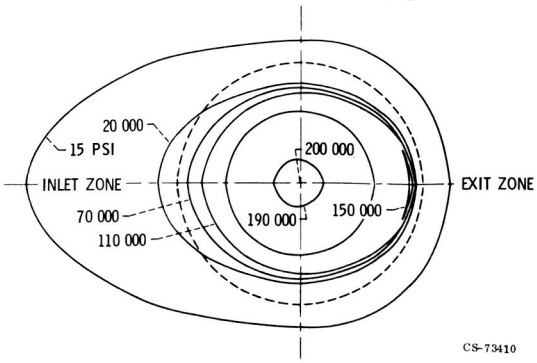
PHOTOMICROGRAPH
LUBRICATED SURFACE
DYNAMIC



XI-20

CS-73590

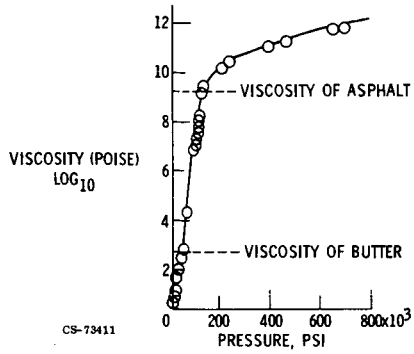
PRESSURE CONTOURS IN LOAD ZONE



CS-73410

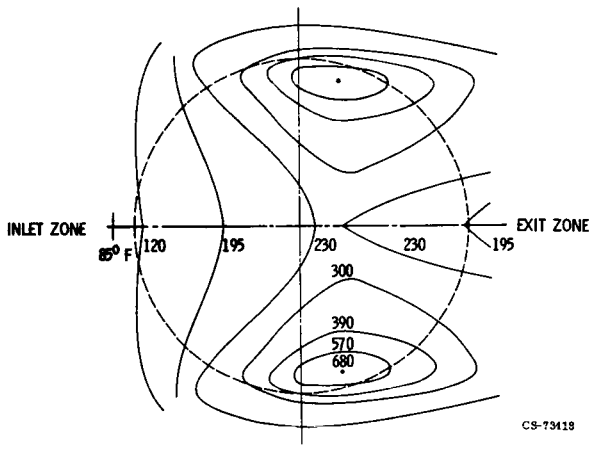
XI-21

PRESSURE VISCOSITY OF SYNTHETIC PARAFFINIC LUBRICANT AT 100°F



XI-22

TEMPERATURE CONTOURS IN LOAD ZONE



XI-23

SUMMARY - ENGINE SEALING AND LUBRICATION

SHAFT SEALS
- SELF-ACTING LIFT PAD SEAL EXCEEDS PERFORMANCE NEEDED FOR ADVANCED ENGINES

PRIMARY GAS PATH SEALS
- SHROUD MATERIAL CONCEPT PROVIDES BOTH RUB TOLERANCE & EROSION RESISTANCE

LUBRICATION
- REAL MEASUREMENTS IN LUBRICATION ZONE ENABLES LIQUID LUBRICANT OPTIMIZATION

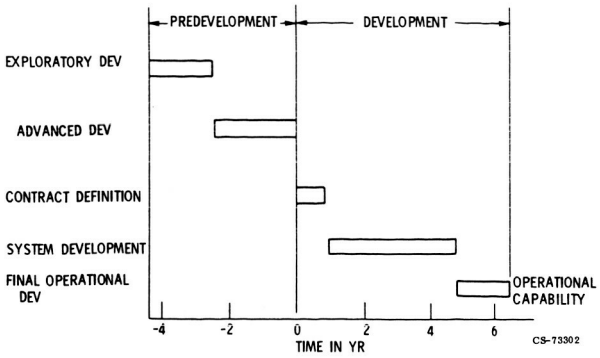
CS-73522

XI-24

XII. ENGINE SYSTEMS TECHNOLOGY

Ross G. Willoh, Jr., Chairman
Robert E. Coltrin
Edwin J. Graber, Jr.
Fred Teren

TYPICAL ENGINE DEVELOPMENT HISTORY



XII-1

PANEL OUTLINE

FULL-SCALE FACILITIES
- 10 x 10 FT WIND TUNNEL
- PROPULSION SYSTEMS LAB

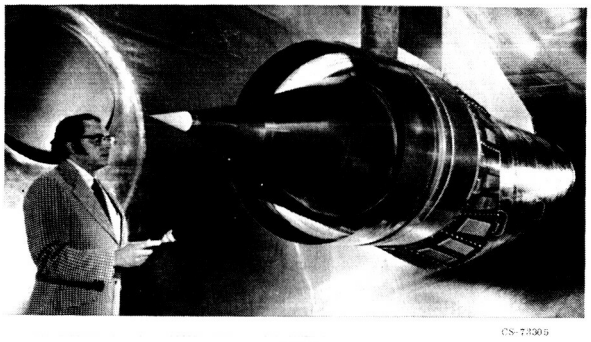
TYPICAL SUPPORT PROGRAMS

FLUTTER PROGRAM

DISTORTION OVERVIEW
- ORIGIN & NATURE OF THE PROBLEM
- STEADY-STATE DISTORTION
- TIME-VARYING DISTORTION
- ANALYTICAL STUDIES

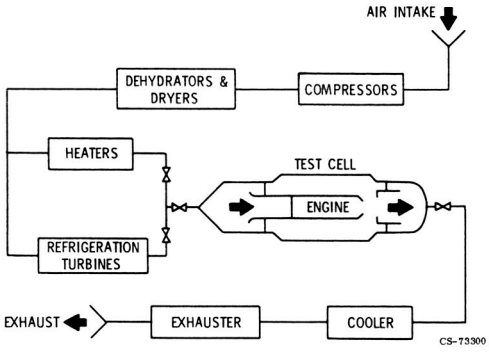
XII-2 CS-73297

INLET AND TF30 TURBOFAN IN 10x10 SWT



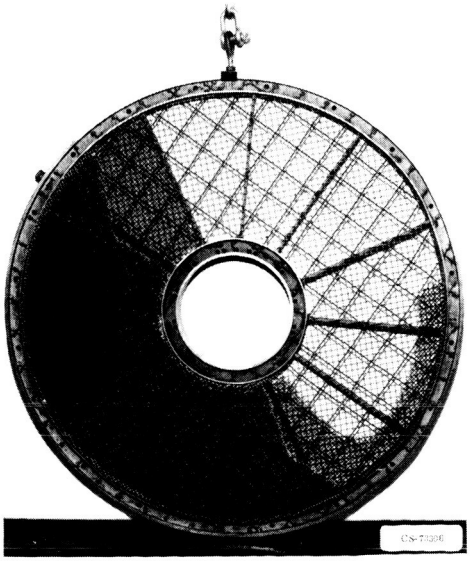
XII-3

PSL SYSTEM SCHEMATIC



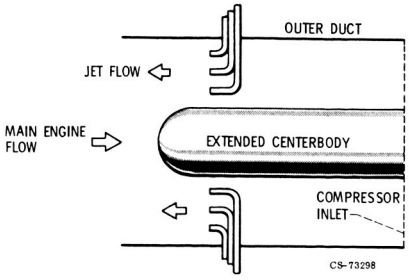
XII-4

TYPICAL DISTORTION SCREEN



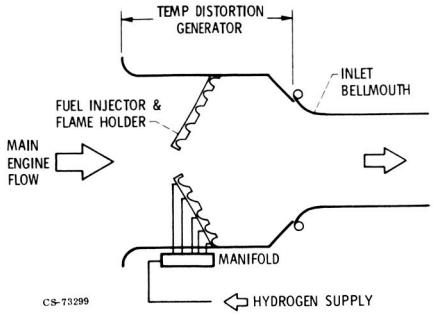
XII-5

SCHEMATIC OF PRESSURE – JET DISTORTION AND PULSE GENERATOR



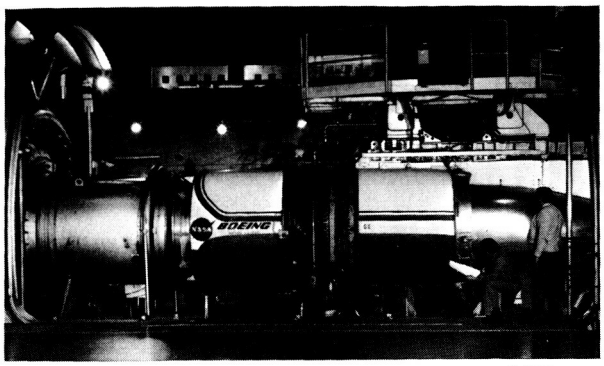
XII-6

HYDROGEN-FUELED TEMPERATURE DISTORTION GENERATOR



XII-7

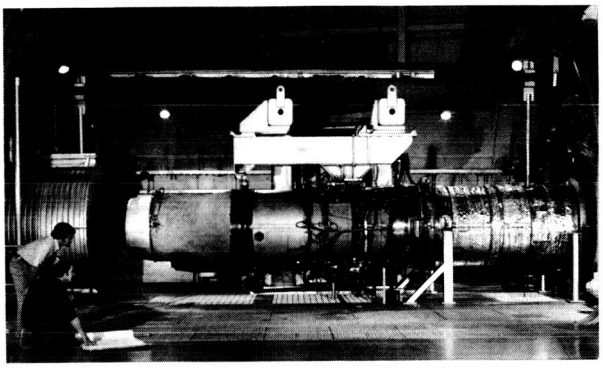
QUIET ENGINE INSTALLED IN PSL



CS-73304

XII-8

REFANNED JT8D INSTALLED IN PSL



CS-73546

XII-9

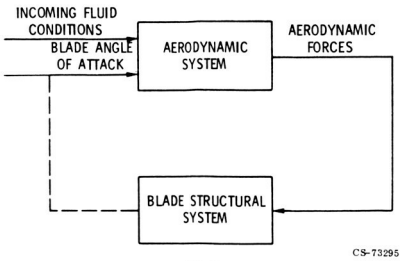
JOINT FULL SCALE ENGINE PROGRAMS

- COMPRESSOR PERFORMANCE
- CONTROLS
- COMPONENT INTERACTION
- FLUTTER

CS-73717

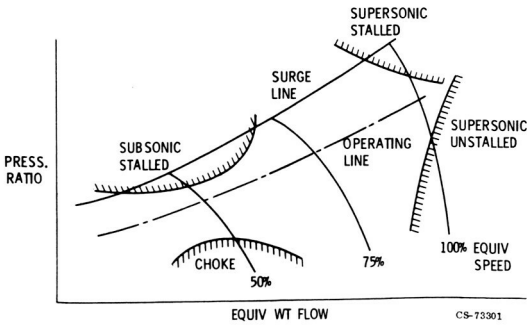
XII-10

FLUTTER MECHANISM



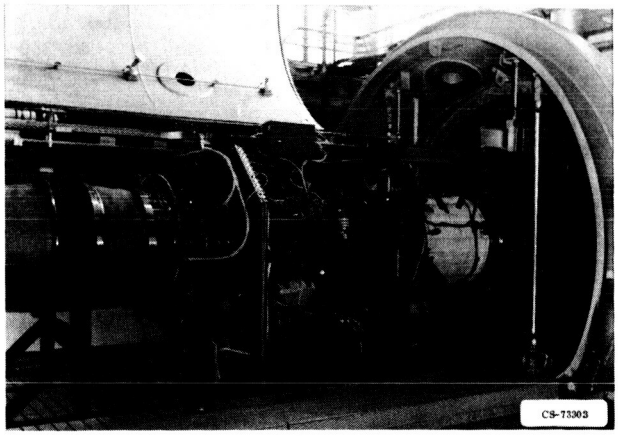
XII-11

AEROELASTIC INSTABILITY REGIONS



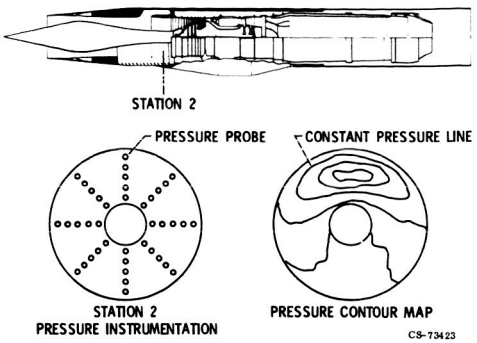
XII-12

F100 ENGINE INSTALLED IN PSL



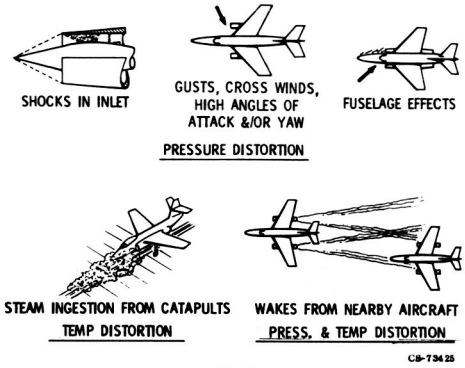
XII-13

INLET DISTORTION



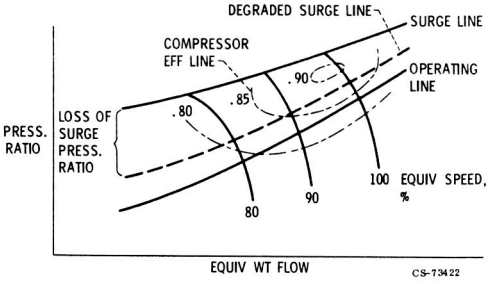
XII-14

SOURCES OF INLET DISTORTION



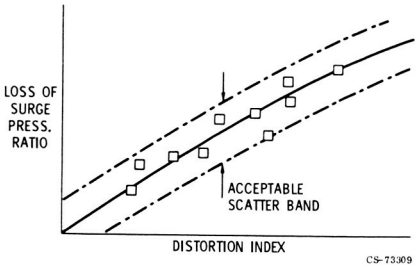
XII-15

COMPRESSOR MAP



XII-16

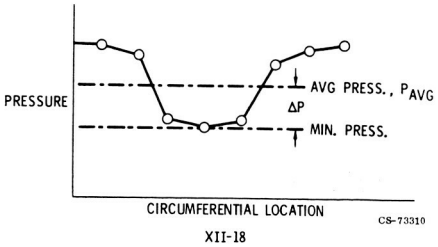
EMPIRICAL DISTORTION CORRELATION



XII-17

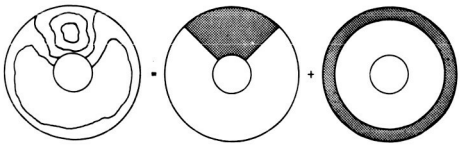
EXAMPLE OF SIMPLE INDEX

$$\text{INDEX} = \frac{\Delta P}{P_{AVG}}$$



XII-18

DISTORTION PATTERN COMPONENTS



$$\begin{bmatrix}\text{COMPLEX}\\ \text{INDEX}\end{bmatrix} = \begin{bmatrix}\text{CIRCUMFERENTIAL}\\ \text{INDEX}\end{bmatrix} + B \begin{bmatrix}\text{RADIAL}\\ \text{INDEX}\end{bmatrix}$$

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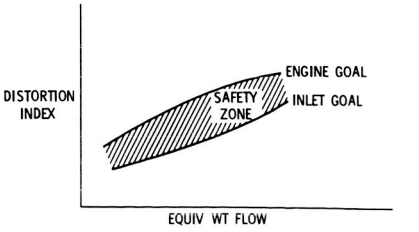
XII-19

PROPULSION SYSTEM INTERFACE AGREEMENT



XII-20

DISTORTION PROGRAM OBJECTIVES

DEVELOP A TECHNOLOGY BASE TO:

- INCREASE UNDERSTANDING
- ESTIMATE EFFECTS OF DISTORTION
- DEVELOP BETTER DESCRIPTORS
- REDUCE AMOUNT OF EXPERIMENTAL DATA

XII-21 CS-73308

ORDER OF PRESENTATION

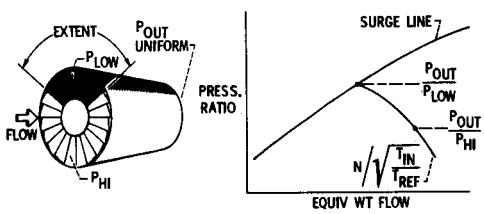
STEADY STATE DISTORTION
- EMPIRICAL METHOD
- SIMPLE COMPRESSOR MODEL
- DETAILED COMPRESSOR MODEL

TIME VARIANT DISTORTION
- EMPIRICAL METHOD
- INSTANTANEOUS INDEX
- ANALYTICAL MODEL

XII-22 CS-73307

PARALLEL COMPRESSOR MODEL

CIRCUMFERENTIAL PRESSURE DISTORTION



$$\text{PARALLEL COMPRESSOR INDEX} = \frac{P_{AVG} - P_{LOW}}{P_{AVG}} \times 100$$

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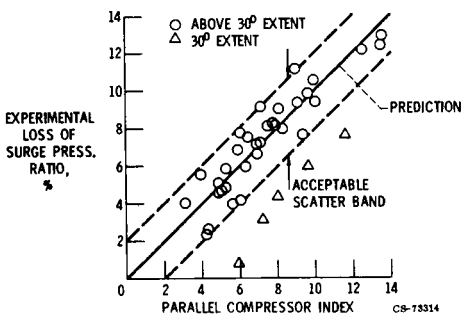
XII-23

PARALLEL COMPRESSOR MODEL RESULTS

CIRCUMFERENTIAL PRESSURE DISTORTIONS



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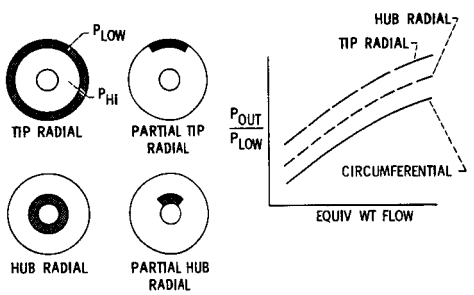
XII-24

PARALLEL COMPRESSOR MODEL

RADIAL PRESSURE DISTORTIONS



$$\text{PARALLEL COMPRESSOR INDEX} = \frac{P_{AVG} - KP_{LOW}}{P_{AVG}} \times 100$$

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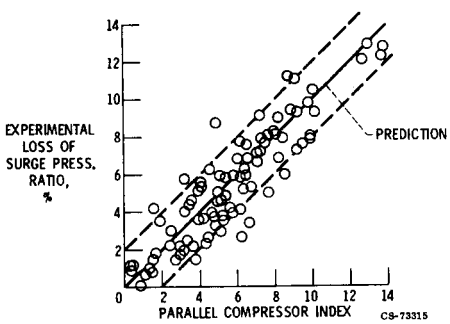
XII-25

PARALLEL COMPRESSOR MODEL RESULTS

COMPLEX PRESSURE DISTORTIONS



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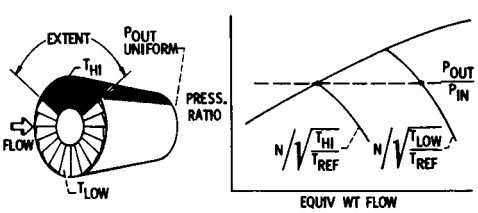
XII-26

PARALLEL COMPRESSOR MODEL

CIRCUMFERENTIAL TEMP DISTORTION



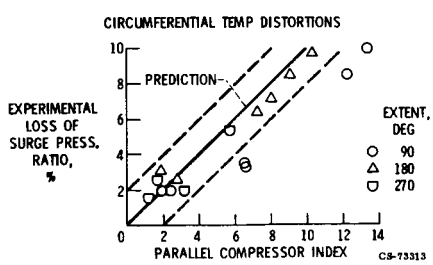
$$\text{PARALLEL COMPRESSOR INDEX} = \frac{T_{HI} - T_{AVG}}{T_{AVG}} \, SF\left(N/\sqrt{\frac{T_{AVG}}{T_{REF}}}\right)$$

CS-73424

XII-27

PARALLEL COMPRESSOR MODEL RESULTS

CIRCUMFERENTIAL TEMP DISTORTIONS

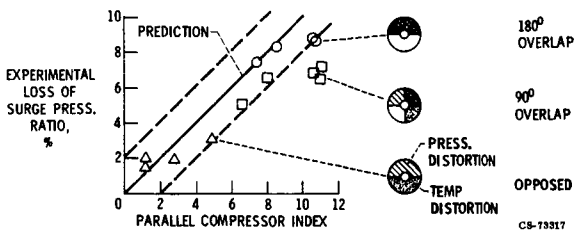


CS-73313

XII-28

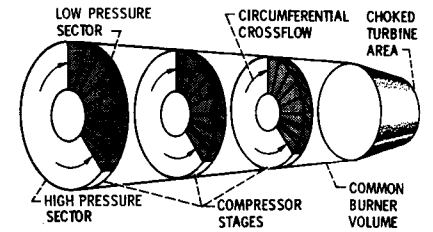
PARALLEL COMPRESSOR MODEL RESULTS

COMBINED PRESSURE & TEMP DISTORTIONS



XII-29

ANALYTICAL DISTORTION MODEL



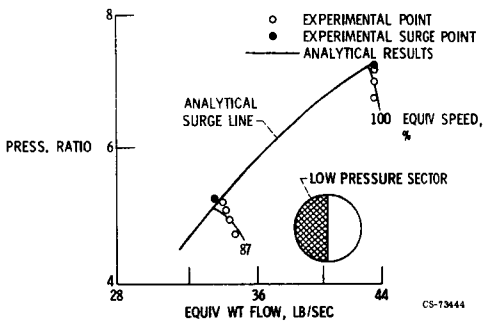
- PARALLEL CALCULATIONS FOR HIGH AND LOW PRESSURE SECTORS
- STAGE-BY-STAGE PERFORMANCE & DYNAMICS
- CIRCUMFERENTIAL CROSSFLOW
- DYNAMIC SURGE PREDICTION
- EFFICIENT DIGITAL CALCULATION

CS-73448

XII-30

ANALYTICAL AND EXPERIMENTAL RESULTS

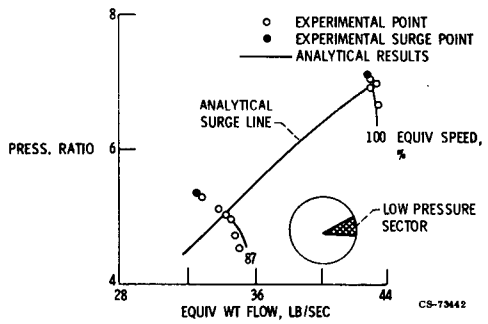
180 DEG CIRCUMFERENTIAL DISTORTION, NO CROSSFLOW



XII-31

ANALYTICAL AND EXPERIMENTAL RESULTS

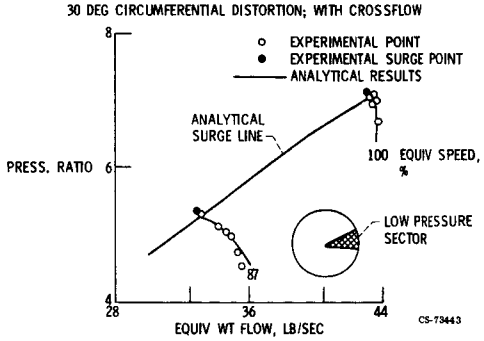
30 DEG CIRCUMFERENTIAL DISTORTION; NO CROSSFLOW



XII-32

ANALYTICAL AND EXPERIMENTAL RESULTS

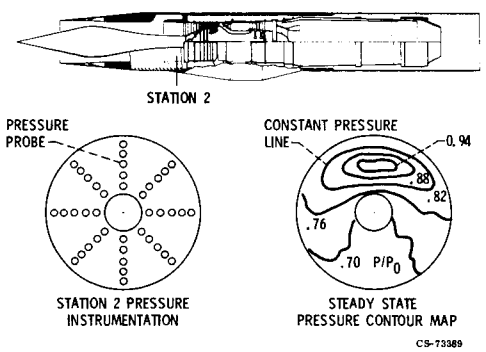
30 DEG CIRCUMFERENTIAL DISTORTION; WITH CROSSFLOW



XII-33

INLET DISTORTION

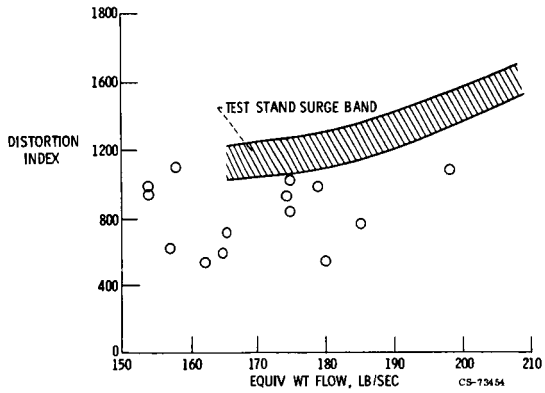
STEADY STATE



XII-34

F-III FLIGHT TEST DATA

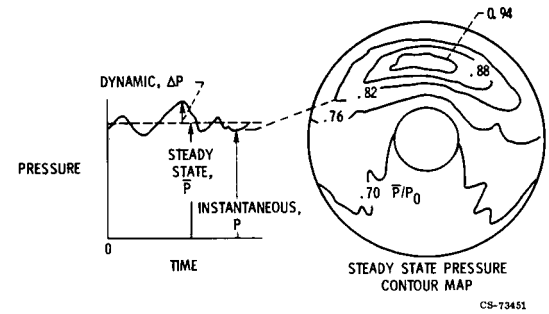
STEADY STATE DISTORTION INDEX



XII-35

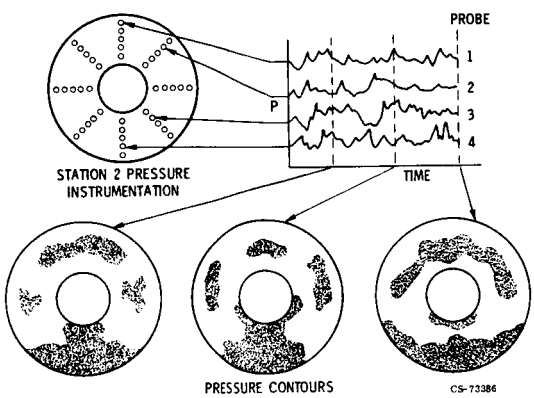
INLET DISTORTION

INSTANTANEOUS



XII-36

INSTANTANEOUS PRESSURE CONTOURS



XII-37

TIME-VARIANT
DISTORTION METHODS

STATISTICAL (RMS)

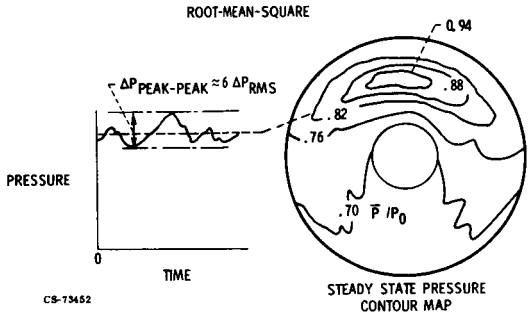
INSTANTANEOUS

CS-73600

XII-38

INLET DISTORTION

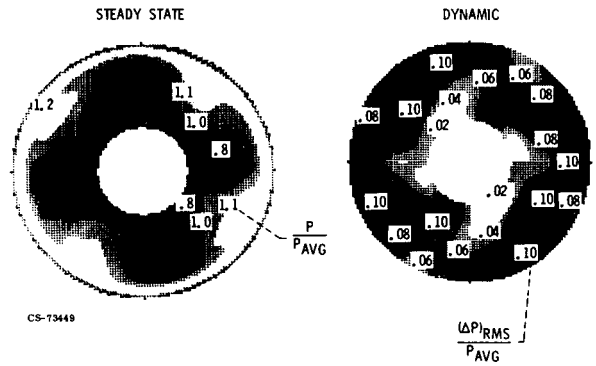
ROOT-MEAN-SQUARE



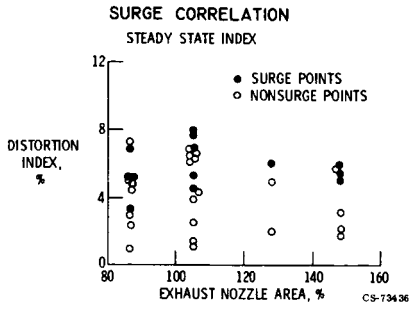
XII-39

PRESSURE CONTOURS

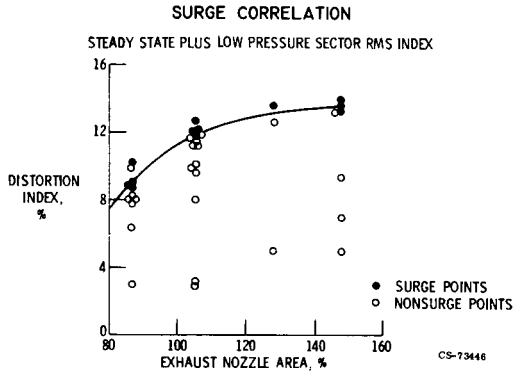
ZERO ANGLE-OF-ATTACK; TF30-P-3



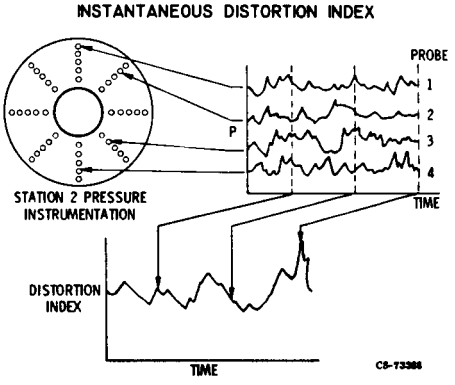
XII-40



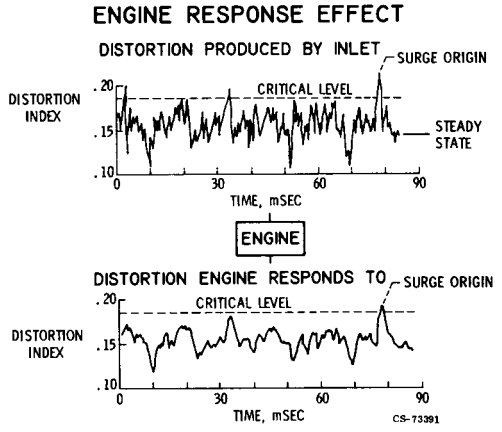
XII-41



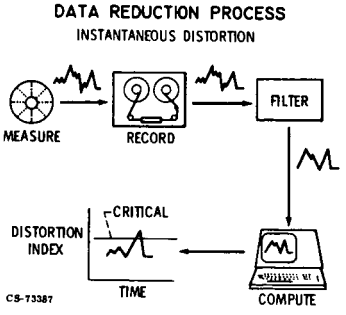
XII-42



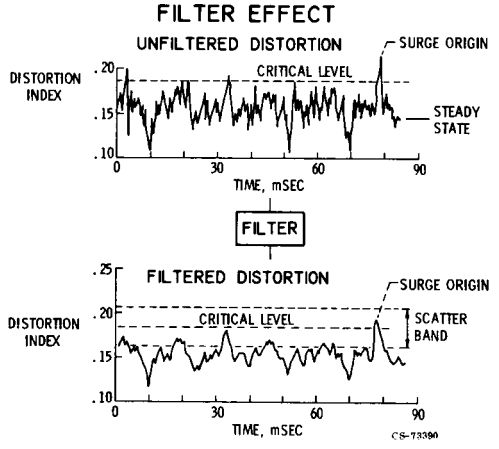
XII-43



XII-44

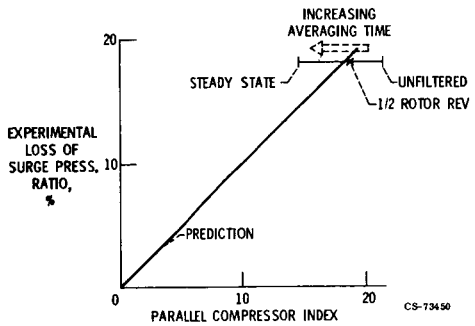


XII-45



XII-46

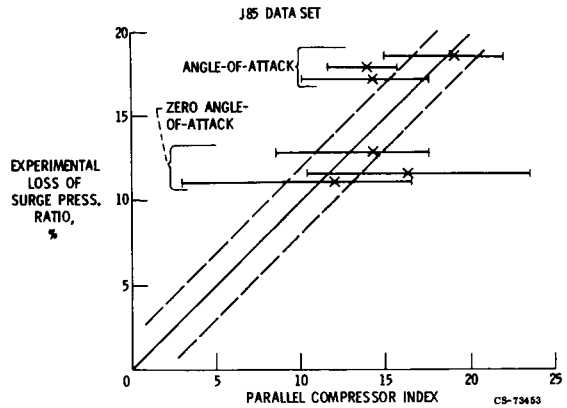
FILTER EFFECT ON PEAK DISTORTION



XII-47

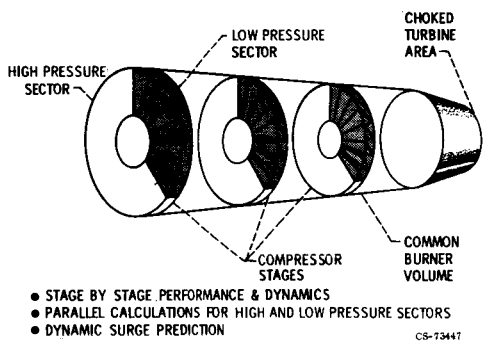
FILTER EFFECT ON PEAK DISTORTION

J85 DATA SET



XII-48

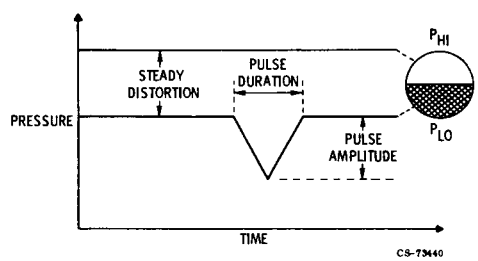
ANALYTICAL DISTORTION MODEL



- STAGE BY STAGE PERFORMANCE & DYNAMICS
- PARALLEL CALCULATIONS FOR HIGH AND LOW PRESSURE SECTORS
- DYNAMIC SURGE PREDICTION

XII-49

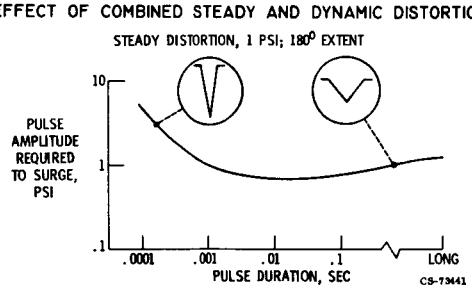
INLET PRESSURES FOR COMBINED STEADY AND DYNAMIC DISTORTIONS



XII-50

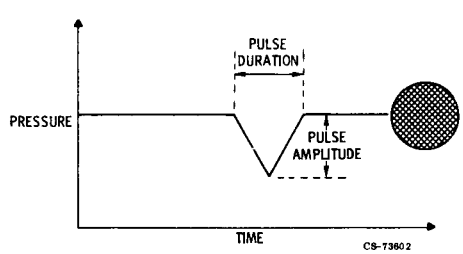
EFFECT OF COMBINED STEADY AND DYNAMIC DISTORTION

STEADY DISTORTION, 1 PSI; 180° EXTENT



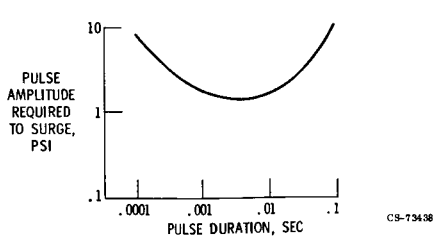
XII-51

FULL-FACE AVERAGE PULSE



XII-52

EFFECT OF FULL-FACE PRESSURE PULSE



XII-53

SUMMARY

DISTORTION DESCRIPTORS
- CONTRACTUAL INTERFACE
- COMPONENT EVALUATION

EMPIRICAL METHODS
- CONCEPTUALLY SIMPLE
- REQUIRE EXTENSIVE TESTING

ANALYTICAL MODELS
- REDUCE TEST REQUIREMENTS
- INCREASE UNDERSTANDING

FURTHER WORK REQUIRED
- INTERNAL FLOW
- TIME VARIATIONS

CS-73296

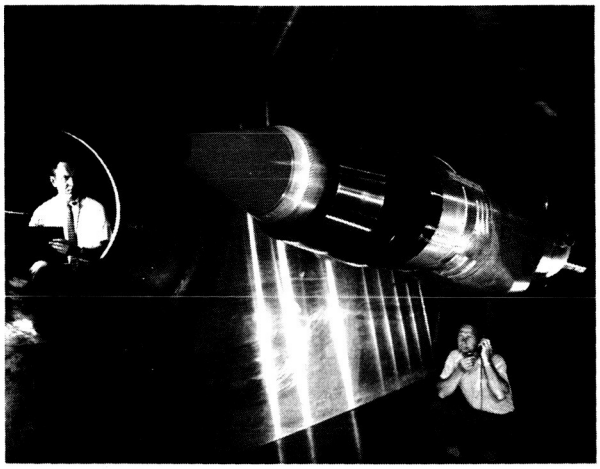
XII-54

XIII. PROPULSION SYSTEMS TECHNOLOGY

Kirby W. Hiller, Chairman
Peter G. Batterton
Paul L. Burstadt
John R. Szuch

SUPERSONIC CRUISE PROPULSION SYSTEM

TURBOJET



CS-73362

XIII-1

SUPERSONIC CRUISE PROPULSION SYSTEM

TURBOFAN

CS-73361

XIII-2

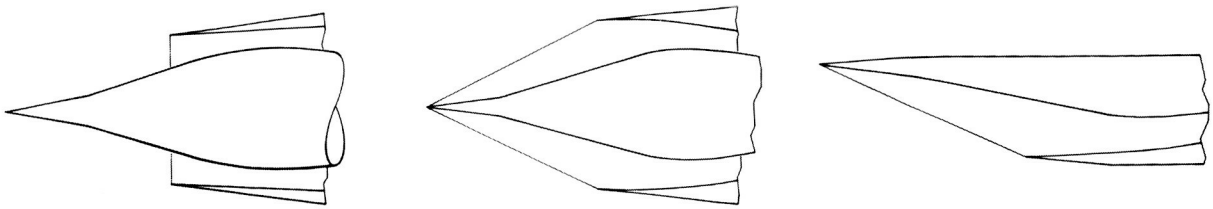
PROPULSION SYSTEMS TECHNOLOGY

- ⇨ INLET DESIGN
- INLET CONTROL
- INTEGRATED INLET-ENGINE CONTROL
- SYSTEM SIMULATION
- APPLICATIONS OF CONTROL THEORY

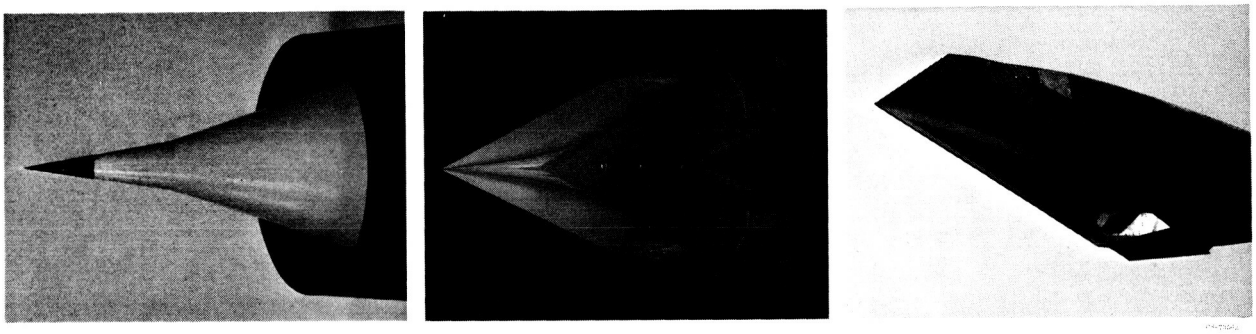
CS-73365

XIII-3

INLET CONCEPTS

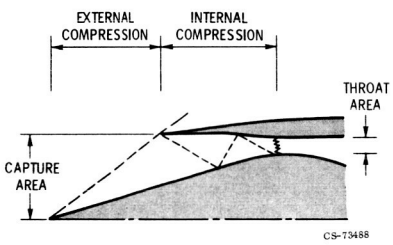


AXISYMMETRIC | TWO-DIMENSIONAL DOUBLE WEDGE | TWO-DIMENSIONAL SINGLE WEDGE



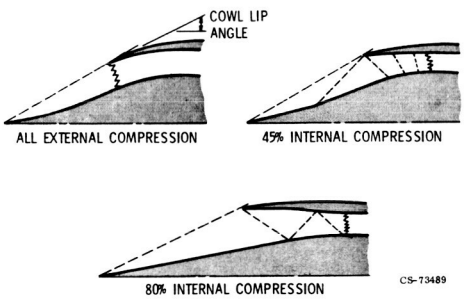
XIII-4

DEFINITION OF INTERNAL COMPRESSION



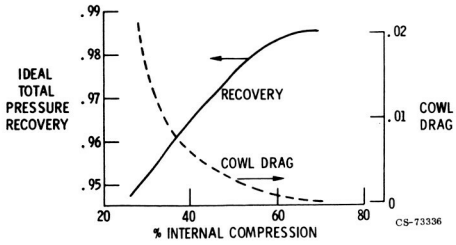
XIII-5

ALTERNATE INLET DESIGNS



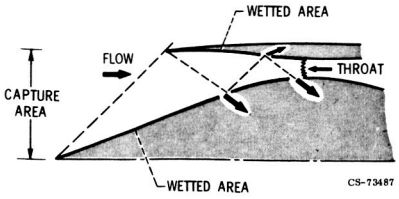
XIII-6

EFFECT OF INTERNAL COMPRESSION ON TOTAL PRESSURE RECOVERY AND DRAG
MACH 2.5



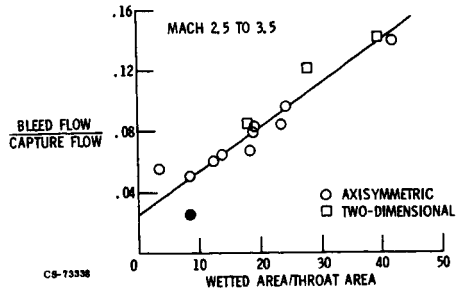
XIII-7

BOUNDARY LAYER BLEED IN A SUPERSONIC INLET



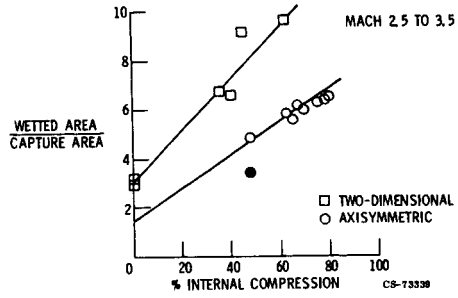
XIII-8

CORRELATION OF BLEED FLOW WITH WETTED AREA



XIII-9

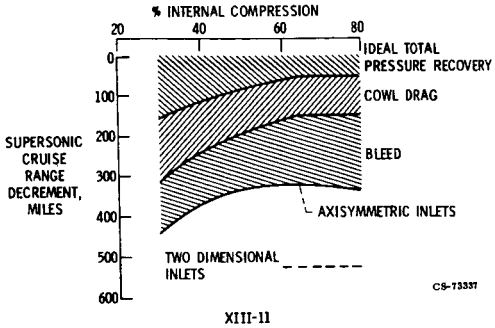
CORRELATION OF WETTED AREA WITH INTERNAL COMPRESSION



XIII-10

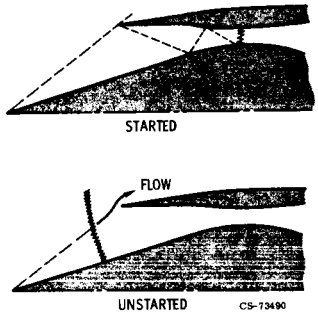
EFFECT OF INTERNAL COMPRESSION ON RANGE

MACH 2.5



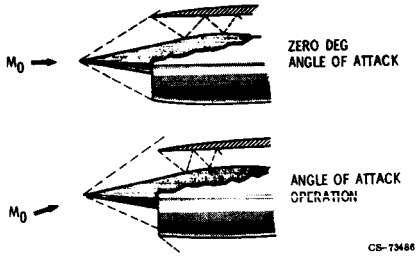
XIII-11

INLET OPERATION



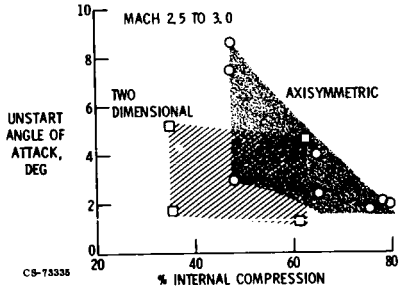
XIII-12

MODIFICATION OF INLET SHOCK STRUCTURE AT ANGLE OF ATTACK



XIII-13

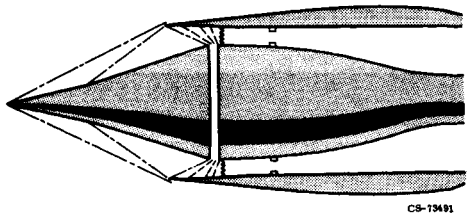
ANGLE OF ATTACK LIMITS FOR INLETS



XIII-14

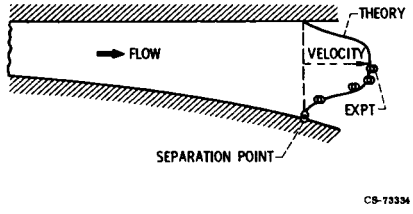
LOW BLEED INLET

45% INTERNAL COMPRESSION
MACH 2.5
AXISYMMETRIC



XIII-15

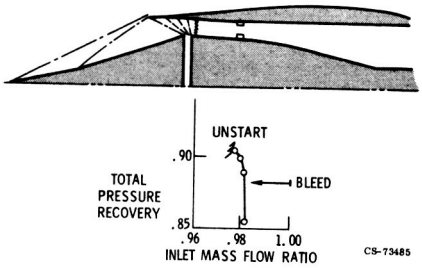
FLOW SEPARATION IN THE SUBSONIC DIFFUSER



XIII-16

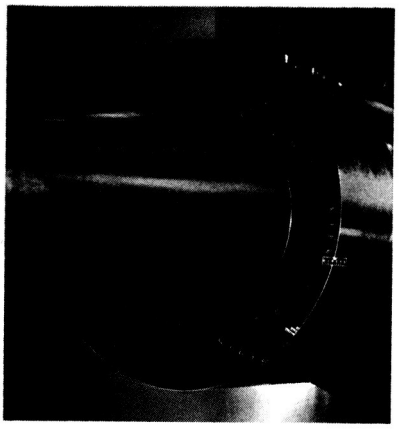
LOW BLEED INLET

45% INTERNAL COMPRESSION; MACH 2.5; AXISYMMETRIC



XIII-17

LOW BLEED INLET



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XIII-18

PROPULSION SYSTEMS TECHNOLOGY

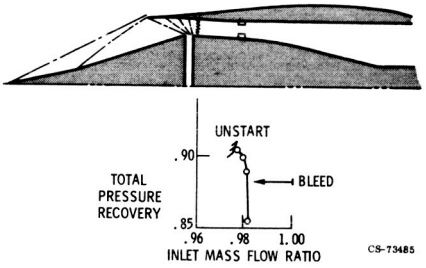
- INLET DESIGN
- ⇨ INLET CONTROL
- INTEGRATED INLET-ENGINE CONTROL
- SYSTEM SIMULATION
- APPLICATIONS OF CONTROL THEORY

CS-73366

XIII-19

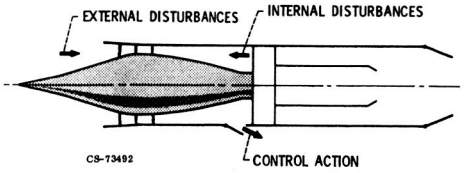
LOW BLEED INLET

45% INTERNAL COMPRESSION; MACH 2.5; AXISYMMETRIC



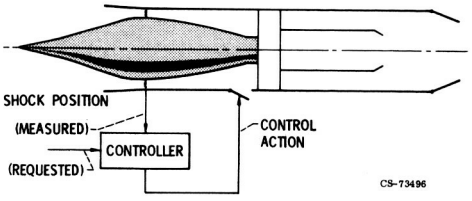
XIII-20

INLET CONTROL PROBLEM



XIII-21

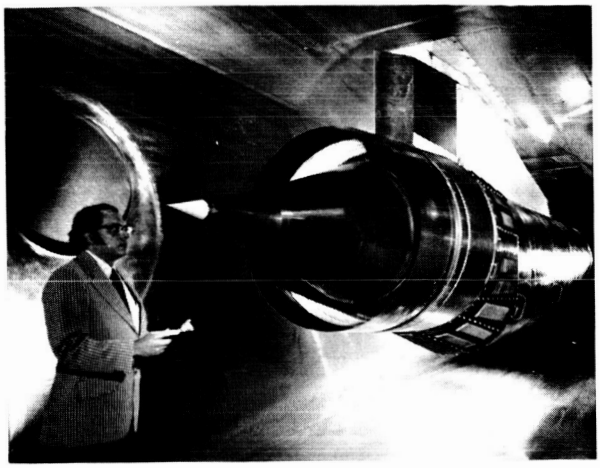
INLET CONTROL WITH BYPASS DOORS



XIII-22

SUPERSONIC CRUISE PROPULSION SYSTEM

TURBOFAN



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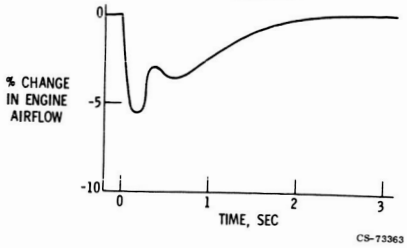
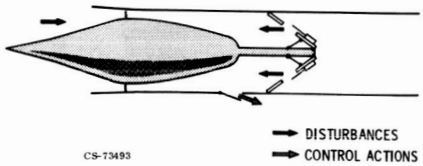
XIII-23

AIRFLOW DISTURBANCE INDUCED BY AFTERBURNER LIGHTOFF



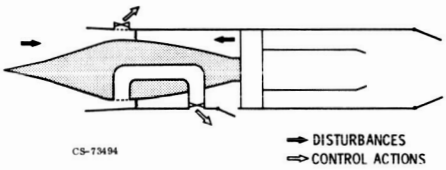
XIII-24

ENGINE SIMULATOR



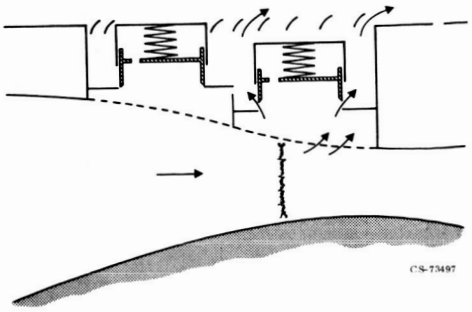
XIII-25

INLET CONTROL WITH THROAT BYPASS



XIII-26

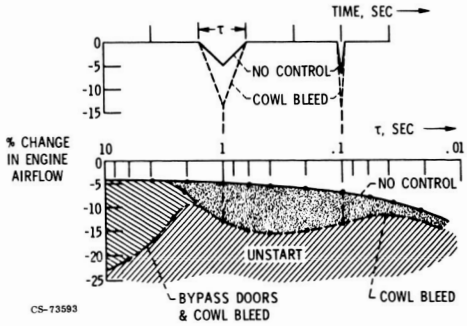
INLET WITH STABILITY VALVES



XIII-27

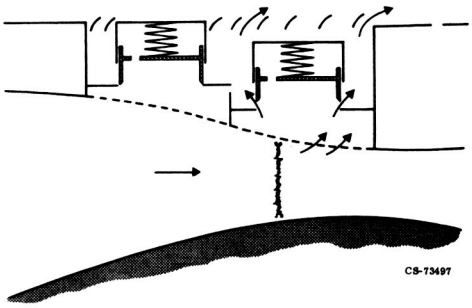
EFFECTIVENESS OF COWL BLEED SYSTEM

YF-12 INLET AT MACH 2.5



XIII-28

INLET WITH STABILITY VALVES



XIII-29

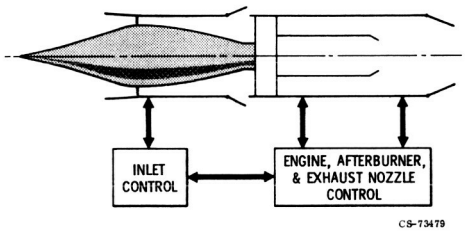
PROPULSION SYSTEMS TECHNOLOGY

- INLET DESIGN
- INLET CONTROL
- ⇨ INTEGRATED INLET-ENGINE CONTROL
- SYSTEM SIMULATION
- APPLICATIONS OF CONTROL THEORY

CS-73367

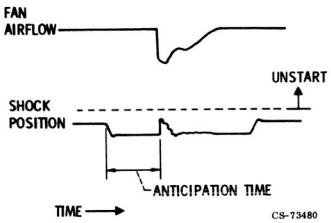
XIII-30

INTEGRATED CONTROL



XIII-31

CONTROL WITH ANTICIPATION FOR AFTERBURNER LIGHT-OFF



XIII-32

IPCS FEATURES

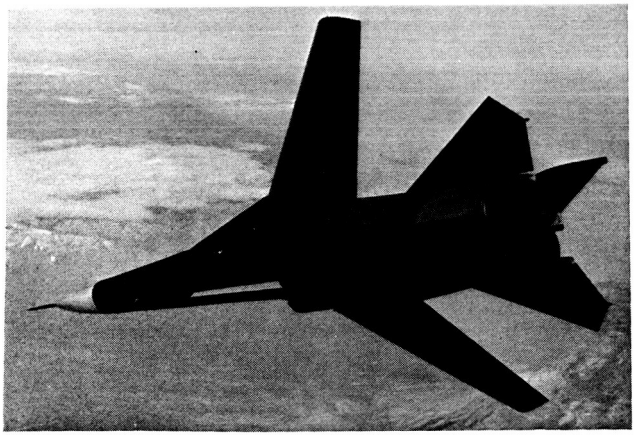
INLET-ENGINE AIRFLOW MATCHING

NEW CONTROL INPUTS
- TURBINE INLET TEMP
- COMPRESSOR DISCHARGE MACH NO.
- INLET BUZZ
- INLET DISTORTION
- A/B RUMBLE

CS-73349

XIII-33

IPCS PROGRAM



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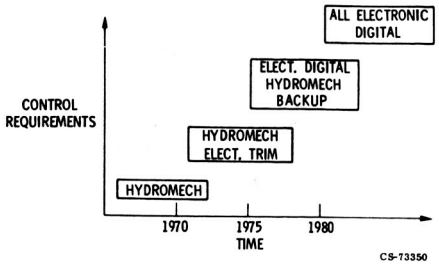
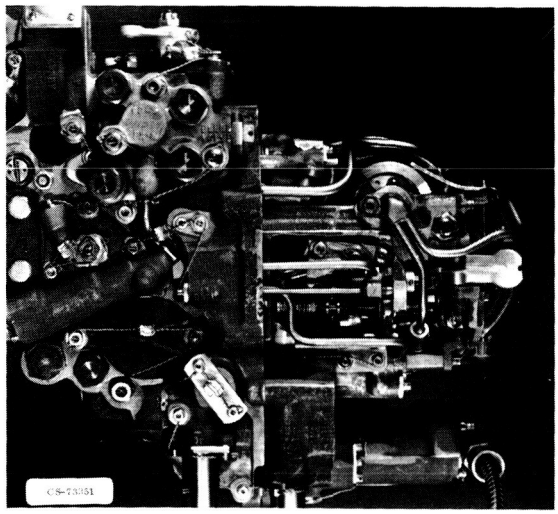
XIII-34

CONTROL MECHANIZATIONS



XIII-35

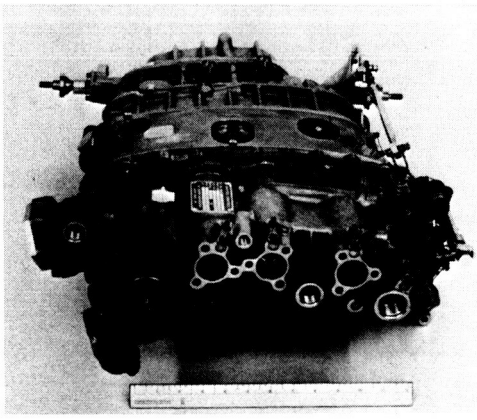
HYDROMECHANICAL FUEL CONTROL-TF 30



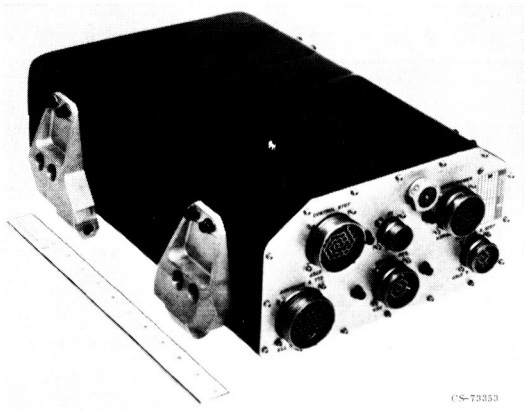
XIII-36

HYDROMECHANICAL ENGINE CONTROL WITH ELECTRONIC TRIM-F100

HYDROMECHANICAL

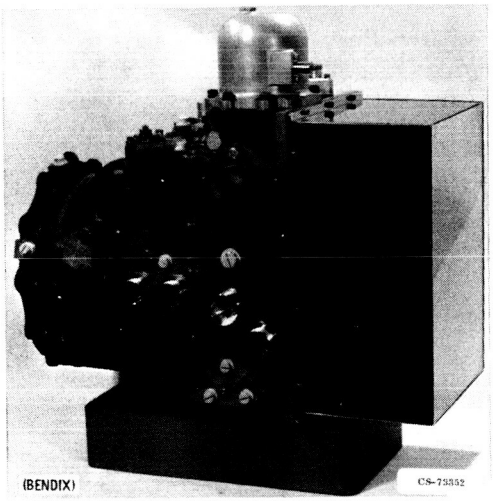


ELECTRONIC TRIM COMPUTER



XIII-37

ALL ELECTRONIC ENGINE CONTROL



XIII-38

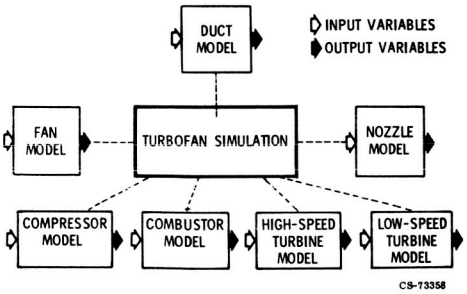
PROPULSION SYSTEMS TECHNOLOGY

- INLET DESIGN
- INLET CONTROL
- INTEGRATED INLET-ENGINE CONTROL
- ⇨ SYSTEM SIMULATION
- APPLICATIONS OF CONTROL THEORY

CS-73368

XIII-39

APPROACH TO SIMULATING COMPLEX SYSTEMS

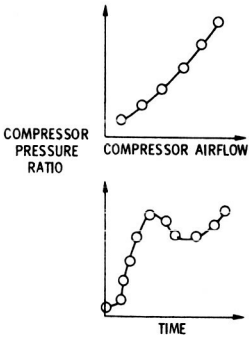


XIII-40

PROPULSION SYSTEM SIMULATIONS

STEADY-STATE
- SOLUTION WITH FIXED
  - FLIGHT CONDITION
  - PILOT COMMANDS
  - SYSTEM PARAMETERS

TRANSIENT
- RESPONSE TO CHANGES IN
  - FLIGHT CONDITION
  - PILOT COMMANDS
  - SYSTEM PARAMETERS



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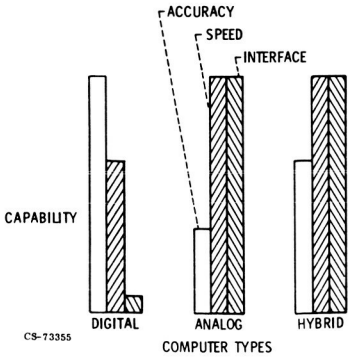
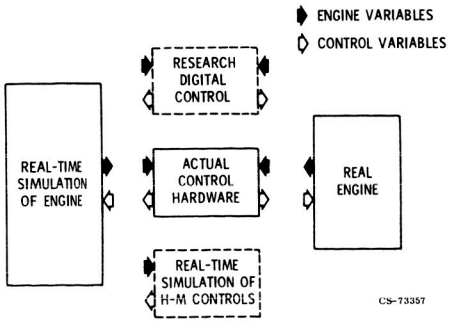
XIII-41

COMPARISON OF COMPUTERS USED FOR SIMULATION



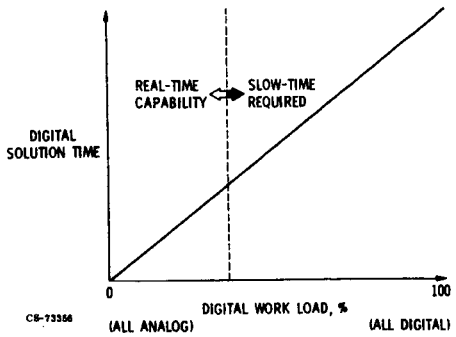
XIII-42

CONTROL SYSTEM EVALUATION USING A REAL-TIME COMPUTER SIMULATION



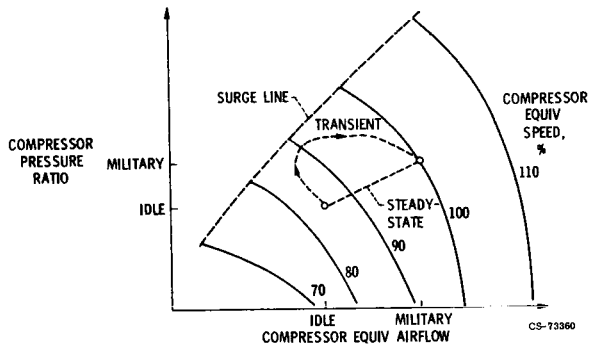
XIII-43

EFFECT OF DIGITAL WORK LOAD ON THE HYBRID COMPUTER



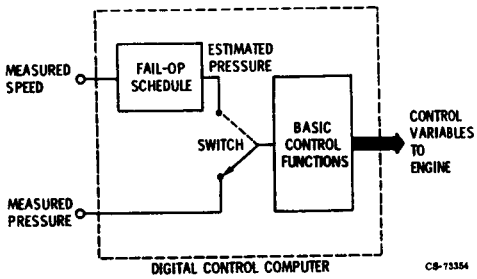
XIII-44

COMPRESSOR TRANSIENT PERFORMANCE



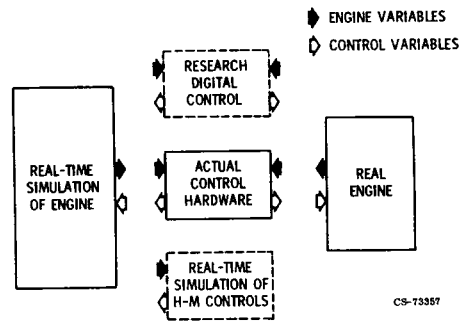
XIII-45

FAIL-OPERATIONAL CONTROL



XIII-46

CONTROL SYSTEM EVALUATION USING A REAL-TIME COMPUTER SIMULATION



XIII-47

PROPULSION SYSTEMS TECHNOLOGY

- INLET DESIGN
- INLET CONTROL
- INTEGRATED INLET-ENGINE CONTROL
- SYSTEM SIMULATION
- ⇨ APPLICATIONS OF CONTROL THEORY

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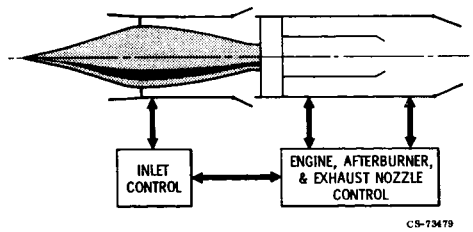
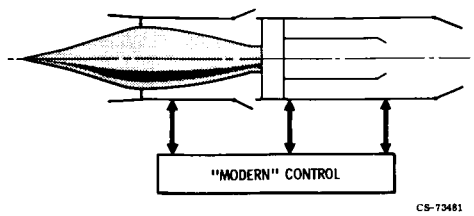
XIII-48

INTEGRATED CONTROL



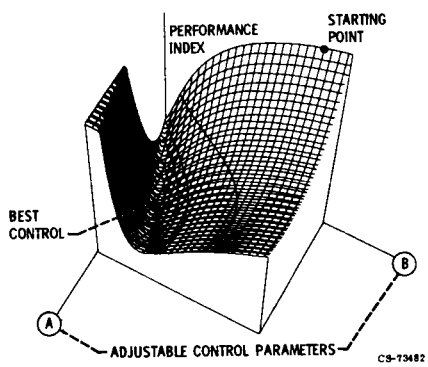
XIII-49

ADVANCED CONTROL THEORY



XIII-50

CONTROL OPTIMIZATION



XIII-51

PROPULSION SYSTEMS TECHNOLOGY

INLET DESIGN

INLET CONTROL

INTEGRATED INLET-ENGINE CONTROL

SYSTEM SIMULATION

APPLICATIONS OF CONTROL THEORY

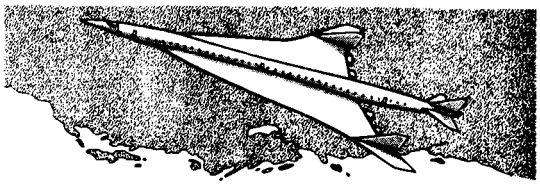
CS-73364

XIII-52

XIV. SUPERSONIC PROPULSION

John B. Whitlow, Jr.

SUPERSONIC CRUISE AIRPLANE & RELATED TECHNOLOGIES



ARROW WING AERODYNAMICS & STRUCTURE
COMPOSITE STRUCTURAL MATERIALS
ACTIVE CONTROLS
ADVANCED PROPULSION SYSTEM

CS-73821

XIV-1

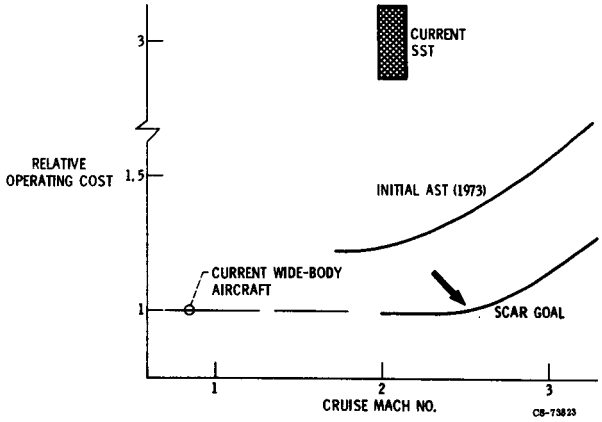
ROADMAP

MISSION CHOICE
CYCLE CONSIDERATIONS
ENGINE EVALUATION
STUDY RESULTS

CS-73812

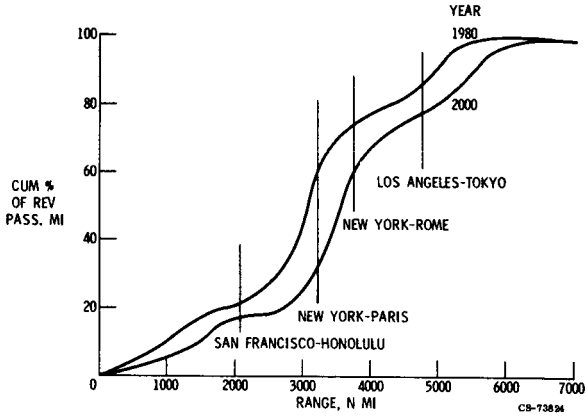
XIV-2

SCAR ECONOMICS



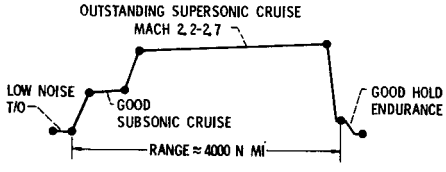
XIV-3

DISTRIBUTION OF REVENUE PASSENGER MILES



XIV-4

TYPICAL SCAR MISSION



XIV-5

ROADMAP

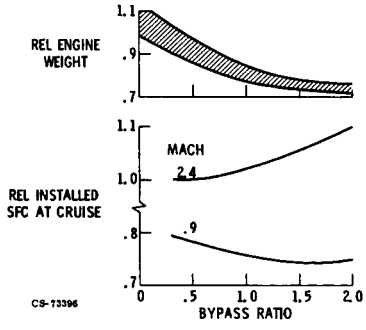
MISSION CHOICE
➡ CYCLE CONSIDERATIONS
ENGINE EVALUATION
STUDY RESULTS

CS-73813

XIV-6

FACTORS TO CONSIDER IN CYCLE SELECTION

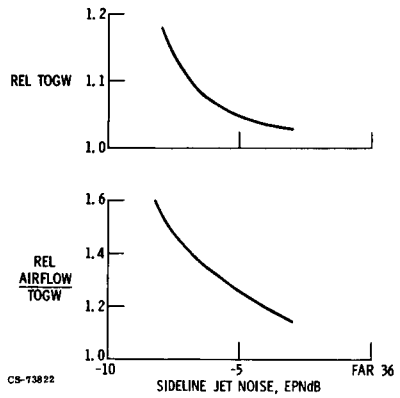
DUCT-BURNING TURBOFAN; CONSTANT NOISE



XIV-7

MORE FACTORS TO CONSIDER

SCAR ENGINES WITH SUPPRESSION



CS-73822

XIV-8

ROADMAP

MISSION CHOICE
CYCLE CONSIDERATIONS
➡ ENGINE EVALUATION
STUDY RESULTS

CS-73814

XIV-9

SCAR ENGINE CANDIDATES

CONVENTIONAL

AFTERBURNING TURBOJET	DUCT BURNING TURBOFAN*
DRY TURBOJET	MIXED FLOW TURBOFAN
	"MINI-BYPASS" TURBOJET*

VARIABLE CYCLE

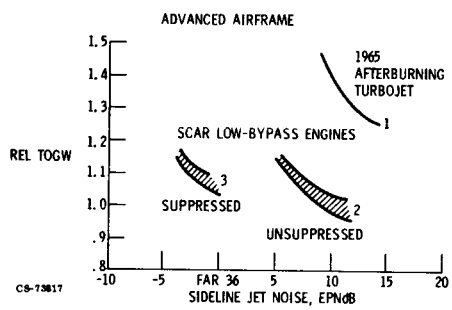
AUXILIARY ENGINE	FRONT VALVE SERIES - PARALLEL
FAN-IN-WING	DUAL VALVE SERIES - PARALLEL
AUGMENTOR WING	REAR VALVE TURBOFAN/TURBOJET*
TURBOFAN-RAMJET	VARIABLE BYPASS, SUPERSONIC FAN*
TURBO-AUGMENTED CYCLE	MMIPS CYCLE
FLEX CYCLE	
TRIPLE ROTOR, MOD AIRFLOW	DUAL CYCLE/DOUBLE BYPASS*

CS-73819

XIV-10

ENGINE COMPARISONS

ADVANCED AIRFRAME

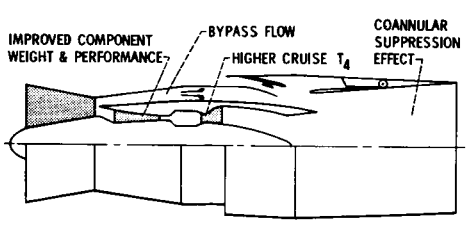


CS-73817

XIV-11

SCAR ENGINE IMPROVEMENTS RELATIVE TO SST

DUCT-BURNING TURBOFAN

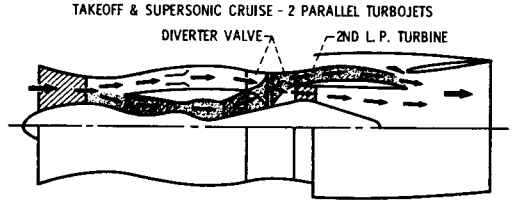


CS-73394

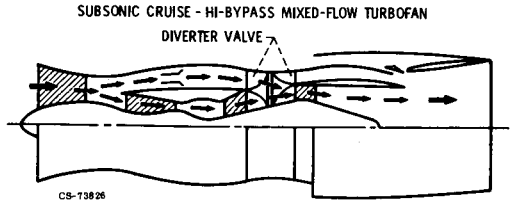
XIV-12

VARIABLE CYCLE CONCEPTS – REAR VALVE VCE

TAKEOFF & SUPERSONIC CRUISE - 2 PARALLEL TURBOJETS



SUBSONIC CRUISE - HI-BYPASS MIXED-FLOW TURBOFAN



CS-73826

XIV-13

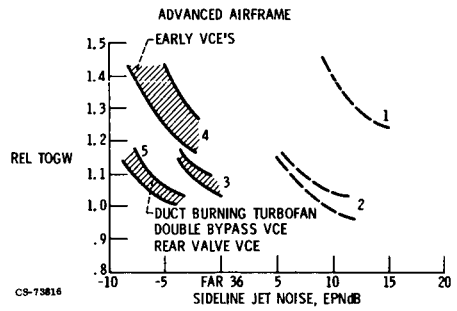
ROADMAP

MISSION CHOICE
CYCLE CONSIDERATIONS
ENGINE EVALUATION
➡ STUDY RESULTS

CS-73815

XIV-15

ENGINE COMPARISONS



CS-73816

XIV-16

TECHNOLOGY FOR SCAR ENGINES

DISCIPLINE	BASE	SPECIFIC
ACOUSTICS	NOISE SOURCES SUPPRESSION	COANNULAR SUPPRESSION FLIGHT EFFECTS
COMBUSTORS	CLEAN PRIMARY COMBUSTORS	LOW CRUISE NOX CLEAN AUGMENTORS
CONTROLS	FULL-AUTHORITY ELECTRONIC	
FANS, COMPRESSORS, & TURBINES	HIGH AERO LOADING ADVANCED COOLING MATERIALS	HIGHLY VARIABLE FLOW LARGE FIBER BAI COMPOSITES
INLETS & NOZZLES	MIXED COMPRESSION INLETS EXHAUST SYSTEM AERO	INLET STABILIZATION COANNULAR NOZZLE AERO SIC COMPOSITES
UNIQUE COMPONENTS		FLOW CONTROL VALVES SUPERSONIC FAN

CS-73820

XIV-17

STUDY RESULTS & OBJECTIVES

	CURRENT AIRCRAFT		SCAR STUDIES	
	WIDE-BODY	CONCORDE	PRESENT	GOAL
TOGW, LB	~750 000	~400 000	760 000	600 000
PAX	~390	~135	290	290
RANGE, N MI	~5000	~3200	~4000	3800-4000
M_{CRUISE}	0.8	~2.0	2.2-2.7	2.2-2.5
90 dB FOOTPRINT, MI^2	~10	~70	~20	10-20
REL OPER COST/ SEAT, MI	1.0	~3.2	~1.4	1.0

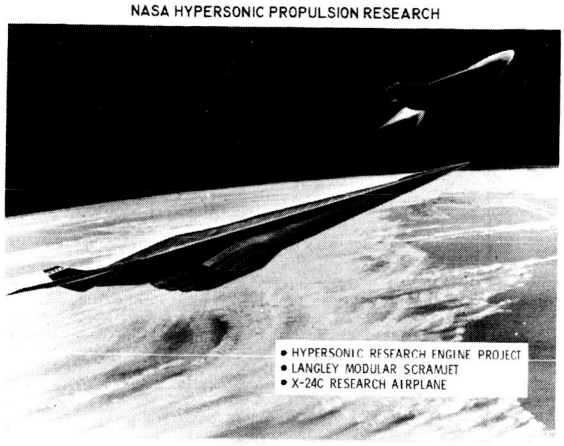
CS-73818

XIV-18

XV. HYPERSONIC PROPULSION

Griffin Y. Anderson

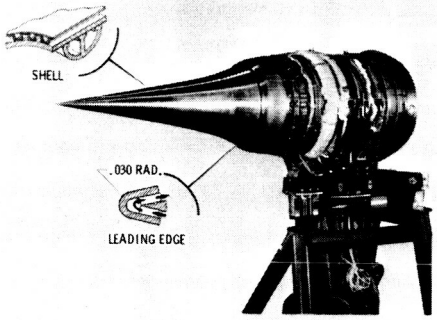
NASA HYPERSONIC PROPULSION RESEARCH



XV-1

NASA HYPERSONIC RESEARCH ENGINE

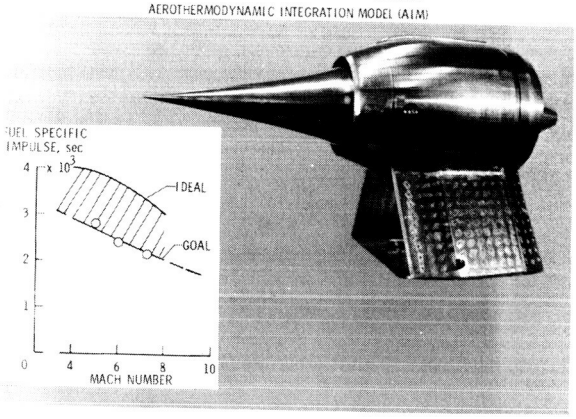
STRUCTURAL ASSEMBLY MODEL (SAM)



XV-2

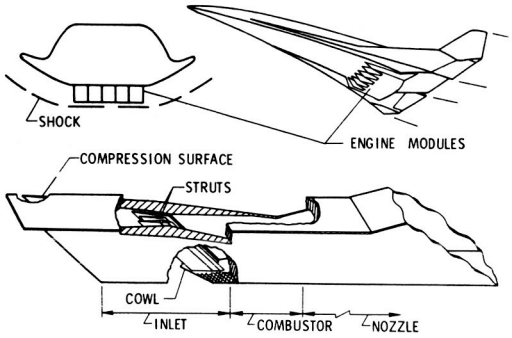
NASA HYPERSONIC RESEARCH ENGINE

AEROTHERMODYNAMIC INTEGRATION MODEL (AIM)



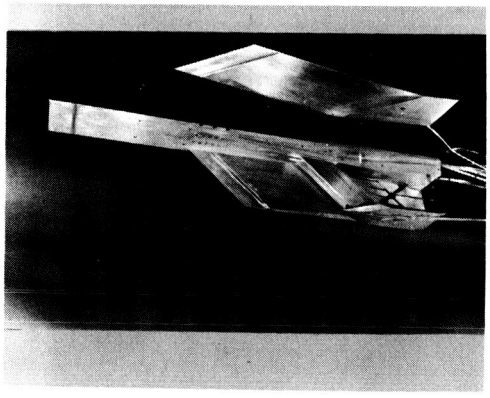
SCRAMJET MODULE CONCEPT

FIXED GEOMETRY MACH 3 TO 10



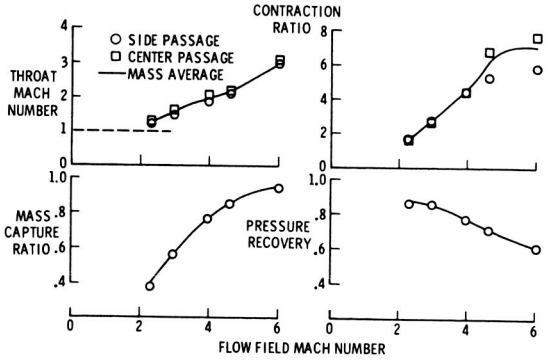
XV-4

SCRAMJET INLET MODEL



XV-5

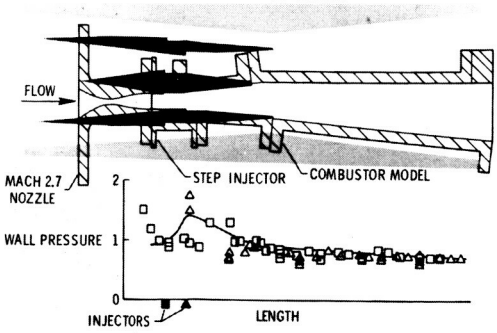
SCRAMJET MODULE INLET PERFORMANCE



XV-6

SCRAMJET COMBUSTOR MODEL

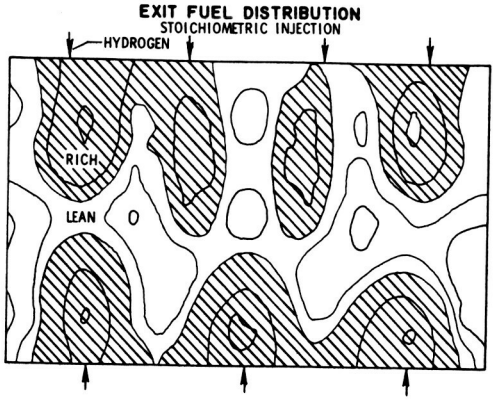
STRUT INJECTOR SIMULATION



XV-7

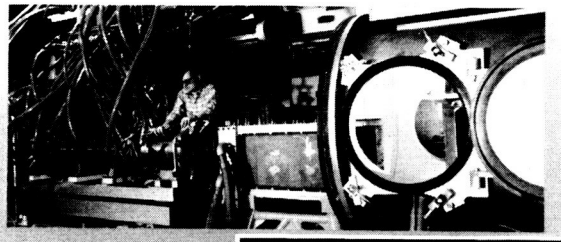
EXIT FUEL DISTRIBUTION

STOICHIOMETRIC INJECTION



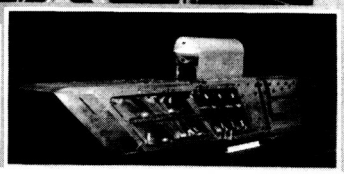
XV-8

MACH 7 SUBSCALE ENGINE TEST FACILITY



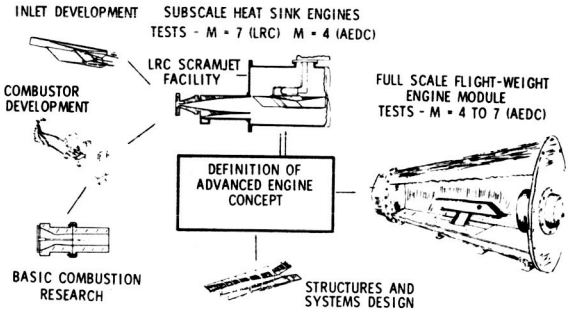
STATUS

- ARC HEATER SHAKEDOWN COMPLETED TO FULL POWER
- FACILITY CALIBRATION IN PROGRESS
- ENGINE MODULE INSTALLATION UNDERWAY



XV-9

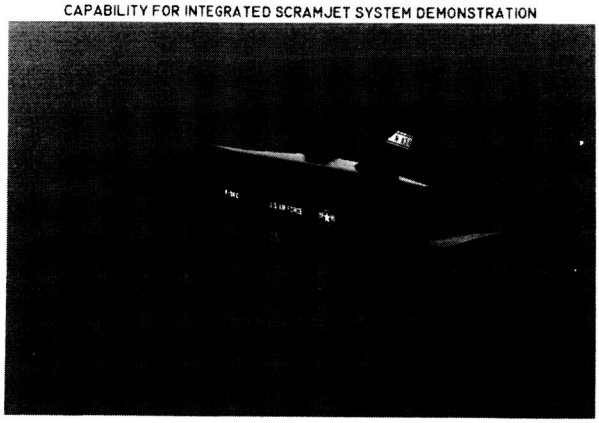
SCRAMJET ENGINE RESEARCH PROGRAM



XV-10

JOINT NASA–USAF X–24C RESEARCH AIRPLANE

CAPABILITY FOR INTEGRATED SCRAMJET SYSTEM DEMONSTRATION



XV-11

NASA HYPERSONIC PROPULSION SUMMARY

HRE ACCOMPLISHMENTS

- COOLED FLIGHT STRUCTURE DEVELOPED
- HIGH LEVELS OF INTERNAL THRUST DEMONSTRATED
- BASIS FOR ON - GOING PROGRAM

LANGLEY MODULAR SCRAMJET RESEARCH PROGRAM

- FOCUS RESEARCH ON ENGINE - AIRFRAME INTEGRATION
- HIGH PERFORMANCE FIXED GEOMETRY INLET DESIGN VERIFIED
- STRUT INJECTOR SIMULATION INDICATES ADEQUATE MIXING
- MACH 7 ENGINE TESTS GETTING UNDERWAY

X-24C RESEARCH AIRPLANE

- VERSATILE DESIGN WITH BROAD FLIGHT RESEARCH CAPABILITY
- OPPORTUNITY FOR COMPLETE SCRAMJET SYSTEM DEMONSTRATION

XV-12