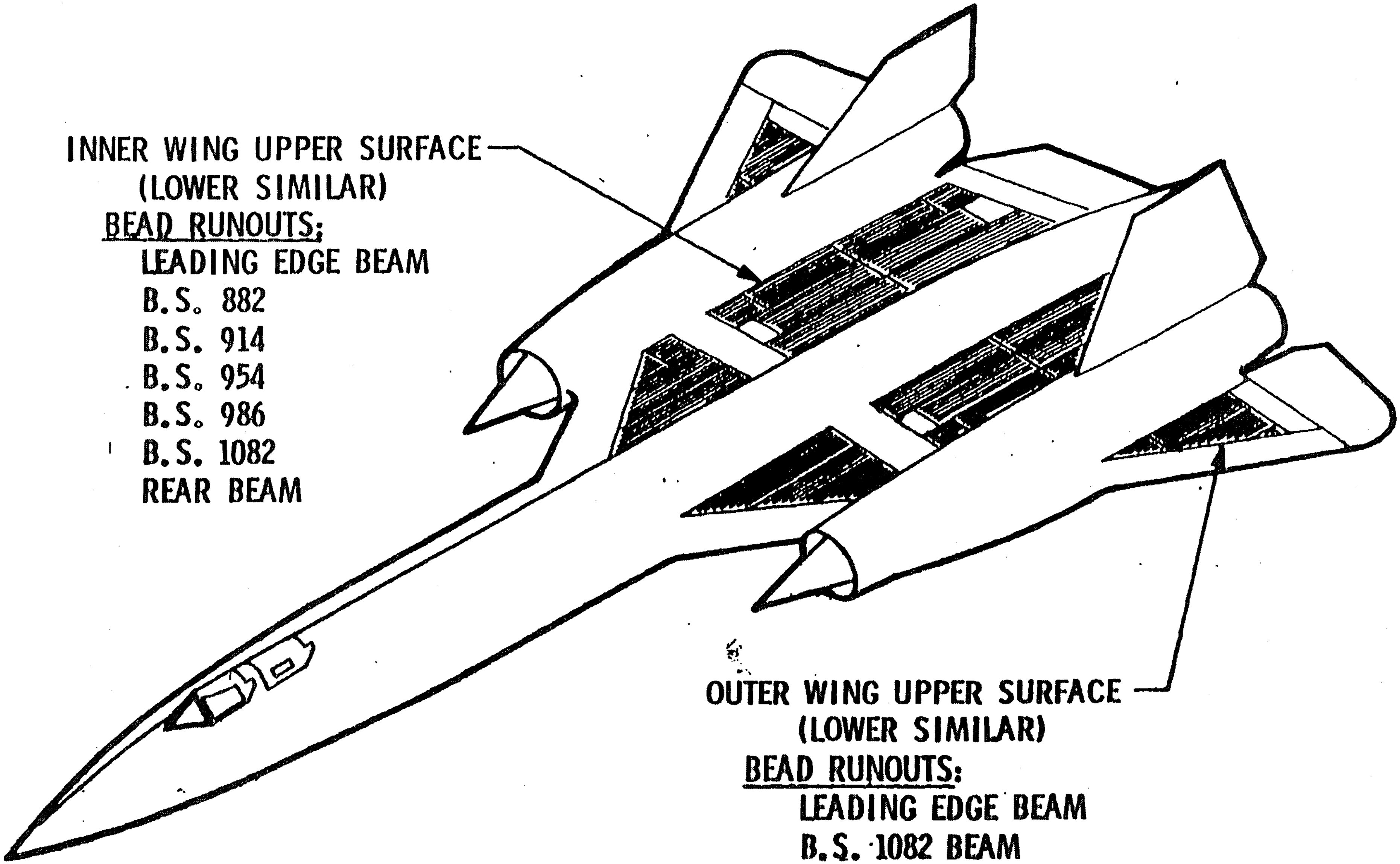
SR-71 BEADED S[illegible] WING SURFACES



PLASTIC PANEL USAGE

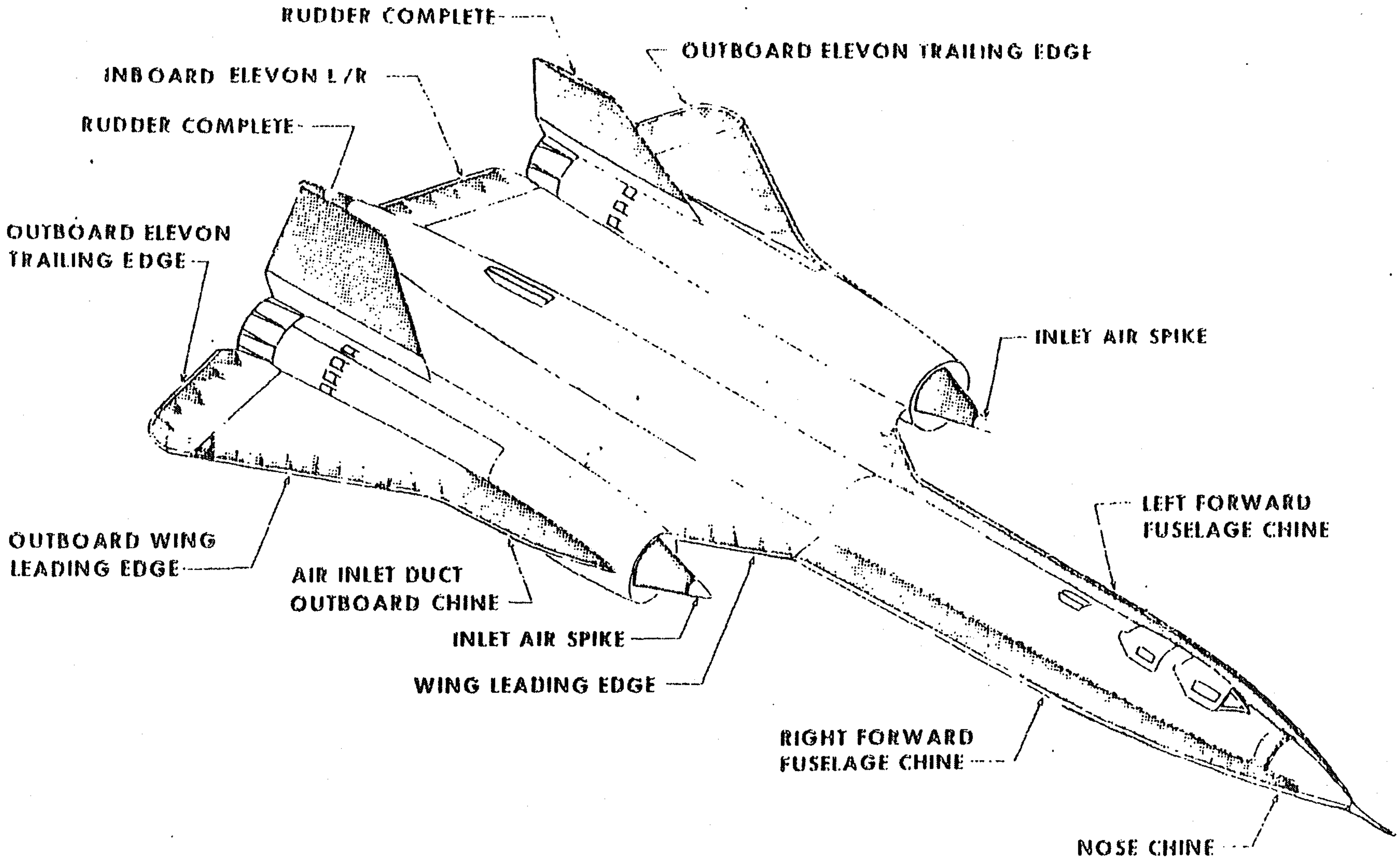
IN ORDER TO PROVIDE THE REQUIRED LEVEL OF "STEALTH" THERE WAS A LARGE AMOUNT OF EDGE TREATMENT PROVIDED IN THE FORM OF PLASTIC PANELS.

THESE PANELS WERE SUBJECTED TO TEMPERATURES IN THE RANGE OF 550°F. THIS NECESSITATED DEVELOPMENT OF COMPOSITES AND RESINS NOT YET IN EXISTENCE.

THE VERTICAL FINS USED ON THE EARLY A-12 AIRPLANES WERE FULLY STRUCTURAL COMPONENTS. MOST OF THE REMAINING PLASTIC PARTS WERE CONSIDERED AS SECONDARY STRUCTURE. HOWEVER, THEY WERE REQUIRED TO CONFORM TO ALL LOCAL AIRLOADING AND THERMAL GRADIENT LOADS.

THE WINDSHIELD AND CANOPY TRANSPARENCIES WERE LAMINATED QUARTZ GLASS.

PLASTIC P. NEL USAGE



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TANK SEALING

ALL WING FUEL TANKS ARE ACCESSED BY REMOVING UPPER SURFACE PANELS FROM THE WING .

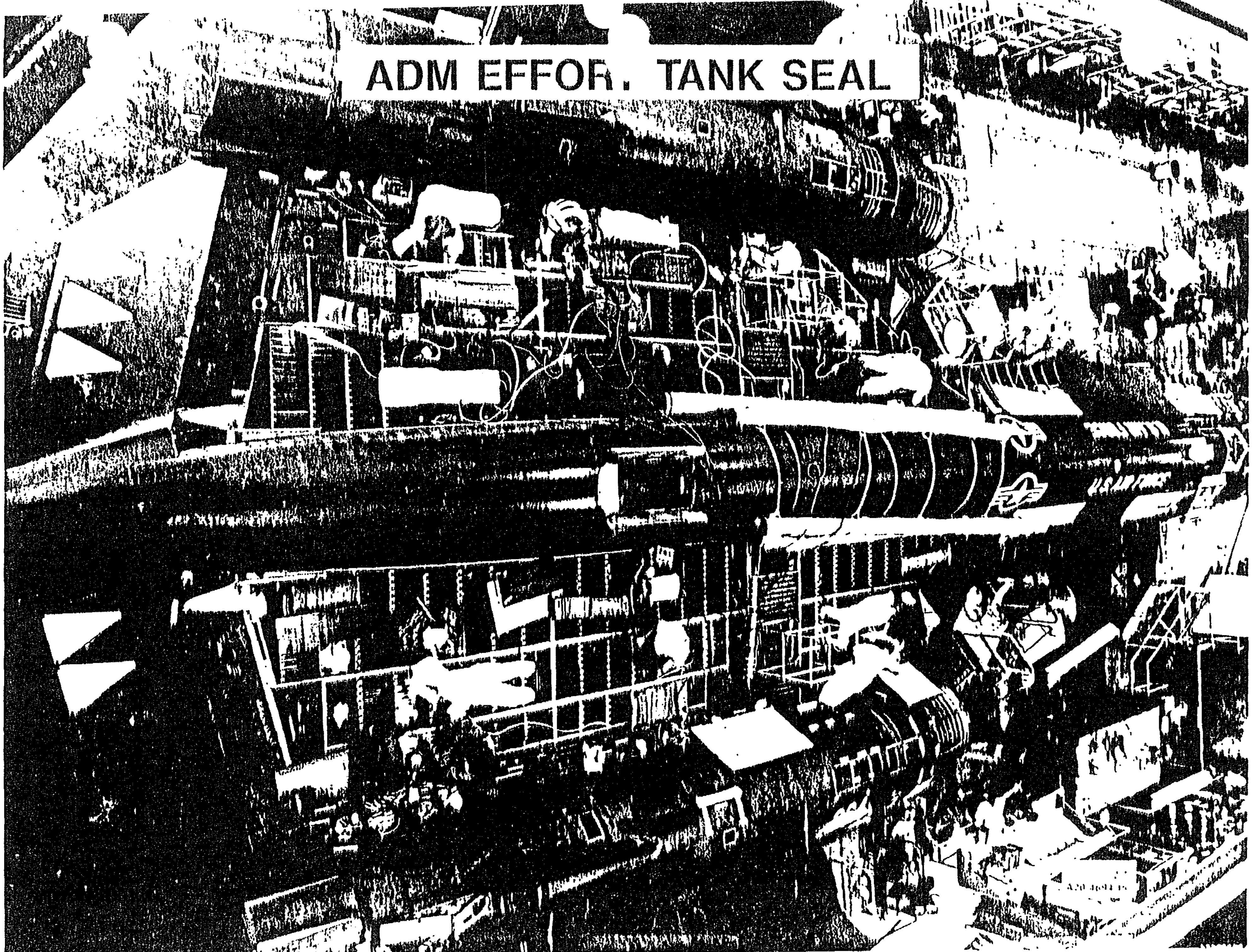
THE ESPECIALLY DEVELOPED TANK SEALANT MATERIAL IS APPLIED THROUGH UPPER SURFACE ACCESS.

THE UPPER SURFACE PANELS ARE SEALED AGAINST THE SUBSTRUCTURE USING TEFLON VOLUME COMPRESSED SEAL WINGS AND STRIPS.

THE DIFFICULTY IN SEALING THE FUEL TANK HAS BEEN A CONTINUING AND BOTHERSOME PROBLEM THROUGHOUT THE "BLACKBIRD" OPERATION. HOWEVER, THE PARTICULAR FUEL WE ARE USING HAS A HIGH FLASH POINT AND DOES NOT CONSTITUTE A SAFETY HAZARD

THE DRAG CHUTE CAVITY IS SHOWN WITH THE DOORS IN THE OPEN (DEPLOY) POSITION.

THE UPPER FULCRUM FOR THE LANDING GEAR IS EXPOSED BY UPPER SURFACE PANEL REMOVAL.


ADM EFFOR. TANK SEAL

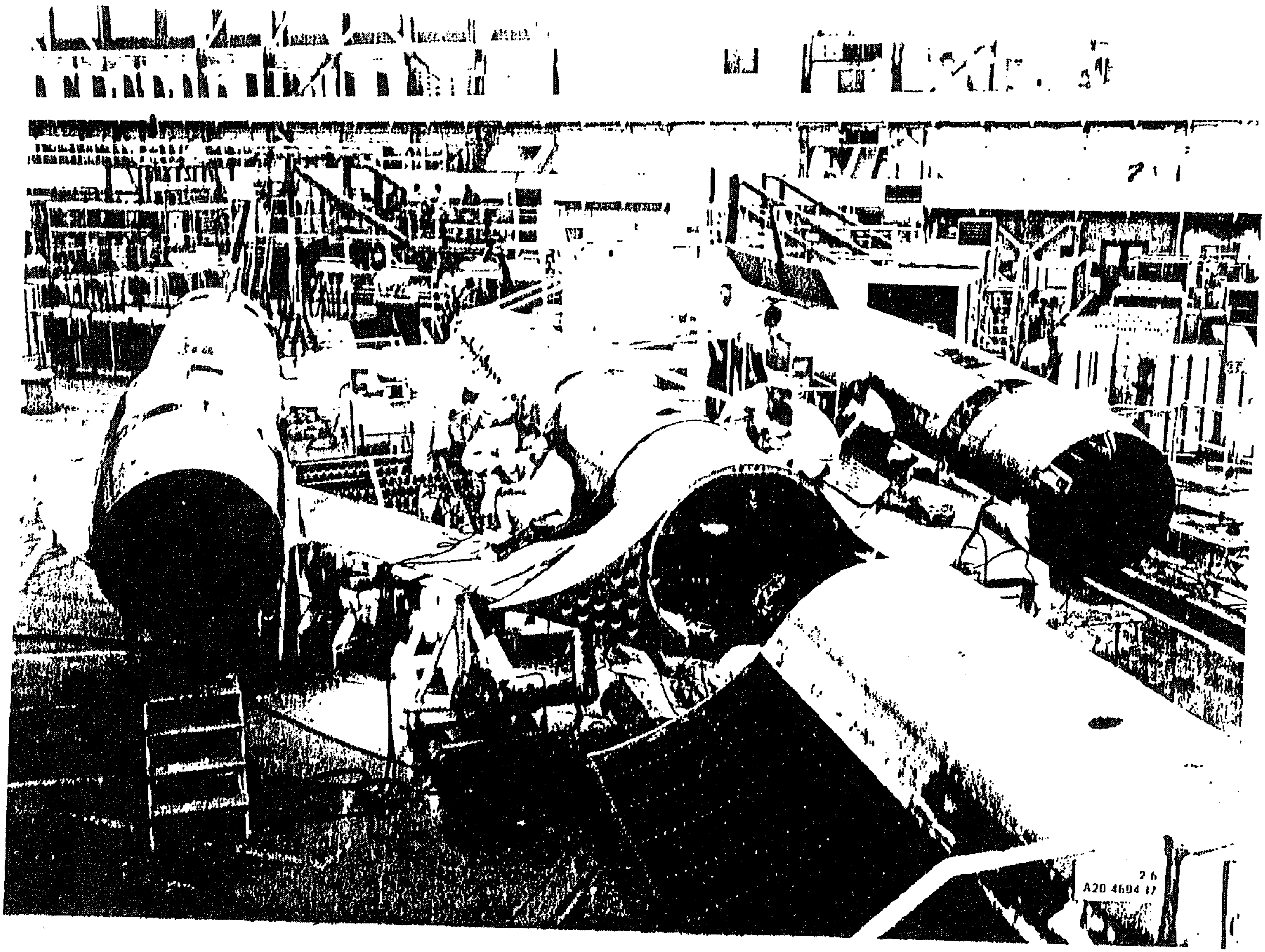
STA "715"

THE STA "715" JOINT IS A MANUFACTURING JOINT BETWEEN THE FUSELAGE FOREBODY AND THE WING/AFT FUSELAGE ASSEMBLY.

THE RIGHT HAND WING FROM CENTERLINE TO WING TIP, INCLUDING THE NACELLE, WAS BUILT AS ONE SUB-ASSEMBLY. THE LEFT HAND SIDE WAS BUILT SIMILARLY. THEN THE RIGHT HAND AND THE LEFT HAND WERE JOINED ALONG THE CENTERLINE, TOP AND BOTTOM, INCLUDING THE WING SPARS.

NOTE THE STEEL POSTS FOR MOUNTING AND HINGING THE MOVING VERTICAL TAIL SURFACES.

DURING
ORIGINAL M NUFACTURE



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MATERIAL SELECTION

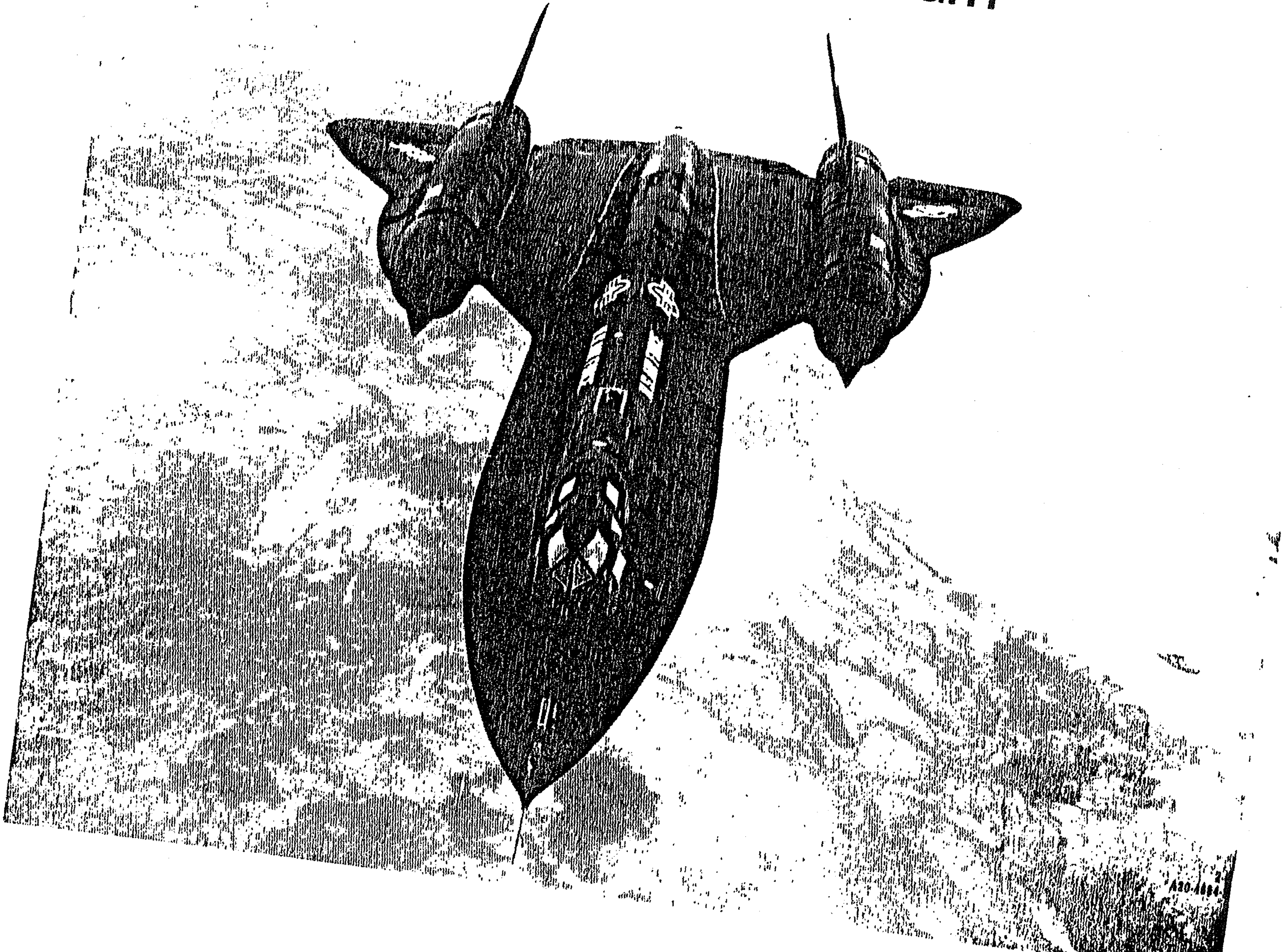
GENERALLY, MATERIAL SELECTION IS BASED UPON THE FOLLOWING:

- PROPERTIES
- AVAILABILITY
- FABRICABILITY
- ENDURANCE
- COST
- ENVIRONMENTAL/HEALTH AND SAFETY CONSIDERATIONS

THE SR-71, HOWEVER, IS A MACH 3+ AIRCRAFT. THE ABOVE CONSIDERATIONS WERE OF NECESSITY SKEWED TOWARDS PROPERTIES AT TEMPERATURE BECAUSE OF THE REQUIREMENT THAT VIRTUALLY ALL OF THE MATERIALS WERE SUBJECTED TO TEMPERATURES WELL ABOVE THOSE NORMALLY ENCOUNTERED IN HIGH PERFORMANCE JET AIRCRAFT.

NOTE THAT IN TODAY'S ENVIRONMENT MORE ATTENTION MUST BE PAID TO ENVIRONMENTAL HEALTH/SAFETY CONSIDERATIONS. THESE CONCERNS HAVE, FOR EXAMPLE, ADVANCED THE STATE THE ART IN AIRCRAFT PAINTS WITH THE DEVELOPMENT OF WATER REDUCIBLE PAINTS.

THE BLACKBI D IN-FLIGHT



THERMAL REQUIREMENTS

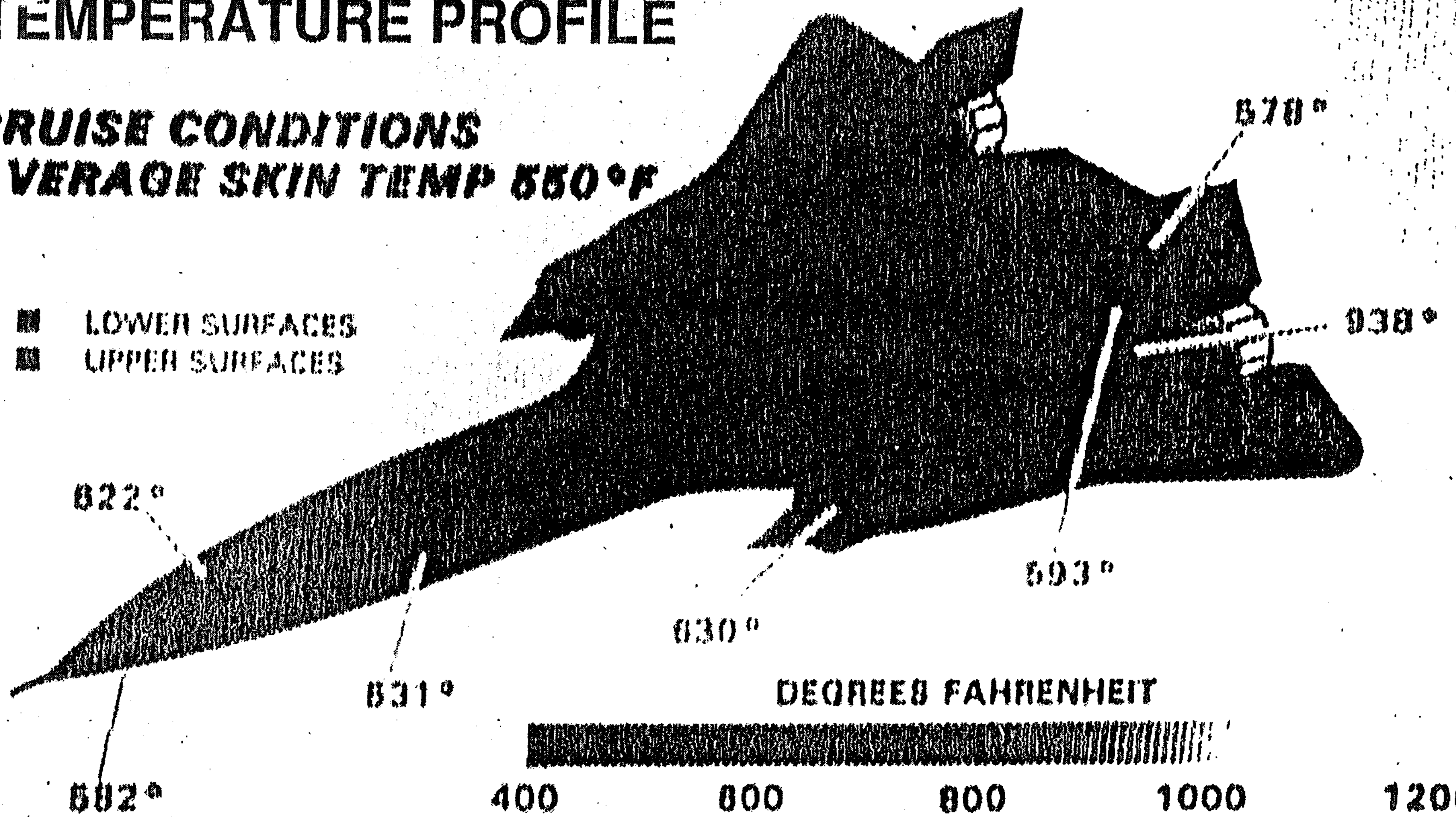
THE THERMAL ENVIRONMENT AT OPERATIONAL SPEED NECESSITATED THE DEVELOPMENT AND USE OF MATERIALS HERETOFORE UNTRIED IN THE AVIATION INDUSTRY.

- THE TITANIUM INDUSTRY WAS IN ITS INFANCY.
- FIBER REINFORCED PLASTICS WERE VIRTUALLY UNHEARD OF EXCEPT FOR FIBERGLASS. USE AT ELEVATED TEMPERATURE WAS OUT OF THE QUESTION.
- WINDSHIELDS WERE NOT DEVELOPED THAT COULD SUSTAIN THE TEMPERATURES REQUIRED.
- HYDRAULIC FLUID WAS NOT CAPABLE OF OPERATING AT THE 600° F REQUIRED IN THE SR-71.
- SEALANTS HAD TO BE DEVELOPED FOR OPERATING AT REQUIRED TEMPERATURES.

TEMPERATURE PROFILE

CRUISE CONDITIONS
AVERAGE SKIN TEMP 550°F

- LOWER SURFACES
- UPPER SURFACES

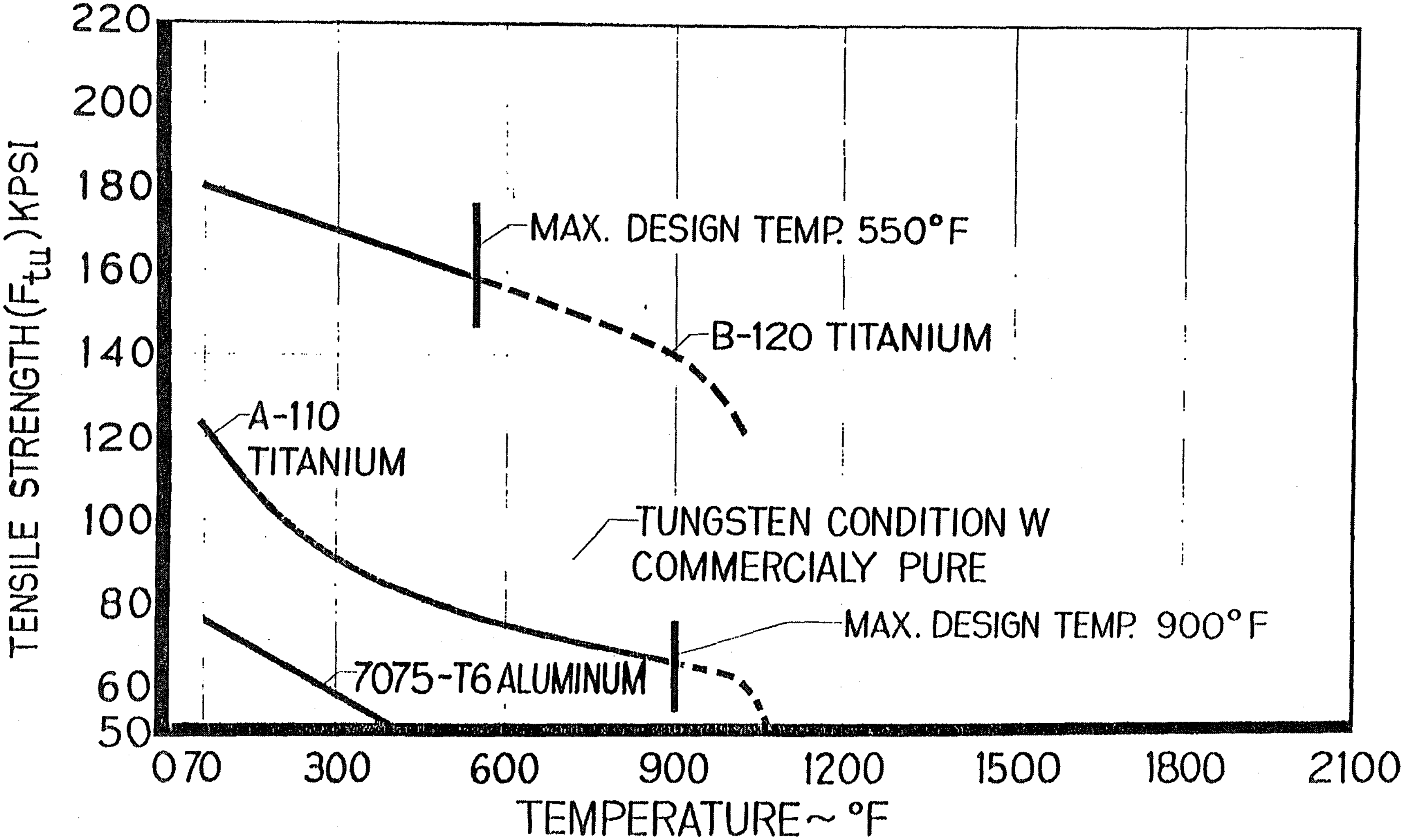


MATERIAL SELECTION
METALLICS

- ALUMINUM ALLOYS WERE GENERALLY LIMITED TO APPROXIMATELY 250°F DURING THE 1960s.
- AN INITIAL DECISION WAS MADE THAT THE SR-71 WOULD NOT FOLLOW THE DESIGN POLICY USED ON THE B-70 WHICH WAS A HONEYCOMB STRUCTURE.
  - INSTEAD, A STIFFENED SKIN APPROACH WOULD BE USED.
  - THE TWO TITANIUM ALLOYS SHOWN HERE PROVIDE GOOD PROPERTIES AT TEMPERATURE AND ARE FORMABLE, PROVIDE EXCELLENT CORROSION RESISTANCE, ARE WELDABLE AND WERE AVAILABLE AT THAT TIME.
  - ALSO USED WAS C-120, BETTER KNOWN AS Ti-6Al-4V STA.
- NOTE THE TEMPERATURE CUT-OFF FOR B-120 IS 550°F AND FOR A-110 IS 900°F.

LOCKHEED
SR-71
BLACKBIRDS

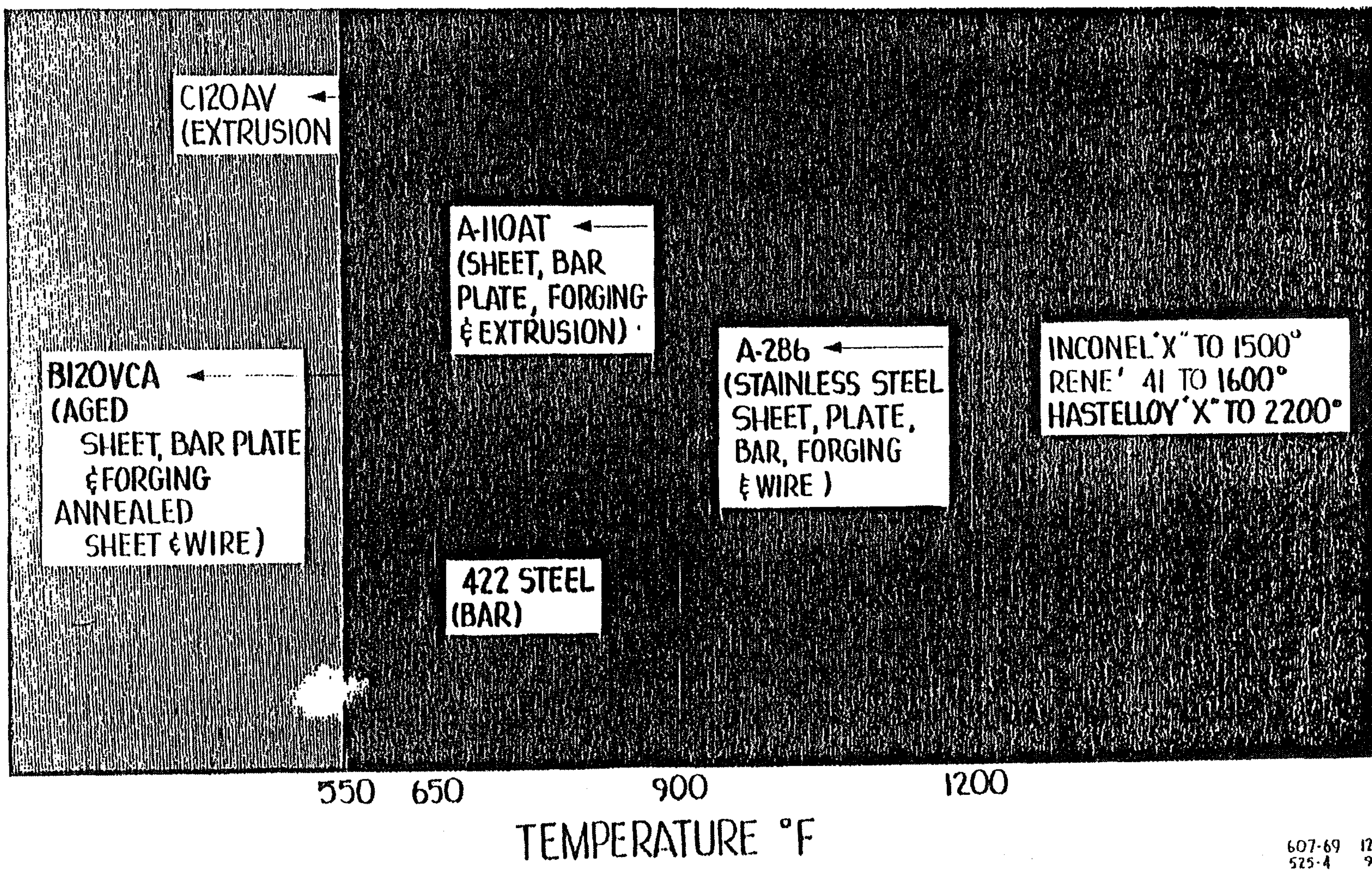
MATERIAL USEFUL STRENGTH VS TEMPERATURE



MATERIAL SELECTION
METALLICS

- TITANIUM WAS NOT THE ONLY METAL USED. TWO ALLOYS WERE USED FOR THE MAJOR PART OF THE AIRCRAFT STRUCTURE. VIRTUALLY ALL OF THE SHEET METAL STRUCTURE WAS EITHER B-120 OR A-110. TITANIUM PARTS, SUCH AS FITTINGS WERE MACHINED FROM B-120, A-110, OR C-120, DEPENDING UPON THE STRENGTH AND TEMPERATURE REQUIREMENTS.
- STAINLESS STEEL WAS ALSO USED TO A LESSER EXTENT. NOTE THE USAGE FOR WIRE. ALTHOUGH THEY ARE VERY DIFFICULT TO DRIVE, RIVETS MADE FROM A-286 WERE THE ONLY PRACTICAL FASTENERS FOR USE ABOVE 550°F.
- THE "SUPER ALLOYS", NICKEL OR COBALT BASED ALLOYS, WERE USED IN VERY "HOT" AREAS. RENÉ 41 WAS USED FOR THE INSIDE SKINS AND INCONEL "X" FOR THE OUTSIDE SKINS OF THE EJECTOR FLAPS AND HASTELLOY "X" FOR THE NOZZLE.
- NOTEWORTHY: THE SR-71 LANDING GEAR IS FORGED B-120. THIS IS THE ONLY PRODUCTION TITANIUM LANDING GEAR IN USE TODAY. THERE HAVE BEEN NO SERVICE PROBLEMS WITH WITH THE GEAR.

MATERIAL SELECTION



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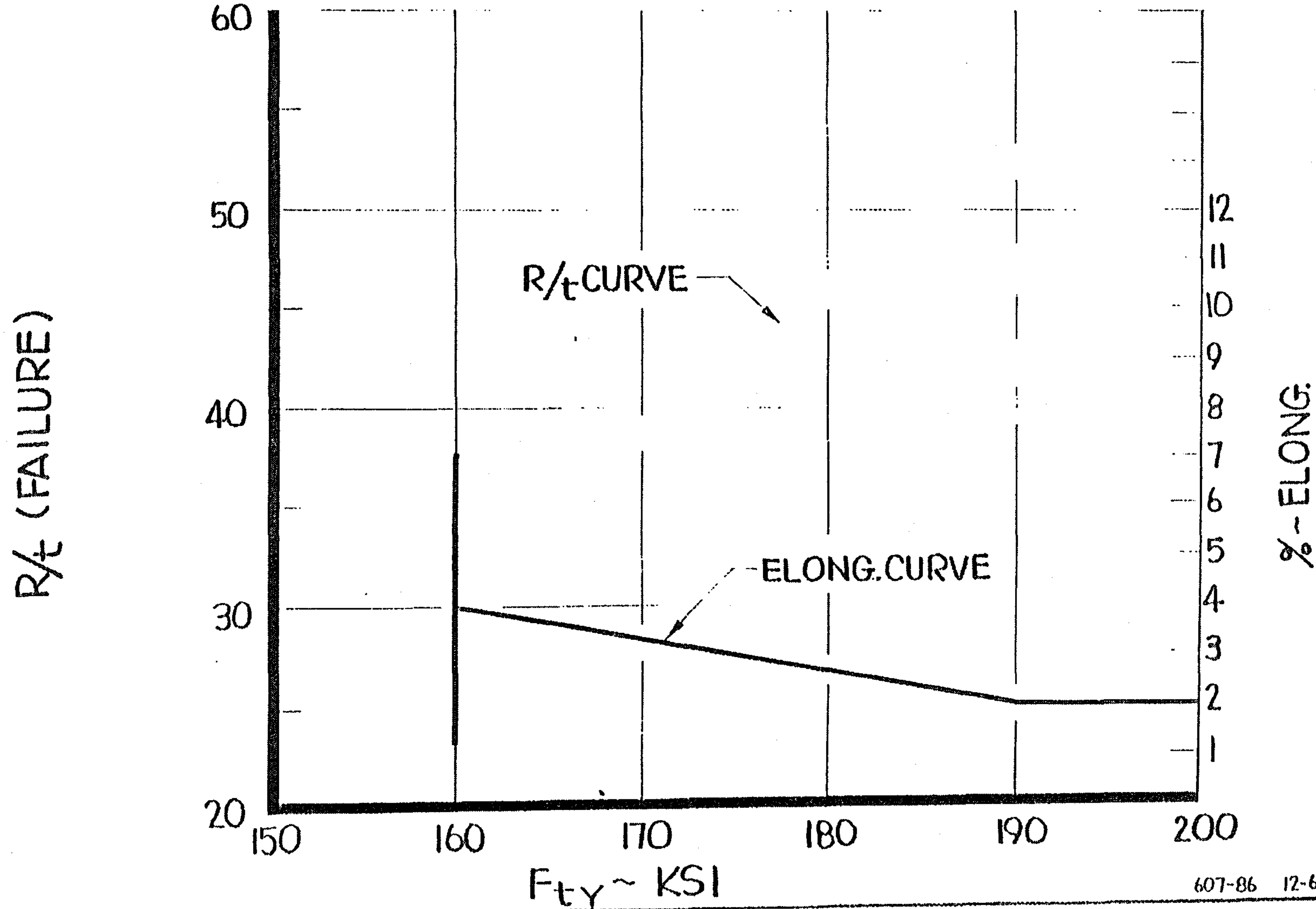
QUALIFICATION OF B-120 SHEET

- ONE OF THE PRINCIPAL CONCERNS WITH HIGH STRENGTH METAL IS NOTCH SENSITIVITY. B-120 WAS NO EXCEPTION. THIS ALLOY WAS USED IN SHEET FORM IN BOTH THE SOLUTION-TREATED AND SOLUTION-TREATED AND AGED CONDITION. IT WAS DETERMINED THAT THERE WAS A LARGE VARIATION IN THE AGE RESPONSE FROM SHEET TO SHEET, BOTH WITH RESPECT TO TENSILE STRENGTH AND NOTCH SENSITIVITY.

- A QUICK AND RELATIVELY INEXPENSIVE TEST WAS DEVELOPED TO EVALUATE THE NOTCH SENSITIVITY TO FACILITATE 100% TESTING OF THE SHEET. THIS TEST WAS NAMED THE "NOTCH BEND TEST". THIS CURVE WAS DEVELOPED AND THE RESULTS OF EACH TEST WERE COMPARED WITH THIS CURVE FOR AGED MATERIAL. GENERALLY, IF A SPECIFIC SHEET FELL OUTSIDE OF THE ACCEPTANCE RANGE, ADDITIONAL AGE TIME WOULD BRING IT INTO LIMITS. IF THIS WAS NOT POSSIBLE, THE SHEET WAS SCRAPPED.

- IT MUST BE NOTED THAT THE SHEET WAS TESTED TWICE. THE FIRST TEST WAS TO QUALIFY A SPECIFIC SHEET. THEN EACH PRODUCTION RUN OF PARTS FROM THAT SHEET WAS ALSO TESTED AFTER THE AGE CYCLE TO VERIFY THE PROCESS. THIS REQUIRED THAT ALL OF THE PARTS FROM A PRODUCTION RUN BE MADE FROM ONE SHEET AND THAT COUPONS FROM THAT SHEET ACCOMPANY THE PARTS THROUGH EACH THERMAL AND CHEMICAL PROCESS.

QUALIFICATION PLOT
B-120 SHEET



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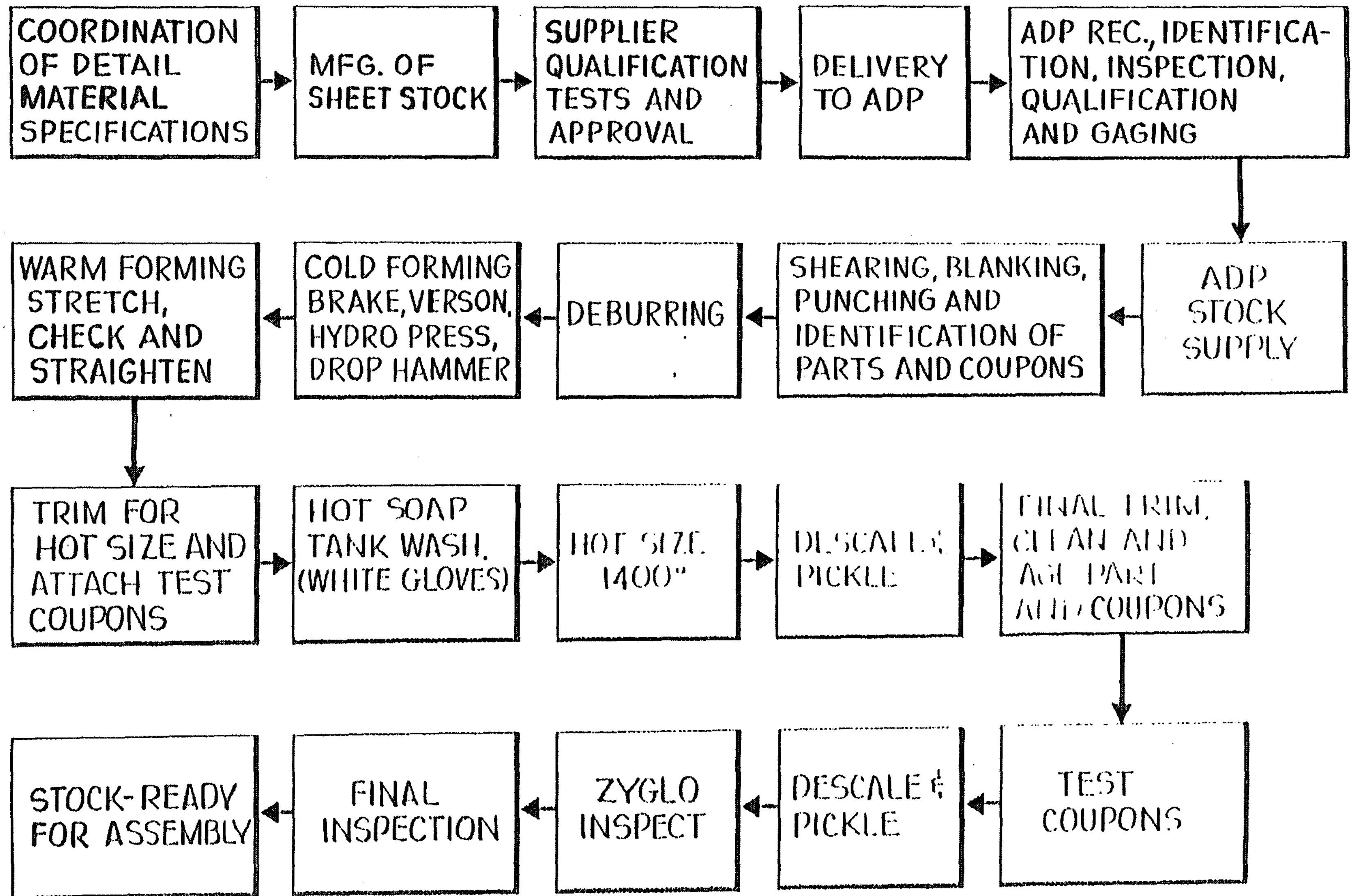
TYPICAL MANUFACTURING SEQUENCE
TITANIUM SHEET METAL PART

- THIS FLOW DIAGRAM IS SELF-EXPLANATORY. HOWEVER, ONE ITEM IS NOT SHOWN BUT IS EXTREMELY IMPORTANT. THAT ITEM IS, STRESS CORROSION CRACKING WHICH IS ATTRIBUTED TO CHLORINE CONTAMINATION.
  - ALL PRODUCTS USED IN THE FABRICATION OF TITANIUM PARTS WERE TESTED FOR THE PRESENCE OF CHLORINE.
  - ADDITIONALLY, NO CHLORINATED PARTS WERE USED ON THE AIRPLANE.
  - TAP WATER CONTAINS THE ELEMENT BUT IT WAS DETERMINED THAT THE CONCENTRATION VARIED AT DIFFERENT TIMES OF THE DAY. DURING PERIODS OF HIGH CONCENTRATION, USAGE WAS CURTAILED.
- A SECOND CONTAMINATE THAT COULD PRESENT PROBLEMS WAS CADMIUM.
  - NO CADMIUM PLATED TOOLS WERE ALLOWED IN THE SHOP AREA.

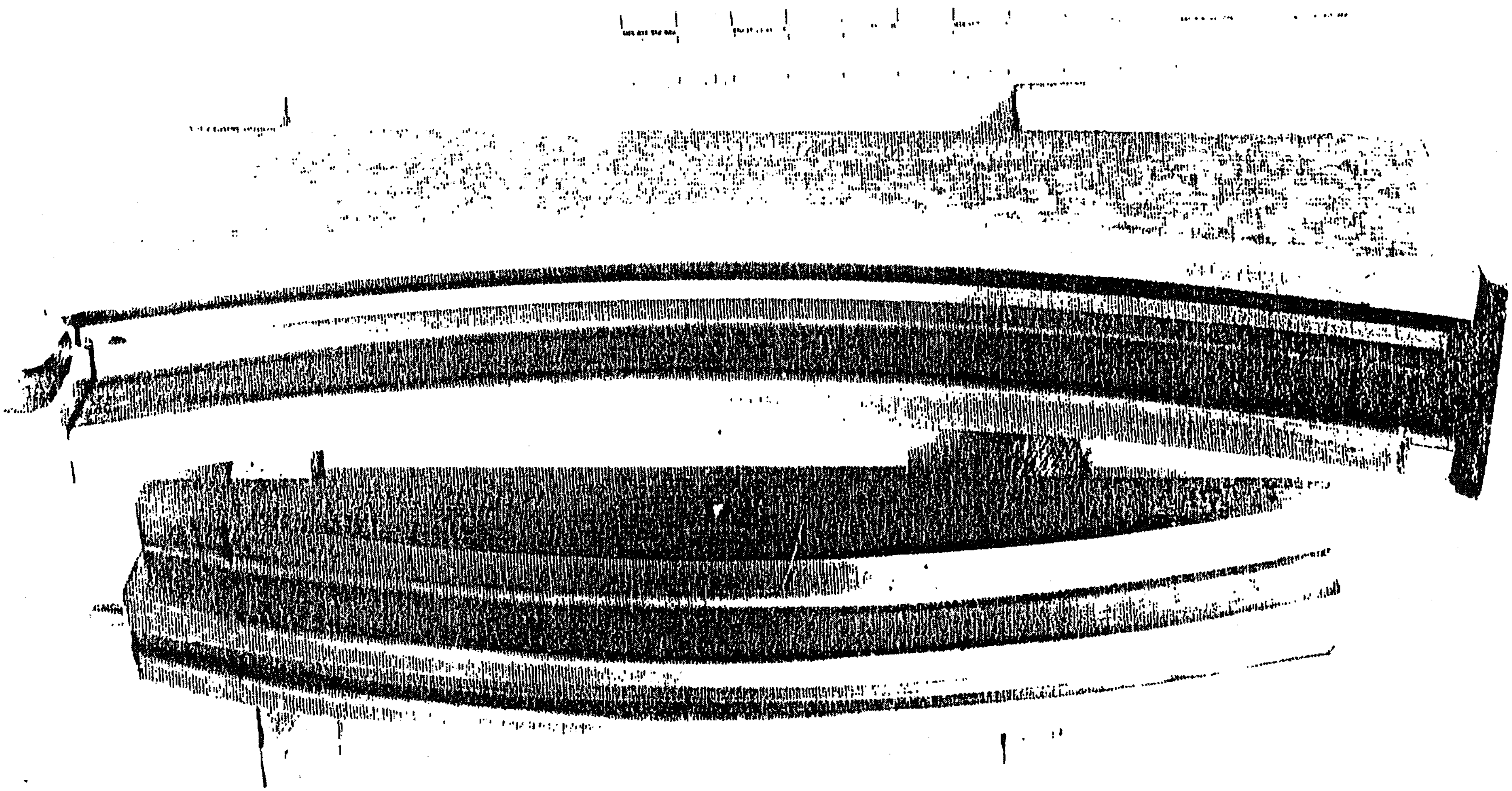
TITANIUM SHEET METAL/PART FAB.



FORMING OF TITANIUM SHEET METAL PARTS

- SMALL BEND RADIUS IS GENERALLY DESIRABLE FOR A SHEET METAL PART.
  - WEIGHT IS SAVED BY USING A SHORTER FLANGE, AND TIGHT BEND RADIUS IMPROVES THE BUCKLING EFFICIENCY OF THE PART.
- THE MINIMUM BEND RADIUS IS GOVERNED BY THE CHARACTERISTICS OF THE ALLOY, AND IS A FUNCTION OF FORMING TEMPERATURE.
  - FOR THIS REASON, A PROCESS NAMED "HOT SIZING" WAS DEVELOPED.
  - THIS PROCESS REQUIRED MATCHED TOOLING AND A HOT PRESS.
  - HOT SIZING TEMPERATURE IS 1450°F.
  - TOOLING WAS COSTLY; DESCALING AT 850°F AND PICKLING IN A HF/HNO_3 SOLUTION ARE VERY DANGEROUS PROCESSES WHICH MUST BE CLOSELY CONTROLLED.

HOT S[illegible]E BLOCKS



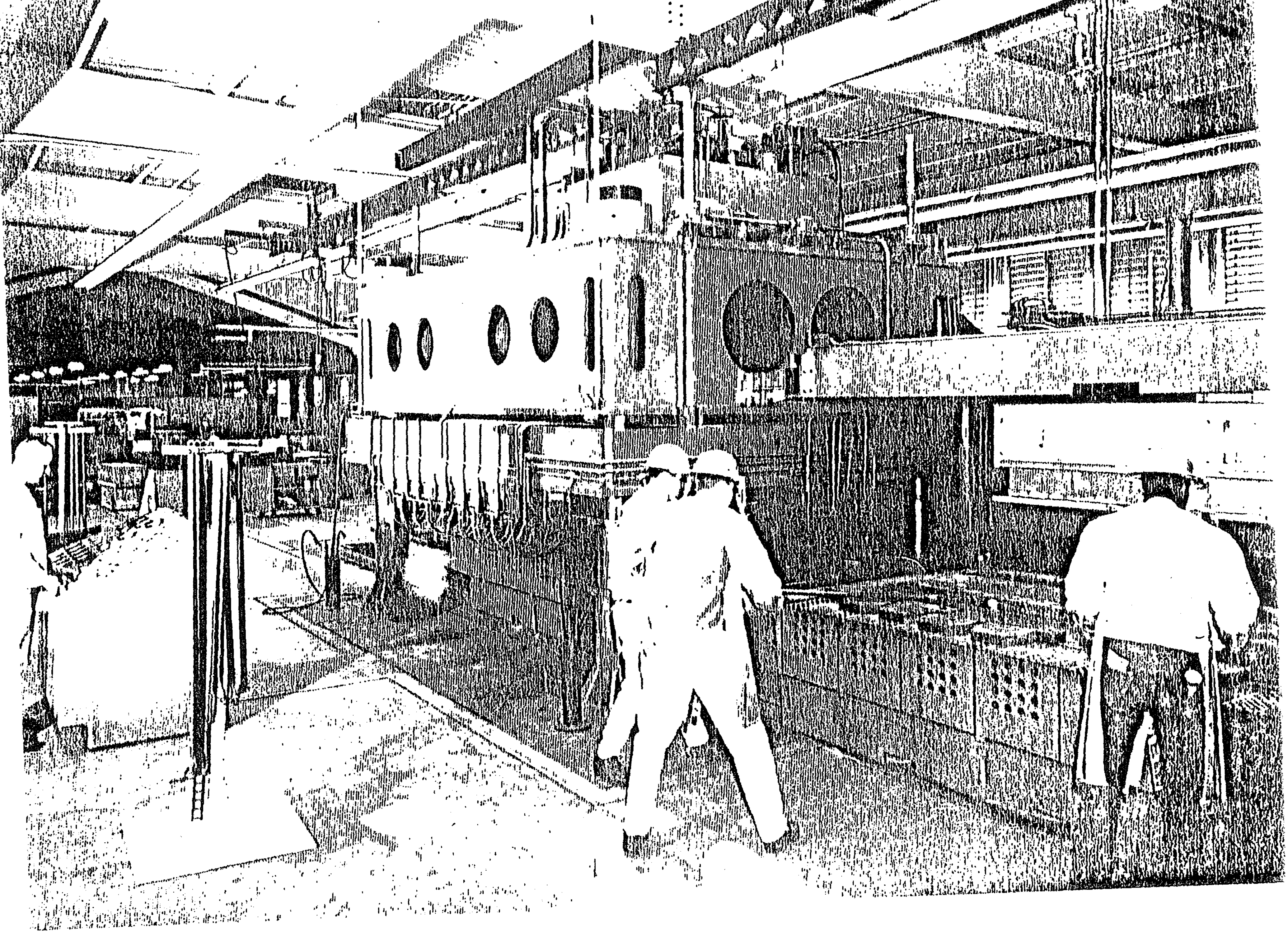
HOT SIZING PROCESS

- THIS IS A BLISS PRESS ESPECIALLY DESIGNED AND BUILT FOR LOCKHEED TO HOT SIZE TITANIUM PARTS

- AT HOT SIZING TEMPERATURE THE TOOLING IS APPROXIMATELY 1450°F.

- THIS PRESS IS STILL IN OPERATION TODAY IN A BUILDING WE RIGHTLY CALL THE "HOT SHED".

BLISS PRESS



THE COST OF FORMING SHEET METAL TITANIUM PARTS TO FINAL SHAPE BY "HOT SIZING" IS VERY DEPENDENT ON THE MATCHED SETS OF TOOLING REQUIRED. THE COST OF THE TOOLING REQUIRED TO PRODUCE A PART MUST BE DISTRIBUTED OVER A REASONABLE REPEATED USAGE. OTHERWISE, THE FINAL SINGLE PART WILL COST MORE THAN PURE GOLD ON A PER POUND BASIS.

A COMPLEX HOT-SIZED PART MAY REQUIRE "HOT SIZING" MORE THAN ONE TIME IN STAGES WITH INTERMEDIATE RE-HEATING AND PROGRESSIVE SHAPING.

HOT SIZING COST FACTORS

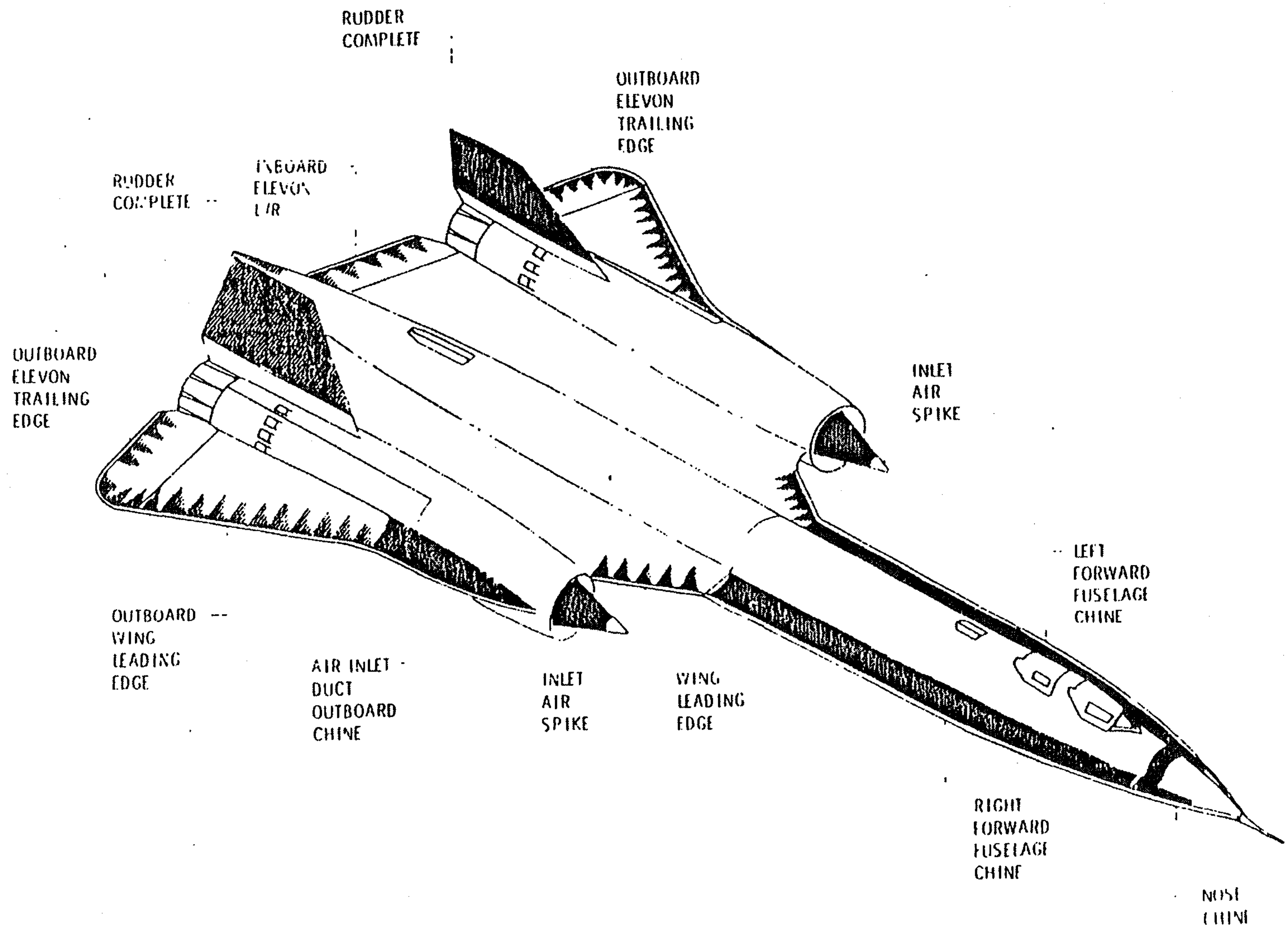
(BASED ON 50 PARTS)

		COST FACTOR
1	FORMED PART WITHOUT H.S.	1.00
2	SIMPLE H.S. PART	2.74
3	AVERAGE H.S. PART	3.24
4	COMPLEX H.S. PART	3.70
5	SEVERE H.S. PART	4.16

COMPOSITES

- COMPOSITES ARE THOUGHT OF AS A RECENTLY DEVELOPED MATERIAL FOR USE IN THE AEROSPACE INDUSTRY.
  - HOWEVER, A COMPOSITE MATERIAL IN THE FORM OF SILICONE ASBESTOS WAS DEVELOPED FOR USE IN HIGH TEMPERATURE AREAS FOR THE SR-71. THIS MATERIAL IS USED IN HIGH TEMPERATURE APPLICATIONS UP TO 600°F. ALTHOUGH THERE IS SOME WEIGHT LOSS ASSOCIATED WITH EXPOSURE TO ELEVATED TEMPERATURE, PROBLEMS WITH THE PARTS HAVE BEEN LESS THAN ORIGINALLY EXPECTED.

PLASTIC PANEL USAGE
(SILICONE ASBESTOS)



SEALANTS

FUEL TANK SEALING IS A MAJOR PROBLEM ON THE SR-71.

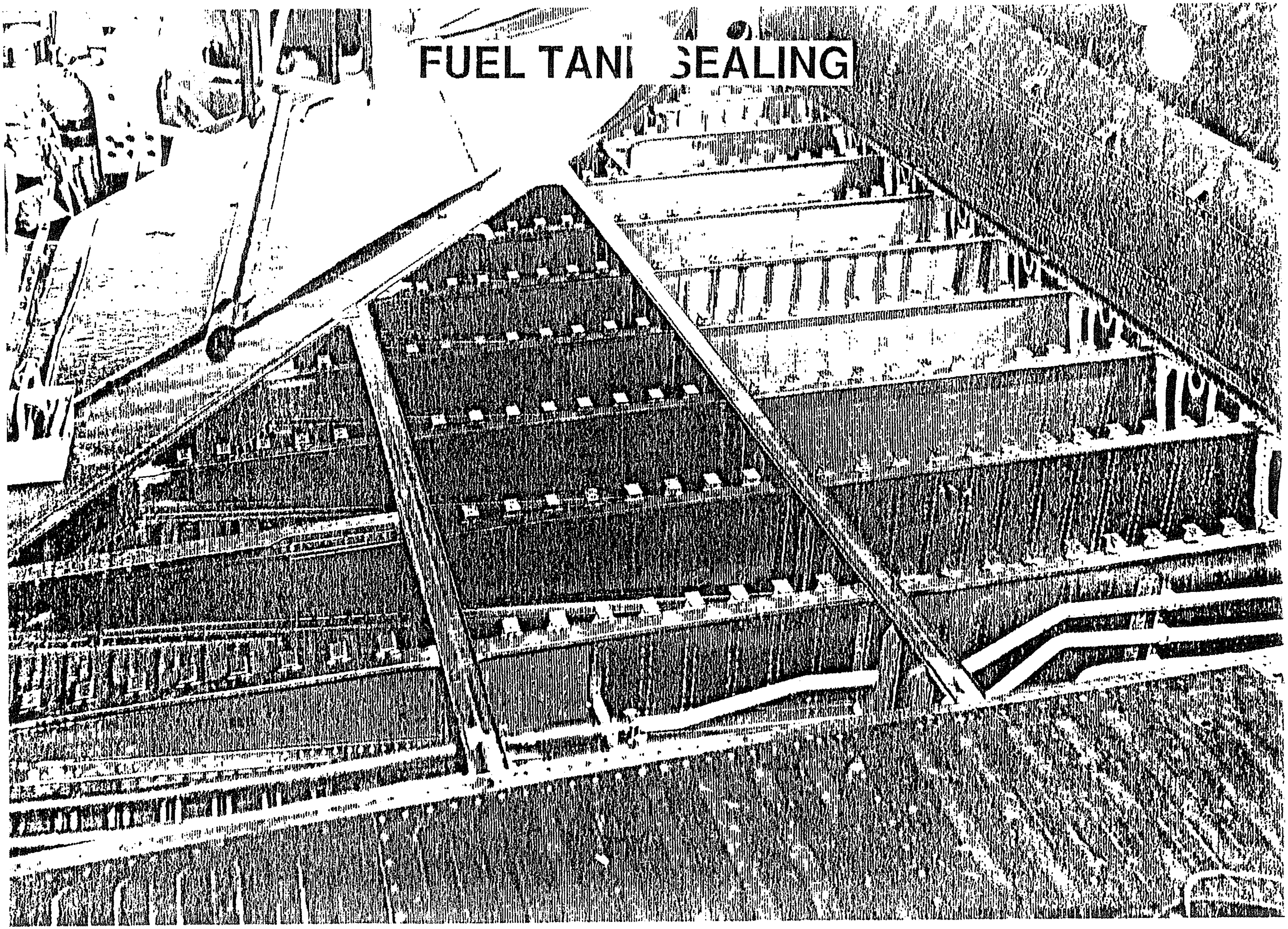
- THERE ARE APPROXIMATELY 2 MILES OF FILLET SEAL.
- THE SEALING MATERIAL USED WAS A FLUOROSILICONE.

ONE MUST CONSIDER THE AEROELASTIC DEFORMATION THE AIRCRAFT IS SUBJECTED TO AND THE TEMPERATURE EXTREMES TO APPRECIATE PROBLEMS ENCOUNTERED IN TRYING TO LEAK PROOF THE AIRPLANE.

- AS FOR THE DEFORMATION, YOU WILL SEE A PICTURE OF THE FUSELAGE IN STATIC BENDING DURING THE NEXT HOUR. TRY TO IMAGINE THE SEALING PROBLEMS THAT ARE ENCOUNTERED UNDER CONDITONS ONLY HALF AS SEVERE.

- THIS SEALANT HAD TO FUNCTION AT TEMPERATURE EXTREMES OF -60°F TO 600°F.

- THIS PHOTOGRAPH EXHIBITS THE TEMPERATURE RANGE THAT OCCURS IN THE WING TANK. PLEASE NOTE THE CHANGE IN COLOR FROM A DARK BROWN ON THE LEFT TO SILVERY METALLIC ON THE RIGHT.


FUEL TANI SEALING

DESIGN AND MANUFACTURING APPROACH

- TIME FROM LIMITED GO-AHEAD TO FIRST FLIGHT WAS 30 MONTHS.
- REQUIRED TOTAL OVERLAP IN ALL DESIGN AND MANUFACTURING PHASES. NOT ENOUGH TIME TO DO THINGS PROGRESSIVELY AND IN SEQUENCE.
- MEANS THAT DESIGN ACTION MUST BE TAKEN BASED ON ESTIMATES.
- MANUFACTURING MUST BE SEQUENCED AND DONE ON A LEAST RISK BASIS IN INTIMATE COOPERATION WITH ENGINEERING.
- ENGINEERING MUST ISSUE A "BASIS FOR STRUCTURAL DESIGN" DOCUMENT VERY EARLY WITH ENOUGH LOADING INFORMATION TO ALLOW THE DESIGNERS TO SET DESIGN DETAILS AND RELEASE DRAWINGS TO THE SHOP WITHOUT DELAY.

BLACKBIRD MILESTONE SUMMARY

MODEL	CONTRACT	FIRST FLIGHT
A-11	SEPTEMBER 1959	APRIL 1962
YF-12A	OCTOBER 1960	AUGUST 1963
SR-71	FEBRUARY 1963	DECEMBER 1964

DESIGN AND MANUFACTURING APPROACH
(SHEET 2)

- ENGINEERS MUST DESIGN ALL COMPONENTS TO BE AS LIGHT AS THE "BASIS FOR STRUCTURAL DESIGN" DOCUMENT WILL PERMIT.

- THE "BASIS FOR STRUCTURAL DESIGN" DOCUMENT WILL BE UPDATED AS NEW INFORMATION BECOMES AVAILABLE AND IS DEEMED SIGNIFICANT.

- IF NECESSARY, COMPONENTS WHICH HAVE ALREADY BEEN DESIGNED AND BUILT WILL BE CHANGED AS REQUIRED TO MEET THE LATEST VERSION OF THE "BASIS FOR STRUCTURAL DESIGN".

- CONDUCT EXTENSIVE COMPONENT TESTING EARLY IN THE PROGRAM SO AS TO VALIDATE THE DESIGN THAT IS ALREADY BEING BUILT. IF THE TESTING DICTATES A CHANGE, THIS IS ACCOMPLISHED AS A PROGRESSIVE MODIFICATION BEFORE FIRST FLIGHT.

DESIGN AND MANUFACTURING APPROACH
(SHEET 3)

- BUILD A STATIC TEST VEHICLE AND RUN CRITICAL LOADING CONDITIONS TO 115% OF DESIGN LIMIT LOAD BEFORE FIRST FLIGHT. USE STRAIN GAGE DATA FROM THESE TESTS TO VALIDATE OR TO CHANGE DESIGN REQUIREMENTS OF INDIVIDUAL VEHICLE COMPONENTS. MAKE CHANGES TO FLIGHT VEHICLE, IF NEEDED.

- MAKE INSTRUMENTATION ON FLIGHT VEHICLE CORRESPOND TO SOME POINTS BEING MEASURED ON THE STATIC TEST VEHICLE. THEN COMPARE FLIGHT TEST DATA WITH STATIC TEST DATA IN ORDER TO VALIDATE AND/OR UPDATE THE LOADS AS DEFINED IN THE "BASIS FOR STRUCTURAL DESIGN".

- COMPLETE THE STATIC TEST VEHICLE PROGRAM TO "ULTIMATE" BEFORE PERFORMING "LIMIT" LOAD DEMONSTRATIONS ON THE FLIGHT VEHICLE.

STRUCTURAL ANALYSIS AIRFRAME LIFE

- 2600 HRS MINIMUM TIME TO FAILURE AFTER A FLAW IS DETECTED IN F-1 JOINT (MOST CRITICAL STRUCTURAL AREA)
- NO VEHICLES, TO DATE, HAVE FLAW
- AT CURRENT USAGE VEHICLE LIFE IS PROJECTED TO BE 16 YEARS AFTER FLAW IS DETECTED
- CONCLUSION:

  AIRFRAMES WILL BE AVAILABLE FOR SERVICE BEYOND YEAR 2000

FATIGUE TESTS OF F-1 JOINT RESULTED IN 4500 HOURS LIFE AFTER FIRST CRACK APPEARED

DESIGN AND MANUFACTURING APPROACH
(SHEET 4)

- FOR THE MOST PART, THE STRUCTURE WAS MOST CRITICALLY LOADED IN THE LOW TEMPERATURE TRANSONIC REGION. THEREFORE, ROOM TEMPERATURE TESTING ON THE STATIC TEST VEHICLE WAS ADEQUATE. IN SOME CASES WE USED ROOM TEMPERATURE OVER-LOAD TO SIMULATE HOT CONDITIONS: FOR MANY COMPONENTS WE DID TEST AT ELEVATED TEMPERATURES.

- TODAY'S COMPUTER CAPABILITY DID NOT EXIST 30 YEARS AGO. FOR THE SAKE OF THE SR-71 PROTOTYPE PROGRAM THAT MAY HAVE BEEN FORTUNATE. IT CAUSED US TO REDUCE PROBLEMS TO THEIR LOWEST COMMON DENOMINATOR BEFORE DOING THE CALCULATIONS.

- R.F. (BOB) O'CONNEL (CALTECH CLASS OF '51) WAS THE ENGINEER WHO DID THE MOST TO SUPPORT THE SR-71 WITH JUST THE RIGHT AMOUNT OF COMPUTER INVOLVEMENT SO AS TO HELP RATHER THAN HINDER THE SR-71 DEVELOPMENT.

DESIGN AND MANUFACTURING APPROACH
(SHEET 5)

- "THE MOST VALUABLE DESIGN ENGINEER" IS THE ENGINEER WITH THE ABILITY TO "BALL PARK" A DESIGN BASED ON RAW DATA, AND THEN HAVE IT PROVE TO BE CLOSE TO CORRECT WHEN ALL SUPPORTING INFORMATION IS FED TO THE COMPUTERS.

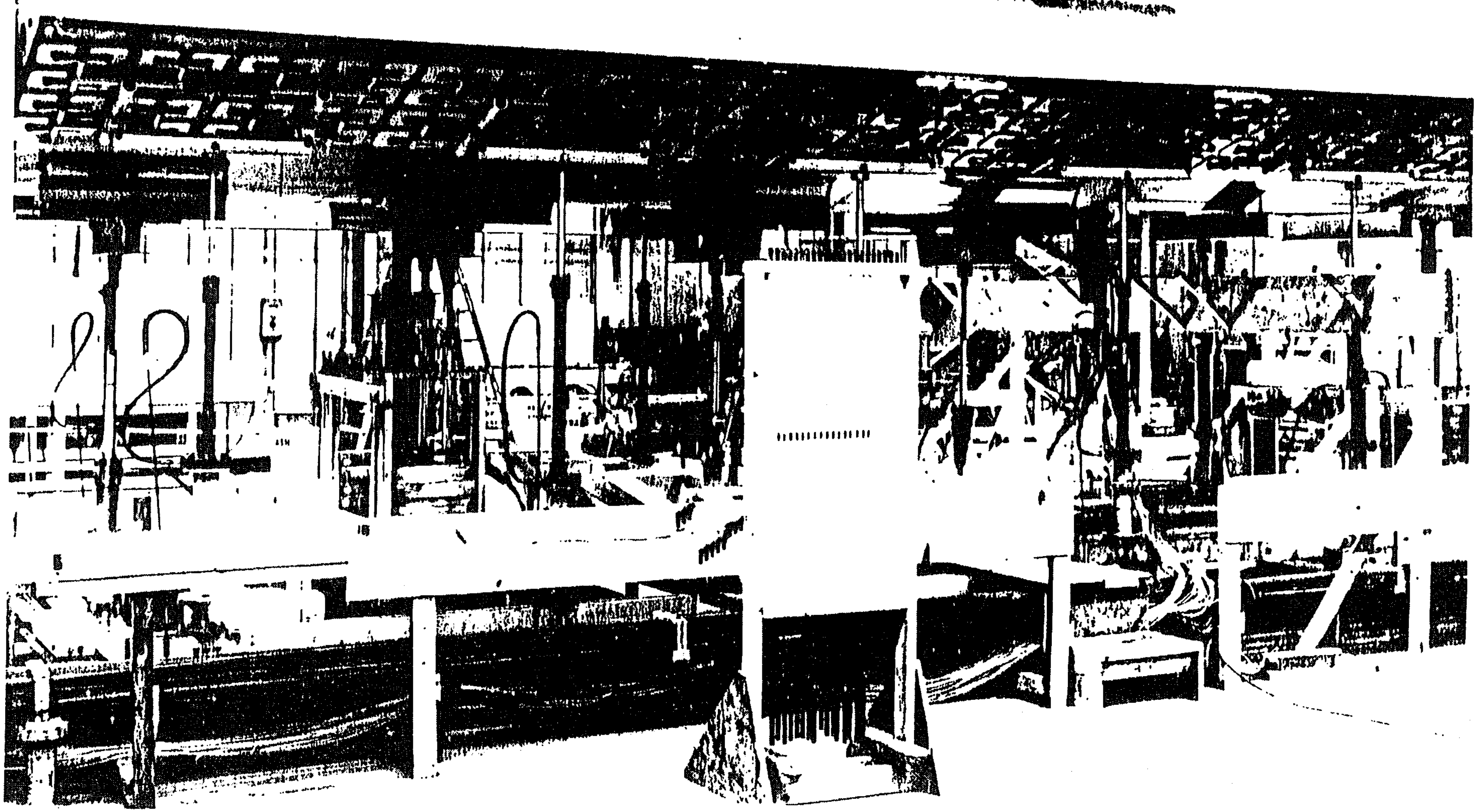
FUSELAGE FOREBODY

THE FUSELAGE FOREBODY AS LOADED FOR 1G CRUISE IS RELATIVELY SMOOTH.

THE STATIC TESTS LOADS WERE APPLIED TO THE LOWER SURFACE BY MEANS OF PADS ATTACHED WITH RTV ADHESIVE.

AT 1G SUPERSONIC CRUISE, THE NET FUSELAGE BENDING IS VERY LOW. THE AIRLOAD SUPPORTING THE FOREBODY IS CANCELLING THE INERTIA LOADING OF THE FOREBODY WEIGHT. THEREFORE, THE FUSELAGE PANELS ARE RELATIVELY SMOOTH.

FUSELAGE FOREBODY AT 1G CRUISE



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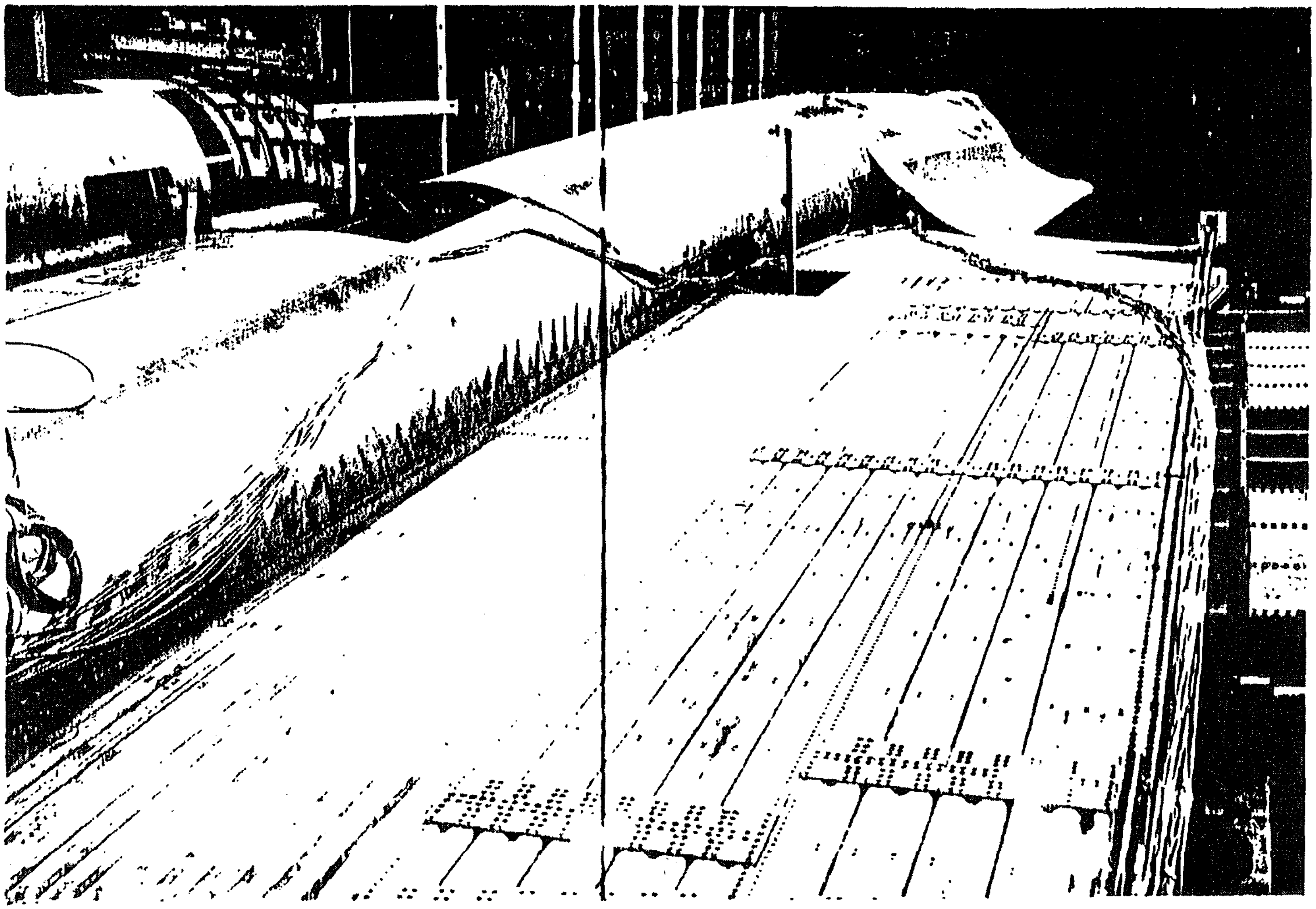
STATIC TEST VEHICLE

THE STATIC TEST VEHICLE INCLUDED THE ENTIRE LEFT HAND OUTER AND INNER WING AND NACELLE. THE FUSELAGE WAS COMPLETED ALL THE WAY TO THE NOSE. THE RIGHT HAND INNER WING WAS JOINED TO AN IRON STRUCTURE SIMULATING THE RIGHT HAND NACELLE.

INSTRUMENTATION WAS INSTALLED SO AS TO BE ABLE TO COMPARE MEASURED INTERNAL STRAINS WITH PREDICTED VALUES.

NOTE THE LOAD BUCKLING IN THE FUSELAGE ALONG WITH THE NOSE DROOP. THE FUSELAGE WAS BUILT STRAIGHT AND WILL RETURN TO STRAIGHT WHEN THE LOADING IS REMOVED.

FUSELAGE BENDING STATIC TEST



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FUSELAGE FOREBODY AT LIMIT CRUISE

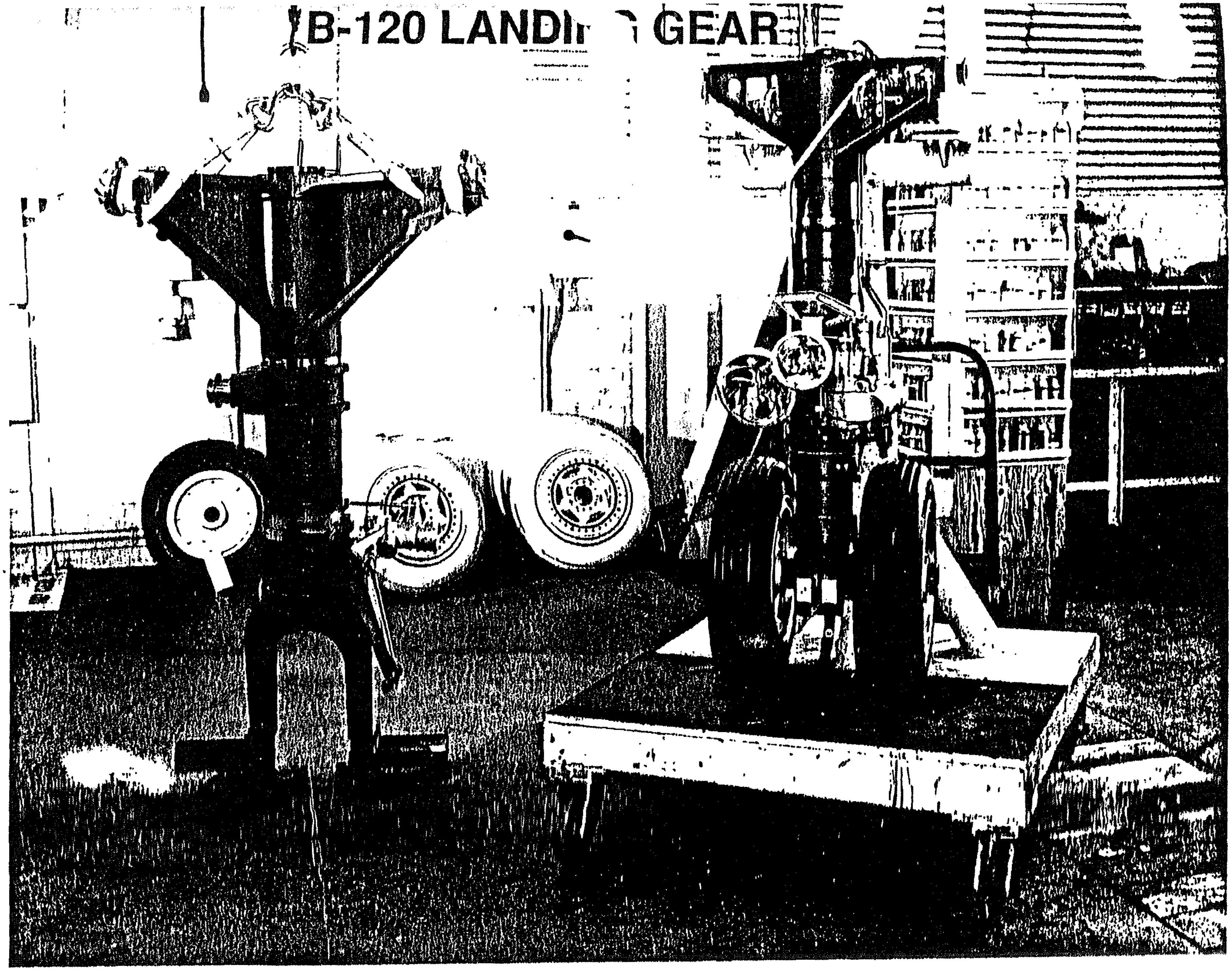
THE AIRLOAD EFFECTIVENESS OF THE FOREBODY PLANFORM IS MUCH GREATER AT SUPERSONIC SPEEDS THAN AT SUBSONIC SPEED.

THEREFORE, FOR A 2-1/2 G MANEUVER LOAD FACTOR SUBSONICALLY, THE JOINT AT STA 715 IS CRITICAL IN DOWNBENDING. AT SUPERSONIC SPEEDS, A MANEUVER OF 2-1/2 G PRODUCES UP-BENDING IN THE FOREBODY.

NOTE THE BUCKLE SHOWING IN THE UPPER PART OF THE FUSELAGE.

IN EARLY PRODUCTION, THE NACELLE MAIN FRAMES WHICH CARRIED WING BENDING WERE FABRICATED FROM EXTRUSIONS AND SHEET METAL. LATER, WHEN PRODUCTION QUANTITIES WERE LARGER, THESE FRAMES WERE CHANGED TO FORGINGS WHICH WERE MACHINED TO FINAL DIMENSIONS.

THE LANDING GEAR STRUTS AND TRUNNIONS WERE FORGED FROM B-120 TITANIUM AND MACHINED TO FINAL CONFIGURATION. THEY HAVE PERFORMED FLAWLESSLY FROM THE VERY BEGINNING.


B-120 LANDI
GEAR

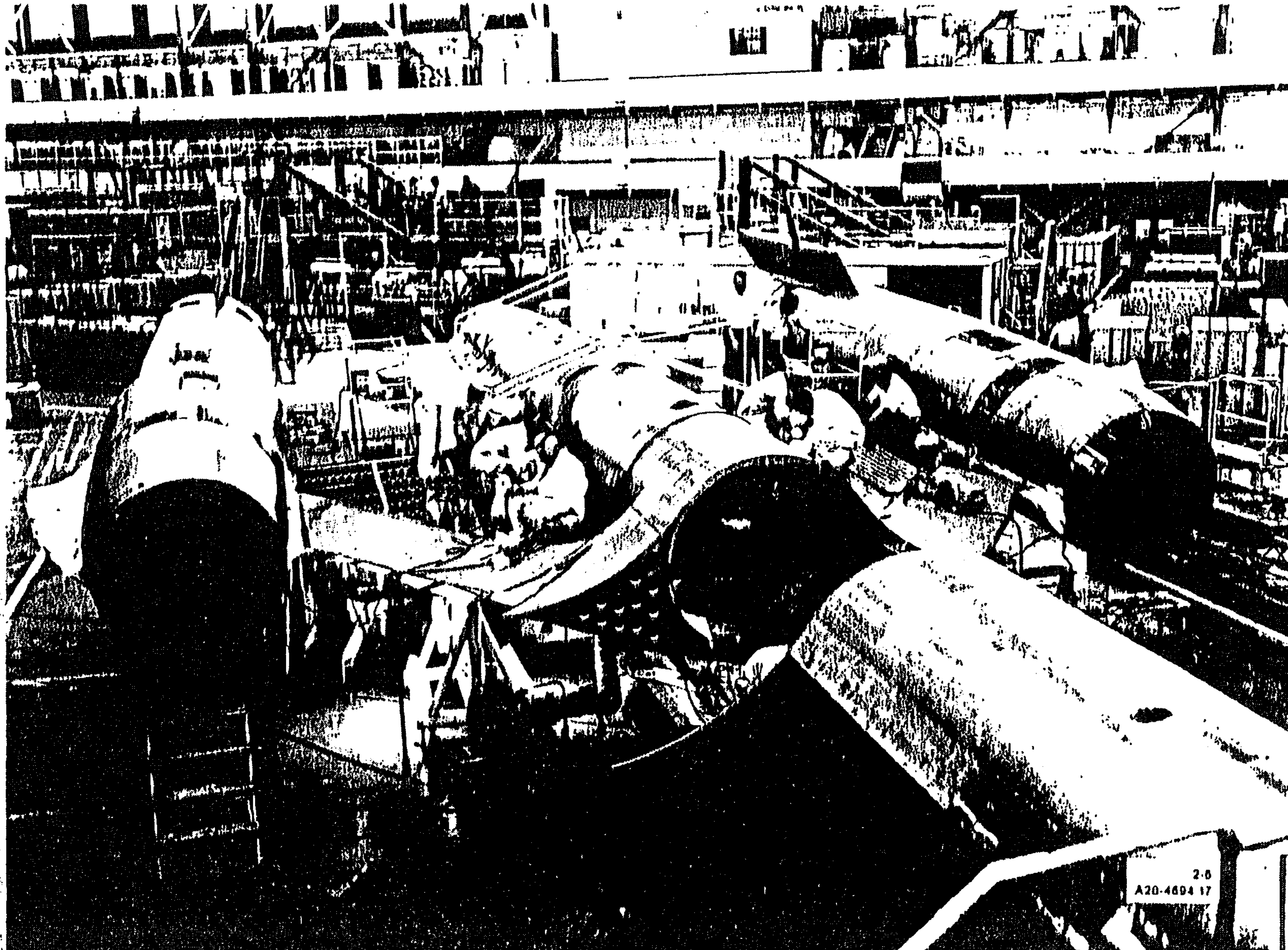
THE MULTIPLE SPAR WING IS INHERENTLY FAIL-SAFE. SINCE THE WING IS ALSO FUEL TANK, IT IS OBVIOUS THAT ANY SIGNIFICANT CRACKING WILL SHOW UP AS EXCESSIVE FUEL LEAK LONG BEFORE IT BECOMES LARGE ENOUGH TO HAZARD THE STRUCTURAL INTEGRITY OF THE WING.

HOWEVER, THE FUSELAGE BENDING IS CARRIED BY SINGLE LOAD PATH LONGERONS WHICH ARE NOT FAIL-SAFE.

THE MOST CRITICAL STRUCTURAL AREA IS THE 715 JOINT.

THE REMAINDER OF THE AIRPLANE IS LONGER LIVED THAN THIS JOINT WHICH HAS BEEN SUBJECTED TO A COMPREHENSIVE FATIGUE TEST PROGRAM.

"715" JOIN DURING ORIGINAL MANUFACTURE



SR-71

CONFIGURATION DEVELOPMENT

presented by Jerry Meyer, Div. Manager (retired)
Flight Sciences

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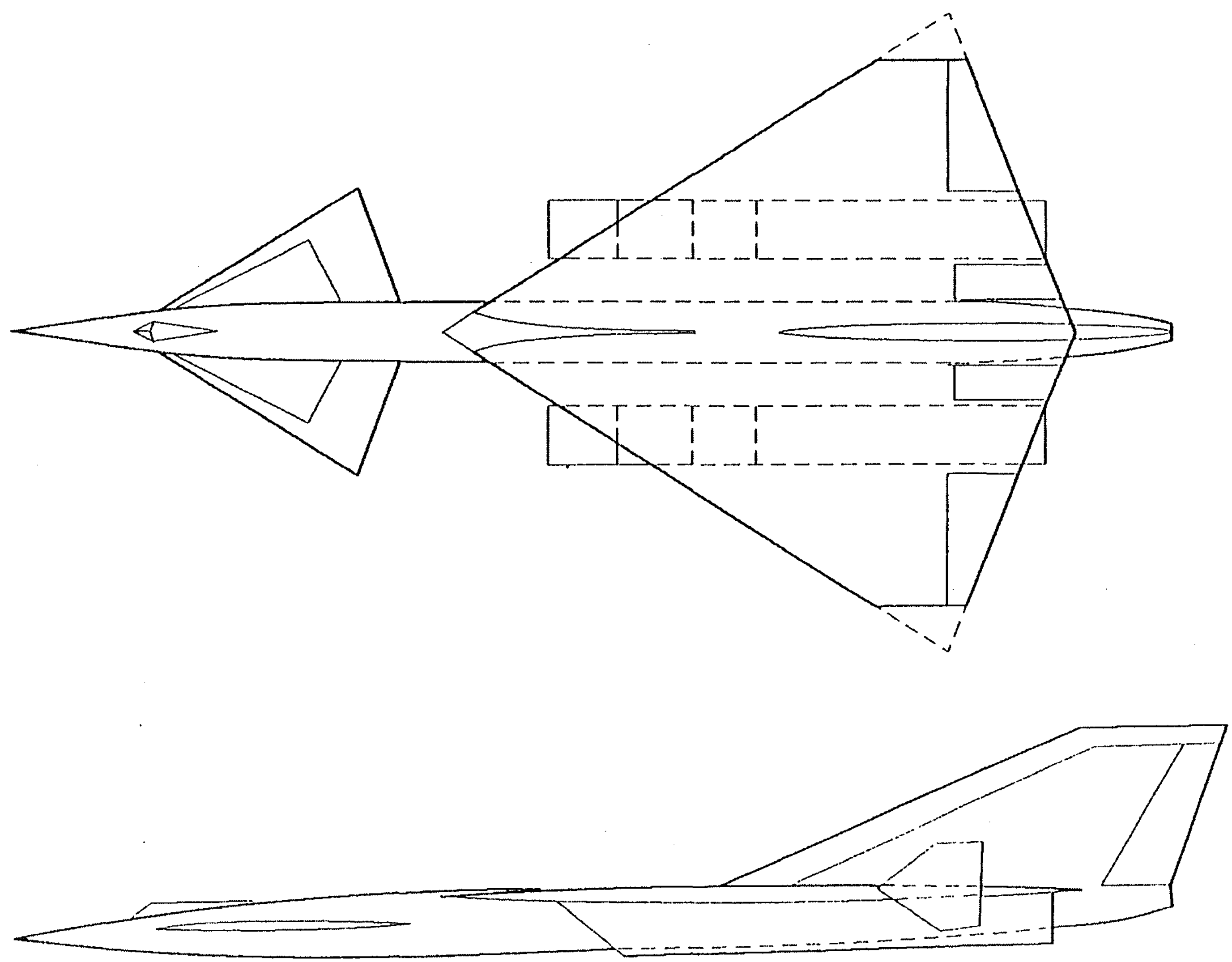
CONFIGURATION DRIVERS

- POINT DESIGN CRUISE MISSION
  - IN EXCESS OF MACH 3.0 AND 80,000 FT ALTITUDE
  - MINIMIZE TRIM DRAG AT CRUISE
  - LOW DRAG BASIC CONFIGURATION
- STABILITY AND HANDLING QUALITIES DRIVERS
  - LOW STABILITY MARGINS (1.5 PERCENT S.M. AT CRUISE)
  - SAS AUGMENTATION BUT SAFE WITHOUT SAS
  - MAXIMUM POWER ENGINE FAILURES AT ALL FLIGHT CONDITIONS
  - FUEL CONTROLLED C.G. FOR MAXIMUM EFFICIENCY

INITIAL WIND TUNNEL CONFIGURATION



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CONFIGURATION DRIVERS

- POINT DESIGN CRUISE MISSION
  - IN EXCESS OF MACH 3.0 AND 80,000 FT ALTITUDE
  - MINIMIZE TRIM DRAG AT CRUISE
  - LOW DRAG BASIC CONFIGURATION
- STABILITY AND HANDLING QUALITIES DRIVERS
  - LOW STABILITY MARGINS (1.5 PERCENT S.M. AT CRUISE)
  - SAS AUGMENTATION BUT SAFE WITHOUT SAS
  - MAXIMUM POWER ENGINE FAILURES AT ALL FLIGHT CONDITIONS
  - FUEL CONTROLLED C.G. FOR MAXIMUM EFFICIENCY

06-JM-0002-03-25-91-DS

WIND TUNNEL DEVELOPMENT

	HOURS
AERO	1884
INLET	1185
EJECTOR	320
BYPASS AIR	228
TOTAL TO 1ST FLIGHT	3617

APPROXIMATELY 2 YEARS FROM GO AHEAD

06-JM-0004-03-25-01-D3

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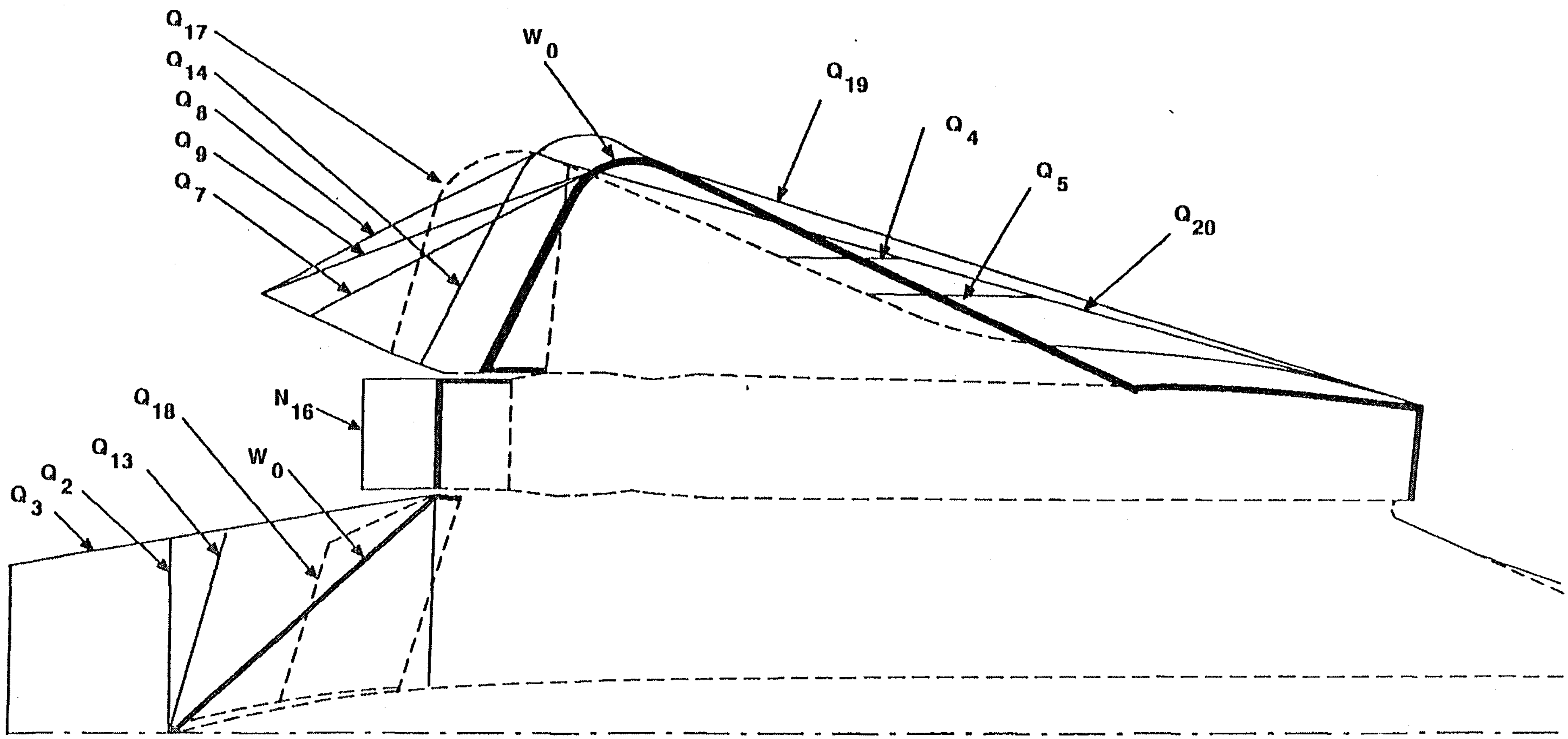
WIND TUNNEL P_ANFORM MODS



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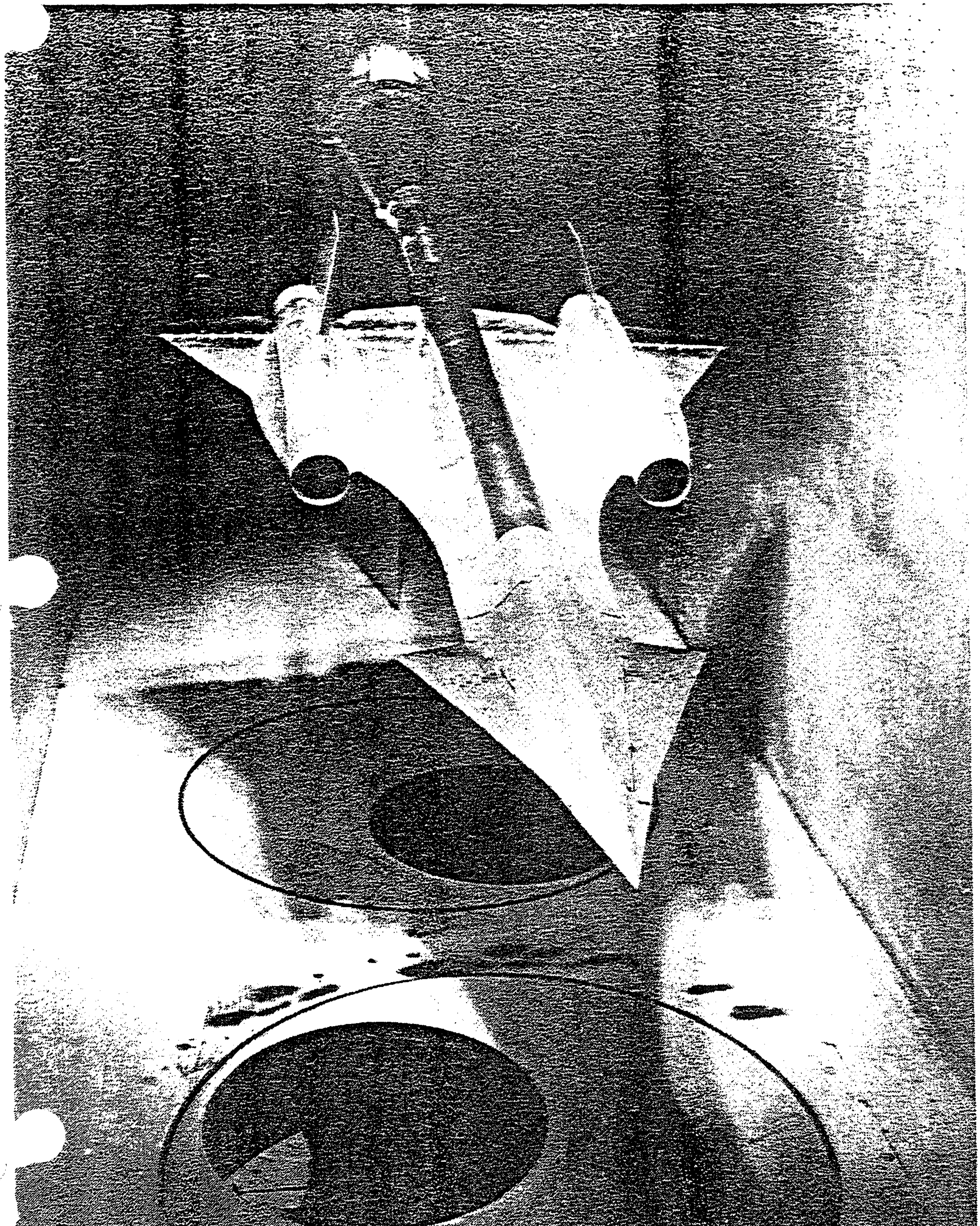

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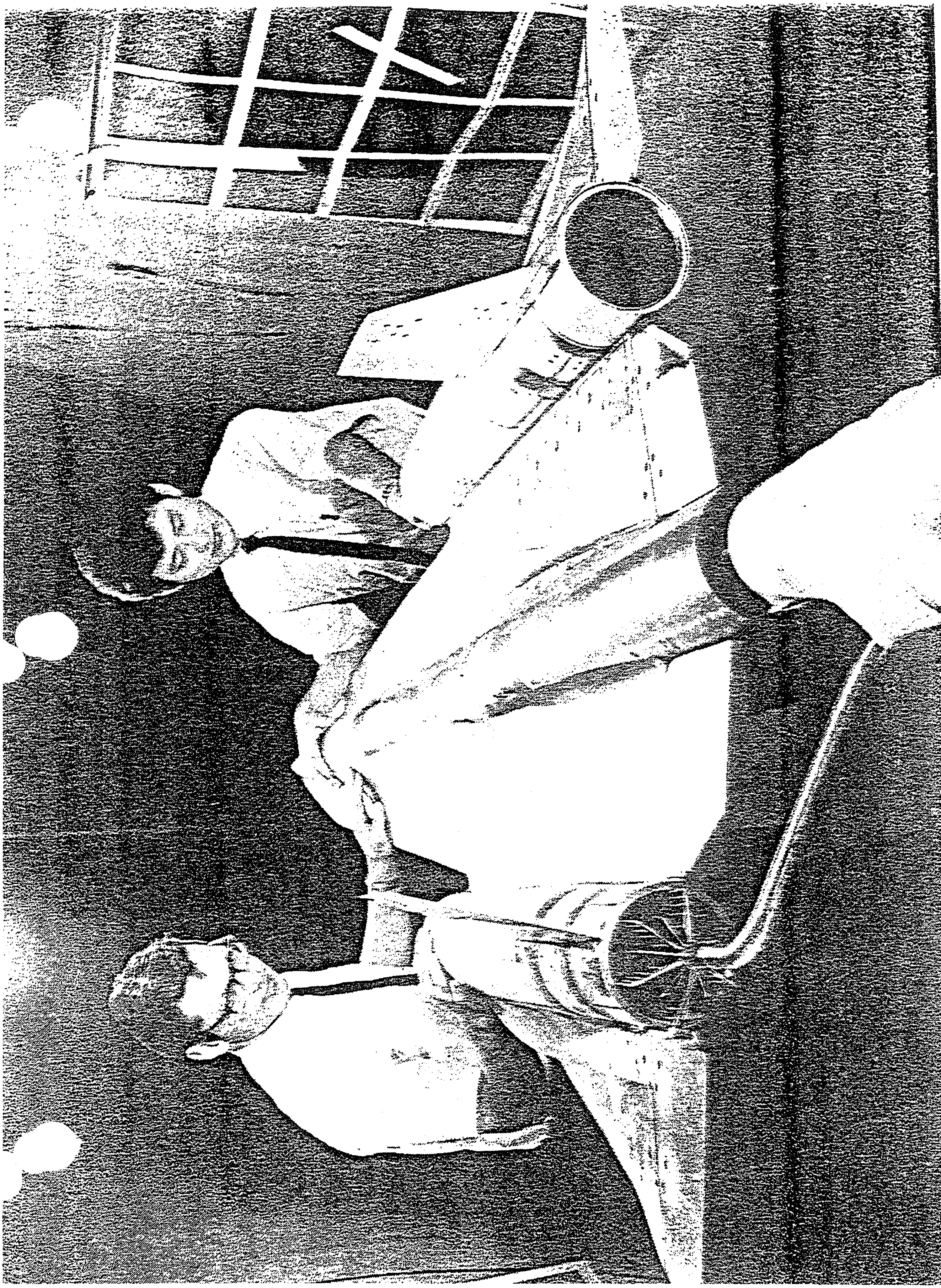
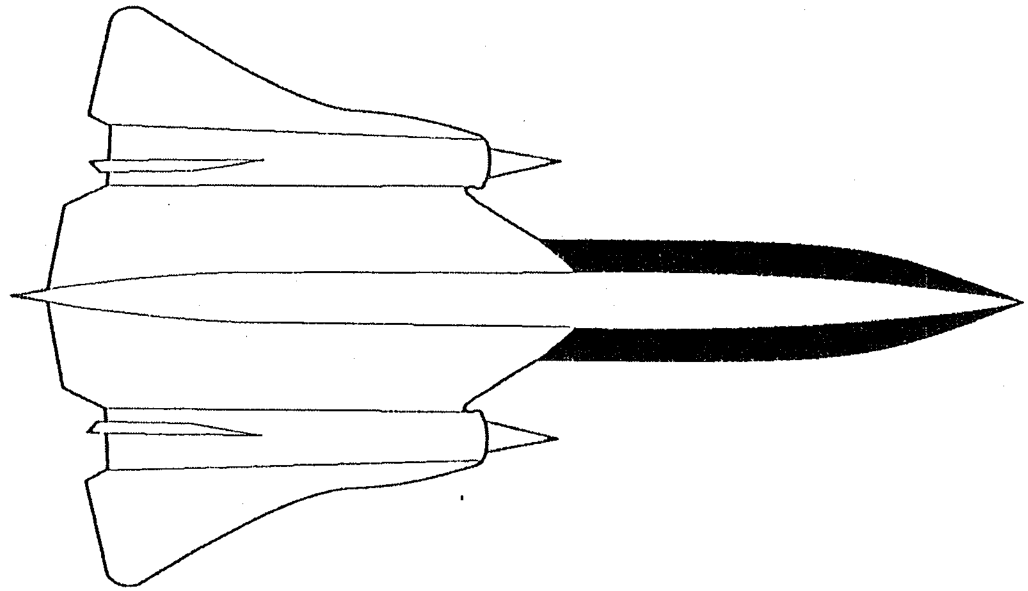
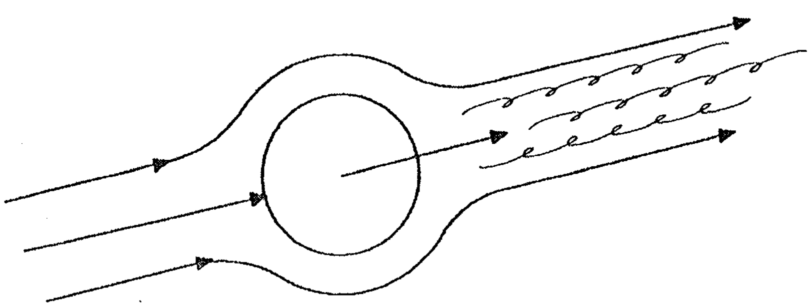
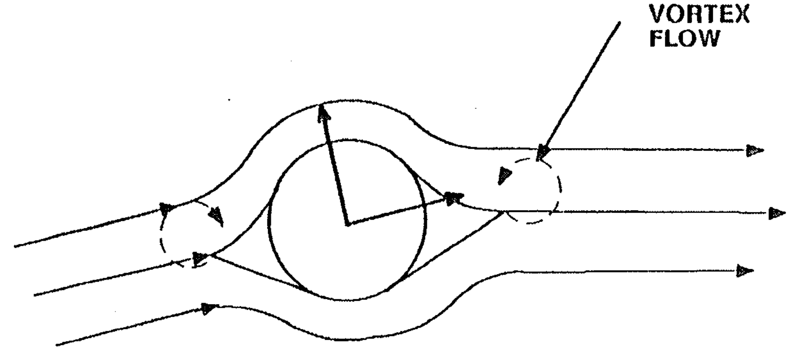


WHY CHINES ?



FOREBODY CROSS FLOW AT ANGLE OF ATTACK





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BENEFITS OF CHINES

- STABILITY
  - DESTABILIZING IN PITCH – REDUCES CRUISE TRIM DRAG
  - STABILIZING DIRECTIONALLY – REDUCES FOREBODY INSTABILITY
- RADAR CROSS SECTION
  - IMPROVES ANGULAR DISPERSION
- EQUIPMENT VOLUME – BODY A FUEL TANK
  - CLEAN AREA FOR ELECTRICAL WIRES, HYDRAULICS, ETC.
  - PAYLOAD VOLUME – SENSORS, MISSILES
  - EASY ACCESS FOR MAINTENANCE

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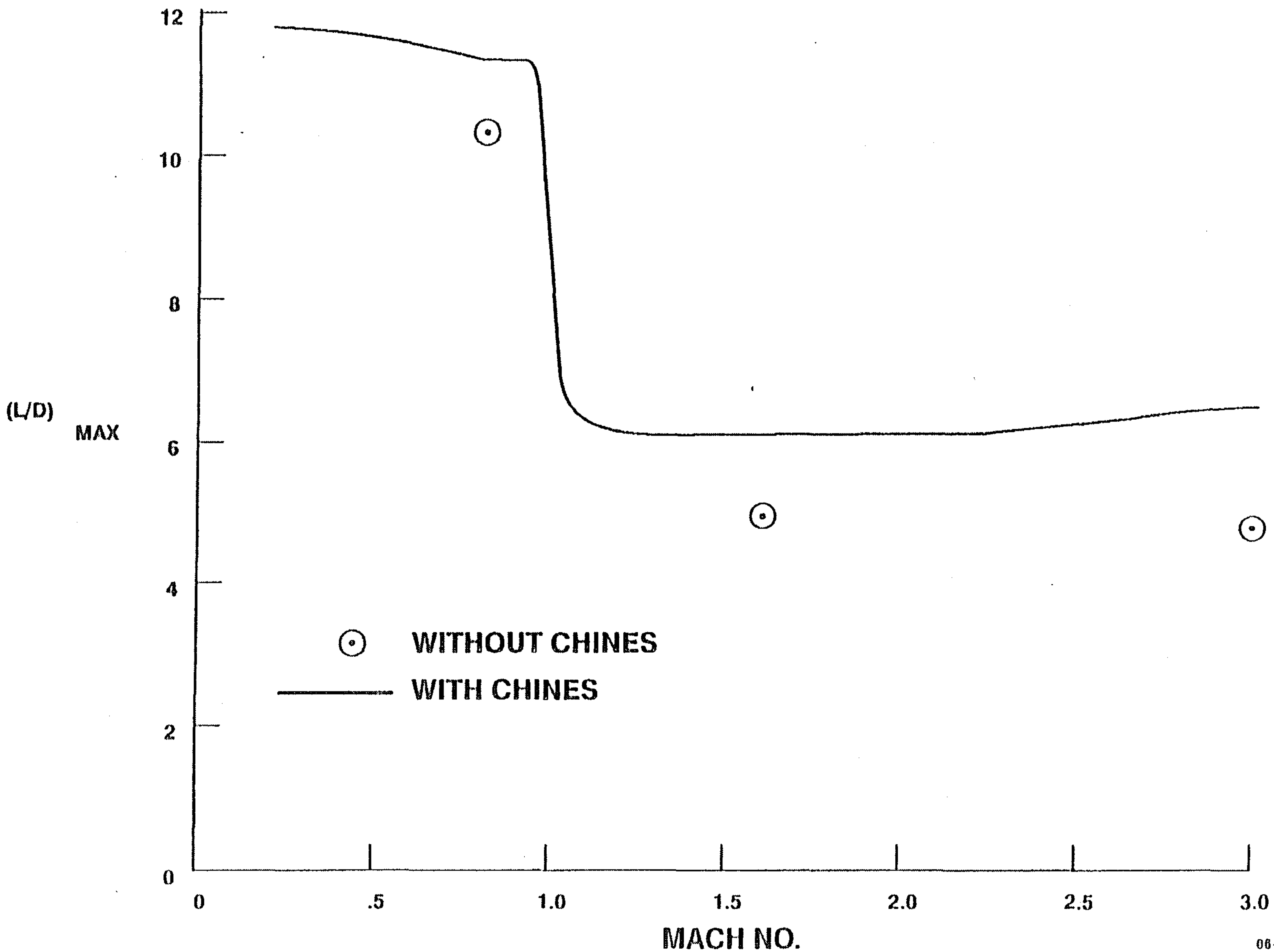
TRIMMED MAXIMUM L / D RATIO



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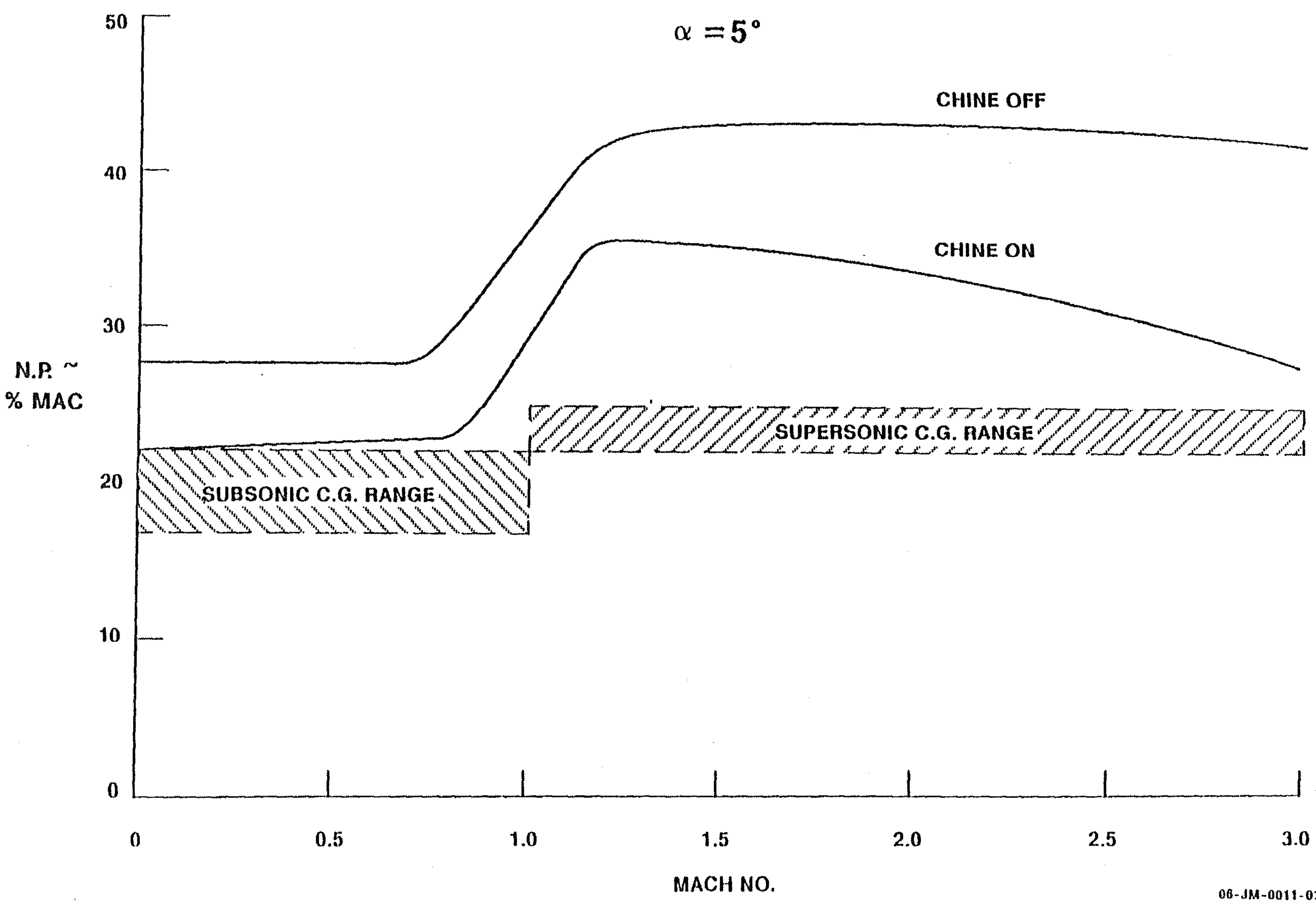
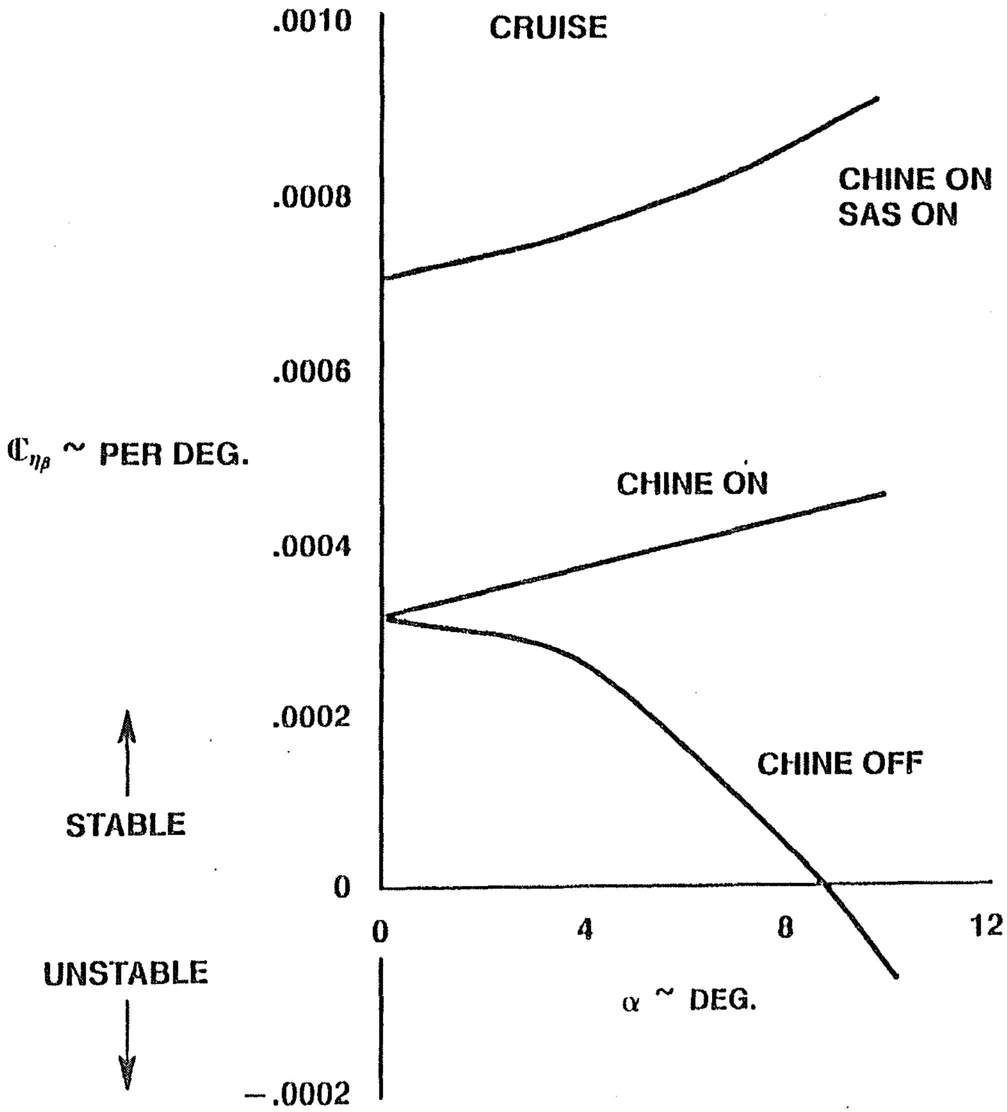
EFFECT OF CHINE ON NEUTRAL POINT
RIGID AIRPLANE



06-JM-0011-03-28-91-GM

EFFECT OF CHINE ON DIRECTIONAL STABILITY



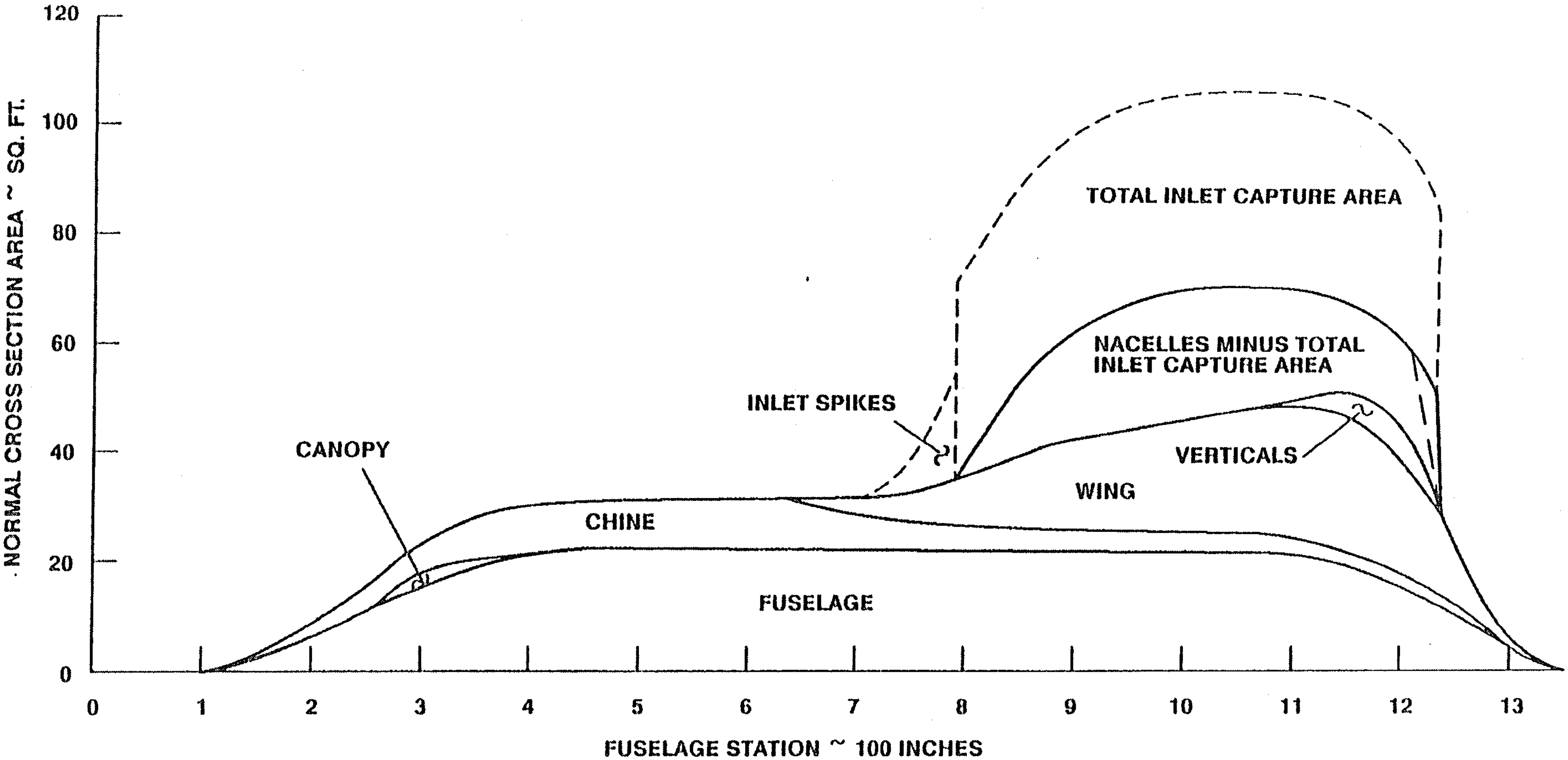
06-JM-0012-04-02-91-CB

THE "FINAL" CONFIGURATION

HOW DID WE FAIR IN FLIGHT TEST

06-JM-0013-03-25-91-DS

AREA DISTRIBUTION



06-JM-0014-03 26-91-QM

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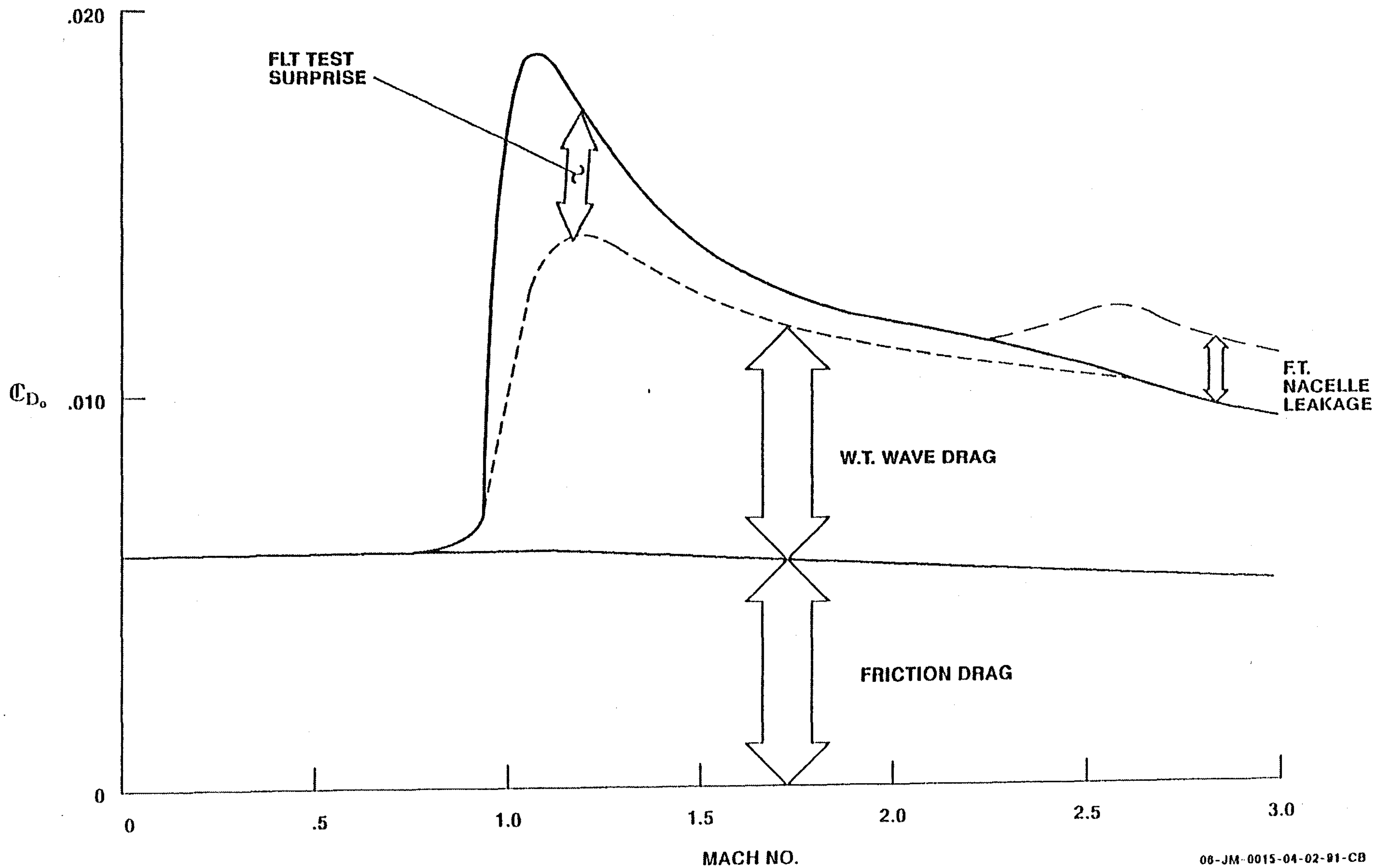
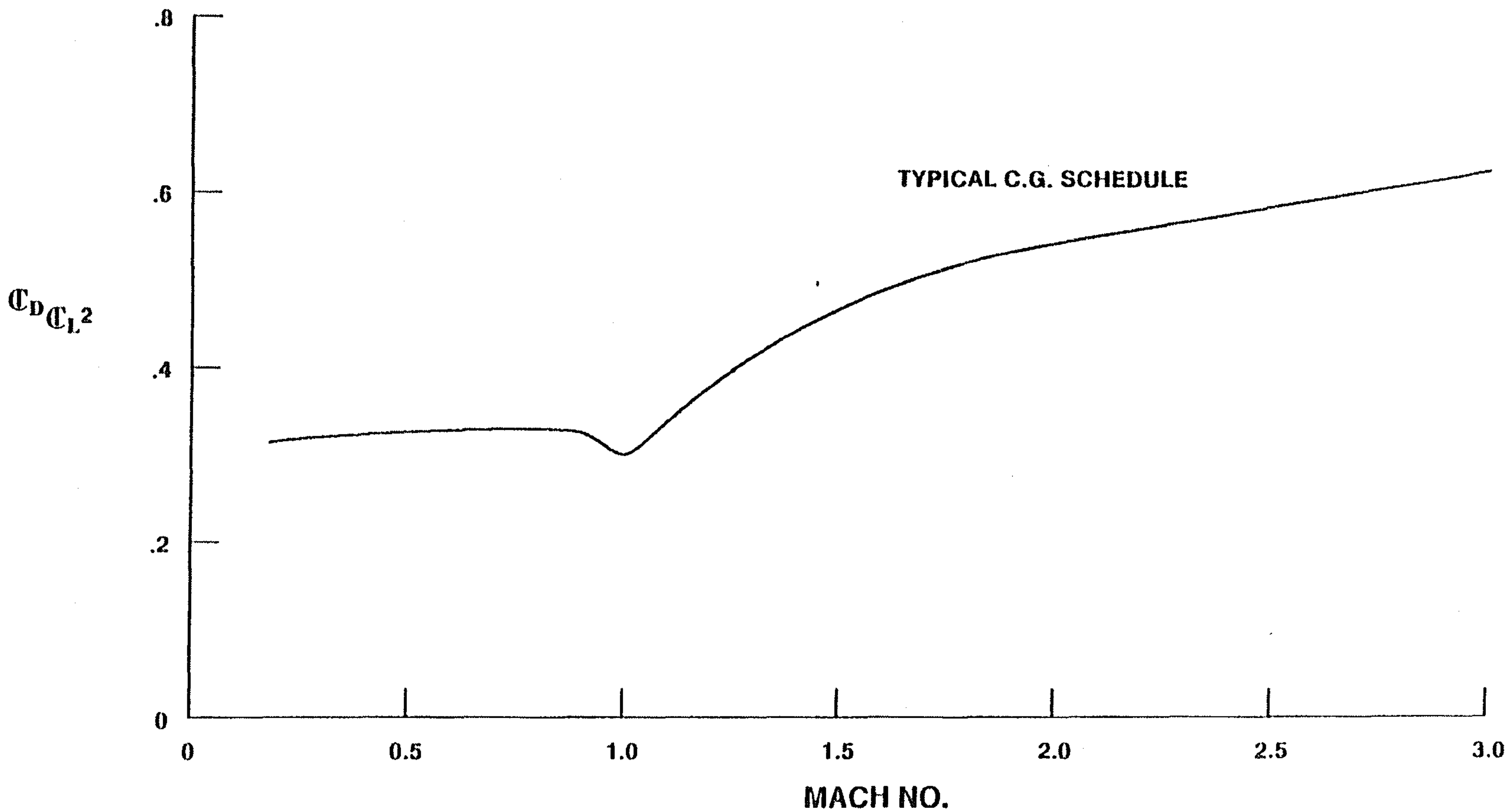
ZERO LIFT DRAG



DRAG DUE TO LIFT



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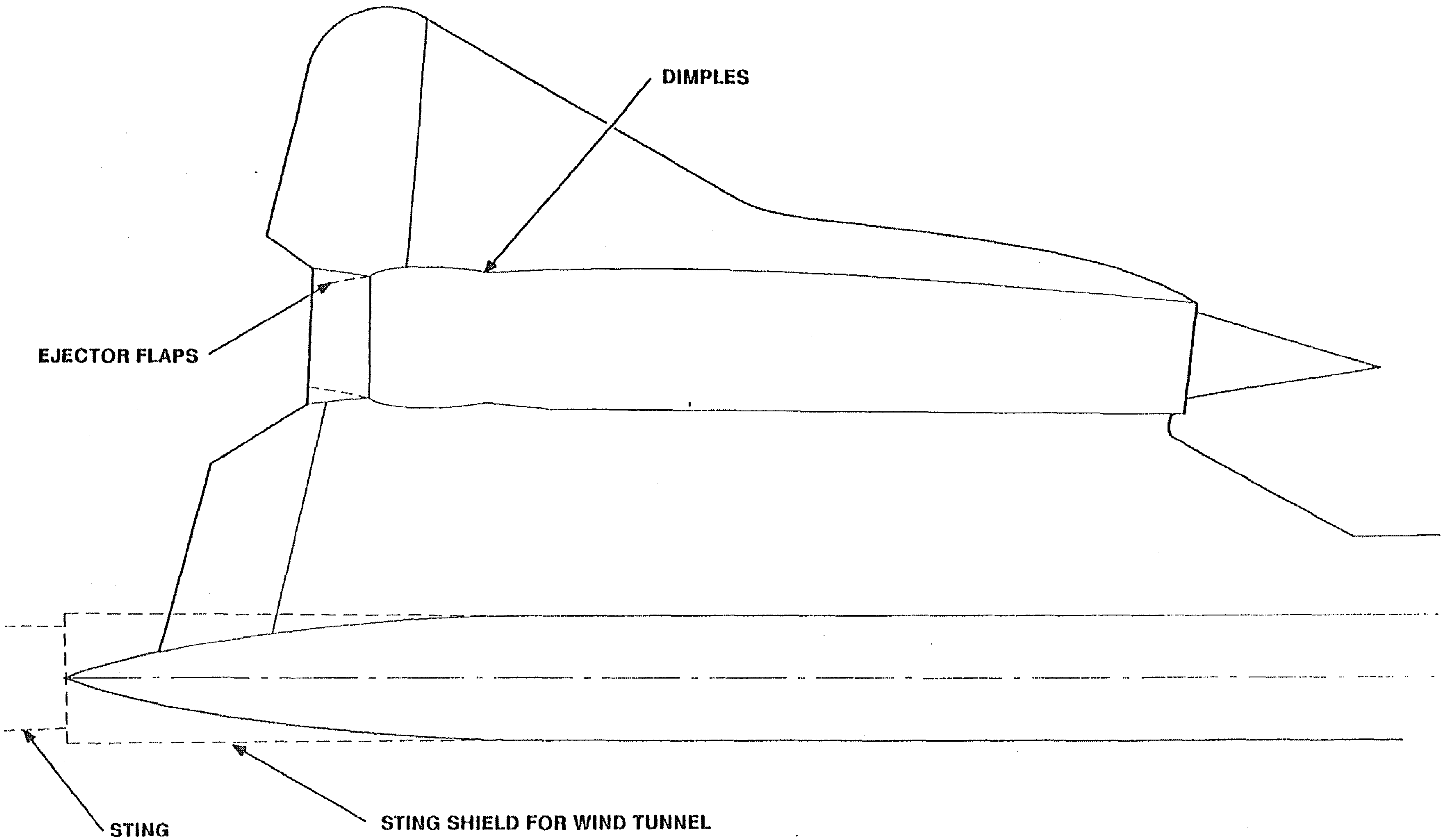
CONTRIBUTORS TO INCREASED TRANSONIC DRAG



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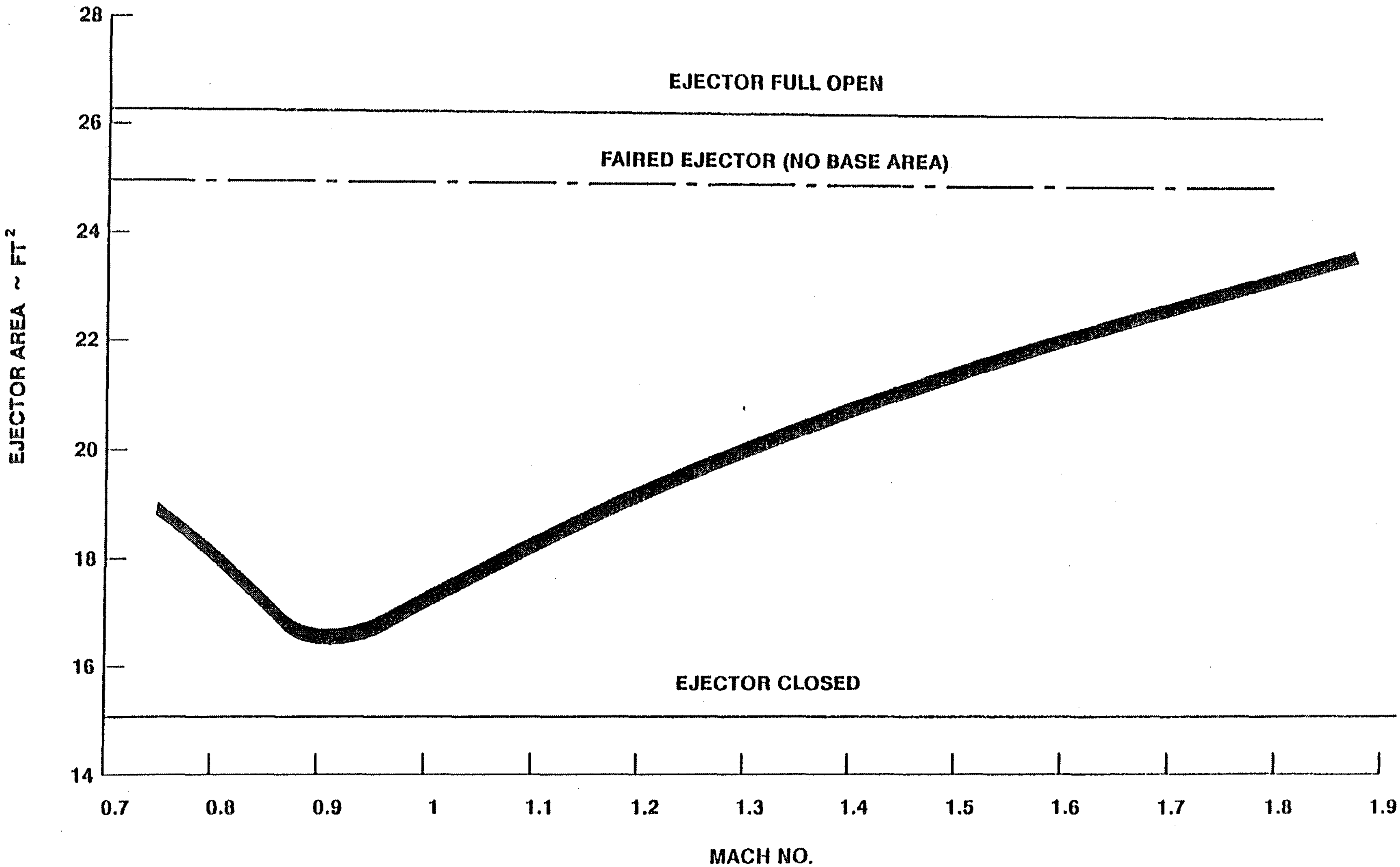
EJECTOR SCHEDULE



06-JM-0018-04-03-01-CB

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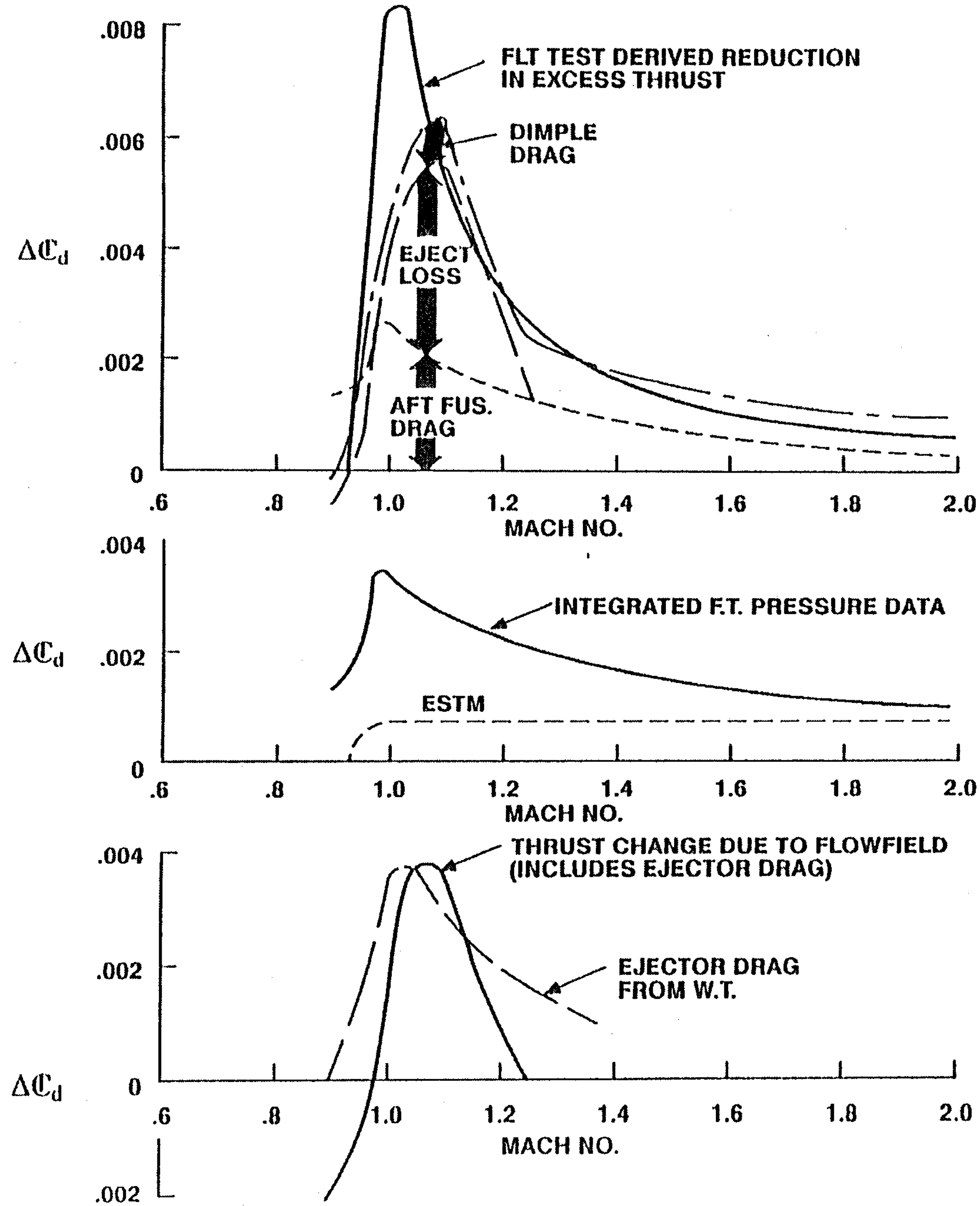
CONTRIBUTORS TO INCREASED TRANSONIC DRAG

- FUSELAGE BOATTAIL DRAG WAS INCORRECTLY ESTIMATED
- WIND TUNNEL WALL SHOCK REFLECTION ON MODEL CAUSED DRAG REDUCTION
- PRATT & WHITNEY RESPONSIBLE FOR EJECTOR BOATTAIL DRAG
  - TESTED EJECTOR NOT IN PRESENCE OF WING
  - LATER TESTS OF EJECTOR IN PRESENCE OF WING CAUSED:
    - -- REDUCED EJECTOR RECOVERY
    - -- NEGATIVE PRESSURE FIELD ON WING
    - -- INCREASED BOATTAIL DRAG
- NEITHER PROPULSION NOR P&W ACCOUNTED FOR THE DIMPLE DRAG

REDUCED TRANSON PERFORMANCE
UNEXPLAINED DIFFERENCE



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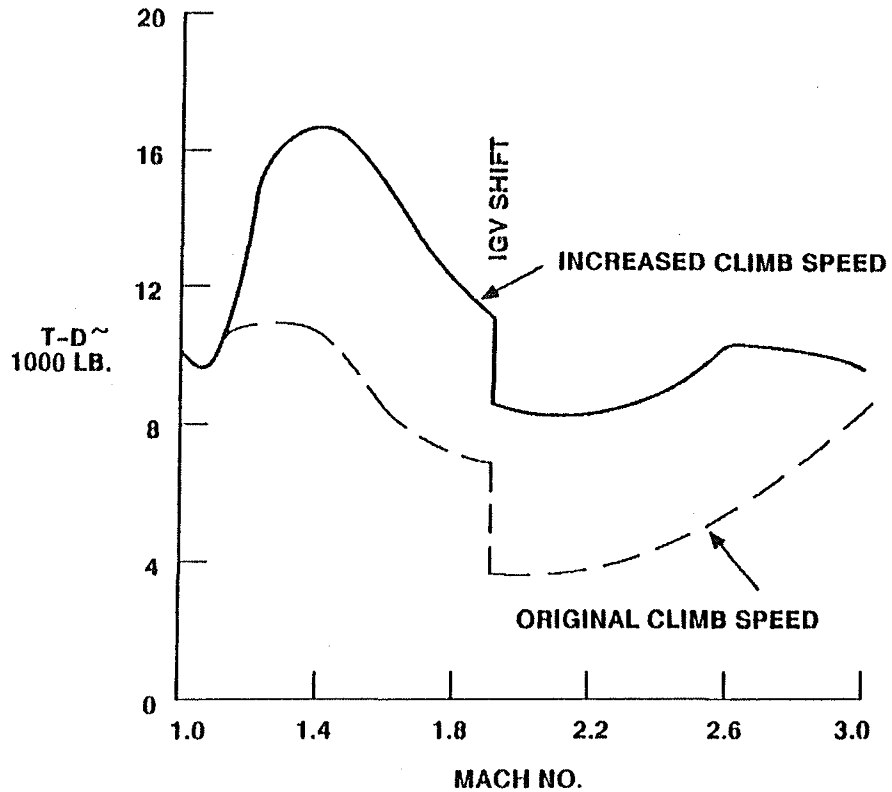
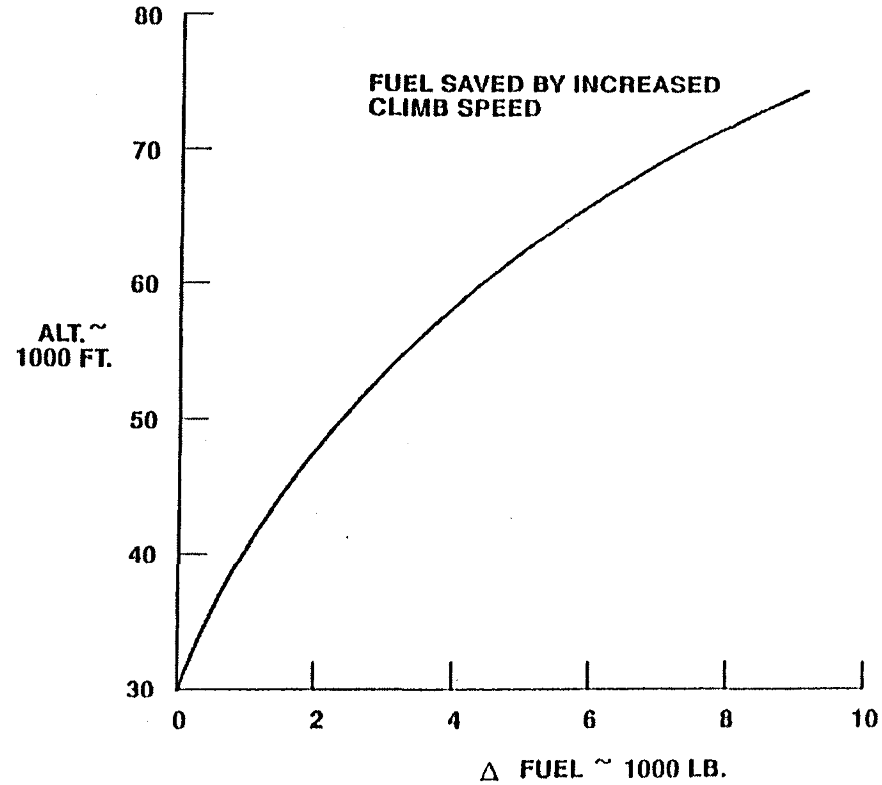
PERFORMANC_ RECOVERY
FROM TRANSONIC THRUST / DRAG DIFFERENCES





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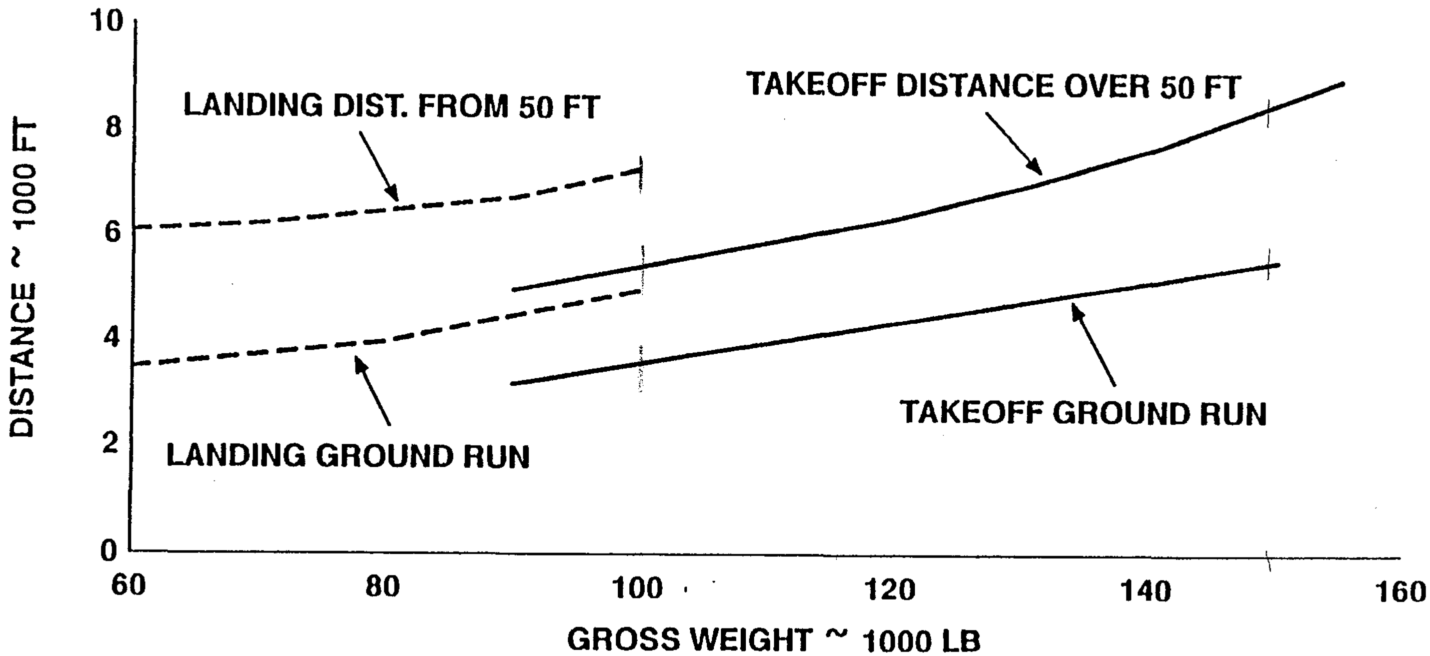
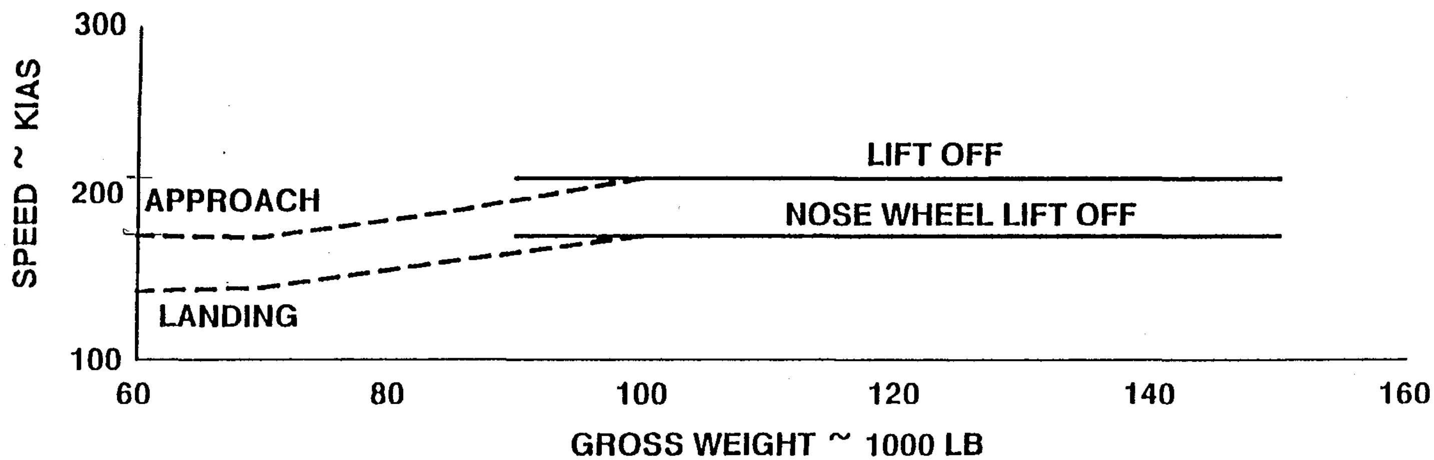
AIRPORT PERFORMANCE

- DELTA WINGS NORMALLY HAVE HIGH C_{ℓ_β}
  - CHINES AND CANTED VERTICALS REDUCE C_{ℓ_β}
  - CONICAL CAMBER IN OUTBOARD WING ALSO REDUCED C_{ℓ_β}
- ALL-MOVABLE CANTED VERTICALS PROVIDE BOTH ENGINE OUT CONTROL AND CROSSWIND LANDING CAPABILITY
- ALL THESE CONTRIBUTIONS REDUCE PILOT WORKLOAD IN TAKE-OFF, LANDING OR GO-AROUND
- DELTA WINGS RESULT IN AUTOMATIC FLARE NEAR TOUCH DOWN
- DELTA WINGS PRODUCE HIGH TAKE-OFF AND LANDING SPEEDS
- FOR TYPICAL TAKEOFF WEIGHT: LIFT-OFF SPEED, 210 KTS
GROUND ROLL, 5400 FT
- TYPICAL LANDING: TOUCHDOWN SPEED, 150 KTS
GROUND ROLL, 3600 FT

06-JM-0022-03-25-91-DS

TAKEOFF AND LAND 'G PERFORMANCE





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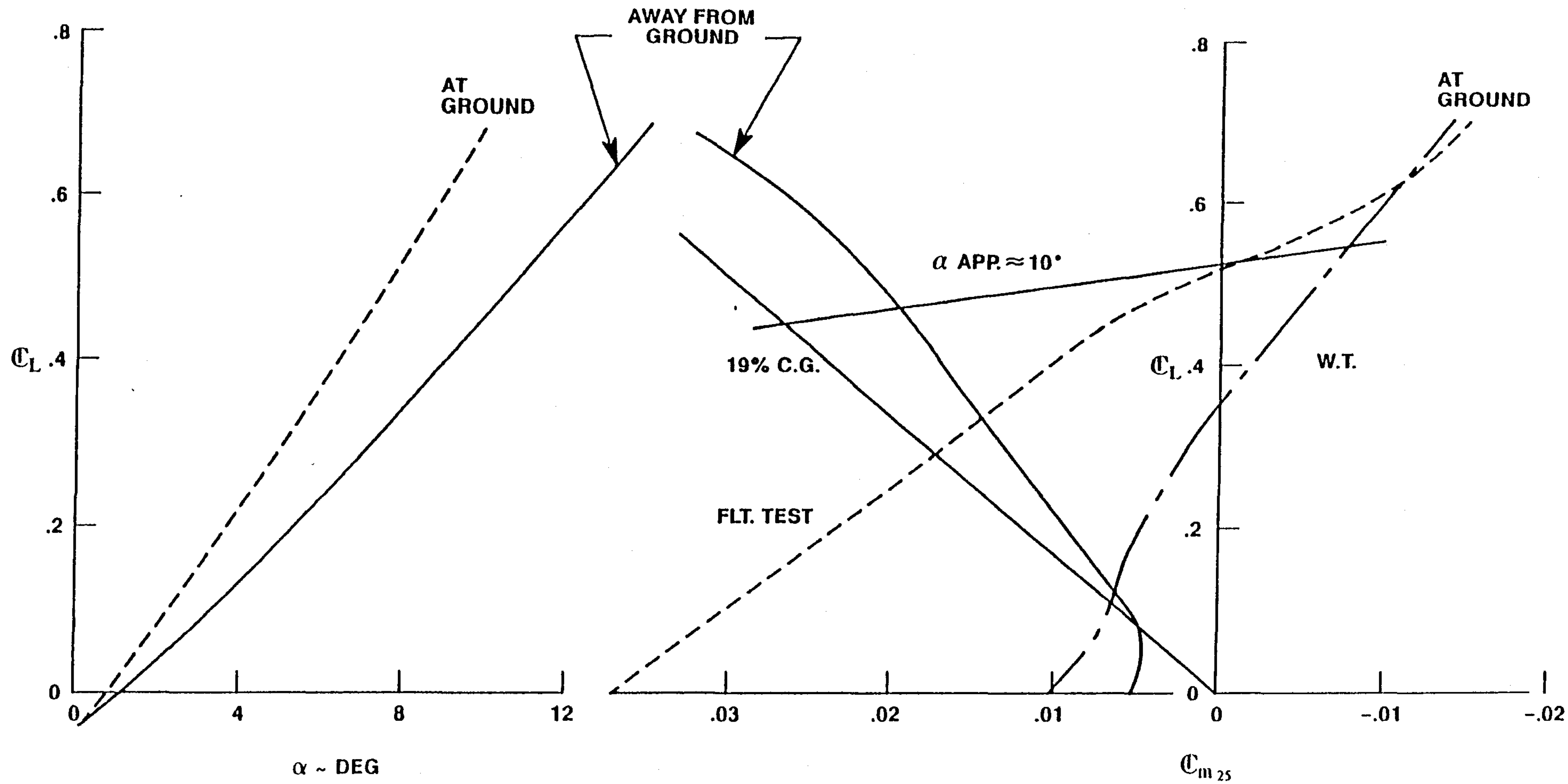
BASIC STABILITY AND CONTROL CHARACTERISTICS

06-JM-0024-03-25-91-DS

LOW SPEED LIFT AND PITCH CHARACTERISTICS



06-JM-0025-04-15-91-CB

101

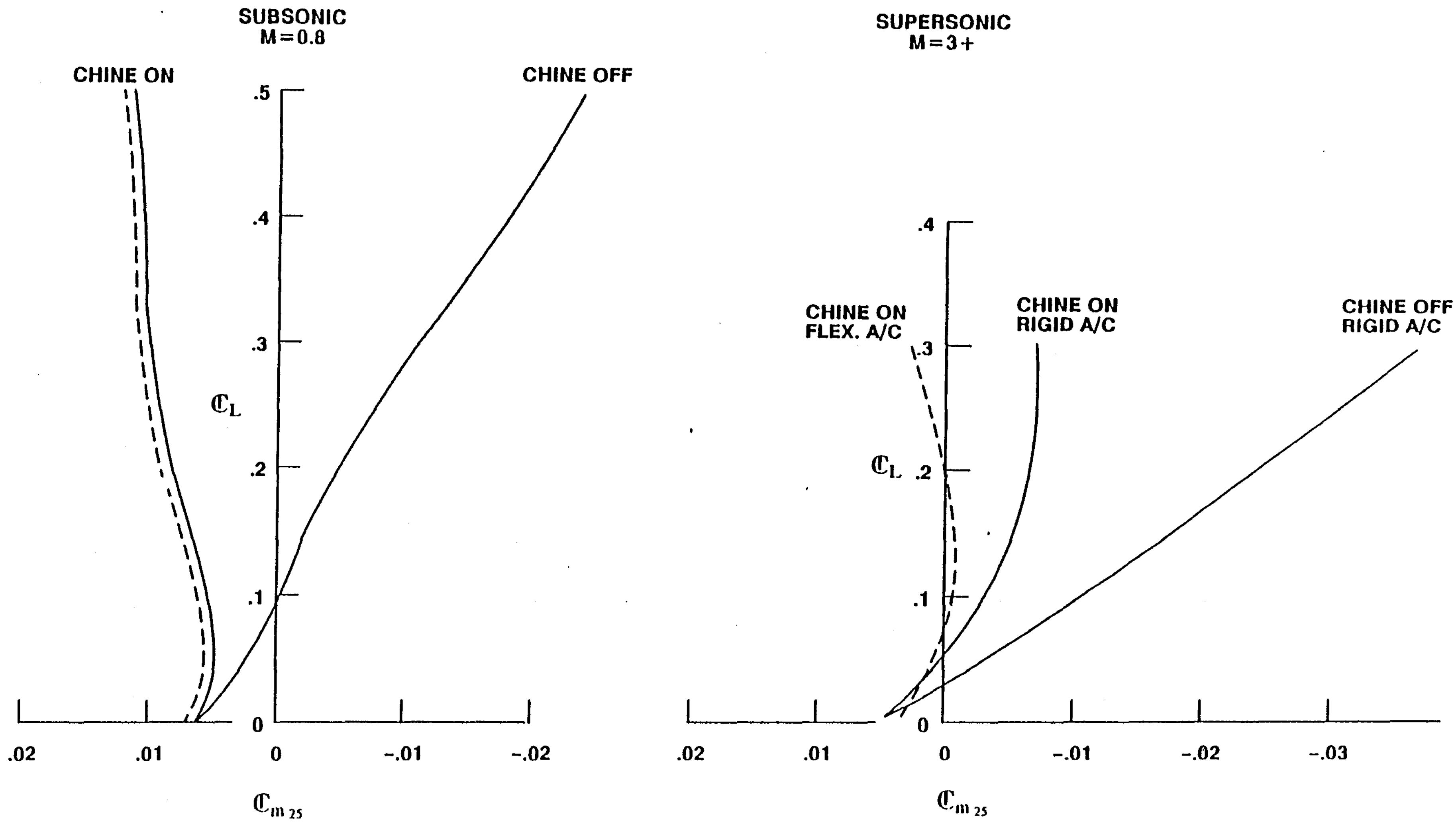
AIRCRAFT REQUIRED LESS CONTROL FOR NOSE WHEEL LIFT-OFF

- FLIGHT TEST SHOWED MUCH GREATER GROUND EFFECT ON PITCH THAN WIND TUNNEL GROUND PLANE DATA

- ELEVON CONTROL IN PITCH AT GROUND WAS 25 PERCENT GREATER THAN AWAY FROM GROUND

06-JM-0026-03-25-91-DS

EFFECT OF CHINE ON PITCH STABILITY



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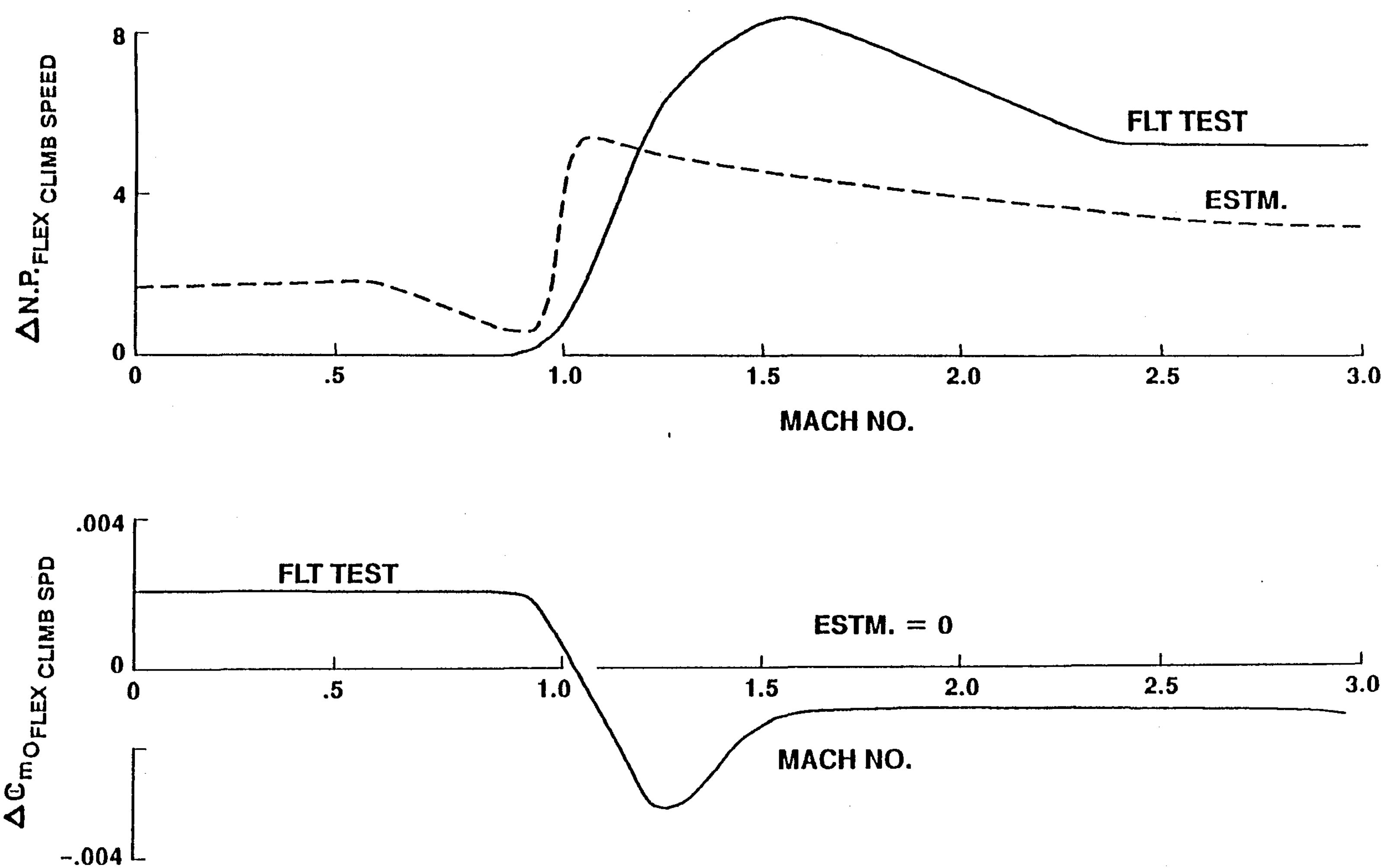
FLEXIBILITY EFFECTS ON PITCH

- EFFECT ON NEUTRAL POINT
  - FLEXIBLE AIRCRAFT AT CRUISE APPROXIMATELY 1.5 PERCENT MORE UNSTABLE THAN ESTIMATED
  - ELIMINATED 1.5 PERCENT STATIC MARGIN PLANNED IN DESIGN
  - AIRCRAFT STILL “SAFE” TO FLY SAS OFF BUT VERY SENSITIVE
- ELEVON CONTROL EFFECTIVENESS
  - RIGID CONTROL AT CRUISE ONLY 20% OF LOW SPEED CONTROL
  - ANOTHER 40% CONTROL POWER LOSS DUE TO FLEXIBILITY AT CRUISE
  - CONTROL STILL ADEQUATE FOR HIGH SPEED CRUISE

06-JM-0028-03-25-91-DS

EXIBILITY CORRECTIO S TO PITCH STABILITY

NORMAL CLIMB SPEED



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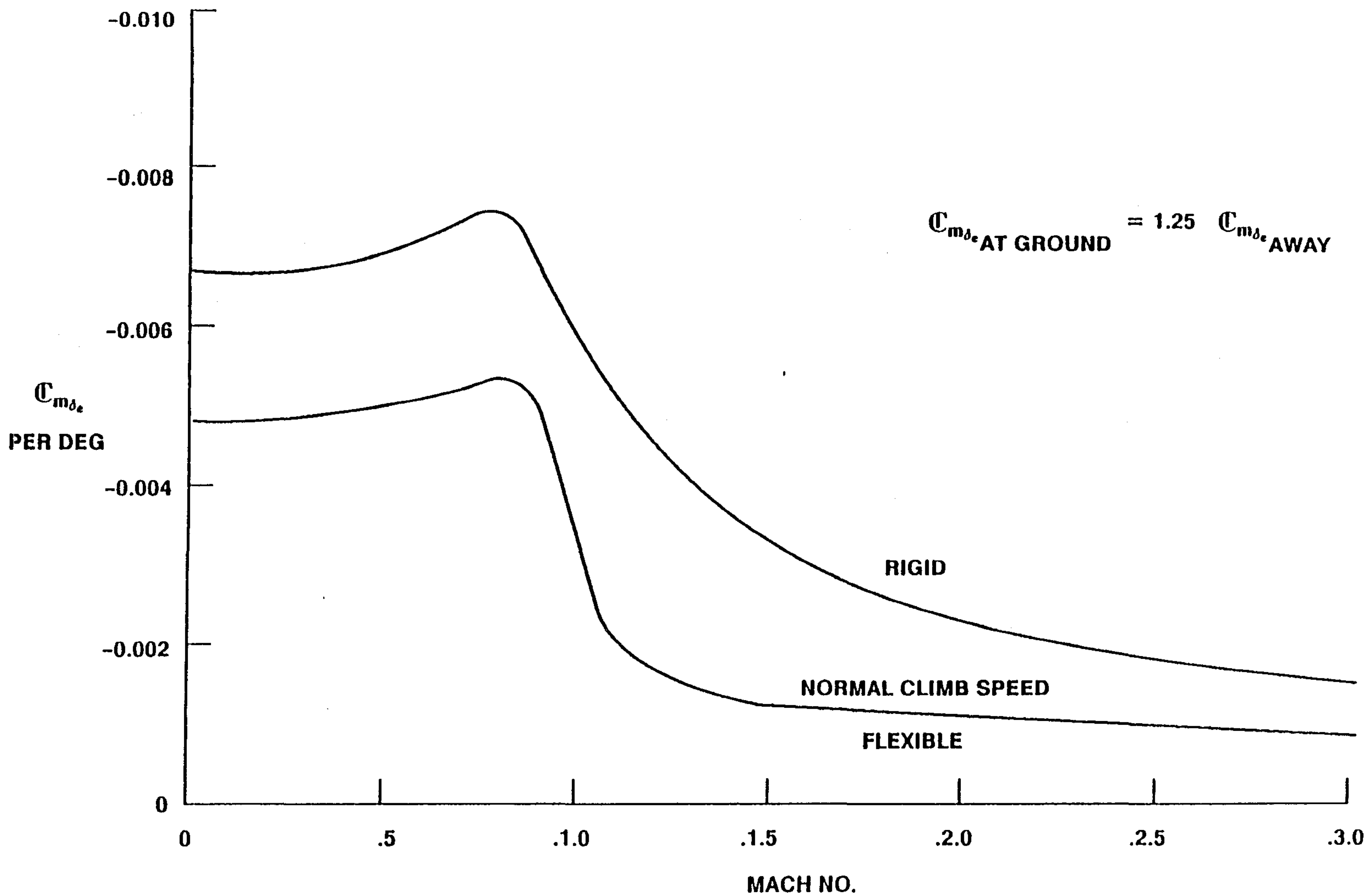
ELEVON EFFECTIVENESS IN PITCH



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DIRECTIONAL STABILITY

- BASIC DIRECTIONAL STABILITY AT CRUISE IS 20% OF LOW SPEED LEVEL
- NO FLEXIBILITY EFFECT ON DIRECTIONAL STABILITY
- DIRECTIONAL STABILITY IS LOW BUT ADEQUATE AT CRUISE
- STABILITY AUGMENTATION DOUBLES BASIC STABILITY
- VERTICALS WERE SIZED FOR MINIMUM ACCEPTABLE LEVEL OF DIRECTIONAL STABILITY WITH ADEQUATE CONTROL POWER

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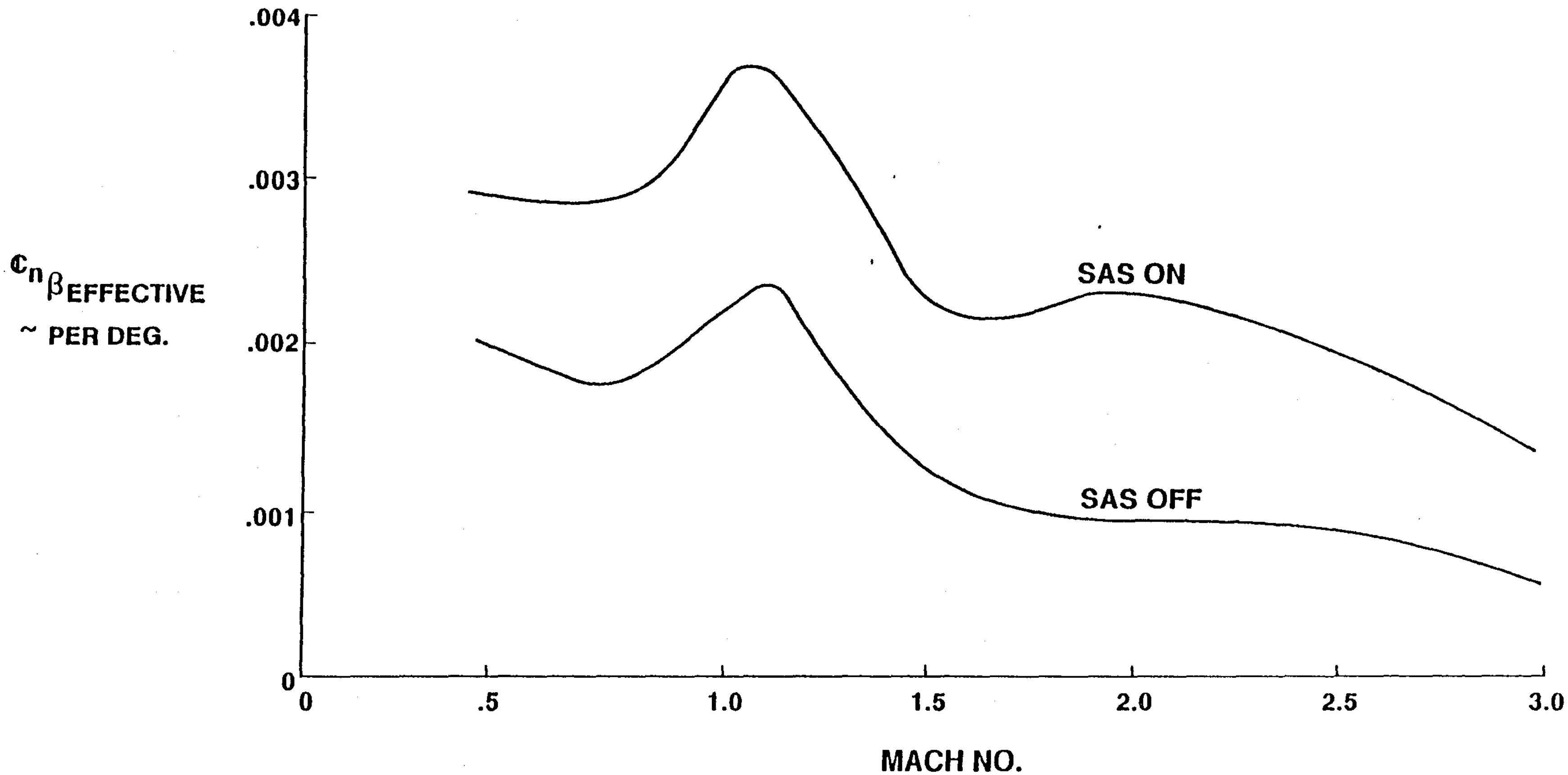
DIRECTIONAL STABILITY
STANDARD CLIMB SCHEDULE



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:FFECT OF VERTICALS ɔN LATERAL STABILITY

- COMBINATION OF CANTED FINS AND ALL-MOVABLE VERTICALS REDUCED ROLL DUE TO SIDESLIP AND VERTICAL DEFLECTION AS ANGLE OF ATTACK INCREASES

- LOW ASPECT RATIO, LOWER SWEEP FINS MINIMIZE FLEXIBILITY LOSSES ON BOTH STABILITY AND CONTROL

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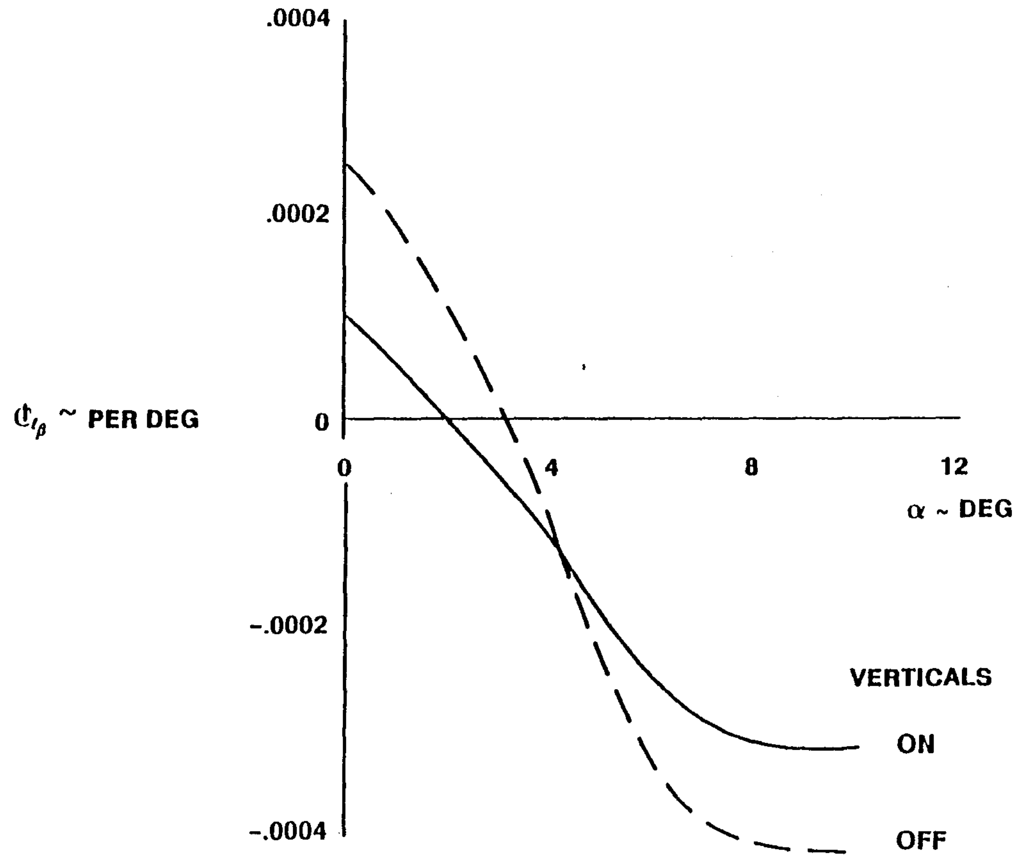
EFFECT OF VERTICAL TAILS ON LATERAL STABILITY
CRUISE CONDITION



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LATERAL-DIRECTIONAL CONTROL

- LATERAL CONTROL AT CRUISE, LIKE ELEVONS IN PITCH, IS ONLY 20 + % OF LOW SPEED CONTROL
- FLEXIBILITY ACCOUNTS FOR ANOTHER 40% LOSS AT CRUISE
- ALL-MOVABLE VERTICALS AT CRUISE ONLY 55% AS EFFECTIVE AS AT LOW SPEED
- NO FLEXIBILITY LOSSES – MORE RIGID STRUCTURE
- BOTH ARE ADEQUATE FOR ENGINE OUT AND MANEUVER CONTROL

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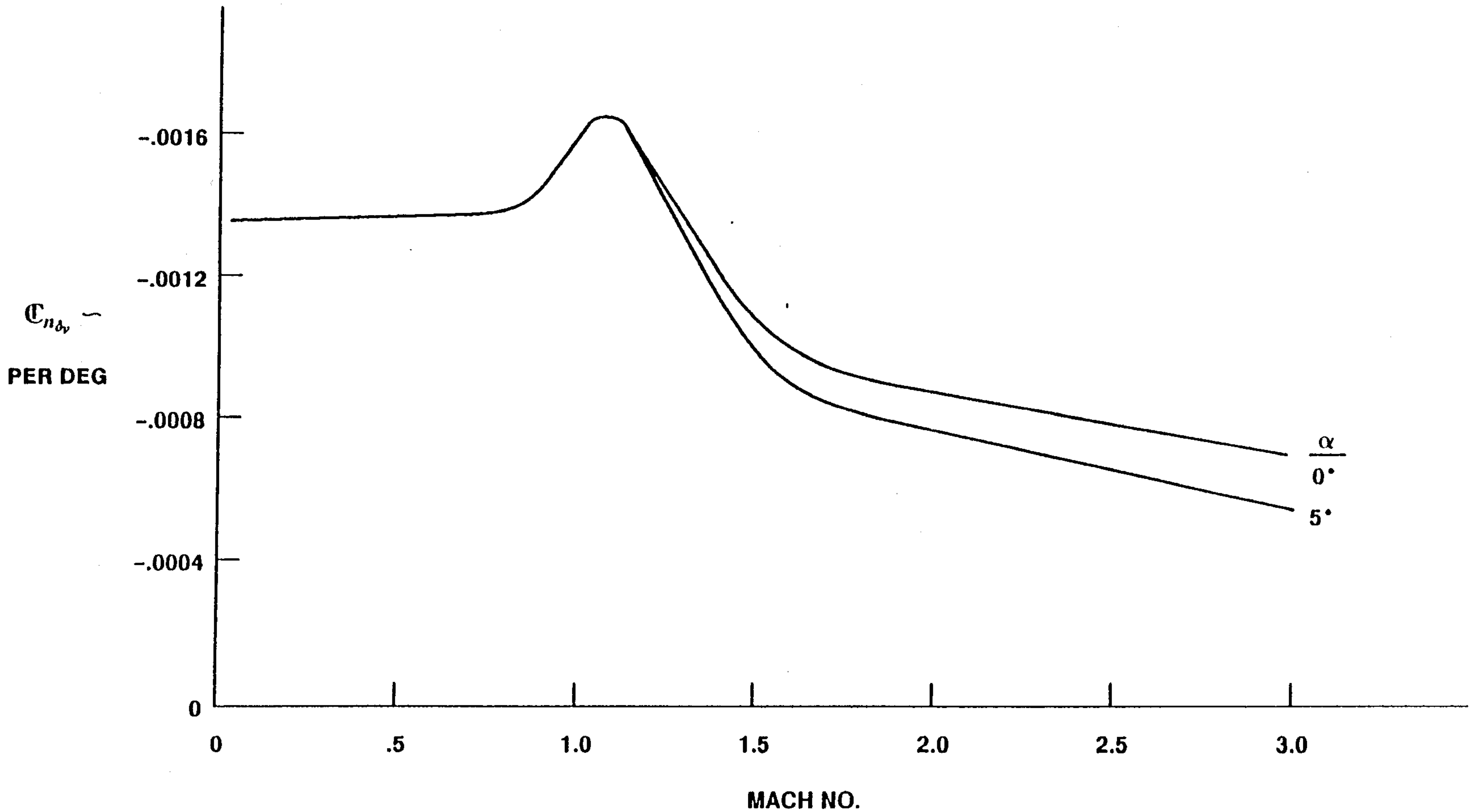
ALL–MOVEABLE VERTICALS EFFECTIVENESS
(BOTH SURFACES)



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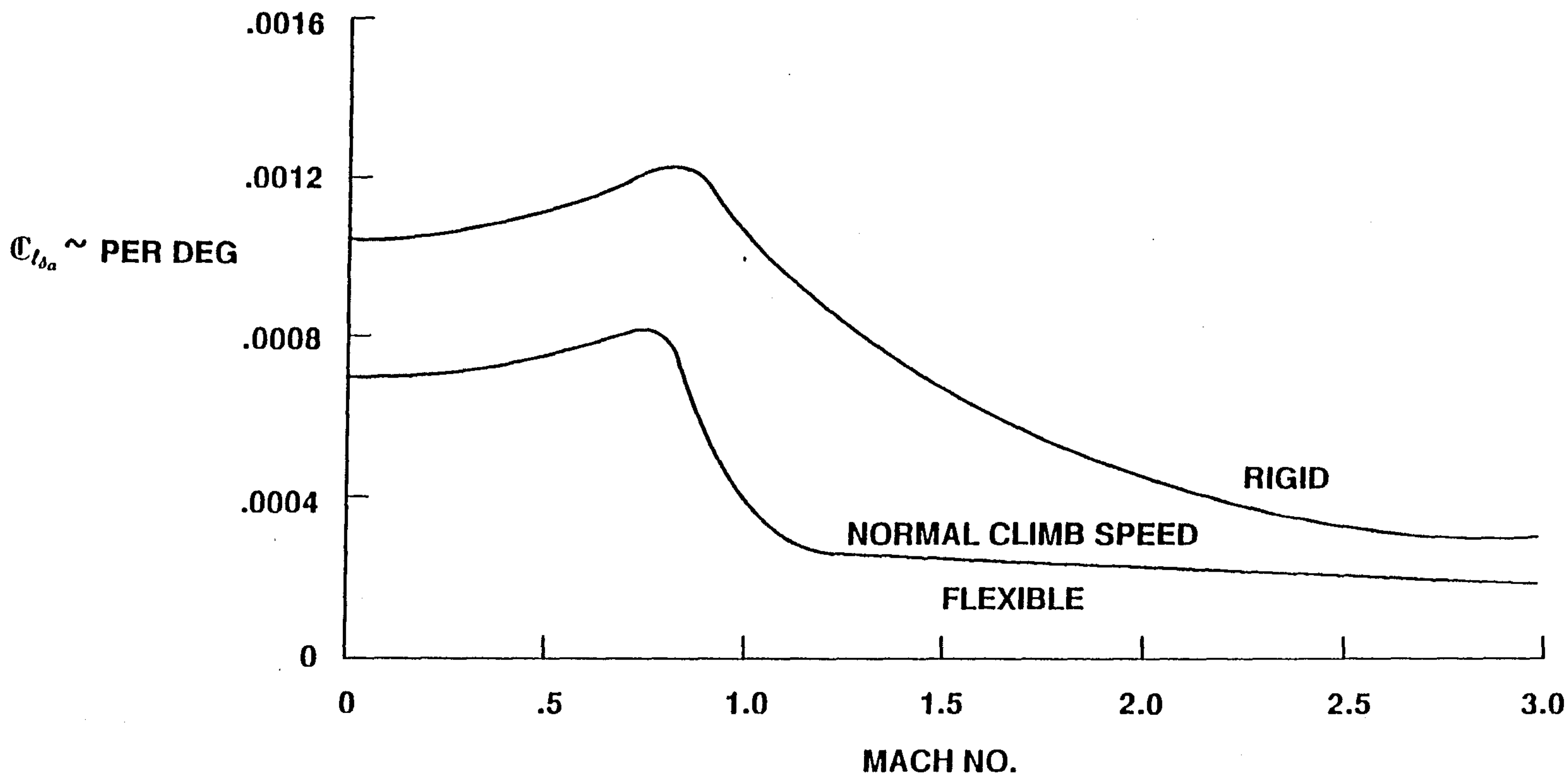
ELEVON EFFECTIVENESS IN ROLL

$(\delta_a = \delta_{e_{LT}} - \delta_{e_{RT}})$



06-JM-0037-04-03-91-CB

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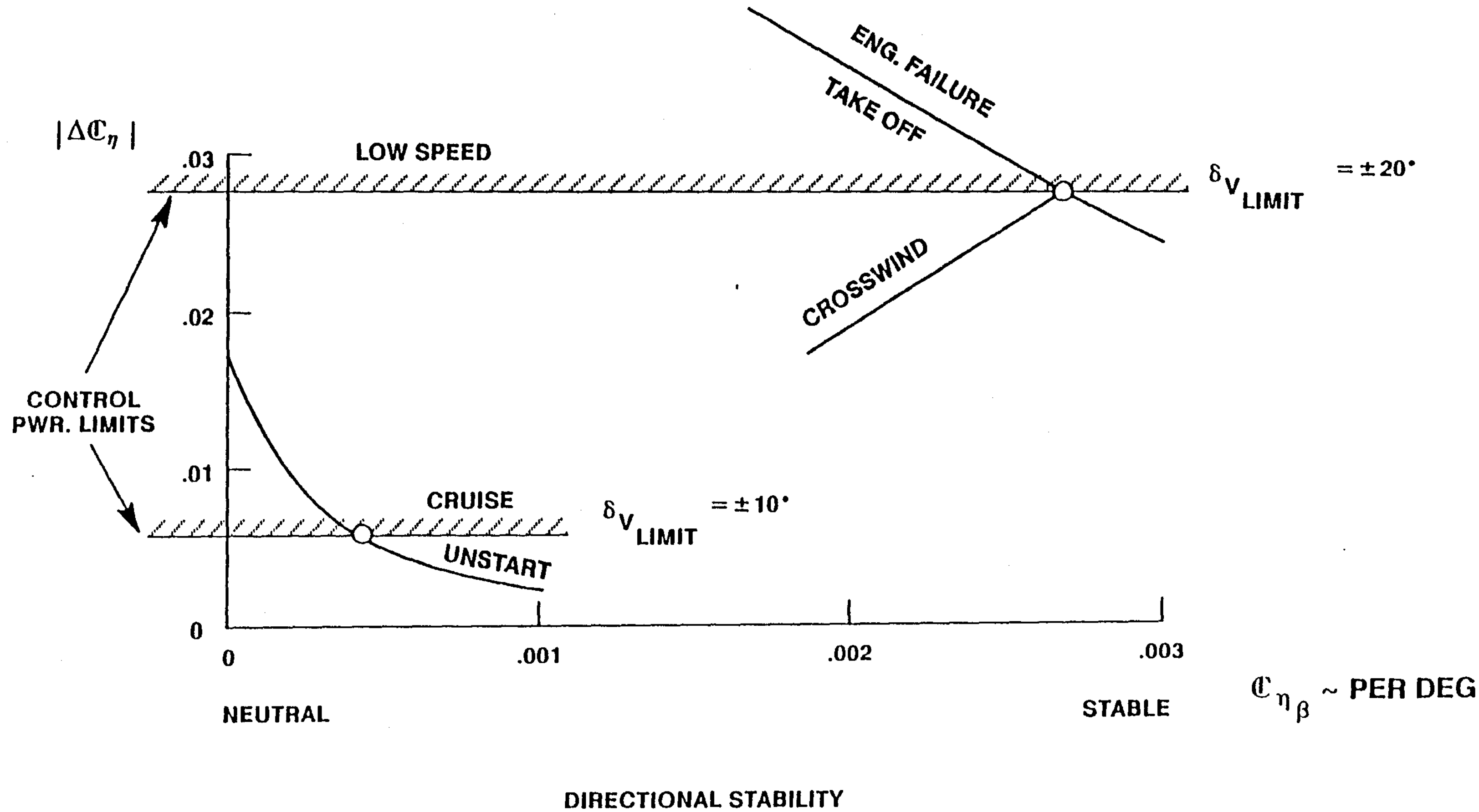
DIRECTIONAL CONTROL POWER REQUIREMENTS

- LOW SPEED DRIVERS
  - ENGINE FAILURE ON TAKEOFF
  - SINGLE ENGINE GO AROUND
  - CROSSWIND LANDING WAS SEMI-FALLOUT BUT COULD EXCEED 30 KTS AT NORMAL LANDING WEIGHT

- HIGH SPEED DRIVERS
  - NO CROSS-TIE UNSTARTS AT MAXIMUM A / B
  - RUDDER LIMITED TO 10 DEGREES AT M $\geq$ 0.5
    - -- PREVENT EXCESSIVE CONTROL
    - -- PREVENT EXCESSIVE TAIL LOADS
    - -- REDUCE ACTUATOR SIZE / HINGE MOMENTS

06-JM-0038-03-25-91-DS

L.IRECTIONAL CONTROL ᴘOWER REQUIREMENTS
ALL MOVING FIN DEFLECTION RATE LIMIT 31 DEG/SEC NO LOAD



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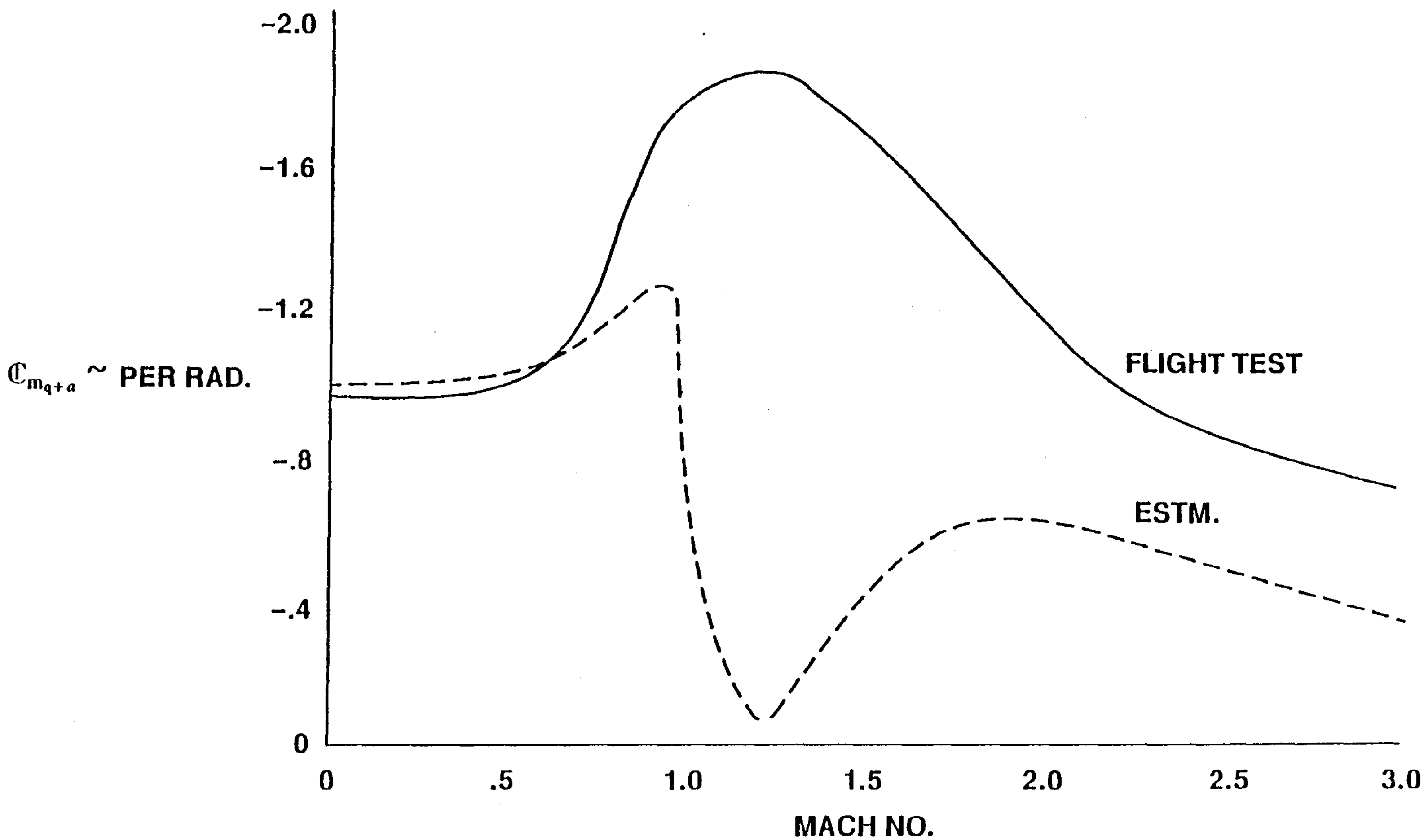
50e

VEHICLE NATURAL DAMPING

- DAMPING IN ALL THREE AXES WAS EXPECTED TO BE LOW AT CRUISE
- STABILITY AUGMENTATION SYSTEM (SAS) WAS DESIGNED TO PROVIDE NECESSARY DAMPING
- DAMPING IN PITCH AND ROLL WAS UNDER-ESTIMATED BY A FACTOR OF 2 PRIOR TO FLIGHT TEST
- THIS MADE VEHICLE SLIGHTLY BETTER THAN EXPECTED

06-JM 0040-04 02-91 CB

PITCH DA.·.IPING



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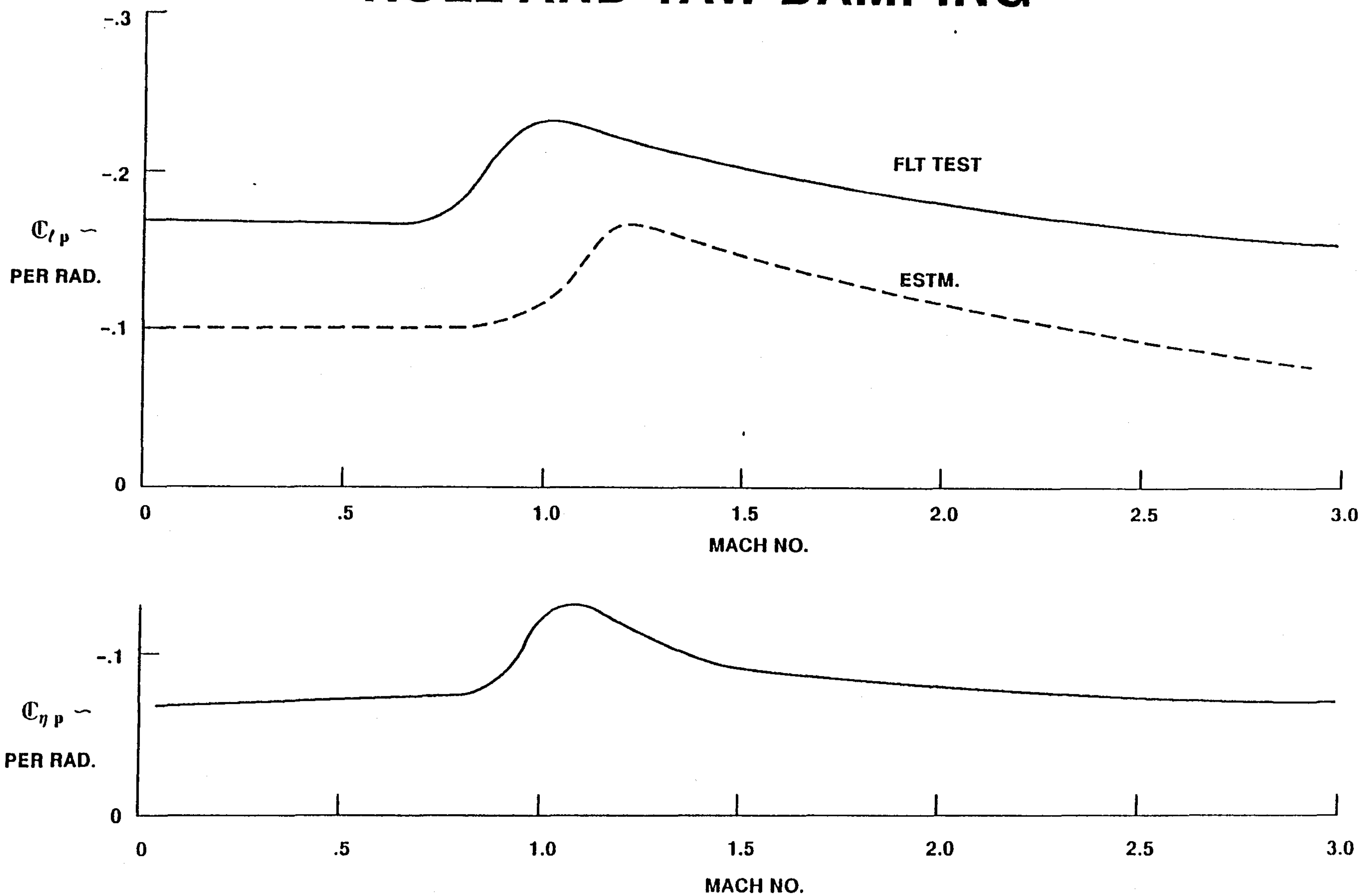
ROLL AND YAW DAMPING



06 JM 0042 04 02 91 CD

SR-71

FLIGHT CONTROLS

presented by Bob Loschke, Lockheed fellow

17-BL-0001-04-10-91-CB

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SR-]
FLIGHT CONTROLS TOPICS

- CONFIGURATION DEVELOPMENT PROCESS
- FLIGHT CONTROL SYSTEM DESCRIPTION
- DEVELOPMENT PROBLEMS AND SOLUTIONS
- DAFICS UPGRADE

17-BL-0002-04-10-91-CB

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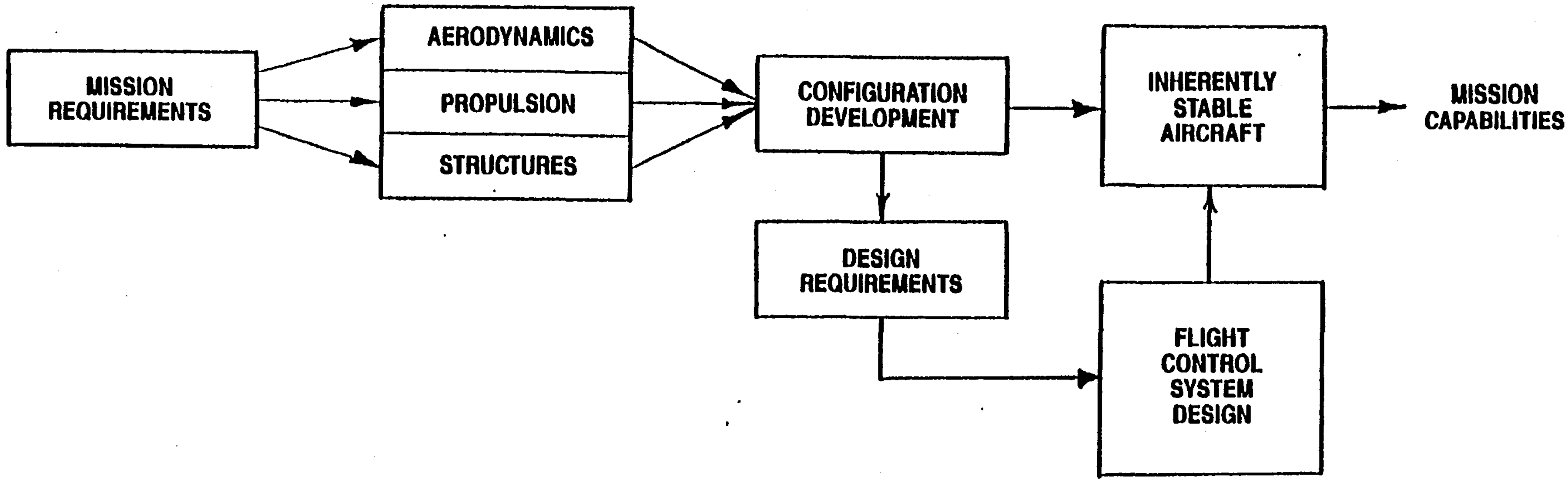
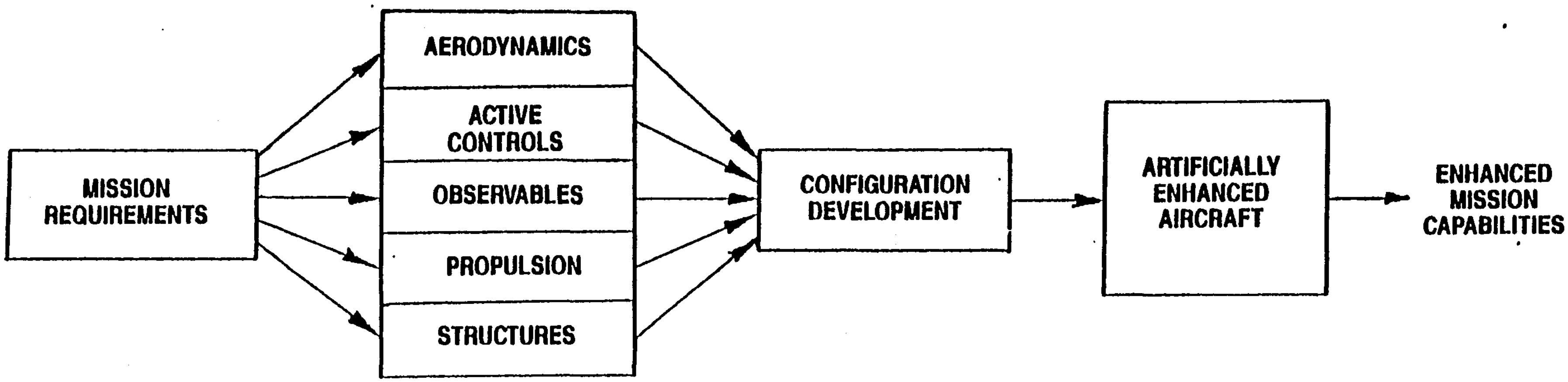
CLASSICAL AIRCRAFT DESIGN PROCESS

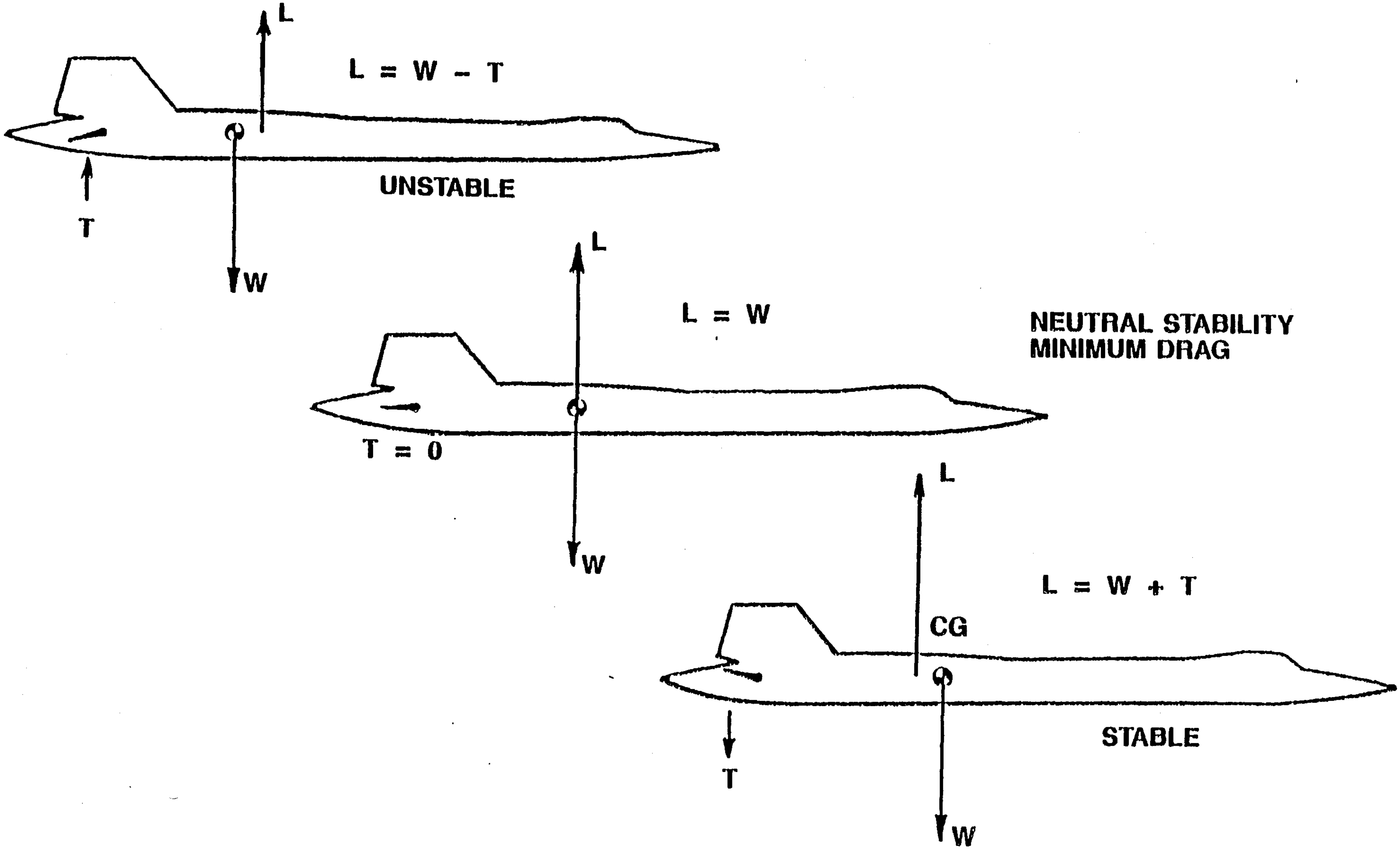


SR-71 DESIGN PROCESS



A20-4699-2

RELAXED STATIC STABILITY



A20-4699-5

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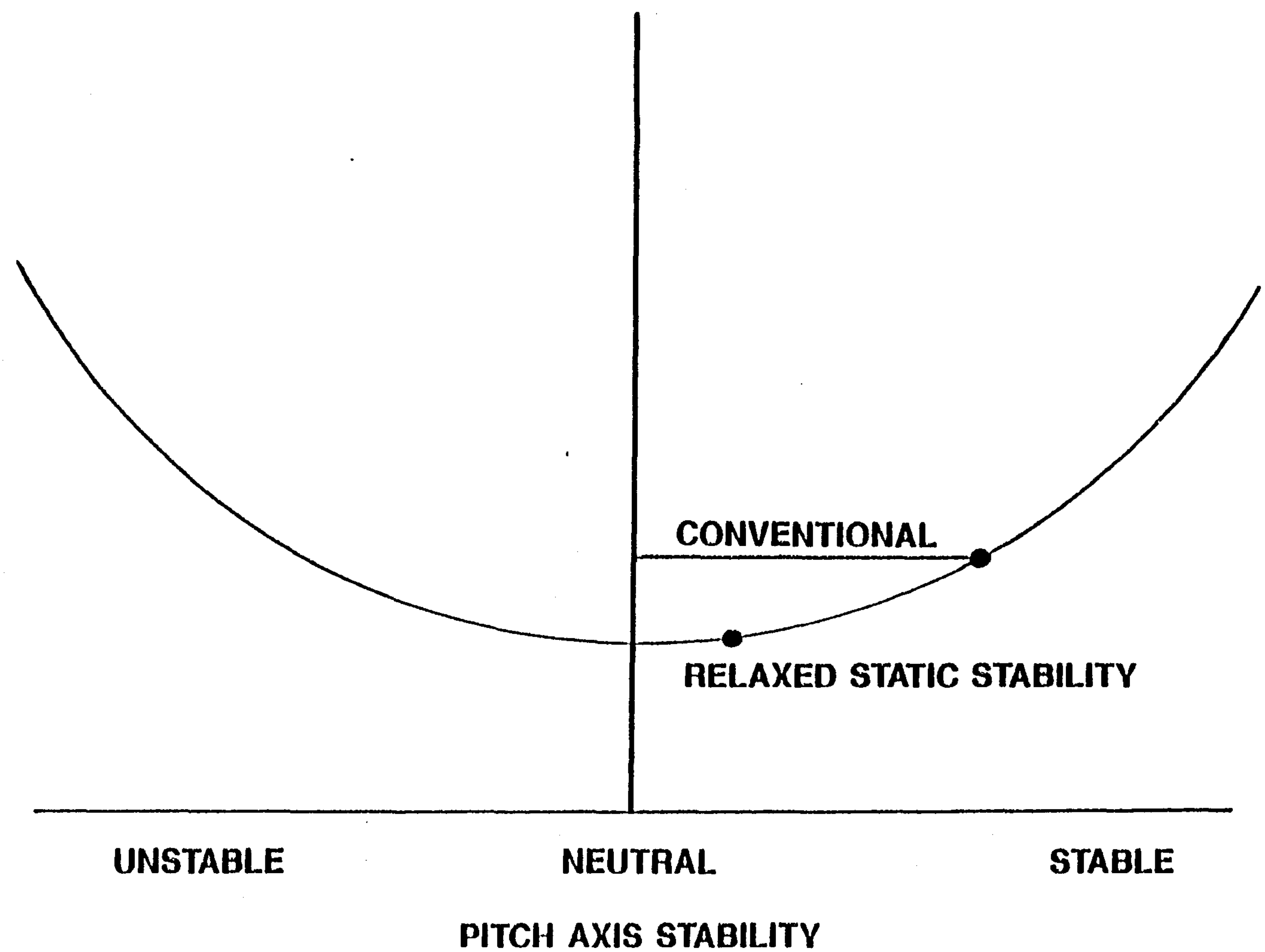
SR-71 CRUISE TRIM DRAG



A20-4699-6

SR-71 FLIGHT CONTROL SYSTEM

MAINTAINING A LOW LEVEL OF PITCH AND DIRECTIONAL STABILITY RESULTED IN

- SMALLEST POSSIBLE ELEVONS & FIN CONTROL SURFACES AT THE REAR OF AIRCRAFT
- SMALLEST POSSIBLE ACTUATORS
- MINIMIZED HYDRAULIC POWER REQUIREMENTS
- LEAST WEIGHT IN TERMS OF HYDRAULIC LINE LENGTHS
- LESS COMPLICATED CONTROL SYSTEM MECHANIZATION

CANTING THE FINS INBOARD RESULTED IN

- REDUCTION OF ADVERSE ROLL DUE TO FIN DEFLECTION
- REDUCTION OF ROLL DUE TO SIDE SLIP
- REDUCTION OF SIDE SECTOR OBSERVABILITY

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A20-4699-8

SR-71
FLIGHT CONTROL SYSTEM DESCRIPTION

- REQUIREMENTS
- DESIGN DRIVERS
- PRIMARY FLIGHT CONTROLS
- AUTOMATIC FLIGHT CONTROLS
- AIR INLET CONTROLS

17-BL-0003-04-10-91-CB

SR-71 FLIGHT CONTROL SYSTEM REQUIREMENTS

FLIGHT SAFETY

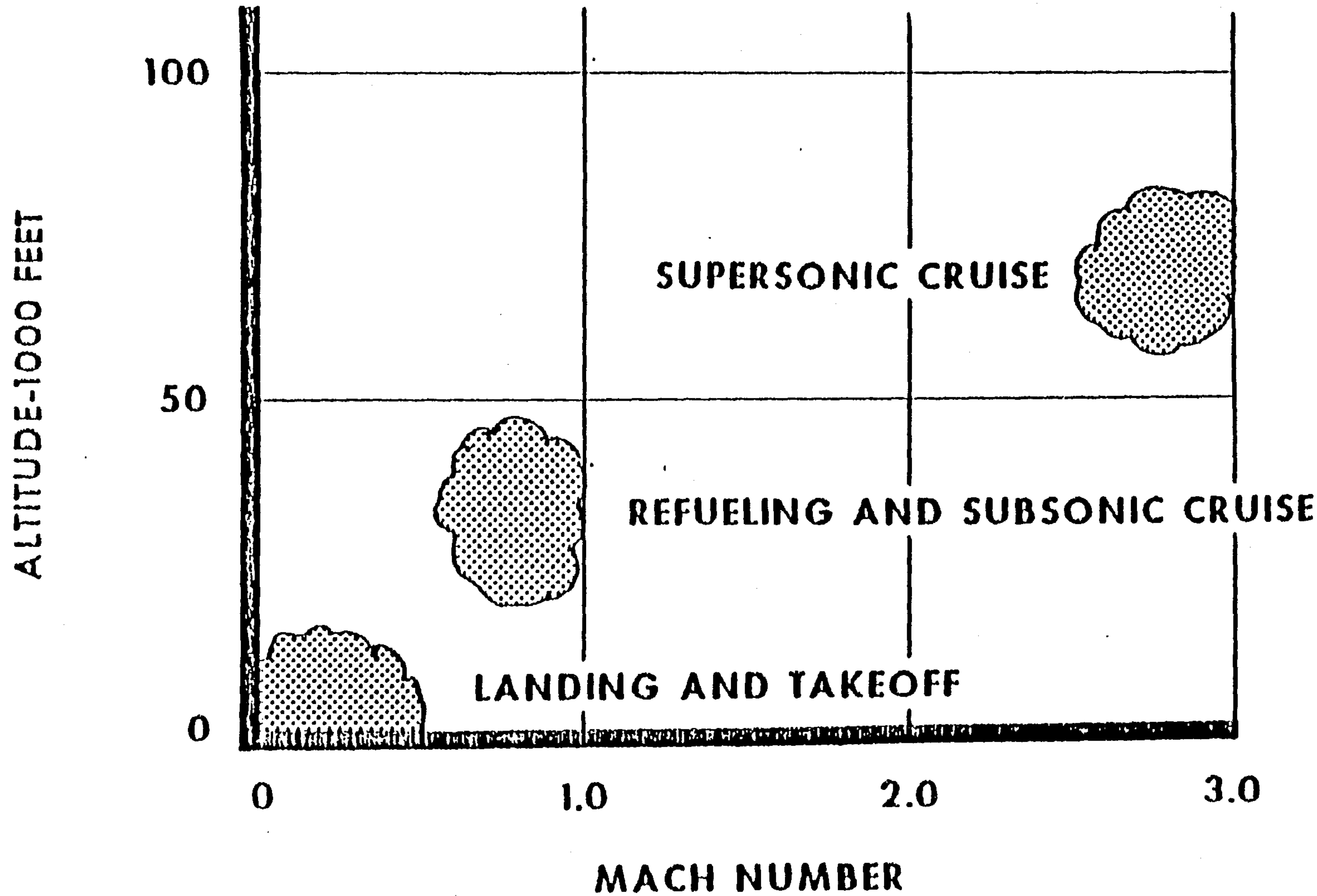
- THE PILOT MUST HAVE THE CAPABILITY TO SAFELY FLY THE AIRCRAFT AND LAND AFTER
  - ANY TWO FLIGHT CONTROL SYSTEM ELECTRONIC FAILURES
  - ANY SINGLE CONTROL SYSTEM MECHANICAL FAILURE COMBINED WITH ANY SINGLE ELECTRONIC FAILURE
  - ANY SINGLE HYDRAULIC SYSTEM FAILURE
  - ANY SINGLE ENGINE FAILURE

HANDLING QUALITIES

- HANDLING QUALITIES SHALL BE OPTIMIZED FOR TAKEOFF AND LANDING, AIR REFUELING, AND CRUISE
- NO RESIDUAL OSCILLATIONS IN EXCESS OF ± 5 MILS (± 0.28 DEGREES)
- MIL-F-8785 SHALL BE USED AS A GUIDE BUT DEVIATIONS WILL BE TAKEN WHERE NECESSARY

A20-4699-10

SYSTEM — DESIGN CRITERIA



Design flight areas for F-12 type automatic flight control.

A20-4699-11

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SR-71 CONTROL SYSTEM MECHANIZATION

TO MEET THE SPECIFIED FLIGHT SAFETY AND HANDLING QUALITIES REQUIREMENTS

- A FLY-BY-WIRE IMPLEMENTATION WITHOUT MECHANICAL BACK UP WAS STUDIED BUT WAS CONSIDERED TOO RISKY BASED ON THE PROJECTED RELIABILITY OF THE THEN STATE-OF-THE-ART ELECTRONICS
- AN "ADAPTIVE" FLIGHT CONTROL SYSTEM WAS CONSIDERED BUT WAS ALSO REJECTED BECAUSE NO SUCCESSFUL APPLICATIONS HAD BEEN DEMONSTRATED IN 1959
- RELIABILITY REQUIREMENTS DICTATED A SIMPLE, WELL PROVEN, CONVENTIONAL IMPLEMENTATION INCORPORATING
  - A MECHANICAL INPUT SYSTEM WITH ARTIFICIAL FEEL
  - LIMITED AUTHORITY, MULTI-REDUNDANT STABILITY AUGMENTATION SYSTEM (SAS)
  - ANALOG ELECTRONICS FOR SAS COMPUTERS (DIGITAL MACHINES AVAILABLE AT THE TIME WERE TOO SLOW AND DID NOT HAVE SUFFICIENT CAPACITY)
  - CONVENTIONAL ELECTRO-HYDRAULIC SERVO ACTUATORS TO POSITION THE CONTROL SURFACES IN RESPONSE TO COMMANDS FROM THE PILOT, AUTOPILOT, AND SAS

SR-71 FLIGHT CONTROL SYSTEM DESIGN DRIVERS

AIRPLANE CHARACTERISTIC	CONTROL SYSTEM FEATURE
• SPEED UNSTABLE IN SUBSONIC AND TRANSONIC FLIGHT	• MACH TRIM PROVIDES APPARENT SPEED STABILITY
• PITCH UP AT HIGH ANGLE-OF-ATTACK (AOA)	• AUTOMATIC PITCH WARNING (APW) SHAKES STICK AND PUSHES NOSE DOWN AS A FUNCTION OF AOA AND PITCH RATE
• LOW PITCH STABILITY AND DAMPING IN CRUISE	• TRIPLE REDUNDANT LAGGED PITCH RATE FEED BACK IN THE PITCH SAS TO PROVIDE SATISFACTORY HANDLING QUALITIES
• PRECISE FLIGHT PATH CONTROL IN CRUISE REQUIRES A HIGH DEGREE OF PILOT CONCENTRATION	• AUTOPILOT PROVIDES ATTITUDE AND HEADING HOLD, MACH HOLD, EQUIVALENT AIRSPEED HOLD, AND AUTOMATIC NAVIGATION FOR PILOT RELIEF
• STRONG INTERACTIONS BETWEEN AIRFRAME AND PROPULSION SYSTEM CAUSING UNACCEPTABLE HIGH MACH PHUGOID CHARACTERISTICS	• INLET CONTROL SYSTEM SCHEDULES BIASED BY AOA, NORMAL LOAD FACTOR, AND SIDE SLIP ANGLE

A20-4699-14

SR-71 FLIGHT CONTROL SYSTEM DESIGN DRIVERS

AIRPLANE CHARACTERISTIC	CONTROL SYSTEM FEATURE
• LOW DIRECTIONAL STABILITY AND DAMPING IN CRUISE	• TRIPLE REDUNDANT YAW RATE AND LATERAL ACCELEROMETER FEEDBACKS IN THE YAW SAS TO PROVIDE SATISFACTORY HANDLING QUALITIES
• POTENTIALLY VIOLENT YAW TRANSIENTS INDUCED BY INLET UNSTARTS	• YAW SAS TAILORED TO MAINTAIN STRUCTURAL LOADS ON FINS WITHIN DESIGN LIMITS WHILE THE AIR INLET CONTROL SYSTEM AUTOMATICALLY SENSES THE UNSTART AND RESTARTS THE INLET
• POTENTIAL FOR COUPLING BETWEEN THE FLIGHT CONTROL SYSTEM AND THE LOWEST FREQUENCY STRUCTURAL MODES	• CAREFUL CHOICE OF SAS FEEDBACKS, SENSOR LOCATION ON AIRFRAME, AND INCLUSION OF ELECTRONIC FILTERING TO ELIMINATE POSSIBILITY OF COUPLING

A20-4699-15

SR-71 FLIGHT CONTROL SYSTEM
PILOT vs SAS AUTHORITIES

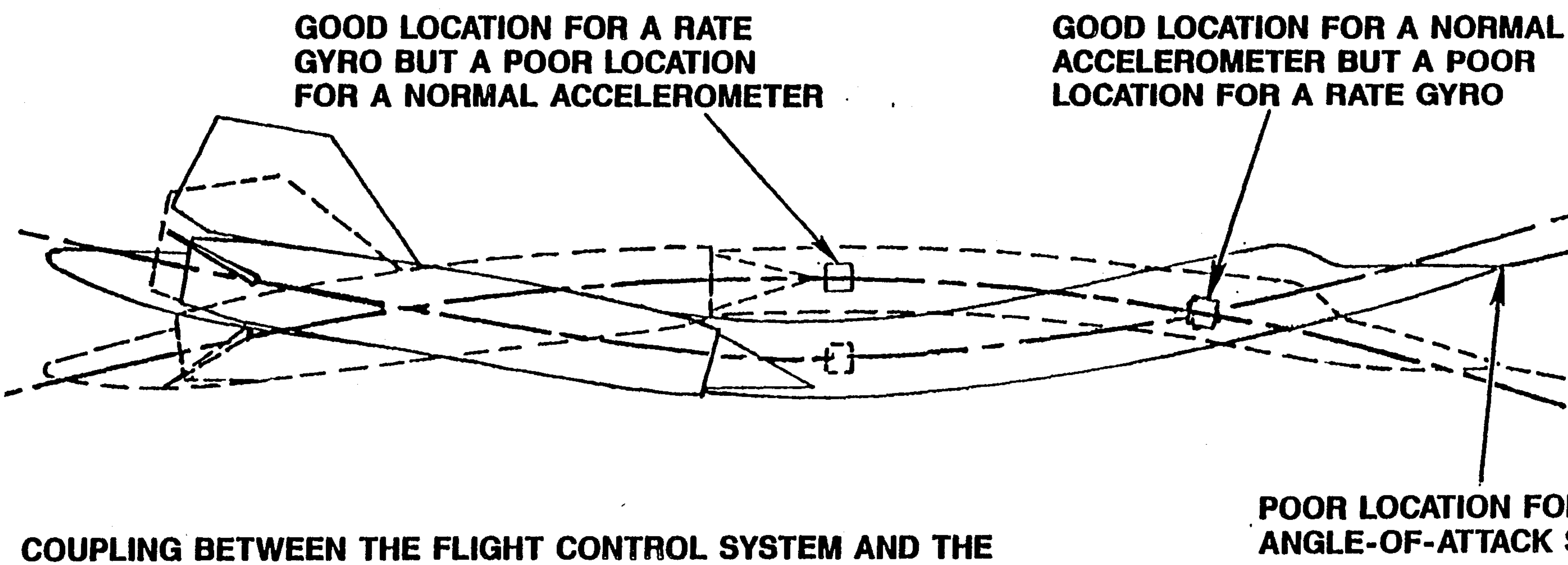
AXIS	CONTROL SURFACES	DIRECTION	MAXIMUM CONTROL SURFACE DEFLECTIONS ~ DEGREES			
			PILOT COMMAND AUTHORITY		SAS COMMAND AUTHORITY	
PITCH	ELEVONS	TRAILING EDGE UP (TEU) TRAILING EDGE DN (TED)	24.0 11.0		2.5 6.5	
			BELOW 0.5 MACH	ABOVE 0.5 MACH	BELOW 0.5 MACH	ABOVE 0.5 MACH
ROLL	ELEVONS	ONE SIDE TEU OTHER SIDE TED	24.0	14.0	4.0	4.0
YAW	FINS	TRAILING EDGE LEFT TRAILING EDGE RIGHT	20.0 20.0	10.0 10.0	8.0 8.0	8.0 8.0

PILOT ALWAYS HAS AUTHORITY TO OVERPOWER HARDOVER SAS MALFUNCTIONS

A20-4699-13

PREVENTION (' POSSIBLE STRUCTURAL MODE COUPLING

EXAMPLE: DIVERGENT OSCILLATIONS COULD OCCUR IF THE PITCH RATE GYRO IS IMPROPERLY LOCATED, SENSES THE RATE INDUCED BY THE FIRST FUSELAGE BENDING, AND THEN FEEDS BACK THROUGH THE PITCH SAS TO THE ELEVONS IN PHASE WITH THE BENDING



COUPLING BETWEEN THE FLIGHT CONTROL SYSTEM AND THE VIBRATIONAL MODES OF THE STRUCTURE WAS PREVENTED BY CAREFUL SELECTION OF SENSOR LOCATION AND BY SELECTIVE FILTERING OF THOSE SIGNALS WHERE THE SENSOR LOCATION WAS DICTATED BY OTHER CONSIDERATIONS

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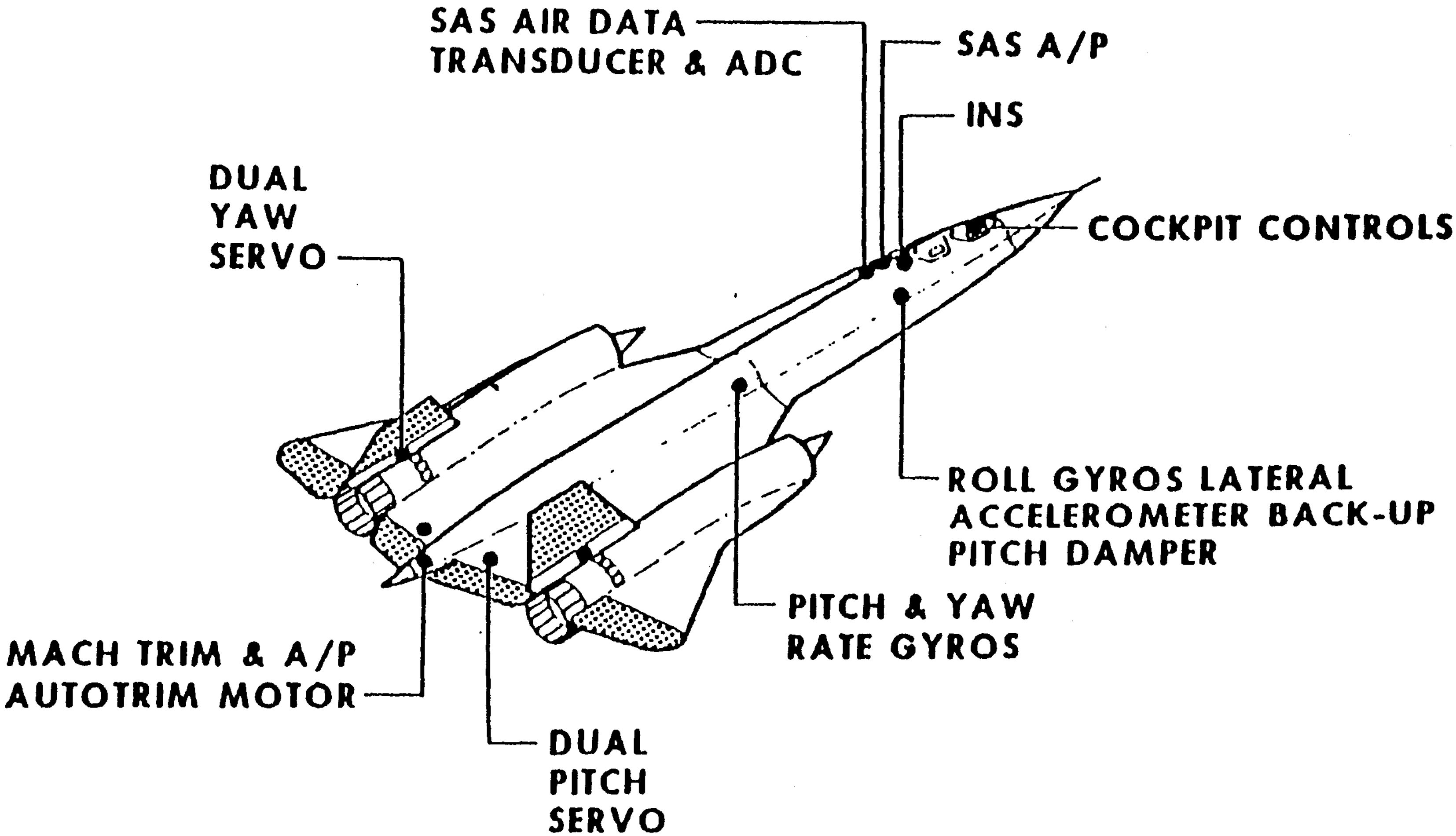
A20-4699-16

F-12 SERIES AIRCRAFT CONFIGURATION AND CONTROL SYSTEM COMPONENT LOCATIONS



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SR-71 FIN CONTROLS

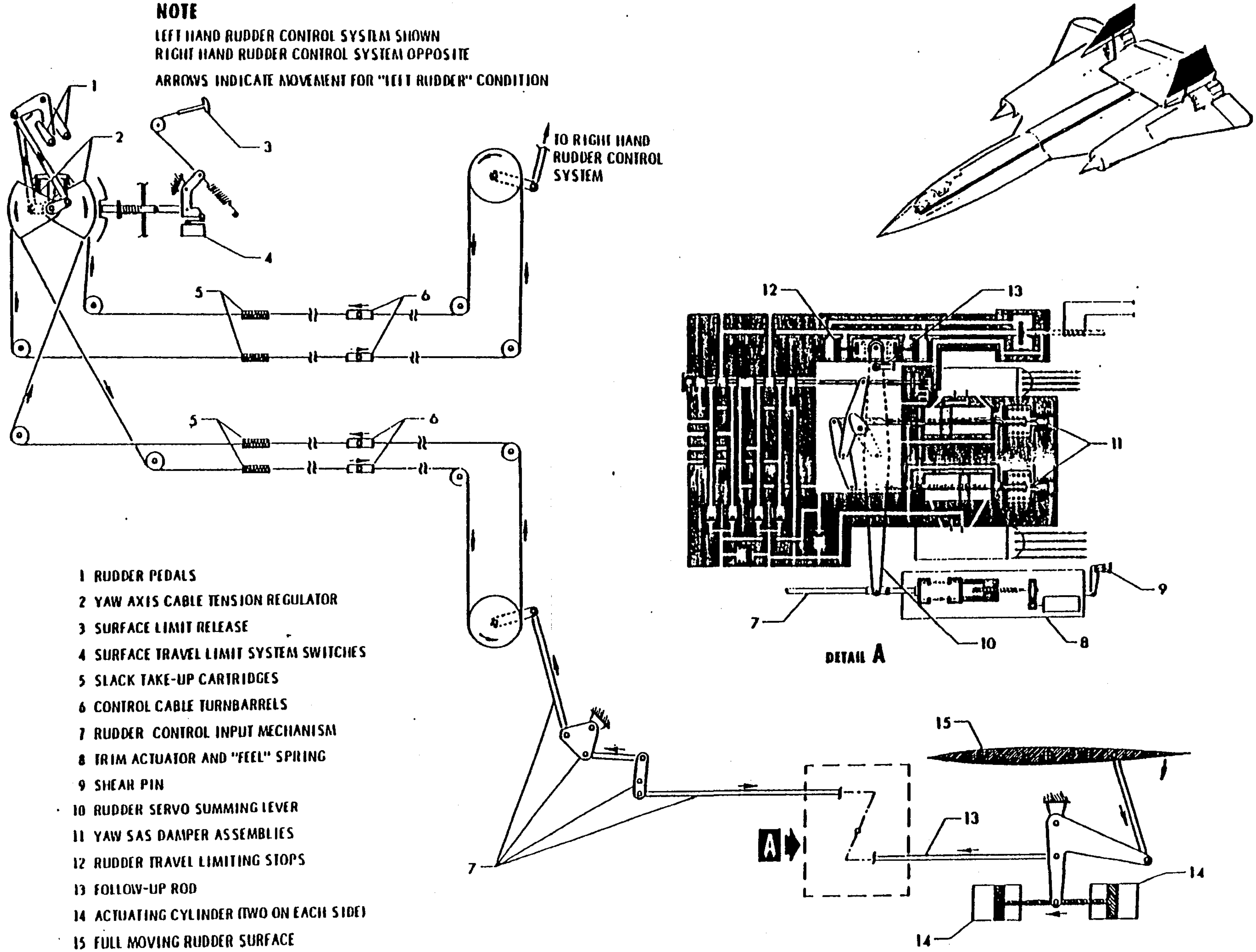
- PILOT COMMANDS FIN POSITION THROUGH MECHANICAL INPUTS TO YAW SERVOS

- YAW SAS COMMANDS FIN POSITION THROUGH ELECTRICAL INPUTS TO THE YAW SERVOS

- YAW SERVOS MECHANICALLY LIMIT THE YAW SAS COMMANDS TO PREDETERMINED AUTHORITY VALUES, SUMS THE PILOT AND LIMITED YAW SAS COMMANDS, AND METERS THE HYDRAULIC FLOW TO THE POWER ACTUATORS WHICH POSITION THE FINS

SR-71 FIN CONTROL SCHEMATIC

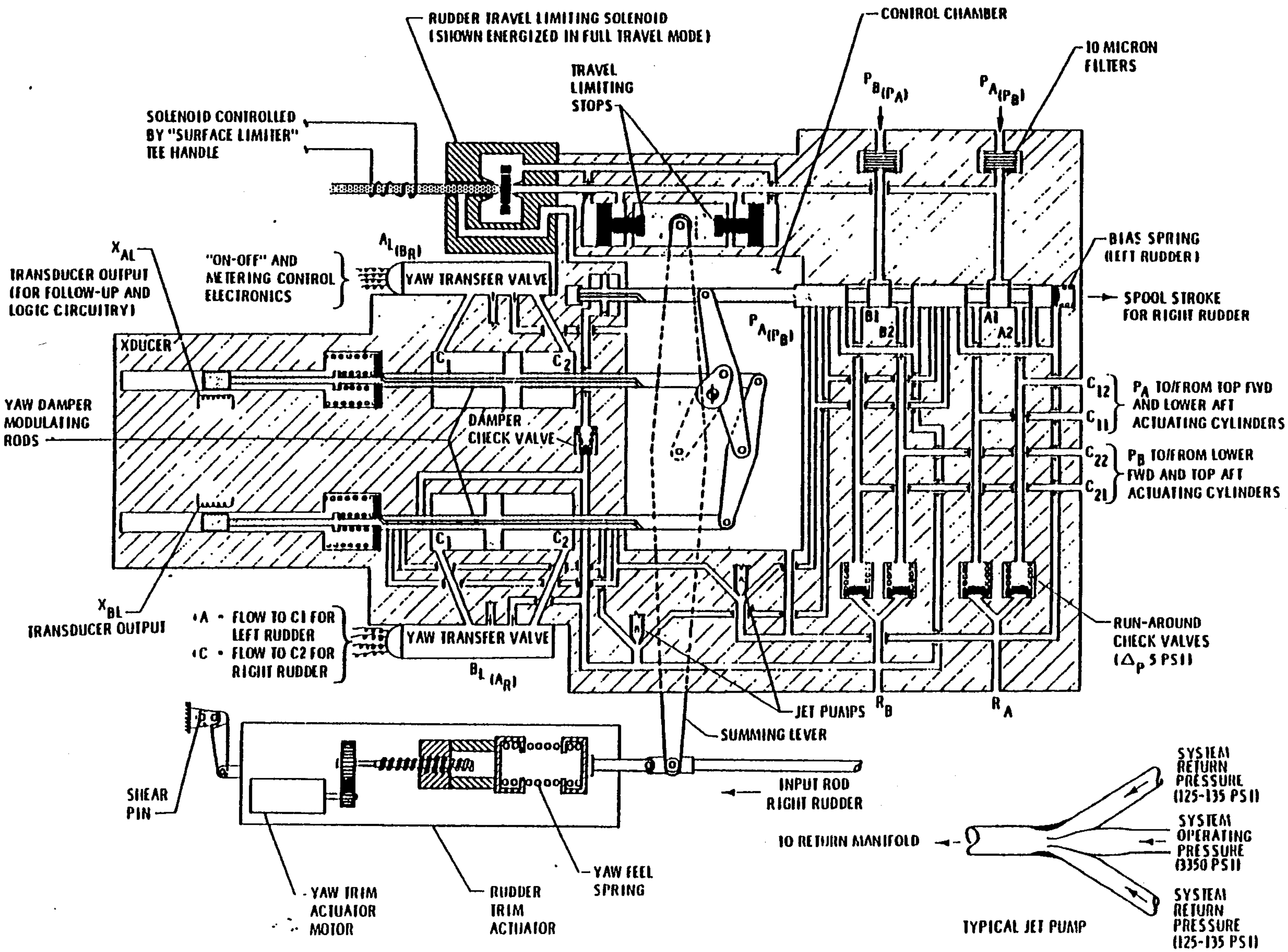
NOTE
LEFT HAND RUDDER CONTROL SYSTEM SHOWN
RIGHT HAND RUDDER CONTROL SYSTEM OPPOSITE
ARROWS INDICATE MOVEMENT FOR "LEFT RUDDER" CONDITION



1 RUDDER PEDALS
2 YAW AXIS CABLE TENSION REGULATOR
3 SURFACE LIMIT RELEASE
4 SURFACE TRAVEL LIMIT SYSTEM SWITCHES
5 SLACK TAKE-UP CARTRIDGES
6 CONTROL CABLE TURNBARRELS
7 RUDDER CONTROL INPUT MECHANISM
8 TRIM ACTUATOR AND "FEEL" SPRING
9 SHEAR PIN
10 RUDDER SERVO SUMMING LEVER
11 YAW SAS DAMPER ASSEMBLIES
12 RUDDER TRAVEL LIMITING STOPS
13 FOLLOW-UP ROD
14 ACTUATING CYLINDER (TWO ON EACH SIDE)
15 FULL MOVING RUDDER SURFACE

A20-4699-19

SR-71 YAW SERVO ACTUATOR



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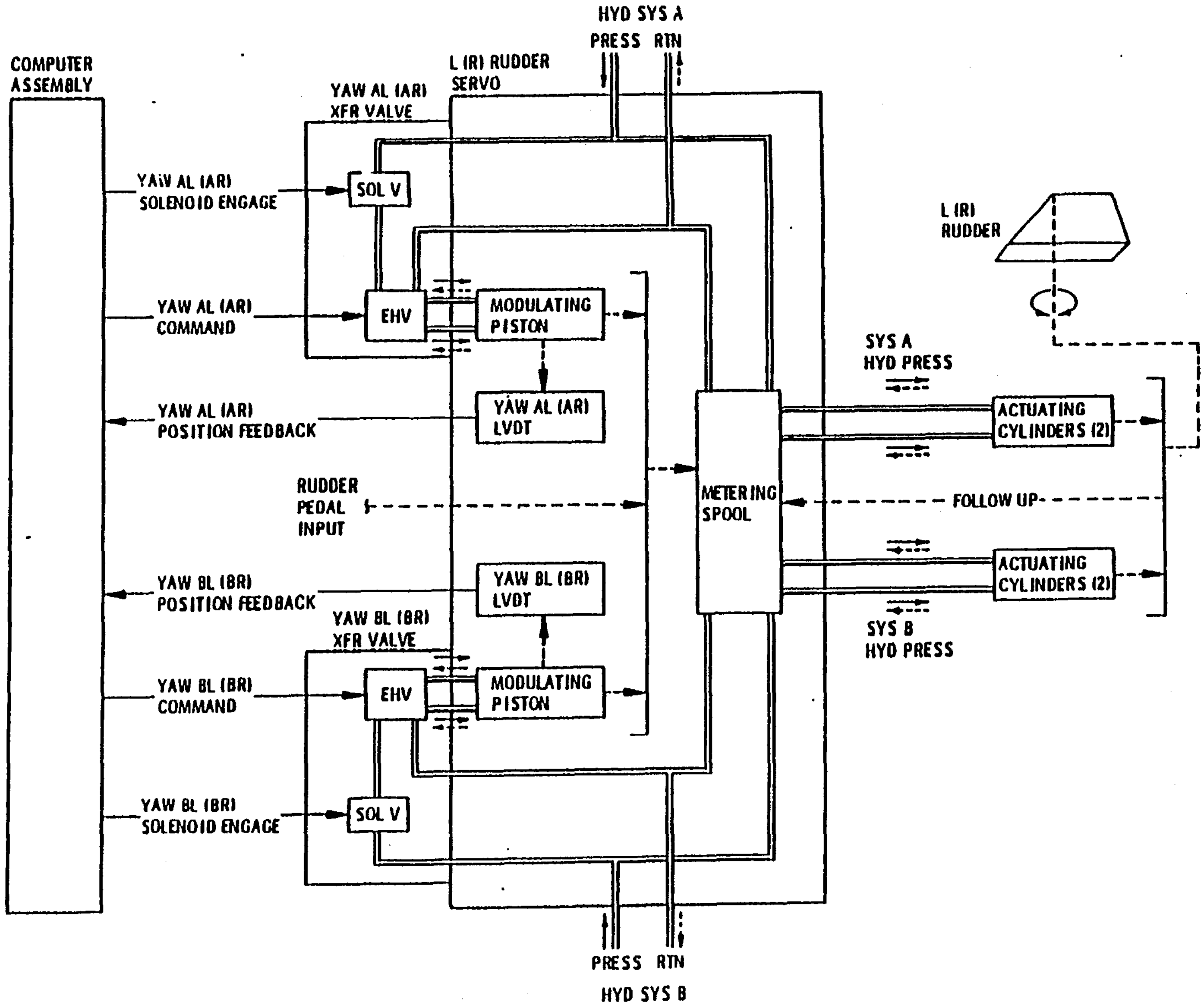
SR-71 YAW SAS/YAW SERVO INTERFACE



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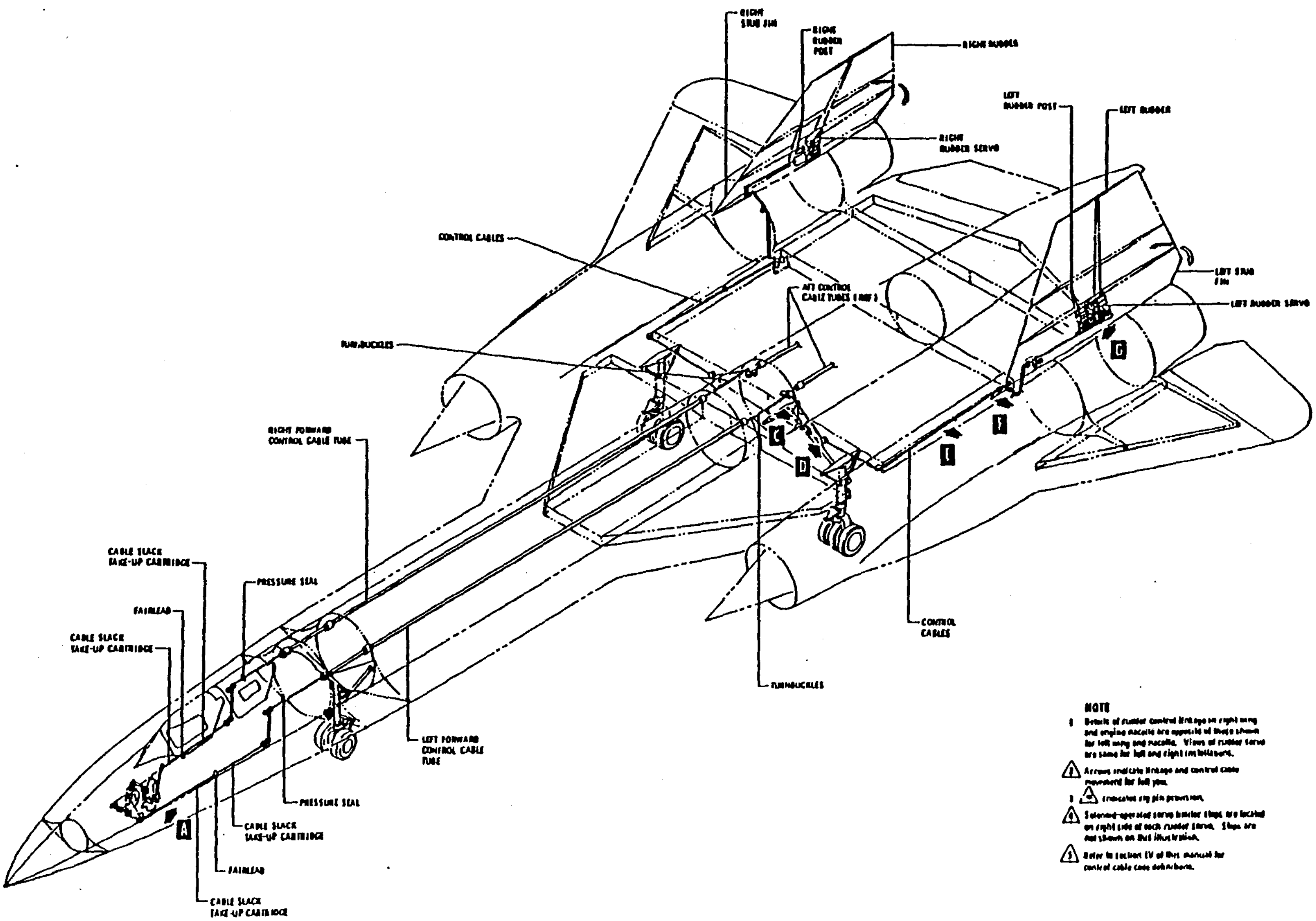
SR-71 FIN CON RɪOL SYSTEM



NOTE

1 Details of rudder control linkage in right wing and engine nacelle are opposite of those shown for left wing and nacelle. Views of rudder servo are same for left and right installations.

2 Arrows indicate linkage and control cable movement for left yaw.

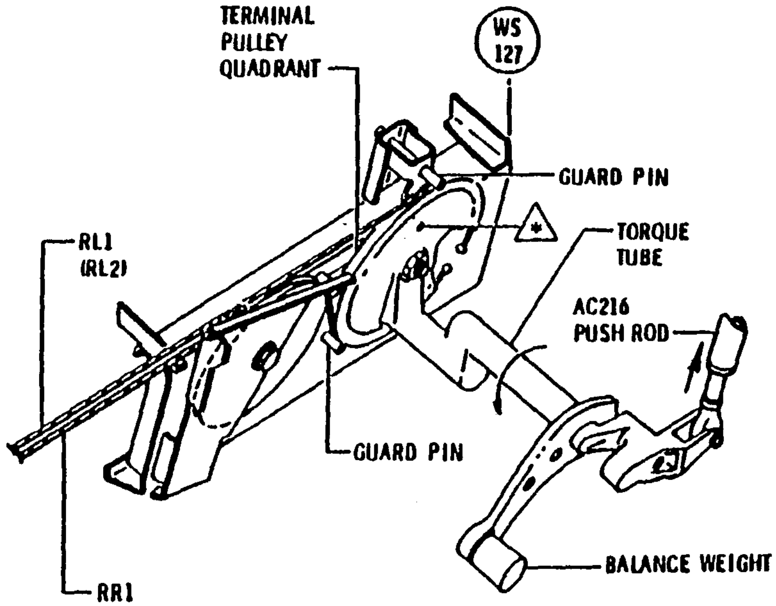
3 Indicates rig pin provision.

4 Solenoid-operated servo limiter stops are located on right side of each rudder servo. Stops are not shown on this illustration.

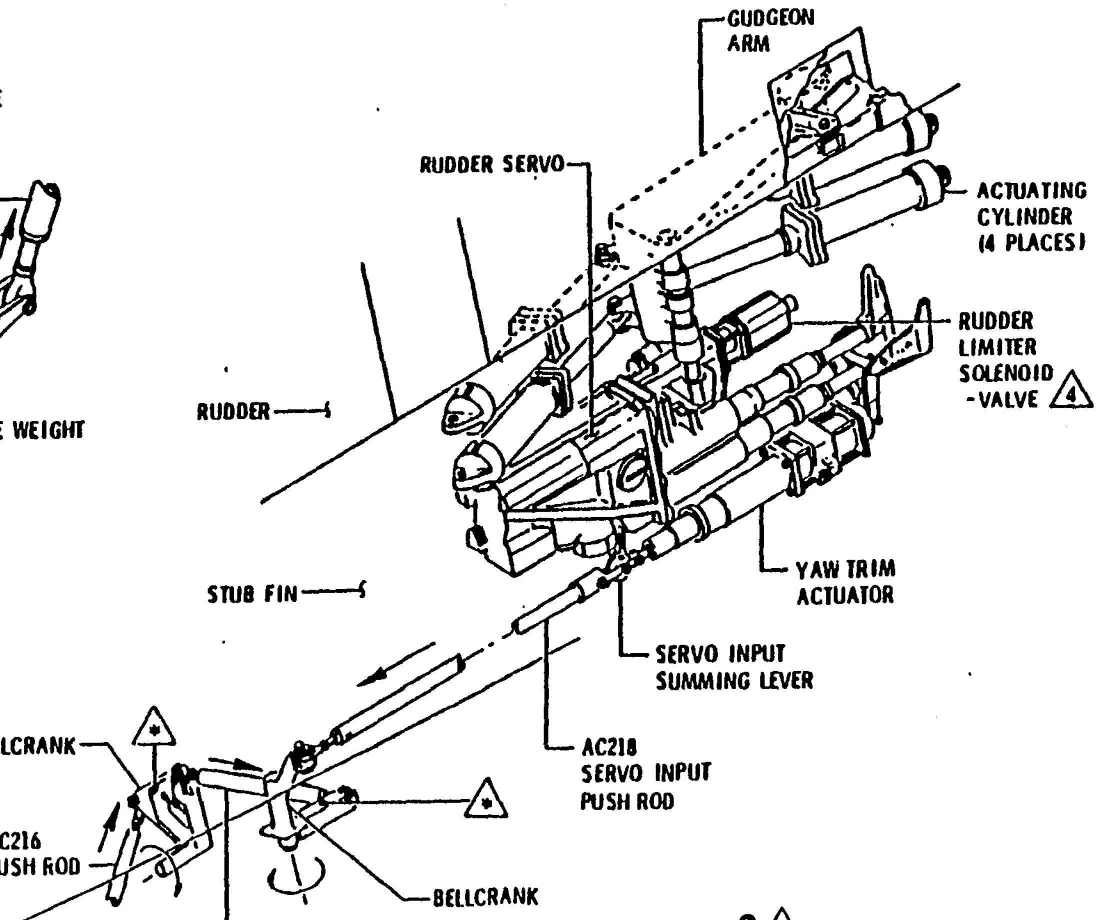
5 Refer to section IV of this manual for control cable code definitions.

A20-4699-20

SR-71 FIN CONTROL SYSTEM DETAILS



DETAIL F 2 5



DETAIL G 2

M203-7-428(c)
A20-4699-21

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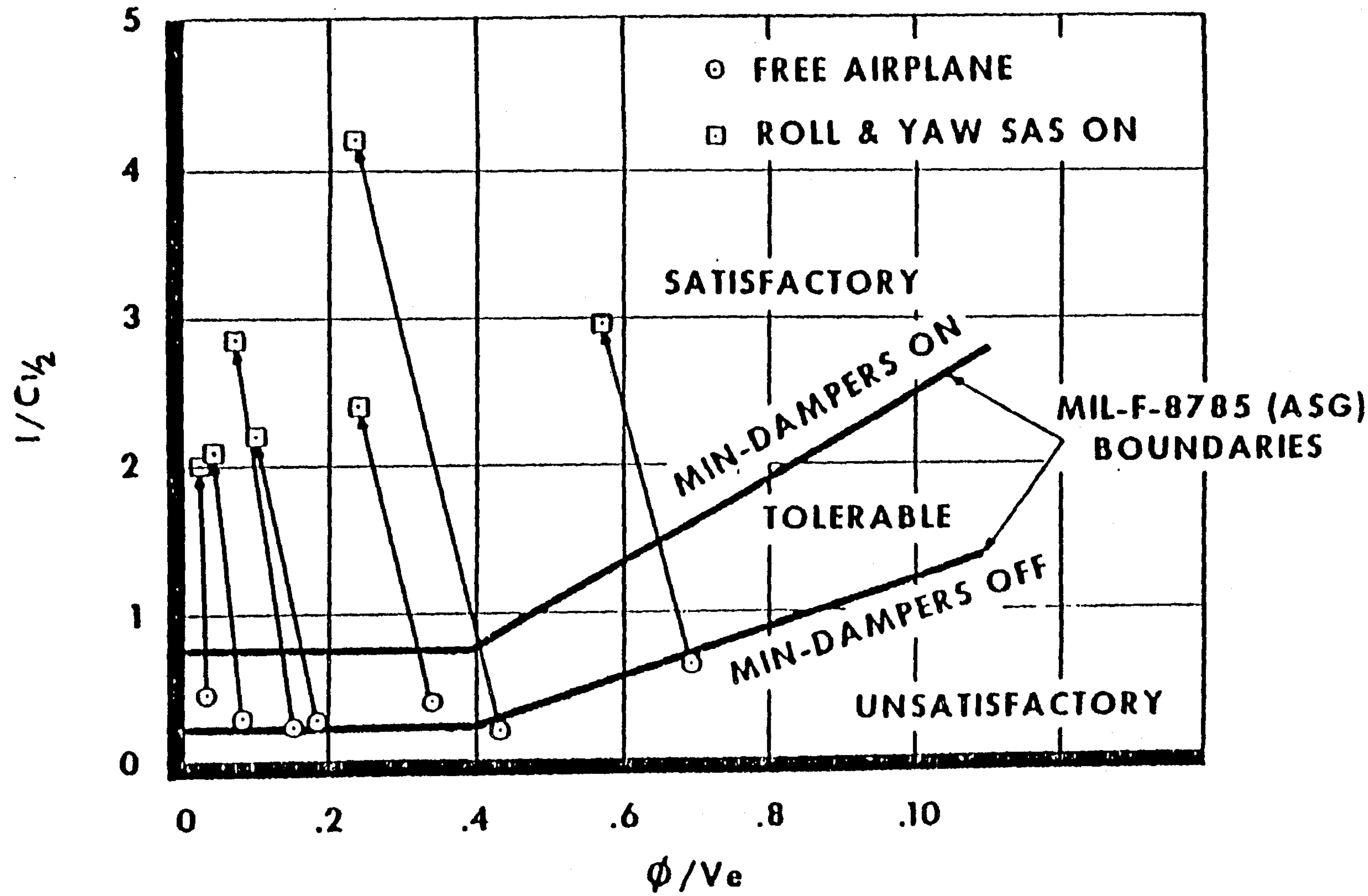
SR-71 FLIGHT CONTROLS HANDLING QUALITITES



Typical Dutch roll characteristics.

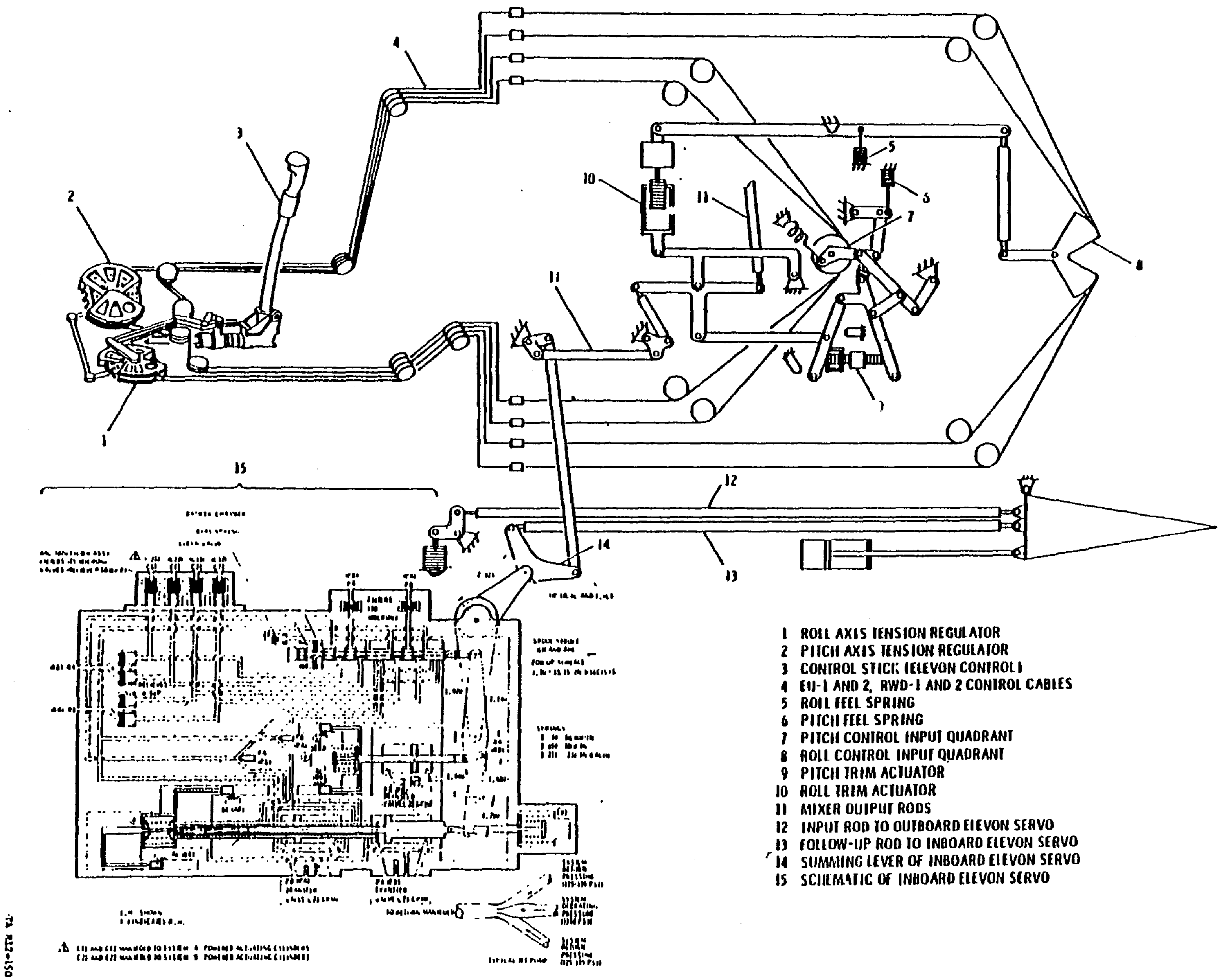
A20-4699-22

SR-71 ELEVON CONTROLS

- PILOT COMMANDS ELEVON POSITIONS THROUGH MECHANICAL INPUTS TO THE INBOARD ELEVON SERVOS VIA THE PITCH/ROLL MIXER
- PITCH AND ROLL SAS COMMAND ELEVON POSITIONS THROUGH ELECTRICAL INPUTS TO THE INBOARD ELEVON SERVOS
- THE INBOARD ELEVON SERVOS MECHANICALLY LIMIT THE PITCH AND ROLL SAS COMMANDS TO PREDETERMINED AUTHORITIES, SUMS THE PILOT AND LIMITED SAS COMMANDS, AND METERS HYDRAULIC FLOW TO THE POWER ACTUATORS WHICH POSITION THE INBOARD ELEVON CONTROL SURFACES
- THE INBOARD ELEVON POSITIONS MECHANICALLY COMMAND THE OUTBOARD ELEVON SERVOS WHICH METER HYDRAULIC FLOW TO THE POWER ACTUATORS WHICH THEN POSITION THE OUTBOARD ELEVON CONTROL SURFACES

A20-4699-23

SR-71 INBOARD ELEVON CONTROL SCHEMATIC



1 ROLL AXIS TENSION REGULATOR
2 PITCH AXIS TENSION REGULATOR
3 CONTROL STICK (ELEVON CONTROL)
4 EU-1 AND 2, RWD-1 AND 2 CONTROL CABLES
5 ROLL FEEL SPRING
6 PITCH FEEL SPRING
7 PITCH CONTROL INPUT QUADRANT
8 ROLL CONTROL INPUT QUADRANT
9 PITCH TRIM ACTUATOR
10 ROLL TRIM ACTUATOR
11 MIXER OUTPUT RODS
12 INPUT ROD TO OUTBOARD ELEVON SERVO
13 FOLLOW-UP ROD TO INBOARD ELEVON SERVO
14 SUMMING LEVER OF INBOARD ELEVON SERVO
15 SCHEMATIC OF INBOARD ELEVON SERVO

A20-4699-24

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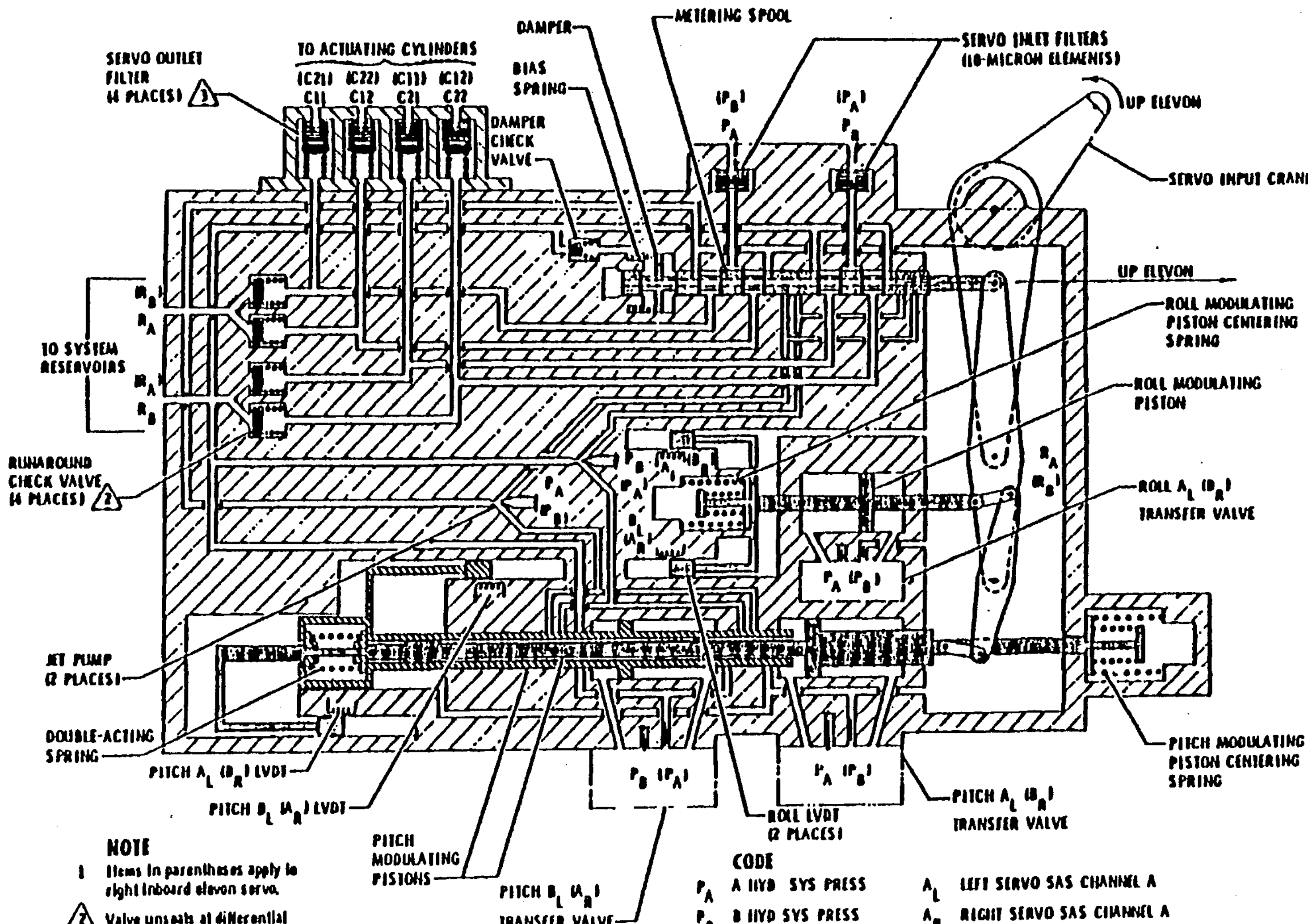
SR-71 INBOARD ELEVON SERVO ACTUATOR



NOTE

1 Items in parentheses apply to right inboard elevon servo.

2 Valve unseats at differential pressure of 5 psi.

3 Filter relieves at differential pressure of 200 (± 30) psi.

CODE

P_A	A HYD SYS PRESS	A_L	LEFT SERVO SAS CHANNEL A
P_B	B HYD SYS PRESS	A_R	RIGHT SERVO SAS CHANNEL A
R_A	A HYD SYS RETURN	B_L	LEFT SERVO SAS CHANNEL B
R_B	B HYD SYS RETURN	B_R	RIGHT SERVO SAS CHANNEL B

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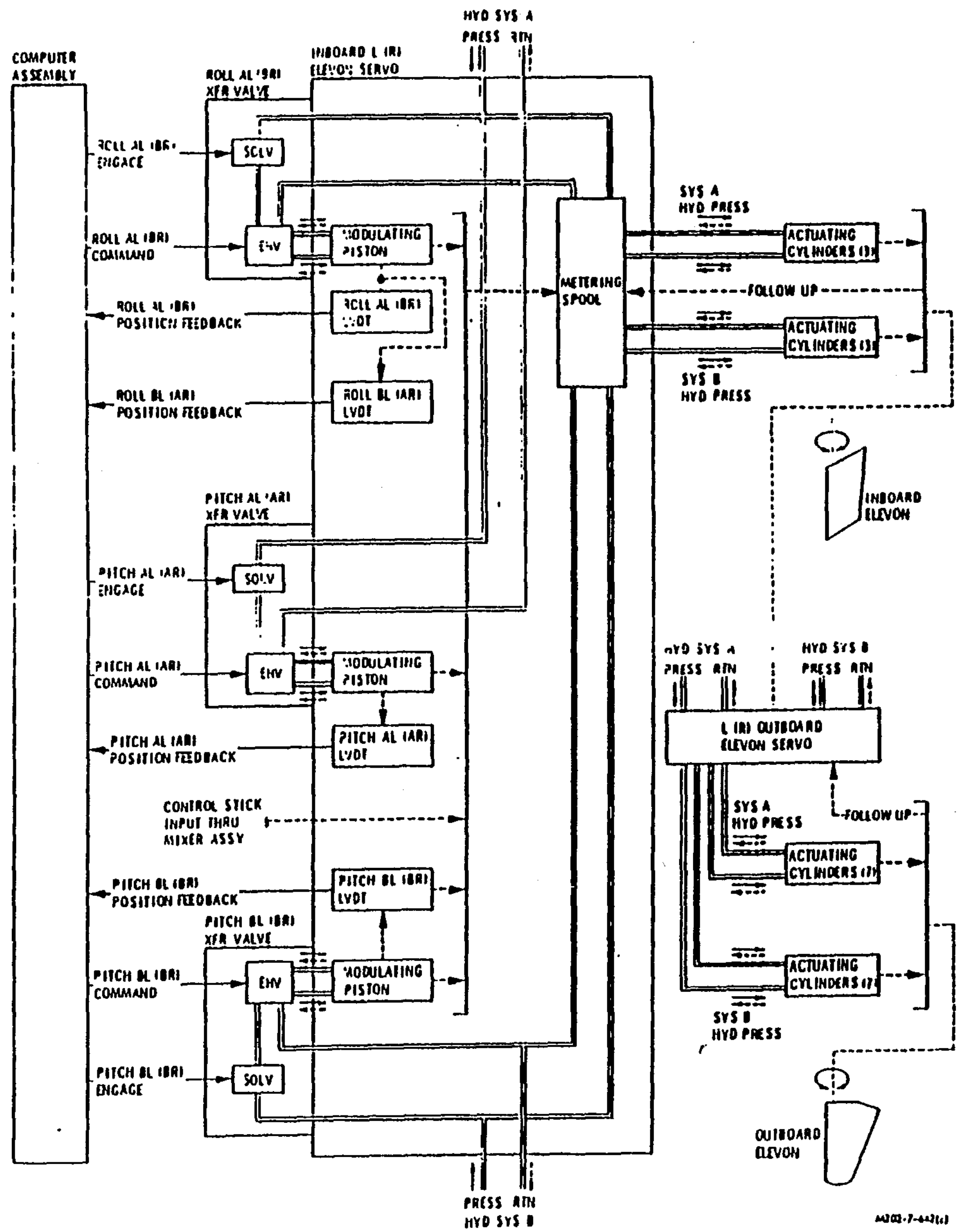
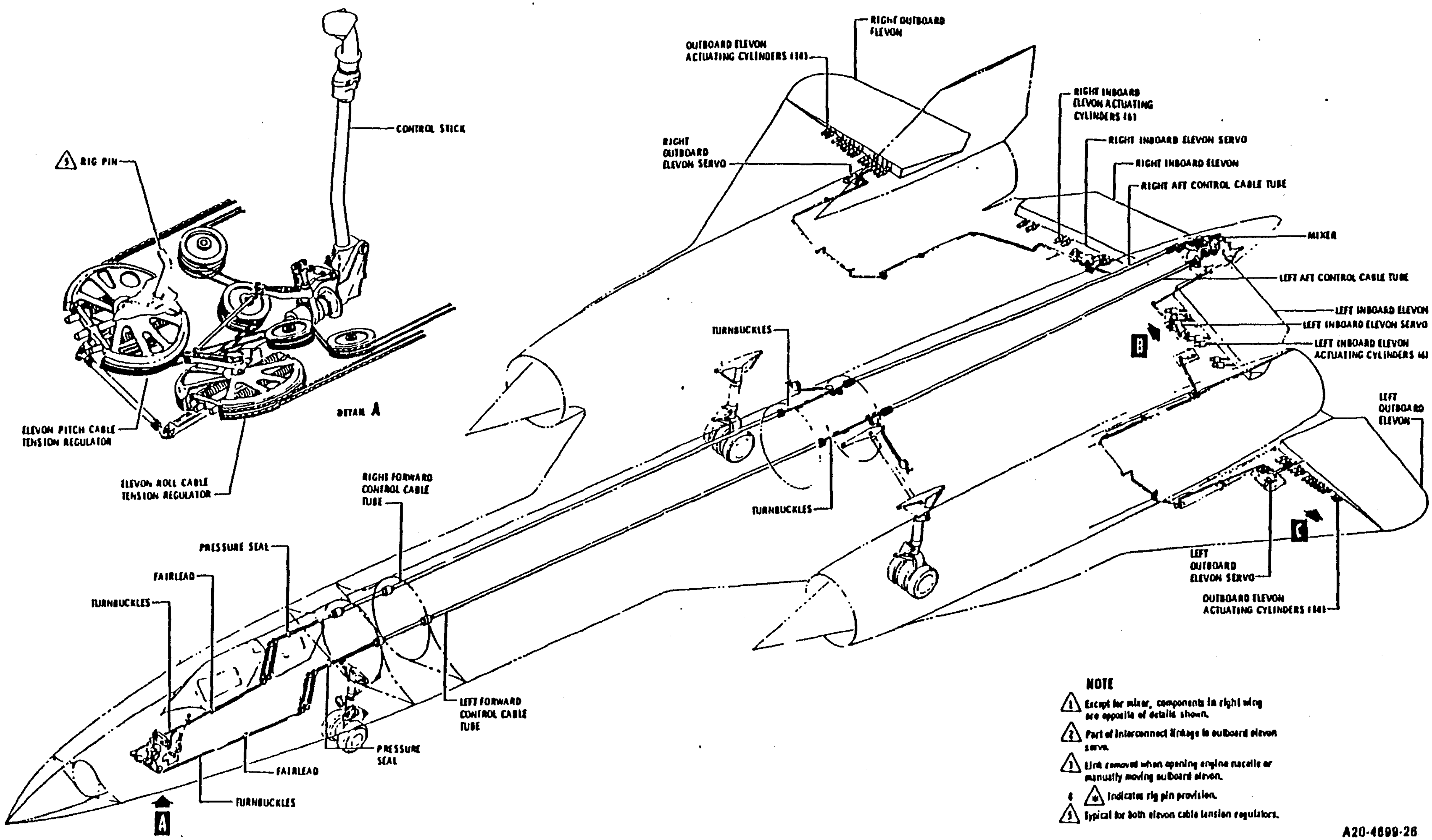
SR-71 PITCH & ROLL SAS INTERFACES



A20-4699-25

SR-71 ELEVON CONTROL SYSTEM



NOTE

1. Except for mixer, components in right wing are opposite of details shown.
2. Part of interconnect linkage to outboard elevon servo.
3. Link removed when opening engine nacelle or manually moving outboard elevon.
4. Indicates rig pin provision.
5. Typical for both elevon cable tension regulators.

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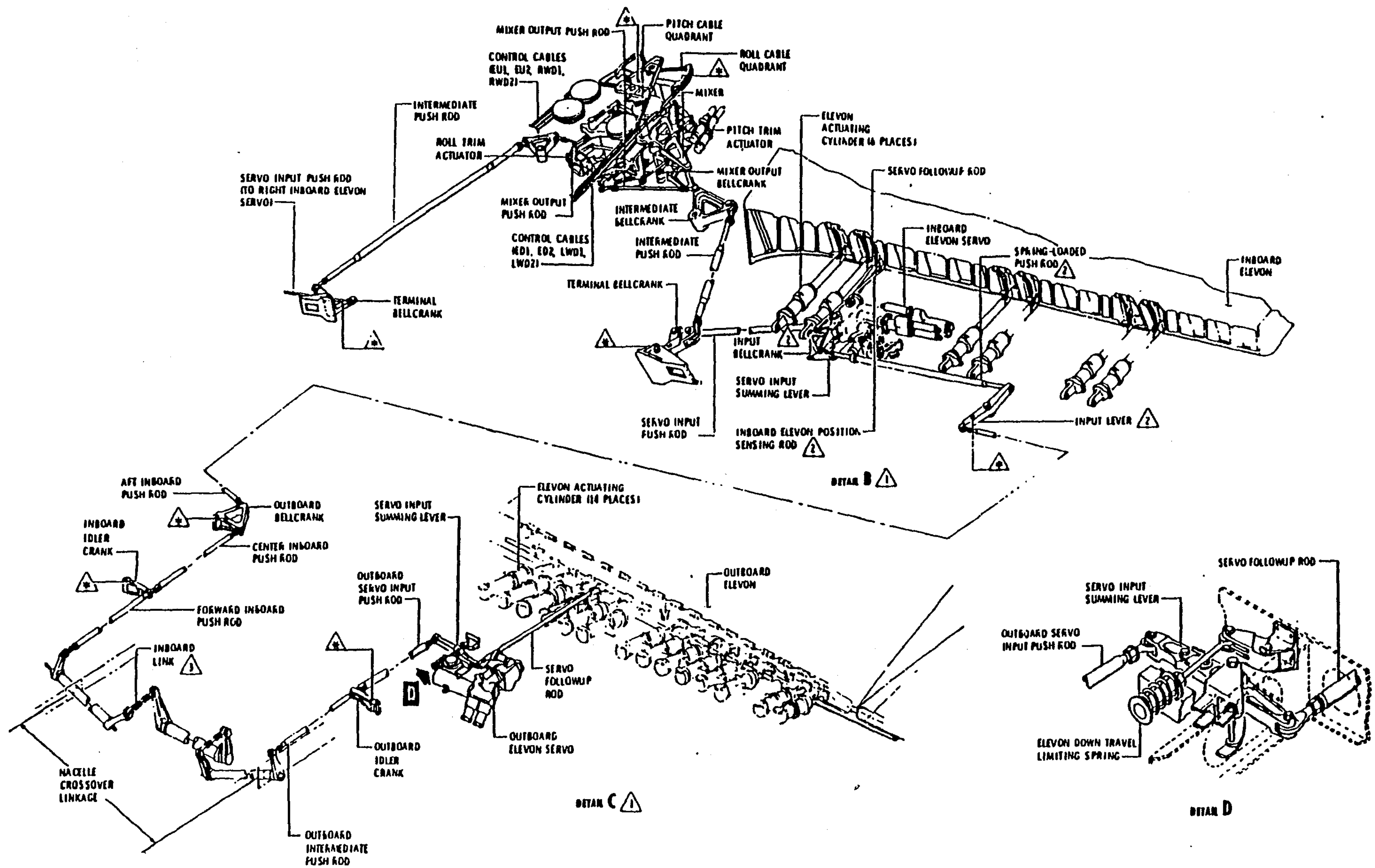
SR-71 ELEVON CONTROL DETAILS



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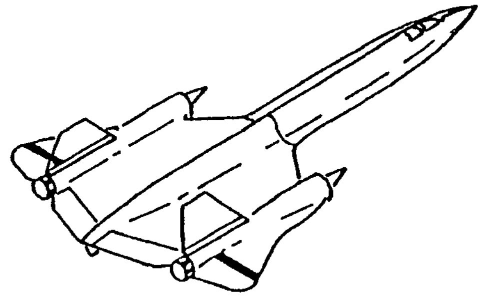
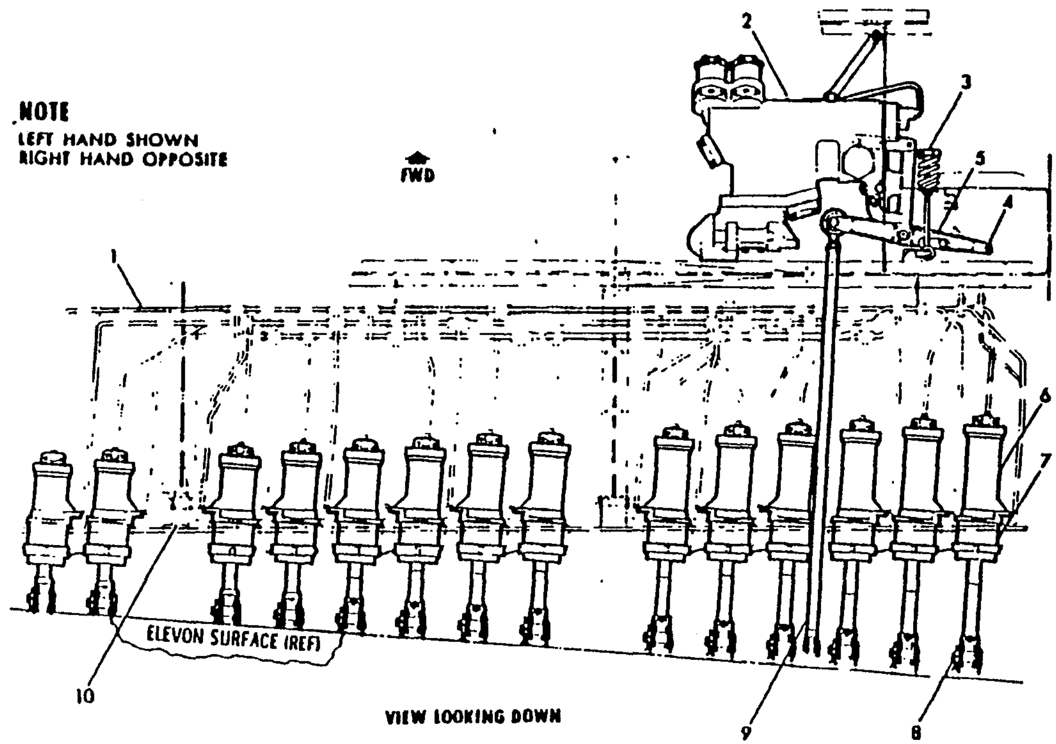
SR-71 OUTBOARD ELEVON ACTUATION



1 METERED HYDRAULICS TO THE ACTUATING CYLINDERS
2 OUTBOARD ELEVON SERVO
3 LIMITING INPUT SPRING CARTRIDGE
4 INPUT PUSH-ROD ATTACH POINT TO SUMMING LEVER
5 SUMMING LEVER
6 ACTUATING CYLINDER (MOST INBOARD ONE)
7 FLANGE MOUNTING OF ACTUATING CYLINDERS (TYP)
8 ACTUATING CYLINDER ROD ATTACHMENT TO ELEVON SURFACE
9 FOLLOW-UP ROD
10 HINGE FITTING TO TOP OF ELEVON SURFACE

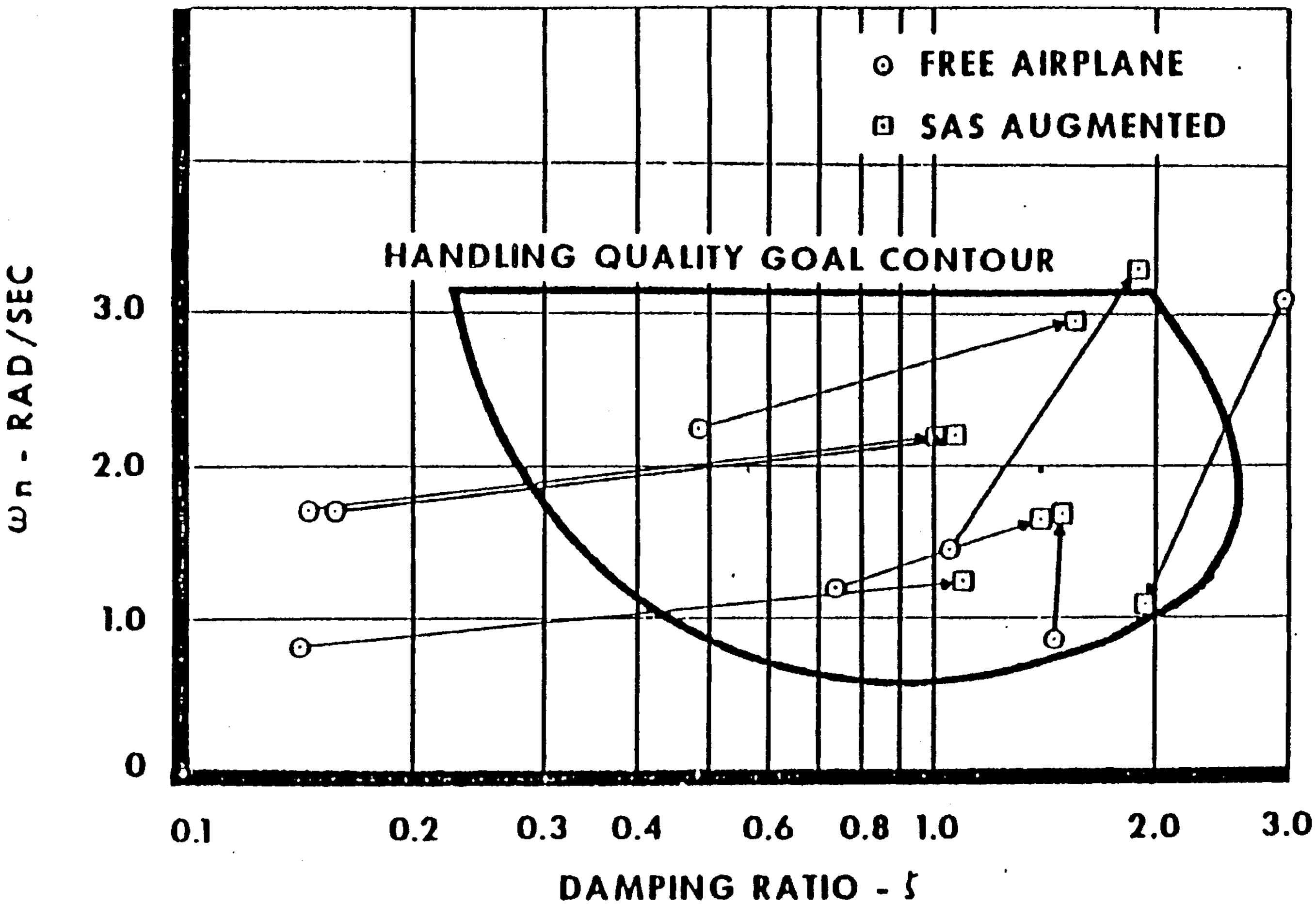
NOTE
LEFT HAND SHOWN
RIGHT HAND OPPOSITE



VIEW LOOKING DOWN

A20-4699-28

SR-71 HANDLIN QUALITIES



Typical pitch short period characteristics.

A20-4699-29

SR-71 AUTOMATIC FLIGHT CONTROL SYSTEM (AFCS)

- STABILITY AUGMENTATION
- AUTOPILOT SYSTEM
- MACH TRIM SYSTEM

A20-4699-30

SR-71 FLIGHT CONTROL SYSTEM

SERIES AUTOPILOT MECHANIZATION
(STICK DOES NOT MOVE DURING AUTOPILOT OPERATION)

PILOT RELIEF MODES

- PITCH, ROLL, AND HEADING HOLD
- MACH HOLD
- EQUIVALENT AIRSPEED HOLD

AUTOMATIC NAVIGATION

- LATERAL STEERING VIA PRE-PROGRAMMED FLIGHT PROFILES

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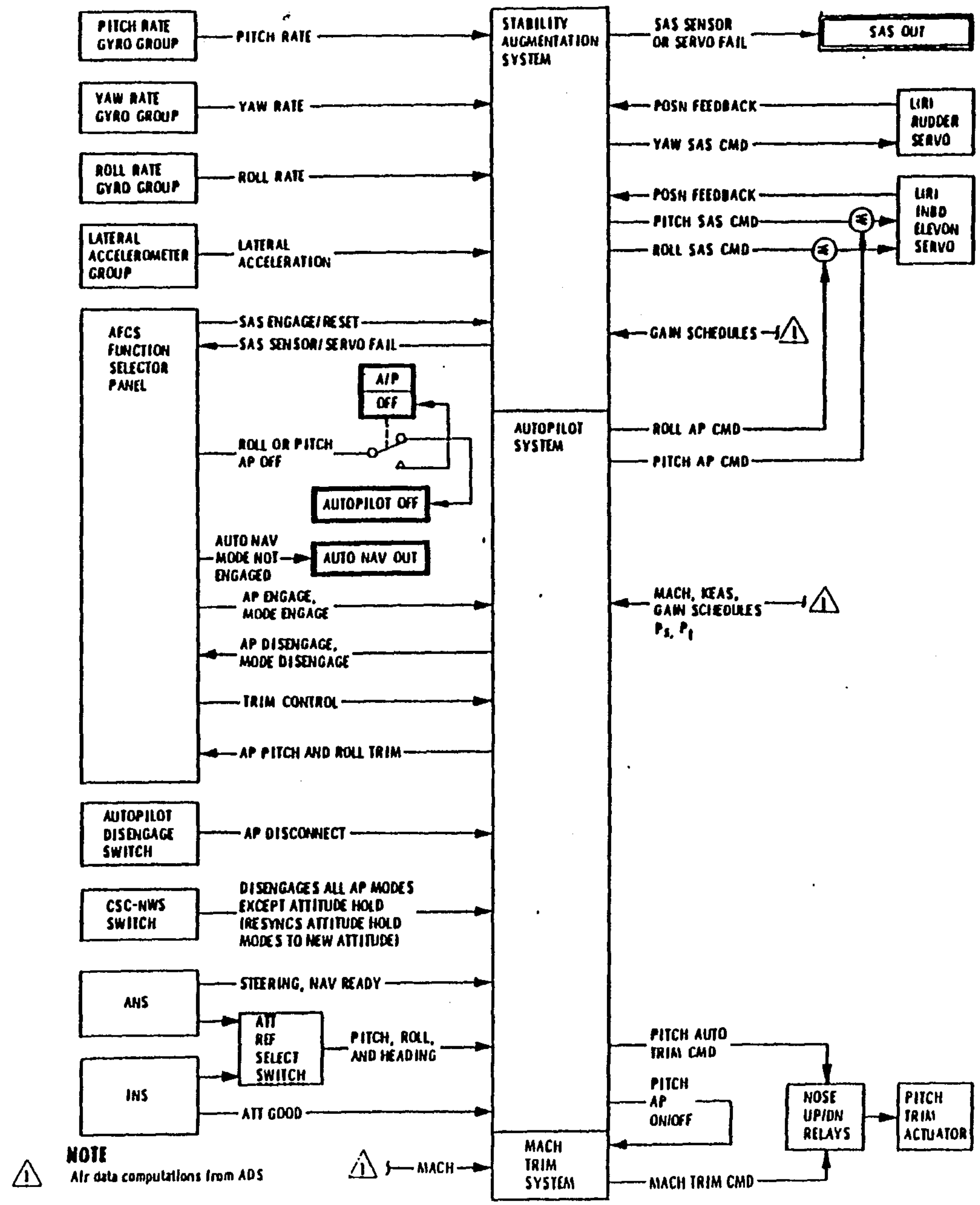
SR-71 AFCS BL[illegible]CK DIAGRAM



NOTE

1 Air data computations from ADS

A20-4699-32

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SR-71 AIR INLET CONTROL SYSTEM

- SPIKE CONTROL
- BYPASS DOOR CONTROL

A20-4699-33

SR-71 AIR INLET DESIGN DRIVERS

FUNCTIONAL REQUIREMENTS FOR THE ENGINE INLET

- MATCH THE AIR FLOW CAPTURED BY THE INLET TO THE AIR FLOW REQUIRED BY THE ENGINE FOR ALL CONDITIONS
- AT SUPERSONIC CRUISE, REDUCE THE VELOCITY OF THE CAPTURED AIR TO ABOUT 0.4 MACH REQUIRED AT THE ENGINE FACE
- MAXIMIZE THE PRESSURE RECOVERY AT THE ENGINE FACE WHILE REDUCING THE VELOCITY
- MINIMIZE THE TRANSIENT FLOW EFFECTS OF EXTERNAL DISTURBANCES

NO FIXED INLET CONFIGURATION CAN SIMULTANEOUSLY SATISFY THESE REQUIREMENTS OVER THE ENTIRE FLIGHT ENVELOPE AND ENGINE OPERATING RANGES

- VARIABLE INLET GEOMETRY IS REQUIRED

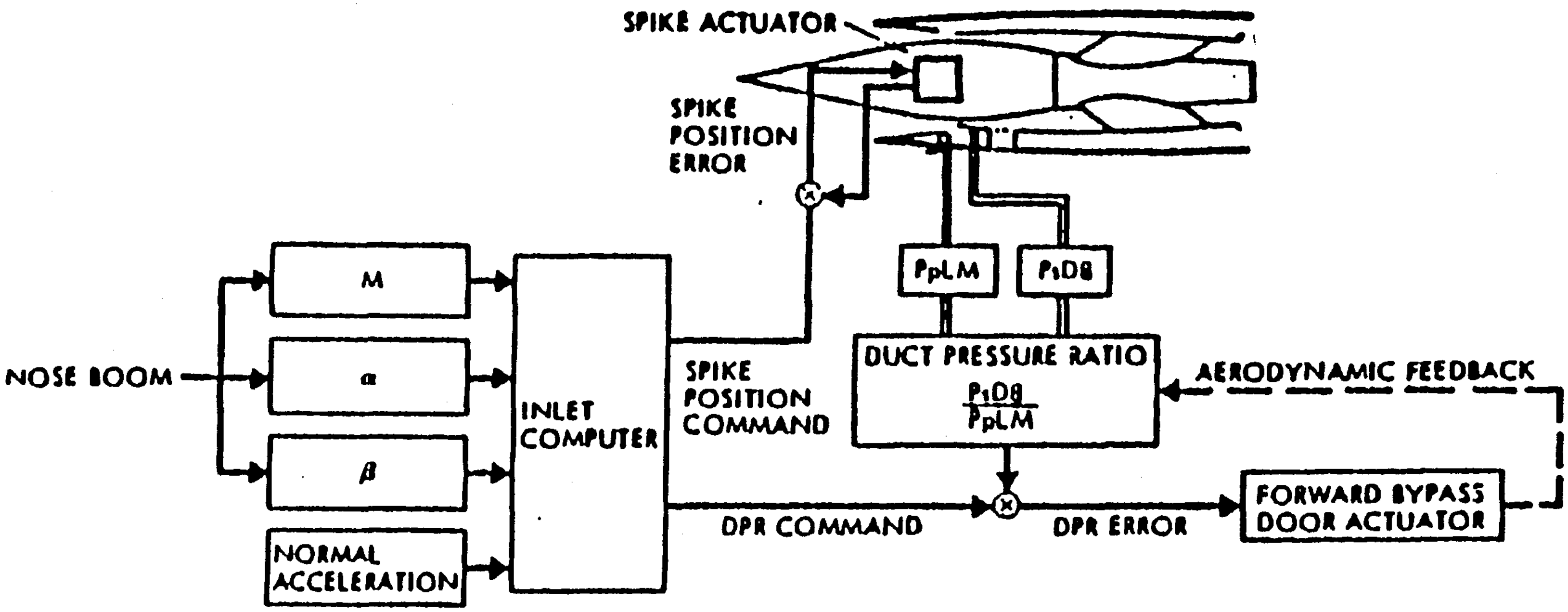
A20-4699-34

SR-71 AIR INLET CHARACTERISTICS

- AXI-SYMMETRIC MIXED COMPRESSION INLET CHOSEN BECAUSE
  - LOWER WEIGHT, DRAG, AND SIGNATURE OF AXI-SYMMETRIC
  - DESIRED RANGE AND CRUISE PERFORMANCE REQUIRED PRESSURE RECOVERIES HIGHER THAN POSSIBLE WITH AN EXTERNAL COMPRESSION INLET AT MACH 3.0+
- MIXED COMPRESSION INLETS CAN ATTAIN HIGH PRESSURE RECOVERY ABOVE MACH 2.2
  - IF NORMAL SHOCK CAN BE KEPT AT THE DESIGN LOCATION JUST DOWNSTREAM OF THE MINIMUM CROSS SECTIONAL FLOW AREA (INLET THROAT)
  - IF NORMAL SHOCK CAN BE MAINTAINED NEAR THE DESIGN LOCATION DURING INTERNAL OR EXTERNAL FLOW PERTURBATIONS
- IF NORMAL SHOCK CANNOT BE MAINTAINED DOWNSTREAM OF THE THROAT ABOVE MACH 2.2
  - INLET IS SAID TO BE UNSTARTED
  - NORMAL SHOCK POPS OUT AND STABILIZES FORWARD OF THE INLET LIP
  - PRESSURE RECOVERY, AIR FLOW, AND THRUST DROP TO LOW LEVELS
  - DRAG INCREASES SIGNIFICANTLY
  - INLET MUST BE RESTARTED AS FAST AS POSSIBLE TO PREVENT ENGINE DAMAGE AND MINIMIZE AIRPLANE YAW TRANSIENT

A20-4699-35

R-71 AIR INLET CONTF L SYSTEM SCHEMATI



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SR-71 AIR INLET CONTROL SYSTEM FUNCTIONS

- FORWARD BYPASS DOORS ARE OPEN WITH THE GEAR DOWN, CLOSE WHEN LANDING GEAR RETRACTS, BUT BEGIN TO OPEN AGAIN AT MACH 1.4 TO DUMP EXCESS FLOW CAPTURED BY INLET
- SPIKE IS FULL FORWARD AT LOW MACH NUMBERS AND IS PROGRESSIVELY RETRACTED FOR MACH NUMBERS ABOVE 1.6
- CONTROL SYSTEM POSITIONS SPIKE AS A FUNCTION OF MACH NUMBER WITH AOA, SIDESLIP, AND NORMAL ACCELERATION BIAS
- NORMAL SHOCK MOVES DOWNSTREAM OF THE INLET THROAT (INLET STARTS) AT APPROXIMATELY MACH 1.7
- ABOVE MACH 2.2, BYPASS DOORS MODULATE AS REQUIRED TO KEEP NORMAL SHOCK AT THE DESIGN LOCATION
- IF AN UNSTART OCCURS IN ONE INLET ABOVE MACH 2.3, BOTH SPIKES ARE DRIVEN TO THE FORWARD POSITION AND THE FORWARD BYPASS DOORS ARE OPENED TO OBTAIN A RESTART AND MINIMIZE YAW TRANSIENTS
- AFT BYPASS DOORS ARE SCHEDULED MANUALLY TO PROVIDE COOLING AIR TO ENGINE BAY AND EJECTOR

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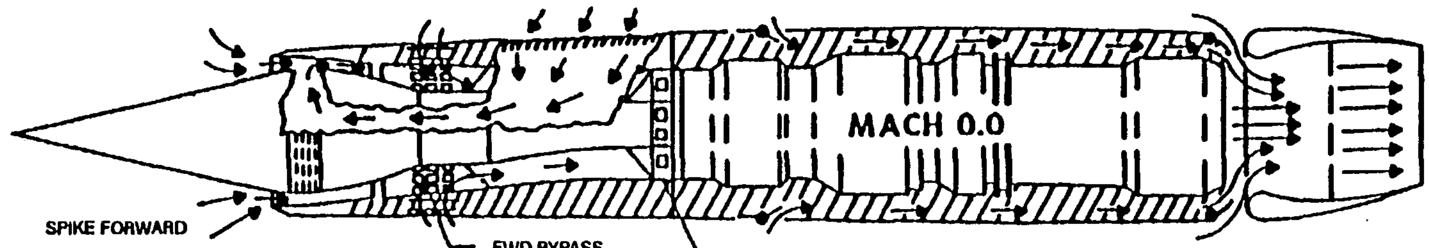
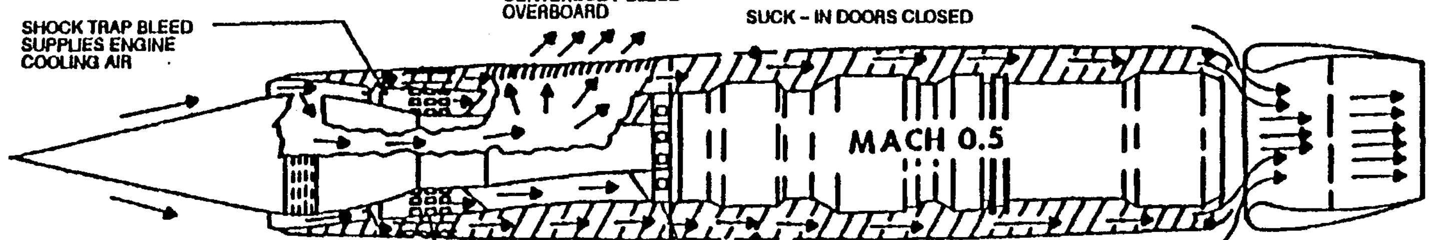
SR-71 INLET/EXHAUST SUBSONIC FLIGHT

AIRFLOW PATTERNS





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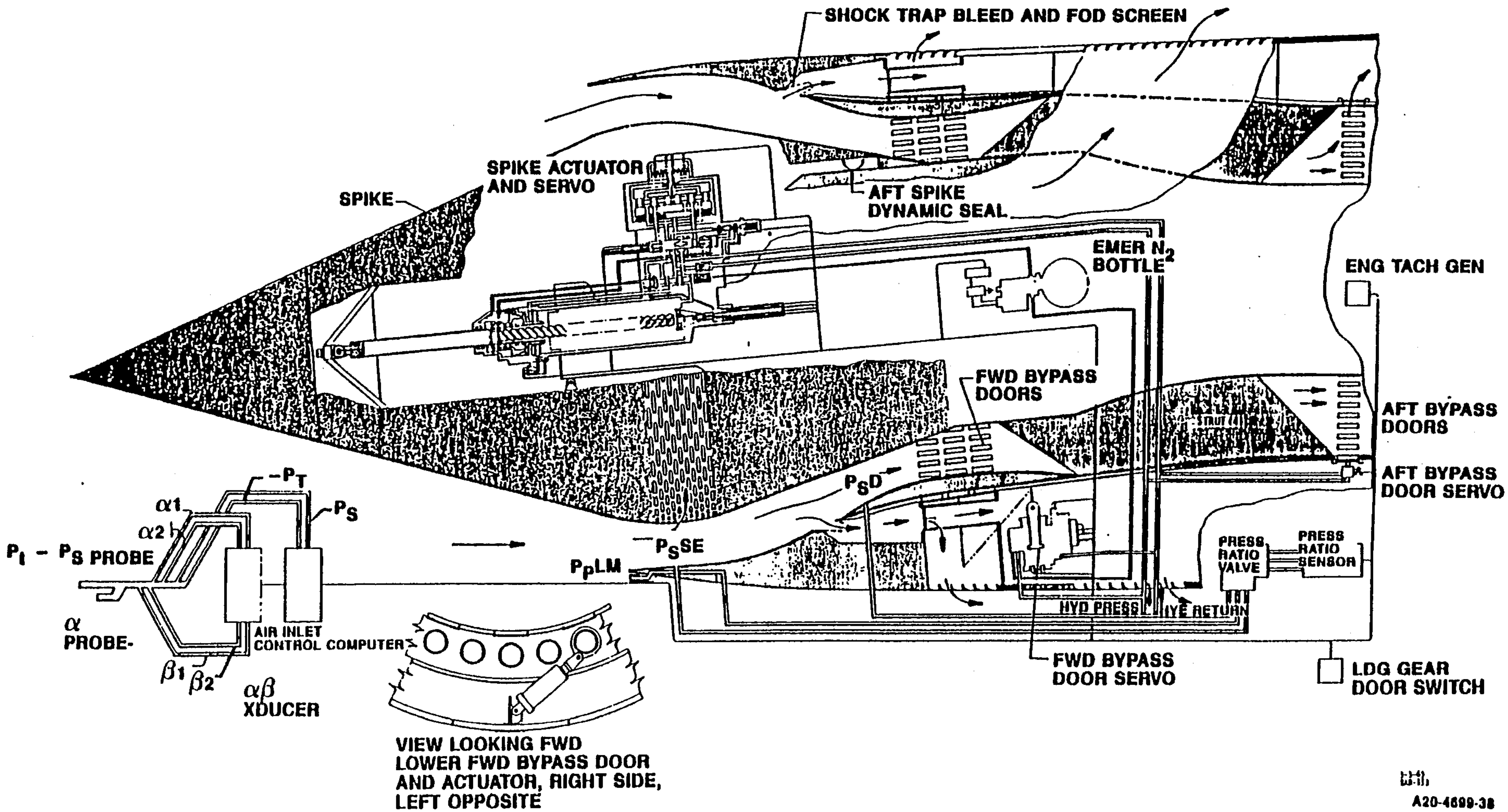
SR-71 AIR INLET CON ROL COMPONENTS



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SR-71 FLIGHT CONTROL SYSTEM DEVELOPMENT PROBLEMS

- **NUMEROUS INLET UNSTARTS DURING INITIAL FLIGHT TESTING**
  - INTERMITTENT OPERATION OF ELECTRICAL COMPONENTS IN 650°F AMBIENT TEMPERATURES AND HIGH VIBRATION LEVELS IN NACELLES
  - FULL SCALE INLET TOLERANCES HAD LARGE EFFECT ON BOUNDARY LAYERS CAUSING AERODYNAMIC THROAT TO SHIFT RELATIVE TO THE GEOMETRIC THROAT
  - SHOCK WAVES OFF THE FLEXING FOREBODY DISTURBED FLOW AT THE INLET

- **PROBLEMS SOLVED BY**
  - IMPROVEMENT TO ELECTRICAL COMPONENTS AND CONNECTORS
  - ADJUSTMENT OF INLET CONTROL SYSTEM SCHEDULES
  - MODIFICATION OF AOA, SIDE SLIP ANGLE, AND NORMAL ACCELERATION BIAS

A20-4699-42

SR-71 FLIGHT CC..TROL SYSTEM DEVELOPMENT PROBLEMS

- UNSATISFACTORY AUTOPILOT MACH HOLD PERFORMANCE
  - PURPOSE OF MACH HOLD THROUGH THE PITCH AXIS AUTOPILOT WAS TO MAXIMIZE RANGE BY AUTOMATIC CONSTANT MACH CRUISE CLIMB
  - GOOD MACH CONTROL POSSIBLE, BUT LARGE AMPLITUDE, LONG PERIOD ALTITUDE OSCILLATIONS COMBINED WITH ROUGH RIDE ($\pm$ 0.4g AT COCKPIT) IS UNSATISFACTORY
- CAUSES
  - VERY LOW DAMPING OF PHUGOID MODE IN SUPERSONIC CRUISE
  - AIRFRAME/INLET INTERACTIONS
  - AIR DATA PROBE SENSING ΔP ERRORS
  - FLEXIBLE AIRFRAME
  - EXCITATION FROM AMBIENT TEMPERATURE GRADIENTS
- OPERATIONAL WORK AROUND
  - USE AUTOPILOT ATTITUDE HOLD INSTEAD OF MACH HOLD
- FINAL FIX WILL REQUIRE AN AUTOTHROTTLE

A20-4600-43

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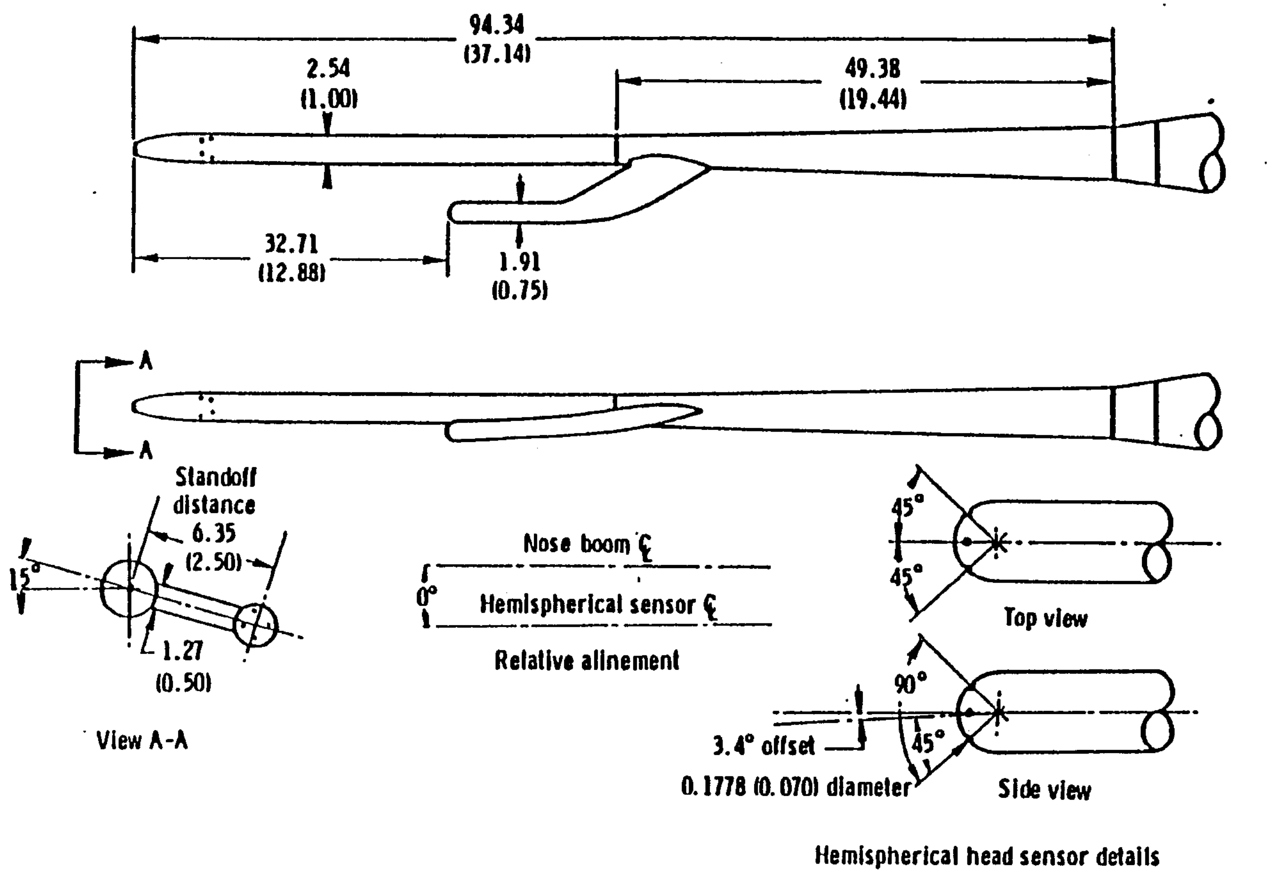
SR-71 AIR DATA SENSING PROBE



Three-view drawing of nose boom and pitot-static probe showing hemispherical head flow direction sensor. Dimensions in centimeters (inches).

A20-4699-47

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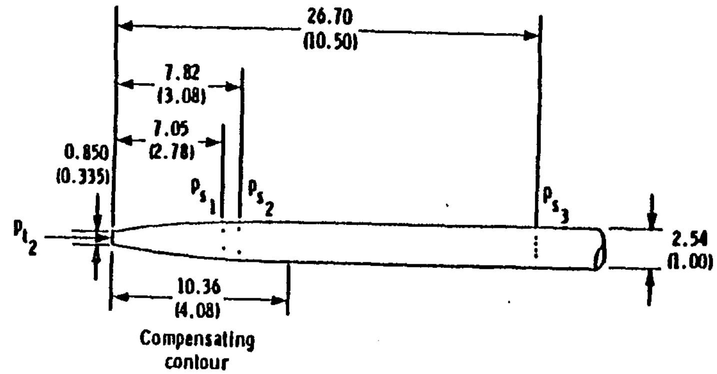
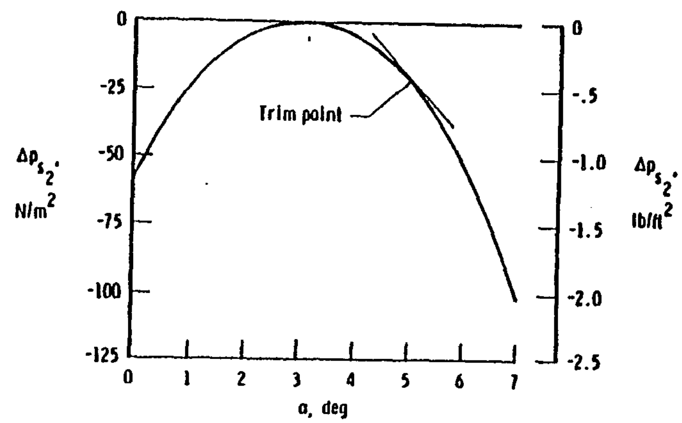
SR-71 STATIC PRESSURE ERROR DUE TO ANGLE-OF-ATTACK



Static pressure source locations

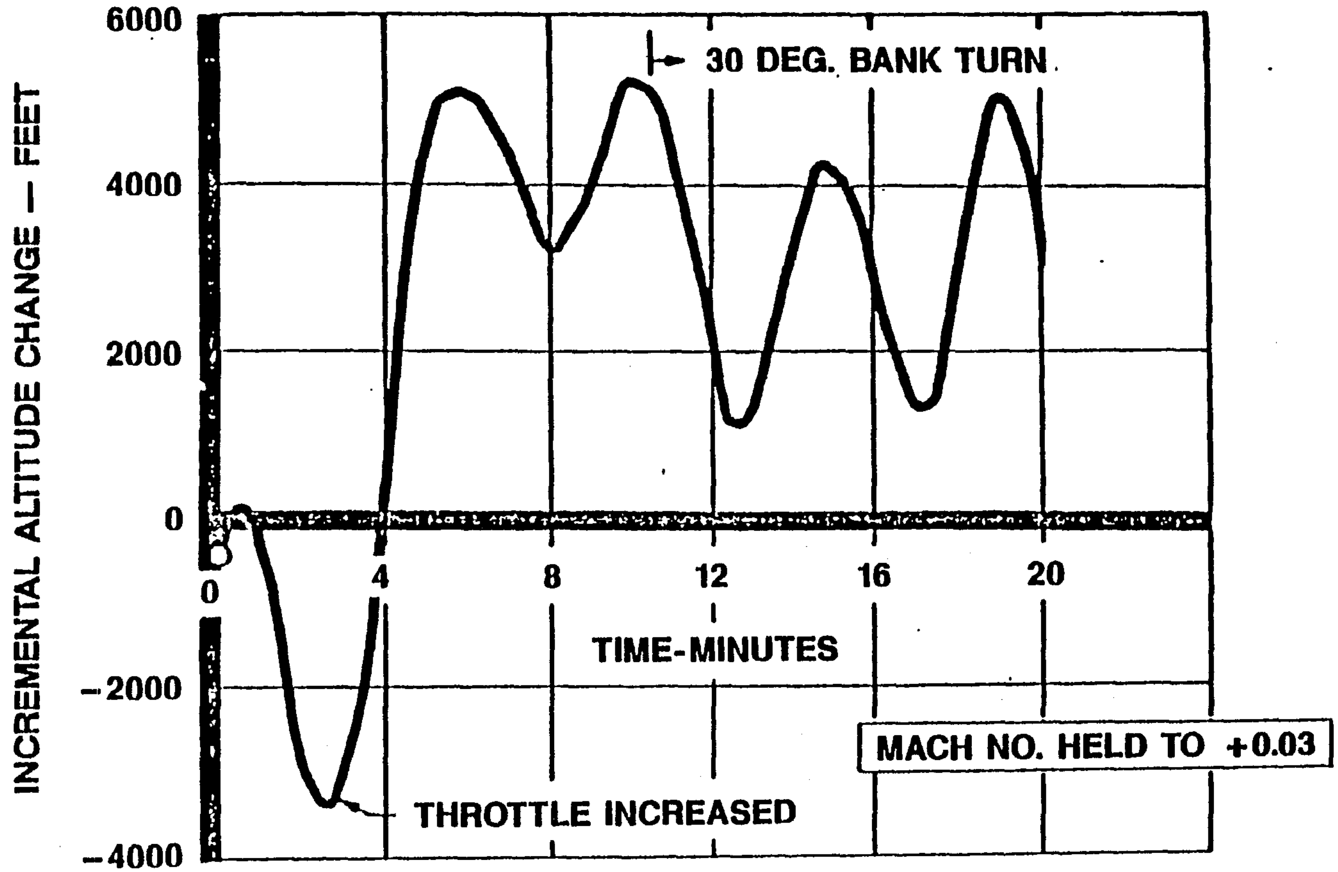


Variation of static pressure error with angle of attack, $p_s(\alpha)$. $M \approx 3.0$; $h = 23{,}600$ m (77,500 ft). At the trim point, $\Delta p_{s_2}/\Delta\alpha = -23.9$ N/m^2/deg (-0.50 lb/ft^2/deg), which is equivalent to $\Delta h/\Delta\alpha = 49$ m/deg (161 ft/deg) or $\Delta M/\Delta\alpha = 0.011$/deg.

A20-4699-48

SR-71 AUTOMATIC FLIGHT CONTROLS

- AUTO INLET
- AUTOPILOT MACH HOLD ON



HIGH MACH PHUGOID

A20-4699-44

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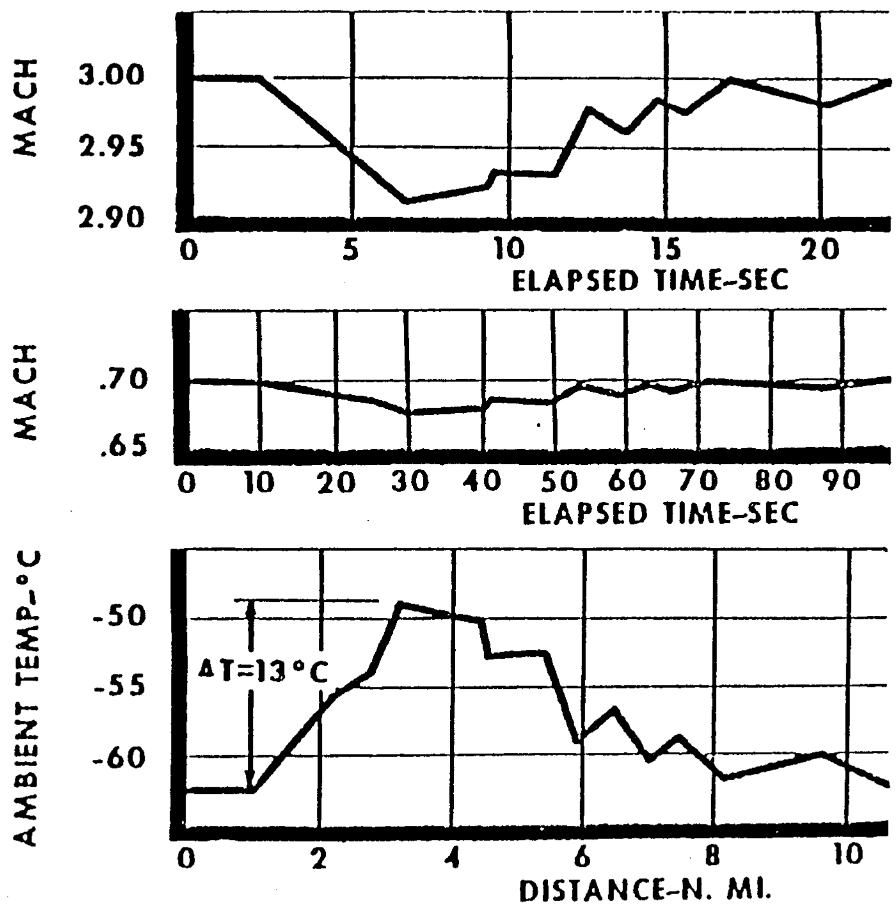
SR-71 FLIGHT CONTROL SYSTEM



Effect of temperature gradients on Mach number at constant velocity.

A20-4899-49

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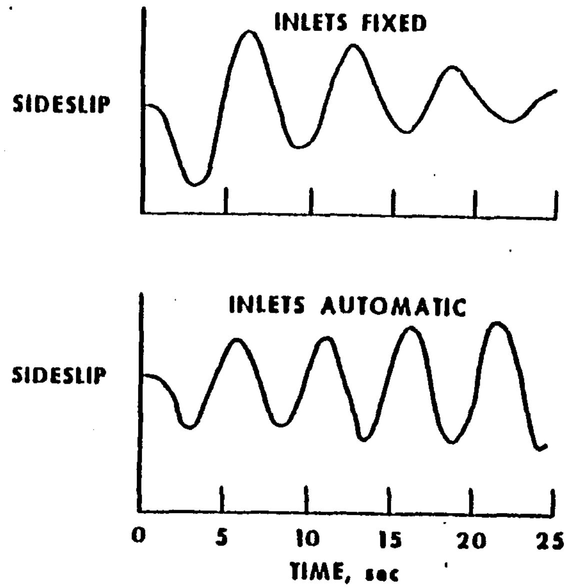
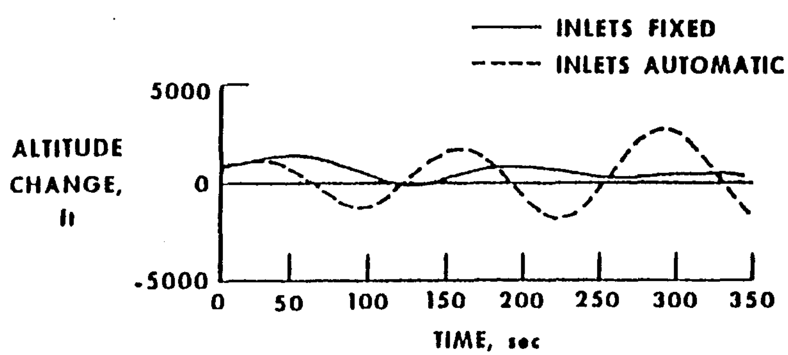
SR-71 FLIGHT CONTROL SYSTEM
EARLY FLIGHT TEST RESULTS BEFORE INLET CONTROL SYSTEM MODIFICATIONS



YAW SAS OFF

YAW SAS OFF



PITCH SAS ON
STICK FIXED

A20-4699-45

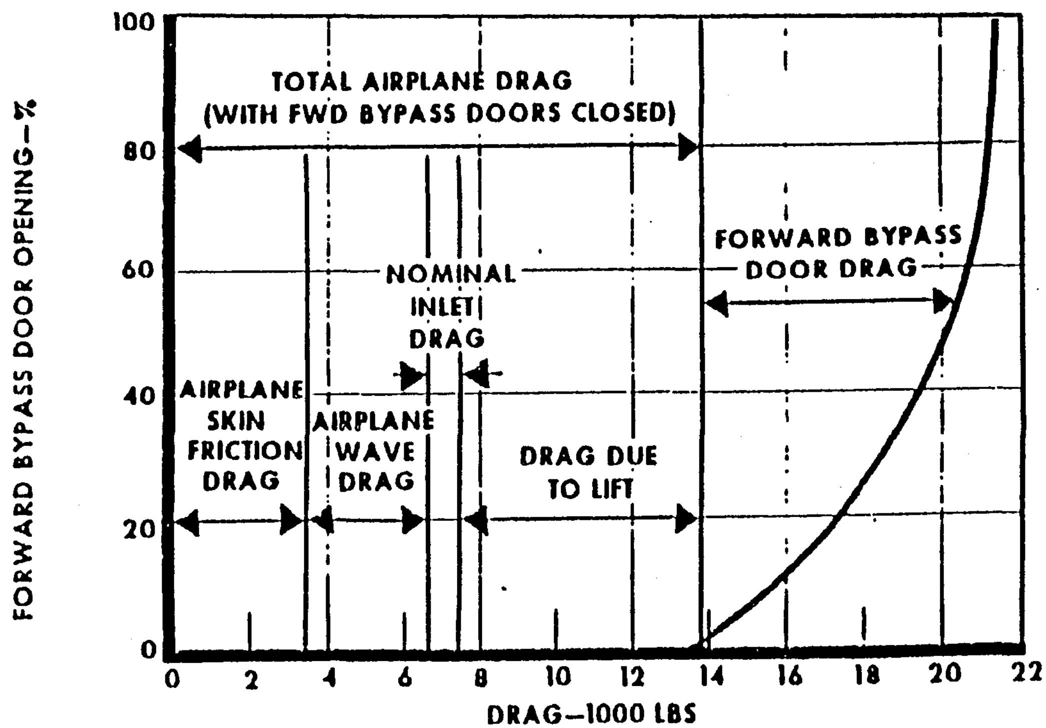
SR-71 FLIGHT CONTROL SYSTEM DEVELOPMENT PROBLEMS

- NUMEROUS INLET UNSTARTS DURING INITIAL FLIGHT TESTING
- UNSATISFACTORY PERFORMANCE OF AUTOPILOT MACH HOLD

17-BL-0005-04-10-91-CB

SR-71 DRAG CO… ·RIBUTION OF INLET BYPASS DOORS

ASYMMETRIC BYPASS DOOR OPERATIONS CAN CAUSE DIVERGENT DUTCH ROLL OSCILLATIONS IF THE YAW SAS IS OFF



Forward bypass door drag at cruise.

A20-4699-46

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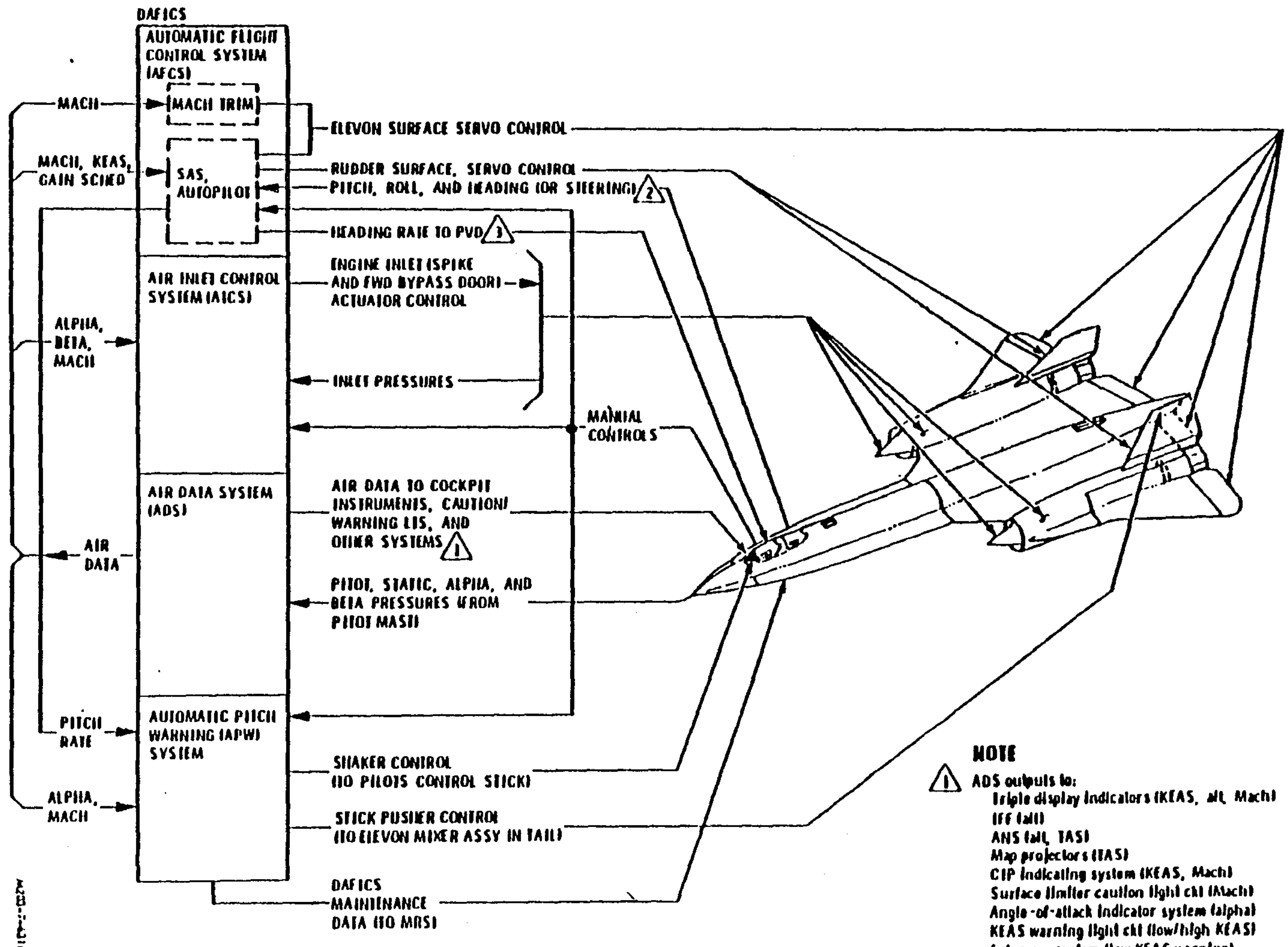
SR-71 DIGITAL AUTOMATIC FLIGHT AND INLET CONTROL SYSTEM (DAFICS)

THE DAFICS PROGRAM STARTED IN 1978 TO

- IMPROVE SYSTEM RELIABILITY AND REDUCE MAINTENANCE (ORIGINAL ANALOG SYSTEM WAS REACHING END OF USEFUL LIFE)
- REPLACE THE ANALOG ELECTRONICS WITH DIGITAL IMPLEMENTATION
  - ELIMINATE "VANISHING VENDOR" PROBLEM
  - ELIMINATE CONNECTORS BY CONSOLIDATING COMPONENTS INTO FEWER BOXES
  - IMPROVE PROBABILITY OF MISSION COMPLETION WITH MORE REDUNDANCY
  - IMPROVE BUILT IN TEST EQUIPMENT (BITE)

SR-71 DIGITAL AU .OMATIC FLIGHT & INLET CONTROL SYSTEM



NOTE

1. ADS outputs to:
   - Triple display indicators (KEAS, alt, Mach)
   - IFF (alt)
   - ANS (alt, TAS)
   - Map projectors (TAS)
   - CIP indicating system (KEAS, Mach)
   - Surface limiter caution light ckt (Mach)
   - Angle-of-attack indicator system (alpha)
   - KEAS warning light ckt (low/high KEAS)
   - Intercom system (low KEAS warning)
2. Attitude and heading signals from ANS or INS (Only ANS supplies steering signal.)
3. Aircraft with SB R-2478

A20-4699-51

SR-71 FLIGHT CONTROL SENSOR & ELECTRONIC REDUNDANCY

SYSTEM	ORIGINAL ANALOG SYSTEM	DAFICS
PITCH SAS	TRIPLE (WITH BACK UP DAMPER)	TRIPLE
YAW SAS	TRIPLE	TRIPLE
ROLL SAS	DUAL	DUAL
AUTOMATIC PITCH WARNING	DUAL	DUAL
MACH TRIM	SINGLE	TRIPLE
PITCH AUTO PILOT	SINGLE	DUAL
ROLL AUTO PILOT	SINGLE	DUAL
AIR DATA COMPUTATION	SINGLE	TRIPLE
AIR INLET CONTROLS	SINGLE (WITH MANUAL BACKUP)	DUAL (WITH MANUAL BACKUP)

A20-4699-52

SR-71 FLIGHT CONTROL SYSTEM

	ORIGINAL ANALOG SYSTEM	DAFICS
NUMBER OF LINE REPLACEABLE UNITS	15	6
VOLUME ~ CUBIC INCHES	6,800	6,550
WEIGHT ~ POUNDS	180	163

DAFICS IMPROVES RELIABILITY AND REDUCES REQUIRED MAINTENANCE BECAUSE

- NUMBER OF CONNECTORS IS REDUCED
- LARGE SCALE INTEGRATED CIRCUITS ARE USED IN THE DIGITAL COMPUTERS
- BUILT IN TEST FEATURES ARE MORE COMPREHENSIVE

A20-4899-58

SR-71 FLIGHT CC .TROL SYSTEM

IMPROVEMENTS SINCE INTRODUCTION OF DAFICS IN 1983

- SYSTEM MEAN TIME BETWEEN FAILURE INCREASED BY A FACTOR OF EIGHT

- REDUCED AIR DATA LAGS DUE TO SHORTER PITOT STATIC LINES AND SMALLER TERMINATING VOLUMES IN PRESSURE TRANSDUCERS RESULT IN BETTER AIR INLET CONTROL ACCURACIES AND IMPROVED PERFORMANCE

- PROBE STATIC PRESSURE ERRORS INDUCED BY AOA VARIATIONS ARE MORE ACCURATELY COMPENSATED IN THE DIGITAL AIR DATA COMPUTATIONS WHICH RESULT IN IMPROVED STABILITY OF AUTOPILOT SPEED HOLD MODES

- IMPROVED MISSION COMPLETION CAPABILITY SINCE PREFLIGHT BITE INSURES ALL SUBSYSTEMS ARE OPERATIONAL TO A 95% CONFIDENCE LEVEL

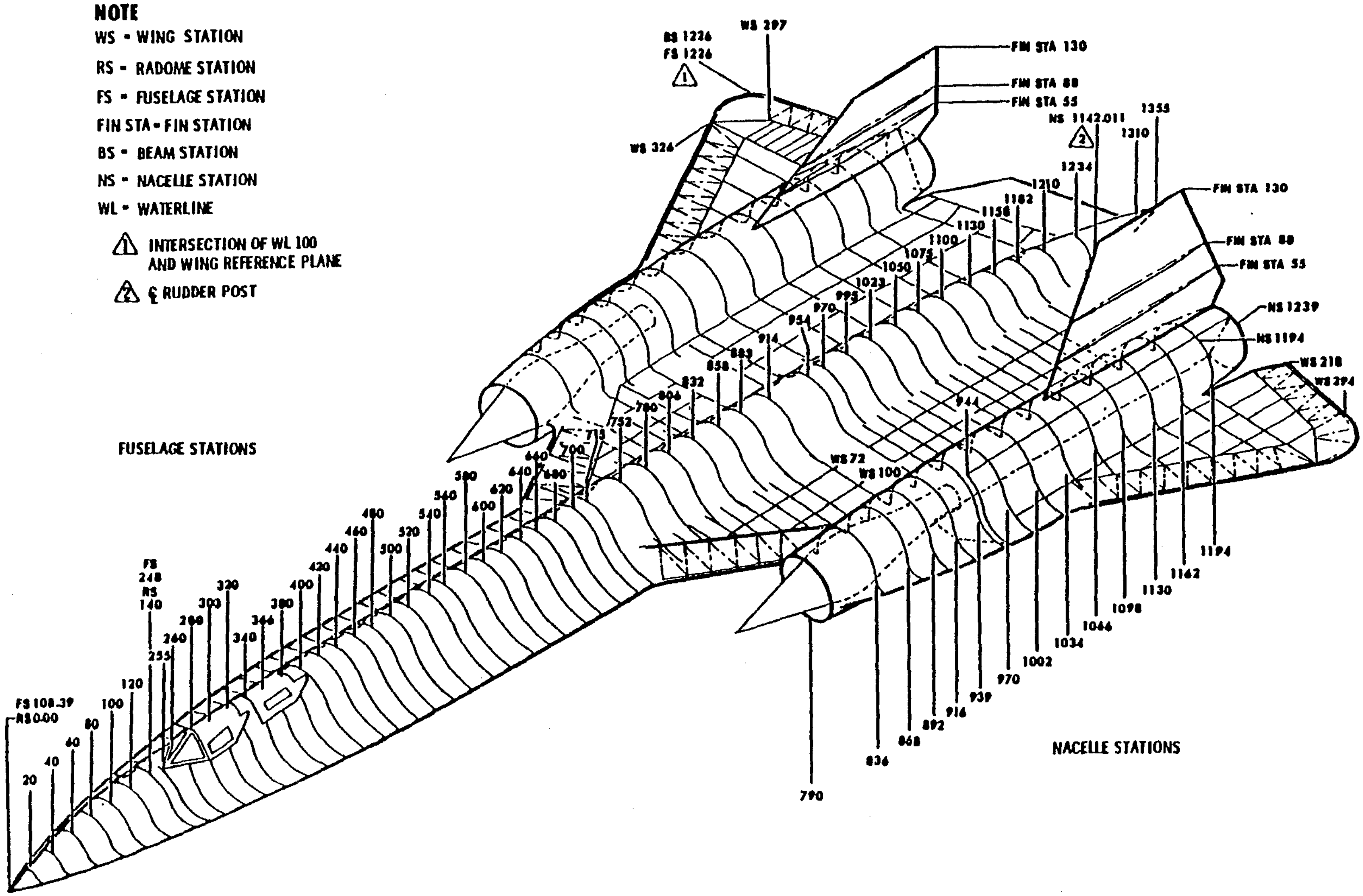
- REDUCED MAINTENANCE MAN HOURS PER FLIGHT HOUR BY A FACTOR OF SIX BECAUSE INFLIGHT BITE ISOLATES FAILURES AND IDENTIFIES FAULTY SYSTEM COMPONENTS

A20-4699-53

GENERAL STATION LOCATIONS

NOTE
WS - WING STATION
RS - RADOME STATION
FS - FUSELAGE STATION
FIN STA - FIN STATION
BS - BEAM STATION
NS - NACELLE STATION
WL - WATERLINE

⚠1 INTERSECTION OF WL 100 AND WING REFERENCE PLANE
⚠2 ℄ RUDDER POST



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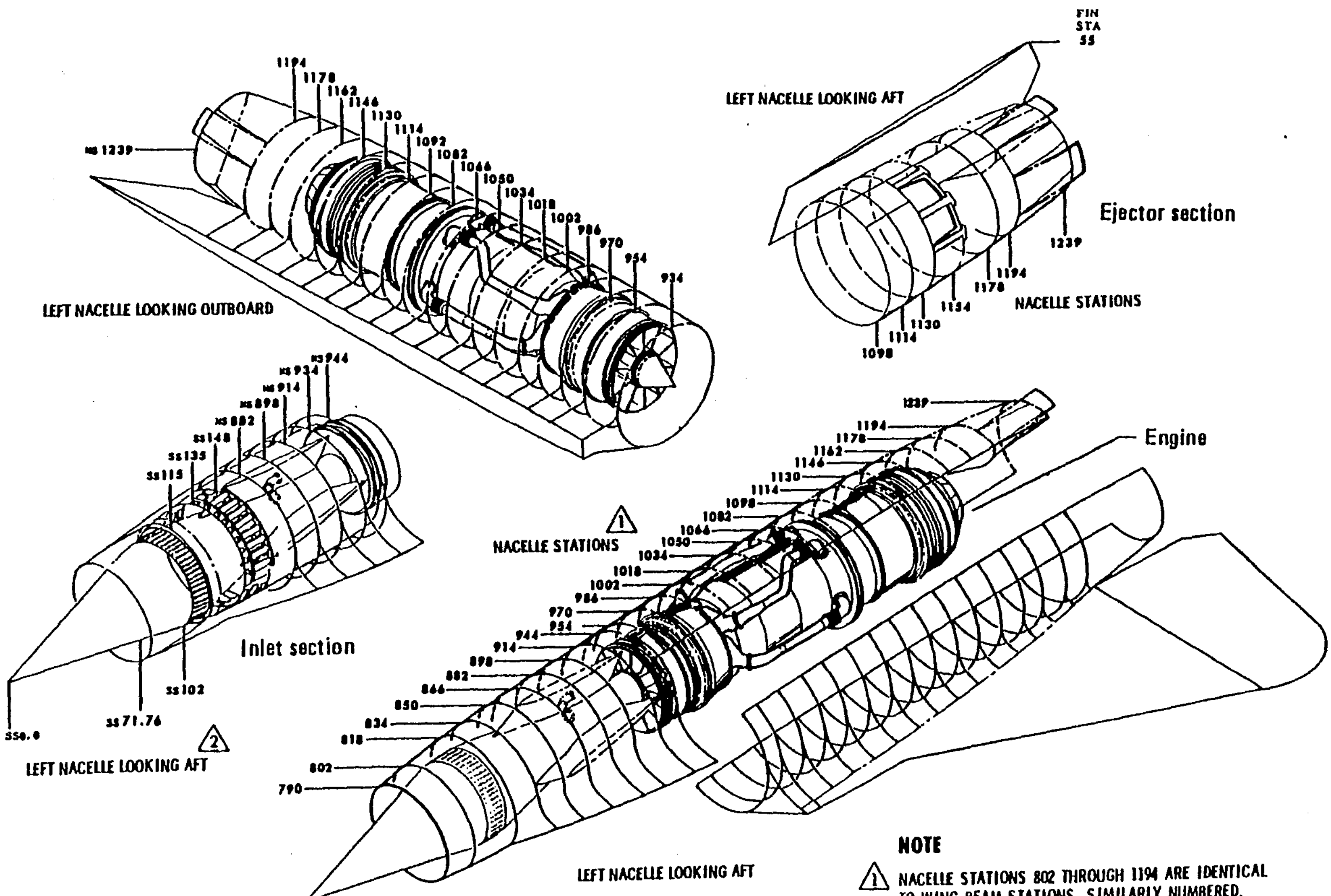
PROPULSION SYSTEM STATION LOCATIONS



NOTE

1. NACELLE STATIONS 802 THROUGH 1194 ARE IDENTICAL TO WING BEAM STATIONS, SIMILARLY NUMBERED, EXCEPT FOR NS944, NEAREST EQUIVALENT OF WHICH IS BS934 (NOT SHOWN)
2. SS - SPIKE STATION

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THERMAL EN' RONMENT

- THE SR-71 THERMAL ENVIRONMENT IS MUCH MORE SEVERE THAN MOST OPERATIONAL AIRCRAFT FLYING TODAY AND IN THE PAST.
- THE HEAT GENERATED BY THE HIGH SPEED (MACH 3+) RESULTS IN SKIN FRICTION HEATING AND IN STAGNATION TEMPERATURES OVER 800°F, DEPENDING UPON HIGH ALTITUDE AMBIENT TEMPERATURES.
- AERODYNAMIC HEATING RESULTS IN LEADING EDGE TEMPERATURES OF UP TO 800°F, EXTERNAL SURFACE TEMPERATURES ON THE FUSELAGE AND WINGS OF UP TO 640°F AND SURFACE AND STRUCTURAL TEMPERATURES IN THE ENGINE NACELLE OF OVER 1100°F.
- TYPICAL DESIGN TEMPERATURES DURING HIGH SPEED CRUISE FLIGHT (MACH 3+) ARE PRESENTED TO DOCUMENT THE SEVERE THERMAL ENVIRONMENT ENCOUNTERED FOR STEADY STATE STRUCTURAL DESIGN.

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THERMAL ENVIRONMENT

- EFFECT OF THE SEVERE THERMAL ENVIRONMENT ON THE DESIGN OF THE VEHICLE
  - ALL THE MATERIALS HAD TO SUSTAIN STRENGTH AND LIFE DURING STEADY-STATE-OPERATION AT THE TEMPERATURES EXPECTED IN THE VARIOUS AREAS OF THE VEHICLE. SYSTEMS AND SYSTEM COMPONENTS HAD TO BE DESIGNED FOR STEADY-STATE-OPERATION IN THE ADVERSE THERMAL ENVIRONMENT. FLUIDS, LUBRICANTS AND SEALANTS ALSO HAD TO BE FOUND TO FUNCTION IN THESE SEVERE CONDITIONS.
- DESIGN DRIVERS
  - TO MAKE THE STRUCTURE, THE FUNCTIONAL SYSTEMS, AND THE MISSION EQUIPMENT LIVE IN THE EXTREME THERMAL ENVIRONMENTS, NEVER ENCOUNTERED BEFORE AS STEADY-STATE-OPERATING CONDITIONS FOR AN AIR VEHICLE, AND OPERATE RELIABLY FOR LONG PERIODS OF TIME WITH MINIMAL MAINTENANCE AND RELATIVELY LOW DEVELOPMENT RISK.
- SOLUTIONS TO THE THERMAL DESIGN CHALLENGES
  - FINDING SOLUTIONS TO THE DESIGN CHALLENGES WAS A THERMODYNAMICS DEPARTMENT DREAM OR NIGHTMARE, DEPENDING UPON HOW ONE LOOKED AT THE CONCERN TO BE ADDRESSED. THE CHALLENGES WERE MET AND SUCCESSFULLY OVERCOME. THE ENVIRONMENT OF EACH AREA IN THE VEHICLE WAS RELATIVELY EASY TO DETERMINE, BUT FINDING WAYS TO ALLOW EQUIPMENT TO LIVE WAS DIFFICULT.

THERMAL ENVIRONMENT

- GENERAL AREAS OF CONCERN
  - EXTERNAL THERMAL ENVIRONMENTS
    - ALL SURFACES; FUSELAGE, WING, NACELLE, AND CONTROL SURFACES
  - STRUCTURAL THERMAL ENVIRONMENTS
    - ALL STRUCTURE; BEAMS, LONGERONS, RINGS, MOUNTS, BRACKETS, SKINS, AND NACELLE STRUCTURAL ELEMENTS
  - INTERNAL THERMAL ENVIRONMENTS
    - CREW COMPARTMENTS, COOLED EQUIPMENT BAYS, UNCOOLED EQUIPMENT BAYS, FUEL TANKS, WHEEL WELLS, ENGINE COMPARTMENTS, AND DRAG CHUTE COMPARTMENT
  - SYSTEMS AND SYSTEM COMPONENT THERMAL ENVIRONMENTS
    - FUEL SYSTEM; TANKS, PUMPS, VALVES, LINES, HEAT SINK SYSTEM, AND ENGINE SUPPLY AND RETURN-BLEED HARDWARE; FUEL TANK SEALANT
    - HYDRAULIC SYSTEM; PUMPS, VALVES AND ACTUATORS
    - FUEL TANK INERTING SYSTEM; NITROGEN TANKS AND DISTRIBUTION HARDWARE
    - OXYGEN SYSTEM; BOTTLES, VALVES AND REGULATORS
    - ENVIRONMENTAL CONTROL SYSTEM; HARDWARE AND DUCTING
    - POWER GENERATION SYSTEM AND CONSTANT SPEED GEAR BOX SYSTEM
    - MAINTENANCE RECORDING SYSTEM
    - DIRECTIONAL GYRO PACKAGE COOLING

THERMAL ENVIRONMENT
SPECIFIC AREAS OF CONCERN

- **EXTERNAL AND INTERNAL ENVIRONMENT SUMMARY**

	DESIGN EXTERNAL ENVIRONMENT	INTERNAL (MAX DESIGN)
– FUSELAGE		
■ NOSE	570°F → 640°F	250°F
■ COCKPIT	510°F → 570°F	80°F
■ FUEL TANKS	500°F → 550°F	550°F
■ EQUIPMENT BAYS	525°F → 550°F	160°F
■ WHEEL WELLS	525°F → 550°F	NOSE: 160°F; MAIN: 400°F
– WINGS		
■ INBOARD	480°F → 640°F	550°F
■ OUTBOARD	510°F → 640°F	550°F
– NACELLE		
■ INLET SPIKE	800°F	800°F
■ INLET COWL	800°F	800°F
■ ENGINE COMPT	900°F +	900°F +
■ ENGINE & A.B.	900°F +	900°F +
■ EJECTOR NOZZLE	1000°F	1300°F
■ EXHAUST FLAPS	1100°F	1700°F
– CONTROL SURFACES		
■ HORIZONTAL	460°F → 550°F	550°F
■ VERTICAL	470°F → 640°F	640°F

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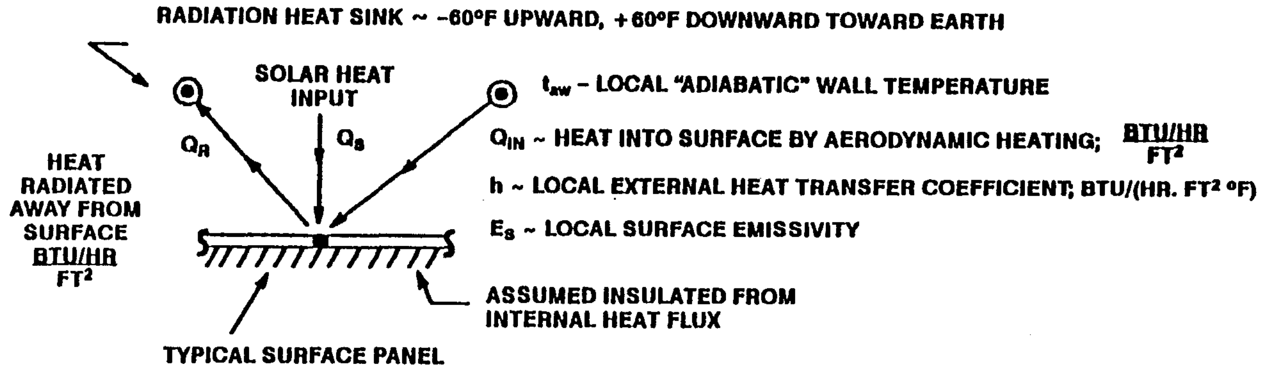
EXTERNAL THERMAL ENVIRONMENT

- **EXTERNAL SURFACE TEMPERATURES – AREAS EFFECTIVELY INSULATED FROM HEAT SOURCES**
  - **METHODS TO DETERMINE RADIATION EQUILIBRIUM SURFACE TEMPERATURES (ABBREVIATED)**
    - **TYPICAL THERMAL HEAT BALANCE**



- **TYPICAL THERMAL ASSUMPTIONS:**
  - AMBIENT CONDITIONS: 1959 ARDC STANDARD ATMOSPHERE
  - SOLAR HEAT LOADS: 0, 200, 400 BTU/HR. FT^2 NORMAL TO SURFACE
  - SURFACE EMISSIVITIES: 0.5 (UNPAINTED), 0.9 (BLACK AREAS)
  - SURFACE SOLAR ABSORPTIVITY: 0.6 (UNPAINTED), 0.93 (BLACK AREAS)
  - RADIATION HEAT SINK TEMPERATURES:
    - ✓ UPPER SURFACES: −60°F USED AS OUTER SPACE VALUE
    - ✓ LOWER SURFACE: +60°F USED AS EARTH SURFACE VALUE
    - ✓ NO RADIATION FROM OTHER SURFACE FOR "ACREAGE" PANELS

EXTERNAL THERMAL ENVIRONMENT

(CONTINUED)

- **METHODS TO DETERMINE SURFACE TEMPERATURES (CONTINUED)**
  - **LOCAL ADIABATIC WALL TEMPERATURE: (TEMPERATURES IN °F)**

    $t_{aw} = t_a + 0.89\,(T_{RAM} - t_a)$ where t_a is ambient temperature ~°F,
    T_{RAM} is stagnation temperature ~°F

  - **LOCAL TURBULENT HEAT TRANSFER COEFFICIENT: (BTU/(HR.FT²°F))**

    $$h_\ell = 41.7\,C_f\,\frac{p_\ell V_\ell}{T_{ref}}\,(c_p)_{ref};$$

    c_p is specific heat at $T_{ref} \sim \frac{BTU/\#}{°F}$
    p_ℓ is local static pressure ~ PSFA
    V_ℓ is local velocity ~ feet/sec.

  - **LOCAL BOUNDARY LAYER REFERENCE TEMPERATURE: (TEMPERATURES IN R)**

    $T_{ref} = 0.5\,t_w + t_\ell\,(0.5 + 0.0394\,M_\ell^2)$ local static conditions

    where: t_w is wall temperature, t_ℓ is local static ambient temperature, M_ℓ is local Mach number

  - **LOCAL SKIN FRICTION COEFFICIENT**

    $$C_f = \frac{0.585\,\overline{C}_f}{0.557 + 2.(\overline{C}_f)^{1/2}} \quad ; \quad \overline{C}_f = \left[\frac{0.242}{\log_{10}(R_{e\,ref}\,\overline{C}_f)}\right]^2$$

    (iterative solution required)

  - **REFERENCE REYNOLDS NUMBER: (TEMPERATURES IN °R, V_ℓ is ft/sec, p_ℓ is PSFA)**

    $$R_{e_{ref}} = 25{,}600.\,p_\ell\,V_\ell\,X\,(T_{ref} + 200.)\,/\,(T_{ref})^{2.5}$$

    where: X is reference distance from leading edge parallel to fuselage centerline in feet

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EXTERNAL THERMAL ENVIRONMENT

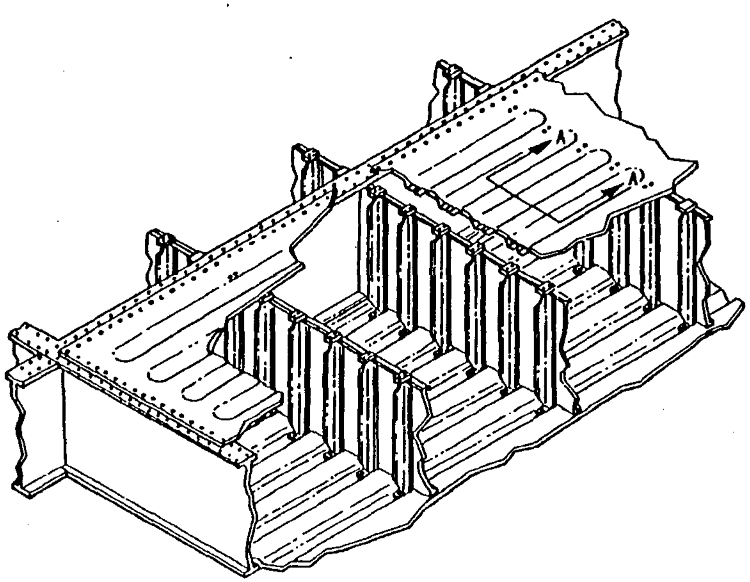
EXTERNAL SURFACE TEMPERATURES (CONTINUED)

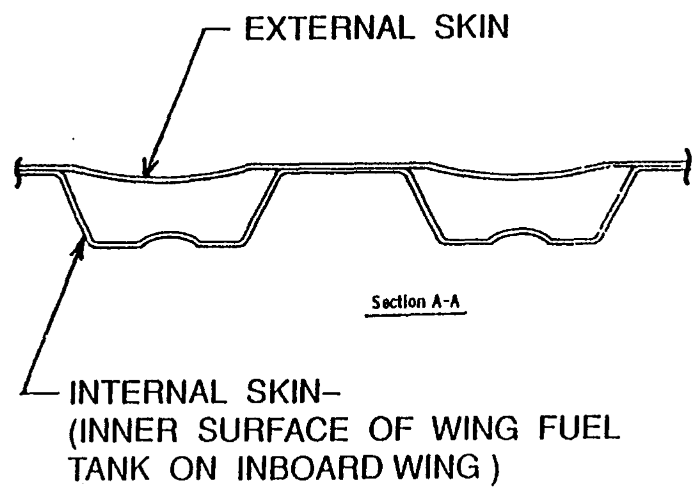
- DETAILED AREAS OF CONCERN (FORE-TO-AFT)
  - NOSE PITOT BOOM — 800°F (STAINLESS STEEL)
  - WINDSHIELD LEADING EDGE — 640°F
  - WINDSHIELD AND CANOPY GLASS — 600°F
  - NACELLE INLET SPIKE TIP — 800°F (STAINLESS STEEL TIP)
  - ANTENNAE — 450°F → 800°F
- DESIGN DRIVERS AT EACH AREA OF CONCERN
  - TEMPERATURES NEEDED TO DETERMINE PROPER MATERIAL SELECTION
  - TEMPERATURES AND MATERIALS DETERMINE WHAT TYPE OF INSULATION MATERIALS ARE NEEDED TO REDUCE HEAT INPUT TO LOW TEMPERATURE AREAS
  - EXTERNAL SOURCE TEMPERATURES NEEDED FOR TRANSIENT ANALYSIS OF CRITICAL BURIED PARTS, I.E., DIRECTIONAL GYROS, DRAG CHUTE, TIRES, AND REFUELING RECEPTACLE
  - EXTERNAL SOURCE TEMPERATURES NEEDED FOR TRANSIENT ANALYSIS OF HEAVY STRUCTURE, I.E., WING BEAMS, NACELLE/WING JOINTS, FUSELAGE LONGERONS, AND OTHER MASSIVE SUBSTRUCTURE ELEMENTS.

EXTERNAL THERMAL ENVIRONMENT

EXTERNAL SURFACE TEMPERATURES

- SPECIAL CONCERN ON WING SURFACES
  - PROBLEM WAS HOW TO ADDRESS DISTORTION OF THE WING SURFACE PANELS DUE TO DIFFERENCES IN THERMAL EXPANSION OF FAST HEATING SKIN PANELS AND SLOWER HEATING INTERNAL SUPPORT STRUCTURE.
  - SOLUTION WAS TO BUILD DOUBLE PANELS WITH FORE-TO-AFT CORRUGATIONS AS SHOWN BELOW. THEREFORE, DISTORTIONS WOULD BE IN A KNOWN DIRECTION AND WOULD NOT ADVERSELY EFFECT AIRFLOW PATTERN OVER WING AND SO LOADS WOULD BE DISTRIBUTED THROUGH KNOWN PATHS. PANELS ARE IN OUTBOARD AND INBOARD WING AREAS.





STRUCTURAL THERMAL ENVIRONMENT

- STRUCTURAL ELEMENTS WERE DESIGNED TO SUSTAIN LOADS DURING STEADY-STATE AND TRANSIENT APPLICATION OF EXTERNAL HEATING. THERMAL LAG WITH RESPECT TO TIME DEPENDED UPON HEAT PATHS AND HEATING MODES; I.E., EFFECTS OF INSULATION, CONDUCTION AND CONVECTION IN SOME AREAS, AND THE EFFECTS OF DIRECT RAM AIR CONVECTION AND ENGINE RADIATION IN OTHERS.

- WINGS AND FUSELAGE STRUCTURE HEATED SLOWLY WHILE ENGINE INLET SYSTEM, NACELLE, AND EXHAUST SYSTEM HEATED QUICKLY.

- AREAS WHERE STRUCTURAL THERMAL GRADIENTS, STEADY-STATE AND TRANSIENT, WERE INVESTIGATED:

<u>NOSE AND FUSELAGE</u>

- NOSE UNCOOLED STRUCTURE
- NOSE COOLED STRUCTURE
- PRESSURIZED COCKPIT
- CANOPY STRUCTURE
- FUSELAGE LONGERONS
- FUSELAGE FUEL TANKS
- WHEEL MOUNT STRUCTURE
- FLIGHT CONTROLS MIXER

<u>WINGS</u>

- MAIN WING BEAMS
- WING/NACELLE INTERFACE
- OUTBOARD WING STRUCTURE
- WING FUEL TANKS
- WHEEL MOUNT STRUCTURE

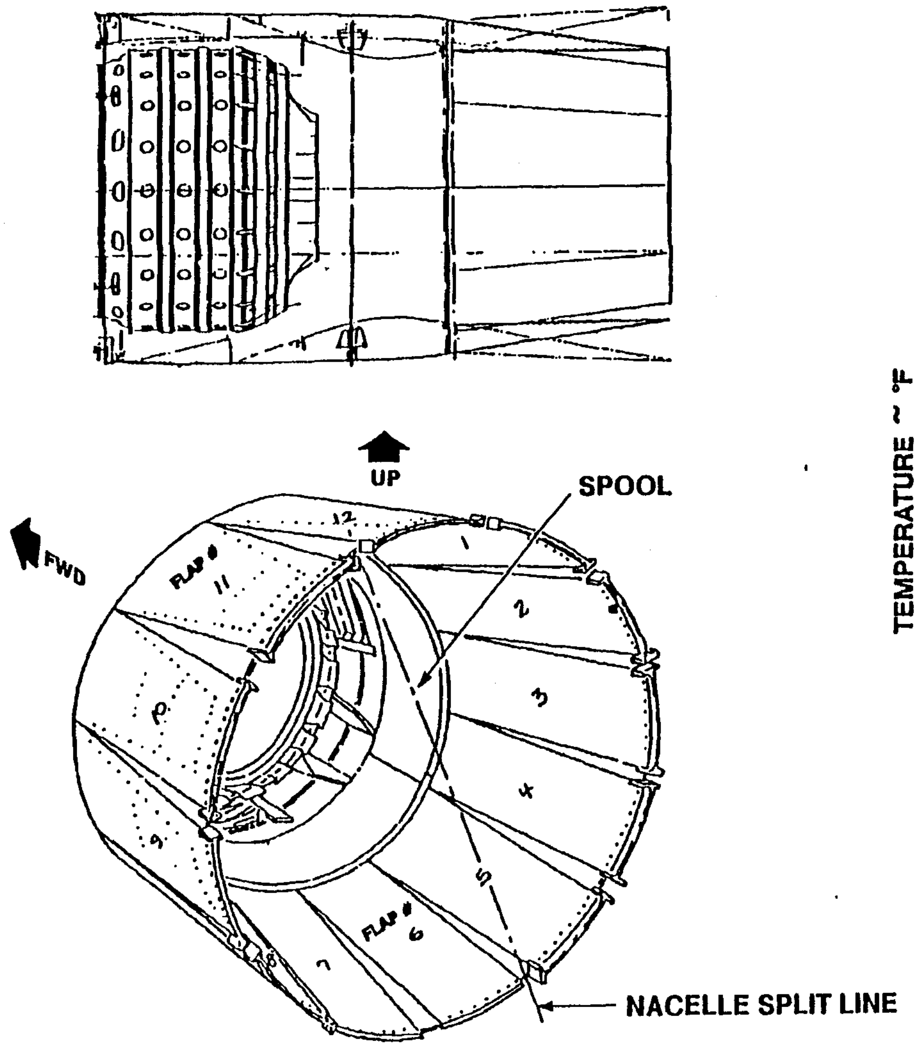
<u>CONTROL SURFACES</u>

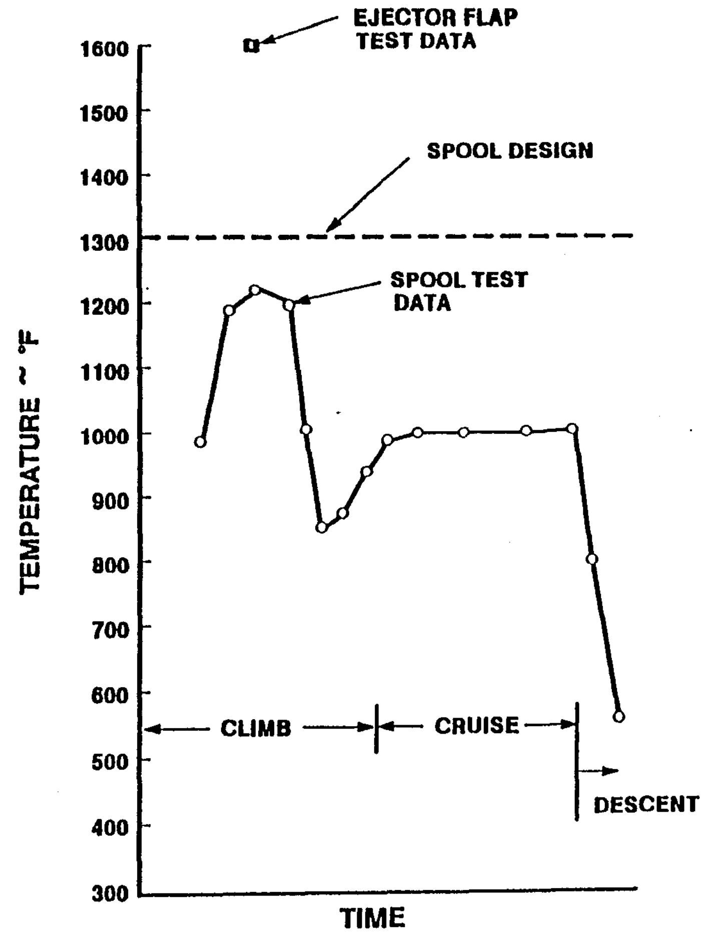
- VERTICAL POST STRUCTURE
- VERTICAL FIN STRUCTURE
- HORIZONTAL CONTROL STRUCTURE

<u>ENGINE SYSTEMS (HOTTEST)</u>

- INLET SPIKE STRUCTURE
- COWLING STRUCTURE
- AIR BYPASS DOOR STRUCTURE
- NACELLE RING STRUCTURE
- EJECTOR SPOOL MOUNTING
- SKIN DOOR STRUCTURE
- EXHAUST FLAP STRUCTURE
- VERTICAL TAIL MOUNT

ENGINE EJECTOR NOZZLE TEMPERATURE DATA





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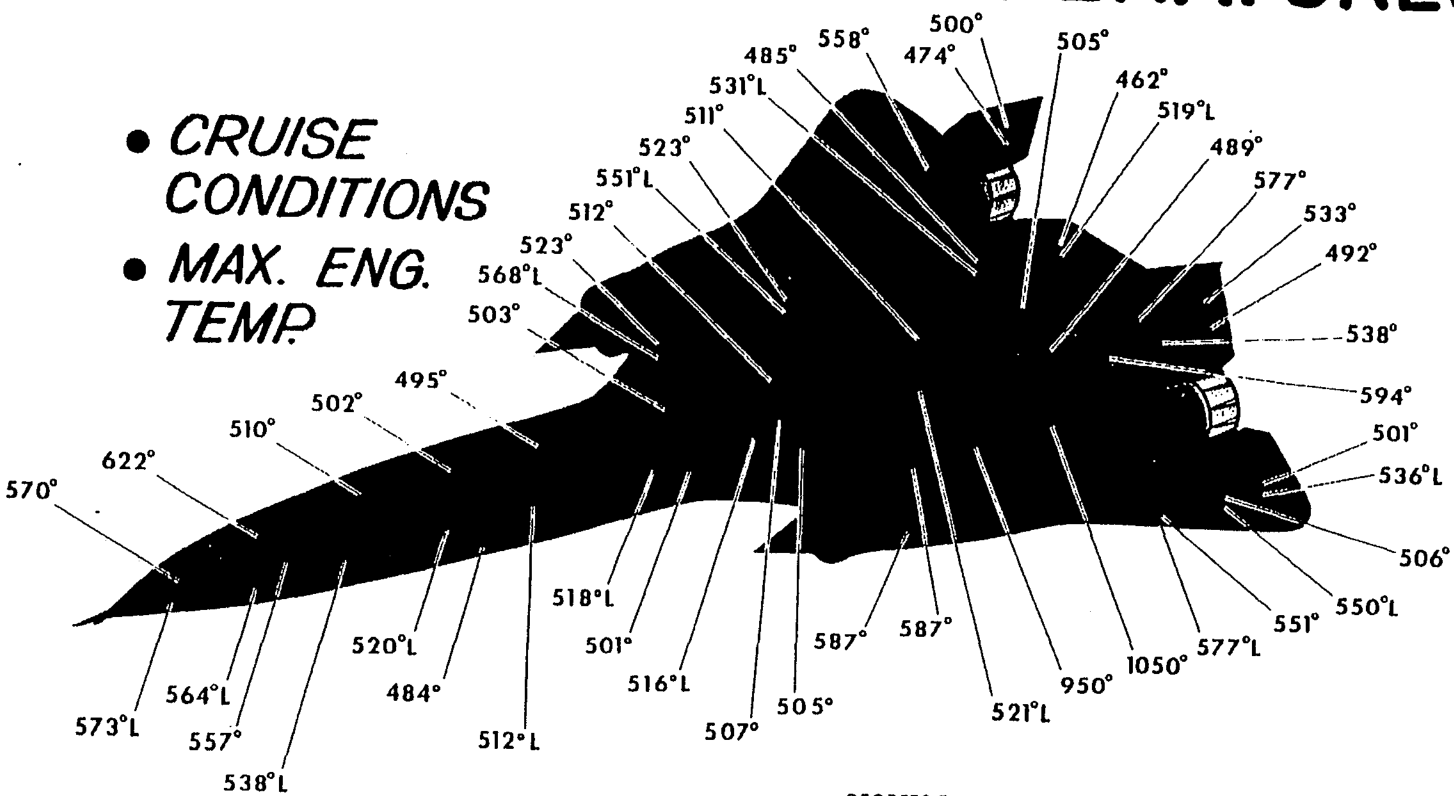
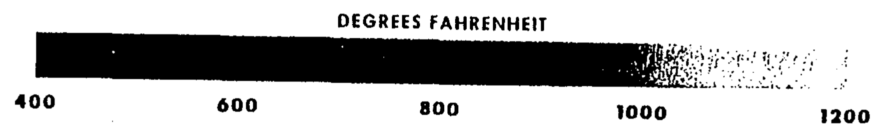
SR-71 SURFACE TEMPERATURES

- *CRUISE CONDITIONS*
- *MAX. ENG. TEMP.*

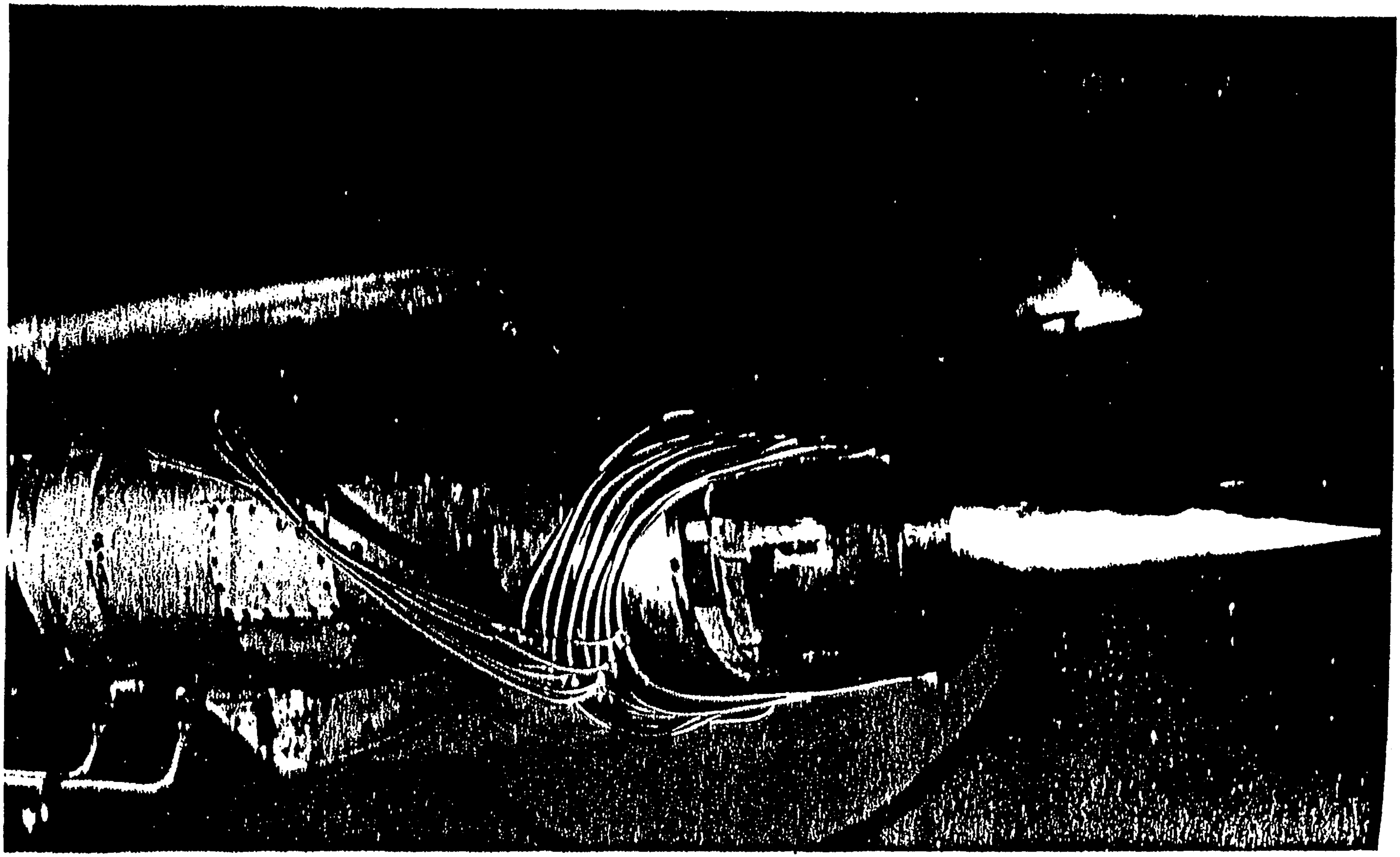




NOTE
L DENOTES LOWER SURFACES

789-33B

CONTROL TEST



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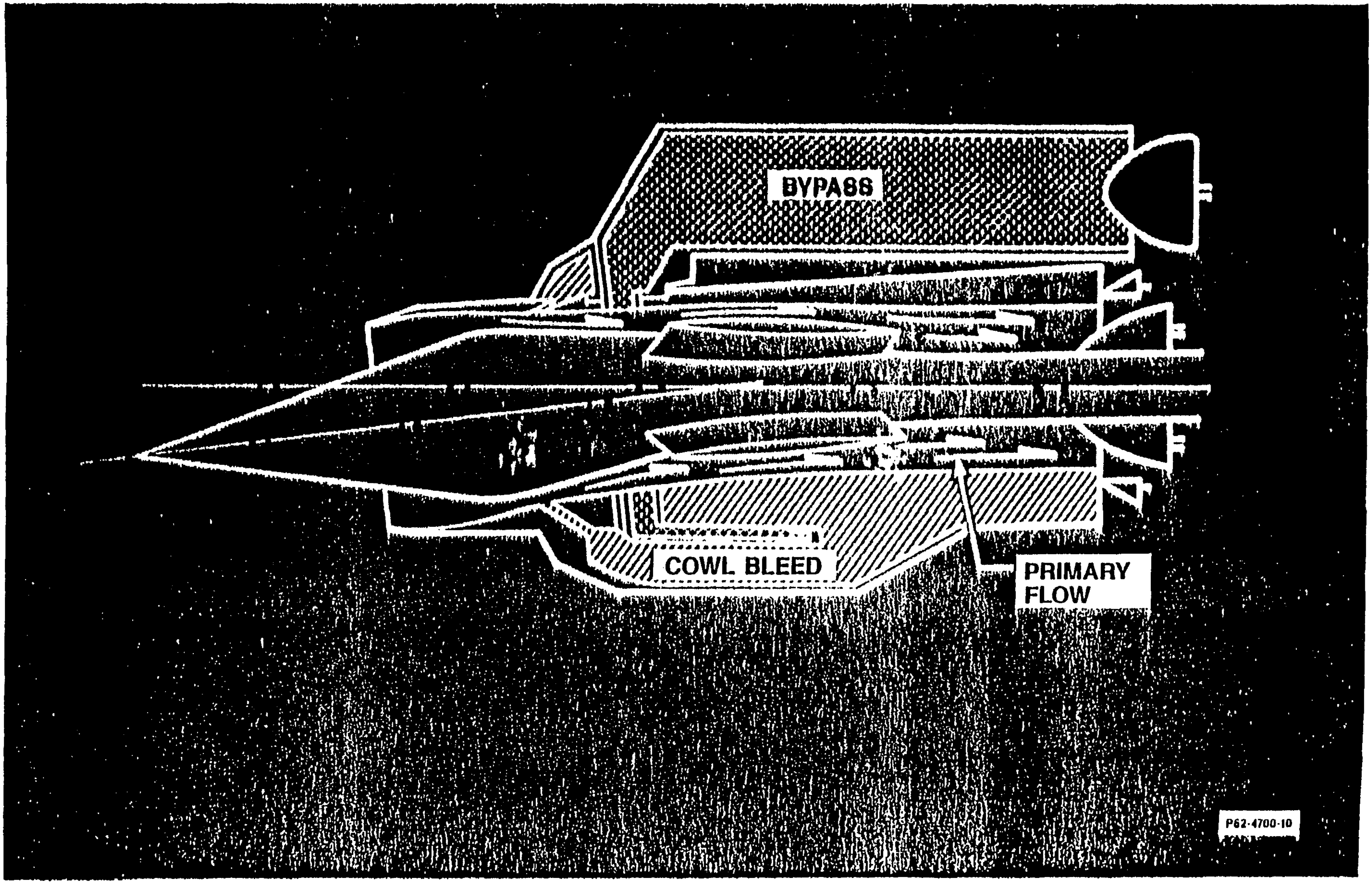
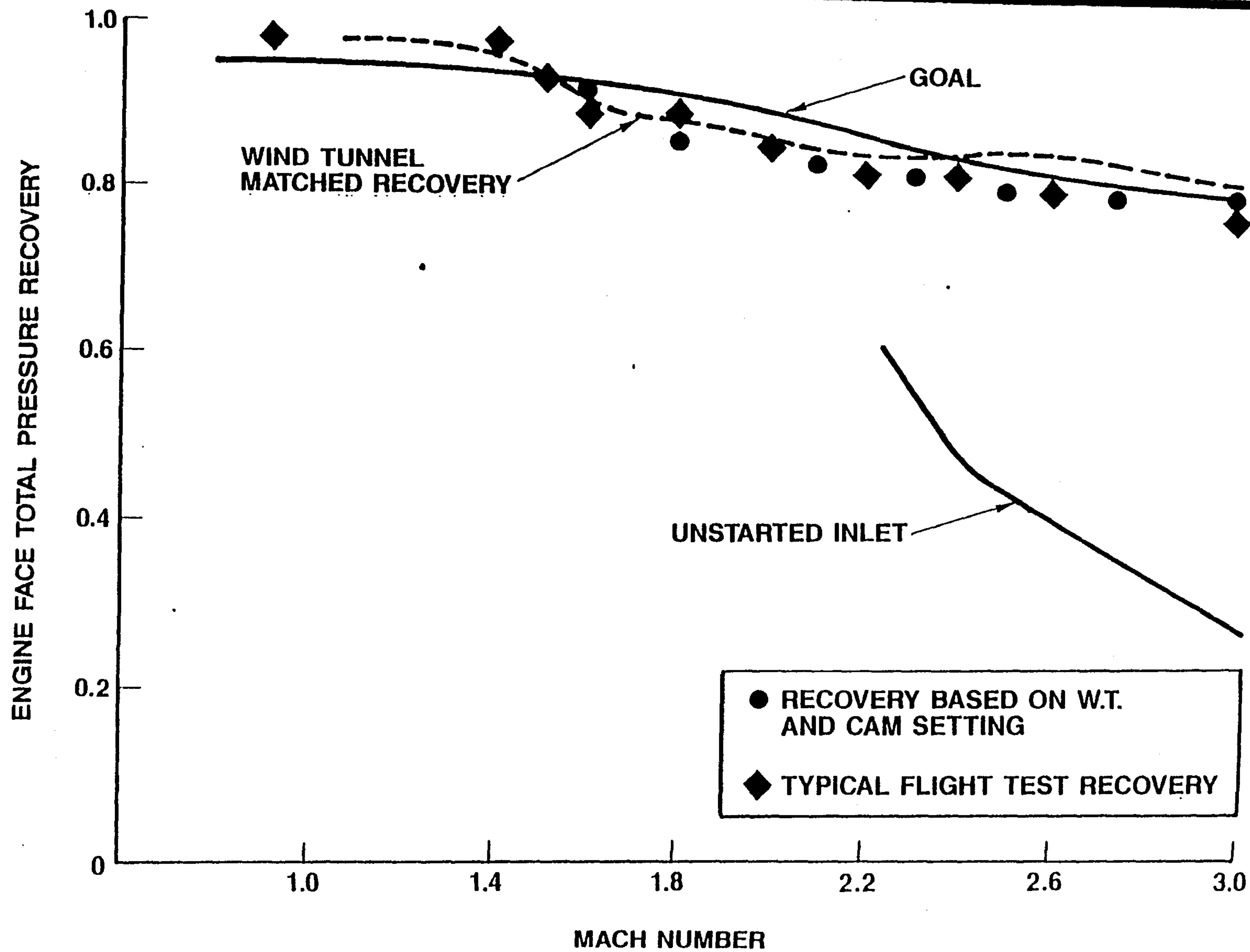
INLET CONTROL MODEL SCHEMATIC



COMPARISON OF WIND TUNNEL AND FLIGHT TEST RESULTS



PROBLEMS ENCOUNTERED DURING FLIGHT TEST PROGRAM

PROBLEM	SOLUTION
• INLET ROUGHNESS	• MICE
• NACELLE LEAKAGE	• MODEL TESTS • IMPROVED SEALING TECHNIQUES
• INLET UNSTARTS	• MODIFY INLET CONTROL PRESSURE SCHEDULES • MODIFY INLET SPIKE TRANSLATION SCHEDULE • IMPROVE RELIABILITY OF INLET CONTROL SYSTEM

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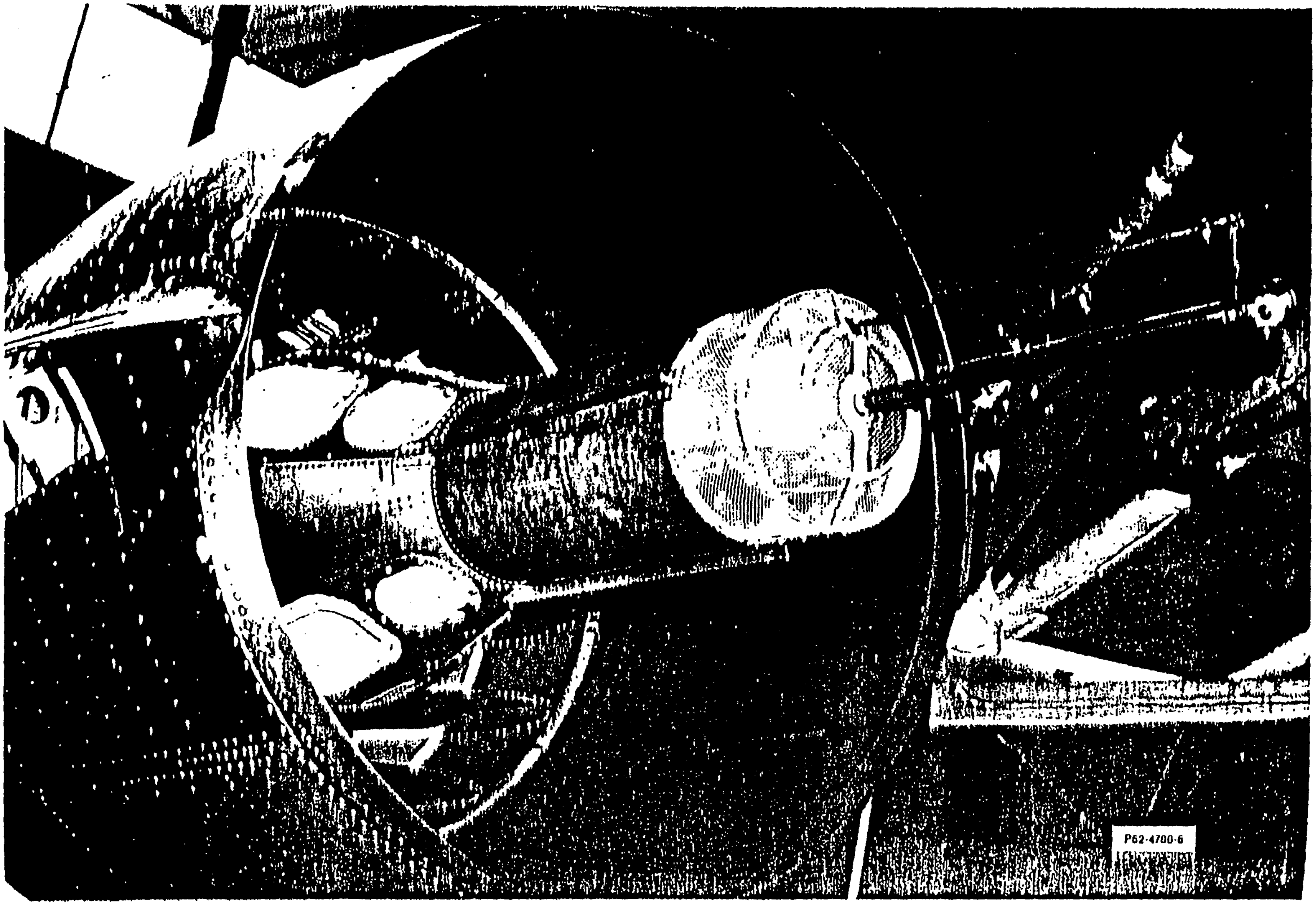
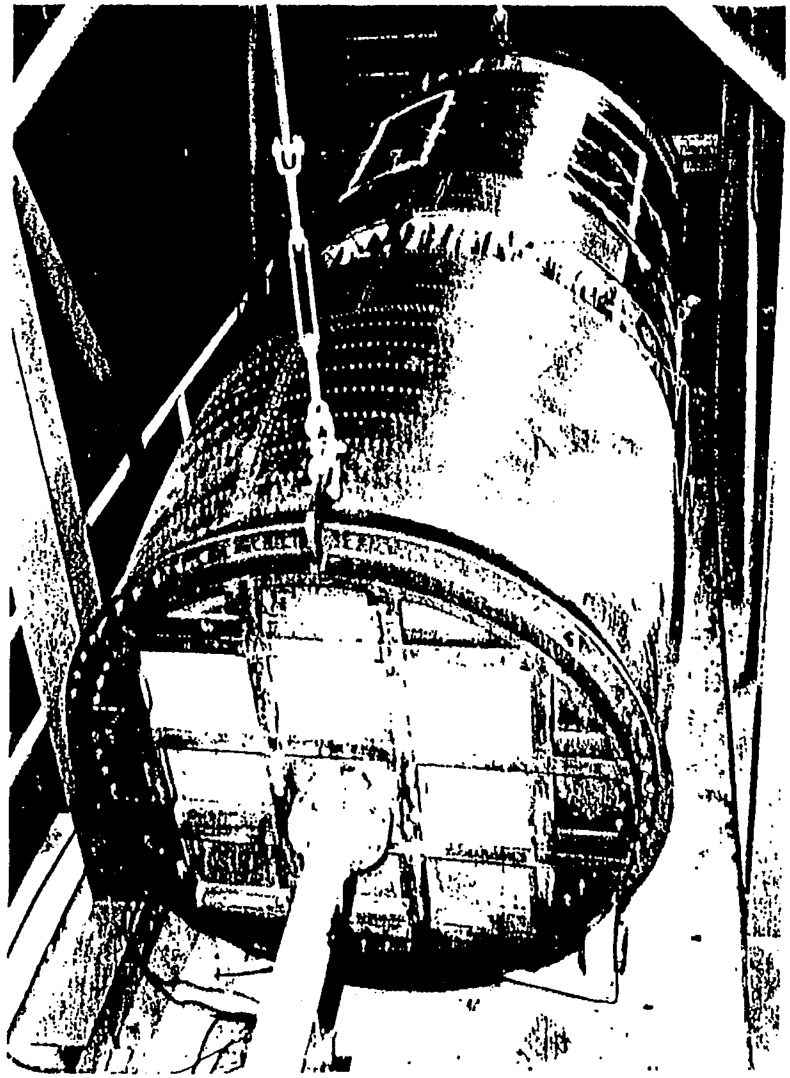
INLET MICE



NACELLE LEAKAGE TEST FIXTURE



ENGINE EXHAUST SYSTEM

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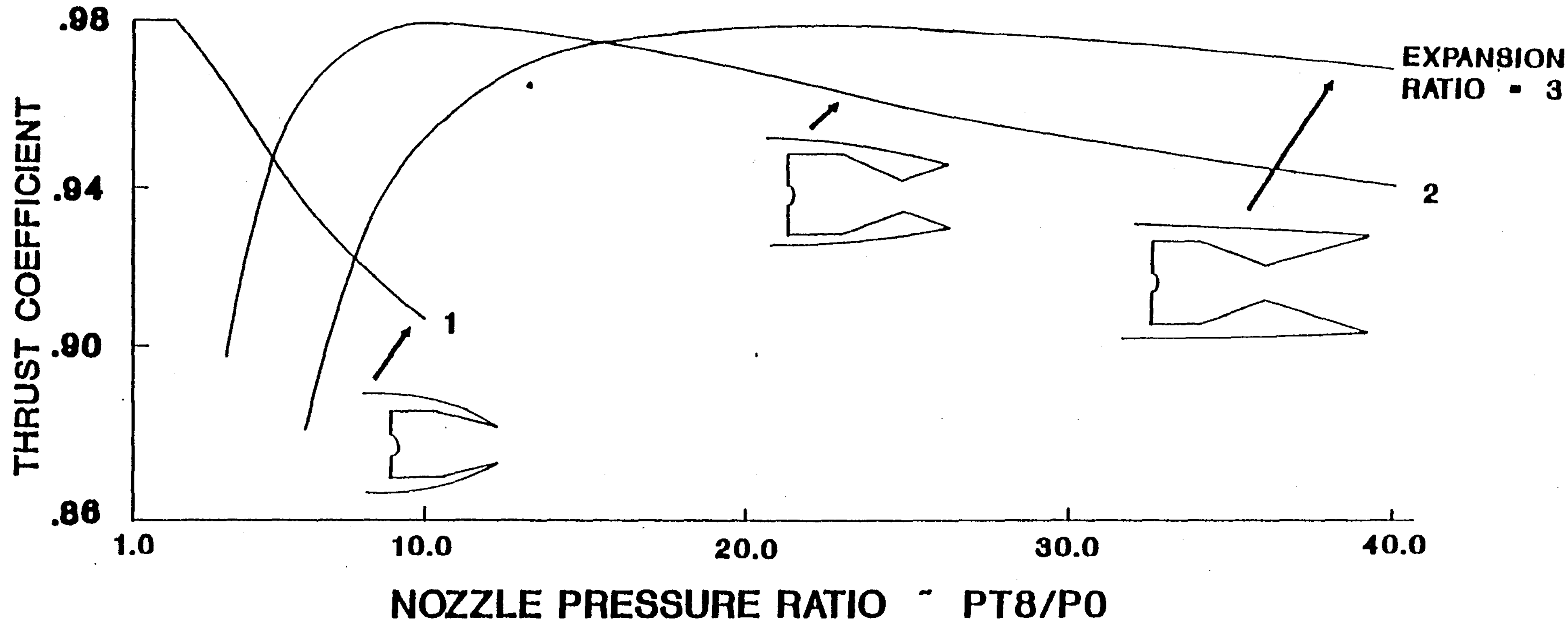
NOZZLE THRUST COEFFICIENT



$$\text{THRUST COEFFICIENT} = \frac{\text{ACTUAL GROSS THRUST}}{\text{IDEAL THRUST (FULLY EXPANDED)}} = \frac{\text{m Vexit} + \text{(Pexit-PO) Aexit}}{\text{m Videal}}$$

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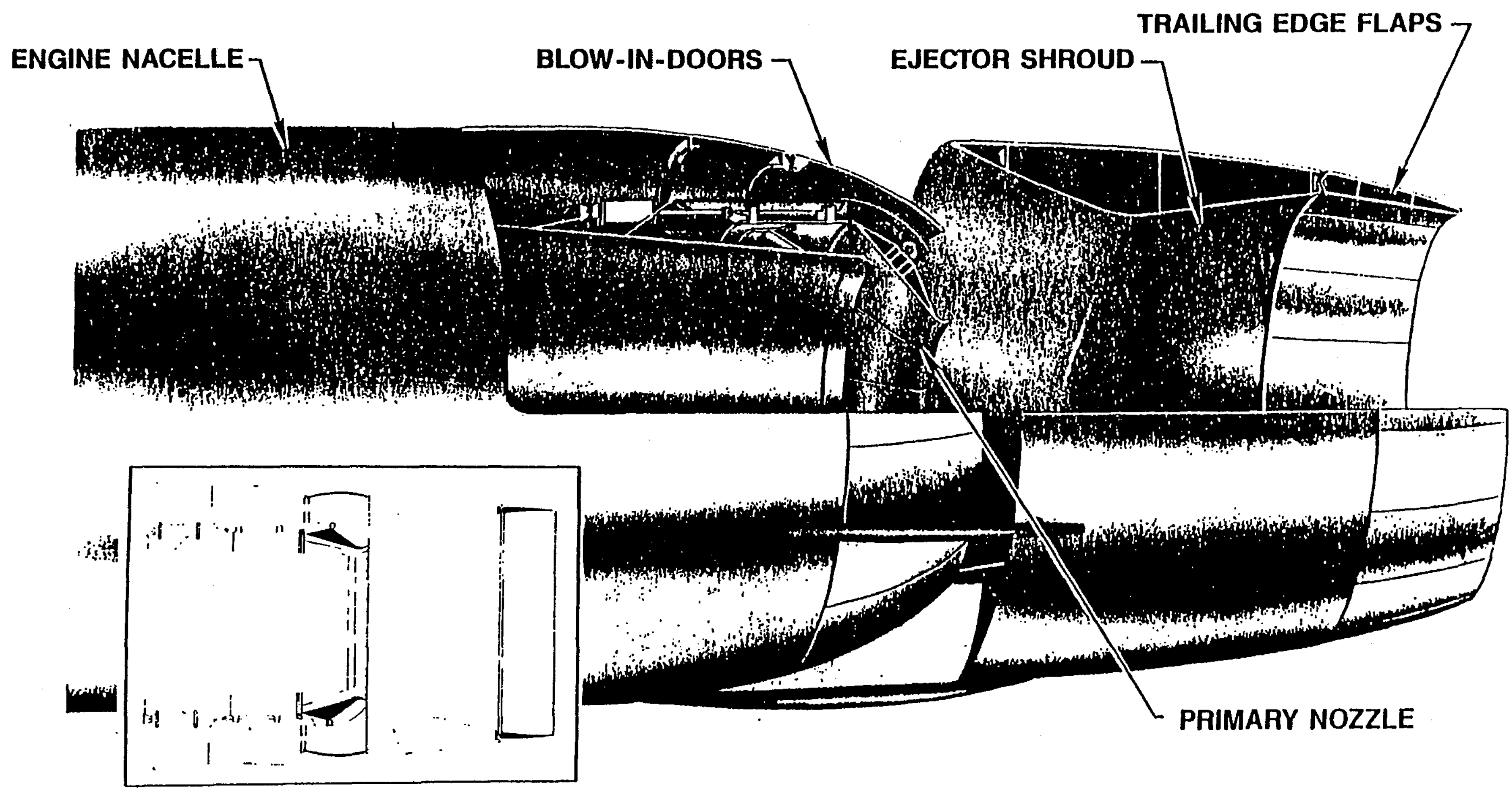
PRATT AND WHITNEY
BLOW-IN-DOOR EJECTOR NOZZLE



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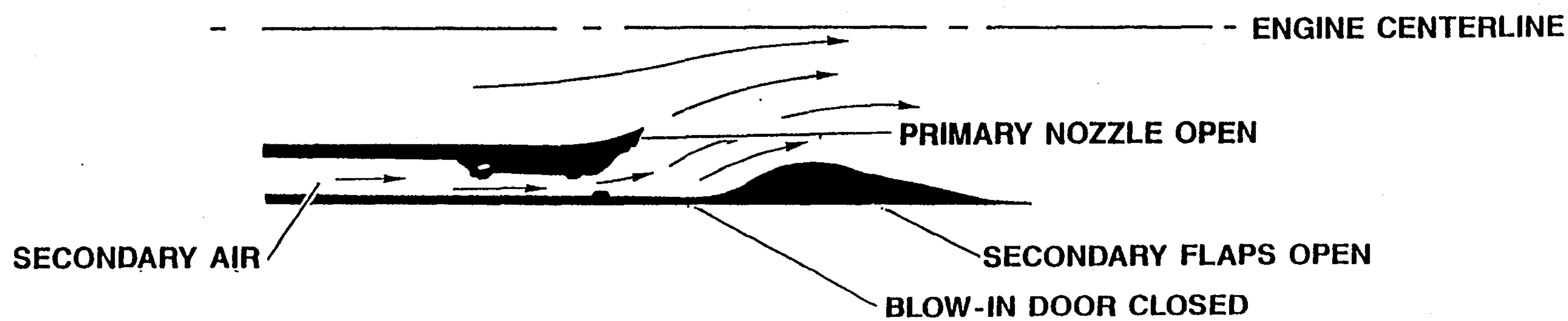
OPERATION OF THE BLOW-IN-DOOR EXHAUST AT HIGH SPEED



HIGH SPEED, AFTERBURNING

G1-4682-13

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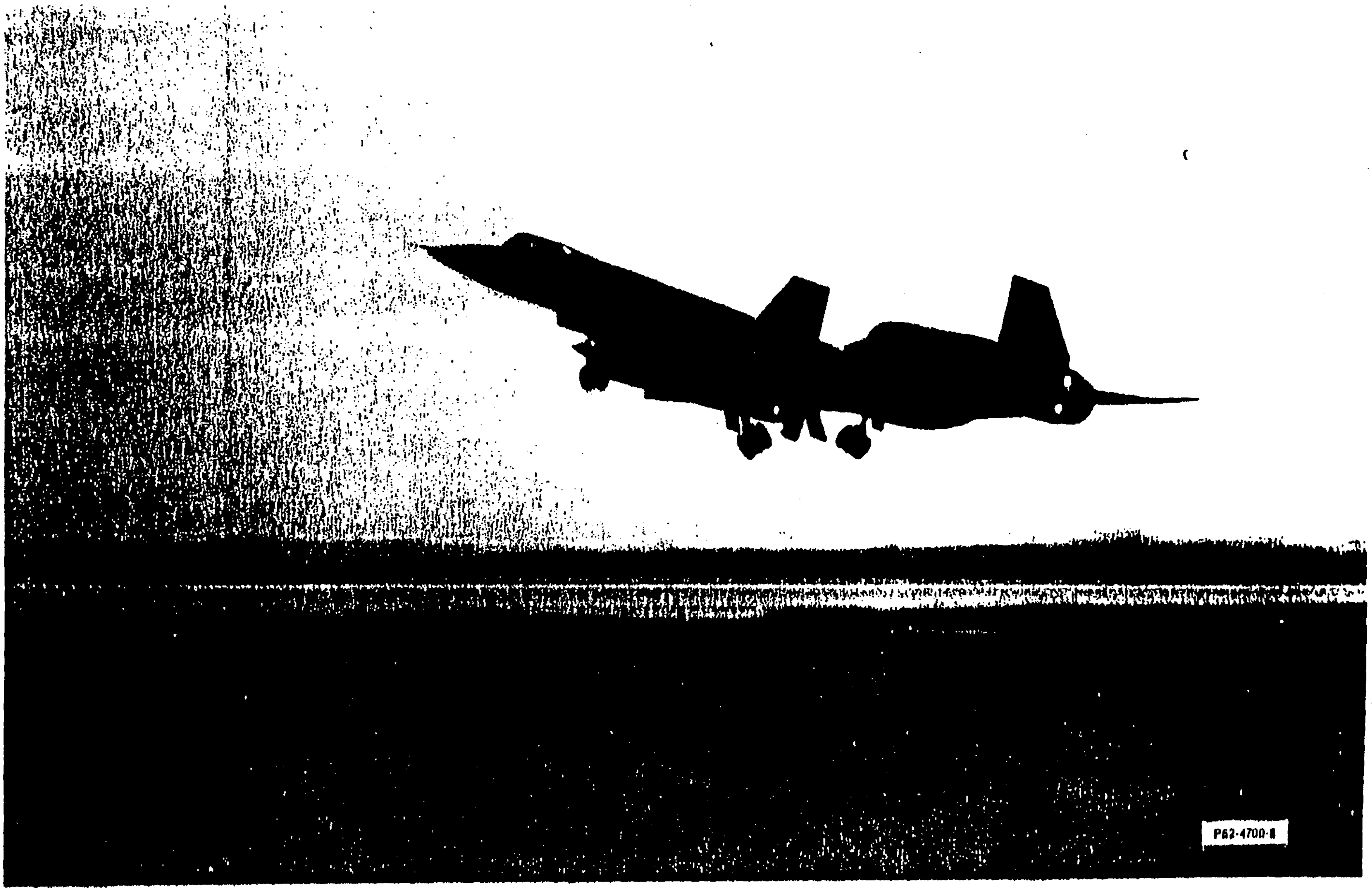
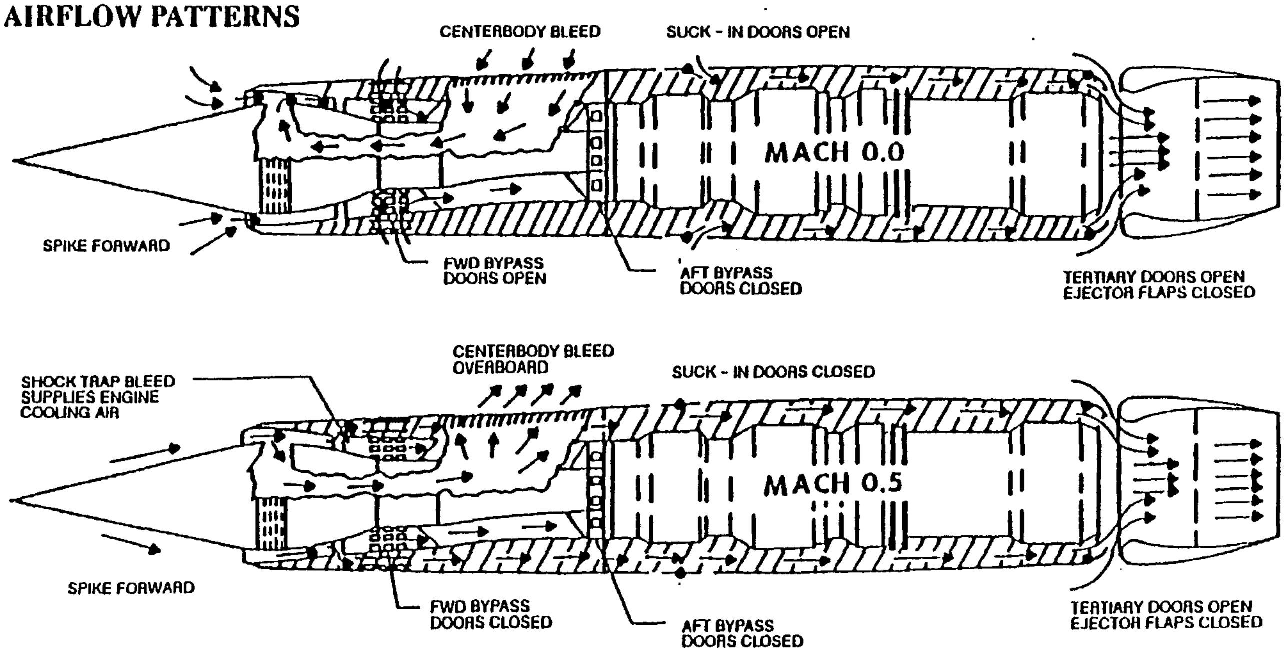
BLOW-IN DOORS OPEN AT LOW SPEED FOR REDUCED AFT NACELLE DRAG



SR-71 INLET/EXHAUST
SUBSONIC FLIGHT

AIRFLOW PATTERNS



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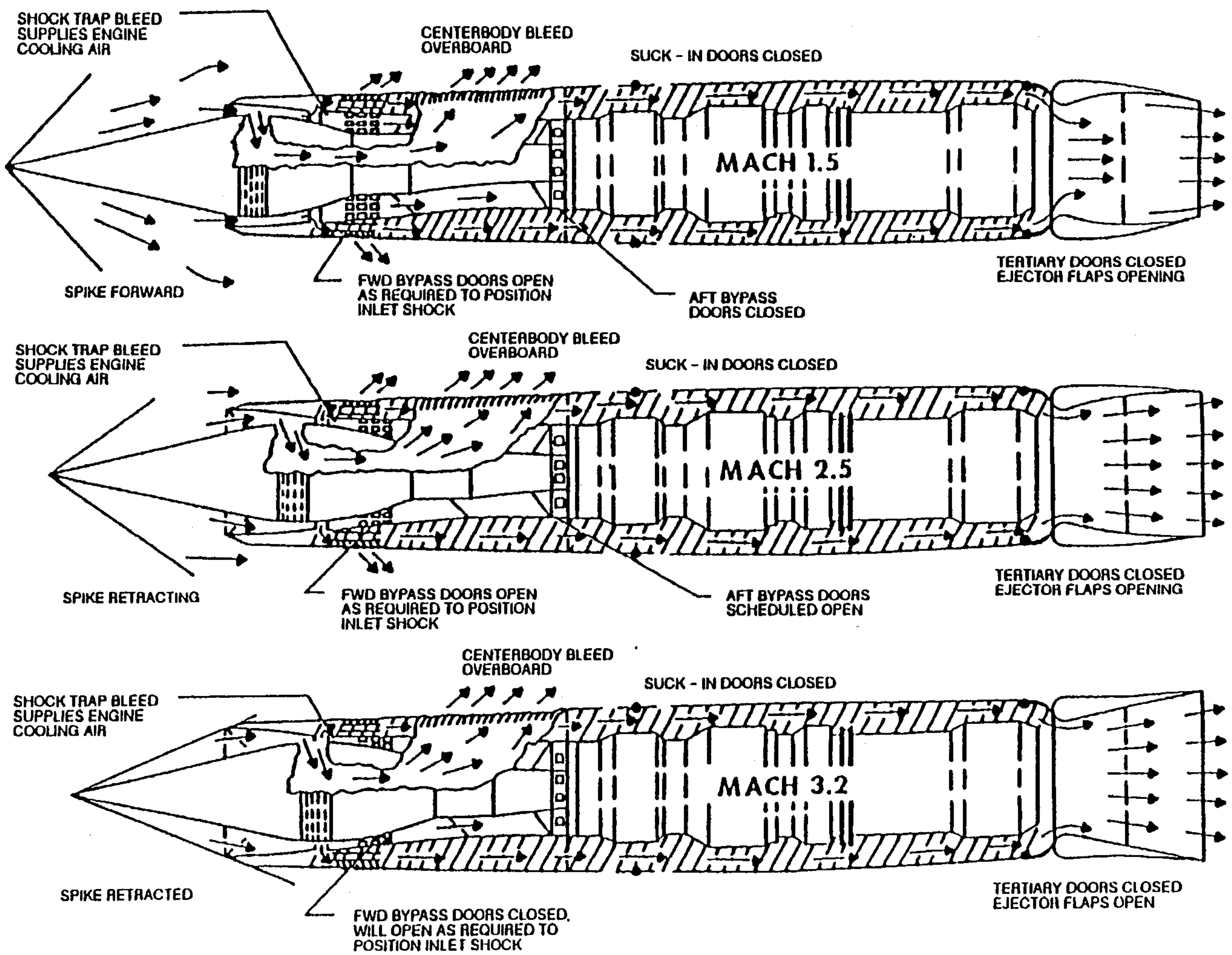
SR-71 INLE1, _XHAUST
SUPERSONIC FLIGHT



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EXHAUST WIND TUNNEL MODEL TEST OBJECTIVES

- **TEST ISOLATED EXHAUST MODEL CONFIGURATION TO**
  - — MAXIMIZE THRUST MINUS DRAG
  - — DETERMINE EJECTOR PUMPING CHARACTERISTICS
- **TEST EXHAUST SYSTEM MODEL WITH FIN AND WING TO**
  - — DETERMINE JET INTERFERENCE EFFECTS
  - — MEASURE INSTALLED THRUST MINUS DRAG

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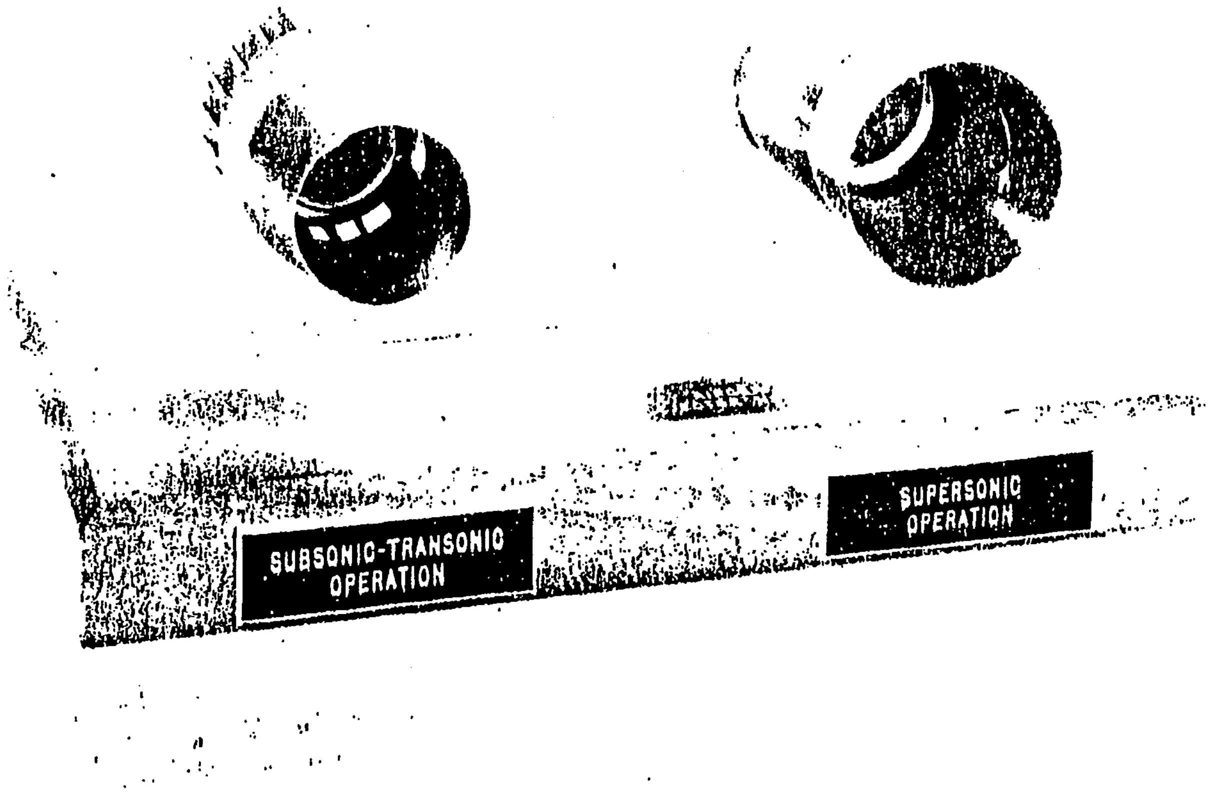
TYPICAL EXHAUST MODELS TESTED BY PRATT AND WHITNEY



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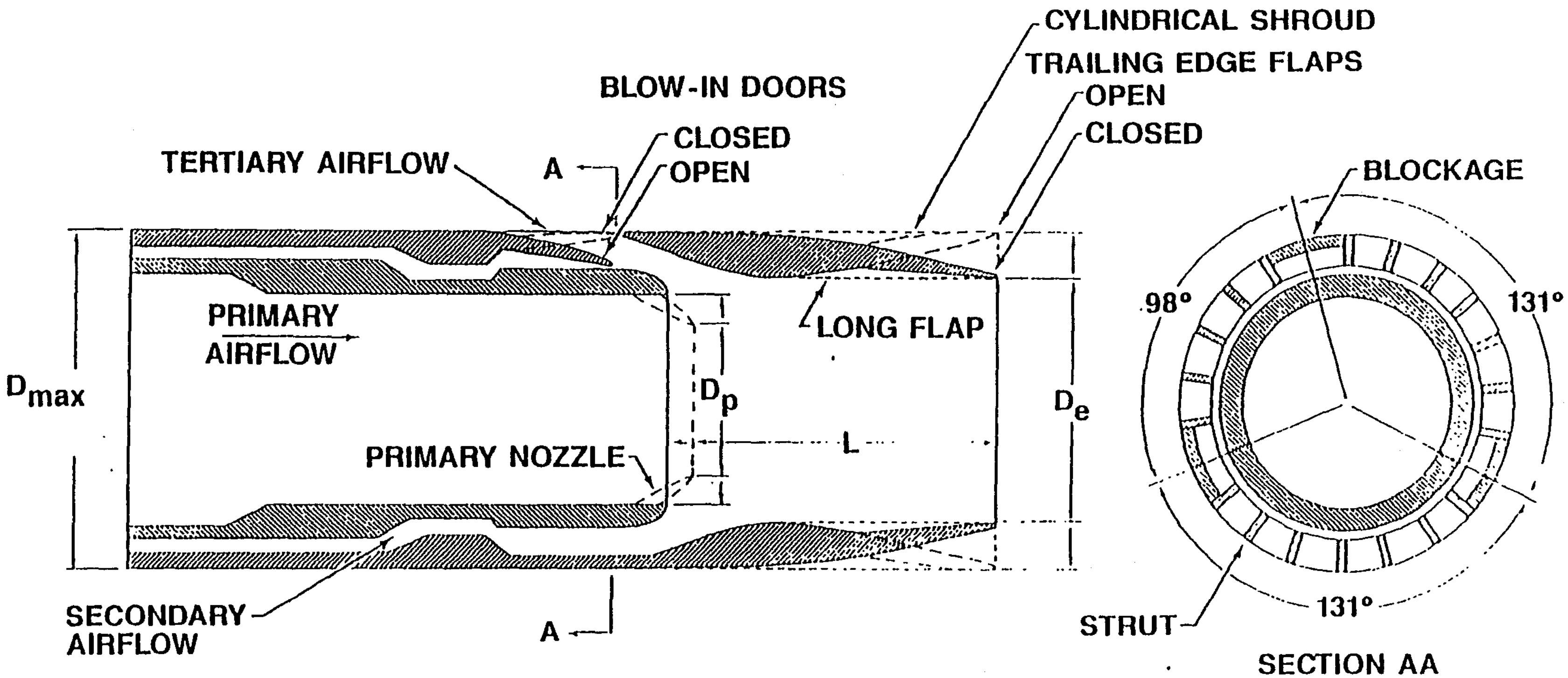
TYPICAL EXHAUST MODEL VARIATIONS



MODEL SPACING RATIOS

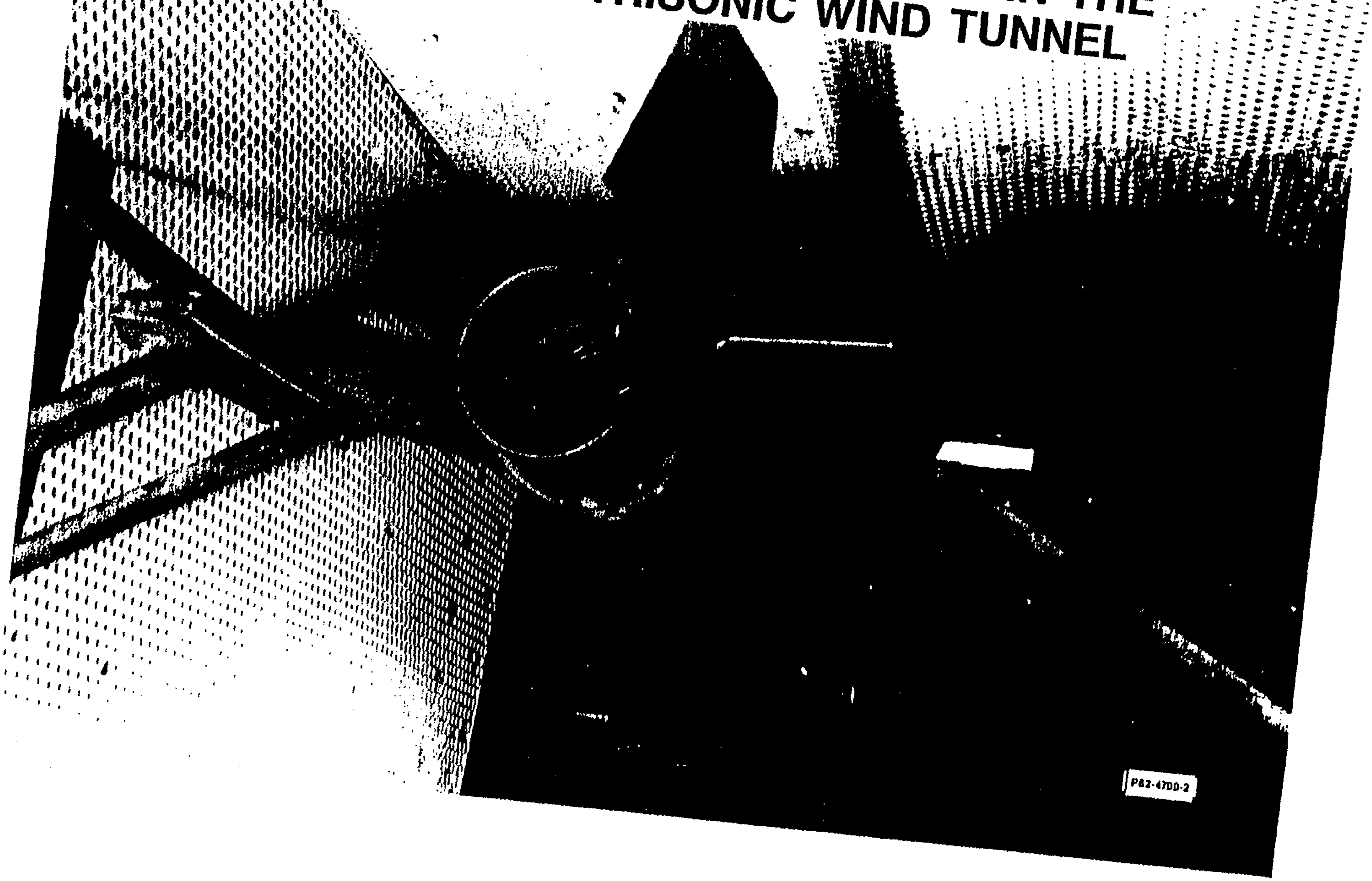
L/D_p
2.320
1.873
1.683
1.648

MODEL EXIT DIAMETERS

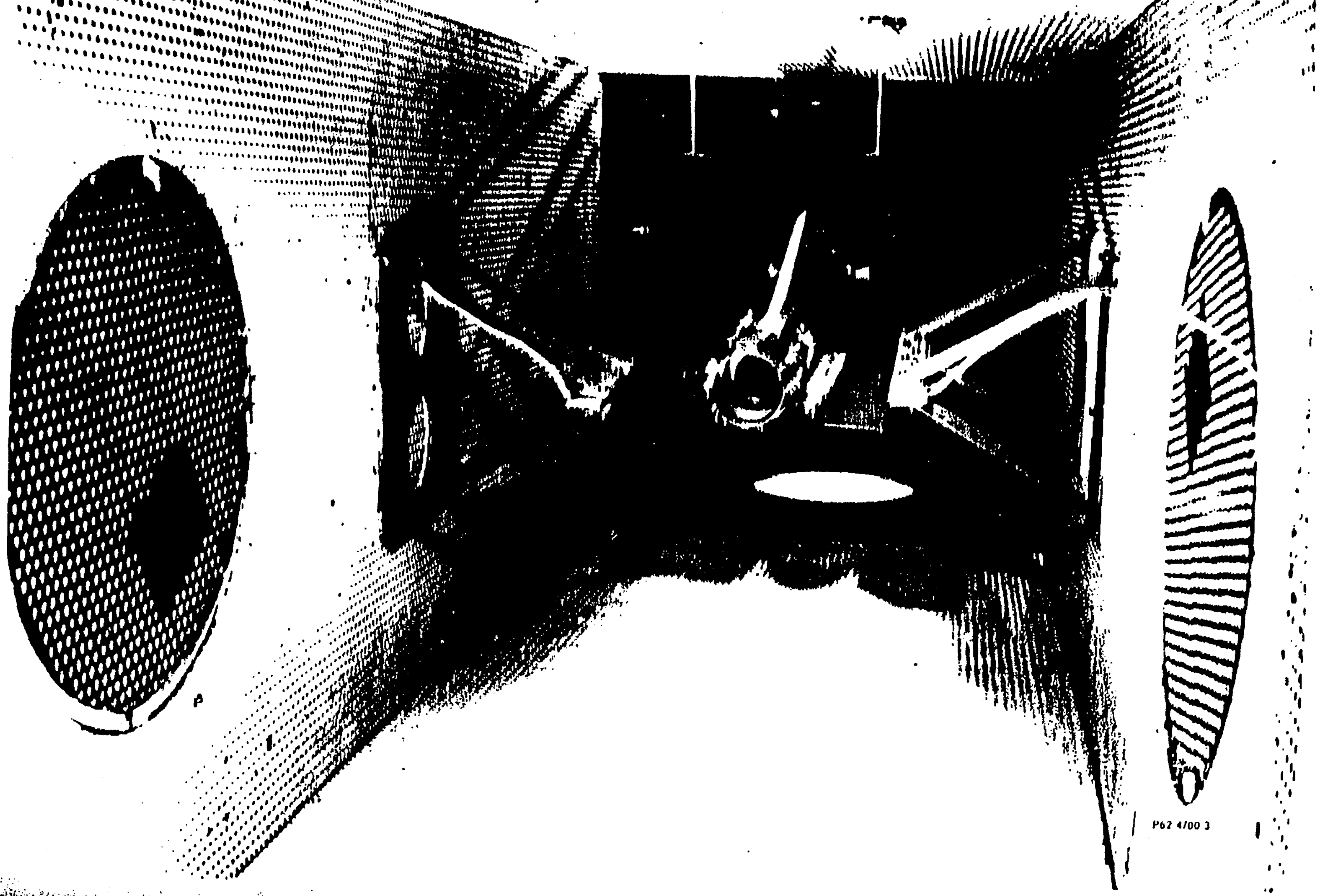
D_e - IN
1.4980
1.6130
1.8340
1.9650

G1-4682-15

INTEGRATED EXHAUST MODEL IN THE LOCKHEED TRISONIC WIND TUNNEL



FLOW VISUALIZATION WITH TUFTS



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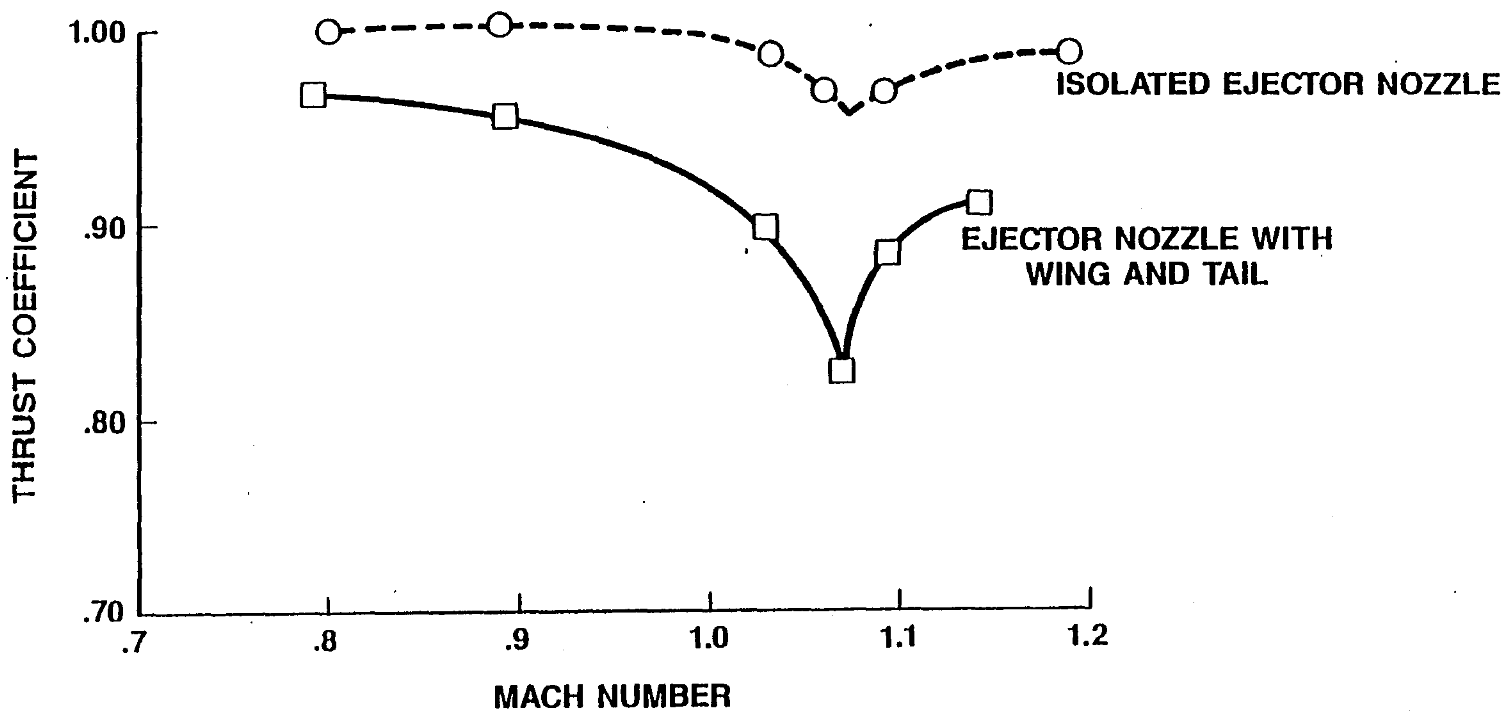
TYPICAL TEST RESULTS SHOWING ADVERSE INTERFERENCE EFFECTS



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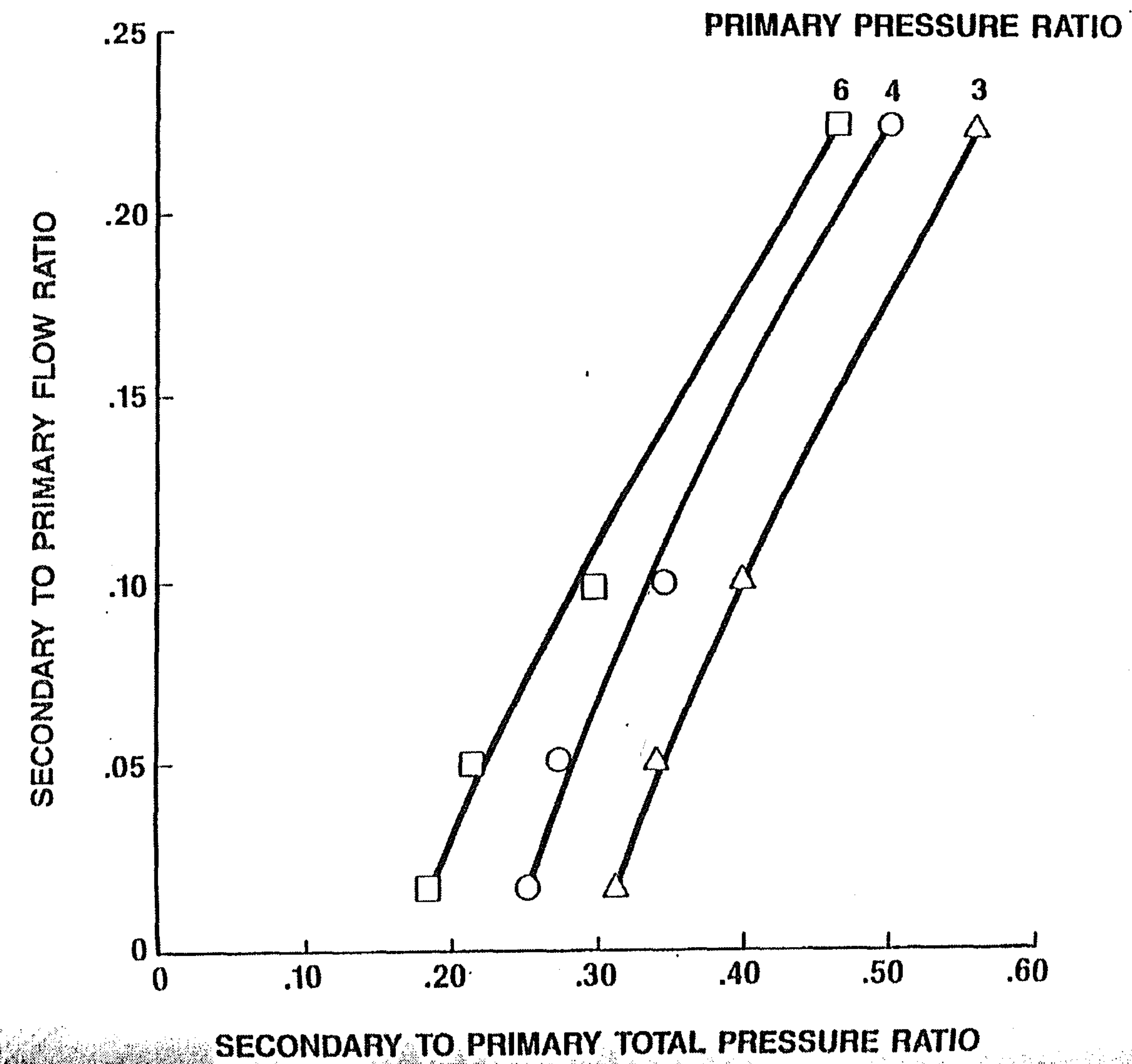
MODEL TESTS DEFINE EJECTOR PUMPING CHARACTERISTICS



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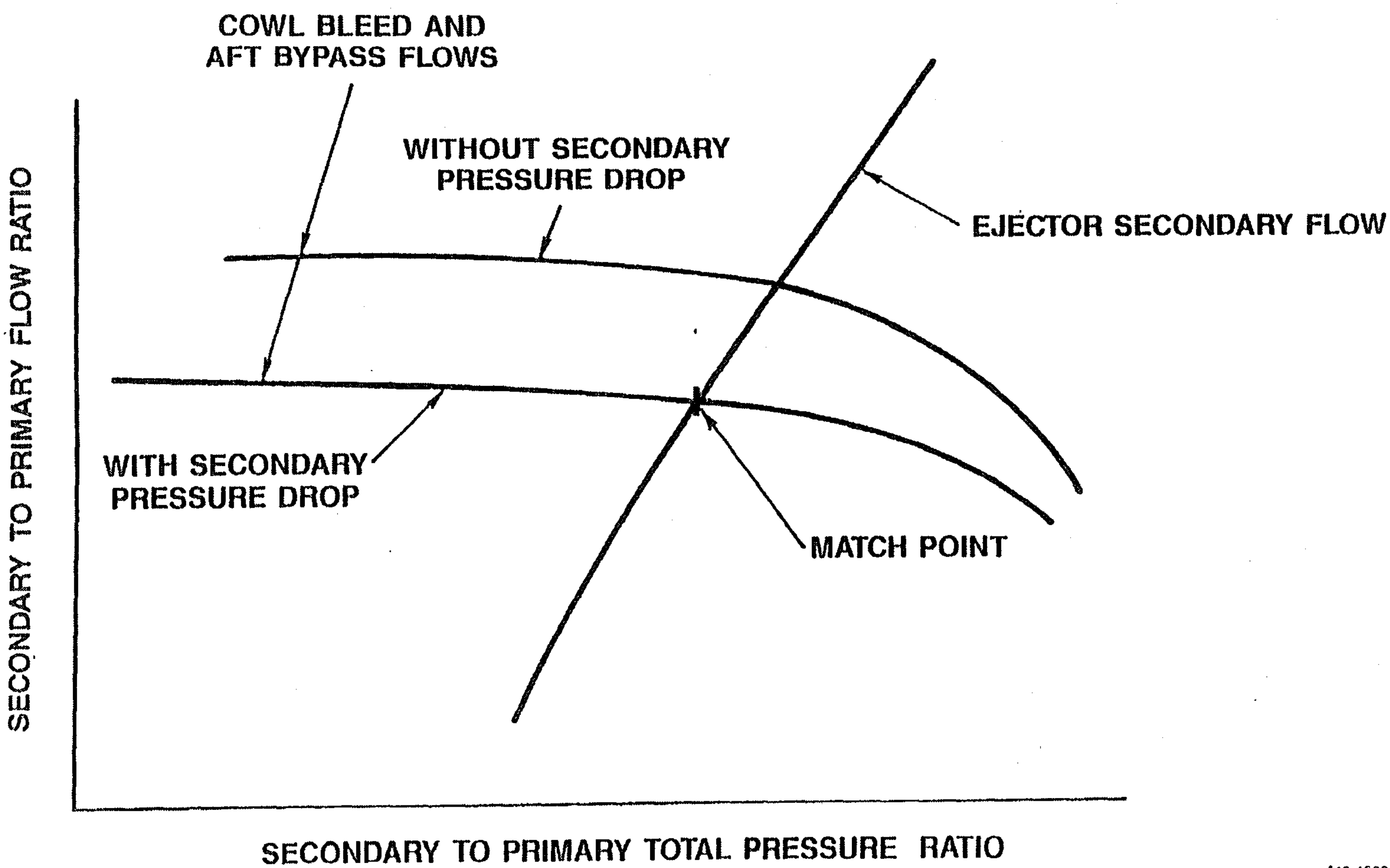
MATCHING INLET AND EXHAUST SECONDARY FLOWS



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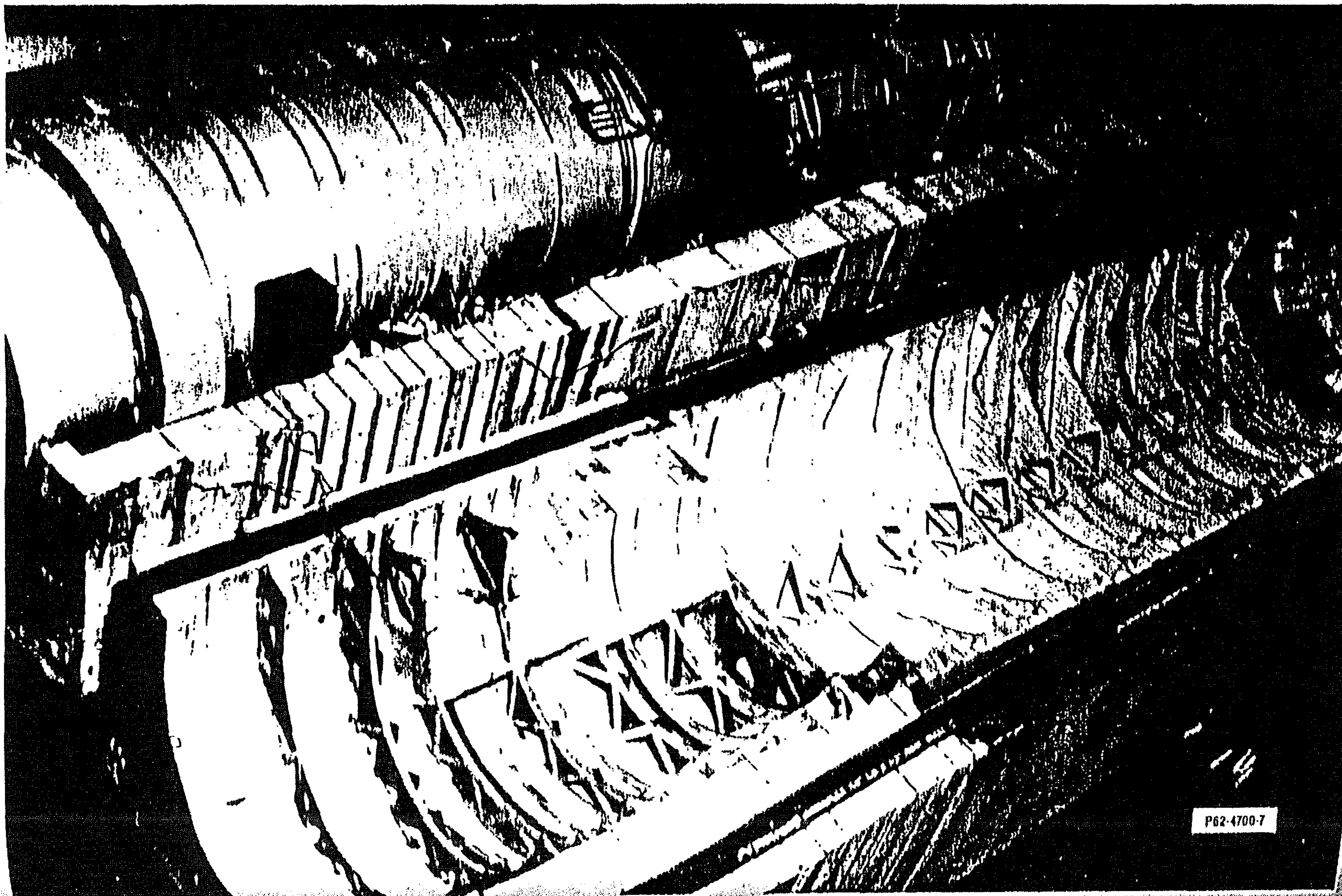
SECONDARY PRESSURE DROP MODEL



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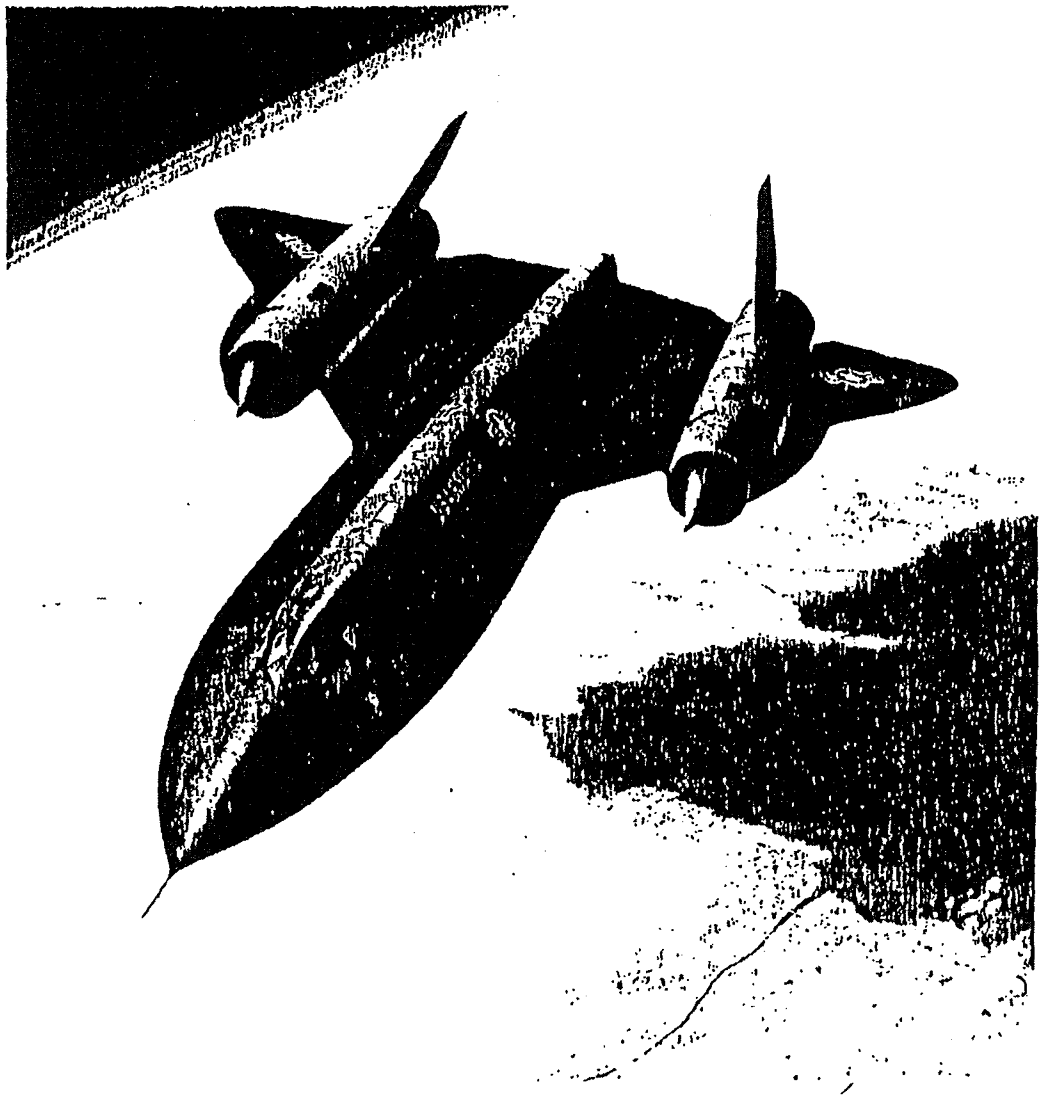
INLET AND EXHAUST CONFIGURATION AT DESIGN MACH NUMBER



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JT11D-20 ENGINE - A SUCCESSFUL LEAP INTO THE TECHNICAL UNKNOWN

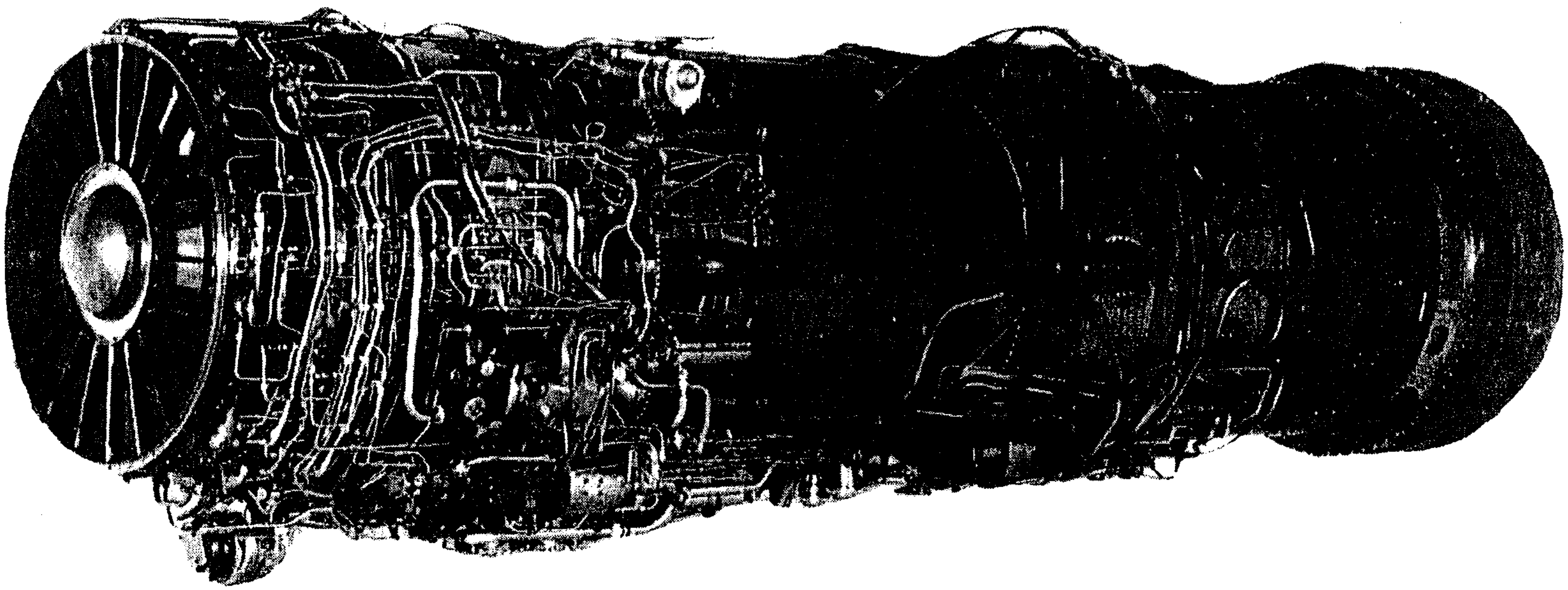

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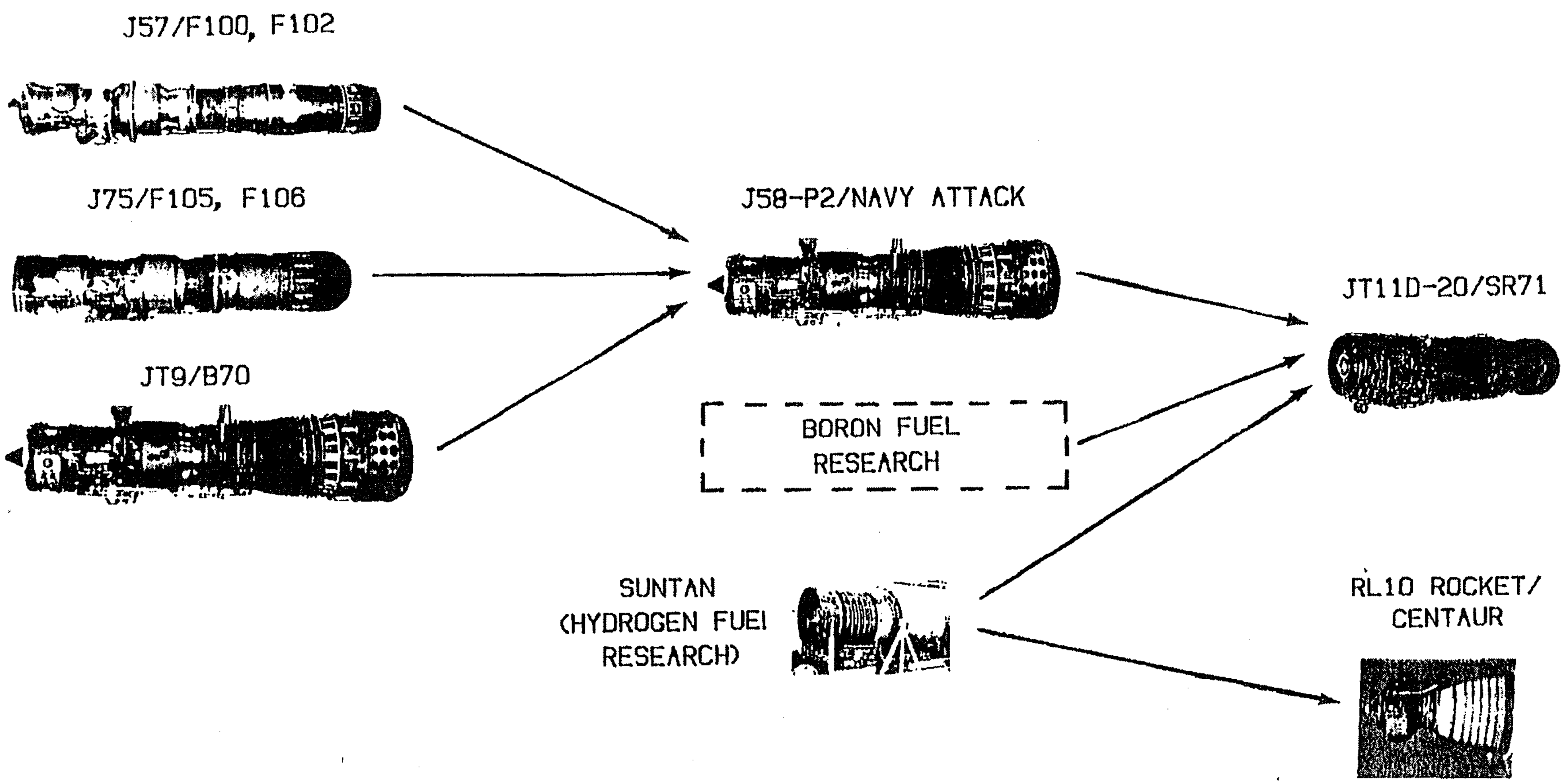
FIGURE 1

BACKGROUND EXPERIENCE



EXPERIENCE AND TECHNOLOGY IS ALWAYS UTILIZED

JT11D-20 ENGINE - A SUCCESSFUL LEAP INTO THE TECHNICAL UNKNOWN

1. BACKGROUND

The JT11D-20/SR-71 program followed the earlier programs shown in figure 1. Some of these programs had seemingly similar elements of technology such as flying at Mach 3.

The first P&W engine designed for Mach 3 operation was the JT9. It was a single spool 8 to 1 pressure ratio engine having a total airflow of approximately 400 pps airflow. It was P&W's offering for the original B-70 airplane. The original J58 was scaled from this engine at a scale of approximately 80%.

The centerline of the basic J58 engine was laid down in late 1956. It was an afterburning turbojet rated at 26,000 lb maximum takeoff thrust and was to power a Navy attack aircraft which would have a dash capability of up to Mach 3 for several seconds. By the time Pratt & Whitney, along with Lockheed and others, began to study the SR-71 "Blackbird" requirements several years later, we had completed approximately 700 hours of full-scale engine testing on the J58.

A second related program was a high energy fueled engine. This consisted of substituting a Boron based fuel for normal Hydro-Carbon fuel to take advantage of the higher density heating value and therefore be able to fly longer on a given fuel volume. This program was terminated relatively early due to (among others) the inability to prevent solids from forming in the fuel system and the inability to assure absence of toxic vapors in the exhaust.

Another program that preceded the JT11D-20 was "Project Suntan". This engine shown in (Figure 2) and schematically in (Figure 3) was a Hydrogen fueled engine that was to power an aircraft that would cruise long distances at Mach 2.7. This program was ultimately terminated (in 1958) when it was decided that the airplane could not perform the intended mission. The technology gained in this program was used in the P&W RL10 hydrogen fueled rocket engine which has been used to launch most of our communication satellites and is the most reliable rocket engine in use today with 174 engines launched without failure.

P&W design approach to the JT11D-20 engine in addition to the programs mentioned earlier was based on the experience accumulated in the successful J-57 and J-75 military programs and their commercial counterparts the JT-3 and JT-4. The J-57 powered the F-100 and F-102 airplanes which were the first supersonic USAF fighters. The J-75 powered the F-105 and F-106 Mach 2 class fighters which meant that on a good day a speed of Mach 2 could be achieved. The J-75 was rated at Mach 2, 55,000 feet for 15 minutes only.

This background existed at P&W when the JT11D-20 design was initiated. Therefore, we knew enough to know we did not know how to design and manufacture an engine that would operate continuously at speeds over Mach 3.

Although minimal, the above-described programs provided some benefits. For instance, the J58-P2 prototype engine revealed that a straight

FIGURE 2

PROJECT SUNTAN HYDROGEN FUELED ENGINE

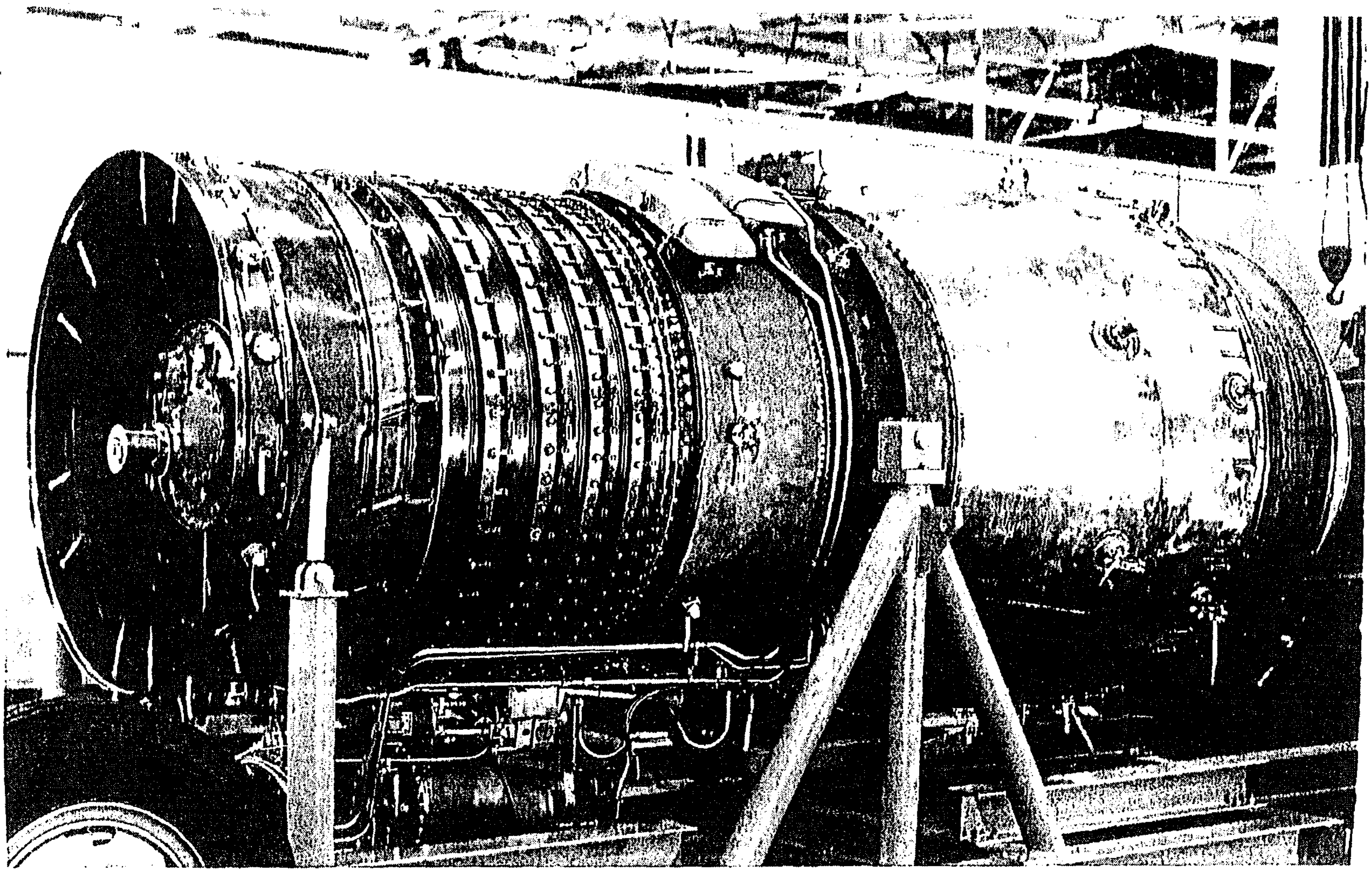


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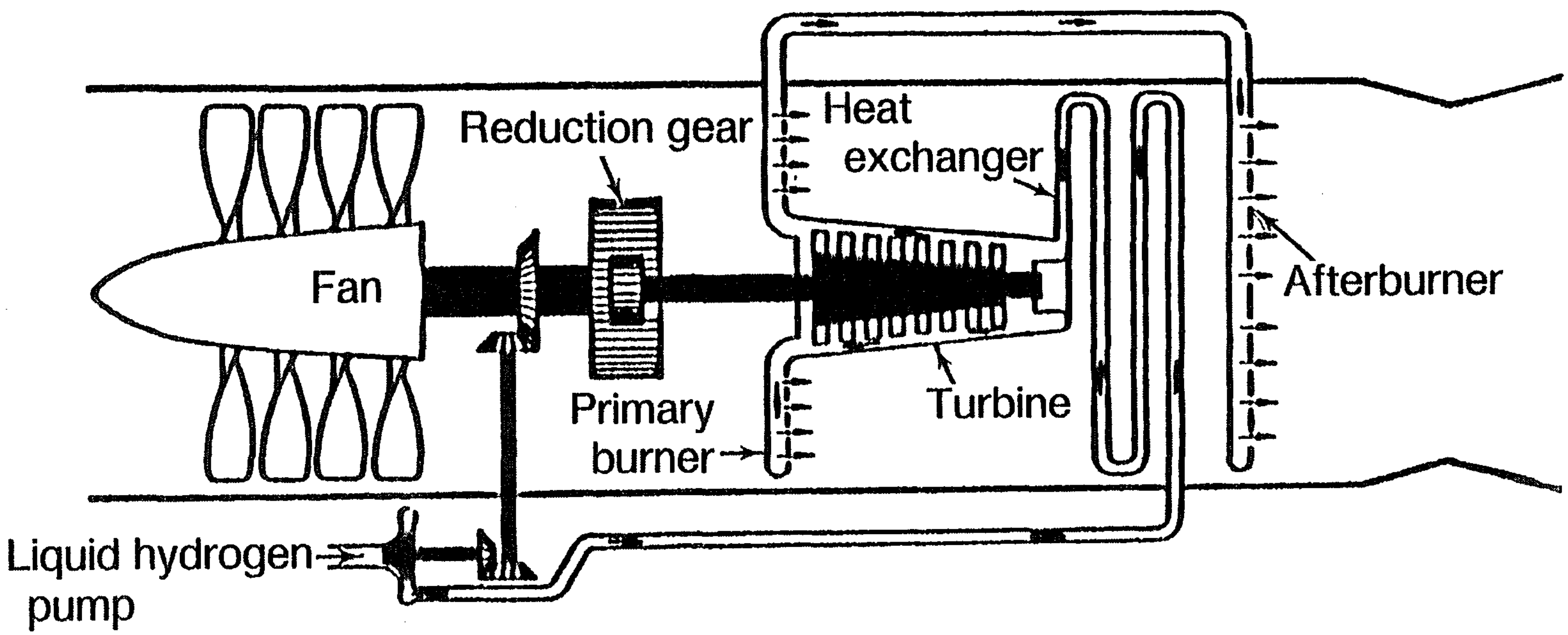
FIGURE

P&W FOLLOWED AIR FORCE AND NACA INTEREST IN HYDROGEN DURING 1955 - WON PROPOSAL TO SUPPLY ENGINE

SUNTAN



Schematic of Pratt & Whitney's model 304 engine designed to use liquid hydrogen as fuel, 1956

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-3-

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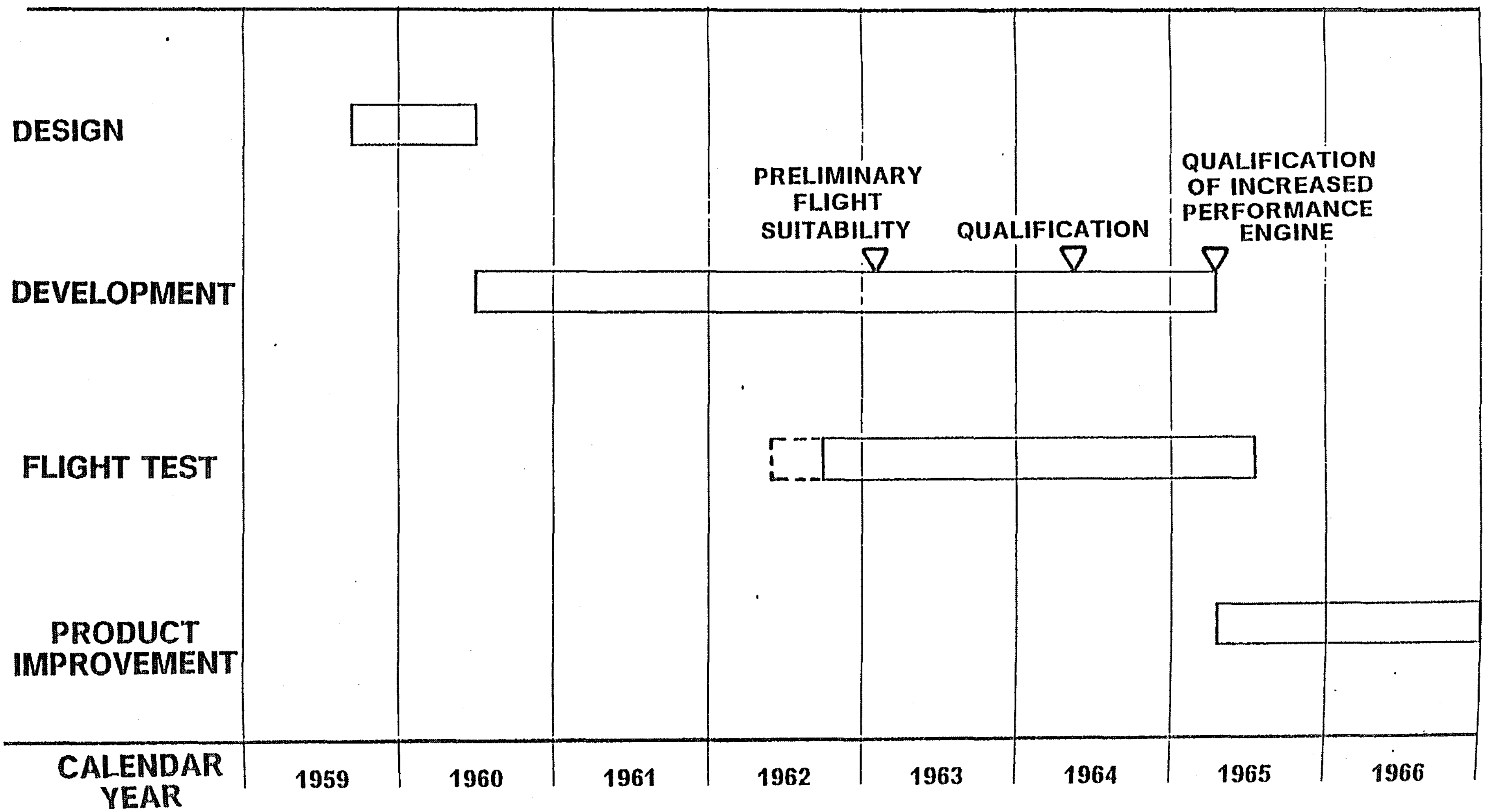
FIGURE 4

JT11D-20 SCHEDULE



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turbojet operating at the J57 and J75 turbine temperatures would not provide enough thrust to meet mission requirements. It also revealed some of the problems we faced in overcoming the thermal environment at cruise speeds.

Because of these extremely hostile environmental conditions, the only design parameters that could be retained from the Navy J58-P2 engine were the basic airflow size and the compressor and turbine aerodynamics. Even these were modified at a later date.

Key milestones in JT11D-20 engine development are shown in Figure 4. First flight was only 3 years and 1 month after the start of design. Even though design was started 30 years ago the aircraft still holds world altitude and speed records! This paper covers design, manufacturing, development and flight tests.

2. DESIGN REQUIREMENTS

Figure 5 shows the increased requirements of the "Blackbird" engine compared to the requirements for the previous J75 engine. As it turned out, even these requirements didn't hold throughout the "Blackbird's" actual mission. For example, the engine inlet air temperature exceeded 800°F under certain conditions. The fuel inlet temperature was normally below 300°F but increased to 350°F during transients. The fuel temperature at the main and afterburner fuel nozzles ranged from 600°F to 700°F. Lubricant temperatures rose to 700°F and even to 1000°F in some localized parts of the engine.

The magnitude of the problem begins to be understood when such things as continuous afterburning is compared to intermittent which means hours instead of minutes and that continuous turbine inlet temperatures greater than the melt temperature of the state-of-the-art materials was required.

As a result of stretched design criteria the engine design required inventions. Key innovations are shown in Figure 6. Increased Mach number and the associated larger corrected airflow turn-down ratio led to a variable cycle engine: the bleed bypass engine. The external/internal compression inlet used for high inlet recovery at high speed requires engine airflow control, inlet/engine airflow matching and a method of discharging inlet bleed air and surplus inlet air that minimizes drag. This resulted in the ejector nozzle. High inlet temperature leads to high turbine temperature requirement and a cooled turbine. High temperatures also required a fuel capable of non-coking operation at over 600°F, engine lubricant that would not break down at temperatures approaching 1000°F, weldable sheet metal made from turbine blade materials, and an engine ignition system that would operate without electrical power.

3. DESIGN TOOLS

It's important to remember that this all started over a quarter of a century ago. Engineers were just graduating from slide rules to digital computers. Although Pratt & Whitney had a very large computer system for it's day (the IBM 710), it was no more sophisticated than some of the hand held calculators now available.

FIGURE 5

DESIGN REQUIREMENTS WERE A LEAP INTO THE UNKNOWN

	PRODUCTION ENGINE EXPERIENCE (J57 and J75)	JT11D-20 DESIGN REQUIREMENTS
MACH NUMBER	2.0 FOR 15 MIN (J75 ONLY)	3+ (CONTINUOUS)
CORRECTED AIRFLOW TURNDOWN RATIO (CRUISE/MAXIMUM)	90%	60%
ALTITUDE	55,000 FT	80,000+ FT
COMPRESSOR INLET TEMPERATURE	-40 °F TO 250 °F (J75 ONLY)	-40 °F TO 800 °F
COMBUSTOR EXIT TEMPERATURE	1750 °F (TAKEOFF) 1550 °F (CONTINUOUS)	2000 °F (CONTINUOUS)
MAXIMUM FUEL INLET TEMPERATURE	110 - 130 °F	350 °F
MAXIMUM LUBRICANT INLET TEMPERATURE	250 °F	550 °F
THRUST/WEIGHT RATIO	4.0	5.2
MILITARY OPERATION	30-MIN TIME LIMIT	CONTINUOUS
AFTERBURNER OPERATION	INTERMITTENT	CONTINUOUS

FIGURE 6

INNOVATIONS ON THE JT11D-20 ENGINE

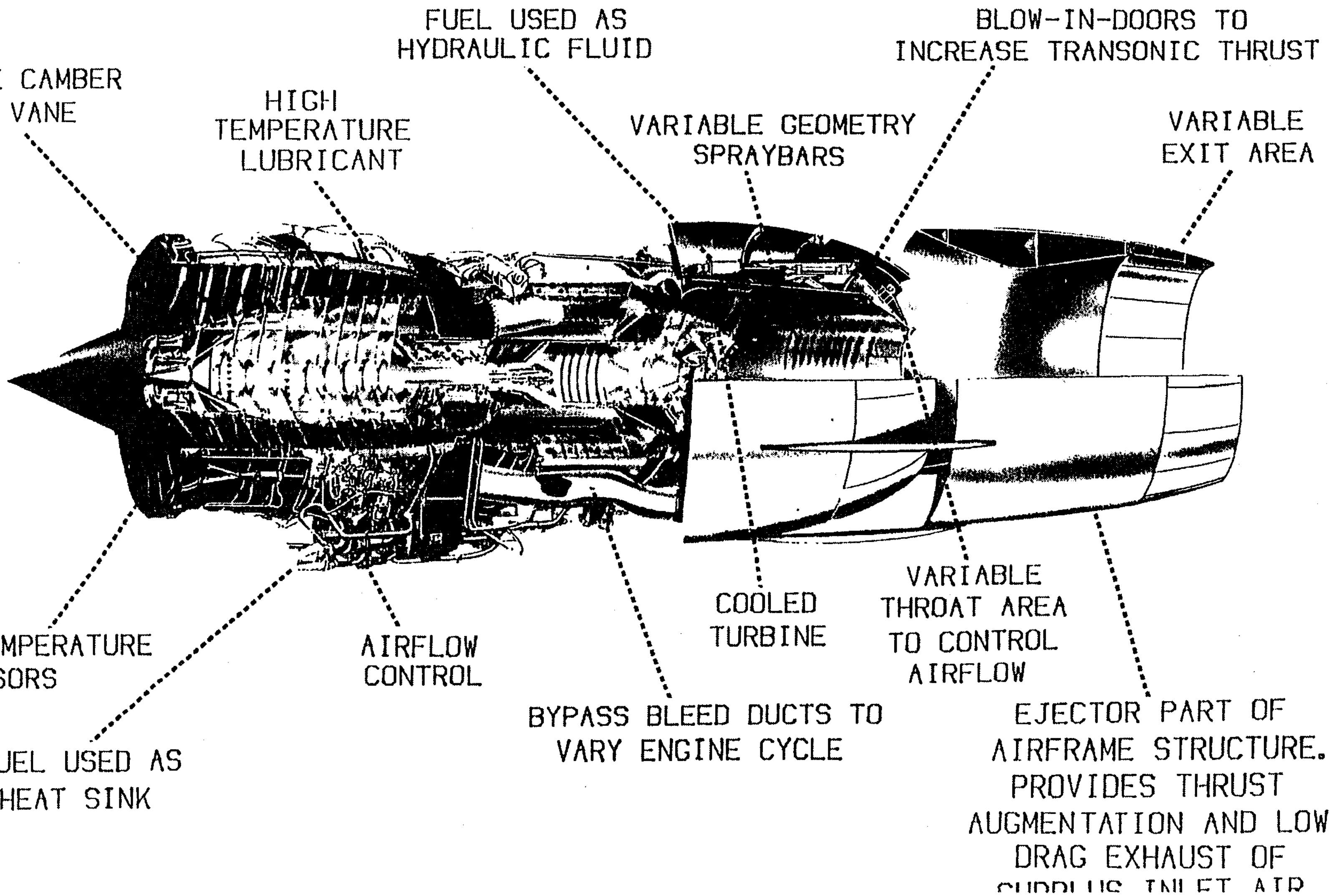


FIGURE .

DESIGN TOOLS PIONEERED IN THE JT11D-20 PROGRAM

- DIGITAL STEADY STATE ENGINE PERFORMANCE SIMULATION
- ANALOG AND DIGITAL TRANSIENT PERFORMANCE SIMULATIONS
- FAILURE MODE AND EFFECTS ANALYSIS
- PLASTICITY COMPUTER PROGRAM
- CREEP CRITERIA FOR TURBINE DISKS
- FRACTURE MECHANICS
- CYCLIC TESTING
- ACCELERATED MISSION TESTING

Several design tools that are universally used today were pioneered in the JT11D-20 program, Figure 7.

A digital steady state engine computer program was used to estimate performance during engine/airplane/mission definition. During engine development it was used to estimate component performance from measured parameters. A copy was supplied to Lockheed in Fortran so they could modify it for use in their flight simulator and flight test performance analysis.

Transient performance was initially estimated using an analog computer. Later a digital transient performance simulation, sponsored by NASA, replaced the analog simulation.

Failure mode and effects analysis led to redundancy and fail-operational logic in parts of the control system. It was also used to focus design and development effort on key components.

A plasticity computer program was developed to predict and analyze deformations that can occur at high temperatures with parts that are subjected to high temperature gradients.

Creep criteria for turbine disks were developed because of the requirement to operate at high temperatures for long periods. These criteria relate the distortion energy to allowable creep stress to enable operation of hot section disks in the creep range of the material.

Rapid transients in temperature, pressure and speed that cover a large operating range can lead to thermal stress cracks in materials. "Fracture mechanics" predicts crack initiation and crack growth and assesses the impact of cracking on failures. Design procedures were developed to reduce these stresses to a minimum.

Some failure modes are more dependent on cycles rather than time; both power lever cycles and mission cycles. The JT11D-20 pioneered cyclic testing to develop component and engine durability and reliability. Engine testing continues today using simulated mission cycles.

It is now common practice to conserve engine test time and induce failures more rapidly by testing at conditions that are more severe than obtained in service. In the JT11D-20 program this was accomplished by testing for a longer time at maximum compressor inlet temperature than experienced on a mission. This determines the life of creep limited parts from relatively short duration tests.

4. MATERIALS

Figure 8 shows a JT11D-20 engine operating on a sea level test stand. This photograph is a good illustration of the need for high temperature materials, especially since the engine surfaces will be still hotter in the nacelle where the cooling air temperature is over 1000°F hotter than the ambient temperature on the test stand.

Figure 9 shows typical temperatures experienced in the engine and nacelle during cruise operation. Choosing the proper materials is always a

FIGURE 8

HIGH TEMPERATURE MATERIALS NEEDED

- THIS PHOTO WAS TAKEN ON A TEST STAND AT 80°F AMBIENT TEMPERATURE THE AMBIENT TEMPERATURE IN THE NACELLE IS 1200°F!

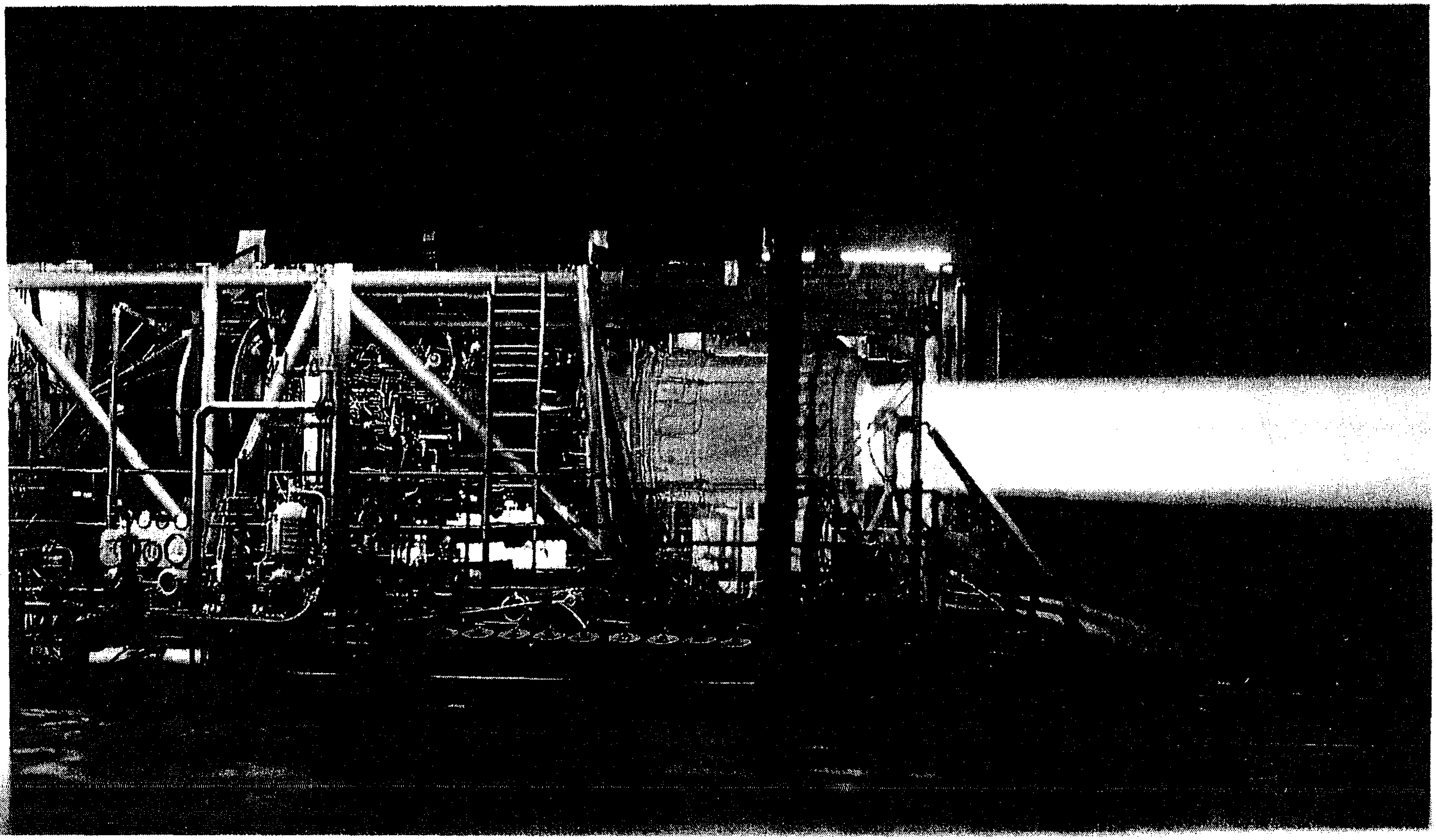


FIG 9

TEMPERATURE EXPERIENCED IN THE ENGINE AND NACELLE

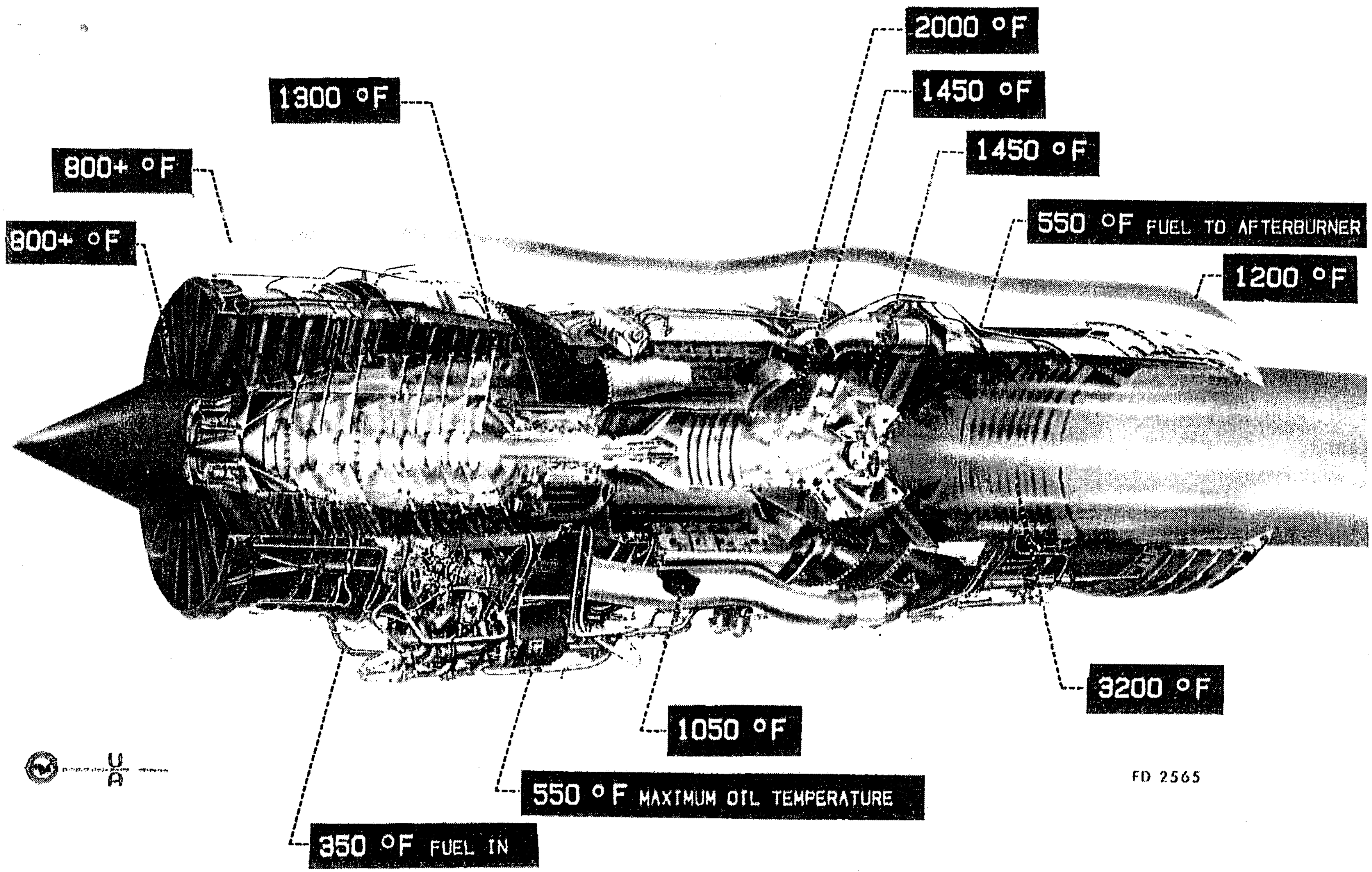
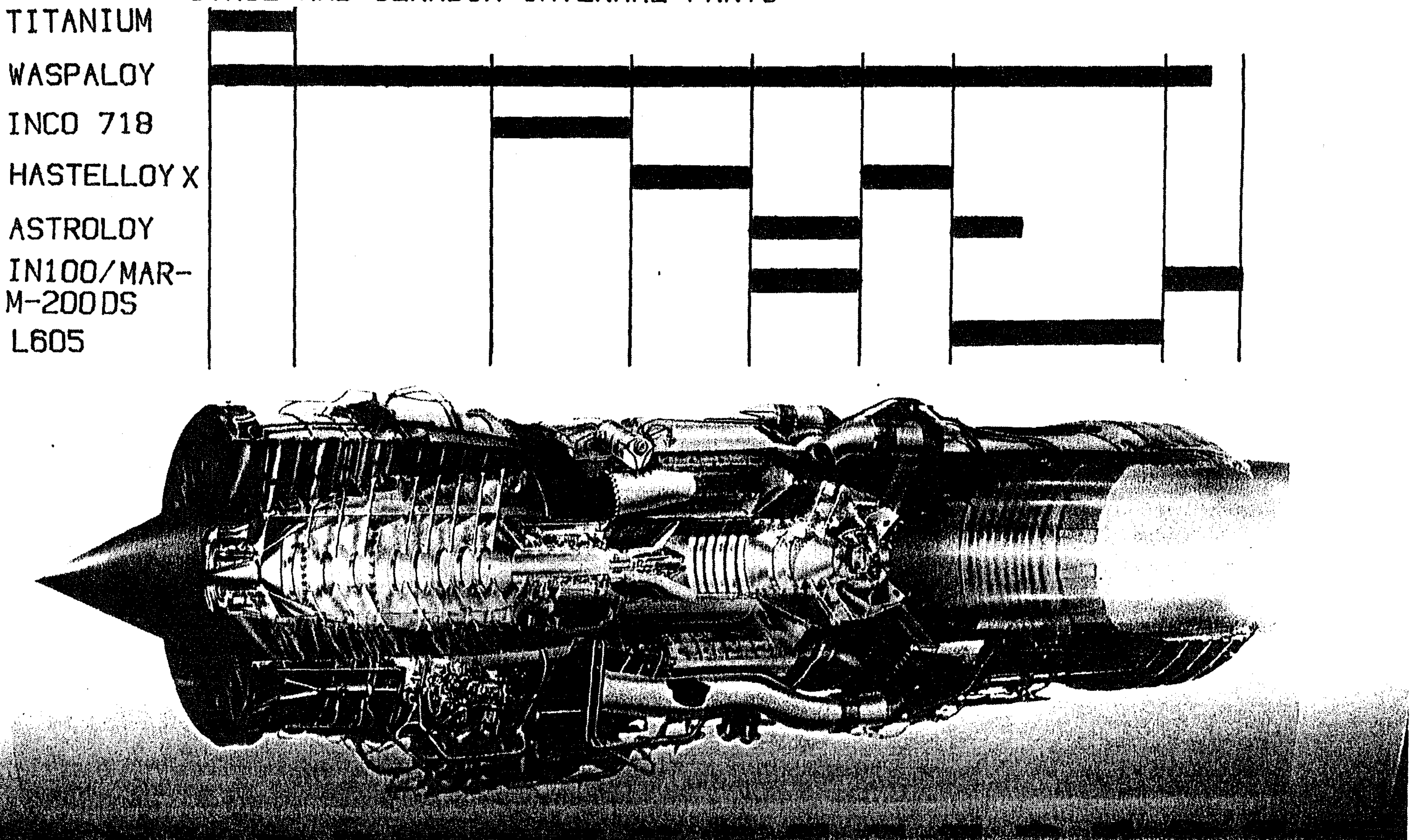


FIGURE 1u

HIGH TEMPERATURES REQUIRED NEW MATERIALS AND PROCESSES

- JT11D-20 ENGINE IS MADE FROM HIGH-TEMPERATURE NICKEL BASE ALLOYS EXCEPT FOR THE INLET GUIDE VANE, FIRST COMPRESSOR STAGE AND GEARBOX INTERNAL PARTS



critical part of the design process. This was especially true in the design of the JT11D-20 engine where materials demonstrating the required properties did not exist in all cases.

As a result of many sleepless nights and a few metallurgical and manufacturing miracles, the engine materials became those shown in Figure 10.

4.1 Materials Selection

4.1.1 Titanium - It was desired to use a titanium alloy for the front stages of the compressor. Titanium is considerably lighter than steel and stronger than aluminum, but possesses limited temperature capabilities. An existing titanium alloy was modified to give good creep properties at temperatures up to 850°F and used for the first stage blade (Ti-8-1-1). Very limited welding data and techniques existed for any titanium alloy and these techniques had to be developed. The welded inlet case was made from Ti-5-2.5.

Materials possessing the necessary fatigue and tensile properties were sometimes found to be brittle and susceptible to other failure modes. Galling of titanium first compressor blade roots resulted in the installation of a thin shoe or shim covering the contact area of the blade with the disk. The shim was plated with nickel which tended to distribute the load on the blade root and reduce stress concentrations.

4.1.2 Waspaloy was the material chosen for most components. Waspaloy is a nickel-base alloy that retains strength and oxidation resistance characteristics to temperatures up to 1400°F. It is however, very tedious to weld and heat treat.

Development of thermo-mechanical processing and control was found necessary to produce more uniform microstructures for adequate mechanical properties of Waspaloy compressor disks.

At the time that materials were chosen for the JT11D-20 engine, Waspaloy was available only as a forging. The Hamilton Watch Company manufactured the first experimental Waspaloy sheets for us; approximately 12" to 48". These were too small to make most parts on a JT11D-20 engine.

Because of its high strength at high temperatures, very thin Waspaloy sheets could be used in some applications. The thinness aggravated the inherent fabrication problems. Forming of the .012" thick corrugated skin for inner burner case required development of special explosive forming techniques.

Welding techniques for Waspaloy sheet less than 0.035" thick had to be developed. With these thin sheets, material mismatch before welding became increasingly critical. Mismatch criteria and techniques for achieving them during fabrication were developed. These techniques continue to be used today in fabricating parts for later P&W engine models.

Weld fabrication of Waspaloy cases required development of a two-furnace heat treatment. Variation in heating rates required the part to be heated relatively slowly to a certain point in one furnace, then transferred to a second furnace. The second furnace was preheated to a much higher temperature, thereby providing rapid heat-up during the subsequent phase of heat treatment.

A 40 hour heat treatment was developed to prevent flow shift in Waspaloy afterburner spraybars during operation. This technique is currently used in the F100-PW-220 engine. A special heat treatment was also developed to adapt Waspaloy to a bearing material for the exhaust nozzle flap rollers.

4.1.3 INCONEL 718 is a nickel-base alloy widely accepted for weldments and castings in static applications up to 1250°F. Among the nickel-base alloys, INCONEL 718 is one of the easier materials to weld and was therefore selected as the material for the diffuser case when fabrication of this intricate weldment from Waspaloy proved too difficult. Heat treatment and thermal rejuvenation at overhaul enables the diffuser case to operate satisfactorily at 1300°F temperature.

4.1.4 Hastelloy X is a non-hardenable nickel-base alloy that is suitable for low stress applications requiring high oxidation resistance up to 2000°F. It readily lends itself to most standard manufacturing processes and to plasma sprayed thermal barrier coatings. It was, therefore, a logical choice for burner components.

4.1.5 Astroloy is a nickel-base, precipitation hardenable alloy possessing creep and tensile properties superior to Waspaloy at temperatures up to 1500°F. It is available as a forging and is particularly suitable for turbine disk applications. However, in the available form it was subject to segregation and inconsistent microstructure.

A parametric study of critical elements provided an Astroloy chemistry that gives the best combination of room temperature and elevated temperature properties. Development and control of ingot size provided minimum segregation for this highly alloyed material. Development of "thermo-mechanical" processing-forging and heat treatment using grain size microstructure (optical and electron microscope) was incorporated so that disks have suitable mechanical properties for engine operation. Sounds simple, doesn't it? Well, it wasn't. This took about a year of hard inventing.

Astroloy processing, particularly forging and heat treatment, requires unique equipment and special care. This makes it a very expensive material specified for only the most rigorous applications.

4.1.6 Powder Metallurgy AF2-1DA was used to produce high temperature compressor tiebolts from near-net-shape isothermal forgings. This material provided improved creep strength over Astroloy.

4.1.7 MAR-M-200DS is a new material that was developed for first stage turbine vanes. It is a nickel based superalloy with columnar material grains. The new casting process causes the material crystals to be directionally solidified so that the grains grow span-wise. The complete absence of chord-wise grain boundaries minimizes the possibility of leading and trailing edge thermal shock cracks characteristic of other nickel alloy castings. This provides an increase in metal temperature capability about 50°F greater than conventionally cast equiaxed material. This new material casting technique along with benefits of internal cooling, provided a turbine with the capability to operate continuously at temperatures that other engines operated at only intermittently.

4.1.8 IN-100 is a cast nickel-base alloy used for first and second stage turbine blades, second stage turbine vanes and JT11D-20 afterburner nozzle flaps. Process control was established to consistently produce fine equiaxed grain castings for engine-ready turbine blades. Heat treatment was developed which incorporated a coating diffusion cycle and which provided adequate strength, creep and rupture capabilities and microstructure stability during engine operation. When first produced, the hollow second turbine vane was the largest airfoil casting attempted. Techniques had to be developed to produce this vane, as well as the nozzle flaps which are a casting of approximately 6" X 12" X 0.050" thick.

4.1.9 L-605 (Haynes 25) is a cobalt-base alloy which is available in sheets and possesses good weldability and formability. It is specified for applications similar to Hastelloy X but requiring greater resistance to buckling and sliding wear. L-605 has been replaced in most applications by later generation alloys such as Haynes 188 and Haynes 230, which have improved oxidation resistance without sacrificing other properties.

4.1.10 Silver Impregnated Carbon bushings were used in lubrication pumps when all conventional bushing materials and lubricating schemes failed to produce durable pumps. This, of course, was because oil as such could not be used because of temperature limits.

4.1.11 Gear and Bearing Materials
Gear and bearing materials such as 440C are suitable for application up to 350°F. JT11D-20 bearings and gears are required to operate at temperatures up to 600°F. Methods of carburizing high temperature tool steel were developed to produce Bower 315 gear material. Similarly, through hardening of high temperature tool steel was developed to produce M50 bearing material which can be hardened in the Rockwell C 65 range.

4.2 PROTECTIVE COATINGS

4.2.1 Pack Coatings
Both the turbine vanes and turbine blades are one-piece castings. Since no microscopic surface pores for cooling air discharge are involved, these designs allow the use of surface coatings to minimize erosion, oxidation, sulfidation and improve thermal fatigue characteristics. Parts are surrounded by aluminum-silicon powder and heated to allow diffusion of the powder into the parts. This process produces a thin (approximately 0.003 inch thick) tough "skin".

4.2.2 Plasma Coatings
Oxidation-thermal protection coating was also used for the thin sheet structures of the engine. Lightweight hardware located in temperature environments of 2000°F plus are subjected to rapid thermal shock that results in additional demands on the protective coating.