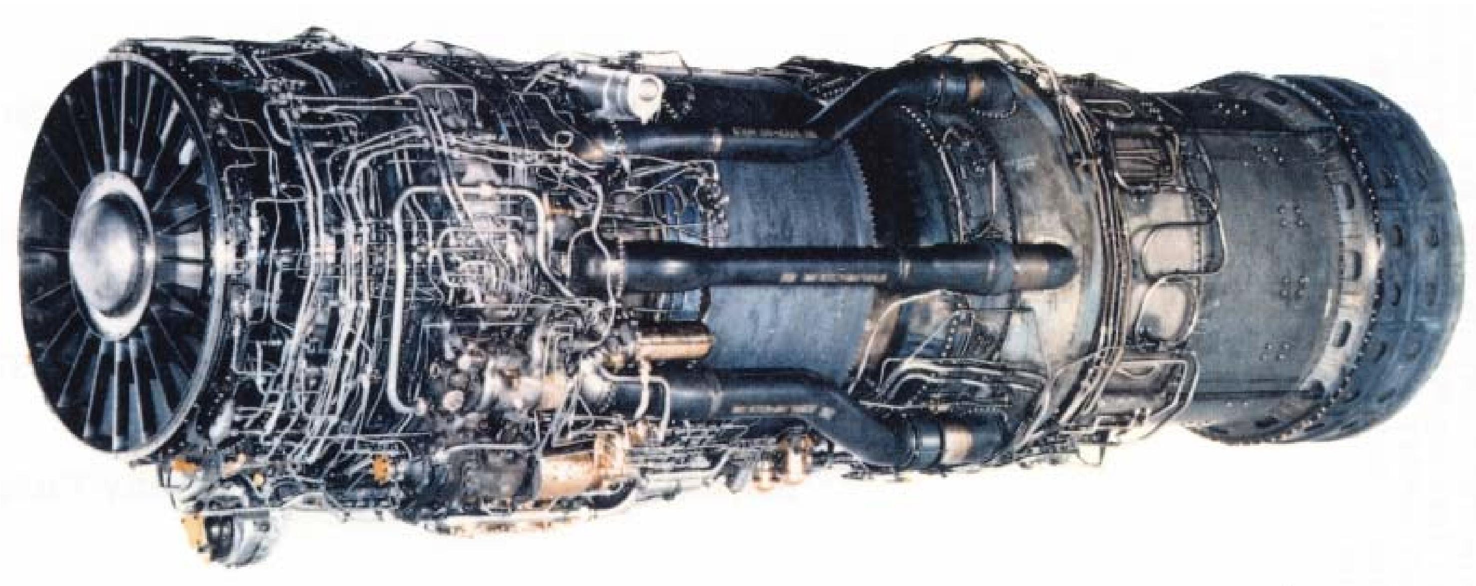
SR-71 PROPULSION SYSTEM
P&W J58 ENGINE (JT11D-20)

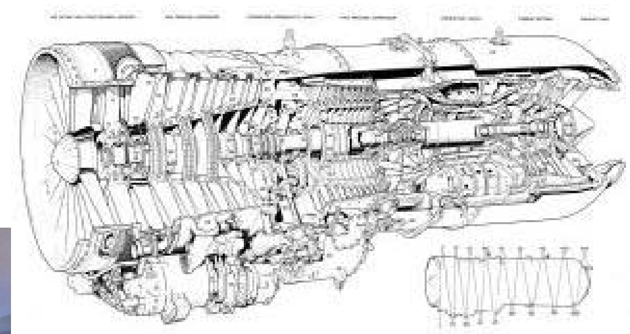
PETER LAW



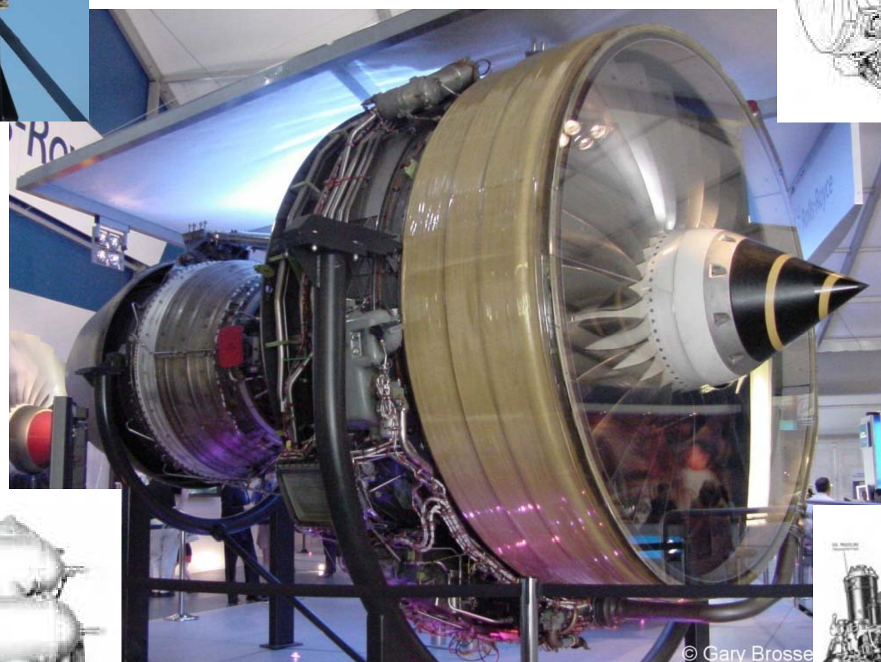
ONE OF THE BEST JET ENGINES EVER BUILT

Rolls-Royce Milestone Engines

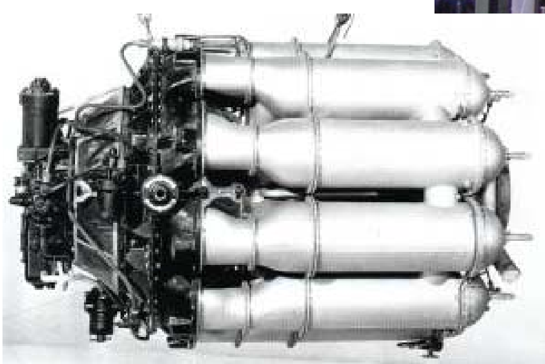
Merlin



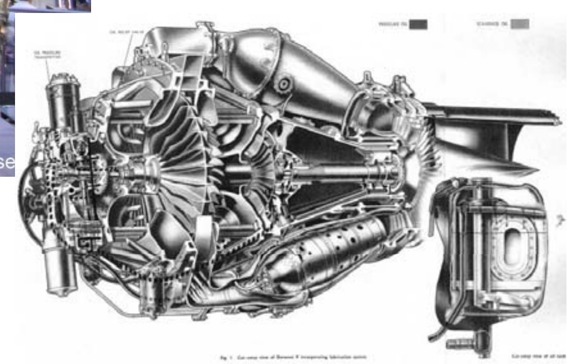
Conway



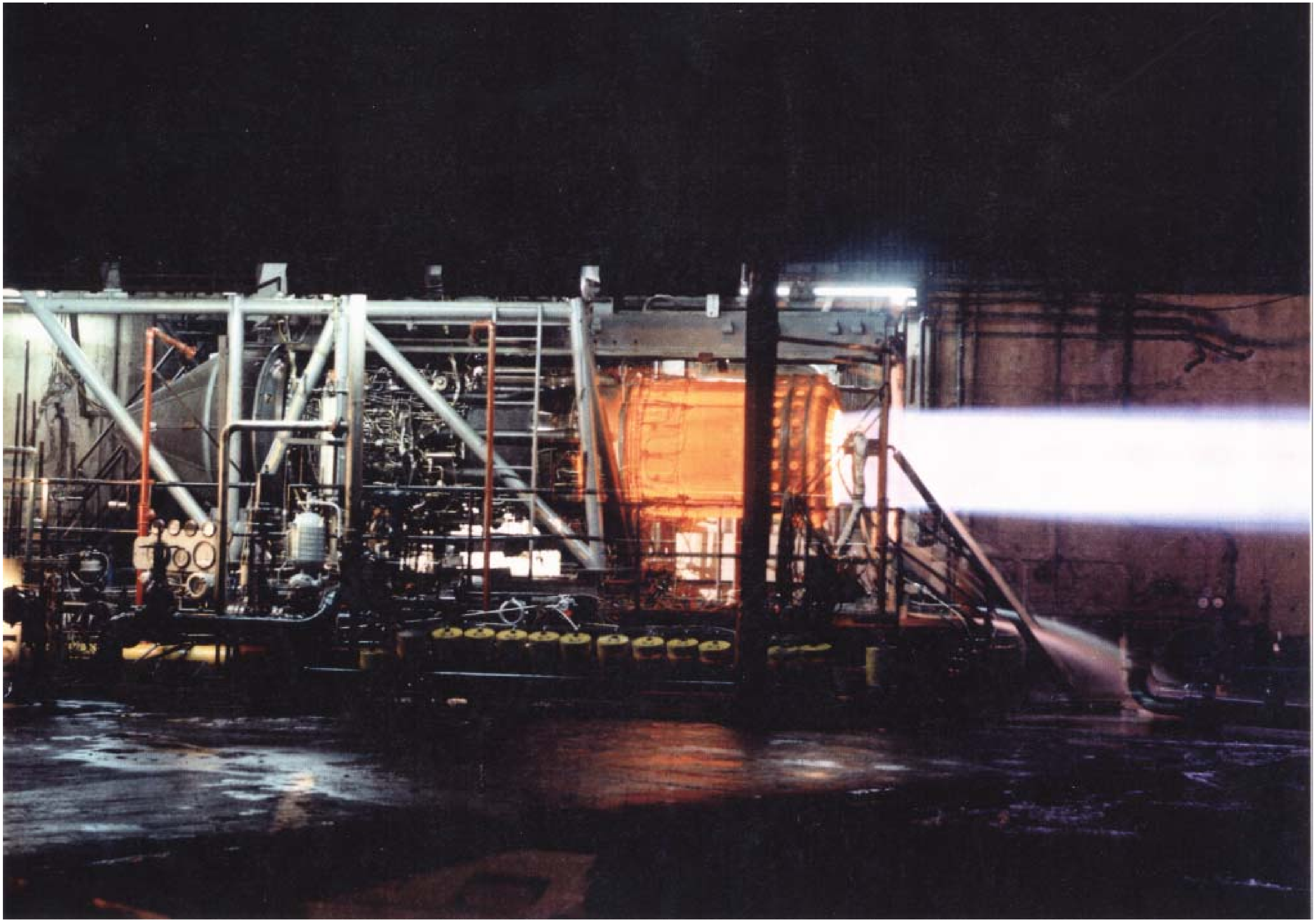
W2B Welland



Derwent



Trent



SR-71 BLACKBIRD


U.S. AIR FORCE

SR-71
GENERAL CHARACTERISTICS

- Two Place High-Altitude High-Speed Reconnaissance Aircraft
- Developed in Early 1960s By Kelly Johnson, Lockheed "Skunk Works"
  - In Burbank, California (Advanced Development Projects - ADP)
- Delta Wing Configuration
- Crew Of Two: Pilot And Reconnaissance Systems Officer (RSO)
  - Seated In Tandem Arrangement
- Inflight Refueling Capability - Crew Endurance is Limit
- Aircraft Length is 107 Feet, Wing Span Is 55 Feet, Height is 18 Feet
- Takeoff Weight is 140,000 Pounds; 80,000+ Pounds Of Fuel
- 93% Of Vehicle Structure And Skin is Titanium
- Aircraft Series Known As "Blackbirds"

SR-71
PERFORMANCE CHARACTERISTICS

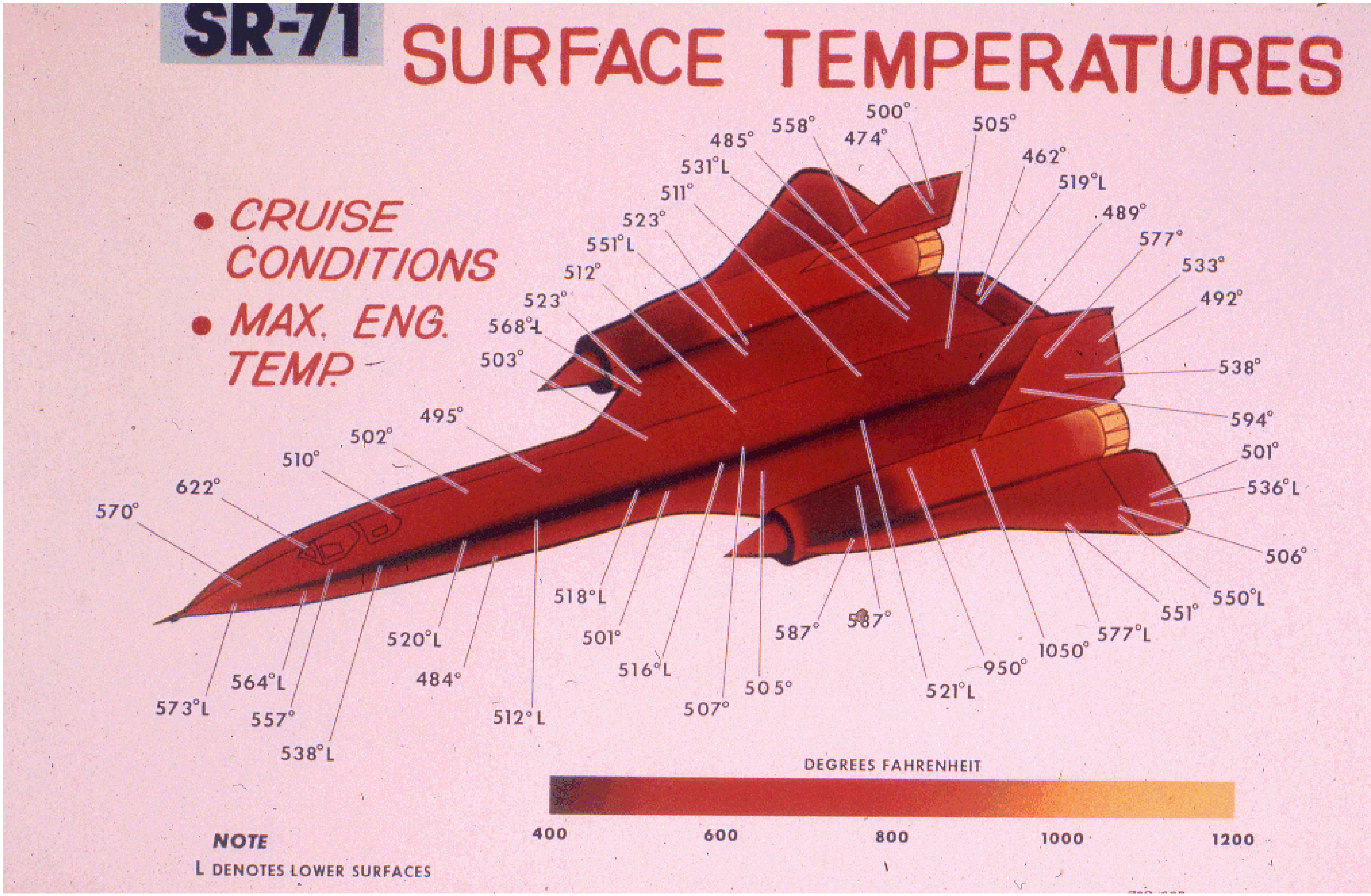
- **Cruising Altitude Is Between 74,000 And 85,000 Feet**
- **Cruising Speed Is Mach 3.2+, 2100+ MPH, 3100+ Feet/Sec**
- **Range Is 3,000 Miles, 15,000 Miles with Refueling**
- **Total Flight Time Of All "Blackbird" Aircraft: 53,000+ Hours**
- **Total Time Above Mach 3.0: 11,000+ Hours (22 Million Miles)**
- **Powered By Two Pratt & Whitney J58 Turbojet Engines, Each With The Power Of The Queen Mary**
- **Vehicle Was Designed With Radar Signature Reduction Techniques**

SR-71

FLIGHT RECORDS

Sustained Speed In Level Flight	7/28/76	2,193.16 mph	
Sustained Altitude In Level Flight	7/28/76	85,069 feet	
New York To London	9/1/74	1806.96 mph	1 Hr 54 Min 32 Sec
London To Los Angeles	9/13/74	1435.59 mph	3 Hr 47 Min 39 Sec
USA Coast To Coast	3/6/90	2124.51 mph	1 Hr 7 Min 53.69 Sec
Los Angeles To Washington	3/6/90	2144.83 mph	1 Hr 4 Min 19.69 Sec
Kansas City To Washington	3/6/90	2176.08 mph	24 Min 58.53 Sec
St. Louis To Cincinnati	3/6/90	2189.94 mph	8 Min 31.93 Sec

NAA Official Data - 1992



SR-71 SURFACE TEMPERATURES
• CRUISE CONDITIONS
• MAX. ENG. TEMP.
558°
500°
485°
474°
505°
531°L
462°
519°L
511°
489°
523°
577°
551°L
533°
512°
492°
523°
568°L
538°
503°
594°
495°
502°
501°
510°
536°L
622°
570°
506°
518°L
550°L
551°
520°L
501°
587°
587°
577°L
1050°
564°L
484°
516°L
950°
505°
521°L
573°L
557°
512°L
507°
538°L
DEGREES FAHRENHEIT
400
600
800
1000
1200
NOTE
L DENOTES LOWER SURFACES

GENERAL COMMENTS ON SR-71 PROPULSION SYSTEM

- THE SR-71 WAS THE FINEST AIR BREATHING JET AIRCRAFT EVER DEVELOPED, BUILT, AND FLOWN. DESIGNED TO FLY AT MACH 3.2, WIND TUNNEL TESTED TO MACH 3.5, AND FLEW MISSIONS AT MACH 3.3+, AT ALTITUDES OF 86,000+ FEET.
- THE P&W J58 (JT11D-20) HAD THE POWER OF THE QUEEN MARY; STARTED LIFE WITH 30,000 POUNDS OF THRUST, AND ENDED WITH 34,000 POUNDS.
- THE “PROPULSION SYSTEM” CONSISTED OF THE AIR INLET AND AIR FLOW CONTROL SYSTEM, THE J58 ENGINE, AND THE EXHAUST NOZZLE ASSEMBLY (PART OF THE AIRFRAME).
- THE IMPORTANT FEATURES OF EACH WILL BE BRIEFLY COVERED, AS EACH PART WAS CRITICAL FOR PROPER OPERATION OF THE INTEGRATED “PROPULSION SYSTEM”.
- AT MACH 3.2, 54% OF THE THRUST WAS PROVIDED BY THE INLET (DIFFERENTIAL PRESSURE BETWEEN EXTERNAL AND INTERNAL SURFACES OF THE INLET SPIKE), 17% BY THE ENGINE, AND 29% BY THE EJECTOR. ENGINE ACTED AS A GAS GENERATOR.
- ENGINE OPERATES FROM 4,000 RPM (IDLE) TO 7,400 RPM (MAX).

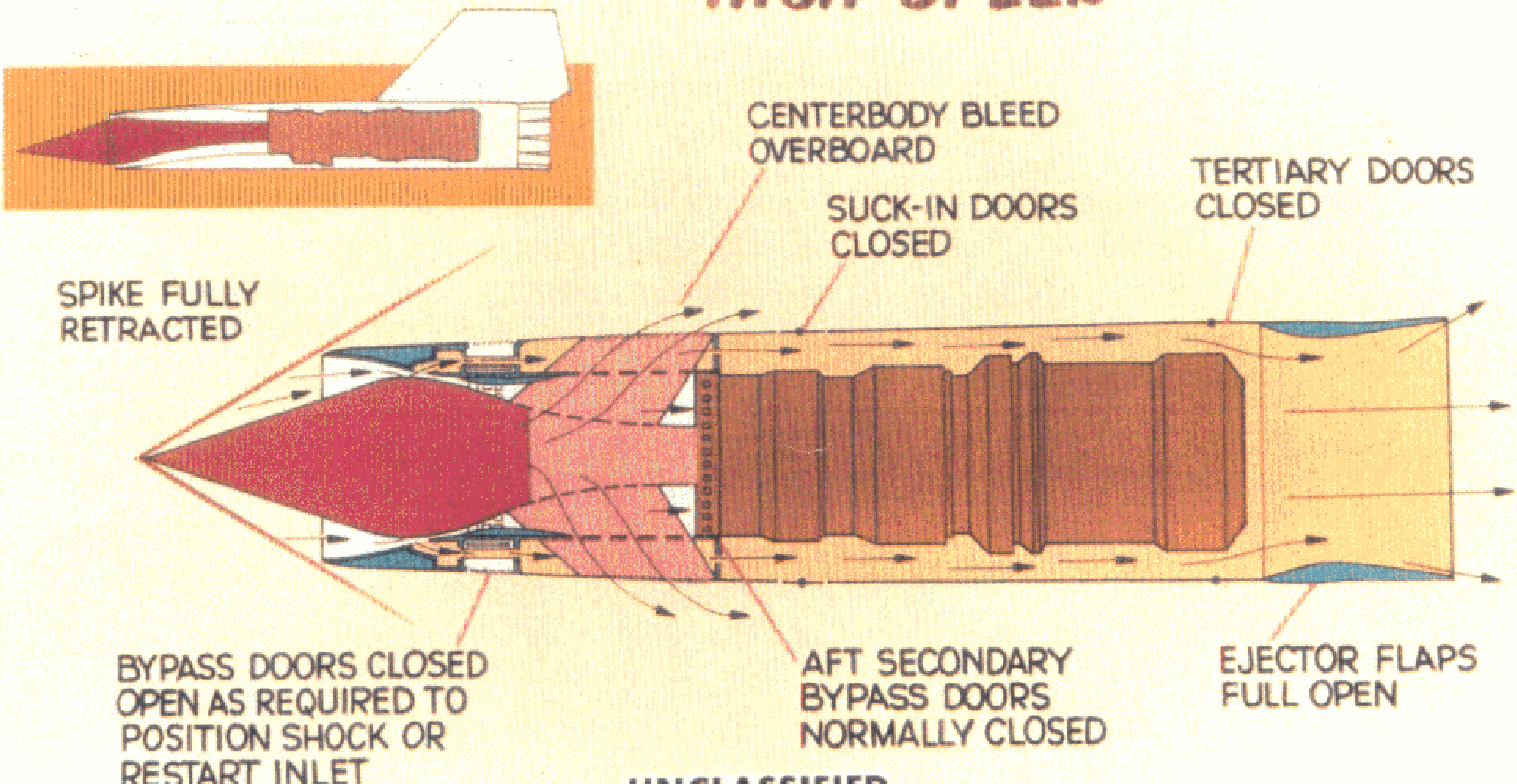
LOCKHEED
SR-71
BLACKBIRDS

UNCLASSIFIED

SENIOR CROWN PROGRAM

NACELLE AIRFLOW

HIGH SPEED

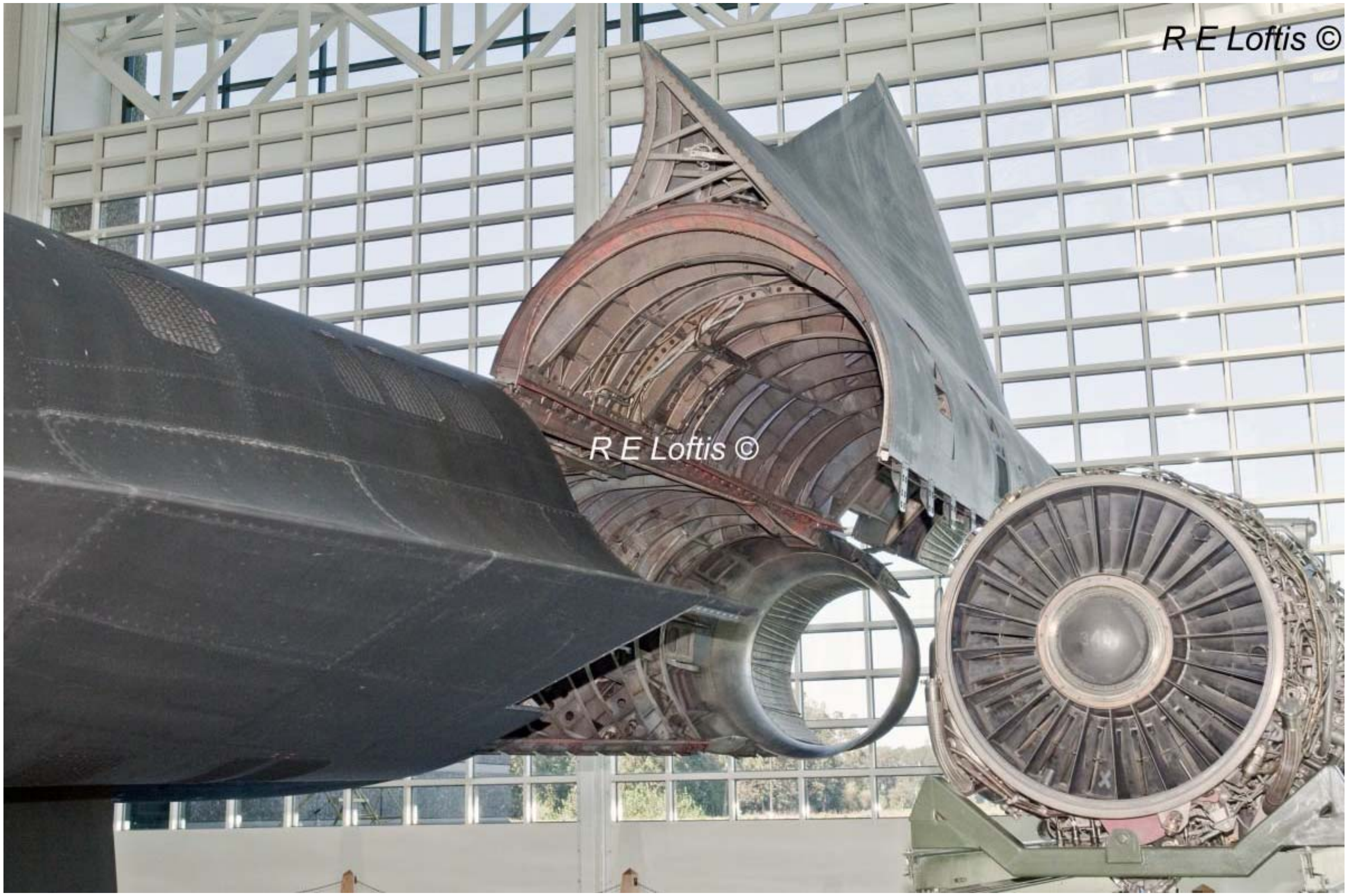


UNCLASSIFIED

THE ENGINE

- THE ENGINE IS THE PRATT AND WHITNEY JT11D-20, DESIGNATED “J58” BY THE MILITARY
  - ENGINE IS A SINGLE-SPOOL, AFTERBURNING TURBO-JET, WITH A 4^{th}-STAGE BLEED BYPASS DUCTING AIR INTO THE AFTERBURNER
  - BLEED SYSTEM IS OPERATED AT HIGH MACH NUMBERS TO PROVIDE INCREASED COMPRESSOR STALL MARGIN
  - BLEED AIR RE-ENTERS THE ENGINE AHEAD OF THE AFTERBURNER WHERE THE AIR IS USED FOR COOLING AND INCREASED THRUST AUGMENTATION
  - BYPASS AIRFLOW IS 20% OF TOTAL FLOW INTO ENGINE
  - ENGINE RPM IS MAINTAINED BY MODULATING THE EXHAUST NOZZLE
    - THIS ARRANGEMENT PROVIDES NEARLY CONSTANT AIRFLOW AT A GIVEN MACH NUMBER FROM BELOW MILITARY POWER TO MAXIMUM AB, WHICH IS VERY DESIRABLE WHEN OPERATING BEHIND A SUPERSONIC MIXED COMPRESSION INLET

J58 Installation in SR-71



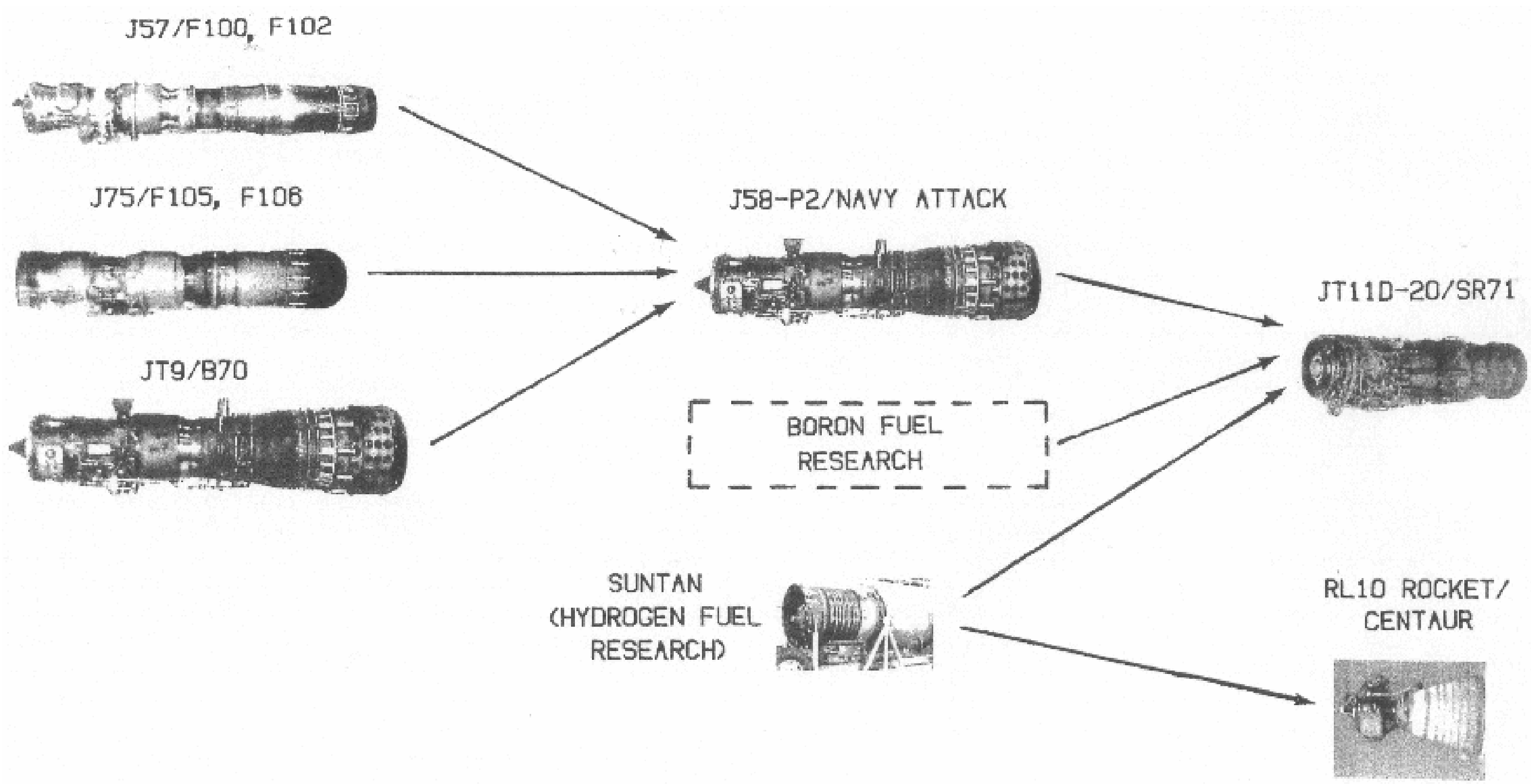
J58 ENGINE SYSTEM

- FUEL CONSUMPTION AT A CRUISING MACH NUMBER IS APPROXIMATELY 8,000 GALLONS PER HOUR
- FUEL IS JP-7, WHICH HAS AN EXTREMELY LOW VAPOR PRESSURE AND A VERY HIGH FLASH POINT
- TO LIGHT THIS FUEL A SPECIAL IGNITION SYSTEM IS USED. A CHEMICAL – PYROPHORIC TRIETHYLBORANE (TEB), IGNITES THE MAIN ENGINE AND THE AFTERBURNER
- THE ENGINE OPERATES IN THE MOST HOSTILE ENVIRONMENT ANY ENGINE HAS EVER BEEN SUBJECTED TO:
  - AIR ENTERING THE COMBUSTOR REACHES 1400°F
  - TURBINE INLET TEMPERATURE IS 2000°F
  - TEMPERATURE IN AFTERBURNER SECTION REACHES 3200°F
- GROUND STARTING REQUIRES USING TWO 300 HP BUICK *WILDCAT* RACING ENGINES CONNECTED TO THE J58 STARTER DRIVE
- AT FULL AFTERBURNER POWER THE AFTERBURNER GLOWS CHERRY RED

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

J-58 DEVELOPMENT WAS STARTED IN LATE 1956

BACKGROUND EXPERIENCE



EXPERIENCE AND TECHNOLOGY IS ALWAYS UTILIZED

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

INNOVATIONS ON THE JT11D-20 ENGINE

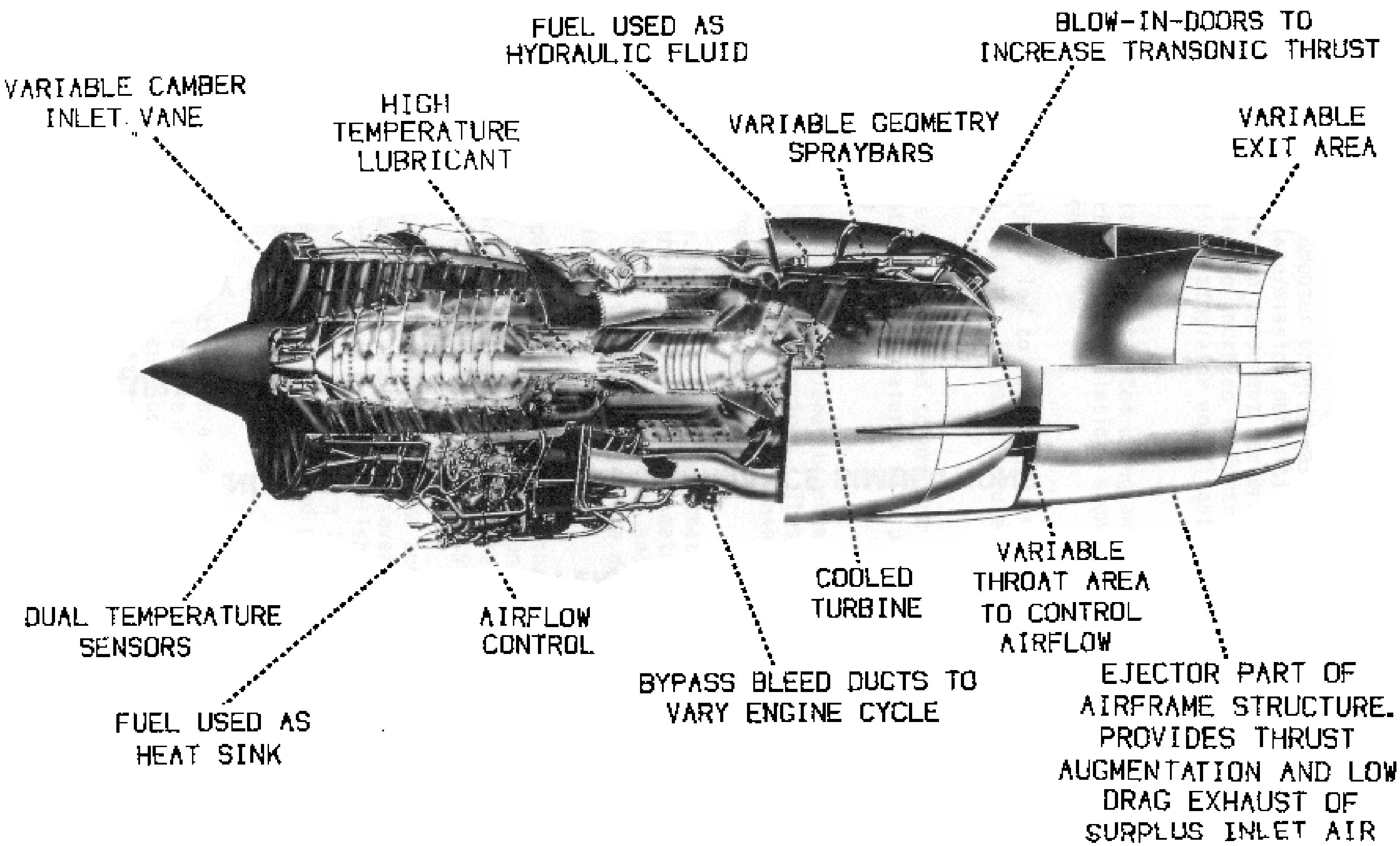
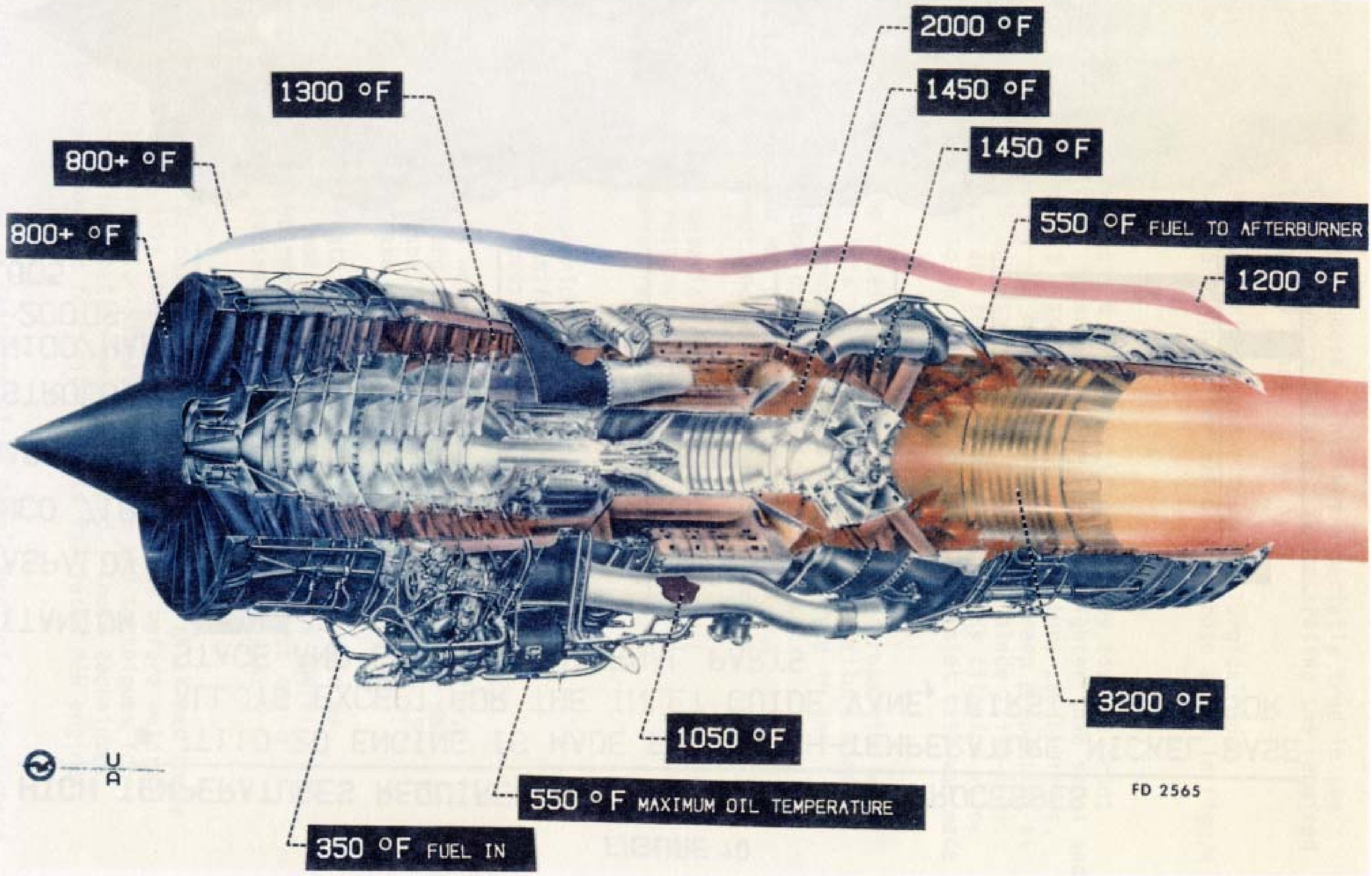


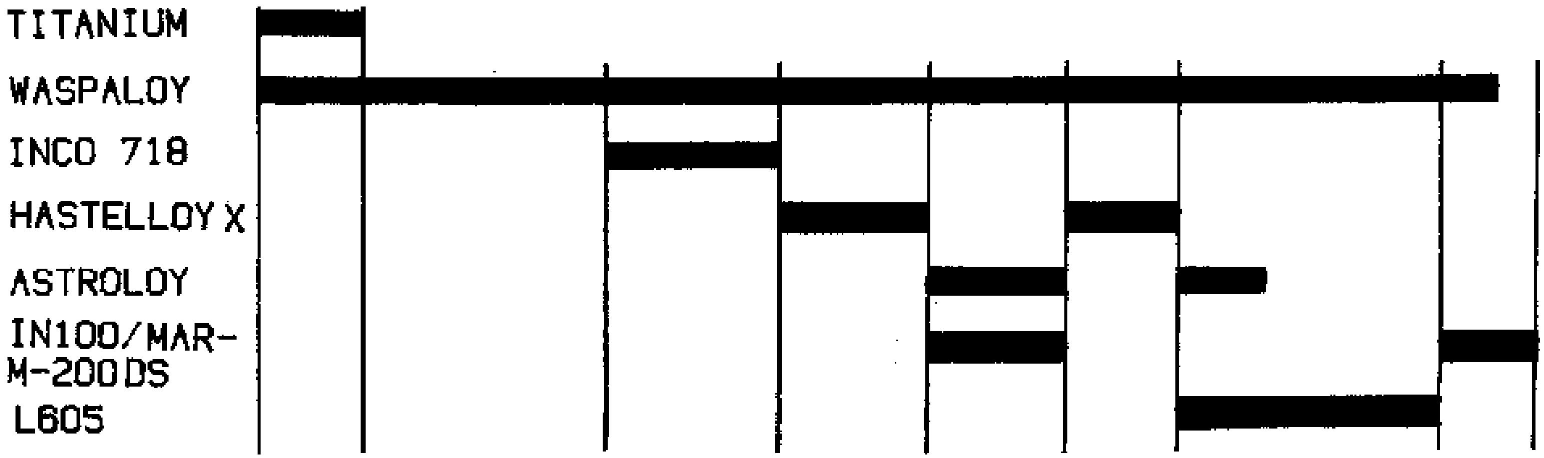
FIGURE 9

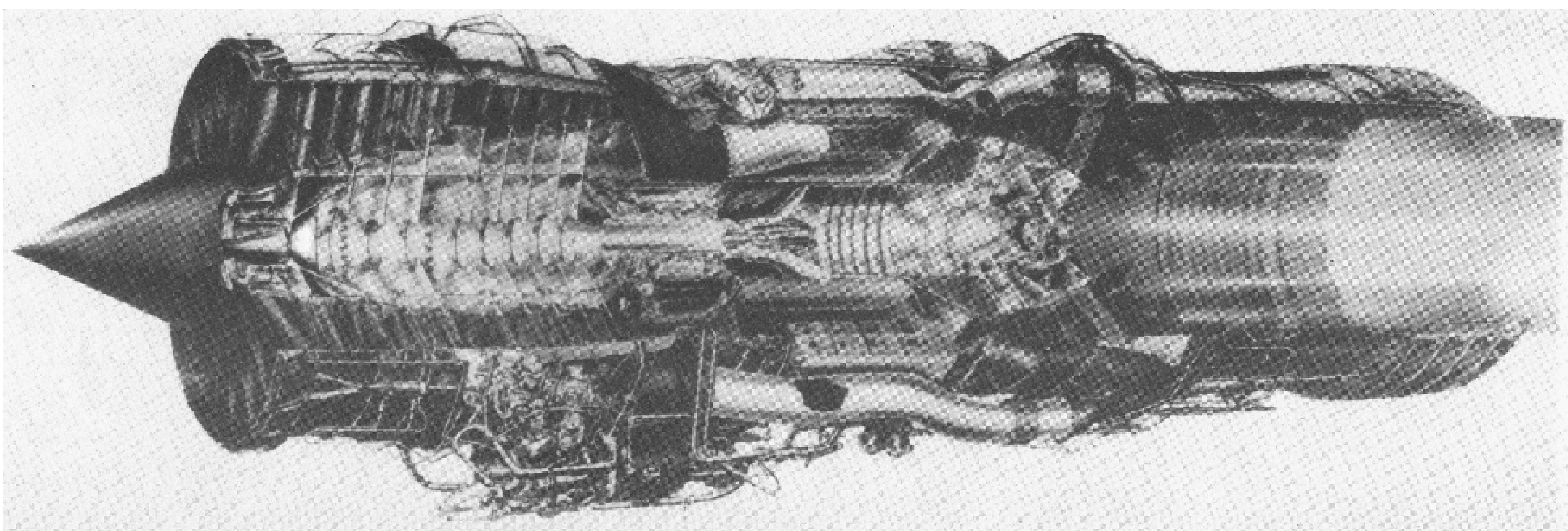
TEMPERATURE EXPERIENCED IN THE ENGINE AND NACELLE



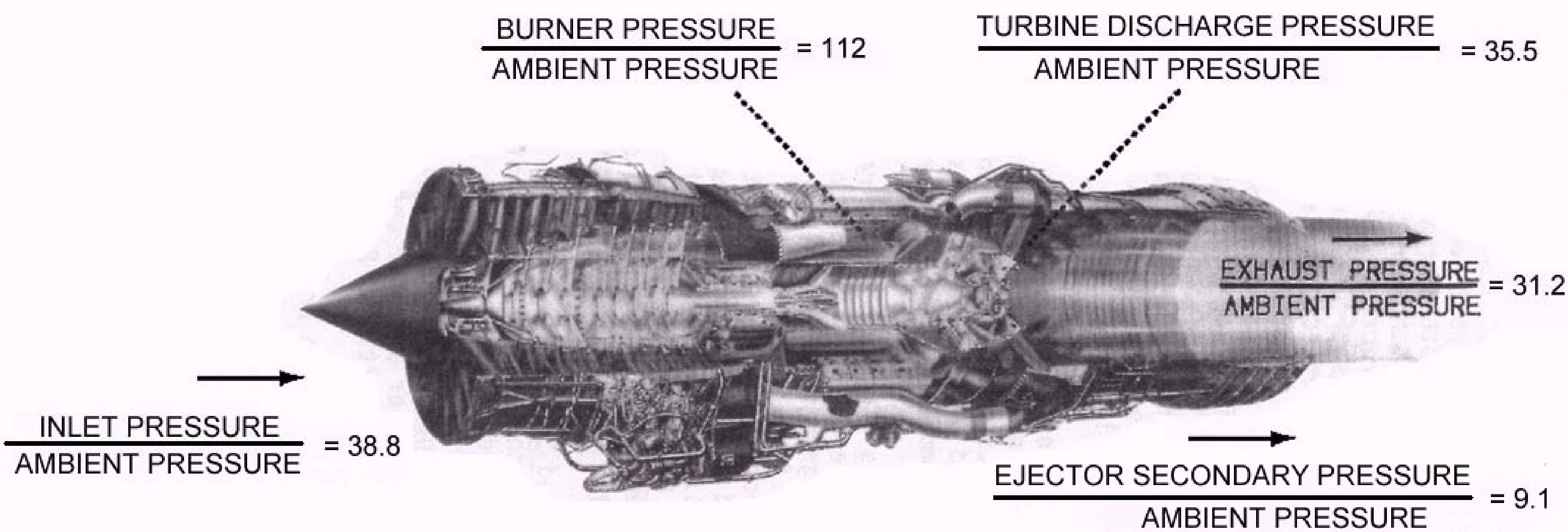
HIGH TEMPERATURES REQUIRED NEW MATERIALS AND PROCESSES

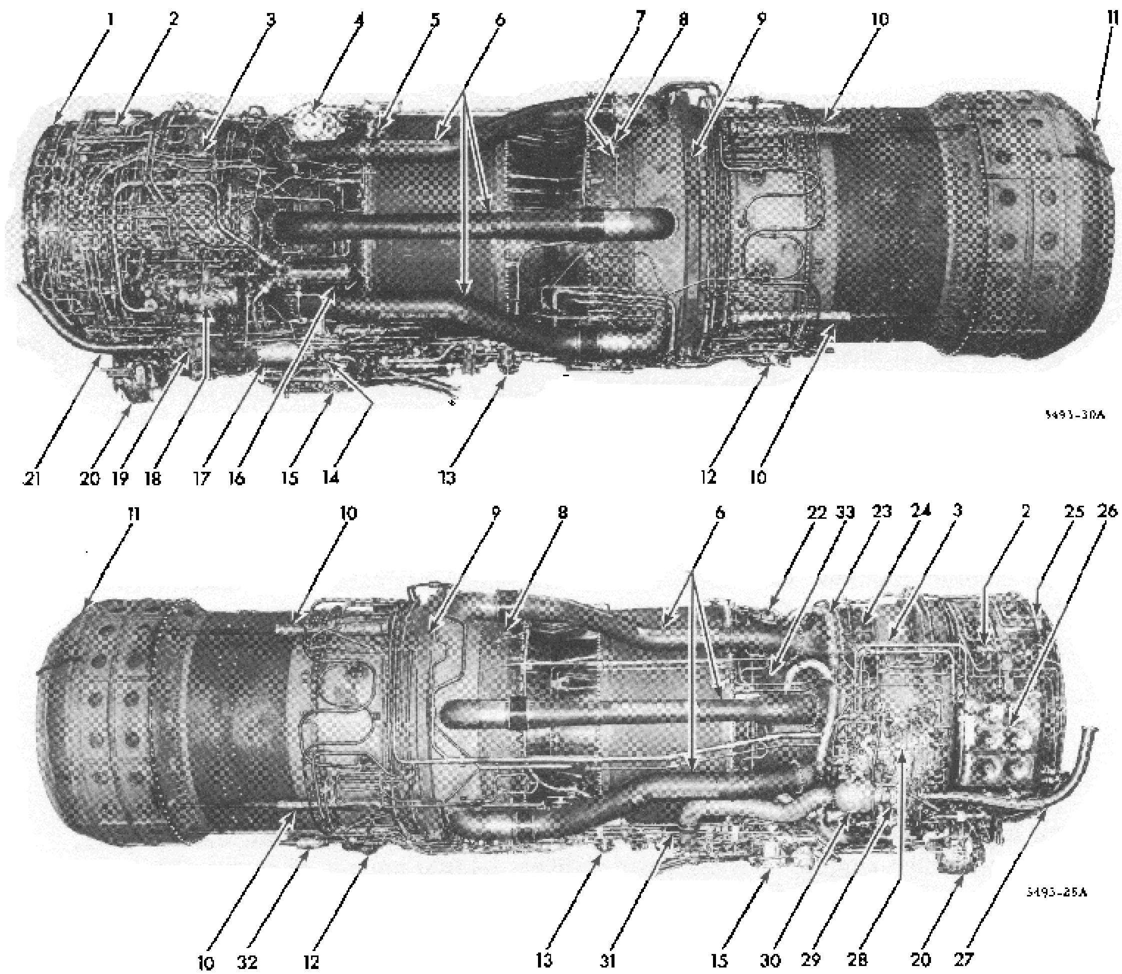
- JT11D-20 ENGINE IS MADE FROM HIGH-TEMPERATURE NICKEL BASE ALLOYS EXCEPT FOR THE INLET GUIDE VANE, FIRST COMPRESSOR STAGE AND GEARBOX INTERNAL PARTS





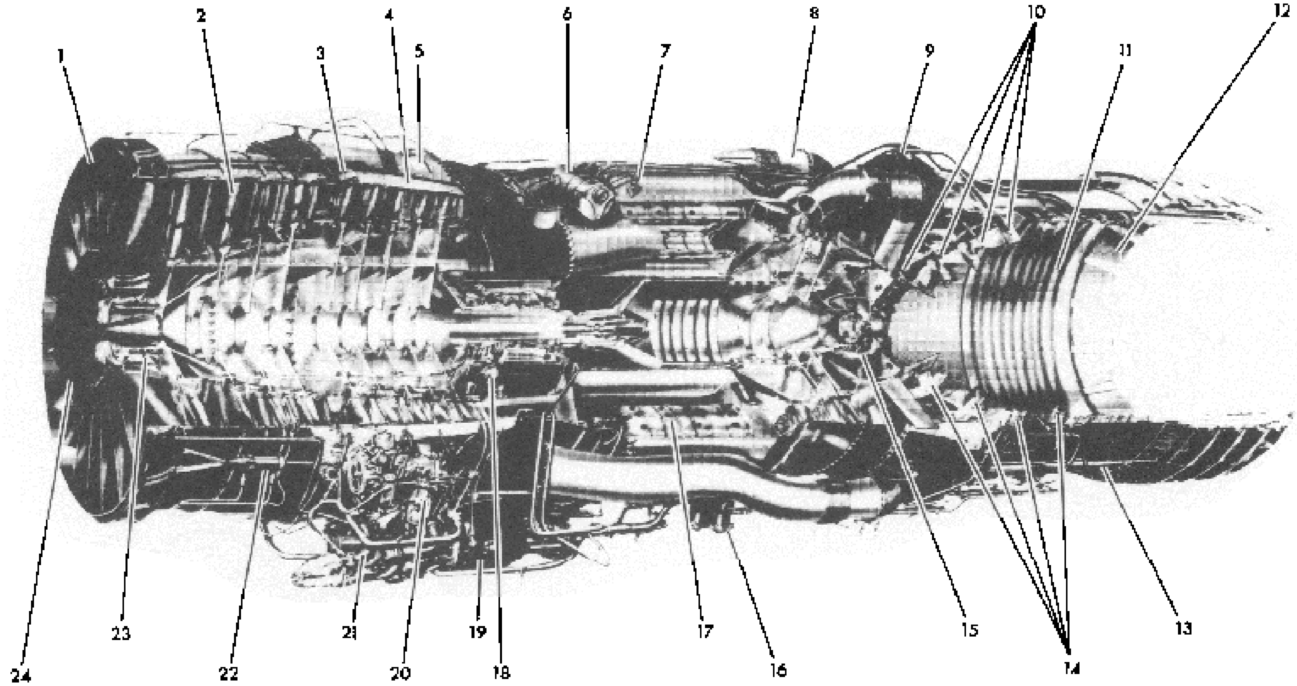
TOTAL PRESSURES IN THE ENGINE AND NACELLE DURING SUPERSONIC CRUISE





1 COMPRESSOR INLET CASE
2 COMPRESSOR BYPASS ACTUATOR (4)
3 START BLEED DOOR ACTUATOR (3)
4 CHEMICAL IGNITION UNIT
5 CHEMICAL IGNITION PROBE
6 COMPRESSOR AIR BYPASS TUBES (6)
7 AFTERBURNER IGNITION PROBE
8 EGT THERMOCOUPLE (9)
9 REAR SUPPORT LUGS
10 EXHAUST NOZZLE ACTUATOR (4)
11 EXHAUST NOZZLE
12 ENGINE NOZZLE CONTROL
13 HYDRAULIC FUEL FILTER (2)
14 OIL PUMP
15 STARTER DRIVE PAD
16 FUEL-OIL HEAT EXCHANGER
17 MAIN GEAR BOX
18 MAIN FUEL CONTROL
19 MAIN FUEL PUMP
20 REDUCTION GEAR BOX
21 FUEL PUMP SUPPLY HOSE
22 FORWARD ENGINE MOUNT
23 BLEED AIR MANIFOLD
24 START BLEED DOOR (12)
25 IGV ACTUATOR (2)
26 OIL TANK
27 A/B FUEL SUPPLY HOSE
28 A/B FUEL CONTROL
29 A/B FUEL PUMP
30 A/B PUMP TURBINE
31 WINDMILL BYPASS VALVE
32 ENP TRANSDUCER
33 DIFFUSER CASE

Figure 2-1. J58 Engine (Sheet 1 of 2)



1 INLET CASE
2 FORWARD COMPRESSOR SECTION (4 STAGES)
3 BLEED BYPASS DOORS (24)
4 BYPASS CHAMBER
5 START BLEED DOORS (12)
6 CHEMICAL IGNITION TANK (TEB)
7 MAIN BURNER INJECTOR PROBE
8 BLEED BYPASS TUBES (6)
9 AFT ENGINE MOUNT RING
10 AFTERBURNER SPRAY RINGS (4)
11 AFTERBURNER LINER
12 VARIABLE AREA EXHAUST NOZZLE
13 EXHAUST NOZZLE ACTUATORS (4)
14 FLAME HOLDERS (4)
15 TURBINE SECTION AND BEARING
16 HYDRAULIC FILTERS (2)
17 BURNER CAN (8)
18 AFT COMPRESSOR BEARING (DUPLEX BALL)
19 MAIN GEARBOX
20 MAIN FUEL CONTROL
21 MAIN FUEL PUMP
22 BYPASS BLEED DOOR ACTUATOR (4)
23 FRONT COMPRESSOR BEARING
24 INLET CASE ISLAND COVER

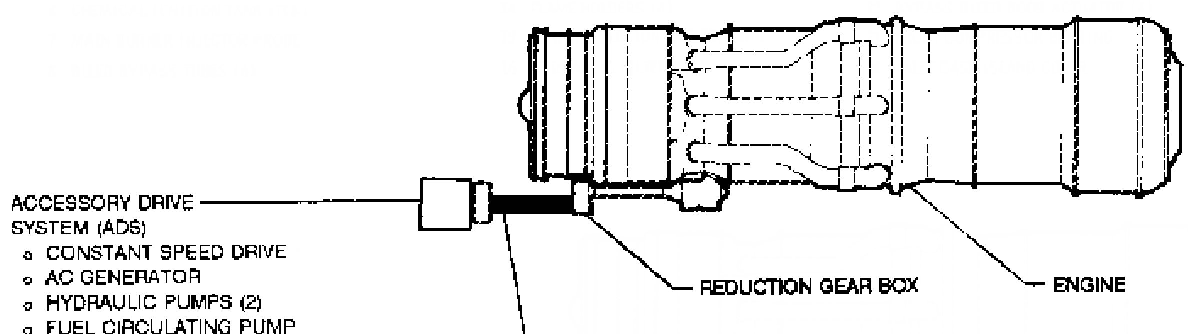
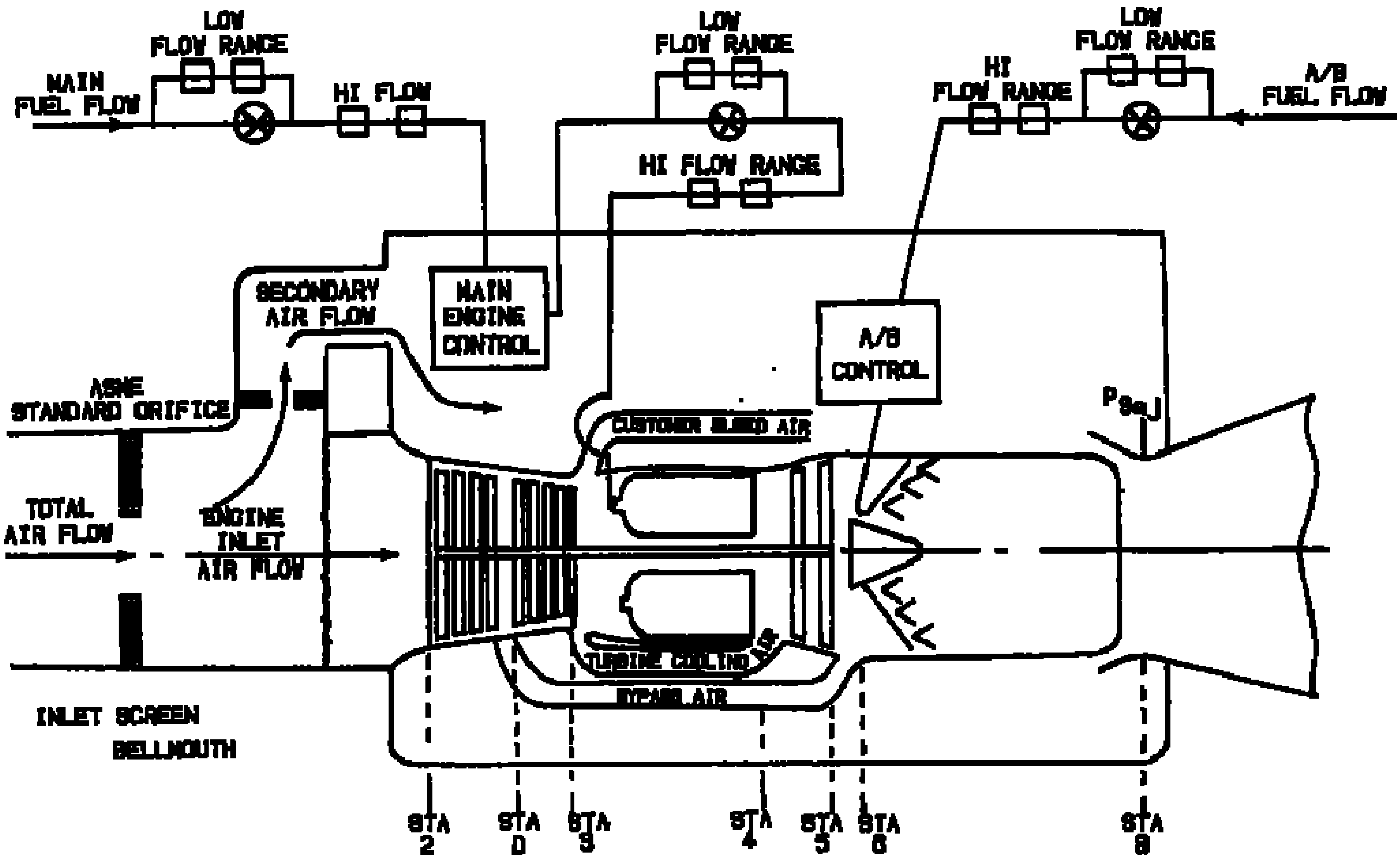


Figure 2-1. J-58 Engine (Sheet 2 of 2)

FIGURE 2.1

SCHEMATIC DIAGRAM OF THE JT11D-20 ENGINE MOUNTED IN THE ALTITUDE TEST FACILITY



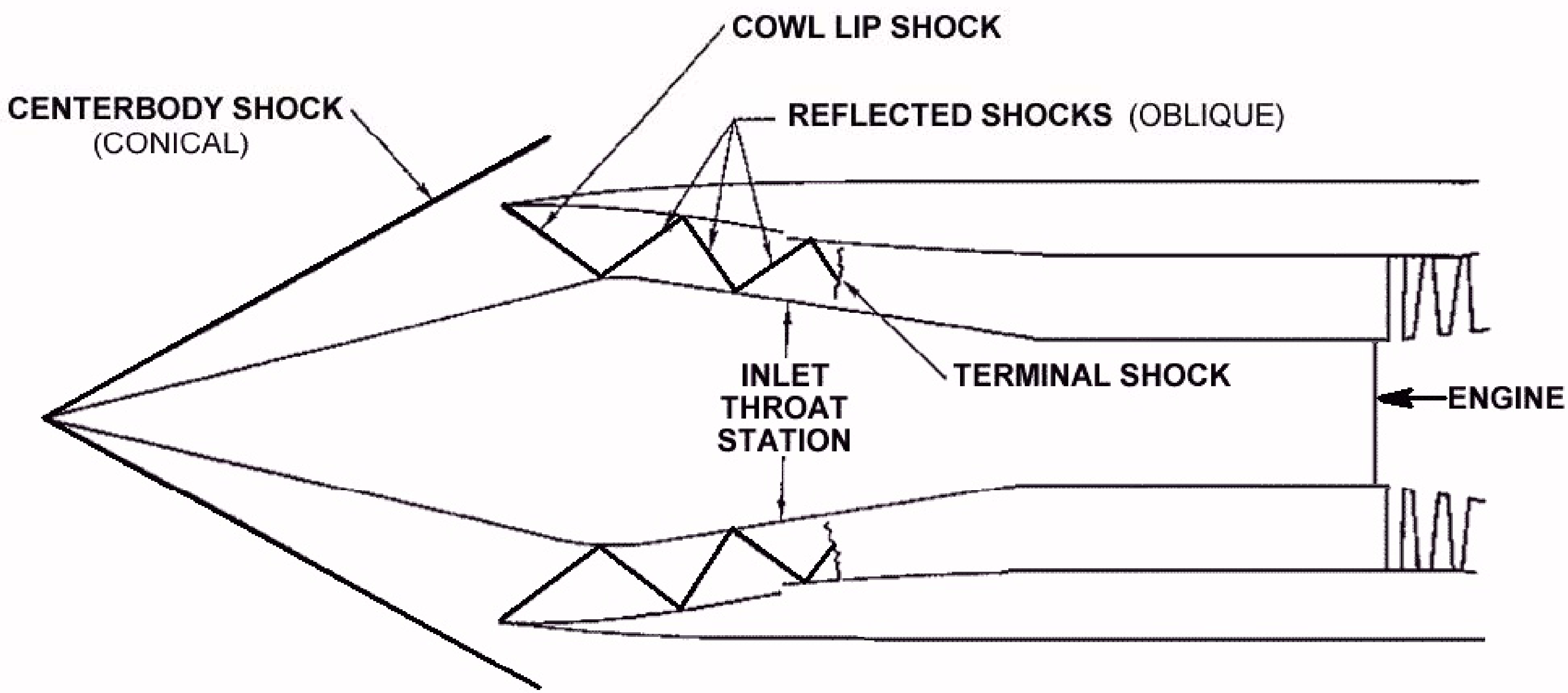
INLET REQUIREMENTS

- HIGH PRESSURE RECOVERY
- MINIMUM DRAG
- AIRFLOW CAPABILITY COMPATIBLE WITH ENGINE AIRFLOW REQUIREMENTS
- DUCT EXIT AIRFLOW DISTORTION ACCEPTABLE TO ENGINE
- AIRFLOW SUPPLY TO COOL ENGINE & OPERATE EJECTOR NOZZLE
- STABLE OPERATION

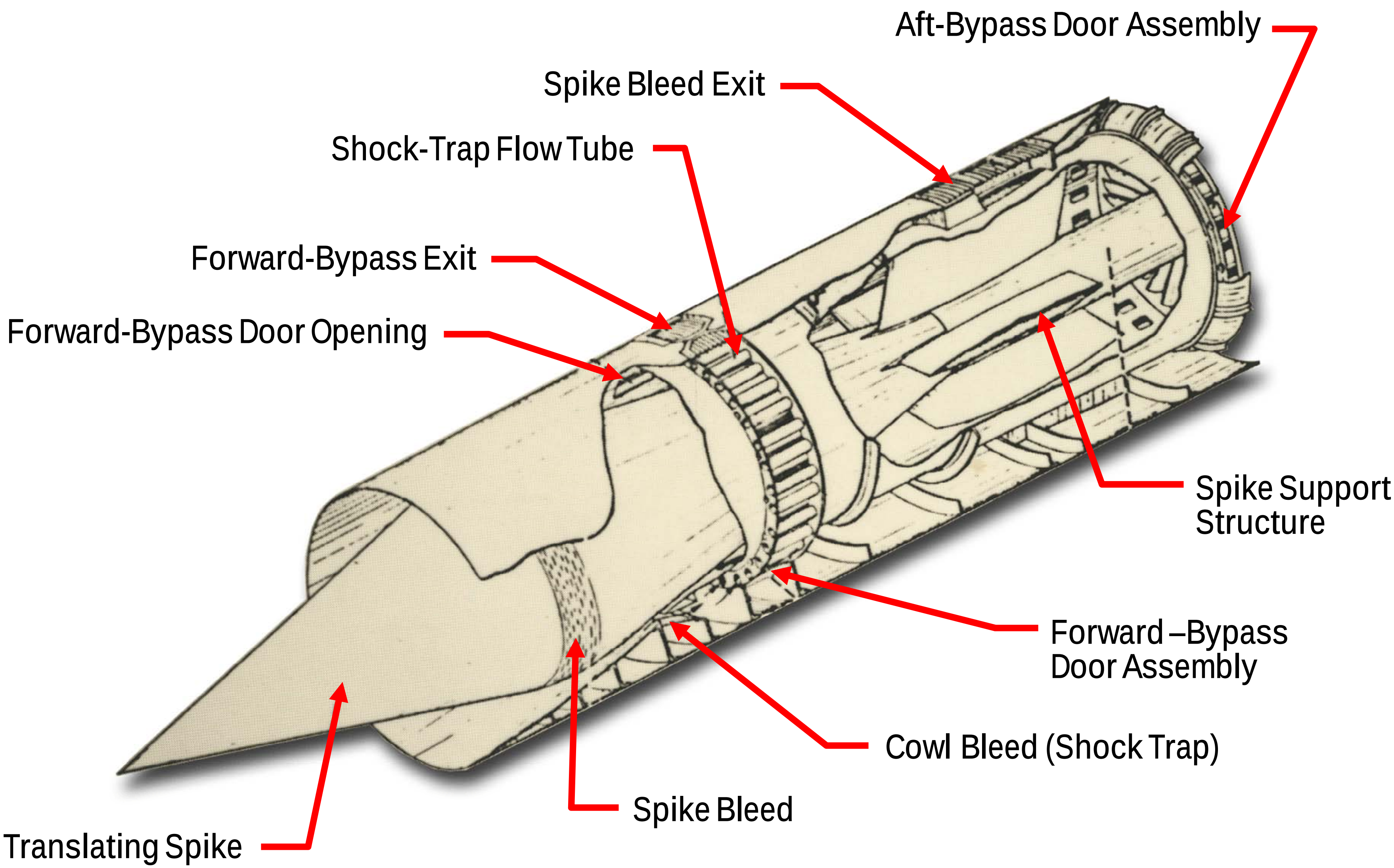
SR-71 AIR INLET DESIGN DRIVERS

- 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 VELOCITY
  - MINIMIZE THE TRANSIENT FLOW EFFECTS OF EXTERNAL DISTRUBANCES
- NO FIXED INLET CONFIGURATION CAN SIMULTANEOUSLY SATISFY THESE REQUIREMENTS OVER THE ENTIRE FLIGHT ENVELOPE AND ENGINE OPERATING RANGES
  - VARIABLE INLET GEOMETRY IS REQUIRED

AXISYMMETRIC MIXED COMPRESSION INLET DESIGN CONCEPT



INLET BLEED and BYPASS ARRANGEMENT



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

INLET SYSTEM

- INLET HAS A TRANSLATING 26-DEGREE CONE WHICH ACTS AS THE INITIAL DECELERATION OR COMPRESSION SURFACE PRODUCING A SERIES OF SHOCK WAVES UP TO THE INLET THROAT
- THE SHOCK TRAIN ENDS WITH A FINAL TERMINAL OR NORMAL SHOCK FOLLOWED BY A SUBSONIC DIFFUSER
- THE PURPOSE OF THE INLET IS TO SUPPLY THE AIR REQUIRED BY THE ENGINE AT THE HIGHEST PRESSURE RECOVERY AND THE LOWEST DRAG, WITH A MINIMUM OF DISTORTION. THIS IS NOT AS SIMPLE AS IT SOUNDS!
  - A TURBOJET ENGINE IS A CONSTANT VOLUME MACHINE. THIS MEANS THAT REGARDLESS OF FLIGHT SPEED – FROM M = 0 TO CRUISE SPEED – THE SPEED OR MACH NUMBER ENTERING THE ENGINE IS RELATIVELY CONSTANT, BETWEEN M = 0.3 AND 0.5

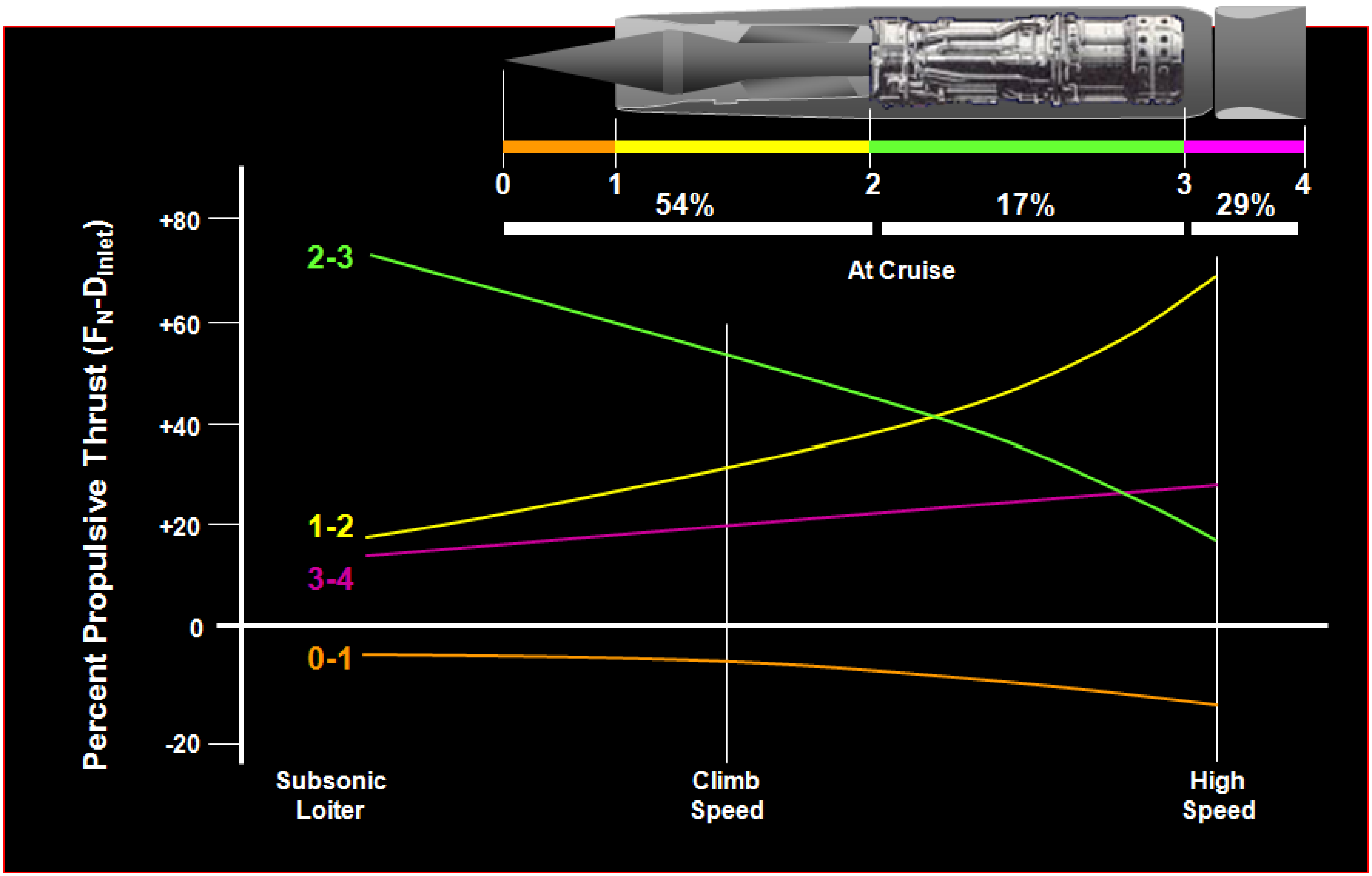
AIR INLET

- THE SR-71 ENGINE AIR INLET IS A MIXED EXTERNAL AND INTERNAL COMPRESSION, AXI-SYMMETRIC INLET, WITH GRADUAL ISENTROPIC COMPRESSION APPROACHING THE THROAT
- THE BOUNDARY LAYER WHICH BUILDS UP ON THE CENTERBODY IS REMOVED AHEAD OF THE TERMINAL SHOCK THROUGH A POROUS BLEED
- THIS BLEED PASSES OVERBOARD THROUGH LOUVERS AT THE ENDS OF THE CENTERBODY SUPPORT STRUTS
- FORWARD BYPASS DOORS, LOCATED CLOSE TO THE THROAT MATCH THE INLET TO THE ENGINE, BY-PASSING AIR OVERBOARD
- THE COWL BLEED IS A "SHOCK TRAP" RAM BLEED WHICH SUPPLIES AIR THROUGH TUBES ACROSS THE BY-PASS DOOR REGION INTO THE ENGINE SECONDARY PASSAGE, WHERE IT IS USED FOR COOLING, AND FED THROUGH TO THE ENGINE EJECTOR
- AFT BY-PASS FLOW JOINS THE COWL BLEED FLOW AND PASSES THROUGH THE ENGINE EJECTOR
- THIS BY-PASS WAS INSTALLED TO PROVIDE SUFFICIENT FLOW TO PERMIT ENGINE OPERATION AT IDLE
- DURING ACCELERATION, AFT BY-PASS IS USED TO REDUCE THE FORWARD OVERBOARD BY-PASS WITH ITS ATTENDANT DRAG

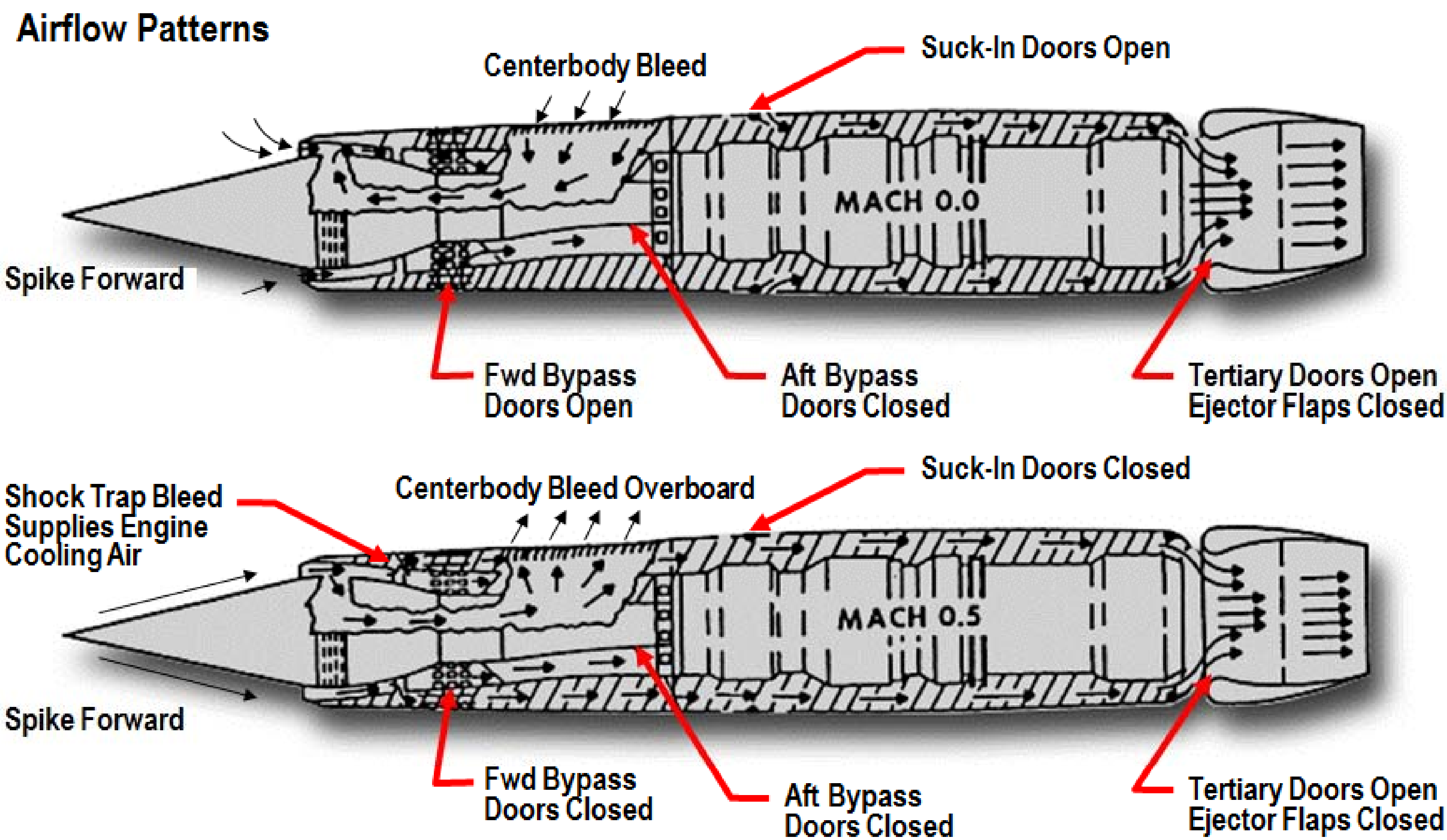
INLET SPIKE

- THE INLET SPIKES REGULATE THE AMOUNT OF AIR ENTERING THE INLET BY MOVING PROGRESSIVELY REARWARDS AS THE AIRCRAFT'S SPEED INCREASES
  - THE FULLY FORWARD POSITION WHICH THE SPIKE MAINTAINS UP TO MACH 1.4
  - THE SPIKE AT THE LIMIT OF ITS 26-INCH AFT TRANSLATION
  - THE CONFIGURATION OF THE INLET AT MACH 3 AND ABOVE
- AT THIS POINT THE CAPTURE AREA HAS INCREASED BY 112%, WHILE THE THROAT DIAMETER AT THE POINT OF MINIMUM CROSS-SECTION FURTHER DOWN THE INTAKE HAS DECREASED BY 54% IN ORDER TO HOLD THE TRI-SONIC SHOCKWAVE IN THE CORRECT POSITION
- AT MACH 2.2 THE INLET PRODUCES 13% OF THE OVERALL THRUST, THE ENGINE AND EJECTOR ACCOUNTING FOR 73% AND 14% RESPECTIVELY
  - THE CORRESPONDING FIGURES AT MAXIMUM CRUISING SPEED, MACH 3+ ARE 54%, 17%, AND 29%
  - MOST OF THE THRUST IS DEVELOPED BY THE INLET SPIKE

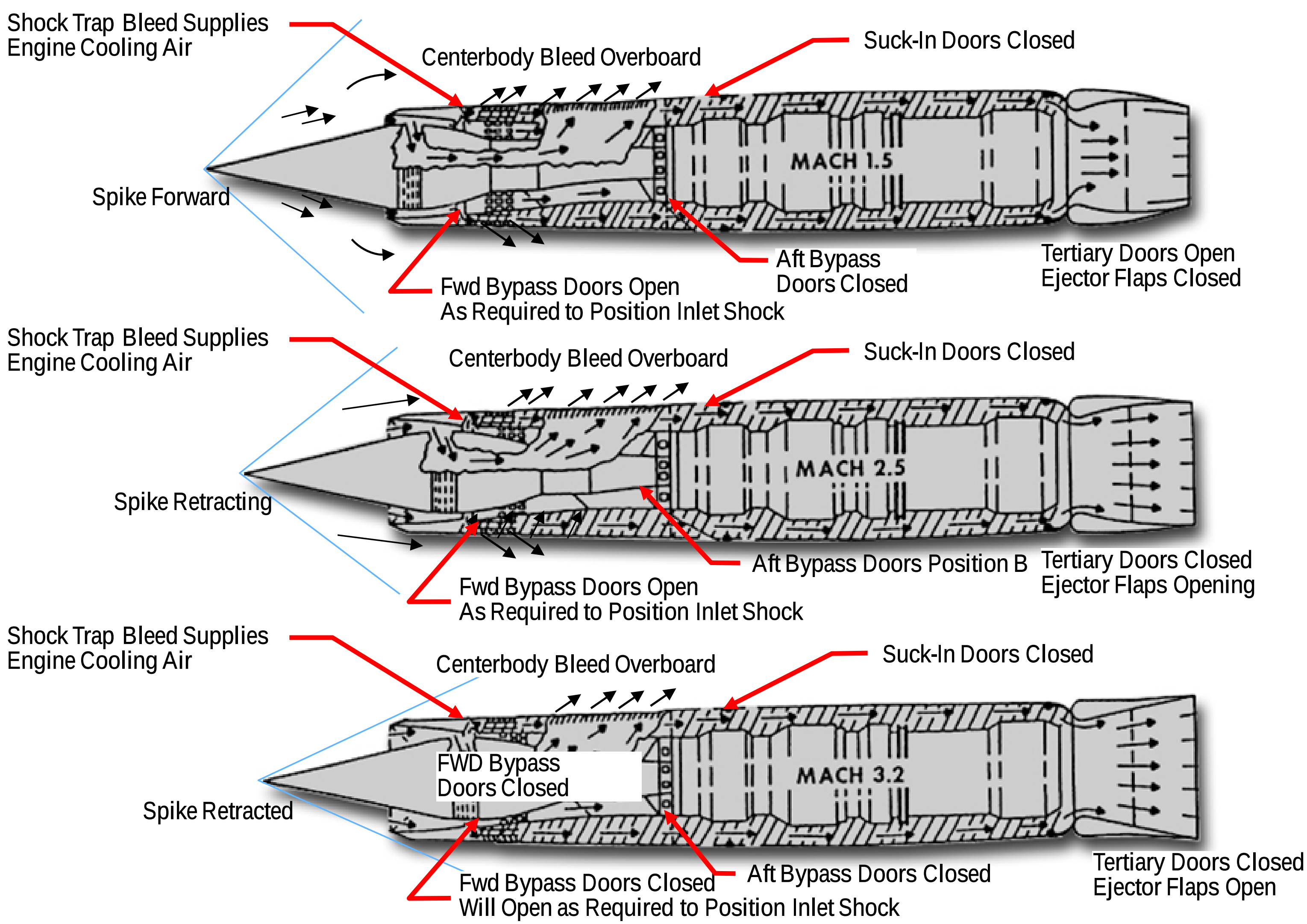
THRUST PRODUCTION



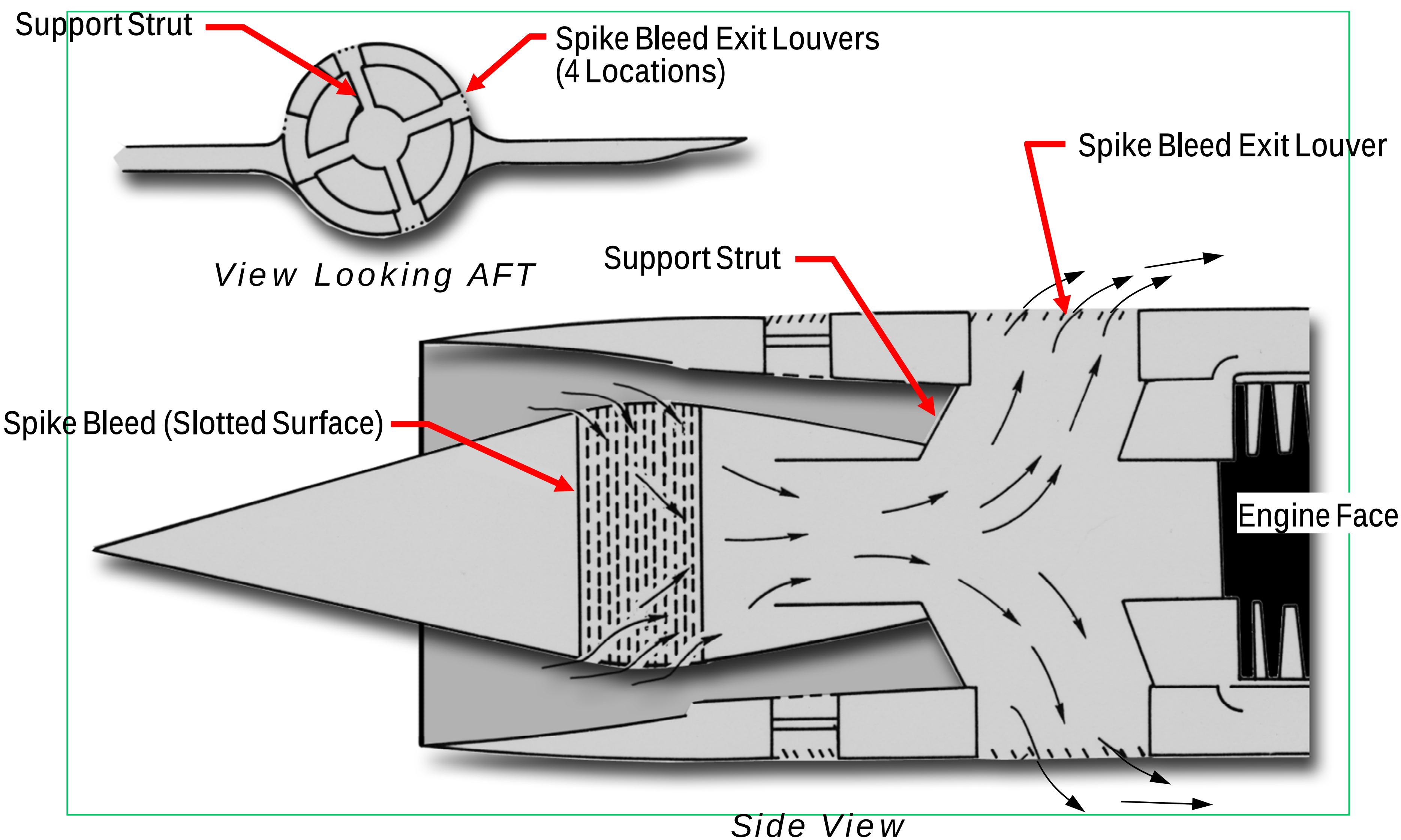
SR-71 INLET/EXHAUST AIRFLOW PATTERNS



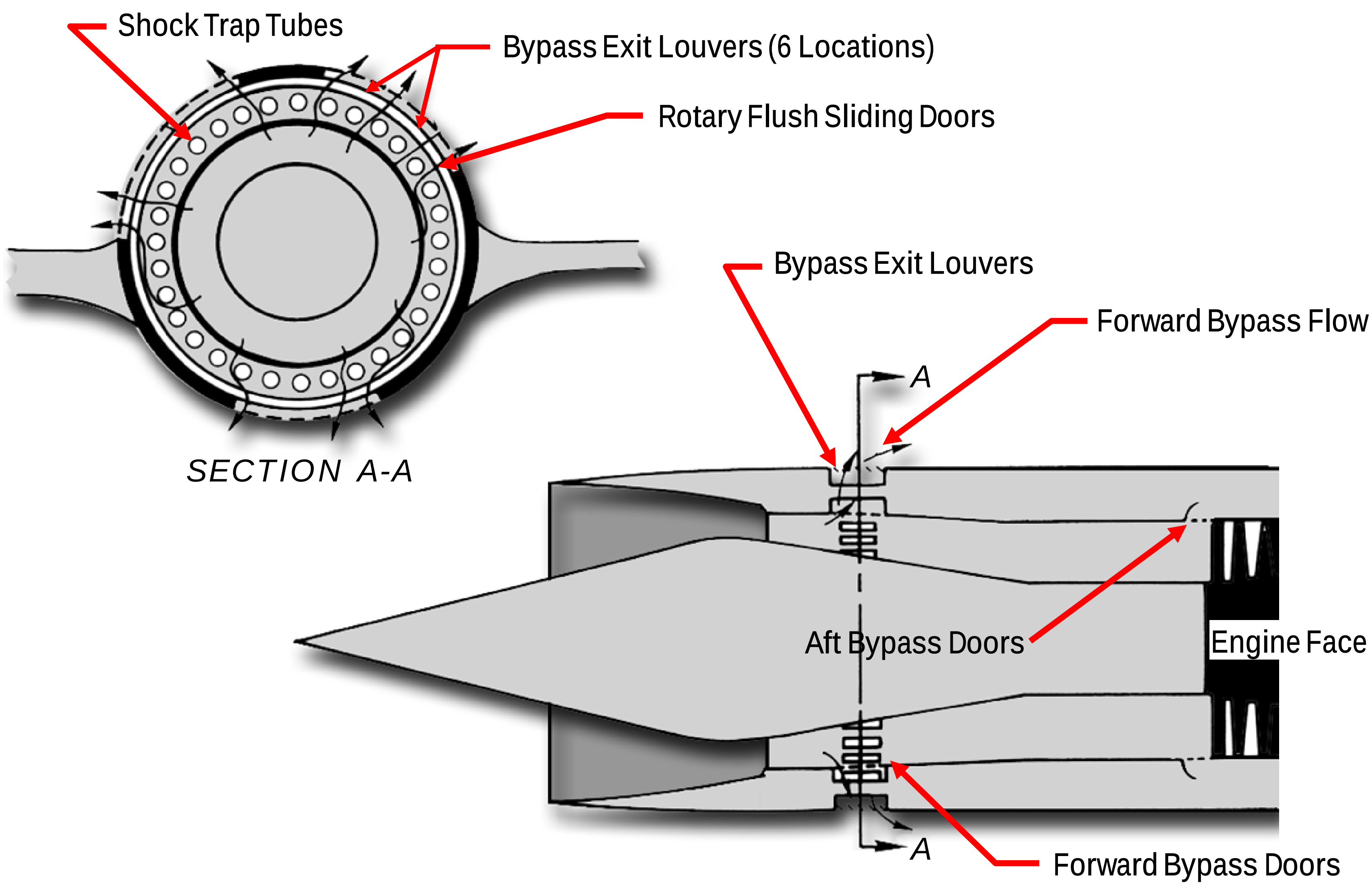
SR-71 INLET/EXHAUST AIRFLOW PATTERNS



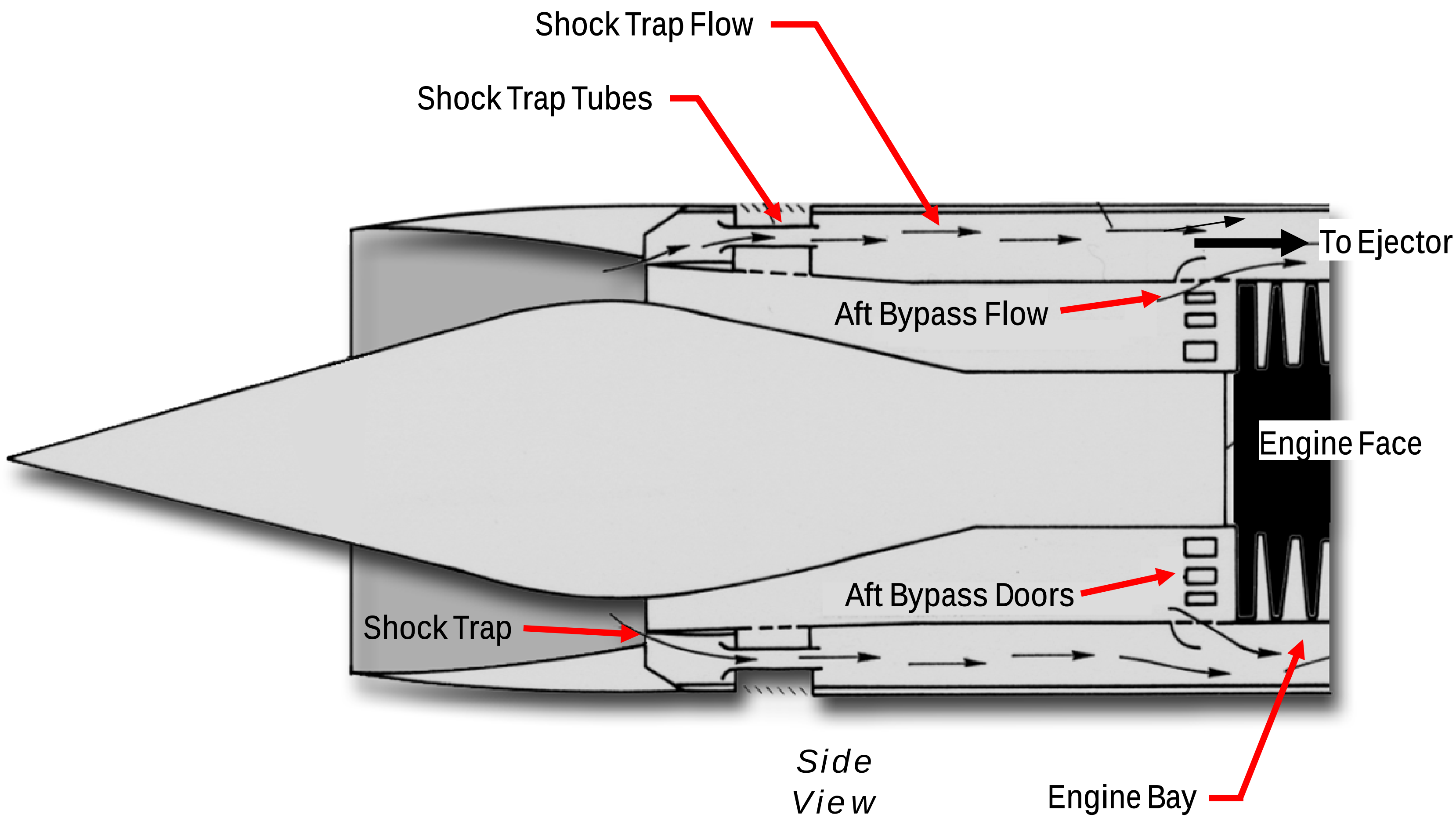
CENTERBODY BLEED ARRANGEMENT



FORWARD BYPASS



SECONDARY FLOW SYSTEMS
COWL BLEED AND AFT BYPASS



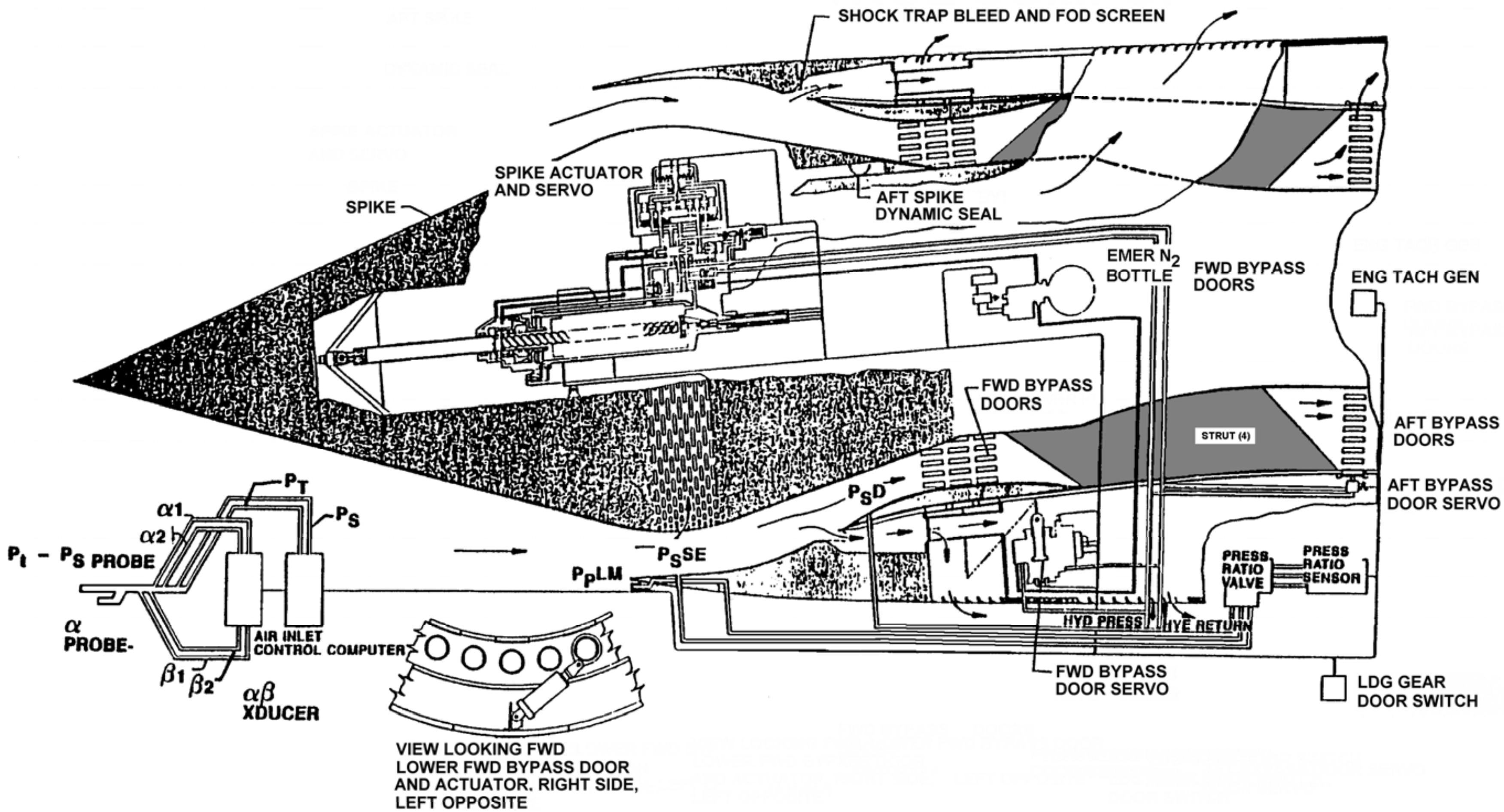
INLET CONFIGURATION AND CONTROL

- THE INLET UTILIZES DAFICS COMPUTERS FOR CONTROL OF SPIKE AND BYPASS DOORS
- SPIKE MOVEMENT IS CONTROLLED BY MACH NUMBER, ANGLE OF ATTACK, ANGLE OF YAW, AND LOAD FACTOR
- THE TERMINAL SHOCK POSITION IS CONTROLLED AND REGULATED BY FORWARD AND AFT BYPASS DOORS WHICH MATCH THE INLET AIR SWALLOWING CAPABILITY TO THE ENGINE REQUIREMENT
- THE COMPRESSION RATIO AT CRUISE IS 40 TO 1
- AT CRUISE, EACH INLET SWALLOWS APPROXIMATELY 100,000 CUBIC FEET OF AIR PER SECOND – EQUIVALENT TO TWO MILLION PEOPLE BREATHING ON THE GROUND
- INLETS CANTED INBOARD 3.2^{O} – EFFECT OF CHINE and FUSELAGE
- INLETS CANTED DOWN 5.6^{O} – EFFECT OF ANGLE OF ATTACK AT CRUISE

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, SLIDESLIP, AND NORMAL ACCELERATION BIAS
- NORMAL SHOCK MOVES DOWNSTREAM OF THE INLET THROAT (INLET STARTS) AT APROXIMATELY 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

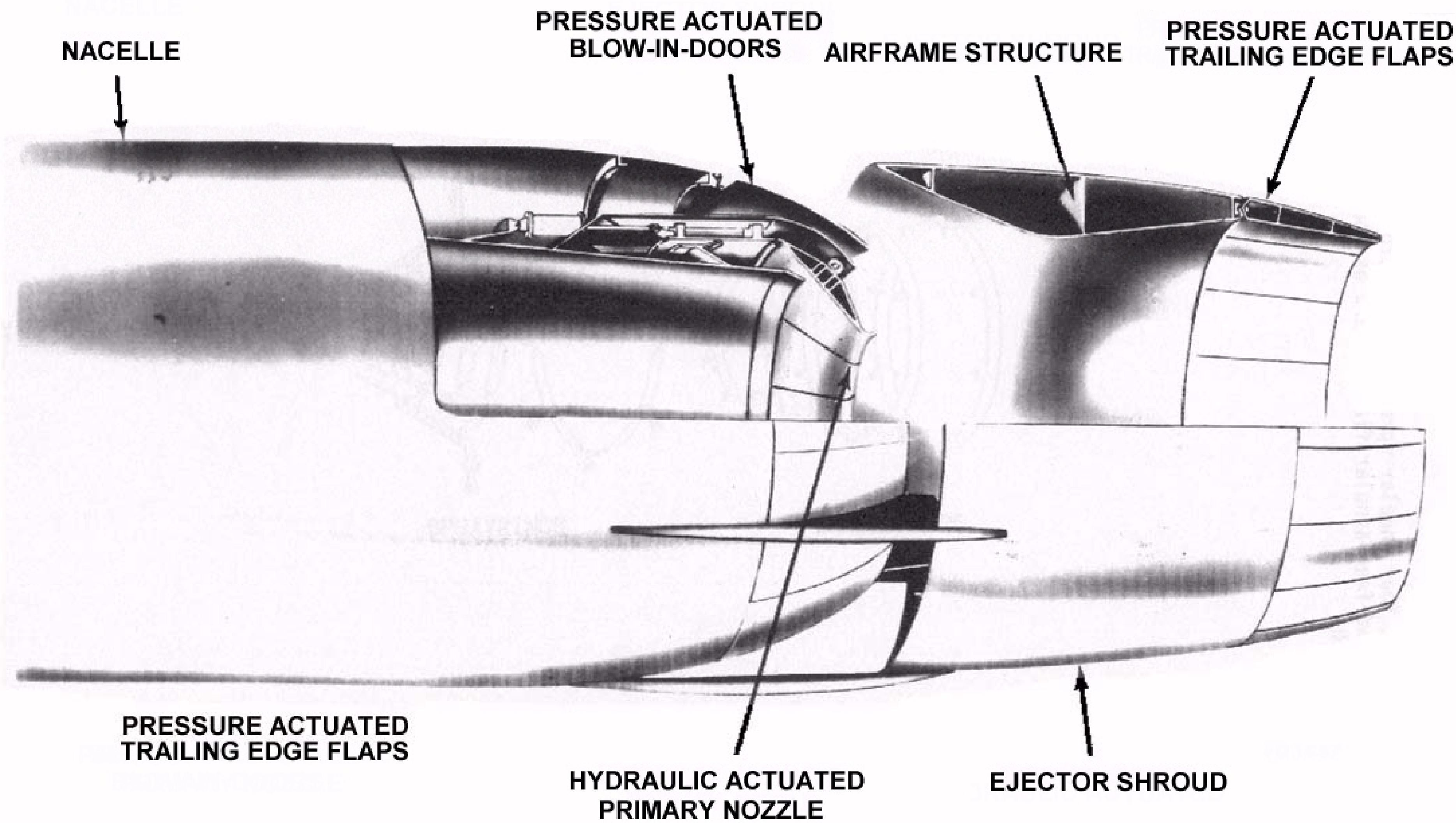
SR-71 AIR INLET CONTROL COMPONENTS



EJECTOR NOZZLE

- THE LAST PART OF THE PROPULSION SYSTEM IS THE EJECTOR
  - THE EJECTOR PERFORMS THE REVERSE FUNCTION OF THE INLET
  - IT ACCELERATES THE AIR COMING OUT OF THE TURBINE AT M = 0.4 UP TO M = 3.0+
  - THE EXIT VELOCITY MUST MATCH OR EXCEED THE FLIGHT SPEED, THEREFORE THE VARIABLE EXIT FLAPS. THEY STAY FULLY CLOSED UNTIL ABOUT M = 1.2, AND ARE FULLY OPEN AT ABOUT M = 3.2
- PRIMARY NOZZLE IS A RING OF BLOW-IN DOORS WHICH PROVIDE TERTIARY AIR TO FILL IN THE EJECTOR AT MACH NUMBERS BELOW 1.2
  - TERTIARY AIR IS PROVIDED BY SUCK-IN DOORS AROUND THE NACELLE, AUGMENTED BY THE COWL (SHOCK TRAP BLEED AND AFT BY-PASS BLEED)
  - MAIN EJECTOR IS SUPPORTED DOWNSTREAM ON STREAMLINED STRUTS AND A RING OF RENE 41 STEEL ALLOY ON WHICH ARE HINGED FREE-FLOATING TRAILING EDGE FLAPS OF HASTELLOY X

BLOW-IN-DOOR EJECTOR NOZZLE



REFERENCES:

1. Connors, Jack, *The Engines of Pratt & Whitney: A Technical History*, AIAA (American Institute of Aeronautics and Astronautics, Inc.), Reston, VA, 2010, pp. 321-332.
2. St. Peter, J., *The History of Aircraft Gas Turbine Engine Development in the United States: A Tradition of Excellence*, ASME, New York, 1999, pp.264-275.
3. Campbell, David H., *F-12 Series Aircraft Propulsion System Performance and Development*, AIAA No. 73821, 1973. Also found in AIAA Journal of Aircraft, Vol. 11, No. 11, November 1974, pp. 670-676. Note: This paper presents information only up to Mach 3.0 due to security restrictions at that time.
4. California Institute of Technology, Course Ae107, *Case Studies in Engineering: The Lockheed SR-71 Blackbird*, Spring 1991. Published by Cal Tech for course students and presenters only.
5. Anderson, J. Thomas, unpublished training course syllabus, *How Supersonic Inlets Work: Details of The Geometry And Operation Of The SR-71 Mixed Compression Inlet*, 2013.