FLIGHT TESTING – USAF PROGRAMS

**PHASE TESTING – CIRCA 1951**

I. AIRWORTHINESS
   - CONTRACTOR TEST PILOTS

II. CONTRACTOR COMPLIANCE
    - USAF TEST PILOTS

III. DESIGN REFINEMENT
     - CONTRACTOR TEST PILOTS

IV. PERFORMANCE & STABILITY
    - USAF TEST PILOTS
    - PRODUCTION AIRCRAFT

V. ALL WEATHER
   - USAF TEST PILOTS
   - PRODUCTION AIRCRAFT

VI. FUNCTIONAL DEVELOPMENT
    - USAF OPERATIONAL PILOTS
    - USAF TEST PILOTS
    - USAF MAINTENANCE PERSONNEL

VII. OPERATIONAL SUITABILITY & V. USING COMMAND

**CATEGORY TESTING – CIRCA 1958**

I. SUBSYSTEM DEVELOPMENT TEST AND EVALUATION
   - AIRWORTHINESS
   - OPERATING
   - CHARACTERISTICS
   - SUBSYSTEM PERFORMANCE
   - CONTRACTOR TEST PILOTS (USAF CONTROL IN 1963)

II. SYSTEM DEVELOPMENT TEST AND EVALUATION
    - SPEC COMPLIANCE
    - WEATHER
    - CONFIGURATION REFINEMENT
    - MAINTENANCE
    - LOGISTICS
    - CONTRACTOR AND USAF TEST PILOTS
    - SOME USER COMMAND PILOTS/PERSONNEL
    - INCLUDES MISSION EQUIPMENT

III. SYSTEM OPERATIONAL TEST AND EVALUATION
    - USER COMMAND

**JTF/CTF – CIRCA 1951**

- AFR 80-14 ESTABLISHED
- DT&E/OT&E TESTING
- CONTRACTOR TEST PILOTS
- USAF TEST PILOTS
- USING COMMAND PILOTS (PRIMARILY RESPONSIBLE FOR OT&E)

- USING COMMAND
## BLACKBIRD FLIGHT TEST PROGRAM

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**CATEGORY I**

**CATEGORY II**

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Lockheed Advanced Development Company
SR-71
FLIGHT TEST'S EARLY INVOLVEMENT IN PROGRAM

- SYSTEM/SUBSYSTEM DEVELOPMENT
  - FUEL SYSTEM MOCK-UP
  - FLIGHT CONTROLS/HYDRAULICS – IRON BIRD
  - FLIGHT SIMULATOR (RYE)
  - ENGINE DEVELOPMENT

- DRAFT FLIGHT MANUAL AND CHECKLISTS

- TEST PLANNING
  - PLANS
  - INSTRUMENTATION REQUIREMENTS
  - EXTEND ANALYSIS CHARTS > 2.0 MACH
    - ALTITUDE/CAS
    - ALTITUDE/EAS
    - $\gamma \neq 1.4$
SR-71
FLIGHT CREW SELECTION & TESTING

- FLYING BACKGROUND
- TEST EXPERIENCE
- PHYSICAL REQUIREMENTS
- TRAINING
SR-71
FLYING OPERATIONS

- GLOBAL FLIGHT TEST PLANNING
- ATC COMMUNICATIONS
- TANKER RENDEZVOUS
- INLET SYSTEM DEMANDS
- CHASE
SR–71 FLIGHT TEST

- TEST PHILOSOPHY
  - USE MILITARY SPECIFICATIONS AS GUIDES
  - TEST DESIGN FLIGHT PROFILE FIRST
  - MAKE OFF DESIGN EXCURSIONS WHERE APPROPRIATE
  - CONFIRM MISSION READINESS
CATEGORY I
SR-71
CATEGORY I FLIGHT TEST
VALIDATION ITEMS

- PERFORMANCE
- STABILITY AND CONTROL
- STRUCTURAL INTEGRITY
- SENSOR PLATFORM SUITABILITY
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SR-71
CATEGORY I FLIGHT TEST
TEST SUMMARY

- AIRCRAFT PERFORMANCE
  - AIRSPEED CALIBRATIONS
    - SUBSONIC
    - TRANSONIC
    - 2.0 AND 2.8 MACH (SPOT CHECKS)
  - AIRSPEED RANGE
    - 135 KEAS - MIN.
    - 500 KEAS - MAX.
    - 3+ MACH - MAX.
  - CLIMB PERFORMANCE
    - CONSTANT EAS ACCELERATIONS
    - SINGLE ENGINE
    - DIPSY-DOODLE
• AIRCRAFT PERFORMANCE (CONT’D)
  - SUBSONIC CRUISE
    - SPEED RANGE 0.7 TO 0.9 MACH
    - ALTITUDE RANGE 20,000 TO 33,000 FEET
  - SUPERSONIC CRUISE (2.0 TO 3+ MACH)

• STABILITY AND CONTROL
  - SAS ON/OFF
  - NOSE TILT CONFIG.

• STRUCTURAL LOADS
  - 80% TO 2.6 MACH/450 KEAS
  - 2.8 G SYMMETRICAL
  - 2.2 G ROLLING PULLOUTS
SR-71
CATEGORY I FLIGHT TEST
TEST SUMMARY
(CONTINUED)

- VEHICLE SYSTEMS
  - FUEL SYSTEM
  - AIRFRAME
  - AIR REFUELING
  - HYDRAULIC SYSTEM
  - ELECTRICAL SYSTEM
  - COMMUNICATIONS
  - FLIGHT CONTROLS
  - ENVIRONMENTAL CONTROL
  - LANDING GEAR/DRAG CHUTE
  - INLET CONTROL SYSTEM
  - PROPULSION

- SENSOR SYSTEM TESTING
  - NAVIGATION INTERFACE
  - RADAR
  - CAMERAS
  - MAP PROJECTORS
  - INFRARED
  - ELECTROMAGNETIC
SR-71

PROGRAM "UNSOLVED OPPORTUNITIES"

- TEMPERATURE RELATED
  - FUEL TANK SEALING
  - INLET SYSTEM STABILITY AND CONTROL/SCHEDULING
  - HYDRAULIC SYSTEM LEAKS
  - DATA ACQUISITION SENSORS

- OTHER
  - ENGINE FOREIGN (& FAMILIAR) OBJECT DAMAGE (FOD)
  - NACELLE EXHAUST NOZZLE MAINTENANCE
SR-71 FLIGHT TEST

- DATA ACQUISITION CHALLENGES - TEMPERATURE
  - TRANSDUCER COOLING
    - IN PLACE
    - MOVE INTERNALLY
  - TEMPERATURE MEASUREMENTS
    - REFERENCE JUNCTIONS
  - POSITION TRANSDUCERS
    - USE VEHICLE HARDWARE
  - STRAIN GAGE INSTALLATION
CATEGORY II
SR-71

CATEGORY II FLIGHT TEST

- PERFORMANCE
  - GROUND PROCEDURES
    - STARTING
    - TAXING
  - TAKEOFF
    - GROSS WEIGHT EFFECTS
    - LIFTOFF SPEED
  - CLIMB
    - SUBSONIC
      - 250, 400 AND 450 KEAS
      - MIN/MAX A/B
      - MILITARY POWER
    - TRANSONIC
      - 0.9 MACH TO 450 KEAS
      - 28,000, 30,000 AND 32,000 FT.
      - DIPSY-DOODLE
SR-71

CATEGORY II FLIGHT TEST
(CONTINUED)

• PERFORMANCE (CONT’D)
  - SUPersonic CLimb
    - 400, 425 AND 450 KEAS
    - CONSTANT MACH
    - 2.0, 2.8, 3.0, 3+
    - REDUCED POWER
  - SUPersonic CRUISE
    - CONSTANT ALTITUDE/MACH (2.0, 2.4, 2.8, 3.0 & 3+)
    - AFT BY-PASS DOOR SCHEDULING EFFECTS
    - RPM TRIM EFFECTS
    - C.G. EFFECTS
  - DESCENTS
    - NORMAL
    - SINGLE ENGINE
SR-71
CATEGORY II FLIGHT TEST
TEST SUMMARY
(CONTINUED)

- STABILITY AND CONTROL
  - LONGITUDINAL STABILITY
    -- STATIC
    -- DYNAMIC
    -- SPEED EFFECTS
  - MANEUVERING STABILITY
  - LATERAL DIRECTIONAL STABILITY
  - HANDLING QUALITIES
    -- TAKEOFF
    -- CLIMB
    -- SUPersonic CRUISE
    -- DESCENT
    -- AERIAL REFUELING
    -- APPROACH AND LANDING
SH-71
CATEGORY II FLIGHT TEST
TEST SUMMARY
(CONTINUED)

• SYSTEMS EVALUATIONS – OPERATIONS/MAINTENANCE VIEWPOINT
  - AIRFRAME
  - LANDING GEAR/DRAG CHUTE
  - HYdraulICS
  - FUEL SYSTEM
    - - OPERATION
    - - IN-FLIGHT REFUELING
  - ELECTRICAL SYSTEM
  - FLIGHT CONTROLS
  - ENVIRONMENTAL/CONTROL
  - COMMUNICATIONS/NAVIGATION
  - CREW SYSTEMS
  - SENSOR SYSTEMS
LOCKHEED SR-71 BLACKBIRD

Crusing speed: Mach 3
Maximum speed: classified
Empty weight: classified

Service ceiling: 85,000-plus ft. (25,900 m)
Normal range: classified
Number produced by Lockheed: classified

For 24 years, top decision-makers, including the president of the United States, relied on photographic and other data gathered by SR-71 Blackbirds during supersonic flights. The Air Force's Strategic Air Command began deploying the SR-71 and its advanced sensor systems on reconnaissance missions in 1966. It was the first operational airplane capable of achieving speeds above Mach 3.

Fabricated of titanium, a major technological breakthrough, Blackbirds withstood the extremely high temperatures encountered by flying three-times the speed of sound. Designer Kelly Johnson and his Lockheed Aeronautical Systems Company "Skunk Works" team had to devise high temperature fuels, sealants, lubricants, special wiring and other components especially for the aircraft.

Although its many contributions to national security will never be fully revealed to the public, the SR-71 wrote a new chapter in the annals of aviation records. An Air Force crew flying an SR-71 on a non-stop, 15,000-mile (24,140-km) flight of 10-½ hours received the 1971 Mackay Trophy for the "most meritorious flight of the year" and the 1972 Harmon International Trophy for the "most outstanding international achievement in the art/science of aeronautics."

On Sept. 1, 1974, an SR-71 set a trans-Atlantic record of 1 hour, 54 minutes, 56 seconds, on a 3,470-mile (5,580-km) flight from New York to London. The same aircraft later established a world speed record of 3 hours, 47 minutes, 36 seconds, on a 5,463-mile (8,790-km) flight from London to Los Angeles.

Three SR-71s flown by three different crews set seven world speed and altitude records on July 27 and 28, 1976. They recaptured three records from the Russian MiG-25 Foxbat and bettered four records held by the Lockheed/USAF YF-12A. These included absolute and class records of 2,193 mph (3,530 km/h) for speed over a straight course. For altitude in level flight, an SR-71 set absolute and class records of 85,069 feet (25,930 m).

The Air Force retired its fleet of SR-71s from service in January 1990. In March of 1990 the Smithsonian Institution received an SR-71 for permanent display at its facility at Dulles International Airport near Washington, D.C.
**IR CONTRIBUTORS (U)**

- **TURBINE FACE = 1500°F**
- **ENGINE SIDEWALL = 1000°F**
- **EARTH SHINE = 60°F**
- **AIRCRAFT EMISSION = 32°F**

**SPECTRAL RADIANCE**

(W/m²/sr/µm)

**WAVELENGTH ~ (MICROMETERS)**
INTERNAL THERMAL ENVIRONMENTS

- INTERNAL THERMAL ENVIRONMENTS WERE ESTABLISHED TO SUSTAIN REQUIRED CREW AND EQUIPMENT OPERATING ENVIRONMENTS

  - CREW COMPARTMENT: INSULATED WITH 3" OF FIBERGLASS INSULATION AND PROVIDED WITH COOLING/HEATING AIR TO PROVIDE A 70°F ENVIRONMENT FOR THE CREW AND COCKPIT EQUIPMENT, WITH DIRECT COOLING TO CREW SUITS FOR TRIM CONDITIONING AND FOR EMERGENCY CONDITIONS.

  - AVIONIC EQUIPMENT AND MISSION EQUIPMENT BAYS DESIGNED FOR MAXIMUM NORMAL OPERATION OF 160°F. COLD AIR (BETWEEN -30°F AND +45°F) SUPPLIED TO EQUIPMENT, AND EQUIPMENT EXHAUST AIR CASCADES FROM BAY-TO-BAY ON ITS WAY OUT OF THE AFT-MOST EQUIPMENT BAY. ACTUAL BAY TEMPERATURES VARY BETWEEN 50°F AND 140°F DEPENDING UPON LOCATION AND HEAT LOAD EXPENDED. DURING SINGLE ECS PACKAGE OPERATION, MISSION EQUIPMENT (AND ITS AIR SUPPLY) ARE SHUT DOWN AND BAY ENVIRONMENT IS ALLOWED TO RISE TO 200°F. PRIMARY AIR COOLING FLOW IS TO CREW COMPARTMENT AND FLIGHT CRITICAL EQUIPMENT.

  - UNCOOLED BAYS, WHERE MISCELLANEOUS EQUIPMENT LINES, WIRES, PIPES AND HOSES ARE LOCATED, ARE INFLUENCED DIRECTLY BY THE SURROUNDING STRUCTURAL TEMPERATURES AND BY THE TEMPERATURE OF ANY INCOMING LEAKAGE AIRFLOW, SUCH AS RAM FLOW OR NACELLE LEAKAGE AIRFLOW. UNCOOLED BAY ENVIRONMENTS RANGE FROM 450°F TO 800°F.
INTERNAL THERMAL ENVIRONMENTS
(CONTINUED)

- **FUEL TANK INTERNAL ENVIRONMENT IS A BALANCE BETWEEN THE FUEL, THE FUEL VAPOR, THE NITROGEN INERTING GAS, AND THE SURROUNDING SKIN AND STRUCTURE. THE ENVIRONMENT OF TANKS CONTAINING FUEL IS FROM 70°F TO 200°F AND OF TANKS EMPTIED DURING FLIGHT, 450°F TO 600°F.**

- **NACELLE ENVIRONMENT IS FROM 800°F TO 1000°F DEPENDING UPON LOCATION.**

- **DRAG CHUTE COMPARTMENT IS SUBMERGED INTO THE LAST FUEL TANK TO BE USED AND IS, THEREFORE, KEPT COOL BY THE SLOW TRANSIENT TEMPERATURE RESPONSE OF THE FUEL; ENVIRONMENT IS 80°F TO 200°F.**

- **NOSE WHEEL WELL IS COOLED BY AIR EXHAUSTING FROM THE ENVIRONMENT CONTROL SYSTEM EQUIPMENT BAY ABOVE; ENVIRONMENT IS 50°F TO 140°F.**

- **MAIN WHEEL WELL COMPARTMENTS ARE COOLED BY CONVECTION AND RADIATION TO FUEL TANK BULKHEAD SURFACES AT THE FORWARD AND AFT ENDS OF THE TWO MAIN WHEEL WELLS. THE MAIN GEAR RETRACTS INTO AN INSULATED CAN WHICH COMPLETELY ENCLOSURES THE WHEELS AND BRAKES AND ACTS TO PROTECT THE FORE AND AFT FUEL TANK BULKHEADS IN CASE OF A TIRE FAILURE. THIS INSULATED TIRE CAN HELPS TO SHIELD THE GEAR STRUCTURE AND THE TIRES FROM THE HOTTER SURFACES IN THE AREA. ENVIRONMENT OF THE MAIN WHEEL WELL SHOULD BE LESS THAN 550°F. TYPICAL MAIN GEAR TEMPERATURES ARE PRESENTED TO SHOW THE TRANSIENT RESPONSE ACTUALLY MEASURED DURING FLIGHT TESTS.
COCKPIT THERMAL ENVIRONMENT

CRUISE MACH NO.

710°F BOUNDARY LAYER AIR

550°F SKIN

90°F TRIM

3 INCHES OF INSULATION

SPECIAL HIGH EMISSIVITY BLACK PAINT

CANOPY
FUEL TANK SURFACE TEMPERATURE DATA

- WING TANK FRONT BEAM (□)
- FUSELAGE TANK TOP SURFACE (△)
- FUEL TANKS
- INLET SPIKE
- ENGINE INLET TOTAL TEMPERATURE
  - WING TANK FRONT BEAM (□ ———)
  - FUSELAGE TANK TOP SURFACE (△ ——— ———)

TEMPERATURE VS. TIME
FUEL TEMPERATURE TEST DATA

--- PREDICTION FOR "DESIGN MISSION" ---

○ TEST DATA FOR TYPICAL FLIGHT △

ENGINE SUPPLY TEMPERATURES

FUEL TANK EXIT TEMPERATURES

TIME

TEMPERATURE - °F

0 100 200 300
SR-71 THERMAL ENVIRONMENT SUMMARY

- Environments were established for all areas of the vehicle.
- Materials were selected and systems, components, and fluids identified.
- Tests were run on most systems and structures at temperature.
- Flight test undertaken to verify environments and equipment operation.
- Vehicle very successful at operating in the severe thermal environment.
- Vehicle still the fastest aircraft flying after 29 years.
SR-71
ENVIRONMENTAL
CONTROL
SYSTEM

PETER V. LAW
DEPARTMENT MANAGER, THERMODYNAMICS
ENVIRONMENTAL CONTROL SYSTEM

- The environmental control system of the SR-71 was unique compared to those of other aircraft flying in the era of its design in that it met at least two criteria never accomplished before during steady-state flight in an operational aircraft.

  - It operated in a steady state environment where the external ram air temperature was 800 °F continuously.

  - It utilized fuel as the primary heat sink in direct contact with the cooling air supplied to the crew station and to all the vehicle's air cooled equipment.

- The ECS also had to utilize engine bleed air above 1200 °F as the source of high pressure air for vehicle air conditioning, and the bleed air had to be cooled to -30 °F to meet the cooling requirements of the crew and avionic equipment contained in the SR-71.

- Integrating the ECS with the vehicle fuel system resulted in one of the first applications of a "thermal management system" in an operational aircraft.
SR-71 ENVIRONMENTAL CONTROL SYSTEM
ENVIRONMENTAL CONTROL SYSTEM FUNCTIONS

- ENVIRONMENTAL CONTROL SYSTEM (ECS) PROVIDES THE FOLLOWING:
  - CREW COMPARTMENT COOLING AND PRESSURIZATION AIR
  - FLIGHT ESSENTIAL EQUIPMENT COOLING AIR
    ■ ELECTRICAL LOAD CENTER EQUIPMENT AND BAY ENVIRONMENT (E-BAY)
    ■ COMMUNICATIONS EQUIPMENT AND BAY ENVIRONMENT (R-BAY)
    ■ ASTROINERTIAL NAVIGATION SYSTEM AND BAY ENVIRONMENT (A/C BAY)
  - MISSION EQUIPMENT COOLING AIR AND BAY ENVIRONMENT
  - CANOPY SEAL PRESSURIZATION AIR
  - WINDSHIELD DEFOGGING AIR
  - WINDSHIELD ANTI-ICING AIR

- DEVELOPMENT OF ECS: A COMBINED EFFORT BETWEEN LOCKHEED AND GARRETT-AIRESEARCH
  - LOCKHEED ESTABLISHED DESIGN REQUIREMENTS AND PERFORMANCE
    ■ LOCKHEED CONTRIBUTORS TOWARD SYSTEM DESIGN: KELLY JOHNSON, BEN RICH, DOUG CONE, RUPE TRINIDAD, JOHN GARDNER, PETE LAW, GENE GALLICK, WILLY CRANS, LEON KROOK, BERT SCATES, AND ALEX SIMAN
  - GARRETT-AIRESEARCH ESTABLISHED HARDWARE REQUIREMENTS AND PRODUCED COMPONENTS
    ■ AIRESEARCH CONTRIBUTORS TOWARD HARDWARE PRODUCTION: PAUL ELKINS, BOB MUELLER, ERV AUSTIN, JIM COOPER, RUDY RASMUSSEN, AND BOB BOSTICK
ENVIRONMENTAL CONTROL SYSTEM BREAKDOWN

- ENVIRONMENTAL CONTROL SYSTEM (ECS) FUNCTIONAL HARDWARE DESCRIPTION
  - AFT FUSELAGE: EQUIPMENT IN ENGINE COMPARTMENT, MAIN WHEEL WELL AND AFT FUSELAGE FILLET AREA
  - FORWARD FUSELAGE: EQUIPMENT IN AIR CONDITIONING BAY (A/C BAY)

- FUEL HEAT SINK SYSTEM PHILOSOPHY AND FUNCTIONAL HARDWARE DESCRIPTION

- CREW COMPARTMENT SYSTEMS
  - CREW COMPARTMENT DISTRIBUTION SYSTEM AND PRESSURE SCHEDULE
  - COCKPIT PRESSURE REGULATOR
  - COCKPIT SAFETY VALVE
  - CANOPY SEAL SYSTEM
  - CREW SUIT CONDITIONING SYSTEM
  - WINDSHIELD DEFOG SYSTEM
  - WINDSHIELD DE-ICE SYSTEM

- COLD AIR DISTRIBUTION SYSTEM DESCRIPTION: EQUIPMENT COOLING AIR

- BAY ENVIRONMENTAL CONDITIONING METHODS: CASCADING AIRFLOW

- MISSION RECORDER SYSTEM DESCRIPTION
GENERAL ECS LAYOUT

- ENVIRONMENTAL CONTROL SYSTEM UTILIZES HIGH PRESSURE/HIGH TEMPERATURE ENGINE COMPRESSOR DISCHARGE BLEED AIR AS THE SOURCE FOR THE AIRCRAFT COOLING SYSTEM.

- AIR FROM EACH ENGINE IS PRE-COOLED AND PRESSURE REGULATED IN A PACKAGE LOCATED ADJACENT TO THE NACELLE OUTBOARD OF THE MAIN WHEEL WELL.

- PRE-COOLED AIR IS ROUTED FORWARD IN THE FUEL TANK/WING FILLET AREA OUTSIDE OF THE FUEL TANK AND ABOVE THE WING.

- AIR THEN ENTERS THE AIR CONDITIONING BAY (A/C BAY) AND EACH ENGINE FEEDS AN INDEPENDENT AIR CONDITIONING SYSTEM CONTAINING SEVERAL COMPONENTS

- AIR IS ALSO AVAILABLE FOR THE WINDSHIELD DE-ICER SYSTEM FROM EACH ENGINE.

- THE DUAL AIR CONDITIONING PACKAGE CONFIGURATION ALLOWS FOR OPERATION WITH ONE ENGINE NOT FUNCTIONING OR ONE ECS PACKAGE NOT FUNCTIONING, RESULTING IN IMPROVED RELIABILITY.

- THE VARIOUS ELEMENTS OF THE ECS WILL BE DISCUSSED IN DETAIL.
AFT ECS EQUIPMENT SCHEMATIC

- SENSE LINE
- PNEUMATIC THERMOSTAT (200° ± 20°F)
- HOT AIR BYPASS SOLENOID VALVE
- MIXING MUFF
- HOT AIR BYPASS VALVE
- RAM AIR INLET
- 760°F
- HOT AIR BYPASS LINE
- PRESSURE REGULATOR AND SHUTOFF VALVE
- TO AIR CONDITIONING BAY
- 160°F
- 130°F
- FUEL LINES
- PRIMARY AIR-TO-FUEL EXCHANGER
- HEAT SINK PACKAGE
- AIR-TO-AIR HEAT EXCHANGER
- ENGINE COMPRESSOR BLEED AIR
- 830°F
- 1230°F
- 130°F
- 830°F
- 1230°F
- PACKAGE AIR-TO-AIR HEAT EXCHANGER
- 1230°F
AFT ECS EQUIPMENT DESCRIPTION

- ENGINE COMPRESSOR BLEED AIR IS COLLECTED FROM THREE ENGINE BLEED PORTS AND DUCTED TO AN AIR-TO-AIR HEAT EXCHANGER IN THE NACELLE, UTILIZING ENGINE INLET DUCT RAM AIR FOR COOLING. THIS RAM AIR IS THEN EXHAUSTED INTO THE ENGINE COMPARTMENT, MIXED WITH OTHER ENGINE BYPASS AIR, AND USED FOR VENTILATION AND COOLING. THE BLEED AIR IS COOLED FROM ABOUT 1250° F TO ABOUT 850° F.

- BLEED AIR IS ROUTED FROM THE NACELLE AREA TO THE HEAT SINK PACKAGE LOCATED JUST OUTBOARD OF THE MAIN WHEEL WELL. THERE IT IS COOLED BY THE PRIMARY AIR-TO-FUEL HEAT EXCHANGER WITH FUEL FLOWING THROUGH THE AIRCRAFT'S FUEL HEAT SINK SYSTEM.

- BLEED AIR IS THEN REGULATED TO REDUCE THE PRESSURE SUPPLIED TO THE FORWARD A/C BAY TO ABOUT 26 PSIG. THE PRESSURE REGULATOR ALSO FUNCTIONS AS A SYSTEM SHUTOFF VALVE.

- BELOW 44,000 FEET THE BLEED AIR IS CONTROLLED TO 200° ±20° F BY A PNEUMATIC THERMOSTAT OPERATING A HOT AIR BYPASS VALVE. THIS WARM AIR IS REQUIRED FOR WINDSHIELD DEFOGGING AIR AND DE-ICER AIR AND FOR TEMPERATURE CONTROL OF COLD AIR SUPPLIED TO THE CREW AND THE AVIONIC EQUIPMENT WHEN OPERATING AT LOW SPEED AT INTERMEDIATE ALTITUDES IN COLD ENVIRONMENTS.
PRIMARY AIR-TO-AIR HEAT EXCHANGER CONFIGURATION
AIR-TO-AIR AND AIR-TO-FUEL HEAT EXCHANGER DETAILS

• AIR-TO-AIR HEAT EXCHANGER:
  - Configuration is plate-fin on each side; flow arrangement is one pass crossflow
  - Construction is of stainless steel
  - Fins are nickel for improved fin effectiveness by conduction
  - Cools engine bleed air from 1250°F to 850°F utilizing ram air

• AIR-TO-FUEL PRIMARY HEAT EXCHANGER (FIRST KNOWN OPERATIONAL APPLICATION)
  - Heat exchanger is a tube-bundle configuration, with bleed air making one pass through the tubes and the fuel making several passes across the tubes
  - Fuel is in direct contact with the tubes containing the bleed air
  - Double header at each end of unit eliminates the problem of fuel leakage into the ECS air due to tube/header interface leaks
  - Vent from double header is overboard, so any fuel leaks can be spotted during ground runs before or after flights
  - Fuel pressure is higher than bleed air pressure in the tubes, so bleed air is never introduced into the fuel. Any air leaking at the tube/header interface flows overboard through the double header vent.
  - Tubes contain turbulators on the air side to increase heat transfer capability

• TEMPERATURE CONTROL
  - Control valve regulates bleed air bypassed around both heat exchangers to achieve desired heat sink package outlet temperature below 40,000 feet.
BLEED DUCTING INSULATION

OUTER COVER ALUMINIZED GLASS CLOTH

SILICONE RUBBER COATING

FIBERGLASS INSULATION (4 LAYERS)

0.005-INCH ALUMINUM FOIL

0.001-INCH ALUMINUM FOIL INNER LINER

BINDING TAPE

SECTION A-A

TYPICAL SECTIONS

AIR CONDITIONING BAY

DEICING SYSTEM

SUPPLY DUCT

BLEED AIR FILTER

BLEED AIR FILTER

EXPANSION JOINT

EXPANSION JOINT

PRIMARY AIR-TO-FUEL HEAT EXCHANGER

PNEUMATIC THERMOSTAT

SUPPLY DUCT
BLEED AIR FILTER AND BLEED AIR DUCTING INSULATION DETAILS

- Air from the heat sink package is ducted forward through 3" O.D. ducts covered with one-half inch of multi-layered fiberglass insulation containing three layers of aluminum foil radiation barriers, with an aluminized outer coating. This reduces the amount of heat the cooled bleed air picks up between the aft heat sink package and the forward air conditioning equipment bay during high-speed operation. Air is ducted along the upper fillet area of the chine.

- Bleed air filter
  - Bleed air filter is identical to the fuel filter located in the main engine feed line, consisting of a very fine wire mesh with an internal bypass valve.
  - Filter is to trap foreign particles that could damage equipment in the air conditioning package in the forward bay, such as the waspaloy particles scavanged from the compressor housing by the compressor blades.
  - Filter was added to the original system when these waspaloy particles actually eroded the aluminum turbine wheel in a turbine/compressor unit in the air conditioning equipment bay. The filter element is periodically inspected and changed.
GENERAL ECS LAYOUT

- AIR CONDITIONING BAY
- BLEED AIR FILTER
- AIR-ID-AIR HEAT EXCHANGER
- RAM AIR INLET
- ENGINE COMPRESSOR BLED AIR
- WINDSHIELD WIPER SYSTEM
AIR CONDITIONING BAY EQUIPMENT DESCRIPTION

- Air ducted from the heat sink package, through the bleed air filter and through the insulated ducting, enters the air conditioning equipment (A/C bay) located just aft of the aft cockpit.

- Windshield de-icer system air is supplied from just upstream of the A/C bay to the de-icer manifold through two shutoff valves.

- Airflow is limited to a specific maximum rate by the flow control valve; the maximum flow is determined by upstream pressure and temperature.

- Air is then compressed to a higher pressure (and temperature) by the compressor portion of the cooling package turbine compressor.

- The high pressure, high temperature air is then cooled by the secondary air-to-fuel heat exchanger, which utilizes fuel circulating through the heat sink system.

- The air is then expanded through the turbine portion of the cooling package turbine/compressor to the low pressure in the cold air manifold. The work expended by this expansion process reduces the energy level of the air, and at high altitude and high speed, with cool fuel, the turbine exhaust temperature can be as low as -70°F. The work taken out of the turbine drives the compressor. This type of cooling method is called a "bootstrap" air cycle system.

- Turbine exhaust air is heated to a value of 37°F below 44,000 ft and -30°F above 44,000 feet through a control valve utilizing compressor inlet air as the heat source.
AIR CONDITIONING BAY EQUIPMENT DESCRIPTION
(CONTINUED)

- CONDITIONED AIR FROM EACH TURBINE IS SUPPLIED TO A COMMON DISTRIBUTION MANIFOLD REFERRED TO AS THE COLD AIR MANIFOLD. THIS AIR IS DISTRIBUTED TO VARIOUS BAYS IN THE AIRCRAFT FOR COOLING THE CREW AND THE EQUIPMENT.

- WARM AIR FOR COCKPIT TEMPERATURE CONTROL IS AVAILABLE FROM A WARM AIR MANIFOLD, WHICH OPERATES BETWEEN 100 F AND 180 F DEPENDING UPON THE AIRCRAFT FUEL TEMPERATURE.

- AT LOW ALTITUDE, MOISTURE IS REMOVED FROM THE AIR SUPPLIED TO THE EQUIPMENT BAYS BY MEANS OF TWO WATER SEPARATORS, ONE FOR EACH SIDE OF THE VEHICLE.

- COOLING TURBINE/COMPRESSOR:
  - SMALL ALUMINUM TURBINE WHEEL WITH A TIP DIAMETER OF 4.5 INCHES
  - SMALL TITANIUM COMPRESSOR IMPELLER WITH A STAINLESS STEEL INDUCER WHEEL WITH A TIP DIAMETER OF 4.35 INCHES

- WATER SEPARATOR DETAILS:
  - REMOVES ABOUT 60% OF THE FREE MOISTURE (FOG) IN THE AIR
  - WATER VAPOR IS COALESCED INTO LARGE WATER DROPLETS WITHIN THE FIBROUS MATERIAL OF THE GLASS MATERIAL BAG. THE WATER DROPLETS ARE CENTRIFUGED, COLLECTED, AND DRAINED OVERBOARD.
1 RIGHT COOLING TURBINE
2 WATER SEPARATOR
3 RIGHT SECONDARY AIR-TO-FUEL HEAT EXCHANGER
4 FUEL LINES
5 RADIO BAY COOL AIR
6 R-BAY COOL AIR
7 DELETED
8 LEFT BAY AIR SHUTOFF VALVE
9 E-BAY COOL AIR
10 BLEED AIR FROM ENGINE

11 EQUIPMENT BAY COOL AIR
12 AIR FLOW CONTROL VALVE
13 SUIT AIR
14 SUIT AIR HEATER
15 HOT AIR MANIFOLD
16 MANIFOLD TEMP VALVE
17 COCKPIT TEMP VALVE
18 COLD AIR MANIFOLD
19 COCKPIT CONDITIONED AIR
20 DEFOG VALVE
21 FUEL FLOW SENSOR
TURBINE/COOLING COMPRESSOR

CODE
HOT PRESSURIZED AIR
COOLED AIR
PARTIALLY COOLED AIR
HOT COMPRESSED AIR

BEARING CARRIER
THERMOSWITCH
FROM HEAT EXCHANGER

SUMP HOUSING

INLET TO COMPRESSOR

TO HEAT EXCHANGER

OIL SLINGER

TURBINE WHEEL SET

TURBINE TORSUS

BEARING CARRIER SUPPORT

WICKS

SECTION B-B

SHROUD SUPPORT

RELIEF ORIFICE

AIR SLINGER

COMPRESSOR IMPELLER

AIR INLET

AIR OUTLET

SCROLL
SR-71 BLACKBIRDS

FUEL SYSTEM

RIGHT FUEL TO LEFT FUEL H.E.
SECONDARY AIR CONDITION H.E.
FLIGHT CONTROL HYD. SYS. H.E.
SPIKE HYDRAULIC SYSTEM H.E.
PRIMARY AIR-CONDITION H.E.
GEAR BOX OIL H.E.

FLOW CONTROL VALVE
HEAT SINK PUMP
A/B PUMP
EXHAUST NOZZLES
BYPASS DOORS
START BLEED DOORS
ACT BOOST PUMP
WIND MILL
BYPASS VALVE
DE-RICH VALVE
MAIN FUEL CONTROL
FUEL/OIL H.E.

ENGINE
AT 300°F MAX, VALVE CLOSES, FUEL RETURNS TO TANK
RETURN TO TANKS
FROM TANKS

TEMP LIMITING

UNCLASSIFIED
FUEL HEAT SINK SYSTEM DESCRIPTION

• FUEL IS PUMPED FROM THE AIRCRAFT FUEL TANKS TO EACH ENGINE, WITH EACH ENGINE BEING SUPPLIED BY SPECIFIC TANKS TO CONTROL THE CENTER OF GRAVITY IN FLIGHT.

• FUEL FOR THE HEAT SINK SYSTEM IS TAKEN FROM THE MAIN FEED LINE JUST BEFORE THE FUEL ENTERS THE NACELLE AND IS ROUTED TO A HEAT SINK PUMP MOUNTED ON THE ACCESSORY GEAR BOX. THE PUMP RAISES THE PRESSURE BY 45 PSI, WHICH ALLOWS IT TO FLOW THROUGH THE VARIOUS VALVES AND HEAT EXCHANGERS IN EACH HEAT SINK SYSTEM AND RETURN TO THE MAIN FEED LINE JUST DOWNSTREAM FROM WHERE IT WAS TAKEN.

• FUEL FROM THE PUMP PASSES THROUGH A FLOW CONTROL VALVE (LIMITS FLOW UNDER CERTAIN FLIGHT CONDITIONS) AND THROUGH A HEAT EXCHANGER THAT BALANCES THE TEMPERATURE DIFFERENCES BETWEEN FUEL SUPPLIED TO THE RIGHT AND LEFT SYSTEMS.

• THE FLOW THEN SPLITS, PART FLOWING FORWARD THROUGH THE SECONDARY AIR-TO-FUEL HEAT EXCHANGER, THROUGH THE FLIGHT CONTROL SYSTEM HYDRAULIC COOLER, AND THEN THROUGH THE SPIKE CONTROL SYSTEM HYDRAULIC COOLER. THE REST OF THE FUEL FLOWS THROUGH THE PRIMARY AIR-TO-FUEL HEAT EXCHANGER, THROUGH THE GEAR BOX OIL COOLER AND THEN REJOINS WITH THE OTHER HEAT SINK FLOW.

• FUEL RETURNED FROM CERTAIN PORTIONS OF THE ENGINE HEAT SINK SYSTEM MIXES WITH THE VEHICLE HEAT SINK FUEL AND PASSES INTO A TEMPERATURE LIMITING VALVE REFERRED TO AS THE "SMART VALVE". THIS VALVE REGULATES THE MAXIMUM FUEL TEMPERATURE SUPPLIED TO THE ENGINE AND RETURNS FUEL TO THE TANKS AS REQUIRED.
HEAT SINK PACKAGE COMPONENTS
VIEW FROM BOTTOM
CREW COMPARTMENT SYSTEMS

- COCKPIT COOLING AIR DISTRIBUTION SYSTEM
- COCKPIT PRESSURE SCHEDULE
- COCKPIT PRESSURE CONTROL SYSTEM
  - COCKPIT PRESSURE REGULATOR
  - COCKPIT SAFETY VALVE
- CREW SUIT CONDITIONING SYSTEM
- CANOPY SEAL SYSTEM
- WINDSHIELD DEFOG SYSTEM
- WINDSHIELD DE-ICE SYSTEM
COCKPIT COOLING AIR DISTRIBUTION SYSTEM

- Windshield defog supply
- Nose equipment
- Forward cockpit
- Aft cockpit
- From warm air manifold
- From cold air manifold
- From cold air manifold
- C-Bay
- Suit heater
- A/C-Bay
- Windshield de-ice supply
COCKPIT COOLING AIR DISTRIBUTION SYSTEM

COOLING AIR IS SUPPLIED TO THE FORWARD AND AFT COCKPITS FROM THE COLD AIR MANIFOLD BY TWO DIFFERENT METHODS:

- NORMAL AIR DISTRIBUTION SYSTEM; CONTAINS FOOT OUTLETS, HEAD OUTLETS, SILL OUTLETS, AND WINDSHIELD AND SIDE WINDOW OUTLETS
- SUIT VENTILATION SYSTEM; PROVIDES COOLED AIR FROM THE COLD AIR MANIFOLD, HEATED BY THE SUIT HEATER IF DESIRED, AND DISTRIBUTES IT TO EACH SUIT. EACH CREW MEMBER CONTROLS THE FLOW TO HIS OWN SUIT THROUGH FLOW CONTROL VALVES WHICH ARE PART OF THE SUIT HOSE.

COCKPIT SUPPLY TEMPERATURE IS CONDITIONED BY A WARM AIR MODULATING VALVE, WHICH IS CONTROLLED EITHER MANUALLY OR AUTOMATICALLY BY SENSING THE TEMPERATURE OF THE AIR LEAVING THE AFT COCKPIT THROUGH THE COCKPIT PRESSURE REGULATOR VALVE. THE COCKPIT SUPPLY AIR TEMPERATURE VARIES AS A FUNCTION OF TIME DUE TO THE CONTINUOUS HEATING OF THE FUEL, SO AUTOMATIC CONTROL IS DESIRABLE.

DEFOGGING AIR IS SUPPLIED FROM THE WARM AIR MANIFOLD, UPON DEMAND, TO THE FORWARD WINDSHIELD COOLING MANIFOLD.

WINDSHIELD DE-ICER AIR IS SUPPLIED FROM THE WARM AIR MANIFOLD, UPON DEMAND, TO THE EXTERIOR OF THE LEFT WINDSHIELD PANEL.

AIR LEAVES THE COCKPIT TO THE NOSE EQUIPMENT THROUGH TWO VENTURI IN THE FORWARD COCKPIT AND THROUGH THE OUTFLOW PRESSURE REGULATOR IN THE REAR COCKPIT.
COCKPIT PRESSURE SCHEDULE

IN HG A

HIGH ISOBARIC RANGE (NORMAL SCHEDULE) UNPRESSURIZED TO 26,000 FT

5 PSIG DIFFERENTIAL RANGE

25,000

COCKPIT ALTITUDE (FEET)

10,000

LOW ISOBARIC RANGE (10,000-FT SCHEDULE) UNPRESSURIZED TO 10,000 FT

5,000

COCKPIT SAFETY RELIEF VALVE

AIRPLANE ALTITUDE (THOUSAND FEET)

50,000

100,000
Cockpit Pressure Control System

- The cockpit pressure is controlled by the cockpit pressure regulator. There are two pressure schedules that can be selected by the crew:
  - Normal Schedule: Unpressurized to 26,000 feet cabin altitude, with a constant 26,000 feet (10.66 ± 0.3 HgA) at higher altitudes.
  - 10,000 Foot Schedule: Unpressurized to 10,000 feet, constant 10,000 feet until a 5.0 psig differential (to ambient) is obtained, and a constant 5.0 ± 0.1 psig differential at higher altitudes. This schedule is used during climb and for ferry operation.

- The cockpit pressure regulator exhausts the air to a bay behind the aft cockpit (C-Bay) and from there the air cascades through several equipment bays, being utilized for environmental conditioning of those bays, before it exhausts from the aircraft through louvers behind the aft-most equipment bay.

- If the cockpit pressure regulator fails in the closed position, a cockpit safety valve is set to relieve at 5.4 ± 0.1 psig with respect to ambient.

- The cockpit safety valve exhausts the air to a bay behind the aft cockpit (A/C bay), and from there exhausts into the nose wheel well and overboard through louvers in the nose wheel doors. The cockpit safety valve also acts as a negative pressure relief valve and a cockpit pressure dump valve.
COCKPIT PRESSURE CONTROL SYSTEM

PRESSURE REGULATOR
STATIC ATMOSPHERIC
PRESSURE PORT

GROUND TEST VALVE
(SAFETY LATCH IN
FLIGHT POSITION)

DUAL RANGE
SECTOR SWITCH

PRESSURE DUMP SWITCH

FORWARD COCKPIT

AFT COCKPIT

PRESS DUMP

ON
OFF

SCARF LIP

C-BAY

10.66 (±0.2)" Hg
PRESSURE REGULATOR
EXHAUST

SAFETY RELIEF
VALVE EXHAUST

A/C BAY

10.96" Hg Δ P

SAFETY RELIEF VALVE
STATIC ATMOSPHERIC
PRESSURE PORT
COCKPIT SAFETY VALVE

LOCATED ON AFT COCKPIT BULKHEAD

PRESSURE RELIEF CONTROL DIAPHRAGM ASSEMBLY
COCKPIT AIR ORIFICE (WITH FILTER)
PRESSURE RELIEF METERING VALVE
PRESSURE RELIEF CALIBRATION SCREW
STATIC PRESSURE LINE
PRESSURE RELIEF CALIBRATION SPRING
DUMP ELECTRICAL CONNECTION
SOLENOID DUMP VALVE
BALL CHECK VALVE
REFERENCE CHAMBER
OUTFLOW VALVE DIAPHRAGM (ACTUATOR SECTION)

CONTROL SECTION
COCKPIT PRESSURE BASE SECTION
DISCHARGE PRESSURE
OUTFLOW VALVE (POPPET)
OUTFLOW VALVE RETURN SPRING
OUTFLOW VALVE PILOT
FLOW RING ASSEMBLY
RAFFLE PLATE
OUTFLOW VALVE DIAPHRAGM (VACUUM RELIEF AND BALANCE SECTION)

COCKPIT PRESSURE REFERENCE PRESSURE STATIC ATMOSPHERIC PRESSURE DISCHARGE PRESSURE
CANOPY SEAL PRESSURIZATION SYSTEM
WINDSHIELD DEFOGGING SYSTEM

CODE
- HOT AIR
- COLD AIR
- CONDITIONED AIR

Cockpit Temperature Sensors
Cockpit Air Defog Valve
Cockpit Distribution Ducting
Cockpit Temperature Valve
Cold Air Manifold
Hot Air Manifold
Windshield Defog Valve
Windshield Manifold

Check Valve

Deco Manifold and Nozzle
Defog Air Inlet (Right Side Only)
Cockpit Cooling Air from Conditioned Air Source (Left System Shown, Right System Similar)

Foot Outlet Cooling Air
WINDSHIELD DE-ICER SYSTEM

- DE-ICER SPRAY BARS
- DE-ICER MANIFOLD
- AIRFLOW
- CHECK VALVES
- RIGHT DE-ICER VALVE
- RIGHT BLEED AIR SUPPLY
- LEFT BLEED AIR SUPPLY
- LEFT DE-ICER VALVE
COLD AIR DISTRIBUTION SYSTEM

TO RIGHT FORWARD CHINE BAY EQUIPMENT

TO COCKPIT
COLD AIR DISTRIBUTION SYSTEM

- Conditioned air is supplied from the cooling turbines to the cold air manifold at between -30°F and 0°F above 44,000 feet, depending upon the fuel temperature during high speed operation. Below 44,000 feet the cold air manifold is controlled to 37°F to minimize the possibility of freezing the water separators.

- Cold manifold air is supplied to the cockpit and several equipment bays. The cold air is supplied directly into the equipment in most instances and blown around equipment in some locations.

- For some mission kit installations, cold manifold air is ducted to the nose for equipment cooling.

- During an emergency condition, with one air conditioning package inoperative, mission equipment bay cooling air is shut off, and the cold air supplies only the crew compartment and the bays containing flight essential equipment (E-bay, R-bay, A/C bay). In that case, mission equipment is turned off and only cooled by the air cascading through the bays on its way overboard aft of the aftmost equipment bay.
BAY ENVIRONMENTAL CONDITIONING METHODS

• THE ENVIRONMENT WITHIN THE VARIOUS EQUIPMENT BAYS, AROUND THE EQUIPMENT ITSELF, IS A FUNCTION OF THE AIR THAT HAS EXHAUSTED FROM ADJACENT BAYS UPSTREAM (FLOW-WISE). THIS COOLING METHOD IS REFERRED TO AS "CASCADING".

• AIR LEAVING THE COCKPIT TO THE NOSE FLOWS THROUGH THE NOSE EQUIPMENT, THEN CASCADES AROUND THE EQUIPMENT, SHIELDING IT FROM THE HIGH NOSE SURFACE TEMPERATURES, THEN EXHAUSTS THROUGH LOUVERS JUST AFT OF THE NOSE IN THE CHINE AREAS ON BOTH SIDES OF THE COCKPIT.


• EACH BAY LOSES A CERTAIN AMOUNT OF AIR AROUND THE BAY DOOR SEALS AS LEAKAGE, BUT SINCE THE BAYS ARE PRESSURIZED TO ONLY 1.0 PSIG, THE DOOR SEALS ARE EFFECTIVE IN FORCING THE AIR TO FLOW DOWN THE BAYS AND EXHAUST THROUGH THE EXIT LOUVERS.
MISSION RECORDER SYSTEM DETAILS

- THE AIRCRAFT'S MISSION RECORDER SYSTEM (MRS) CONTINUOUSLY MONITORS OVER 600 VEHICLE PARAMETERS FOR MISSION ANALYSIS AND FOR MAINTENANCE APPRAISAL FROM ENGINE START TO ENGINE SHUTDOWN. DATA ON SOME CHANNELS IS COLLECTED CONTINUOUSLY AND DATA ON OTHER CHANNELS IS COLLECTED BETWEEN 20 AND 900 TIMES PER MINUTE.

- SEVERAL TEMPERATURES, PRESSURES, FLOWRATES AND SWITCH POSITIONS ARE MONITORED IN THE ENVIRONMENTAL CONTROL SYSTEM AND IN THE HEAT SINK SYSTEM ASSOCIATED WITH THE ECS. TWENTY-THREE PARAMETERS ARE MONITORED EVERY THREE SECONDS. THE DATA COLLECTED ARE ANALYZED AFTER EACH FLIGHT BY A COMPUTER PROGRAM DESIGNED TO FIND OUT-OF-TOLERANCE PARAMETERS WHICH COULD INDICATE HARDWARE COMPONENTS THAT ARE OUT OF LIMITS, ABOUT TO FAIL, OR ALREADY FAILED.

- SYSTEM TROUBLE-SHOOTING IS AIDED BY USE OF THE MRS, AND MANY POTENTIAL PROBLEMS HAVE BEEN DISCOVERED AND FIXED BEFORE A SERIOUS CONSEQUENCE COULD RESULT.
ECS SCHEMATIC SUMMARY

- ENTIRE DETAILED ECS IS SCHEMATICALLY PRESENTED. SOME OF THE COMPONENTS AND FUNCTIONS HAVE NOT BEEN DESCRIBED OR EXPLAINED DUE TO TIME CONSTRAINTS. ENOUGH OF THE OPERATIONAL CHARACTERISTICS OF THE SYSTEM HAVE BEEN DISCUSSED TO GIVE A FAIRLY COMPLETE OVERVIEW OF HOW THE SYSTEM FUNCTIONED AND WHY THE EQUIPMENT AND THE SYSTEM PHILOSOPHY WAS SELECTED.

- TEST DATA INDICATED THAT THE SYSTEMS ALL WORKED AS PREDICTED. THE EQUIPMENT HAS PROVED TO BE RELIABLE, AND THE QUALITY OF THE MISSION EQUIPMENT OUTPUT HAS BEEN MORE THAN ACCEPTABLE. THERE HAVE BEEN A FEW PROBLEMS ENCOUNTERED BUT THEY HAVE BEEN RESOLVED.

- SOME INTERESTING RESULTS WERE OBTAINED:
  - THERE WERE SOME PEOPLE WHO SAID WE COULD NOT TAKE INFRARED PICTURES THROUGH A 450°F WINDOW AND A HOT TURBULENT BOUNDARY LAYER BUT WE SUCCESSFULLY DID WITH PREDICTED RESOLUTION.
  - THERE WERE SOME PEOPLE WHO SAID WE COULD NOT TAKE GOOD OPTICAL PICTURES THROUGH A 450°F WINDOW AND A HOT TURBULENT BOUNDARY LAYER BUT WE DID, WITH RESOLUTION THAT WAS ANTICIPATED.
  - THE ECS HAS PROVIDED THE CREW AND EQUIPMENT WITH AN ADEQUATE ENVIRONMENT.
ENVIRONMENTAL CONTROL SYSTEM SUMMARY

- ENVIRONMENTAL CONTROL SYSTEM COOLING CAPACITY, TO COOL BLEED AIR ONLY:
  - CAPACITY REQUIRED TO COOL ENGINE BLEED AIR FROM 1250°F TO -30°F, WITH COOLING AIRFLOW OF 40 POUNDS/MINUTE/SIDE, OR 80 PPM TOTAL
    - COOLING IN AIR-TO-AIR HEAT EXCHANGER:
      (1250°F → 850°F) 7,700 BTU/MIN 38 TONS 135 KW
    - COOLING IN AIR-TO-FUEL PRIMARY HX:
      (850°F → 160°F) 13,250 BTU/MIN 66 TONS 233 KW
    - COOLING IN ECS PACKAGE:
      (160°F → -30°F) 3,650 BTU/MIN 18 TONS 64 KW
    - TOTALS 24,600 BTU/MIN 123 TONS 433 KW
  - ENOUGH TO COOL 40 HOUSES @ 1500 SQUARE FEET EACH
  - COOLING ACCOMPLISHED WITH THE 80 PPM OF -30°F AIR:
    - AIR HEATED BY EQUIPMENT AND BAY WALLS FROM -30°F TO 140°F: 3260 BTU/MIN 16 TONS 57 KW
    - ENOUGH TO COOL 5 HOUSES @ 1500 SQUARE FEET EACH
  - APPROXIMATE WEIGHT OF HARDWARE REQUIRED TO ACCOMPLISH THE COOLING:
    - WEIGHT IS ABOUT 400 POUNDS
    - WEIGHT IS EQUIVALENT TO THAT OF ABOUT 2 COMMERCIAL HOME REFRIGERATION UNITS FOR A 1500 SQUARE FOOT HOUSE
Hot, high-speed hydraulics

The hydraulic systems of the world's fastest aircraft — the Lockheed SR-71 Blackbird — are unique

R. P. DeGrey

To fly at sustained speeds above Mach 3, an aircraft must be able to operate at high skin temperatures. This means that the aircraft's internal systems are subject to the same or higher temperatures as the entire airframe becomes a heat sink. Accordingly, the hydraulic system of the SR-71 strategic reconnaissance airplane, Figure 1 was designed to operate reliably above 550 F.

When the Lockheed Advanced Development Projects (Skunk Works) began the SR-71 design project in the late 1950's, existing conventional hydraulic systems and components (Type I for 160 F and Type II for 275 F) were inadequate or inapplicable. There were no hydraulic fluids, pumps, or control valves that could operate in that high-temperature environment.

Technology for some of the materials, hardware, and components now routinely used on the SR-71 and elsewhere in the aerospace industry did not exist and had to be invented. Examples of this include:

- Hydraulic fluid for continuous use at temperatures above 275 F
- Standard plumbing hardware to withstand the high temperature
- Reliable control valves to operate in these extreme environments
- Hydraulic pumps that could operate at 550 F with long service life, and
- The test systems used to qualify these components.

Hydraulic systems

The SR-71 has four independent, closed-center hydraulic power systems which operate at a nominal 3000 psi: A and B systems for flight control, and L and R systems for the utility subsystems and air inlet controls, Figure 2. The delta-wing design of the aircraft uses combination elevator-aileron or elevons for control about the pitch and roll axes, and dual, all-flying rudders to control the yaw axis. These primary flight controls are operated by conventional stick and rudder inputs from the cockpit and by an electronic stability augmentation system. The flight controls are powered through electro-hydraulic servovalves.

Independent hydraulic system A and B each supply pressure fluid to six flight control dual servovalves: the left and right rudder, and the inboard and outboard elevon systems. A and B system pressure and return lines are each connected to each dual servovalve, but the two systems are not common at any point. Each system serves as backup for the other.

The L hydraulic system powers the left engine air-inlet and air-bypass controls and these additional circuits: normal brakes, landing gear, nose wheel steering, and an aerial refueling door. The R system powers the right engine air-inlet and air-bypass controls and furnishes emergency power to operate an alternate brake system. The R system also provides
Emergency retraction of the landing gear if the L system becomes inoperative.

...air-inlet control systems position an engine inlet spike and forward and aft bypass doors that control airflow into each engine.

Hydraulic伺服 actuators st the spikes and the doors for each number ...gear box in the accessory drive em (ADS) in each nacelle, ered by engine-driven flexible shafts, drives main-system able-volume, axial-piston hydraulic pumps that have an input pressure-surge damper to deform nonpulsating flows. Each 5 has its own hydraulic system lubrication and is cooled by its hydraulic fluid-to-fuel heat exchanger. Fluid-to-fuel heat exchangers also cool systems A, B, L, R fluid to keep average hydraulic fluid temperature under 250 °F for several stagnant a...ich higher temperatures.

A hydraulic reservoir holds approximately seven gallons of flu...ressurized to 100 psi by gas nitrogen. This pressurization of an inert gas reduces oxidation of system fluid and maintains a positive pressure head to ent capillaries in the pump in line.

The four system reservoirs are full fluid replenishing tanks that supplement fluid that may...t external leakage. They also accommodate volume changes of system fluid caused by thermal expansion and system ation. Conventional airless or strap reservoirs were not used because of the elastomeric seals in moving septums.

Fig. 2. Block diagram of the SR-71’s four independent hydraulic systems.

nects each reservoir to its respective pump return line. System return fluid does not pass through the reservoir but returns directly to the pump inlet port. System return lines could not be routed through the reservoirs because of minimum space availability and weight limitations. This design eliminated large conductors routed to and from the reservoir; smaller-sized lines from the reservoirs could then be used.

Hydraulic fluid

Hydraulic fluid plays an extremely important role in the SR-71 high-temperature hydraulic systems. In addition to the usual jobs of transmitting power, lubrication, and the need to be compatible with system materials, the fluid must also combat oxidation and breakdown at temperatures above 550 °F.

Readily available petroleum-based hydraulic fluid was unsatisfactory, because it would...nish, coke, and contaminate the fluid and the working surfaces of system components because of the heat generated at three-plus Mach numbers. Mandatory capabilities required that the high-temperature fluid have:

- an operating temperature range of -65 °F to 600 °F
- non-corrosive characteristics
- good boundary lubricity
- minimal varnishing and sludging tendencies
- a specific gravity compatible with MIL-H-5606 fluid
- stability through the temperature range
- flash point, pour point, viscosity, bulk modulus, and thermal conductivity compatible with the operating environment, and
- good storage life.

The basic formulation and processing of deep-dewaxed, super-refined petroleum-based oil was developed by The Pennsylvania State University Petroleum Refining Laboratory. The first batch of
Deep-dewaxed fluid for testing was made at a pilot plant of a major oil company. After a series of tests using actual hardware, the formulation was fixed and is known as MIL-H-2760!A fluid.

**Hydraulic pump**

A hydraulic pump that could reliably operate in the flight environment of the SR-71 had to be developed. The development program began with a test to determine how long a standard variable-displacement, axial-piston pump with pressure compensation could operate at 550°F: it lasted approximately one hour. After studying test results, it appeared that principal problems were:

- pressure sag (a drop in pump outlet pressure with rising-temperature), and
- heavy wear of pump components because of deterioration of metallurgical properties of the pump at elevated temperatures.

As a result of intense research and development, and with design modifications to an existing pump, the high-temperature problems were resolved. The resulting pump met the requirements shown in Table I.

**Seals**

Most hydraulic seals on the SR-71 are metallic, but fluorocarbon-elastomeric O-rings are also used as static and dynamic seals in the cooler areas where in-flight temperatures are below approximately 400°F. Metallic seals are more delicate and susceptible to handling damage than those of elastomers.

The sealing surfaces of the metallic seals are lap-finished or finer in most cases. A minute scratch across the surfaces of a seal or housing, sometimes not visible to the naked eye, or a micrometer-sized piece of contaminant lodged between the sealing surfaces, often results in a major high-temperature leak. A slight imperfection in the seal area may not show leakage at lower fluid temperatures, but it always becomes apparent at higher temperatures in the form of smoke rather than drops. See Table II for the types and uses of seals.

**Leakage testing**

Ground pressure testing of no-leak hydraulic systems at high temperatures is essential. This testing is cumbersome and hazardous, but it is necessary because the leakage rate at 500°F increases to 20 or 30 times the rate at room temperature because of the decrease of fluid viscosity. In other words, one drop per minute leakage at room temperature becomes 1 to 1.5 cm³ per minute at 500°F.

To assure leak-free hydraulic systems in the high-temperature environment, a thorough leak...
check is made on the ground by operating the systems at high temperatures using a hot cart. Figure 3

These ground checks are done following any major maintenance, since some leaks are not visible at room temperature. They also are necessary to determine the origin of a leak that began inflight and was verified by reservoir fluid loss, even though the leak could not be observed when the aircraft cooled off.

When the check is made using the hot cart, it sometimes is necessary for an operator wearing protective clothing, Figure 4, to be within a few feet of the systems to be able to find the leak. Residual fluid lines, fittings, and components causes smoke as the temperature rises during the test. Continual smoking from an area is considered to be a leak, and the system therefore cooled below 200 F for reaction.

The only satisfactory way to guarantee leak-free systems at cruise speeds is to operate the system hot on the ground, mark the leak, cool the system, fix the leak, and then rerun the system hot to prove the fix.

### Table III - Physical Properties, Mechanical Tubing

<table>
<thead>
<tr>
<th>Property</th>
<th>AM 350</th>
<th>AM 355</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength, psi</td>
<td>136,000 @ 0.2% offset</td>
<td>152,000 @ 0.2% offset</td>
</tr>
<tr>
<td>Ultimate strength, psi</td>
<td>288,000</td>
<td>318,000</td>
</tr>
<tr>
<td>Linear coefficient of thermal expansion, in/in/degree F.</td>
<td>6.8 × 10⁶</td>
<td>6.81 × 10⁶</td>
</tr>
</tbody>
</table>

### Plumbing

Plumbing lines are made of AM 350 stainless steel and have good fatigue characteristics and high strength-to-weight ratios. They are joined by threaded or brazed fittings made of AM 355 stainless steel with similar mechanical and physical properties. Tube assemblies are heat-treated to obtain the required hardness and strength. Table III.

In early development, separable plumbing connections used a sleeve with a thin, finely-finished spherical lip which had to mate and seal inside a fitting with a 37-degree internal taper seal surface. We soon learned that these fittings were too costly to make and too delicate to handle. The design was changed to what amounts to the reversal of a standard 37-degree flared fitting. A conical seal made of low-carbon nickel is used between connecting surfaces to insure good contact.

At first, to avoid galling between the tube nut and the fitting threads, the tube nut was made of another stainless steel in the 300 series which, unfortunately, had a different coefficient of thermal expansion than the AM 355 fitting. This resulted in high-temperature leakage that could not be eliminated by tightening. The nut material was then changed to AM 355 and the leakage was eliminated. The galling problem was then eliminated using improved manufacturing techniques on the threads.

All tubes and fittings are furnace or induction brazed to minimize leakage wherever mechanically-threaded joints are not needed. At the brazing temperature of 1950 F and the process annealing temperature of 1710 F, the special relationship between the fittings and tubing must be maintained as needed for the finished assembly.

A brazing fixture is used to do this. Figure 5. The fixture locates all braze fittings and supports all connecting tubing. Multi-assembly fixtures permit simultaneous brazing and heat treating of assemblies which require a definite spacing relationship when finally assembled.

### Thermal insulation

In the nacelle area of the SR-71 where inlet bleed air is above 600 F and the radiation heat from the engine is above 1000 F, tube assemblies are insulated and shielded to keep fluid temperatures below 600 F. The insulation is 3/16-inch thick batting and is covered by shielding made of Inconel foil.

Where flexible connections are required, for landing gear actuators and door actuators, for example, coiled tubing segments replace...
conventional swivel fittings and Teflon-lined hose. These coiled tubes are designed to last the life of the aircraft. Figure 6.

Valves
Hydraulic directional control valves and servovalves were designed to function at flight temperatures. Materials were selected for their compatibility with each other to prevent thermal expansion or contraction problems. Proper valve function required moving-part clearances that were adequate for the entire temperature range. These clearances also allow some internal leakage to prevent excessive varnishing and provide cooling for electrical components in the valves. Those valves that function infrequently are periodically ground-operated to prevent gradual functional degradation because of varnishing.

Electrical solenoids and wires in transfer valves and the servovalves of spike actuators in the nacelle are directly exposed to temperatures between 600 and 800 F. The controlled leakage in these servovalves keeps the temperatures of their electrical solenoids within design limits.

Intricate servovalves are functionally tested at room temperature of 550 F to verify satisfactory operation, and then thermally shocked. The shock tests are performed using a flow of 500 F air and a valve whose temperature rises lower.

Filters
The filters are placed in locations in the systems to protect against contamination. A common filter arrangement in fluid systems includes a three-stage filter system—starting with a screen, followed by a filter with flow ratings of 0.2 gpm at 15 psid at 500 F. Most filter elements are disposable and are replaced periodically. Judicious filter element replacement is essential because of accelerated particle contamination rates caused by high oil temperatures. Figure 7 shows a filter arrangement in a nacelle protected with thermal insulation.

Successful SR-71 operations over the years are a tribute to the remarkable maintenance and engineering performed routinely by Air Force and contractor personnel.
### Pump Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated speed</td>
<td>4600 rpm</td>
</tr>
<tr>
<td>Outlet pressure</td>
<td>3200 psi at full flow, 3350 psi at cut-off (no flow)</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>100 psi at full flow &amp; rated speed</td>
</tr>
<tr>
<td>Inlet fluid temperature</td>
<td>550 °F</td>
</tr>
</tbody>
</table>

### Types and Use of Seals

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear dynamic</td>
<td>Piston ring</td>
<td>Servovalves, actuators</td>
</tr>
<tr>
<td>Linear dynamic</td>
<td>Lip seal</td>
<td>Surface control actuators</td>
</tr>
<tr>
<td>Linear dynamic</td>
<td>X-seal</td>
<td>Actuators</td>
</tr>
<tr>
<td>Rotary dynamic</td>
<td>Shaft seal</td>
<td>Pump shaft</td>
</tr>
<tr>
<td>Static face</td>
<td>Static spring</td>
<td>Valves, servos</td>
</tr>
<tr>
<td>Static face</td>
<td>Metal O-ring</td>
<td>Valves, servos</td>
</tr>
<tr>
<td>Static face</td>
<td>Conical seal</td>
<td>Tube fittings</td>
</tr>
</tbody>
</table>

**Hi Temp Seals**
**FUEL**

- **NAME:** JP-7 OR PWA 535
- **TYPE:** HYDROCARBON COMPOUNDS
- **ADDITIVES:** TOTAL CONCENTRATION OF 1.0 LB PER 6000 GALS OF FUEL TO PREVENT GUMMING
  75% DITERTIARY BUTYLPHENOL
  10-15% TRITERTIARY BUTYLPHENOL
  10-15% ORTHO-TERTIARY BUTYLPHENOL

<table>
<thead>
<tr>
<th></th>
<th>JP-8</th>
<th>JP-9</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WEIGHT:</strong></td>
<td>6.6</td>
<td>6.7</td>
</tr>
<tr>
<td><strong>FREEZING POINT</strong></td>
<td>-50°F</td>
<td>-76°F</td>
</tr>
<tr>
<td><strong>INITIAL BOILING</strong></td>
<td>375°F</td>
<td>150°F</td>
</tr>
<tr>
<td><strong>FLASH POINT</strong></td>
<td>130°F</td>
<td>NOT SPECIFIED</td>
</tr>
<tr>
<td><strong>VAPOR PRESSURE AT 300°F</strong></td>
<td>3.0 PSIA</td>
<td>60 PSIA</td>
</tr>
<tr>
<td><strong>AT 500°F</strong></td>
<td>43.0 PSIA</td>
<td>60 PSIA</td>
</tr>
</tbody>
</table>

*LOBE OF COMBUSTION:* 125,000 BTU/GAL
INLET AND EXHAUST REQUIREMENTS

INLET

• 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

EXHAUST

• HIGH THRUST COEFFICIENT
• MINIMUM OFF-DESIGN DRAG
• LIGHT WEIGHT
• COMPATIBLE WITH AFTERBURNING EXHAUST GAS TEMPERATURES
LATE 1950's STATE-OF-THE-ART ANALYSIS METHODS

- **COMPUTATION FLUID DYNAMICS**
  - No codes available at beginning of design
  - Method of Characteristics code developed by Lockheed in parallel with inlet design

- **BOUNDARY LAYER PREDICTION**
  - No satisfactory theories available for boundary layers in strong adverse pressure gradients

- **COMPUTING FACILITIES**
  - IBM mainframe available for Method-of-Characteristics program and engine performance prediction
  - All other computing done by four function mechanical calculator or slide rule
MIXED COMPRESSION INLET DESIGN CONCEPT

CENTERBODY SHOCK

COWL LIP SHOCK

REFLECTED SHOCKS

INLET THROAT STATION

TERMINAL SHOCK

ENGINE FACE
INLET BLEED AND BYPASS ARRANGEMENT

AFT-BYPASS DOOR ASSEMBLY
SPIT BLEED EXIT
SHOCK-TRAP
FLOW TUBE
FORWARD-BYPASS EXIT
FORWARD-BYPASS DOOR OPENING
SPIKE SUPPORT STRUCTURE
FORWARD-BYPASS DOOR ASSEMBLY
COWL BLEED (SHOCK TRAP)
TRANSLATING SPIKE
SPIKE BLEED
CENTERBODY BLEED ARRANGEMENT

SUPPORT STRUT

SPIKE BLEED EXIT LOUVERS (4 LOCATIONS)

VIEW LOOKING AFT

SPIKE BLEED (SLOTTED SURFACE)

SUPPORT STRUT

ENGINE FACE

SPIKE BLEED EXIT LOUVER
SECONDARY FLOW SYSTEM-COWL BLEED AND AFT BYPASS
FORWARD BYPASS

SHOCK TRAP TUBES

ROTARY FLUSH SLIDING DOORS

BYPASS EXIT LOUVERS
(6 LOCATIONS)

SECTION A-A

FORWARD BYPASS FLOW

ENGINE FACE

FORWARD BYPASS DOORS
INLET FLOW DISTRIBUTION

MASS FLOW RATIO $\sim \frac{m}{m_0}$

FREE STREAM MACH NUMBER

SUPERCRITICAL SPILLAGE

FORWARD BYPASS

SUBCRITICAL SPILLAGE

AFT BYPASS

BLEED LEAKAGE

ENGINE
DRAG PENALTY OF OVERBOARD BYPASS AT CRUISE

TOTAL AIRPLANE DRAG
(WITH FWD BYPASS DOORS CLOSED)

NOMINAL INLET DRAG

AIRPLANE SKIN FRICTION DRAG

AIRPLANE WAVE DRAG

DRAG DUE TO LIFT

FORWARD BYPASS DOOR DRAG

DRAG - 1000 LBS

FORWARD BYPASS DOOR OPENING - %

0 2 4 6 8 10 12 14 16 18 20 22

0 20 40 60 80 100

GL-4682-S
INLET CHARACTERISTIC

UNSTART

UNSTART

ENGINE W V .5 .76

INCREASING CORRECTED AIRFLOW

OPERATING POINT

SUPERCRITICAL

SUPERCRITICAL

RECOVERY

m_2 / m_0

DISTORTION

m_2 / m_0

INLET DRAG

m_2 / m_0

556
UNSTART/RESTART SEQUENCE

1. OPERATING POINT
2. UNSTART POINT
3. UNSTARTED POINT
3–4. EXTEND SPIKE OPEN BYPASS
4–5. RESTART INLET
5–6. RETRACT SPIKE
6. 1. CLOSE BYPASS

\[
\frac{p_{t2}}{p_{t0}} \quad \frac{m_2}{m_0}
\]
INLET STARTED
MACH = 3.2
ANGLE OF ATTACK = 6.5°
SPIKE POSITION = 0°
INLET UNSTARTED
MACH = 3.2
ANGLE OF ATTACK = 6.5°
SPIKE POSITION = 0.6"
INLET BUZZ
MACH = 3.2
ANGLE OF ATTACK = 6.5°
SPIKE MOVING FORWARD
INLET WIND TUNNEL MODEL
TEST OBJECTIVES

• DETERMINE OPTIMUM SPIKE POSITION AS A FUNCTION OF AIRCRAFT MACH NUMBER AND ATTITUDE
• DETERMINE OPTIMUM INLET BLEED ARRANGEMENT
• MEASURE INLET TOTAL PRESSURE RECOVERY AND DRAG
• DETERMINE EFFECT OF OVERBOARD BYPASS FLOW ON INTERNAL PERFORMANCE
• MEASURE AIRFLOW DISTORTION AT DUCT EXIT
• FIND INTERNAL PRESSURES SUITABLE FOR USE IN INLET CONTROL SYSTEM
FEATURES OF THE INLET MODEL

- TRANSLATING CENTERBODY
- ALTERNATE BLEED CONFIGURATIONS FOR CENTERBODY & COWL
- ALTERNATE COWL FOR INCREASED THROAT AREA
- EXIT RESTRICTORS TO REGULATE BYPASS AND BLEED FLOWS
- TOTAL PRESSURE RAKE AT ENGINE FACE STATION
- TRANSLATING PLUG AFT OF RAKE TO REGULATE DUCT FLOW
- STATIC PRESSURE INSTRUMENTATION
WIND TUNNEL TEST PROCEDURE

- ESTABLISH TUNNEL MACH NUMBER AND ANGLES OF ATTACK AND SIDESLIP
- RETRACT CENTERBODY SPIKE TO DETERMINE UNSTART LOCATION
- RESTART INLET BY MOVING SPIKE FULL FORWARD
- RETRACT SPIKE TO OPTIMUM POSITION JUST FORWARD OF UNSTART LOCATION
- MOVE MASS FLOW CONTROL PLUG FORWARD IN SMALL STEPS
- RECORD DATA AT EACH PLUG POSITION UP TO THE POINT OF UNSTART
PERFORMANCE IMPROVEMENT WITH INLETS CANTED INBOARD

- Diagram showing the relationship between engine face total pressure recovery and sideslip angle.
- Two curves comparing inlets parallel to fuselage and inlets canted 3° inboard.

- Sideslip angle range: -4 to 4.
INLET CONTROL SYSTEM

NOSE BOOM

\[ M \]

\[ \alpha \]

\[ \beta \]

NORMAL ACCELERATION

INLET COMPUTER

SPIKE ACTUATOR

SPIKE POSITION ERROR

SPIKE POSITION COMMAND

DUCT PRESSURE RATIO, \( \frac{P_{SD8}}{P_{PLM}} \)

FORWARD BYPASS DOOR ACTUATOR

ANERODYNAMIC FEEDBACK

DPR COMMAND

DPR ERROR

P02-4700-9