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A Qualitative Piloted Evaluation of the Tupolev Tu-144 Supersonic Transport

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February 2000

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Abstract

Two U.S. research pilots evaluated the Tupolev Tu-144 supersonic transport aircraft on three dedicated flights: one subsonic and two supersonic profiles. The flight profiles and maneuvers were developed jointly by Tupolev and U.S. engineers. The vehicle was found to have unique operational and flight characteristics that serve as lessons for designers of future supersonic transport aircraft. Vehicle subsystems and observed characteristics are described as are flight test planning and ground monitoring facilities. Maneuver descriptions and extended pilot narratives for each flight are included as appendices.

Nomenclature

da	asymmetric elevon (aileron) deflection
de	symmetric elevon (elevator) deflection
AC	alternating current
ACM	air cycle machine
ADI	Attitude Director Indicator
AGL	above ground level
AOA	angle of attack
APU	Auxiliary Power Unit
A/T	autothrottle
CG	center of gravity
DC	direct current
DME	Distance Measuring Equipment
EGT	exhaust gas temperature
FE	flight engineer
HSR	High Speed Research
ICS	Interphone Communication System
IDG	Integrated Drive Generator
ILS	Instrument Landing System
IMN	indicated Mach number
INS	Inertial Navigation System
ITB	Integrated Test Block
LG	landing gear
MAC	mean aerodynamic chord
MCP	Mode Control Panel
N1	engine fan speed
N3	engine turbine speed
PID	parameter identification
PIO	pilot-induced oscillation
PLA	power lever angle (throttle setting)
s	Laplace operator
SPI	Sensitive Pitch Indicator
RPM	revolutions per minute
TACAN	Tactical Air Navigation
T.E.	trailing edge
UHF	Ultra High Frequency
V_1	decision speed
V_2	safety speed
VHF	Very High Frequency
V_{lof}	liftoff speed
VOR	Very High Frequency Omnidirectional Range
V_r	rotation speed
VRI	Vertical Regime Indicator

Introduction

Under the auspices of the NASA High-Speed Research (HSR) program, an out-of-service Tu-144 supersonic transport aircraft was re-engined, refurbished and proven as an experimental supersonic flying laboratory by Tupolev Aircraft Company (Tupolev ANTK). Nineteen flights of the modified aircraft (Tu-144LL) were flown by Tupolev research pilots in 1996-1997 and data for six flight experiments were acquired.

A subsequent eight-flight program, flown in 1998, included three flights during which an evaluation of the handling qualities of the Tu-144LL was performed by NASA research pilots. This report describes the conduct and results of these three flights (known as flights 21, 22 and 23).

Participants in the flight program included IBP Aircraft, Ltd. (as exclusive contractual representative of Tupolev), Tupolev ANTK, and the U.S. Piloted Evaluation Team: representatives from NASA Dryden Flight Research Center (DFRC), NASA Langley Research Center (LaRC), and the Boeing Company. The flight experiments were performed jointly at Tupolev's flight research facility near Zhukovsky, Russia.

The objectives of the follow-on eight flights were:

1. Provide the United States with first-hand piloting experience of the Tu-144LL Supersonic Flying Laboratory. The Tu-144LL was developed to support flight research beneficial to the development of a next generation supersonic transport aircraft. The Tu-144LL is one of only two supersonic transport aircraft types that are flying in the world today. To maximize the benefit of the Tu-144LL to U.S. aviation, members of the piloting community needed to understand the characteristics and capabilities of the research airplane. The pilots' understanding of the airplane will greatly aid the planning of future aeronautical experiments using the Tu-144LL, and perhaps will lead to experiments relating to operational requirements for future high-speed civil transport aircraft.

2. Collect additional supersonic quantitative handling qualities data for the Tu-144 aircraft. By comparing the quantitative test results to the qualitative pilot evaluations, handling qualities criteria boundaries can be set for design of future supersonic transports.

3. Carry out qualitative handling qualities evaluations of the Tu-144 using multiple pilots. The maneuvers for the Tu-144 evaluation represented normal operational maneuvers for this type of aircraft. The U.S. team, with the help of Tupolev, defined the maneuvers for this testing. Where possible each evaluation pilot flew and evaluated the same set of maneuvers at the same flight conditions in order to account for pilot variation in the evaluation process.

This report represents a summary of the aircraft systems, handling qualities, and flight characteristics of the Tu-144LL aircraft. Also covered are the experiment and flight preparation processes that were used in conducting these three test flights.

The information on Tu-144 systems was obtained over a two-week period of instruction by Tupolev engineers and pilots in a lecture format. No written documents were available to the U.S. team with the exception of the untranslated Russian flight manual. The system lectures were in Russian and were interpreted by translators provided to the U.S. team. Considering this, the information contained below may have minor discrepancies, but it can be considered accurate to the degree of providing a general description of system operation.

Aircraft Description

Tu-144LL Serial Number 77114 (figure 1) is a modified Tu-144D aircraft with newer engines necessitating nacelle modifications (fully described in the following section). Aircraft 77114 was built in 1981 and was the final aircraft off the production line. It has only been used as a research aircraft, accumulating approximately 83 hours prior to being placed in nonflyable storage in 1990. In 1993 the aircraft was brought out of storage and modifications were commenced leading to the "LL" or "Flying Laboratory" designation and a return to flight on November 29, 1996.

Aircraft Geometry

The aircraft is a delta planform, low wing, four-engine supersonic transport, with a retractable canard

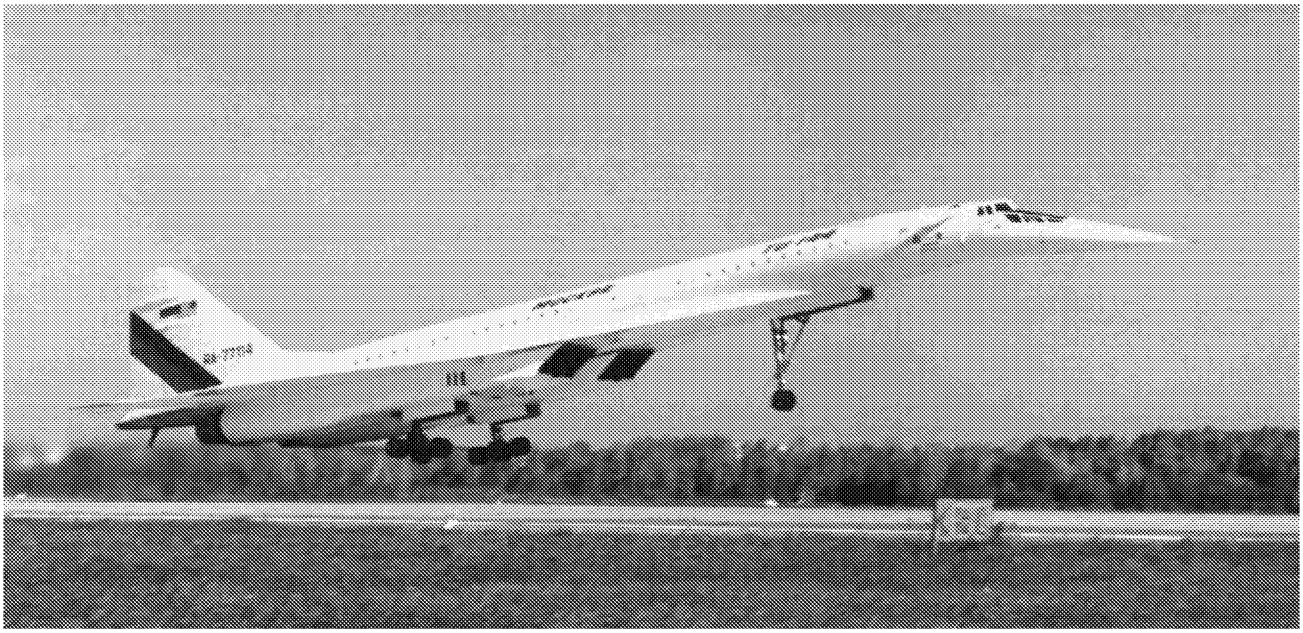

Figure 1. Tu-144LL Flying Laboratory

and hinged nose, as shown in figure 2. The nominal cockpit crew consists of two pilots, a navigator seated between the pilots, and a flight engineer. General specifications of the aircraft are listed in Table 1.

Aerodynamic Surfaces

In addition to the main wing, a unique retractable canard is located just aft of the cockpit on top of the fuselage. The canard includes both leading- and trailing-edge flaps that deflect when the canard is deployed; they are faired when the canard retracts. These devices are not actuated as part of the control system, but are deployed into a fixed position when the canard is extended. The canard provides additional lift forward of the center of gravity to aid in reducing the takeoff and landing approach pitch angle and reducing the trailing-edge-up deflection of the elevons during low-speed

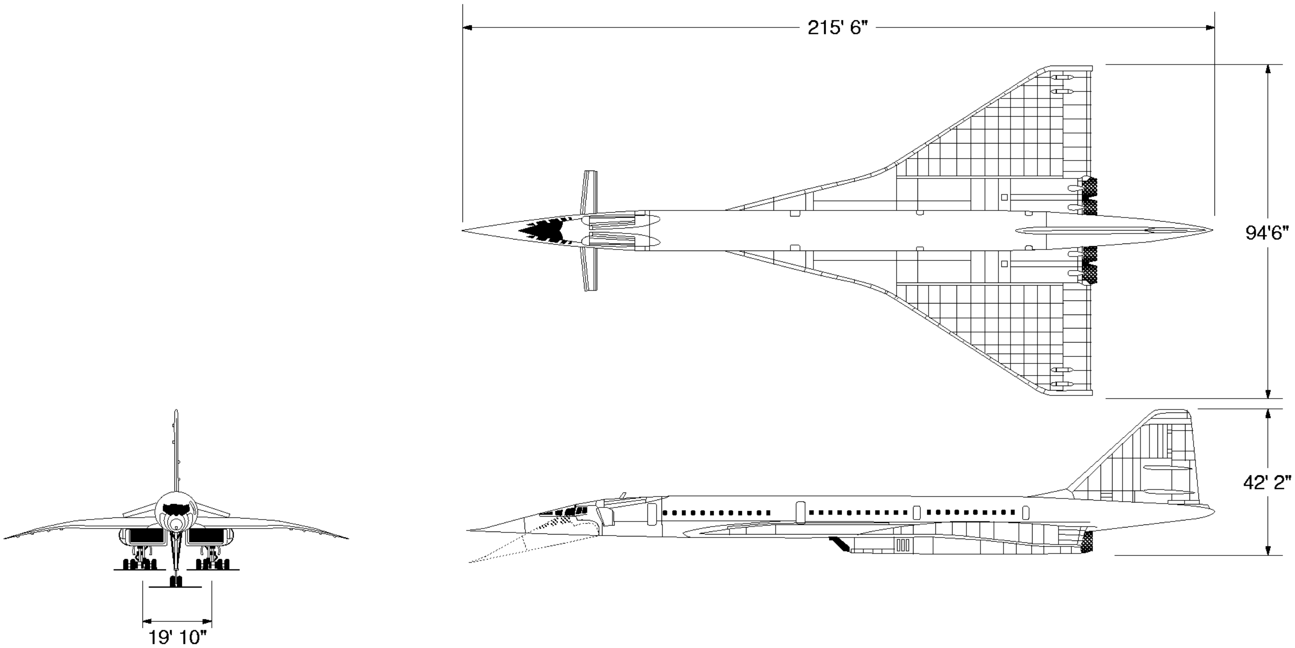

Figure 2. Three-view drawing of Tu-144

Table 1. Tu-144LL Vehicle Characteristics

Length	65.7 m (215 ft 6 in.)
Wingspan	28.8 m (94 ft. 6 in.)
Height, wheels up	12.85 m (42 ft. 2 in.)
Maximum takeoff weight	203,000 kg (447,500 lbs.)
Maximum fuel capacity	95,000 kg (209,440 lbs.)
Estimated maximum range	3000 km (1,620 nm.)
Maximum ceiling	19,000 m (62,335 ft.)
Maximum Mach number	2.4 (Envelope expanded to 2.0 to date)
Maximum indicated airspeed	1000 km/hr at 14,500 m (540 kts at 47,500 ft.)

flight.

The aerodynamic control surfaces include eight trailing edge elevons, each powered by two actuators, and two (upper and lower) rudder segments.

Propulsion System

The Tu-144LL was derived from a Tu-144D model originally equipped with Kolesov RB-36-51A engines. Since these engines are not in production and consequently could no longer be supported, newer power plants were required for the Tu-144LL modification. Kuznetsov NK-321 engines rated at 55,000 lb sea level static thrust in afterburner and 31,000 lb dry thrust were selected. These engines are 1.5 meters longer and over 10 mm wider than the RD-36-51A engines which necessitated extensive modifications to the engine nacelles and nozzle assemblies. The NK-321 engines were mounted 1.5 m further forward in the nacelles, and to accommodate the larger nozzles, the inboard elevons were modified. New higher capacity fuel pumps (jet pumps) were installed in all of the fuel tanks with peak pressure capacity of 20 atm.

The axisymmetric, afterburning, three stage fan, five stage intermediate, and seven stage high pressure compressor NK-321 engines are digitally controlled, and this dictated a redesigned flight engineer's panel containing eight rows of electronic engine parameter displays. The fuel control consists of a two channel digital electronic control and a back-up hydromechanical control. The pilot is only presented with N1 RPM indications and throttle command information which is used to set the desired thrust through power lever angle (PLA) in degrees (referred to as throttle alpha by Tupolev). All other engine information including fuel flows and quantities, oil pressures and temperatures, and exhaust gas temperatures are displayed on the flight engineer panel, which is not visible to the pilot. The pilots' throttles mounted on the center console have a very high friction level, and in normal situations the flight engineer sets the thrust as commanded by the pilot in degrees PLA. Autothrottles are normally used for approaches and landings. Typical PLA settings are 72° for maximum dry power, 115° for maximum wet power (afterburner), 100° for Mach 2.0 cruise, and 59° for supersonic deceleration and initial descent. For takeoff weights less than 160 metric tons, 72° PLA is commanded; for weights from 160 to 180 metric tons, 98° PLA is commanded; and for takeoff weights greater than 180 metric tons, 115° is used. Operations in the 88° to 95° PLA range are avoided for undisclosed reasons.

A two-channel autothrottle (A/T) system is available for approach and landing. It is characterized by a 20 sec time constant and an accuracy of ±7 km/hr. The A/T control panel is located on the center console with the two channel selectors, a left/right airspeed command selector switch and a rocker switch to set the speed bug on the respective pilot's airspeed indicator. A throttle force of 20 kg is needed to override the A/T, or individual A/Ts can be deselected by microswitches located in each throttle knob. If two or more are deselected, the entire system is disconnected. For the system to be engaged, the flight engineer must engage A/T clutches on the flight engineer throttle quadrant. The A/T can be used from 160 km/hr up to 400 km/hr indicated airspeed normally or up to 500 km/hr under test conditions. Use of A/T was authorized only below 1000 m above sea level.

The variable geometry inlets are rectangular in shape with a moderate fore-to-aft rake. An internal horizontal ramp varies from an up position at speeds below Mach 1.25 to full down at Mach 2.0. Three shocks are produced in the inlet during supersonic flight in order to slow the inlet flow to subsonic speeds. The inlets showed no tendency for stalling or other undesired responses during supersonic flight. Full rudder deflection steady heading sideslip maneuvers were flown at Mach 2.0 as well as 30° banked turns and moderately aggressive pitch captures with no abnormal results from engines or inlets. Afterburner is required to maintain Mach 2.0 cruise at cruise altitudes. It appeared, but was not confirmed, that the RD-36-51A engines did not require afterburner during supersonic cruise even though the sea level static thrust rating was lower than the NK-321 engines.

Fuel System

The fuel system is comprised of 8 fuel storage areas composed of 17 separate tanks containing a total operating capacity of 95,000 kg. The nomenclature refers to fuel tanks 1 through 8, but only tanks 6, 7, and 8 are single units. Tanks 1, 2, and 8 are balance tanks used to maintain the proper center of gravity (CG) location through high capacity fuel transfer pumps. These transfer pumps are hydraulically driven and controlled by DC power. Fuel boost pumps located in each tank are powered by the main AC electrical systems. Tank system 4 consists of 6 total tanks, four of which provide fuel directly to the engines. A crossfeed capability exists to control lateral balancing. Emergency fuel dumping can be accomplished from all fuel tanks. All fuel system information is displayed on the flight engineer panel, and all fuel system controls are accessible only to the flight engineer.

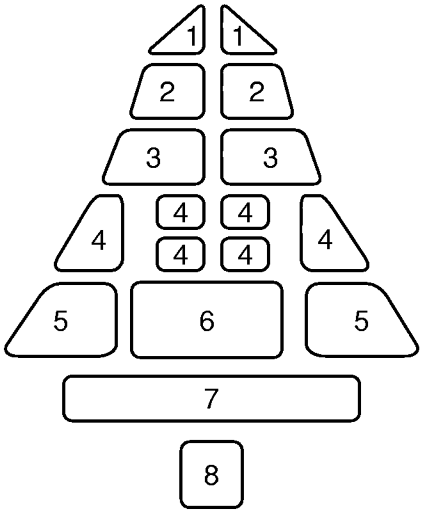

Figure 3. Fuel tank arrangement

Numerous fuel quantity probes are used to provide individual tank system quantity indications and to provide inputs to the CG indicator on the flight engineer panel. A computer within the CG indicator system continuously calculates and displays the CG location. The hydraulic fuel transfer pumps, operated manually by the flight engineer, provide fuel balancing using the following transfer routings: to move the CG aft, fuel is pumped from tank 1 to tanks 4, 6, or 8 and fuel is pumped from tank 2 to tank 8. To move the CG forward, fuel can be pumped from tank 8 to tanks 1, 2, 4, or 6. The general arrangement of the fuel tanks is shown in figure 3. A discussion of CG management may be found later in this report.

Hydraulic System

The Tu-144LL utilizes four separate hydraulic systems, each pressurized by two pumps driven by separate engines, all of which are connected to separate flight control systems. The flight controls consist of four elevons per wing and an upper and lower rudder. Each control surface has two actuators with two hydraulic channels per actuator so that each hydraulic system partially powers each control surface. Up to two hydraulic systems can totally fail without adversely affecting flight control capability.

The four hydraulic systems are powered by variable displacement engine driven pumps. There are no electrically powered pumps. Engine numbers 1 and 2 each power both the number 1 and 2 hydraulic systems and engine numbers 3 and 4 each power both the number 3 and 4 hydraulic systems. Systems 1 and 2 and systems 3 and 4 share reservoirs, but dividers in each reservoir preclude a leak in one system from depleting the other. Reservoir head pressure is maintained at 3.2 atm of dry nitrogen. Should nitrogen head pressure be lost, air conditioning system pressure is utilized to provide head pressure. Hydraulic fluid temperature is maintained within limits by a hydraulic fluid/fuel heat exchanger. The heat exchanger is utilized automatically if temperatures exceed 60° C. System pressure is nominally between 200 and 220 atm, and a warning indication is displayed to the pilot should the pressure in a system fall below 100 atm. In the event of the loss of two hydraulic systems, an emergency hydraulic system is available powered by an Auxiliary Power Unit (APU) air driven pump (or external pneumatic source), but the APU can only be operated below 5 km altitude (and cannot be started above 3 km altitude). For emergency operation of the landing gear (lowering only), a nitrogen system serviced to 150 atm is available. If one hydraulic system fails, the aircraft should be slowed to subsonic speeds. If a second system fails, the aircraft should be landed as soon as possible.

The wheel brake system is normally powered by the number 1 hydraulic system, but there is a capability to interconnect to the number 2 hydraulic system if necessary. There is an emergency braking capability using nitrogen gas pressurized to 100 atm. Independent braking levers on both the pilot and co-pilot's forward center console areas allow differential braking with this system.

A locked wheel protection circuit prevents application of the brakes airborne above 180 km/hr airspeed. On the ground full brake pressure is available 1.5 sec after full pedal pressure is applied. Above 180 km/hr on the ground the brake pressure is reduced to 70 atm. Below 180 km/hr brake pressure is increased to 80 atm. After the landing gear is retracted, wheel brake pressure at 45 atm is applied to stop wheel rotation. A parking brake, referred to as a starting brake, is available to hold the aircraft in position during engine runups. It is electrically controlled by the pilot and is pressurized to 210 atm.

A nose gear steering system is available in two modes of operation. In the high ratio mode, ±60° of nose gear deflection is available for slow speed taxiing. In the low ratio mode, nose gear deflection is limited to ±8°. Steering is accomplished from either pilot position through rudder pedal deflection. The pedal shaping appears to be parabolic, and this allows precise control at taxi speeds. The 8° mode is used for takeoff and landing. The two modes are selected by a switch on the overhead instrument panel.

Electrical System

The Tu-144 is supplied with main AC power at 115 volts and 400 Hz, secondary AC power at 36 volts and 400 Hz, and DC power at 27 volts. Each engine is connected to its respective Integrated Drive Generator (IDG). Each of the four AC generators is rated at 120 kV-A and provides independent AC power to its respective bus. There is no parallel generator operation under normal circumstances. Each IDG is managed by a Generator Control Unit to maintain quality of the power supply. Additionally, there are left and right Electrical Generator Logic Units for power control. Most systems can be powered from more than one bus, and one generator can provide all of the electrical power requirements except for the canard and inlet anti-ice. Also available are a separate APU generator rated at 60 kV-A at 400 HZ and provisions for external AC power. The many fuel tank boost pumps are the main electrical power consumers. The high capacity fuel transfer pumps are hydraulically driven and controlled with DC power. Other important electrically driven systems are the canard and the retractable nose.

36 volt AC power is provided by two main and one back-up transformer. This power is used for the aircraft's flight instruments, and the total draw is typically on the order of 1 kW out of a normal 200 kV-A main AC load.

The DC system consists of four transformer/rectifiers and four batteries. The normal DC load is 12 kW. The APU is started from battery power, and DC power is used for communication units, relays, and signaling devices.

An Essential Bus is supplied by the aircraft's batteries and provides power to an inverter for driving essential flight instruments. In an emergency the APU may be used to supply 115 volt, 400 Hz AC power. When operating on Essential Power, the normally electrically driven nose can be lowered with a nitrogen backup system.

Fire Detection and Extinguishing Systems

Fire detection sensors and extinguishing agents are available for all engines, the APU, and the two cargo compartments. The extinguishing agent is contained in six canisters of eight liter capacity each. These canisters are divided into three stages. The first stage operates entirely automatically and consists of two of the canisters. The remaining two stages are manually controlled. When an overheat condition is detected, an annunciation is displayed on the flight engineer panel showing the affected area. The pilot receives only a "Fire" light on the forward panel without showing which area is affected. In the case of an APU fire detection, the extinguishing agent is automatically released into the APU compartment. In the case of an engine fire, the pilot can do nothing, since all engine fire extinguishing and shutdown controls are located on the flight engineer panel.

Each engine nacelle contains 18 fire detection sensors, three to a group. If any one of the groups detects an overheat condition, an "Overheat" annunciation is displayed on the flight engineer panel, and a first stage canister automatically releases extinguishing agent to the appropriate area. If a second group in the nacelle senses an overheat condition, the "Fire" light is displayed on the pilot's forward panel. The APU compartment has three groups of three sensors each. Any group sensing an overheat condition will result in automatic release of extinguishing agent. The sensors use a temperature rate logic for detection of an overheat condition. The temperature rate must be 2° C per sec or greater to indicate an overheat condition. Each sensor has four thermocouples to detect the temperature gradient. With a valid overheat detection, a signal is sent to the pyrotechnic initiator and valve for the appropriate canister to discharge automatically. For a second fire signal the extinguisher must be manually discharged by the flight engineer. The flight engineer can reset the system to regain the automatic function by waiting ten seconds and closing the extinguisher valve to the affected engine. The first stage may be operated with battery power only.

Air Conditioning and Pressurization Systems

The air conditioning and pressurization system consists of identical, independent left and right branches. Any one branch can sustain pressurization during high altitude operations. Number 1 and 2 engines and number 3 and 4 engines share common ducts for their respective bleed air. The right system provides conditioned air to the cockpit and forward cabin areas, and the left system furnishes conditioned air to the middle and aft passenger cabin areas. The pressurization system provides a 15 kg per person per hour air exchange rate, and the total air capacity is four metric tons per hour. Air is not recirculated back into the cabin. The pressurization controller maximum change rate is 0.18 mm Hg per sec.

Hot engine bleed air is cooled initially to 190° C by engine inlet bleed air in an air-to-air heat exchanger. The air is then compressed in an air cycle machine (ACM) to 7.1 atm with an exit temperature of 304° C after which the air is cooled in a secondary heat exchanger to 190° C or less. If the air temperature is in excess of 90° C and fuel temperature is less than 70° C the air is passed through a fuel-air heat exchanger. Pressure at this point is approximately 3 atm. Passage through a water separator precedes entry into the expansion turbine of the ACM. Exit temperature from the turbine must be less than or equal to 30° C or the turbine will shut down. Cockpit and cabin temperature is controlled by the flight engineer using a hot air mix valve to control the temperature in the supply ducts. Supply duct temperature must remain between +60° and +10° C. The nominal engine bleed air pressure is 5 atm with 7 atm being the maximum allowed before the engine bleed must be secured. An idle descent from high altitude may result in an ACM overheat. In this case speed must be increased to provide more air for the inlet air heat exchanger. There are four outflow valves on the left side of the fuselage and two on the right. The landing gear and brakes are cooled on the ground with air from the outflow valves.

The flight engineer controls the air conditioning and pressurization system. Desired cabin pressure is set in millimeters of Mercury with 660 mm Hg nominally being set on the ground. During high altitude cruise the ambient cabin altitude is nominally 2800 to 3000 m. Warnings are displayed in the cockpit for cabin altitudes in excess of 3250 m, and 4000 m is the maximum limit. Air is bled from the cabin in order to cool the flight instruments. There is a maximum temperature limit of 30° C in the instrument and cargo areas.

Anti-Ice System

There is no provision for wing leading edge anti-icing. Flight testing of the Tu-144 prototype indicated this was not necessary due to the high speeds normally flown by the aircraft and the large degree of leading edge sweep. The canard, however, is electrically heated for anti-ice protection requiring 20 kV-A of AC power. No information was available on engine anti-icing, but the inlets are electrically heated for anti-ice protection.

Navigation and Communications

Communication capability consists of standard UHF and VHF band radios and an Interphone Communication System (ICS). Each cockpit crewmember can control his communication selection with an ICS control panel. The aircraft is equipped with two VHF and one UHF radios, and up to two radios can be selected for monitoring at one time using a microphone select wafer switch (which automatically selects the associated receiver) and a receiver select wafer switch. A variety of aural tones and messages are available including master warning messages, radio altitude calls (inoperative on the Tu-144LL), and marker beacon tones. The annunciation is in a synthetic female voice.

Navigation capability consists of three Inertial Navigation Systems (INS), VOR/DME and ILS receivers, and a Russian version of TACAN. (The ILS receivers are not compatible with Western transmitters.) The three INS units are controlled by a navigation computer. The mutually independent INS units provide attitude and true heading information to the modified Sperry attitude director indicators (ADI) and horizontal situation indicators provided to each pilot. Number 3 INS provides inputs to the pilot's instruments, number 2 to the co-pilot's instruments, and number 1 can be selected by either pilot if necessary. The sensitive pitch angle indicator (SPI, figure 4) mounted above the center glareshield on the center windshield post is driven by the number 3 INS. If the navigation computer fails, the pilot can select raw INS data. Each INS can only accept 20 waypoints. When within 100 km of the base airport, magnetic heading is used, but outside of that distance, true heading is manually selected. The crew has the ability to correct the computed position of each INS separately in 1.6 km increments.

Providing guidance to the pilot for the rather complex climb and acceleration to cruise conditions and descent and deceleration from cruise conditions is the Vertical Regime Indicator (VRI, figure 5). This effective and unique instrument is mounted on each pilot's instrument panel and consists of a horizontal indicated airspeed display superimposed over a moving vertical profile graphical display. The movable display is driven by altitude inputs to display the various climb and descent profiles versus altitude. The indicated airspeed pointer index travels back and forth on the airspeed scale, and by adjusting pitch attitude to keep the air-

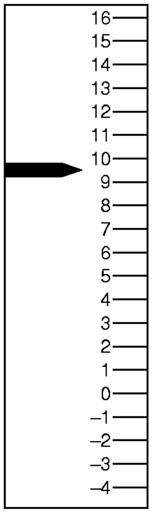

Figure 4. Sensitive Pitch Angle Indicator (SPI) schematic showing a pitch attitude of +9.5 degrees

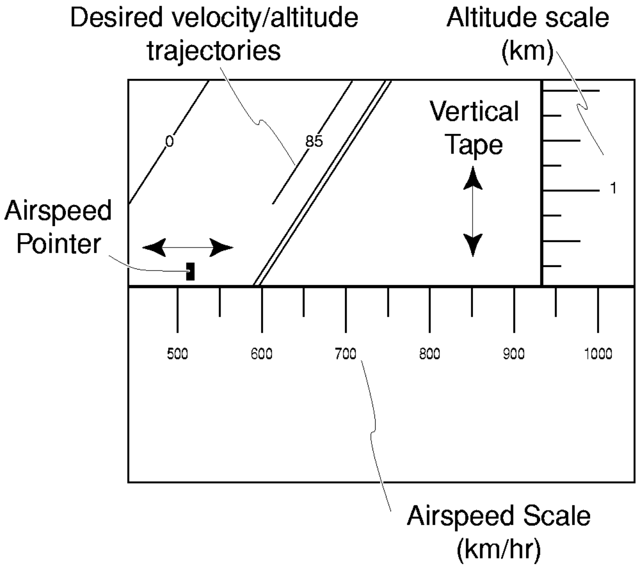

Figure 5. Vertical Regime Indicator (VRI) schematic displaying information typical of flight conditions just after takeoff

speed index over the appropriate climb/descent curve, the pilot is able to fly the proper profile. The sensitive head-up pitch angle indicator is used in conjunction with the VRI to maintain the appropriate pitch angle.

Manual Flight Control System

A schematic of the Tu-144 flight control system is shown in figure 6. The system provides a conventional aircraft response with stability augmentation and an aileron-to-rudder interconnect.

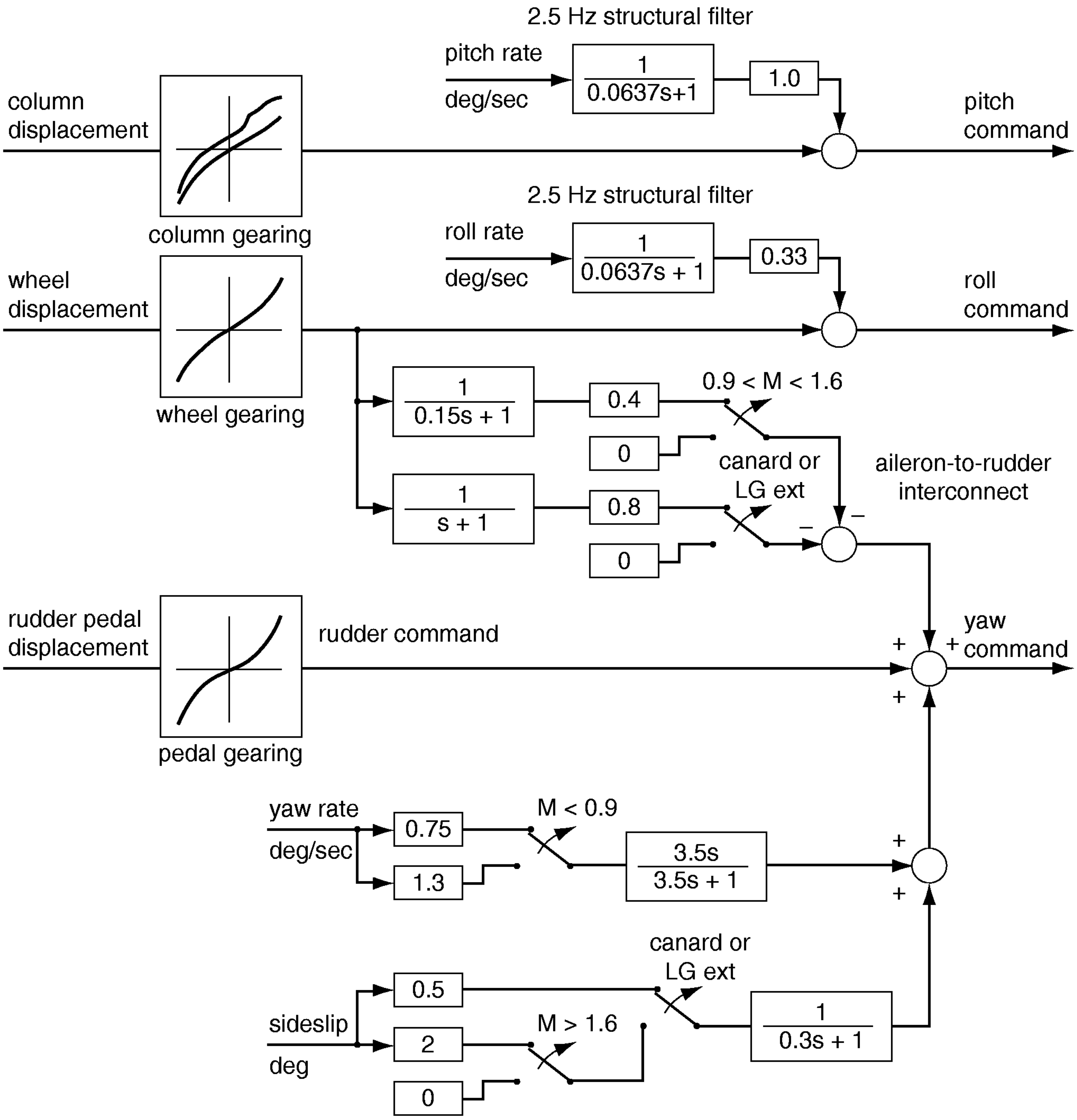

Figure 6. Tu-144 manual control system

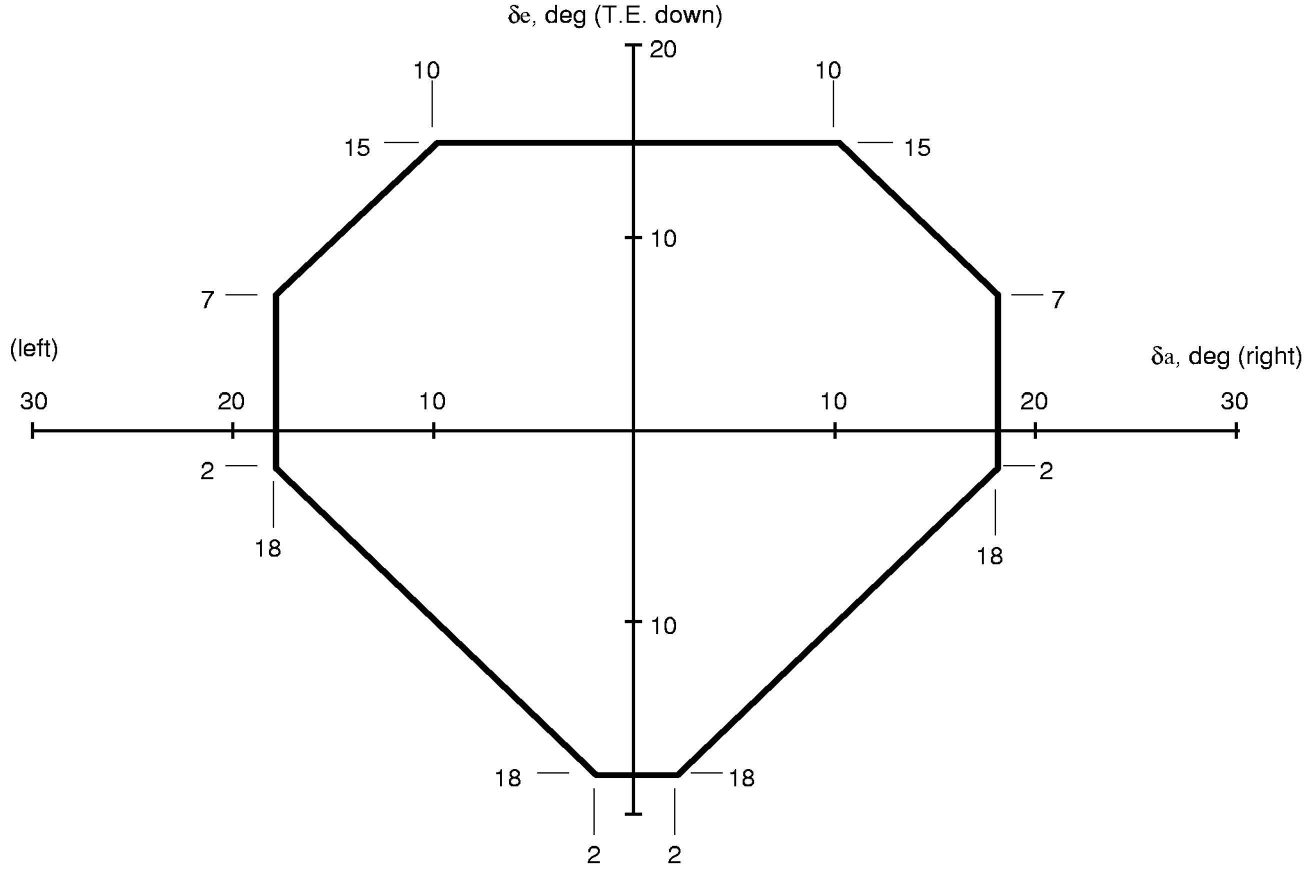

Figure 7. Elevon mixer deflection limits

As shown in figure 6, pitch and roll rate sensor feedbacks pass through a 2.5 Hz structural filter to remove aeroservoelastic inputs from the rate signals. Sideslip angle feedback is used to improve directional stability above Mach 1.6 or whenever the canard or landing gear is extended. A yaw rate sensor signal is fed back through a lead-lag filter to allow for steady turn rates while opposing random yaw motion.

The pitch and roll command signals are fed through mixer logic which limits the combined pitch and roll commands to allowable elevon travel, as shown in figure 7. Aileron deflection, δa, represents a differential signal subtracted from the symmetric elevator deflection, δe, signal to obtain the right elevon command; similarly, δa is added to δe to obtain the left elevon command.

An aileron-to-rudder interconnect exists to provided additional coordination in banking maneuvers between Mach 0.9 and 1.6, and whenever the canard or landing gear is extended, through separate first-order lag filters.

The pitch inceptor, or column, force-displacement characteristics were depicted on a chart shown to the evaluation team by Tupolev employees. It has been reproduced in figure 8 as accurately as possible, but some information may have been lost. The deflection of the column is given in millimeters, and the pull/push force is in kilograms. The feel characteristics are not symmetric, with more travel available in the forward, or nose down, direction, as shown in the figure. The exact magnitudes of the aft-most travel forces were not recorded exactly but are similar to the quantities shown.

Figure 9 depicts the approximate gearing relationships between column displacement in millimeters and pitch input to the control system in degrees. Note that the gearing changes depending on whether the landing gear or canard is extended. Some data may be missing.

The roll inceptor, or wheel, force-displacement characteristics (as presented by Tupolev) are shown in

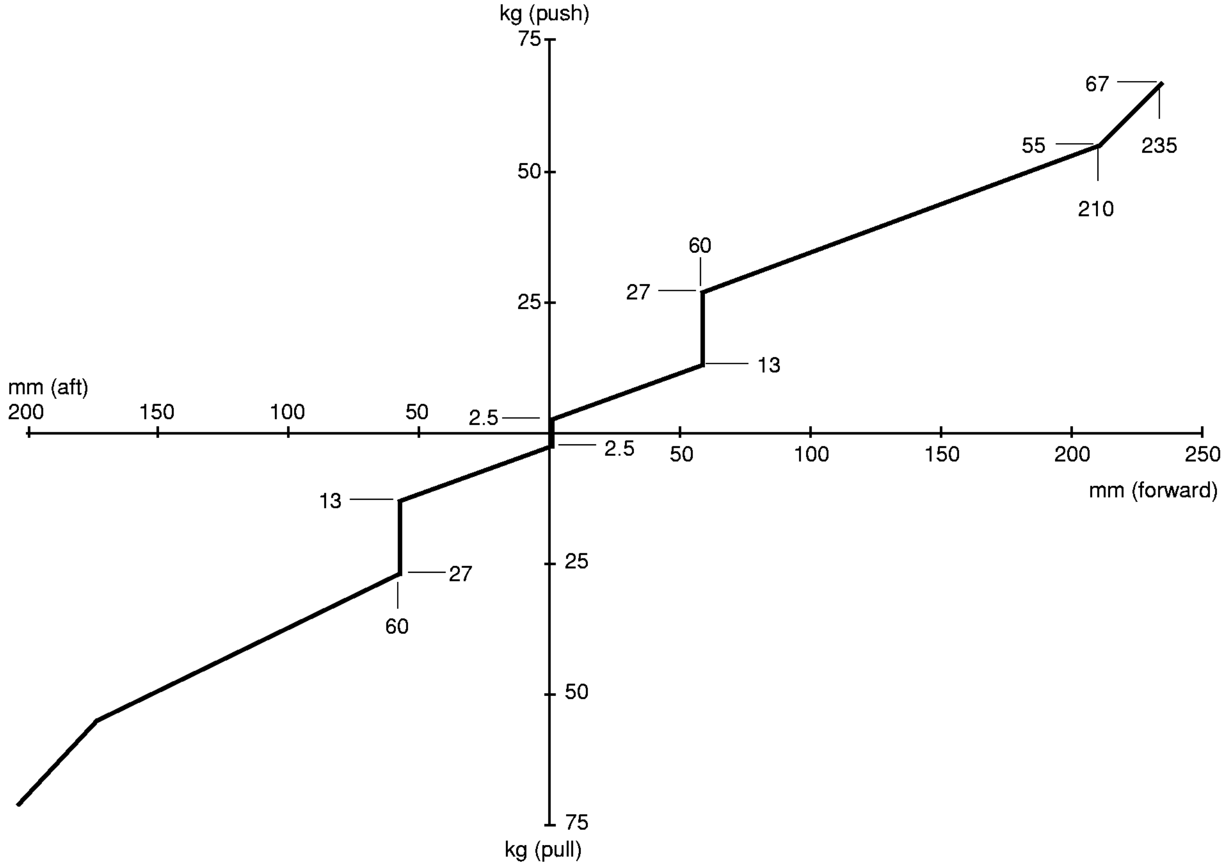

Figure 8. Approximate pitch inceptor (column) force-displacement characteristics

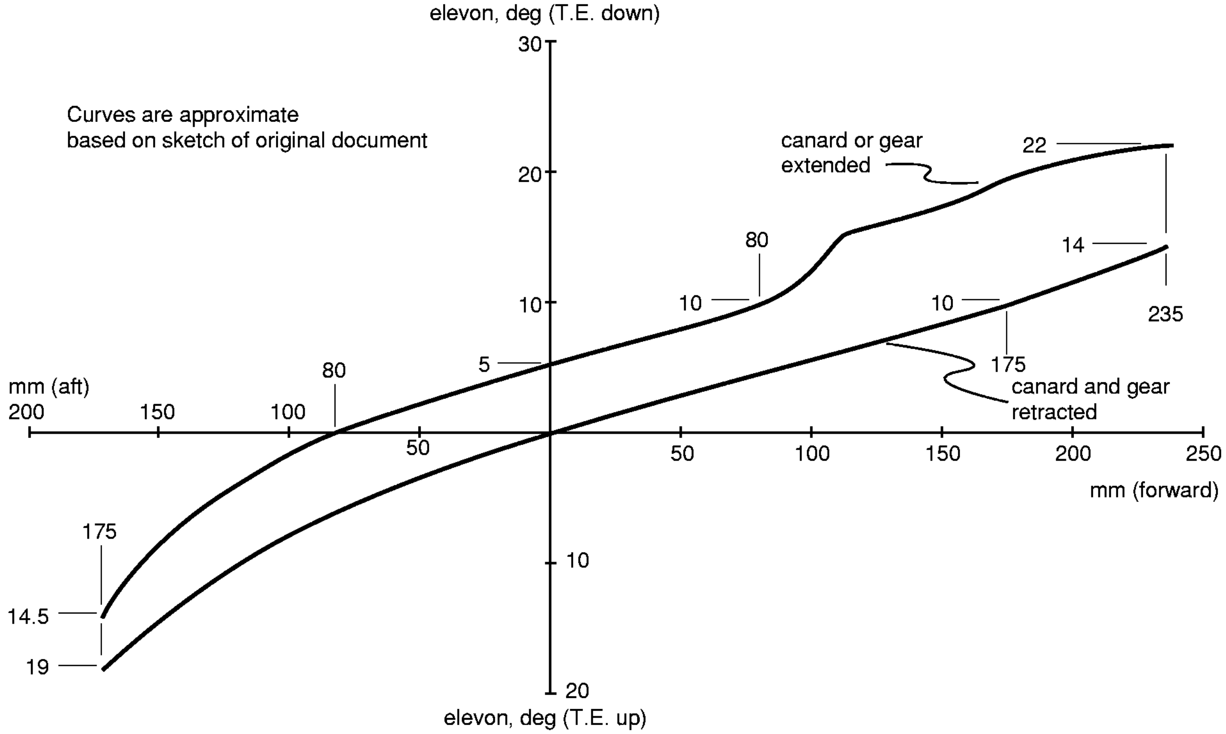

Figure 9. Approximate pitch inceptor (column) command gearing

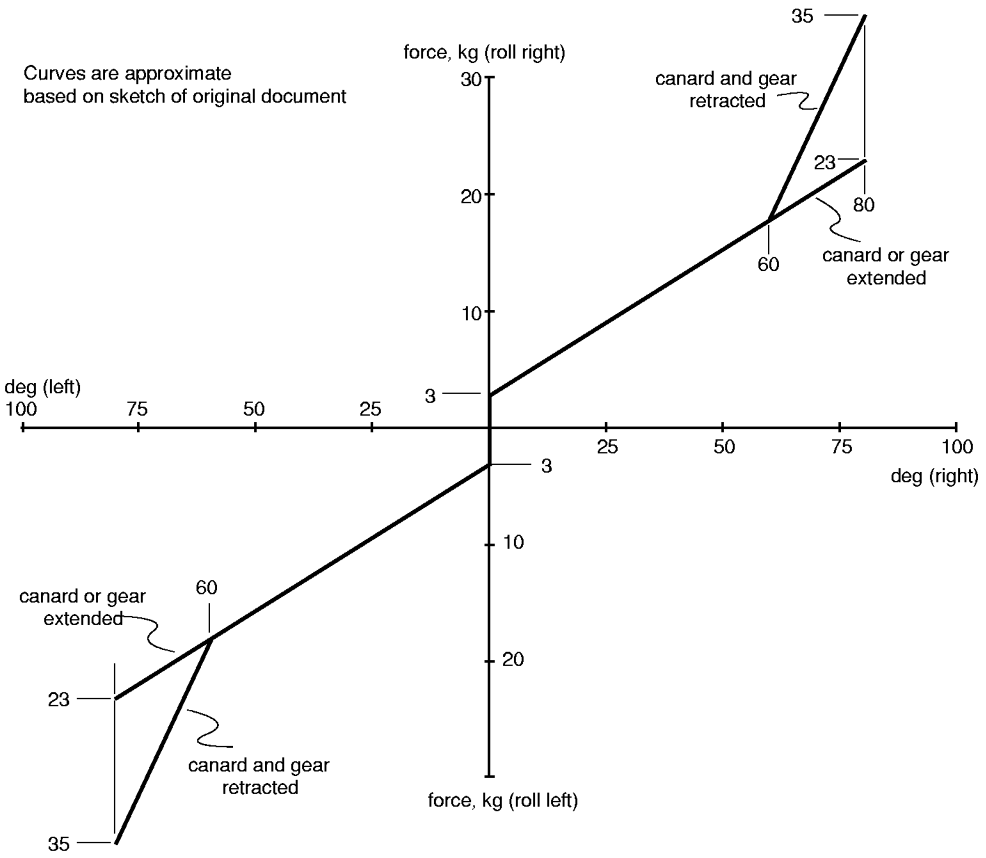

Figure 10. Approximate roll inceptor (wheel) force-displacement characteristics

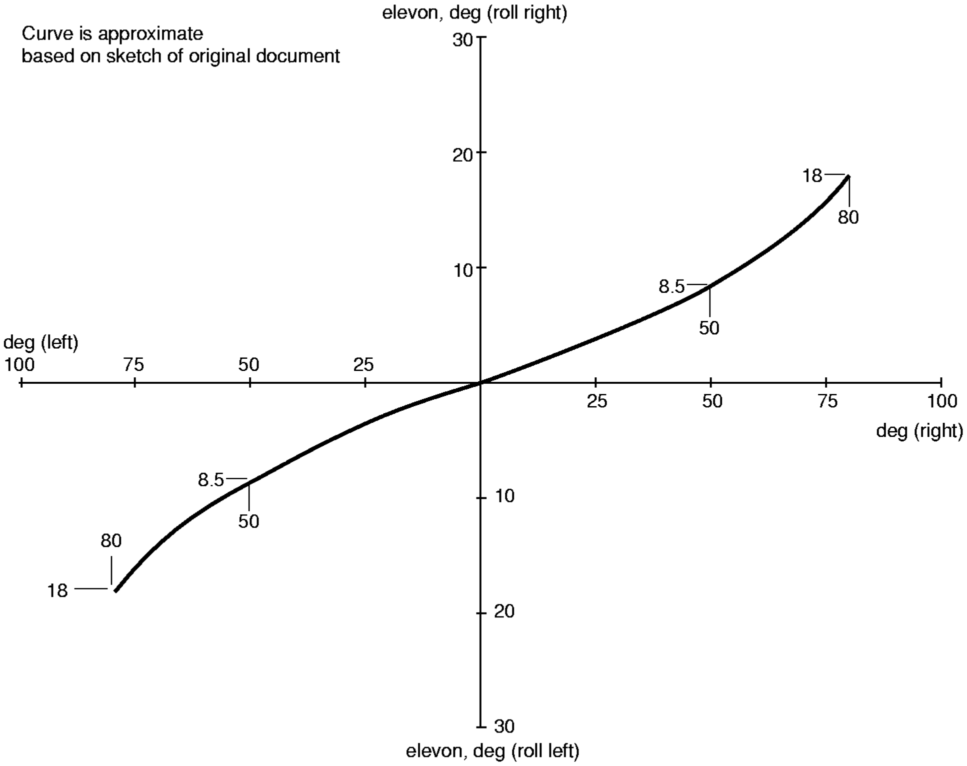

Figure 11. Approximate roll inceptor (wheel) command gearing

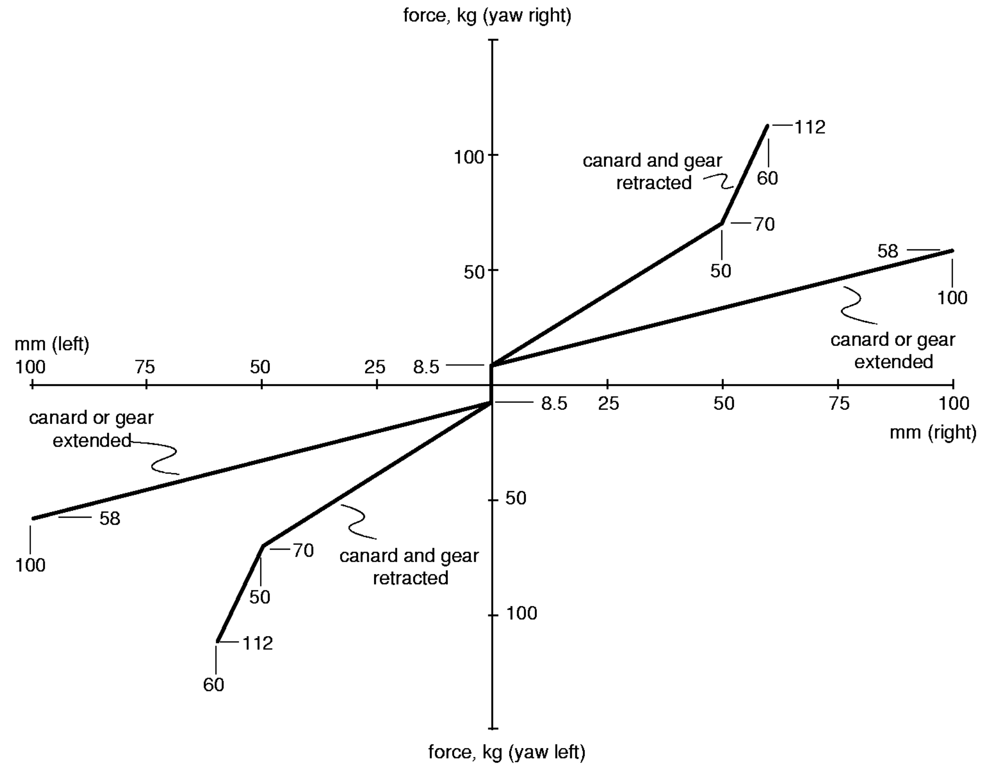

Figure 12. Approximate yaw inceptor (rudder pedal) force-displacement characteristics

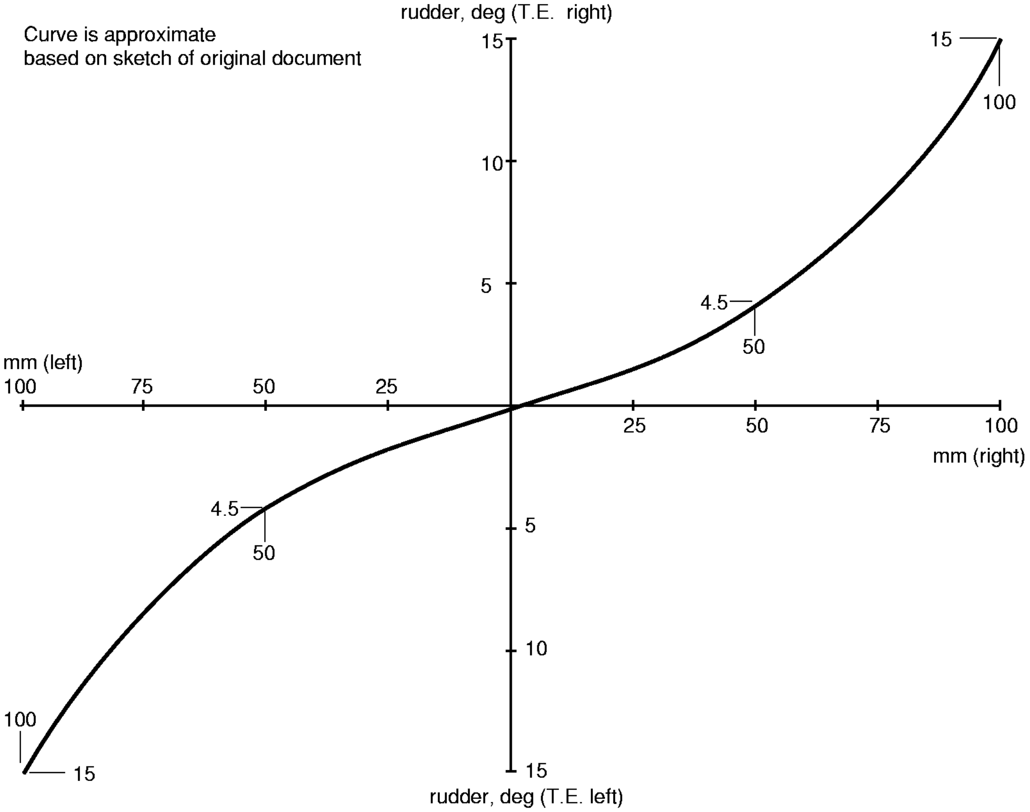

Figure 13. Approximate yaw inceptor (rudder pedal) command gearing

figure 10. This is a symmetric curve that changes the force characteristics if the landing gear or canard is extended. Figure 11 shows the gearing between wheel displacement in degrees and roll stick command input in degrees to the control system.

The yaw inceptor, or rudder pedal, force-displacement characteristics (as presented by Tupolev) are shown in figure 12. This is a symmetric curve that changes the force characteristics if the landing gear or canard is extended. Figure 13 shows the gearing between rudder pedal displacement in millimeters and rudder pedal command input in degrees to the control system.

Autopilot System

The autopilot uses the same servoactuators as the manual flight control system and is considered a subsystem of the entire flight control system. The rate dampers in all three axes must be operative for the autopilot to be used. It is a simple two axis system that is operated from mode control panels (MCP) located on the pilots' control wheels. Autopilot longitudinal and lateral modes include attitude hold, altitude hold, Mach hold, bank angle hold, heading hold, localizer tracking, and glideslope tracking. Each mode is selected by pressing a labeled button on the MCP. Selection logic is as follows: For Mach hold to be engaged, attitude hold must first be selected. Similarly, attitude hold must first be selected and in operation as indicated by a light on the overhead panel prior to engaging bank angle hold. Two autopilot disconnect switches are located on each MCP, the left one to engage/disconnect the lateral channel and the right one to engage/disconnect the longitudinal channel. In addition a red emergency disconnect switch is located on each control wheel. The autopilot channels can also be manually overridden and will disconnect with a 30 mm pitch input or a 15° roll input, respectively.

Altitude hold can be selected above 400 m altitude, but cannot be used between 0.85 indicated Mach number (IMN) and 1.2 IMN. The lateral modes of the autopilot will command roll angles up to 30°, but 25° is the nominal limit. The longitudinal modes operate between 30° nose up to 11° nose down and have a 10° elevon trim range capability.

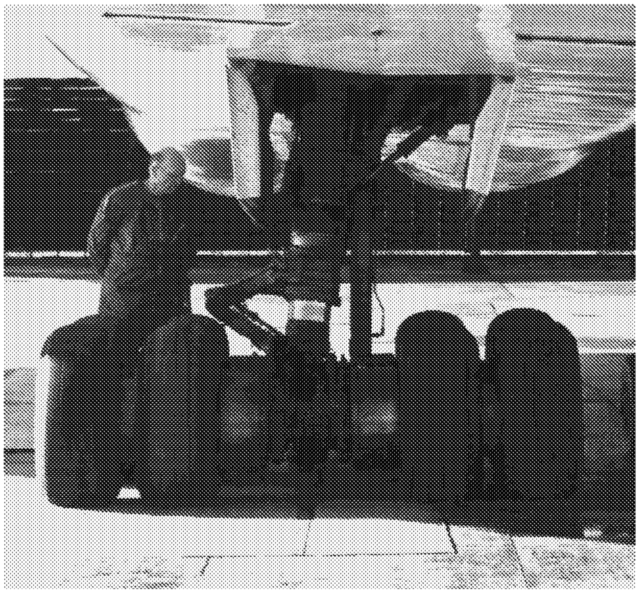

Figure 14. Tu-144 main landing gear

Landing Gear

The Tu-144 has a conventional tricycle arrangement with twin nose gear wheels and a left and right main landing gear with eight wheels each. The main landing gear, shown in figure 14, has several unique features.

Each main gear is a single strut with a dual-twin-tandem wheel configuration. The main landing gear includes a ground lock feature that prevents the strut from pivoting about the bogey when on the ground. This provides the aircraft with a slightly farther-aft ground rotation point (with the wheel bogey pivot locked, the aircraft will pitch around the aft wheels instead of the strut pivot point) as shown in figure 15. This assists in preventing the aircraft from tilting back onto the tail during loading.

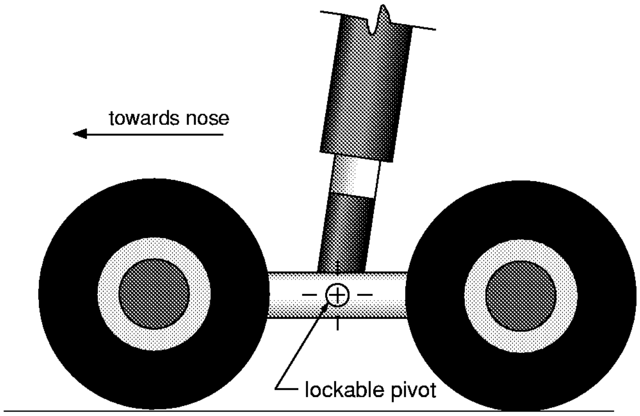

Figure 15. Schematic of bogey rotation lock operation

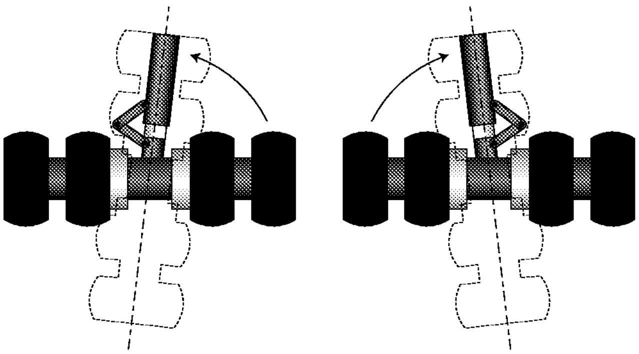

Figure 16. Schematic of initial gear retraction motion

Another unique feature of the gear concerns the lateral placement of the main gear attachment and stowage when retracted. The Tu-144 prototype design placed the four main engines closely together between the landing gear struts. In the later models, including the -LL derivative , the engines were moved farther apart. This placed the main landing gear squarely in the middle of the engine inlet ducting. To accommodate this change, the retracted landing gear was designed to fit between the inlet ducts of two engines. This was achieved by having the gear bogey rotate ninety degrees about the strut longitudinal axis (as shown in figure 16) before retracting into the tall but narrow wheel well.

Cockpit Layout

The cockpit crew of the Tu-144, including the -LL version, consists of two pilots, a navigator, and a flight engineer. The pilots sit side-by-side, with the navigator located on a seat between and behind the pilots, as shown in figures 17 and 18. The flight engineer station is located aft of the other three crewmembers on the right side of the cockpit, as shown in figure 19. The pilots have duplicated round-dial type flight instruments. A set of throttle levers is located between the two pilots, and another set of throttle levers is located at the flight engineer station. Radio and navigation controls are located on an overhead panel that is hinged to swing down in front of the navigator.

When the hinged nose is raised to cruise position, forward visibility is severely limited. To provide attitude reference information, each pilot has a conventional hemispheric attitude indicator located in the center of the instrument panel. Because pitch attitude is quite critical for this aircraft, the SPI is located above the glareshield directly in the center of the cockpit. This gauge has an expanded vertical scale with a pointer indicating aircraft pitch attitude and is calibrated in degrees.

Power lever angles are annunciated on four vertical tape indicators in front of the throttle levers. Afterburner selection is made above 72° PLA, without any detent in the motion of the throttle levers to indicate afterburner selection.

All engine controls and displays are contained at the flight engineer's station. The pilots have no direct knowledge of engine conditions, fuel flow, or power setting, aside from the power lever angle and N1 RPM indicators.

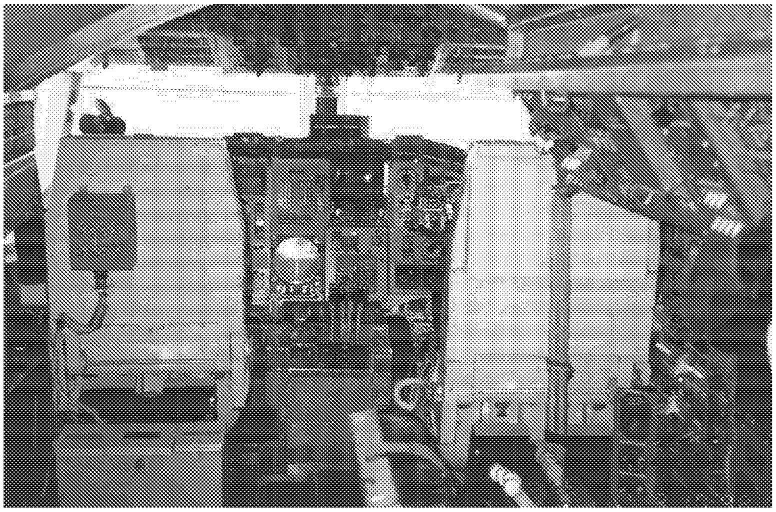

Figure 17. Tu-144LL cockpit seating arrangement

Crew Arrangement

During the three U.S. piloted evaluation flights, the left pilot seat was occupied by the Tupolev chief test pilot, Mr. Borisov. The U.S. evaluation pilot sat in the right pilot seat. The navigator and flight engineer were Tupolev personnel (Mr. Pedos and Mr. Kriulin, respectively).

Flight Equipment

Flight crew were issued partial pressure suits and helmets with oxygen masks. Parachutes were provided in the aircraft for emergency bail-out.

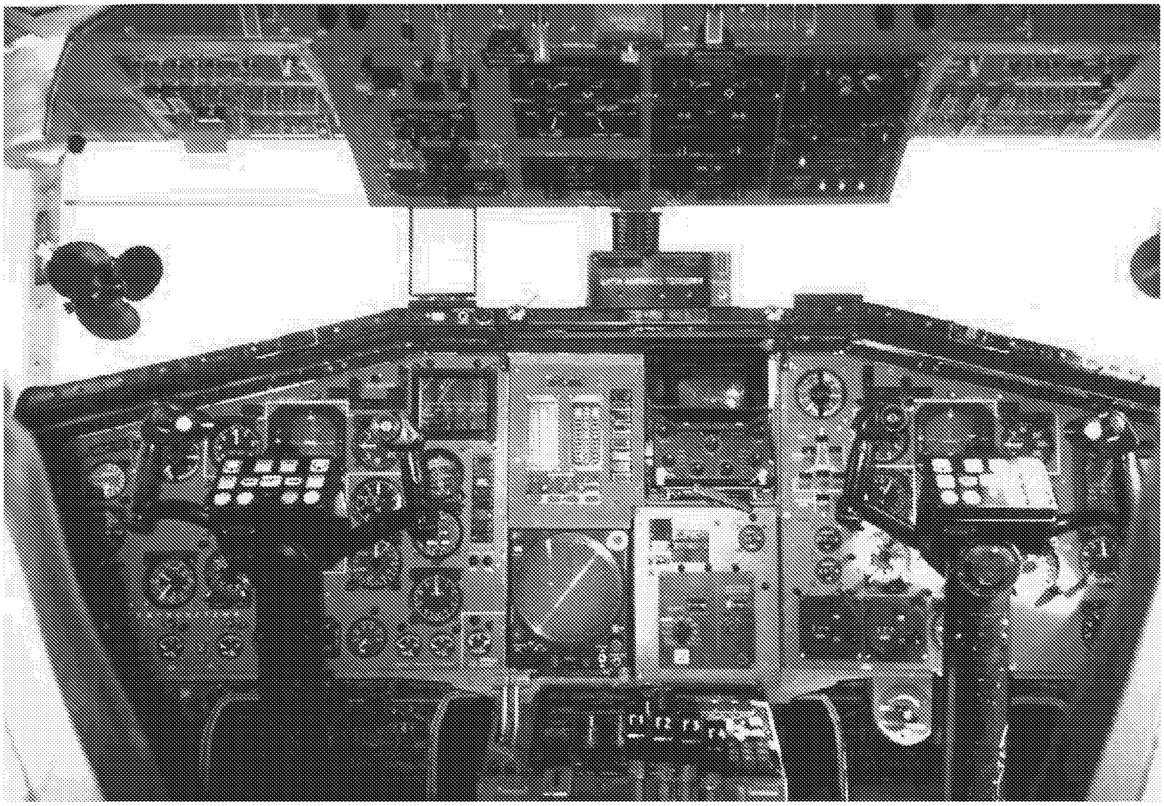

Figure 18. Tu-144LL cockpit instrumentation

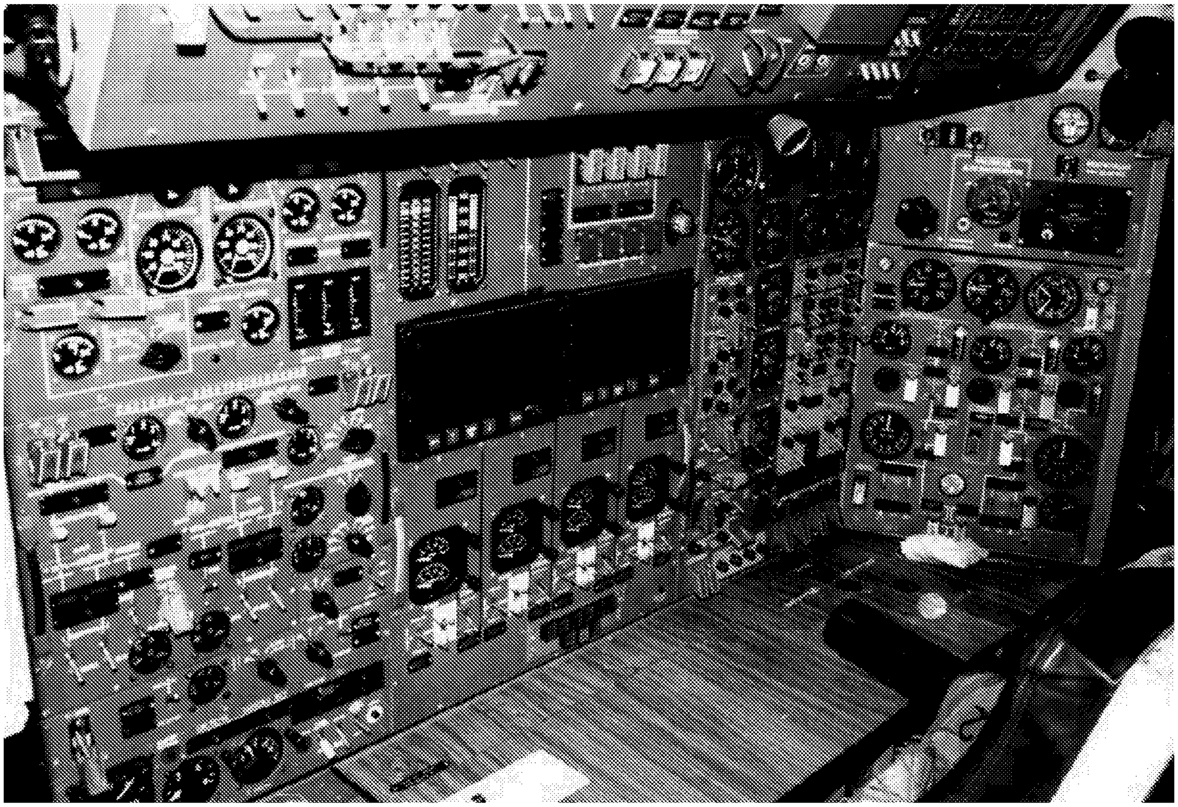

Figure 19. Tu-144LL Flight engineer's panel

Flight Test Planning & Preparation

Method of Tests

Through discussion among the U.S. team a consensus was reached on what were the highest priorities for the evaluation program. It was strongly desired that both U.S. pilots evaluate the Mach 2 flight regime and the approach characteristics to an altitude as low as Tupolev would allow. To assist in the evaluations, specifically defined maneuvers were established and repeated for different flight conditions and aircraft configurations. A brief description of these maneuvers is listed below with a fuller description in Appendix A.

Integrated Test Block (ITB) - This was a standard block of maneuvers designed to provide a consistent evaluation of the airplane for different flight regimes and configurations. The maneuvers consisted of: pitch attitude captures, bank captures, heading captures, steady heading sideslips, and a level deceleration/acceleration.

In addition to the ITB, other individual maneuvers were performed at specific conditions during the flights:

Parameter Identification (PID) Maneuvers - These maneuvers involved generating either a sinusoidal frequency sweep or a timed pulse train as an input to the axis of interest.

Simulated Engine Failure - This maneuver involved retarding an outboard engine to its minimum throttle setting, stabilizing flight, and then performing a heading capture.

Slow Flight - This maneuver involved pulling back on the column to achieve a certain deceleration to capture the minimum speed. This maneuver was done for level flight and banked flight.

Approaches & Landing - Approaches for differing configurations were designed such as: canard retracted, lateral offset, manual throttle, nose 0°, visual, engine out, and ILS. ILS approaches involved only the localizer, as the airfield glideslope transmitter was inoperative.

Structural Excitation Maneuvers - These maneuvers consisted of a sharp rap on each control inceptor in an attempt to excite and observe the aeroservoelastic reponse of the aircraft structure.

Due to the lack of simulator support and experience flying the airplane, it was decided not to collect handling qualities ratings. Such ratings could be misleading since they might reflect to a large degree the learning curve with no possibility for repeats to eliminate the effect. Thus, the primary data collected from these flights is pilot comment data. However, during the post-flight interviews a determination of flying qualities levels was made.

Planning Process

Tupolev imposed various requirements which affected the flight test planning. The first flight was to be subsonic and flown with an all Russian crew. The remaining three flights, with the first restricted to subsonic, were to be flown by one U.S. pilot per flight. Switching pilots in the middle of the flight was not allowed, as it necessitated the flight engineer and navigator leaving their stations, momentarily leaving flight critical systems unattended. This meant one U.S. pilot would have two flights, one subsonic and one supersonic, and the other would have one supersonic flight. However, Tupolev agreed to allow the second U.S. pilot not flying to observe the second, subsonic flight from the cockpit. Tupolev also preferred to not perform touch-and-goes, which meant that only one approach to touchdown could be done per flight.

In addition to these requirements there were several operational restrictions as well. Even though the airplane can take off with a 200 metric tons gross weight, Tupolev recommended against performing flying handling qualities tests at such high weights. A takeoff weight limit of 180 metric tons was therefore observed. In order to provide the correct fuel transfer capability for the Mach 2.0 flights, fuel had to be consumed until gross weight was below 140 tons prior to supersonic deceleration and descent. Approaches with go-around could not be flown until weight was below 135 tons, and the maximum landing weight was 125 tons. A 14 metric ton fuel reserve was planned for each flight leading to a target landing weight of 117 tons.

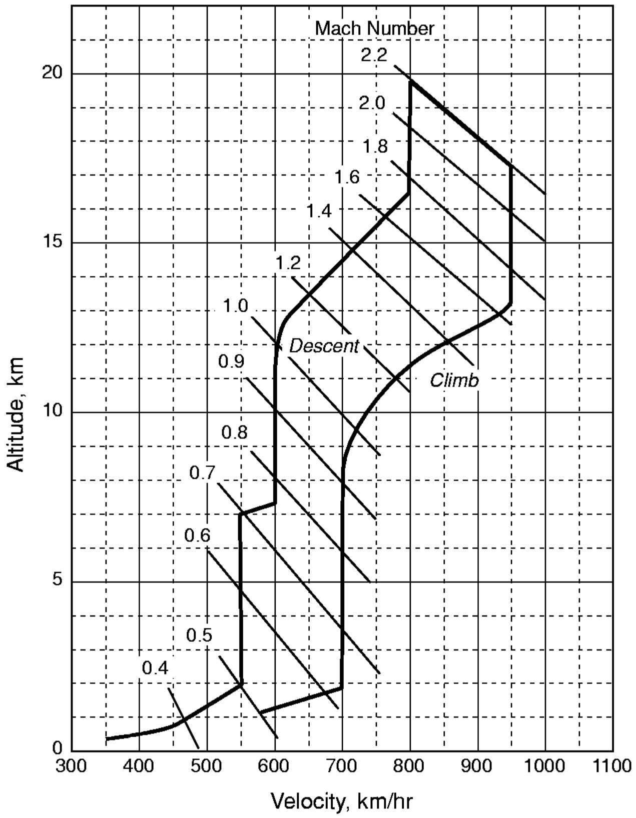

Figure 20. Tu-144 climb and descent profiles

The aircraft center-of-gravity had to be maintained at all times within a defined envelope as a function of Mach number and altitude. The CG was required to be forward during subsonic operations, and aft for supersonic operations. When accelerating or decelerating through transonic conditions, CG had to be maintained within a narrow location only 0.5% mean aerodynamic chord in length. CG location was controlled by fuel transfers between forward and aft fuel tanks controlled by the flight engineer.

The climb and descent profiles utilized by Tupolev to climb to and descend from supersonic conditions are shown in figure 20. These profiles were followed in flights 22 and 23 up to Mach 2.0 conditions.

The planning process with Tupolev personnel for each flight involved joint development of a flight profile in which the altitude, velocity, fuel loading and CG position within the above constraints were specified along with a sequence of maneuvers. The U.S. team would propose a set of maneuvers and flight conditions for each flight, usually no more than three days before each flight. The Tupolev flight test engineer, Vladimir Sysoev, and the Tupolev pilot, Sergei Borisov, would review the proposal and offer suggestions relating to safety, efficiency, and feasibility of the profile and each maneuver. Generally two to three days were required to reach consensus on how each flight would be flown and how much fuel would be loaded on the aircraft. From this consensus Mr. Sysoev would generate a detailed report of the profile and the maneuvers. The actual profiles flown (see figures 23 to 25 in Flight Test Summaries section) were close to planned, with additional approaches added for conservative fuel estimates.

Flight Readiness Review and Flight Task Examination

On the afternoon before a flight, the various Tu-144 specialists would meet in a conference room to be briefed on the plan of flight. The aircraft crew would be present as well. Weather and aircraft maintenance status would be reported, and the chief of the Calculation and Experimental Branch, Mr. Sysoev, would present an overview of the planned flight maneuvers. The specialists then had an opportunity to raise safety concerns and offer modifications to the flight plan. Typically none of the specialists would raise concerns except for the engine specialist, who for flights 22 and 23 placed a restriction on a small range of throttle settings for the #2 engine. Once agreement was reached, the schedule for the next day would be announced, the flight plan was signed by all parties, and the meeting concluded in about thirty minutes.

Pilot Briefing

Following the Flight Readiness Review and Flight Task Examination meeting, the aircraft commander, Mr. Borisov, the evaluation pilot, and the U.S. and Russian engineers would have a meeting to review the maneuvers in detail. Final decisions on how the maneuvers would be performed were made and any necessary modifications based on the flight readiness review were incorporated with the aircraft commander making the final decision regarding in-flight issues.

Flight Monitoring and Control

The flights were monitored from a control room located at the Gromov Russian Federation State Scientific Center. Telemetry and radio communications from

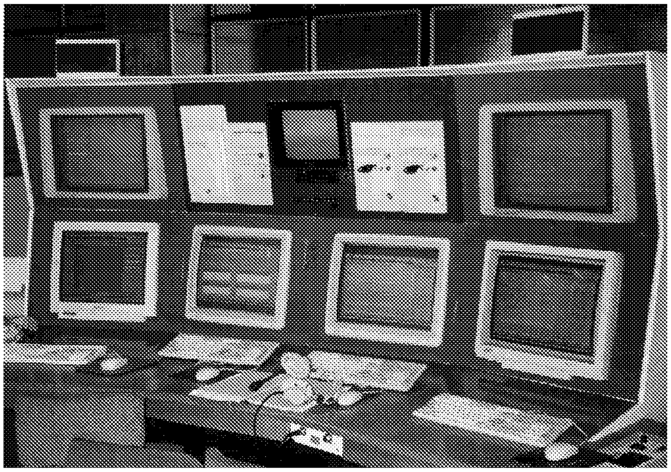

Figure 21. Gromov flight test monitoring area

the aircraft were received and processed at this location. Four consoles were provided to monitor propulsion and flight parameters (figure 21). A flight controller maintained communications with the flight crew, and for two of the three U.S. flights, a U.S. flight test engineer was provided with two-way communications with the U.S. evaluation pilot. Several parameter graphical readouts were provided in five different formats to the engineers, including a takeoff/landing display, a general controls display, a pitch display, a lateral/directional display, and a transonic flight display. In addition, another display showed: the position of the aircraft relative to the airport, a horizontal profile of altitude versus time, and altitude versus airspeed with the flight envelope overplotted. During landing approaches, these displays were replaced with a plot of the altitude of the aircraft versus time. In addition to monitoring the progress of the flight on the ground, instrumented fuel quantities were compared to predicted values at points along the profile.

Following each flight, hardcopy printouts of various parameters were plotted using a multicolor pen plotter on B-size graph paper. This allowed many parameters to be plotted on a single piece of paper and assisted in preparing for later flights. As an example (figure 22), a chart with 27 parameters overplotted in three colors clearly showed the change in vehicle weight, throttle settings, and Mach number that allowed rapid calculation of fuel flow vs. flight conditions.

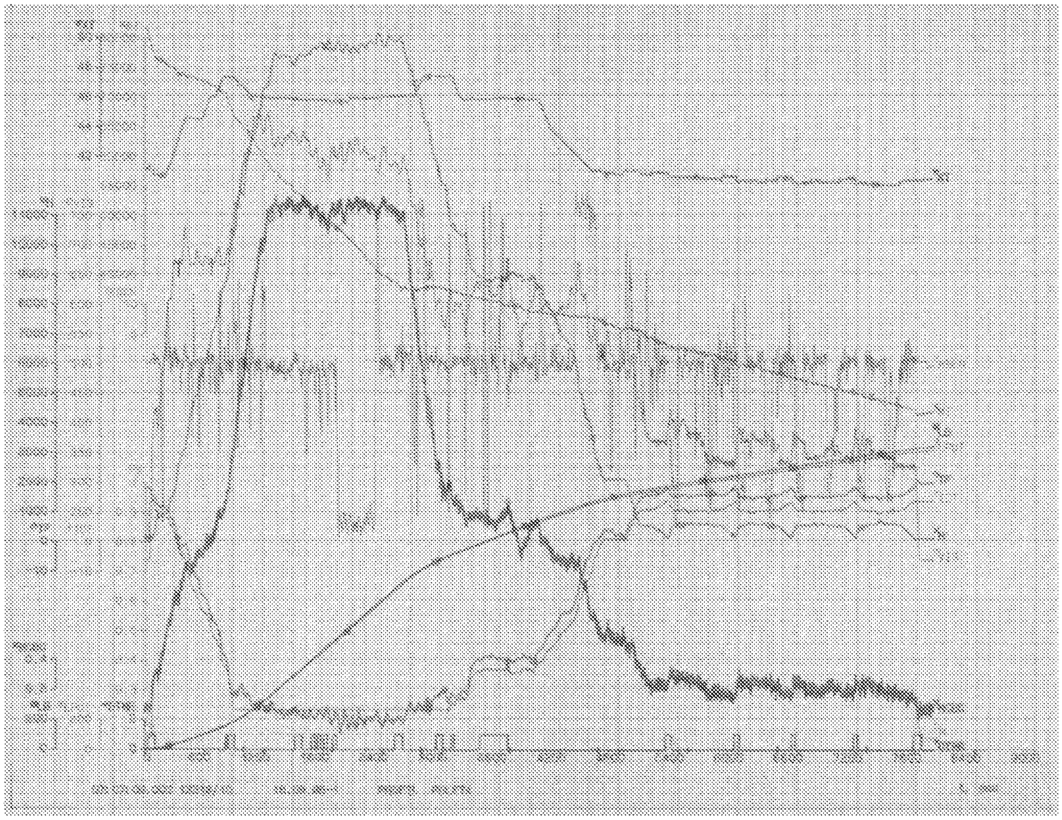

Figure 22. Example flight test data plot from Gromov facility

Flight Test Summaries

Flight 21 - September 15, 1998

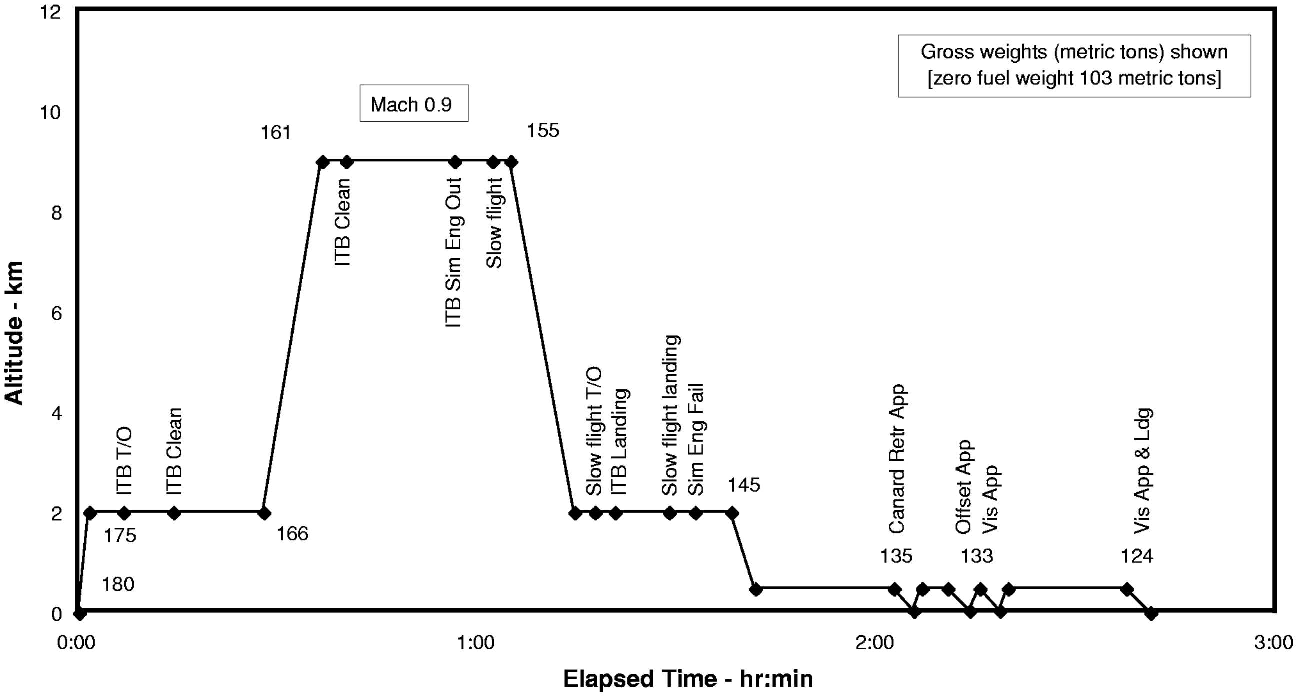

Figure 23. Flight 21 profile flown on September 15, 1998

The flight profile for flight 21, flown on Sept 15, 1998, is shown in figure 23. The evaluation pilot was Gordon Fullerton. Rob Rivers acted as an observer on the flight deck. Shortly after take-off a series of ITBs were conducted for the take-off and the clean configurations at 2 km altitude. An acceleration to 700 km/hr was initiated followed by a climb to the subsonic cruise condition of Mach 0.9, altitude 9 km. Another ITB was performed followed by evaluations of a simulated engine failure and slow speed flight. After descent to 2 km evaluations of slow speed flight in the take-off and landing configurations were conducted, as well as an ITB and a simulated engine failure in the landing configuration. Following a descent to pattern altitude three approaches to 60 m altitude were conducted with the following configurations: a canard retracted configuration using the ILS localizer, a nominal configuration with a 100 m offset correction at 140 m altitude, and a nominal configuration using visual cues. The flight ended with a visual approach to touchdown in the nominal configuration. However, due to unusually high winds the plane landed right at its crosswind limit, necessitating the Russian pilot in command to take control during the landing. Total flight time was approximately 2 hours 40 minutes. The maximum speed and altitude was 0.9 Mach and 9 km. A description of the maneuvers flown is found in Appendix A. A summary of the flight written by the evaluation pilot is found in Appendix B.

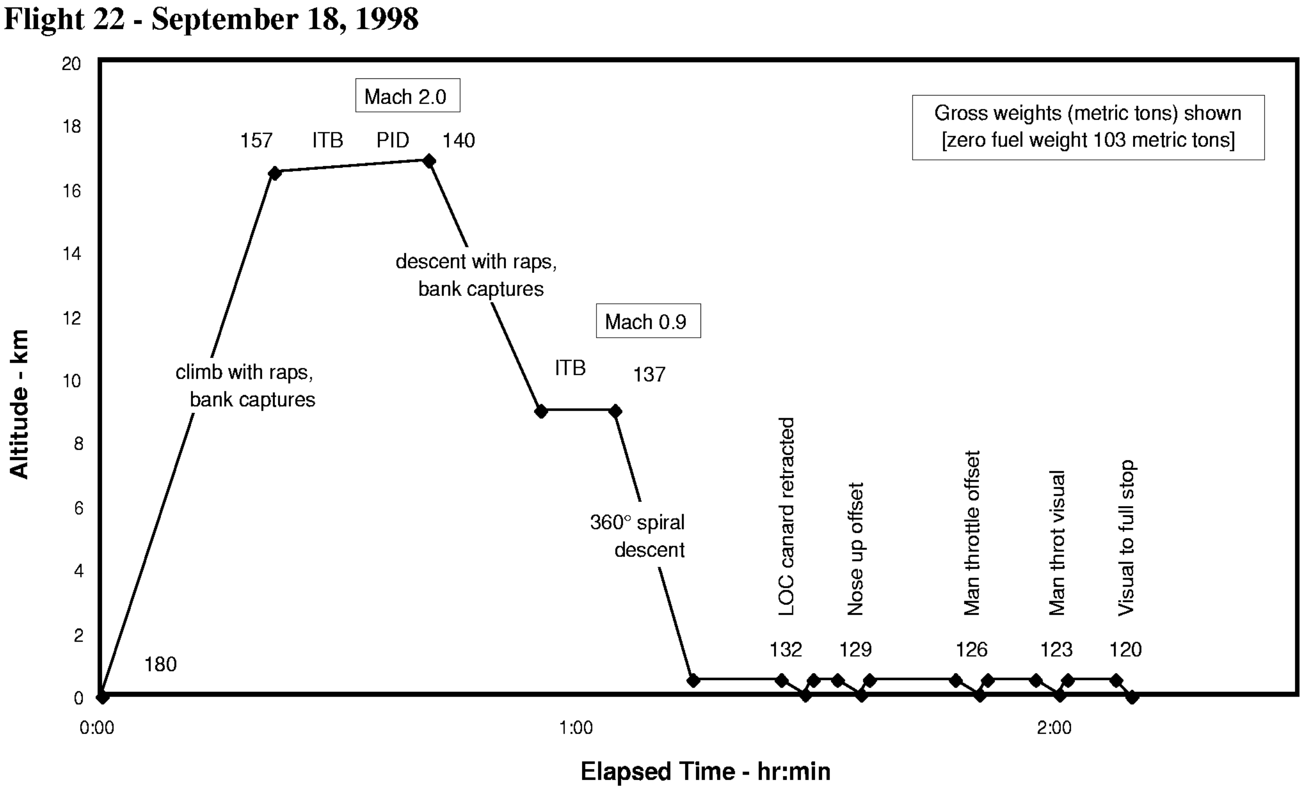

Figure 24. Flight 22 profile flown on September 18, 1998

The flight profile for flight 22, flown on Sept. 18, 1998, is presented in figure 24. This flight was a supersonic flight with Rob Rivers as the evaluation pilot. After take-off a nominal climb profile was flown to establish the supersonic cruise condition of approximately Mach 2 at an altitude of 16.5 km. A series of control system raps and bank angle captures were performed during the climb to evaluate lateral/directional and structural characteristics throughout the climb profile. At cruise an ITB was performed with the roll and heading capture portions conducted during a 180° turn midway through the cruise portion of the flight. Parameter identification (PID) inputs were conducted during the remainder of the cruise portion. Upon reaching a minimum fuel weight a nominal descent was conducted to the subsonic cruise condition of 0.9 Mach and 9 km altitude. Once again control system raps and bank angle captures were performed during the descent. At Mach 0.9 an ITB was conducted followed by a descent to pattern altitude. Four approaches were conducted: a canard retracted approach using the ILS localizer, a nominal approach (with 0° droop nose position on downwind, base, and the initial final legs) with an 100 m offset correction at 140 m altitude, and two visual approaches with the autothrottle off (one with and one without an offset). The flight concluded with a visual approach in the nominal configuration to touchdown. Maximum speed and altitude were Mach 1.97 and 17 km. Total flight time was approximately 2 hours, 10 minutes. A description of the maneuvers flown is found in Appendix A. A summary of the flight written by the evaluation pilot is found in the Appendix B.

Flight 23 - September 24, 1998

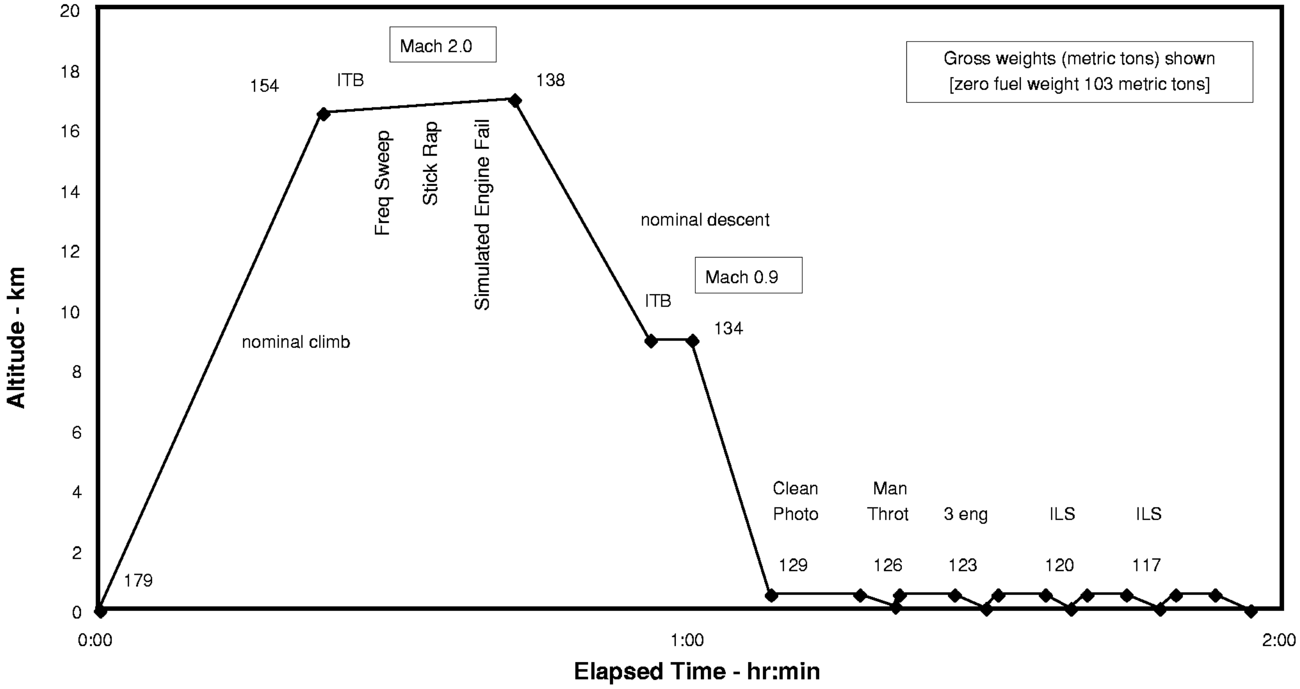

Figure 25. Flight 23 profile flown on September 24, 1998

The flight profile for flight 23, flown on Sept. 24, 1998, is presented in figure 25. This flight was a supersonic flight with Gordon Fullerton as the evaluation pilot. After take-off a nominal climb profile was flown to establish the supersonic cruise condition of approximately Mach 2 at an altitude of 16.5 km. At cruise an ITB was evaluated, with the roll and heading capture portions conducted during a 180° turn midway through the cruise portion of the flight. One set of frequency sweeps was conducted in each axis during the remainder of the cruise portion. At the end of the cruise portion a simulated engine failure was used to initiate a nominal descent. At 0.9 Mach and 9 km altitude an ITB was conducted followed by a descent to pattern altitude. A low altitude pass was conducted for photo purposes with the airplane in a clean configuration followed by three approaches to 60 m: a visual approach with the auto-throttle off, a simulated engine out approach and go-around using the ILS localizer, and a nominal approach using the ILS localizer. The flight concluded with an approach to touchdown in the nominal configuration using the ILS localizer. Maximum speed and altitude were Mach 1.98 and 16.6 km. Total flight time was approximately 2 hours. A description of the maneuvers flown is found in Appendix A. A summary of the flight written by the evaluation pilot is found in Appendix B.

Observed Vehicle Characteristics

Ground Handling

Nose wheel steering was active at all times on the ground and was controlled from either pilot position by rudder pedal deflection. Two ratios were selectable; 8° and 60° of total nose wheel deflection. In the 60° ratio precise control at taxi speeds was easy. A well designed pedal shaping allowed straight ahead control without jerking, but permitted a very tight 180° turn to be accomplished smoothly. The 8° ratio, used for takeoff and landing, was found to be adequate for lineup control throughout takeoff and landing roll, including while landing in a 30-40 kt crosswind.

Visibility with the nose drooped at 11° (takeoff setting) was adequate for comfortable taxi maneuvering, although it was impossible to see any part of the wing. Accelerations at the cockpit were very mild, considering its location was considerably ahead of the nose and main gear. The amount of cockpit overshoot required when turning to line up on the runway centerline was easily judged. The general feeling during taxi was much like in the Boeing 747.

The hydraulically powered carbon brakes were surprisingly ineffective when cold. The normal pre-takeoff procedure required a brake warmup taxi run. Power was advanced to produce a very slow acceleration and the brakes were applied full on. At first there was no deceleration at all, but as the brakes warmed they became effective. This procedure was done to be ready for a low speed takeoff abort. For landing, warmup was not required because the first brake application at high speeds after touchdown quickly heated the surfaces to an effective temperature.

Thrust Management

Retrofit of the NK-321 engines for the Tu-144LL configuration required replacement of the original cockpit engine instrumentation. As in the original design, the flight engineer (FE) station had a complete set of controls and displays for engine and inlet operation from startup to shutdown after flight. The pilots had only minimal engine information. PLA and N1 were the only engine displays, and they were hard to see from the right pilot seat. Four power levers, one for each engine, were the only engine controls at the pilot station. These power levers move through a range of 0 (idle thrust) to 115° PLA (maximum afterburner). There were no markings on the PLA instrument nor any force detent in the throttle quadrant to provide any indication to the pilot of afterburner ignition. Confirmation of afterburner operation was a verbal communication from the FE.

The rerouting of throttle control cables for the NK-321 engines resulted in extremely high power lever friction forces. Often the pilot not flying or the flight engineer manipulated the throttles to ease the workload of the pilot. One technique used was to adjust thrust first on two engines and then on the remaining two, because of the difficulty of moving all four at once.

The engines themselves had many operational limits and restrictions, some of which were specific to an individual engine. More time was spent in each preflight readiness meeting reviewing the engine operation than all other subsystems combined. A 30-minute engine ground run at relatively high power settings was required to stabilize engine operating temperatures prior to flight. If a takeoff was not performed within 1.5 hours of the ground run, the engine ground run had to be repeated.

Takeoff/Cleanup

Once lined up on the runway the starting brake was switched on, which applied full hydraulic system pressure to the brakes. This was sufficient to hold the aircraft while takeoff thrust was set and stabilized. Takeoff thrust setting depended on the gross weight; 115° PLA (full afterburner) for weights in excess of 180 tons, 98° PLA (midrange afterburner) for weights from 160 to 180 tons, and 72° PLA (maximum dry power) for weights less than 160 tons.

Takeoff roll was commenced by releasing the starting brake and the aircraft accelerated rapidly. For a 180 ton takeoff weight, V1 was 255 km/hr, Vr was 335 km/hr, Vlof was 355 km/hr, and V2 was 375 km/hr. Time from brake release to liftoff was about 30 sec. Directional control presented no problems. Moderate back stick pressure produced a slow rotation to a target attitude of 8°. Care had to be taken to not exceed 9° to preclude contacting the runway with the exhaust nozzles. After liftoff the pitch attitude had to be increased to approximately 16° to control airspeed before raising gear and flaps. After a positive rate of climb was established, the landing gear was raised.

A very high ambient noise level and a moderate buffet was experienced in the cockpit with the nose drooped and the canard deployed. The canard could be seen through the side window in a constant, obvious vibration. After climbing through 120 m altitude, the canard was retracted and the nose was raised to the 0° cruise position, resulting in a dramatic reduction in the noise and buffet level.

Visibility with the nose retracted was significantly restricted. The forward view was completely blocked, and the view through the somewhat distorted and crazed side windows was so poor that one's sensitivity to small pitch and even bank angle changes was greatly reduced. Control of the aircraft became essentially an instrument task. Quickly it became obvious that the SPI was the best source for pitch attitude information.

Handling Qualities

The Tu-144 was equipped with quad-redundant dampers in all three axes, all of which were mandated to be engaged at all times during flight, so the unaugmented characteristics of the aircraft were not examined.

Pitch control forces were moderate and not unusually heavy for a large aircraft. Small movements of the control column resulted in significant pitch motion. Initially there was a tendency to overcontrol during pitch maneuvers, especially at high subsonic and supersonic speeds. However, pilot compensation for this characteristic was easy. In contrast, lateral control forces were very high and wheel deflections required for even low roll rates were large. One could fly pitch with one hand but one tended to use two hands when a bank change was needed. Control harmony was moderately objectionable. Due to this deficiency, it was easy to make inadvertent pitch inputs on purely lateral tasks.

Roll response was very well damped and there was no adverse or proverse yaw even with large lateral inputs and no rudder inputs. Bank angle captures were easy to accomplish precisely. Aileron feel forces were extremely heavy; the aircraft would be much more pleasant to fly if the aileron feel forces were reduced by a factor of two.

One characteristic became consistently apparent during pitch attitude capture tasks. After reaching a desired attitude and releasing stick pressure to stop the rate, there was a rebound or drop back in pitch attitude of about one degree. It was necessary to overshoot a pitch target by this amount whether going nose up or down, and whether at slow speed or supersonic.

Speed changes resulted in the expected pitch trim changes of an aircraft with positive speed stability, and were easily trimmed. The trim rate provided by the wheel mounted electric trim switch was about right. Trim changes due to fuel transfer could be large so it was necessary to continuously trim the aircraft. Canard repositioning produced a very large trim change (deploy, nose up; retract, nose down) requiring a constant trim input during the 20 sec extend or retract cycle.

Response to rudder inputs was conventional, well damped and exhibited a positive dihedral effect. One could input full rudder, release it completely, and the aircraft would return to straight flight with no overshoots. As in the lateral axis, rudder pedal forces were very high. Full pedal deflection required an estimated 250 to 300 lb force.

All of the above characteristics were invariant with speed and configuration, from Mach 2 cruise to minimum speed in the landing pattern, with some small degradation near Mach 1.

Acceleration/Climb

Once in a clean configuration, the normal procedure called for setting the throttles to maximum dry power, 72° PLA, and accelerating in a climb to 600 km/hr. At 2 km altitude a further acceleration to 700 km/hr was accomplished in order to intercept the climb profile depicted on the Vertical Regime Indicator (VRI). This mechanical instrument portrayed altitude versus airspeed on a moving tape (driven by actual altitude) and the desired altitude/speed profile to maintain for optimum climb, normal descent, and emergency descent performance. It was found to be an intuitive presentation. At Mach 0.95, when the CG had been adjusted to 47.5%, the throttles were advanced to full afterburner power (115° PLA), and this throttle setting was maintained until level off.

Because of the restricted outside view, small but significant pitch attitude changes were not obvious to the pilot except as observed on the SPI. The ADI was not sensitive enough for tight control of pitch attitude. Maintaining the desired climb profile was a full time, high workload task due to the inherent flight path sensitivity to small pitch attitude changes, poor outside visibility, and the need for frequent pitch trim changes due to center of lift shifting and CG adjustments as the Mach increased. Also, the location of the instantaneous center of rotation near the cockpit deprived the pilot of motion cues due to pitch rate. Frequent reference to the SPI was found to be essential for smooth control of climb and descent profiles.

The pitch control task remained difficult until leveling off at Mach 2.0 at an initial cruise altitude of 16.5 km. From takeoff to level off at Mach 2.0 and 16.5 km took 19 minutes.

In order to examine handling qualities throughout the envelope the autopilot was not used during the climb, cruise and descent phases of any flight. It was not authorized for use transonically, between Mach .85 and Mach 1.2. The autopilot is described in the Aircraft Description section of this report.

Throughout the climb profile, small step changes in lateral trim occurred frequently, requiring lateral trim switch inputs. No explanation for this was determined.

Supersonic Cruise

After stabilizing at cruise Mach, the trim changes due to speed changes and fuel shifts ceased, reducing the pilot workload considerably. At Mach 2.0 it was noticed that a step increase in pitch force gradient occurred after the aft column breakout. No nuisance pitch/roll aerodynamic coupling existed, and the aircraft was very stable directionally. The engine inlets appeared insensitive to sideslips (up to 4.5° of rudder input) or to pitching motions.

About half of the starting fuel load (80 tons) was consumed for takeoff, climb, and acceleration to Mach 2. The aircraft burned approximately 1 ton of fuel per minute and required midrange afterburner to maintain Mach 2.0.

To simulate an engine failure, an outboard engine was reduced to the minimum allowable thrust setting while at Mach 2. A mild yaw resulted which was easily controlled with rudder trim. There were no apparent effects on any other engine. The remaining three engines were advanced to full afterburning thrust but the thrust was insufficient to maintain speed and a slow deceleration resulted.

Descent

Descent from Mach 2.0 cruise was initiated by retarding the throttles from the afterburner range to 59° PLA and decelerating to 800 km/hr while descending. The VRI descent profile was intercepted during the descent. The next power reduction to 52° PLA occurred at 14 km altitude with a third power reduction to 35° PLA at 11 km. At Mach 0.8 the throttles could be reduced to idle. From Mach 2.0 and 17 km to Mach 0.9 and 9 km altitude took 7 minutes. The CG had to be moved aft from 46% to 47.5% MAC prior to passing transonic speeds followed by a rapid forward shift to 41 % MAC for subsonic speeds. The shifting location of the CG might have contributed to some of the higher workload in controlling the pitch attitude in the transonic region. The pitch sensitivity increased in the Mach 1.2 to Mach 0.95 region especially near Mach 1.0 with a quite definite transonic pitch up just below Mach 1.0. At subsonic speeds the overall descent task became easier.

The SPI was provided primarily for pitch attitude information in the descent. It was a very useful instrument, but its sensitivity, accompanied by a perceived delay between attitude change and flight path angle change, produced a relatively high workload task. This was exacerbated by a lack of pitch reference cues with the nose retracted and a slight difficulty in getting adequately sensitive pitch reference information from the ADI. Very small pitch inputs (less than 0.25 cm) resulted in up to two or more degrees of pitch attitude change. Therefore, the pilot's control gain had to be decreased during the flight in order to not over-control the pitch axis.

Structural Characteristics

Passing 4 km altitude in the climb, the first of a number of control raps for the purpose of exciting aeroelastic modes were accomplished. These maneuvers were repeated at 6 km altitude and accelerating through Mach 0.7, 0.9, 1.1, 1.4, 1.8, and at level off at 16.5 km at Mach 2.0. The control raps consisted of rapid step inputs of small magnitude in each control axis. Responses in all three axes behaved similarly at all subsonic speeds. A rapid 1-2 cm forward or aft pulse of the control column caused a cockpit vertical oscillation of 1 to 2 Hz with 2 to 3 overshoots of about 1° in pitch attitude. A rapid 20 degree wheel input resulted in a lower frequency but higher magnitude lateral response of 1° to 2° and 4-6 overshoots. Rudder raps resulted in almost purely directional aeroelastic response of 4-6 overshoots at about the same frequency as the roll response.

The aeroelastic response of the aircraft differed as the speed increased and also depended on which axis was excited. Each axis of excitation resulted in a different aeroelastic response. In particular, the yaw and roll aeroelastic reponses appeared to be decoupled. In general, the aircraft seemed more heavily damped supersonic than subsonic. At Mach 2.0 in all axes the response was of higher frequency and smaller magnitude than at subsonic speeds.

Low Speed Characteristics

The total airframe drag increased dramatically as speed was decreased. Slowing to the angle of attack (AOA) limit of 16° at 9 km altitude, maximum dry thrust was insufficient to accelerate in level flight. Climb rate at maximum dry thrust was substantially lower (by a factor of four) at 430 km/hr compared to climb rate at 700 km/hr. Control response remained excellent at minimum speeds with motions in all axes well damped.

Traffic Pattern

Once the nose was lowered to the 17° droop position for landing, visibility was adequate for approach maneuvering. Canard extension had to be countered with several seconds of nose-down trim. Nose-down, canard-extended flight produced the same noisy buffeting cockpit environment encountered after takeoff. Landing gear extension produced no noticeable noise, vibration, or trim change.

The Tupolev preferred approach technique was to set up on a long (10 to 12 km) stabilized straight-in final on a shallow (2°) glideslope with established check points of range and altitude. The aircraft was stabilized in level flight at the final approach speed (on the order of 360 km/hr depending on fuel weight) which resulted in an AOA of 10°. At the proper range from the runway the nose was lowered to 8°, setting up a sink rate that was held constant all the way to the runway threshold.

Flight at AOA of 10° was definitely on the back side of the thrust required curve as indicated by frequent power adjustments. To reduce workload the autothrottles were normally used throughout the approach until just prior to touchdown. The autothrottle was a relatively low frequency system (20 sec time constant) but was effective at holding the desired speed. Manual throttle approaches were flown and were found not to be excessively difficult, except for the physical workload from having to overcome the extremely high friction forces. Flight path angle was controlled with pitch inputs and speed with the throttles. Despite being a back-sided aircraft, the engine throttle response time constants were reasonable, and airspeed deviations on approach were kept within 2 to 3 km/hr.

There was a noticeable pitching moment change with thrust change. If large power corrections were made, large pitch trim changes followed. Similarly, if large pitch inputs were made, fairly rapid speed changes resulted which required throttle adjustment. It was possible to get into a throttle/pitch input coupling situation. Once one learned to direct constant attention to maintaining the proper pitch attitude using the SPI, control of the aircraft became easier.

Go-arounds were initiated by setting 72° PLA which provided a brisk acceleration. With a positive climb rate the landing gear was raised. Passing 120 m altitude, the canard was retracted if desired, while applying the required nose-up trim inputs. Power was normally reduced passing 300 m to reduce the climb angle. With the landing gear extended, the bank angle limit was 15° and an aural voice warning triggered when that limit was exceeded. With the gear retracted, it was comfortable to bank up to 30°.

The first evaluation flight was flown under strong gusty wind conditions with moderate turbulence at pattern altitude. Due to the high lateral forces and less than desirable control harmony, the constant control inputs required to maintain attitude became physically tiring. When the autopilot was engaged, it performed acceptably in the relatively turbulent conditions.

An engine-out condition was simulated by retarding an outboard engine to idle. At normal landing weights there was adequate thrust with the remaining engines at dry thrust or less to fly a standard pattern, approach, and go-around. It was found during a three-engine pattern flown on the first mission at a heavier weight that maximum dry thrust was barely adequate for a missed approach. In both cases there was plenty of rudder control power to maintain directional control at all times. Rudder forces could be trimmed out with the electric rudder trim switch.

Several approaches were made with the canard retracted which increased the required final approach speed by about 30 km/hr. There was a slight reduction in the buffet level sensed at the cockpit but no change in handling qualities was noticed.

A nose retracted approach was flown in order to evaluate the ability to land in this very restricted visibility condition. Forward visibility was almost nonexistent due to the metal skin on top of the nose blocking the pilot's forward field of view. A nose-retracted landing may be possible to accomplish through the use of the side window and an angling approach, but this was not evaluated to touchdown.

One clean (gear, nose, and canard retracted) configuration low approach pass was flown for photographic documentation. After lining up with the runway about 10 km out, the nose was raised. It was impossible to see any part of the aerodrome or its surrounding structures, and the only lineup information available was the ILS course deviation indicator.

Several lateral offset approaches were flown to examine handling qualities in this high workload task. The offset was 100 m to the right of the runway centerline. A lineup correction was started descending through 140 m altitude, and a missed approach was initiated at 60 m. Since the approaches could not be flown to touchdown, the workload for this task was not as high as had been desired. The aircraft responded nicely during moderately aggressive lateral maneuvering. It was easy to judge the correction, and roll out was accomplished with no tendency for pilot-induced oscillation (PIO).

Landing/Ground Roll

Descending through 15 m, ground effect caused a strong nose down pitching moment which required a firm pull on the control column to maintain attitude. Normal technique was to maintain or slightly increase the pitch attitude, and allow the aircraft to fly onto the runway. The ground effect cushion provided a soft landing in each case. Care had to be taken to not overflare or to hold the aircraft off, allowing the pitch attitude to exceed 10° and risk contacting the engine exhaust nozzles with the runway.

Derotation was easily controlled. The long nose gear and nominal 3.5° pitch attitude in the three-point stance resulted in the appearance of a significant nose-up attitude at nose gear touchdown. The drag parachutes were deployed after nose gear touchdown, and wheel brakes were applied below 220 km/hr. Only light braking was required to stop the aircraft.

On the first evaluation flight, strong gusty crosswinds were encountered at landing. The aircraft was landed with the recommended crosswind technique, wings level in a crab. It tended to align itself with the runway after touchdown without much rudder input, and there was almost no rolloff tendency. The rudder pedal nose wheel steering in the 8° ratio was exactly right for maintaining runway centerline during drag chute deployment and deceleration.

Conclusions

The opportunity to fly the Russian supersonic transport allowed U.S. pilots to observe the flight characteristics of one of only two such examples of supersonic passenger-carrying aircraft. From this opportunity, several observations are made, and some conclusions can be drawn with application to future supersonic aircraft of this type.

- The Tu-144 exhibited heavy lateral control forces throughout the flight envelope. The pitch axis control forces were more appropriate, but still a bit heavy, for this class of aircraft.
- The lateral axis had a low roll response sensitivity at all speeds which required large control wheel de-

flections to achieve even mild roll rates. The pitch axis demonstrated a correspondingly higher sensitivity throughout the flight envelope. The resulting lack of harmony in the wheel and column control sensitivity led to instances of coupling roll inputs into pitch inputs.

- Due to power changes, fuel transfers, and other unidentified lateral trim changes during climb and cruise, continual adjustments of both pitch and roll controllers contributed to high workload for the pilot. Poor visibility with the nose raised and problems with pitch response dynamics added to the difficulty of pitch control.

- Due to the delta planform of the wing, the instantaneous center of rotation of the Tu-144 in pitch appeared to be near the cockpit. This resulted in little normal acceleration change with pitch changes and, consequently, no motion cues for the pilot. This characteristic is not found in conventional aircraft with aft tails.

- Excessive throttle friction was noted, leading to higher workloads during manual throttle landings. Normally, Tu-144 landings were performed with the autothrottle engaged. Backside-of-the-power-curve characteristics were noted but were not objectionable.

Each of the characteristics just described led to an overall handling qualities rating of Level 1 for the roll axis and Level 2 for the pitch axis (as defined by the Cooper-Harper Pilot Rating scale in reference 1). The Level 2 rating is attributed to poor pitch attitude information and frequent trim changes during climb/descent.

Lessons to be learned for future supersonic aircraft of this type include:

1. Control forces should be reduced in all axes, including throttle.

2. Pitch control sensitivity should be a function of flight regime to increase control harmony.

3. An autothrottle system may not be mandatory for manual landings.

4. A pitch augmentation system that provides automatic trimming, such as a flight-path-angle response-type system, might reduce pilot workload on future supersonic aircraft.

Other observations were:

- The effects of aeroelasticity were apparent, but were considered minor and did not affect the flying qualities of the Tu-144.

- Making the pattern turn to final was possible with the nose retracted, but landing was not attempted. The field-of-view with the nose in the retracted position is extremely limited, but a nose-up landing appears to be feasible.

- The general lateral/directional and longitudinal characteristics remained fairly constant throughout the flight envelope.

- Good crosswind landing capability was demonstrated on the first flight, with a 10 m/sec direct crosswind.

- Operational concerns include the need to warm up the wheel brakes during taxi for takeoff, the requirement to warm up the engines prior to flight (this may be unique to the Tu-144LL) and the utilization of drag chutes on landing rollout for deceleration. Each of these concerns would need to be mitigated for a commercial aircraft.

- Marginal climb rates were noted when using three engines at maximum dry power while the vehicle was heavy; otherwise, control of the vehicle during asymmetric thrust conditions was not difficult.

- Based on only limited evaluation time, a canard-retracted approach showed an obvious trim and airspeed difference from an approach with the canard extended, but other differences in handling qualities were not noticeable.

- Inadequate engine instrumentation was provided at the pilot stations. Changes in power settings were not apparent to the pilots except in pitch coupling due to a lack of visual or aural cues. Particularly missed was any indication of afterburner ignition.

- Ground effects during landing assisted in cushioning the vehicle during the landing flare.

References

1. Cooper, G. E.; and Harper, R. P., Jr: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, April 1969.

Appendix A: Description of Maneuvers

This appendix describes a typical definition of the maneuvers flown in the evaluation program. Modifications to target values were required for some of the maneuvers based on flight condition. This section is intended to provide a general idea of how the maneuvers were defined.

Deceleration/Acceleration

a. Reduce throttle from trim position by approximately 20°.
b. Decelerate and capture an airspeed 70 km/hr less than trim.
c. Advance throttle to full dry power setting.
d. Accelerate and re-capture original airspeed.

Pitch Attitude Capture

a. From trim attitude pull column back to capture a +3° pitch attitude increment.
b. Push column forward to capture original trim attitude.
c. From trim attitude push column forward to capture a -2° pitch attitude increment.
d. Pull column back to capture original trim attitude.
e. Throughout a.-d. keep normal acceleration between 0.8 and 1.2 g.

Bank Angle Capture

a. From steady level flight apply right wheel to capture a +30° bank angle.
b. Apply left wheel to capture level flight.
c. From steady level flight apply left wheel to capture a -30° bank angle.
d. Apply right wheel to capture level flight.

Heading Captures

a. From steady level flight apply right wheel to capture a +30° bank angle.
b. Maintain bank angle and capture +20° heading increment.
c. Apply left wheel to capture a -30° bank angle.
d. Maintain bank angle and capture original heading.
e. Repeat in opposite direction.

Steady Heading Sideslips

a. From steady level flight apply a series of rudder deflections of +2, +4, +6, and +7.5°.
b. Apply appropriate wheel deflection to maintain constant heading, stabilizing for 5 sec on each rudder deflection.
c. Repeat in opposite direction.

Simulated Engine Failure

a. From steady level flight retard throttle #1 to idle.
b. Wait 5 sec and then stabilize transient, maintaining a bank angle less than ±5°.
c. Advance three remaining throttles to capture original airspeed.
d. Perform heading capture maneuver.
e. Recover by slowly advancing #1 throttle and re-establish original flight condition.

Slow Flight

a. From steady level flight pull column back and establish a 2 km/hr per sec deceleration.
b. At minimum airspeed or warning stop deceleration and hold condition for 3 sec.
c. Recover by pushing column forward and establishing original flight condition.
d. From steady level flight establish a 30° bank turn
e. Pull column back and establish a 2 km/hr per sec deceleration.
f. At minimum airspeed + 10 km/hr or warning, stop deceleration and hold condition for 3 sec.
g. Recover by pushing column forward, rolling wings level and establishing original flight condition.

Frequency Sweep PID maneuver

a. Allow 15 sec of steady level flight
b. Commence longitudinal sinusoidal input of 1.5 cm to 2.0 cm (no greater than 0.8 to 1.2 g) with a period of oscillation of 20 sec.
c. Increase frequency at constant amplitude over 80 sec to a period of 1 sec.
d. Wait 15 sec and then recover to original conditions.
e. Repeat a.-d. for lateral wheel input of 15° to 20° (bank angles between 5° and 10°).
f. Repeat a.-d. for rudder pedal input of 1.5 to 2.0 cm (heading changes between ±5°).

Timed Pulse Train PID maneuver

a. Allow 5 sec of steady level flight.
b. Input 2.0 cm forward (of trim) control pulse for 3 sec.
c. Input 2.0 cm aft (of trim) control pulse for 2 sec.
d. Input 2.0 cm forward (of trim) control pulse for 2 sec.
e. Allow 5 sec of steady level flight.
f. Input 2.5 cm left pedal for 3 sec.
g. Input 2.5 cm right pedal for 2 sec.
h. Input 2.5 cm left pedal for 2 sec.
i. Return pedal to neutral while inputting 20° right wheel.
j. Keep right wheel input for 1 sec.
k. Input 20° left wheel input for 1 sec.
l. Release controls for 10 sec.
m. Repeat a.-e. with 4.0 cm amplitude.
n. Repeat e.-l. with 40° (wheel) and 5.0 cm (pedal) amplitude.

Structural Excitation maneuver

a. Sharply deflect control inceptor for a single axis approximately 1-2 cm (column or pedal) or 10° (wheel).
b. Release controller and allow aircraft to aeroelastically respond until all motions are damped

Appendix B. Extended narratives for each U.S. piloted flight

Flight 21

Date of Flight:	September 15, 1998
Flight Crew:	
Pilot in Command:	Sergei Borisov
Evaluation Pilot:	Gordon Fullerton
Navigator:	Victor Pedos
Flight Engineer:	Anatoli Kriulin
Takeoff Time:	10:58 Local
Landing Time:	13:43 Local
Flight Duration:	02:45
Takeoff Weight:	180 metric tons
Landing Weight:	124 metric tons
Landing Fuel:	21 metric tons
Total Fuel Burn:	56 metric tons
Takeoff CG:	40.5%
Landing CG:	40.7%

Flight Summary

The engines were started by the flight engineer in a 2, 3, 4, 1 order. After completing a short pre-taxi checklist the parking brakes were released. The aircraft began to roll slowly with the power levers still at idle. With the 60° steering ratio selected the runway was entered and a brake warm-up procedure was done, consisting of setting the power levers to 35° PLA and applying the brakes. At first full brake pedal deflection would not slow the aircraft, but as the carbon brakes warmed they became more effective.

Holding in lineup position, the steering ratio was set to 8°, and the engines were set at 98° PLA (partial afterburner).The aircraft accelerated rapidly through rotation and liftoff speeds.

After takeoff the landing gear was retracted but the canard and nose were left in takeoff configuration (deployed and 11°, respectively). Leveling at 2000 m a series of maneuvers, called the Integrated Test Block (ITB), was performed to evaluate handling qualities at a heavy weight takeoff configuration. The ITB tasks included a deceleration and acceleration, pitch attitude captures, bank angle captures, heading captures, and steady heading sideslips.

The nose was raised, canard retracted and a climb to subsonic cruise conditions (Mach 0.9 and 9000 m) was made where the ITB series was repeated. Then engine #1 was retarded to near-idle thrust to evaluate handling in an asymmetric thrust condition.

After returning to symmetric thrust the aircraft was slowly decelerated to approach the angle of attack limit of 16°, then recovered by decreasing pitch attitude and increasing power. The slow flight characteristics were further investigated by repeating this procedure in a 30° bank, recovering by leveling the wings as thrust was increased.

Power was reduced, descending to 2000 m and configuring the aircraft with the nose at 11° and canard deployed. The slow flight procedures just described were repeated.

After establishing a landing configuration, nose 17°, canard deployed, and landing gear down, the ITB maneuvers were performed, followed by another slow flight investigation with wings level and in a 15° bank.

Next, an engine failure was simulated by retarding the #1 engine to near idle. After a 5 sec delay with no control inputs to observe the aircraft response, power for level flight was set on engines 2,3, and 4, and the aircraft was trimmed. A descent of 4 m/sec was set up simulating a normal approach glideslope. At 1500 m AGL power was advanced to maximum dry thrust on 2, 3, and 4, establishing a shallow climb. The landing gear and canard were then retracted.

Since gross weight was slightly above the maximum limit for landing, the first approach was a pass down the runway 30 centerline at about 400 m altitude. Winds were unusually strong, gusting from the south up to 20 m/sec (40 knots) with very turbulent conditions at pattern altitude and below.

A closed pattern was flown leading to a visual approach to runway 30 with the canard retracted and initiating a go-around at 60 m above the surface.

The next approach, also to runway 30, was intentionally aligned about 100 m right of the runway centerline until descending through 140 m when an S-turn maneuver was done to correct the lineup error. As before, a go-around was started at 60 m.

A planned low pass down the runway for ground effects data was canceled because the winds were far in excess of the 2.5 m/sec limit. Because of the strong tailwind component on runway 30, the aircraft was maneuvered to a right hand downwind leg for runway 12, followed by an approach and go-around at 60 m.

The airport traffic area was departed to the east out to a distance of about 60 km to burn down fuel prior to the final landing. The autopilot was engaged and evaluated during this delay.

Returning to the runway 12 pattern, a visual approach and full stop landing was made, in a strong crosswind from the right, the strongest ever encountered in this aircraft by Mr. Borisov. The aircraft was stopped using the drag chutes and light braking. After jettison of the chute, the aircraft was taxied back to the startup area and shut down.

Flight 22

Date of Flight:	September 22, 1998
Flight Crew:	
Pilot in Command:	Sergei Borisov
Evaluation Pilot:	Rob Rivers
Navigator:	Victor Pedos
Flight Engineer:	Anatoli Kriulin
Takeoff Time:	11:08 Local
Landing Time:	13:23 Local
Flight Duration:	02:15
Takeoff Weight:	184 metric tons
Landing Weight:	110 metric tons
Landing Fuel:	16 metric tons
Total Fuel Burn:	65 metric tons
Takeoff CG:	41%
Landing CG:	40.4%
Weather:	
Scattered clouds at 6 km, winds 150 degreees at 2-3 m/s, altimeter setting 755 mm Hg QFE	

Flight Profile

The flight profile included takeoff and acceleration to 700 kilometers per hour (km/hr) to intercept the climb schedule to 16.5 kilometers (km) and Mach 2.0. The flight direction was southeast toward the city of Samara on the Volga River at a distance of 700 km from Zhukovsky. Approximately 20 minutes were spent at Mach 2.0 cruise which included an approximately 190 degree course reversal and a cruise climb up to a maximum altitude of 17.3 km. A descent and deceleration to 9 km and Mach 0.9 was followed by a brief cruise period at that altitude and airspeed prior to descent to the traffic pattern at Zhukovsky Airfield for multiple approaches followed by a full stop landing on Runway 30.

Flight Summary

After all preflight checklists had been completed, the evaluation pilot taxied Tu-144LL Serial Number 77144 onto Runway 12, and the brake burn-in process was accomplished. At 11:08 brakes were released for takeoff, power was set at 98° PLA (partial afterburner), the start brake was released, and after a 30 sec takeoff roll, the aircraft lifted off at approximately 355 km/hr. The landing gear was raised with a positive rate of climb, the canard was retracted out of 120 m altitude, and the nose was raised out of 1000 m altitude. The speed was initially allowed to increase to 600 km/hr and then to 700 km/hr as the Vertical Regime Indicator (VRI) profile was intercepted. Power remained at 72° PLA (maximum dry power) for the climb until Mach 0.95 and CG of 47.5% at which point the throttles were advanced to maximum power, 115° PLA. The climb task was a high workload task due to the sensitivity of the head up pitch reference indicator, the sensitivity of the pitch axis, and the continual change in CG requiring almost continuous longitudinal trim inputs. Also, since the instantaneous center of rotation is located at the pilot station, there are no cockpit motion cues available to the pilot for pitch rate or attitude changes. Significant pitch rates can be observed on the pitch attitude reference indicator (SPI) that are not sensed by the pilot. During the climb passing 4 km, the first of a repeating series of bank angle captures (±15°) and control raps in all three axes (to excite any aircraft structural modes) was completed. These maneuvers were repeated at 6 km and when accelerating through Mach 0.7, 0.9, 1.1, 1.4, and 1.8. The bank angle captures demonstrated rather high roll forces and relatively large displacements required for small roll angles. A well damped (almost deadbeat) roll mode at all airspeeds up to Mach 2.0 was noted. The control raps showed in general a higher magnitude lower frequency response in all three axes at subsonic speeds and lower magnitude, higher frequency responses at supersonic speeds. The pitch response was in general of lower amplitude and frequency with fewer overshoots (2-3) than the lateral and directional responses (4-5 overshoots) at all speeds. Also of interest was that the axis exhibiting the flexible response was the axis that was perturbed, i.e., pitch raps resulted in essentially only pitch responses. The motions definitely seemed to be aeroservoelastic in nature, and with the strong damping in the lateral and directional axes, normal control inputs resulted in well damped responses.

Level off at 16.5 km and Mach 1.95 occurred 19 minutes after takeoff. The aircraft was allowed to accelerate to Mach 2.0 IMN as the throttles were reduced to 98° PLA, and a series of control raps was accomplished. Following this, a portion of the Integrated Test Block set of maneuvers consisting of pitch captures, steady heading sideslips, and a level deceleration was completed. The pitch captures resulted in slight overshoots and indicated a moderate delay between pitch attitude changes and flight path angle changes. The steady heading sideslips showed a slight positive dihedral effect, but no more than approximately 5° angle of bank was required to maintain a constant heading. No unpleasant characteristics were noted. At this point the first set of three longitudinal and lateral/directional parameter identification (PID) maneuvers were completed with no unusual results. By this time a course reversal was necessary, and the bank angle and heading capture portions of the ITB were completed during the over 180° turn which took approximately 7 min to complete at Mach 1.95. During the inbound supersonic leg, two more sets of PID maneuvers with higher amplitude (double the first set) control inputs were completed as were several more sets of control raps. Maximum altitude achieved during the supersonic maneuvering was 17.3 km.

The descent and deceleration from Mach 2.0 and 17 km began with a power reduction from the nominal 98° PLA to 59° and a deceleration to 800 km/hr. During the descent bank angle captures (±30°) and control raps were accomplished at or about Mach 1.8, 1.4, 1.1, and 0.9 with similar results as reported above. The aircraft demonstrated increased pitch sensitivity in the transonic region decelerating through Mach 1.0. The pitch task during descent in following the VRI guidance was fairly high in workload, and the head-up pitch reference indicator was very sensitive and indicated fairly large pitch responses from very small pitch inputs. Since the CG is being transferred aft during supersonic descent, frequent pitch trimming is required. A level off at 9 km at Mach 0.9 was accomplished without difficulty, and an ITB (as described above) was completed. Further descents as directed by air traffic control placed the aircraft in the landing pattern with 32 tons of fuel, 6 tons above the planned amount.

Five total approaches including the final full stop landing were completed. These included a straight-in localizer only approach with the canard retracted; an offset approach with the nose raised until on final; a manual throttle offset approach; a manual throttle straight-in approach; and a straight-in visual approach to a full stop landing. The first approach with the canards retracted was flown at 360 km/hr due to the loss of about 12 tons of lift from the retracted canards. Pitch control was not as precise in this configuration. There was also a learning curve effect as the evaluation pilot gained experience in making very small, precise pitch inputs which is necessary to properly fly the aircraft on approach and to properly use the pitch reference indicator. After terminating the approach at 60 m, a canard retracted, gear down low pass up the runway at 30-40 m was completed in accordance with a ground effects experiment requirement. The nose-up approach demonstrated the capability to land this aircraft with the nose retracted providing an angling approach with some sideslip is used. The offset approaches were not representative of the normal offset approaches flown in the HSR program since they are to low approach only and do not tax the pilot with the high gain spot landing task out of the corrective turn. No untoward pitch/roll coupling or tendency to overcontrol the pitch or roll axes was noted. The manual approaches were very interesting in that the Tu-144LL, though a back-sided airplane on approach, was not difficult to control even with the high level of throttle friction present. The engine time constant appears reasonable. It was noted that a large pitching moment results from moderate or greater throttle inputs which can lead to overcontrolling the pitch axis if the speed is not tightly controlled and large throttle inputs are required. The full stop landing was not difficult with light braking required due to the decelerating effects of the drag parachutes. The flight terminated with the evaluation pilot taxiing the aircraft clear of the runway to the parking area. 16 tons of fuel remained.

All test points were accomplished, and several additional optional test points were completed since the flight remained ahead of the planned fuel burn. One additional approach was completed. The planned flight profile was matched very closely, and all flight objectives were achieved.

Flight 23

Date of Flight:	September 24, 1998
Flight Crew:	
Pilot in Command:	Sergei Borisov
Evaluation Pilot:	Gordon Fullerton
Navigator:	Victor Pedos
Flight Engineer:	Anatoli Kriulin
Takeoff Time:	11:00 Local
Landing Time:	12:56 Local
Flight Duration:	01:56
Takeoff Weight:	179 metric tons
Landing Weight:	119 metric tons
Landing Fuel:	16 metric tons
Total Fuel Burn:	60 metric tons
Takeoff CG:	40.8%
Landing CG:	40.6%

Flight Summary

Engines 2, 1, and 3 were started normally by the flight engineer. However, engine #4 temperature approached a limit of 610° C so it was shut down. A slight tailwind condition existed. A successful start was made using cross-bleed air from the #3 engine. After engine start the aircraft was taxied for the brake warmup procedure and then into the lineup position. Power was set at 98° PLA, the start brake was released, and a nominal takeoff was made. The landing gear and canard were retracted on schedule, the nose was raised, and the aircraft was accelerated to an initial climb speed of 700 km/hr. No special test points were planned during climb so that full attention could be devoted to flying the VRI profile as accurately as possible, to allow evaluation of the demanding pitch control task.

The aircraft was leveled at an altitude of 16.5 km and accelerated to Mach 2.0. A pitch capture maneuver of 2° nose up was flown, even though the many pitch adjustments required during the climb profile allowed a thorough examination of pitch control characteristics.

Next the highest priority test point of the supersonic cruise was accomplished: a set of frequency sweep maneuvers in the longitudinal, lateral, and directional axes.

After completion of the longitudinal frequency sweep at 700 km from the takeoff base the navigator called for a course reversal to the left. Lateral and directional sweeps were then completed. Control raps were accomplished in all axes, followed by steady heading sideslip maneuvers out to 4° of rudder deflection in each direction.

Just prior to the planned descent gross weight of 135 tons, the #1 throttle was retarded to 59° PLA and the response of the aircraft noted. The asymmetry was trimmed out with rudder and lateral trim as the other engines were advanced to maximum thrust (115° PLA.) A heading capture maneuver was flown. Speed decreased slowly to about Mach 1.9.

With 32 tons of fuel remaining all engines were set to 59° PLA, and the aircraft was allowed to decelerate to intercept the VRI profile for descent. Control raps in three axes were completed passing Mach 1.6. Level off was at Mach 0.9 and 9 km altitude. At this subsonic cruise condition the ITB series of maneuvers used on the previous flights was completed.

About 200 km out a descent to pattern altitude was begun with control raps made passing Mach 0.8 Approaching the airfield at 500 km/hr the nose was lowered to 11°. About 15 km out and lined up with Runway 30, the nose was raised and the aircraft flown in a clean configuration over the runway at 100 m for a photo pass.

Turning left to downwind, the nose was lowered to 17 deg, the canard deployed, and the landing gear lowered. A visual approach was completed with manual control of thrust down to a go-around at 60 m.

On the downwind leg the #1 engine was retarded to 10 deg PLA, the landing gear lowered, and a three engine approach was flown, using the autothrottle system, with a three engine go-around initiated at 60 m.

The next pattern was set up with the canard retracted and using autothrottle, a descent was made leveling at 20 m above the runway. The autothrottle was disabled, and the aircraft kept level, maintaining 350 km/hr for about 10 sec for ground effects data.

The wind was reported at about 6 m/sec, above the limit of 2.5 m/sec, so the low-pass planned for Experiment 1.6 data was canceled.

The final pattern was begun with 16 tons fuel remaining. The standard configuration and procedure was used, with autothrottle engaged until about 5 m above the runway when the throttles were retarded to idle. After a smooth touchdown the nose gear was lowered, drag chutes deployed, and light braking brought the aircraft to taxi speed. The aircraft was parked and shutdown in the startup area.

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Two U.S. research pilots evaluated the Tupolev Tu-144 supersonic transport aircraft on three dedicated flights: one subsonic and two supersonic profiles. The flight profiles and maneuvers were developed jointly by Tupolev and U.S. engineers. The vehicle was found to have unique operational and flight characteristics that serve as lessons for designers of future supersonic transport aircraft. Vehicle subsystems and observed characteristics are described as are flight test planning and ground monitoring facilities. Maneuver descriptions and extended pilot narratives for each flight are included as appendices.

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