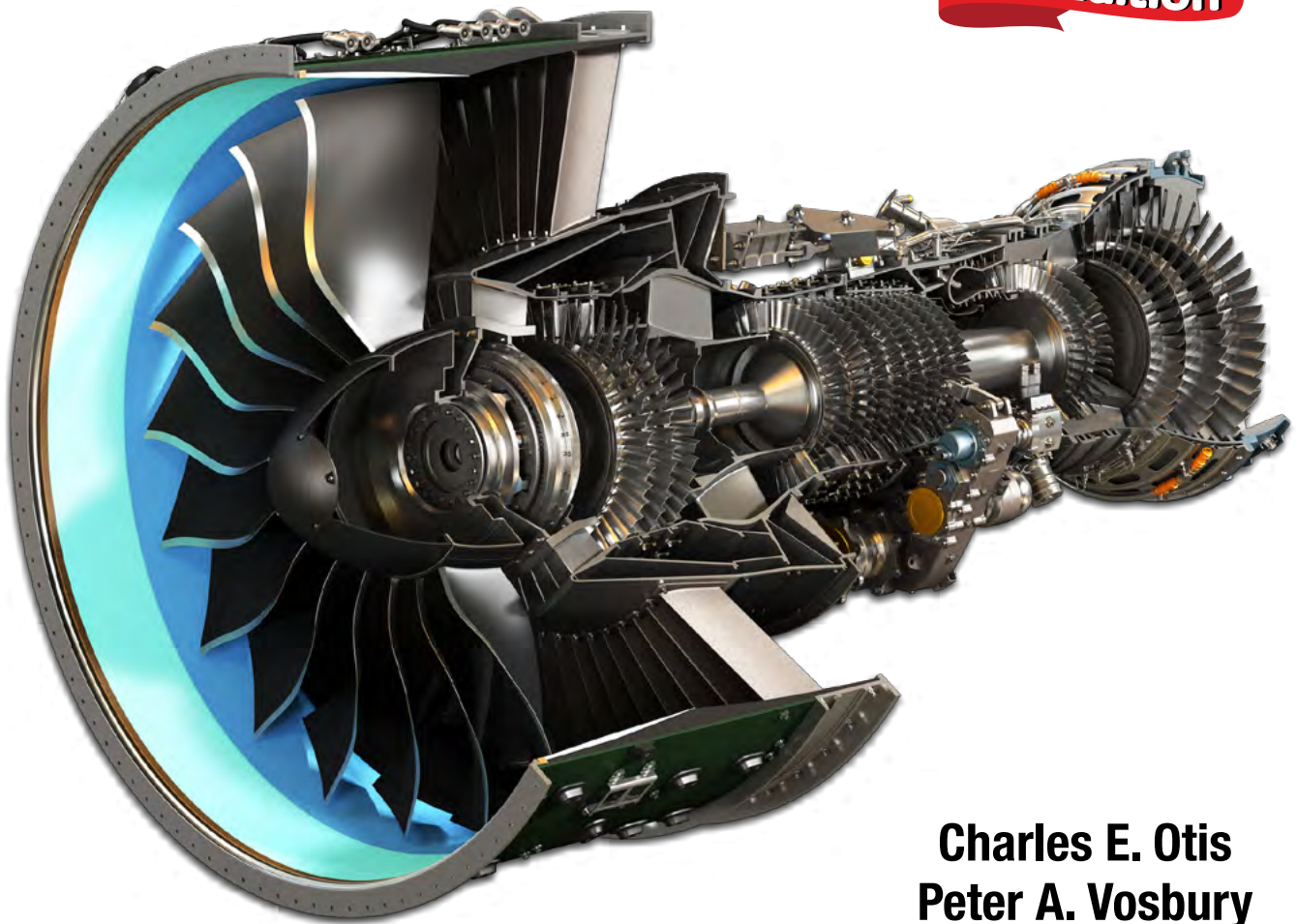


AIRCRAFT GAS TURBINE POWERPLANTS

T E X T B O O K

5th Edition



**Charles E. Otis
Peter A. Vosbury**

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Table of Contents

Preface.....	xvii
Charles E. Otis Biography.....	xviii
Peter A. Vosbury Biography	xix
Introduction	xx
CHAPTER 1	1-1
History of Turbine Engine Development.....	1-1
Hero's Aeolipile.....	1-1
Chinese Rocket.....	1-1
Branca's Turbine Device	1-1
Newton's Horseless Carriage	1-1
Moss Turbo-Supercharger.....	1-2
Sir Frank Whittle, British Development.....	1-2
German and Italian Developments.....	1-5
Early American Gas Turbine Development	1-6
Commercial Aircraft Development	1-6
Commuter and Business Jets	1-8
Other Developments.....	1-9
CHAPTER 2	2-1
Jet Propulsion Theory.....	2-1
Four Types of Jet Engines.....	2-1
Powerplant Selection	2-2
Reciprocating Engine — Turboshift Engine	2-2
Turboprop Engine	2-2
Turbofan (Turbojet).....	2-2
Rating the Power Output of a Gas Turbine Engine.....	2-3
Large vs. Small Gas Turbine Engines	2-4
Turbine vs. Piston	2-5
Turbine Engine Types	2-6
Turbojet Engines.....	2-6
Turboshift Engines.....	2-6
Turboprop Engines	2-6
Ultra High-Bypass Propfan/Unducted Fan Engines	2-6
Turbofan Engines.....	2-8
Ultra High-Bypass Turbofan Engines (Ducted, Variable Pitch)	2-10
Hybrid Turbine-Electric Aircraft Propulsion	2-10
Turbogenerator.....	2-11
Series Architecture	2-11
Parallel Architecture	2-11
Physics of the Gas Turbine Engine.....	2-12
Force	2-12
Work	2-14
Power	2-14
Horsepower.....	2-14
Velocity	2-14
Acceleration	2-15

Potential and Kinetic Energy	2-16
Bernoulli's Principle.....	2-16
Measuring Static Pressure.....	2-17
Measuring Total Pressure	2-18
Measuring Ram Pressure.....	2-18
Pressure-Velocity Through the Engine.....	2-18
The Brayton Cycle	2-18
Newton's Laws and the Gas Turbine Engine.....	2-20
Newton's Second Law.....	2-20
Comparison: Propeller to Turbojet Exhaust Thrust	2-21
Newton's Third Law.....	2-21
Thrust and SHP Calculations.....	2-22
Gross Thrust (Static).....	2-22
Net Thrust.....	2-23
Thrust With a Choked Nozzle	2-23
Thrust Distribution	2-24
Fan Engine Thrust (Unmixed Exhaust)	2-24
Thrust Horsepower (THP) in Turbojet and Turbofan Engines	2-25
Propeller (Turboprop) Thrust	2-26
Equivalent Shaft Horsepower (Turboprop Ground Runup).....	2-26
Horsepower Requirement to Drive the Compressor	2-26
Other Significant Horsepower Terms.....	2-27
Gas Turbine Engine Performance	2-27
Propulsive Efficiency	2-27
Thermal Efficiency	2-28
Thermal Efficiency Curves	2-29
Overall Efficiency	2-30
Factors That Affect Thrust	2-30
Temperature Effect	2-31
Altitude Effect	2-31
Airspeed Effect	2-31
Rpm Effect.....	2-33
Rpm Limits Imposed on Turbine Engines.....	2-33
Axial Flow Compressors.....	2-33
Centrifugal Flow Compressors	2-34
Speed of Sound	2-34
Why the Turbofan Has Replaced the Turbojet	2-34
CHAPTER 3	3-1
Turbine Engine Design and Construction.....	3-1
Turbine Engine Entrance Ducts	3-1
Principles of Operation	3-1
Subsonic Flight Inlet Ducts	3-2
Ram Pressure Recovery	3-2
Supersonic Inlet Ducts	3-3
Bellmouth Compressor Inlets	3-4
Compressor Inlet Screens, Sand, and Ice Separators	3-4
Engine Inlets and Ground Effect	3-5
Accessory Section	3-7
Compressor Section.....	3-8
Centrifugal Flow Compressors	3-9
Axial Flow Compressors and Fans	3-11
Types.....	3-11
Reasons for Multispool Designs	3-14

Blades and Vanes	3-17
Tips and Roots	3-18
Inlet Guide Vanes	3-20
Compressor Pressure Ratio.....	3-20
Pressure Rise Per Stage	3-21
Cycle Pressure Ratio.....	3-22
Fan Pressure Ratio	3-22
Fan Bypass Ratio	3-22
Advantages and Disadvantages of Axial Flow Compressors	3-23
Combination Compressors	3-24
Comparison of Axial and Centrifugal Compressors and Lift	3-24
Compressor Interstage Airflow	3-24
Cascade Effect	3-26
Compressor Taper Design	3-26
Angle of Attack and Compressor Stall	3-27
Relationship Between Compressor Pressure Ratio and Mass Airflow	3-28
Stall or Surge Margin Graph	3-29
Advances in Compressor Design and Compressor Stall Avoidance	3-31
Blades	3-31
Active Clearance Control	3-31
Mixed-Flow Compressors	3-32
Fan and Compressor Rotor Blisks	3-32
Compressor-Diffuser Section	3-32
Combustion Section	3-33
Multiple-Can Combustor	3-35
Can-Annular Combustor	3-35
Annular Combustor (Through Flow)	3-35
Annular Reverse-Flow Combustor	3-36
New Combustor Designs	3-39
Combustor-Generated Emissions	3-39
Turbine Section	3-40
Turbine Rotor and Stator	3-40
Function of Turbine Stators	3-41
Shrouds and Seals	3-43
Impulse-Reaction Blades	3-43
Axial Turbine Construction	3-44
Drive Shafts	3-44
Blade Attachment and Retention Devices	3-45
Shrouded Tips and Knife-Edge Seals	3-45
Counter-Rotating Turbines	3-46
Turbine Vane and Blade Cooling	3-46
Active Clearance Control	3-48
Radial Inflow Turbine	3-48
Exhaust Section	3-49
Exhaust Cone, Tail Cone and Tailpipe	3-49
Convergent “Choked” Nozzle Theory	3-51
Convergent-Divergent Exhaust Ducts for Subsonic Aircraft	3-53
Divergent Exhaust Nozzles	3-53
Convergent-Divergent Nozzle Theory for Supersonic Aircraft	3-53
Afterburning.....	3-54
Vectoring Afterburner Exhaust Nozzles	3-55
Variable Area Exhaust Nozzles for Subsonic Aircraft	3-55
Thrust Reversers	3-56
Other Aspects of Thrust Braking Systems	3-57

Noise Suppression	3-57
Engine Compartment Ventilation and Cooling	3-60
Engine Mounts	3-60
Bearings	3-60
Construction Materials	3-61
Cold Section Construction	3-61
Hot Section Construction	3-62
Construction Processes	3-66
Engine Stations.....	3-66
Directional References	3-67
CHAPTER 4	4-1
Engine Familiarization.....	4-1
The Pratt & Whitney JT8D Turbofan Engine	4-1
Engine Design Features	4-1
Major Engine Sections	4-3
Low-Pressure Compressor — N_1	4-3
High-Pressure Compressor — N_2	4-4
Diffuser Case	4-4
Combustion Case	4-5
Turbine Nozzle Vanes	4-5
High-Pressure Turbine Rotor (N_2)	4-5
Low-Pressure Turbine (N_1)	4-8
Main Accessory Gearbox	4-9
Turbine Exhaust Case	4-9
Main Bearings	4-10
Additional Information	4-12
The Rolls-Royce Allison Model 250 Turboshaft Engine.....	4-12
Gas Path of the Rolls-Royce 250	4-12
Four Major Engine Sections (Modules)	4-12
Compressor Section	4-16
Combustion Section.....	4-18
Gas Producer Turbine.....	4-18
Power Turbine	4-18
Power and Accessory Gearbox	4-20
Engine Bearings and Lubrication System.....	4-22
Main Bearing Numbering.....	4-22
Bearing Lubrication	4-22
Additional Information	4-22
The Pratt & Whitney PT6 Turboprop Engine.....	4-25
Gas Path of the PT6 and Engine Station Numbering	4-25
Five Major Engine Sections	4-25
Compressor Section	4-25
Combustor Section	4-28
Gas Producer Turbine	4-29
Power Turbine	4-29
Exhaust Duct	4-30
Propeller Reduction Gearbox	4-30
Accessory Gearbox	4-32
Additional Information.....	4-32
The GE/SNECMA, CFM56 Turbofan Engine.....	4-32
Fan Module	4-33
Fan and Booster	4-35
Number 1 and 2 Bearing Support Submodule	4-37

Fan Frame Submodule	4-38
Core Engine Module	4-39
High-Pressure Compressor	4-39
Combustion Section	4-40
High-Pressure Turbine	4-41
Low-Pressure Turbine Module	4-42
Turbine Case	4-42
Turbine Nozzles and Disks	4-44
Turbine Blades	4-44
Turbine Shaft	4-44
Rear Frame	4-46
Accessory Drive Module	4-46
Inlet Gearbox	4-46
Radial Drive Shaft	4-46
Transfer Gearbox	4-47
Horizontal Drive Shaft	4-47
Accessory Gearbox	4-47
The Pratt & Whitney PW 1100G Geared Turbofan Engine	4-47
Engine Characteristics (Figure 4-65)	4-47
Engine Modules	4-48
Fan Rotor and Fan Case (Figure 4-66)	4-49
Fan Drive Gear System (FDGS) and Fan Intermediate Case (Figure 4-67)	4-50
Low-Pressure Compressor and Compressor Intermediate Case (Figure 4-68)	4-50
High-Pressure Compressor Rotor (Figure 4-69)	4-50
Diffuser and Combustion Chamber Assembly (Figure 4-70)	4-50
High-Pressure and Low-Pressure Turbines (Figure 4-71)	4-52
Turbine Exhaust Case (Figure 4-72)	4-52
Engine Gearbox (Figure 4-73)	4-52
Engine Bearings (Figure 4-74)	4-52
The GE/Safran LEAP 1B Turbofan Engine	4-53
General Description (Figure 4-75)	4-53
Fan Major Module (Figure 4-76)	4-54
Fan and Booster (Figures 4-77 and 4-78)	4-55
Front Spinner Cone and Platform Front Shroud	4-55
Fan Disk	4-55
Fan Blades	4-55
Booster	4-56
Core Major Module (Figure 4-79)	4-56
High-Pressure Compressor (HPC) (Figure 4-80)	4-56
Rotor	4-58
Front Stator Case	4-58
Rear Stator Case	4-58
Combustion Section (Figure 4-81)	4-58
Combustion Case Assembly	4-59
Combustion Chamber	4-59
High-Pressure Turbine (HPT) (Figure 4-82)	4-59
Stage 1 High-Pressure Turbine Nozzle Assembly	4-60
Two Stage High-Pressure Turbine Rotor	4-60
Hpt Case and Stage 2 Nozzle Assembly	4-60
Low-Pressure Turbine (LPT) Major Module (Figure 4-83)	4-61
Low-Pressure Turbine (LPT) Stage 1 Nozzle Module	4-61
Low-Pressure Turbine Shaft Module	4-61
Low-Pressure Turbine Rotor and Stator Module	4-62
Low-Pressure Turbine Case	4-62

Low-Pressure Turbine Cooling	4-62
Turbine Center Frame (TCF) (Figure 4-84).....	4-63
Number 4 Bearing	4-63
Turbine Rear Vane Module (Figure 4-85).....	4-63
LPT Rear Vane	4-63
Accessory Drive (Figure 4-86).....	4-64
Inlet Gearbox (IGB)	4-64
Radial Drive Shaft (RDS).....	4-64
Transfer Gearbox (TGB)	4-64
Transfer Shaft (TS)	4-65
Accessory Gearbox (AGB)	4-65
Accessories (Figure 4-87).....	4-66
Engine Main Bearing and Seals (Figure 4-88).....	4-66
Sump Seals	4-66
Engine Data Sheets	4-67
CHAPTER 5	5-1
Inspection and Maintenance	5-1
Line Maintenance	5-1
Gas Turbine Special Tools (For Line Maintenance)	5-1
Foreign Object Damage	5-1
Erosion	5-3
Compressor Field Cleaning	5-3
Fluid Cleaning Procedure	5-4
Abrasive Grit Process	5-4
Scheduled Line Maintenance Inspections	5-4
Smaller Turbine-Powered Aircraft	5-6
Business And Commuter Jet Aircraft	5-6
Larger Commercial Jet Aircraft.....	5-7
Scheduled Line Maintenance Repairs	5-7
Unscheduled Line Maintenance	5-7
Shop Maintenance	5-8
Limited Heavy Maintenance	5-8
Unlimited Heavy Maintenance	5-8
Modular Maintenance	5-8
Remanufacturing Facility	5-8
Powerplant Removal and Disassembly	5-8
Nondestructive Inspections and Repairs	5-11
Borescoping	5-11
Other Nondestructive Inspections	5-12
Magnetic Particle Method	5-12
Dye-Penetrant Method	5-14
Radiographic Method	5-14
Eddy Current Method	5-16
Ultrasonic Method	5-16
Cold Section Inspection and Repair	5-16
Compressor Disassembly	5-16
Typical Fan Blade Damage Limits	5-17
Metal Blade.....	5-17
Composite Blade.....	5-17
Axial Compressor Inspection and Repair	5-20
Electron Beam Welding	5-20
Plasma Surface Repair Coating	5-21
Tip Clearance	5-21

Blade Replacement	5-23
Centrifugal Compressor Inspection and Repair	5-24
Stator Vane and Compressor Case Inspection and Repair	5-24
Hot Section Inspection and Repair	5-24
Combustion Section	5-25
Visual Inspection	5-25
Turbine Section	5-26
Turbine Wheel	5-27
Creep and Untwist.....	5-27
Turbine Case, Turbine Vanes, Exhaust Section	5-28
Marking Parts.....	5-32
Main Bearings and Seals	5-32
Bearings.....	5-32
Bearing Seals	5-35
Labyrinth Seals.....	5-35
Carbon Seals.....	5-37
Brush Seals.....	5-38
Bearing Handling And Maintenance.....	5-39
Precautionary Measures.....	5-39
Magnetism Check	5-40
Bearing Installation.....	5-40
Bearing Distress Terms [Figure 5-58]	5-40
Torque Wrench Use	5-42
Torque Wrench Extensions	5-42
Torque Procedure	5-43
Locking Methods for Engine Fasteners	5-44
Lockwiring	5-44
Lock Washers and Tabs	5-46
O-Ring Seals	5-46
Test Cell Maintenance	5-46
Engine Vibration Characteristics	5-48
Analysis of Test Cell Data	5-49
Standard Day Conditions	5-49
Engine Time Change and On-Condition Maintenance Concepts	5-50
Component Expected Service Life	5-52
Troubleshooting – Aircraft Ground Operation	5-52
Fadec Interface With Traditional Engine Systems	5-52
Troubleshooting Aircraft In-Flight Data	5-52
Monitoring Engine Operational Trends and Analysis	5-53
Normal Engine	5-54
Compressor Section Malfunction	5-54
Combustor Section Malfunction	5-54
Turbine Section Malfunction	5-54
Inspection and Troubleshooting Terms	5-54
Technical Data Standards	5-59
CHAPTER 6	6-1
Lubrication Systems	6-1
Principles of Engine Lubrication	6-1
Requirements of Turbine Engine Lubricants.....	6-1
Characteristics of Synthetic Lubricants	6-1
FAA Requirements of Lubrication Systems	6-1
Viscosity	6-1
Petroleum Oils	6-2

Synthetic Oils	6-2
Viscosity Index	6-2
Oil Sampling	6-3
Sampling Intervals	6-3
Traditional Spectrometry	6-4
Rathode Filter Spectroscopy	6-4
Origin Of The Metal Contaminants	6-4
Synthetic Lubricants	6-5
Discoloration of Synthetic Lubricants	6-5
Typical Properties of Turbine Oils	6-5
Servicing	6-6
Common Synthetic Lubricants for Gas Turbine Engines	6-6
Inadvertent Mixing of Oils	6-6
Servicing Intervals	6-6
Turbine Oil Storage	6-8
Oil Consumption and Oil Change	6-8
Wet Sump Lubrication Systems	6-8
Dry Sump Lubrication Systems	6-8
System Components	6-9
Oil Tank	6-10
Oil Pumps	6-11
Vane Pump	6-12
Gerotor Pump	6-12
Gear Pump	6-12
Oil Filters	6-12
Contaminants in Oil	6-12
Microns	6-14
Filter Types	6-15
Filter Assembly Operation	6-16
Filter Cleaning	6-17
Interaction of Oil Filters With Oil Pressure Relief Valves	6-18
Low-Pressure Warning Light	6-19
Filter Bypass Warning Lights and Cockpit Gauges	6-20
Bypass Condition	6-20
Differential Pressure (ΔP) Light	6-20
Dual Cockpit Gauges	6-20
Procedures During Low Oil Pressure Conditions	6-21
Filter Pop-Out Warning	6-22
Other Components of Dry Sump Systems	6-22
Small Engine Lubrication System — General Electric CJ610 Turbojet	6-22
Pressure Subsystem Oil Flow	6-23
Oil Cooler Functions	6-23
General Comments — Oil Jets	6-27
Last Chance Filters	6-28
Scavenge Subsystem	6-28
Chip Detectors	6-28
General Comments — Chip Detectors	6-28
Vent Subsystem	6-28
General Comments — Vent Subsystems	6-29
Small Engine Lubrication System — Pratt & Whitney PT6 Turboprop	6-30
Pressure Subsystem Flow Path	6-30
Scavenge Subsystem Flow Path	6-31
Vent Subsystem Flow Path	6-31
Large Engine Lubrication System — Pratt & Whitney JT8D Turbofan	6-31

Pressure Subsystem Flow Path	6-32
Scavenge Subsystem Flow Path	6-34
Vent Subsystem Sequence of Flow	6-34
Large Engine Lubrication System — CFM56-7B Turbofan	6-34
Oil Supply Circuit	6-34
Oil Tank	6-34
Antileakage Valve	6-36
Lubrication Unit	6-36
Oil Scavenge Circuit	6-37
Oil Venting Circuit	6-37
Hot Tank Versus Cold Tank Systems	6-37
CHAPTER 7	7-1
Fuel Systems	7-1
Principles of Fuel Systems	7-1
Gas Turbine Fuels	7-1
Alternate Fuels, Nonpetroleum	7-3
Fuel Handling and Safety	7-3
Fuel Additives	7-3
Water Detection in Turbine Fuel	7-3
Thrust Specific Fuel Consumption	7-3
Turbofans and TSFC	7-4
TSFC in Flight	7-5
A TSFC Observation	7-6
TSFC Versus Thrust-Horsepower Specific Fuel Consumption	7-6
Best TSFC Versus Best SFC(Hp)	7-7
Fuel Controlling Systems	7-7
Fuel Control Signals	7-8
Simplified Fuel Control Schematic (Hydro-Mechanical Unit)	7-8
Fuel Metering Section	7-8
Computing Section	7-10
Hydro-Pneumatic Fuel Control System - PT6 Turboprop.....	7-11
Fuel Pump	7-11
Fuel Control System	7-11
Fuel Control Unit	7-11
Electronic Fuel Scheduling Systems	7-13
Example System - Rolls Royce RB-211 (High-Bypass Turbofan)	7-13
Example System - Honeywell TFE-731 (Medium-Bypass Turbofan)	7-13
Example System - GE/SNECMA CFM56-7B (High-Bypass Turbofan)	7-13
FADEC Components	7-15
Airplane/EEC Interface	7-16
FADEC Interfaces	7-17
FADEC Design	7-17
Closed-Loop Control Operation	7-17
Input Parameters	7-17
EEC Location	7-17
EEC Reprogramming (by Ground Crew)	7-18
Engine Rating Identification Plug	7-18
EEC Power Supply	7-19
Engine Sensors	7-19
Power Management and Fuel Scheduling (CFM56-7B)	7-20
Throttle Lever (Thrust Lever)	7-20
Ambient Conditions	7-20
Bleeds	7-20

Thrust Control Operating Modes	7-20
Auto-Throttle for the CFM56-7B	7-21
Generic Information on Auto-Throttle Systems	7-21
Auxiliary Power Unit Fuel Controlling System	7-22
Example System - Honeywell GTP-30 (30 To 100 Hp)	7-22
Commercial Aircraft APU Starting and Operation (200 To 1,000 Hp)	7-23
Fuel Control Adjustments, Main Engines	7-24
Specific Gravity Adjustment	7-24
Performance Checks (Turbojet and Turbofan Engines)	7-25
Trimming	7-25
Acceleration Check	7-25
Throttle Spring-Back and Cushion Checks (Non-Electronic Throttles)	7-25
Part Power Trim	7-26
Engine Pressure Ratio Trim and Speed Trim	7-26
Engine Pressure Ratio	7-26
Trimming Procedure for Epr-Rated Engines	7-26
Full Power Check After Trimming	7-27
Trimming Procedure for Speed-Rated Engine	7-28
Trim Procedures for FADEC Controlled Engines	7-28
Data Plate Speed Check	7-29
Trim Restrictions	7-31
Trim Danger Zones	7-31
Ear Protection From Noise	7-32
Flat Rating	7-32
Turboprop and Turboshaft Engine Performance Checks	7-34
Converting Torque (PSI) to Torque in Pound-Feet	7-36
Computing Shaft Horsepower From Cockpit Reading	7-36
Water Injection Thrust Augmentation	7-37
Principles of Operation	7-37
Water Injection Fluids	7-37
Water Injection System (Small Engine)	7-37
Fuel System Components And Accessories	7-39
Main Fuel Pump	7-39
Fuel Heater (Deicer)	7-41
Fuel Filters	7-41
Fuel Filter Warning Switches (Bypass and Low Pressure)	7-43
Micron Rating Versus Mesh Size	7-43
Screen Size Chart.....	7-43
Fuel Nozzles	7-43
Pressure-Atomizing Fuel Nozzles	7-43
Simplex Fuel Nozzles	7-46
Single-Line Duplex Fuel Nozzles	7-47
Staged Fuel Nozzles	7-47
Dual-Line Duplex Fuel Nozzles	7-48
Air Blast Simplex and Duplex Fuel Nozzles	7-48
Fuel Vaporizing Fuel Nozzle	7-48
Fuel Pressurizing and Dump Valve	7-50
Dump Valve	7-52
Combustor Drain Valve	7-52
Drain Tanks	7-53
Example of a Basic Engine Fuel System	7-54
Example of a Commercial Engine Fuel System (Pratt & Whitney JT8D)	7-54
Example of a Commercial Engine Fuel System (GE/SNECMA CFM56)	7-55
GE/SAFRAN LEAP 1B Engine Fuel Distribution.....	7-56

General Description of Fuel Flow.....	7-56
Engine Fuel Distribution - Fuel Manifolds	7-59
Fuel Nozzles	7-59
CHAPTER 8	8-1
Compressor Anti-Stall Systems	8-1
Variable Angle Compressor Stator Vane System (Large Engine)	8-1
System Operation — General Electric CF-6 Turbofan	8-2
Variable Angle Compressor Vane Schedule	8-2
Necessity of Variable Angle Compressor Vanes	8-2
Variable Angle Compressor Vane System With FADEC Interface (GE CFM56 Turbofan)	8-4
Variable Angle Inlet Guide Vane System (Small Engine)	8-5
Compressor Anti-Stall Bleed Systems	8-5
Compressor Bleed System Operation	8-6
Compressor Bleed Band System.....	8-6
Bleed Band Schedule	8-9
Compressor Bleed Valve System	8-9
Variable Bleed Valve and Transient Bleed Valve Systems With FADEC Interface	8-11
CHAPTER 9	9-1
Anti-Icing Systems	9-1
Inlet-Icing Concepts	9-1
Anti-Icing System Operation	9-2
Regulator Valve	9-2
Cockpit Controls and Anti-Ice Valve Operation	9-2
Anti-Ice Switch “ON”	9-2
Anti-Ice Switch “OFF”	9-4
Anti-Icing Interface With an Electronic Engine Control and FADEC	9-4
Electro-Thermal Anti-Icing System	9-4
CHAPTER 10	10-1
Starter Systems.....	10-1
Engine Starter Concepts	10-1
Electric Starters	10-3
Starter-Generator, Small Engines	10-4
Starter-Generator, Large Engines	10-4
Pneumatic (Air Turbine) Starter	10-6
Starter Pressure-Regulating and Shutoff Valve	10-7
Manual Operation With the T-Handle	10-8
Pneumatic (Air Turbine) Starting System	10-9
Starting Procedure	10-9
Cross-Bleed Starting	10-11
Air Starter Duty Cycle.....	10-12
Starter-Fadec Interface	10-12
Typical Start Procedure	10-12
Engine Starting – Bowed Rotor Protection	10-13
Other Starting Systems	10-13
CHAPTER 11	11-1
Ignition Systems.....	11-1
Main Ignition System	11-1
Continuous Duty	11-2
Auto-Ignition	11-2
Special Handling	11-4

Joule Ratings	11-4
Types of Ignition Systems	11-5
Intermittent Duty, Low-Tension Ignition With DC Voltage Input	11-5
Sequence of Events for a DC Exciter System.....	11-6
Intermittent Duty, High-Tension Ignition With AC Voltage Input	11-7
Sequence of Events for an AC Exciter System.....	11-7
Solid-State Circuitry Ignition Systems	11-7
AC Versus DC Systems	11-8
High-Tension Versus Low-Tension Systems	11-8
Igniter Plugs	11-8
Spark Igniters	11-8
Glow Plug Igniters	11-9
High-Tension Igniter Plug Cleaning and Inspection	11-10
Cleaning The Igniter Plug	11-10
Inspection and Operational Checks	11-11
Change Intervals, High-Tension Igniter Plugs	11-11
Low-Tension Igniter Plug Cleaning and Inspection	11-12
Cleaning the Igniter Plug	11-12
Inspection and Operational Checks	11-12
Change Intervals, Low-Tension Igniter Plugs	11-14
Glow Plug Cleaning and Operational Checks	11-14
Inspection	11-14
Special Test Equipment	11-14
Complete Engine Ignition System — GE/SNECMA CFM56	11-16
Power Supply	11-16
Igniter Selection	11-16
System Operation	11-16
CHAPTER 12	12-1
Engine Instrument Systems.....	12-1
Flight Deck Engine Instruments Display	12-1
Exhaust Temperature Indicating Systems	12-4
System Components	12-4
Thermocouples	12-6
System Operation.....	12-7
EGT Limits	12-8
Jetcal Analyzer	12-8
Other EGT System Checks	12-8
Tachometer Percent RPM Indicating Systems	12-9
Percent RPM Indicator	12-9
Three-Phase Generator Percent RPM System	12-10
Magnetic Pickup Percent RPM System	12-10
Example Percent RPM Indicating System (GE CF-6)	12-10
Electronic Gearbox-Mounted N ₂ Speed Sensor	12-11
N ₁ Indication and Speed Sensing for FADEC Systems	12-11
Typical RPM Limits	12-12
Engine Pressure Ratio System	12-12
The EPR Formula	12-12
The Cockpit EPR Gauge in Action	12-15
Example EPR System (Dual- Spool Engine)	12-15
Torque Indicating System	12-16
Hydromechanical Torque Indicating System	12-17
System Operation	12-18
Electronic Torque Indicating System	12-19

Torque Limits	12-19
Fuel Flow Indicating System	12-19
Vane Flowmeter System.....	12-20
Synchronous Mass Flow System.....	12-20
Motorless Mass Flowmeter System	12-20
Oil System Indicators	12-21
Oil Temperature Indicating Systems	12-21
Resistance Bulb	12-22
Thermocouple	12-23
Oil Pressure Indicating System	12-25
Marking of Powerplant Instruments	12-28
Thrust Indicator (Turbojet, Turbofan)	12-30
FAA Suggested Methods of Marking Powerplant Instruments	12-30
CHAPTER 13	13-1
Fire/Overheat Detection and Extinguishing Systems for Turbine Engines.....	13-1
Single-Wire Thermal Fire/Overheat Detection Switch	13-1
Two-Wire Thermal Fire/Overheat Detection Switch	13-1
Continuous Loop Fire/Overheat Detection System	13-2
Pneumatic Fire/Overheat Detection System	13-3
Other Fire Detection Systems	13-4
Fire Extinguishing	13-4
The Fire Extinguishing System For The Engine Nacelle	13-4
Common Extinguishing Agents for Gas Turbine Engines	13-6
Fire Extinguishing (Engine Gaspath)	13-6
Cleaning The Engine After Use of Extinguishing Agents	13-6
Pneumatic Fire/Overheat Detection and Fire Extinguishing System	13-6
CHAPTER 14	14-1
Engine Operation.....	14-1
Safety Precautions	14-1
Turbojet and Turbofan Engine Run-Up	14-1
Normal Operating Procedures	14-1
Prior to Engine Operation	14-1
When First Entering the Aircraft	14-1
Engine Start	14-1
Instrument Checks on Start Cycle	14-1
Instrument Checks When Stabilized at Idle	14-2
Typical High-Power Checks	14-2
Taxi Procedure	14-2
Normal Shutdown Procedure	14-2
Engine Operation With Fadec Capabilities	14-2
Ground Starting	14-2
In-Flight Starting Protection, Crew-Initiated Relight	14-2
In-Flight Starting Protection, EEC - Initiated Relight	14-2
Auto-Throttle	14-3
Emergency Operating Procedures	14-3
Engine Tailpipe Fire During Ground Start	14-3
Hot Start	14-3
Failure to Start	14-4
Engine Purging Procedure (Dry Motoring)	14-4
Emergency Shutdown Procedure	14-4
Emergency In-Flight Ram-Air Starting Procedure	14-4
Engine Runup of Turboprop Engines	14-4

Fixed Turbine Design (Garrett TPE-331)	14-4
Ground Starting Procedure	14-4
Taxi Procedure	14-4
Free Turbine Design (Pratt & Whitney PT6)	14-5
Pre-Starting	14-5
Engine Start	14-6
Ground Runup	14-6
Aircraft Ground Handling	14-6
Engine Purging Procedure (Dry Motoring)	14-6
Engine Shutdown	14-7
FAA Engine Power Ratings	14-7
 Appendix 1.....	 A1-1
Appendix 2.....	A2-1
Appendix 3.....	A3-1
Appendix 4.....	A4-1
Appendix 5.....	A5-1
Appendix 6.....	A6-1
Appendix 7.....	A7-1
Appendix 8.....	A8-1
Appendix 9.....	A9-1
Appendix 10.....	A10-1
 Glossary	 G-1
 Answers To Study Questions	 A-1

Introduction

The first historical application of the jet propulsion principle occurred when a steam-driven toy was demonstrated in Egypt before the Common Era. For nearly twenty centuries, the idea of jet propulsion evolved slowly. It wasn't until the early 20th century that Sir Frank Whittle, an English inventor, first described the possibility of using a gas turbine device as a means of jet propulsion for aircraft. From this modest idea, jet aircraft use has grown into the large multinational industry we know today. Whittle, the "father of the modern gas turbine engine," remained active in gas turbine engine design well into his 70s. He died at the age of 89 in 1996.

To meet the growing demands of modern aircraft, gas turbine engine designs have become increasingly complex and powerful, and the technical tasks required to maintain them have become more and more demanding. It is no longer possible for technicians to gain expertise based on hands on experience alone. Today's complex turbine engines and systems require expert technical training. This textbook serves as a starting point for this training process. It is intended both for those just beginning to explore the world of gas turbine engines and for experienced technicians and flight personnel who are exploring new directions and opportunities within the aviation industry.

Whether you proceed through this book in a formal classroom setting or as an independent student, the material in this textbook provides a sound foundation of the principles of gas turbine engine theory, design, maintenance, and troubleshooting.

Every successful technical educational endeavor begins by providing learners with solid entry-level knowledge. The proven way to acquire this knowledge is to read the material carefully, answer the questions at the end of each chapter, review and research the text, and finally reinforce this knowledge by applying it in actual work experience.

These engines have fans that are not much larger in diameter than the engine core, and they would typically have a bypass ratio of 0.5:1. In other words, 0.5 pounds of air exit the fan duct for every 1 pound of air that goes through the core of the engine. This type of fan engine is typically used on military fighter airplanes, like the Navy F-18 or Air Force F-22, where a larger diameter fan would produce a prohibitive amount of drag.

The low-bypass classification indicates that the fan and the compressor sections use approximately the same mass airflow. They have a bypass ratio of 1:1. The fan discharge may be slightly higher or slightly lower. Keep in mind that the bypass ratio concerns airflow mass. The fan discharge air is ducted along the entire length of the engine from what is called a full fan duct. The end of the duct is configured with a converging discharge nozzle to produce a velocity increase and reactive thrust.

In the fully ducted fan engine shown in Figure 2-16, the hot and cold streams mix before being discharged to the atmosphere, which results in a reduction in the aerodynamic drag associated with short-ducted turbofans. Air passing over the core engine outer surfaces has much less skin friction if the air remains in the fan duct until it leaves the engine. With the full duct, there is gain of mass-airflow and thrust

implied when drag is reduced. This design also has a noise attenuating quality as hot gas becomes diluted by fan air in the common exhaust duct.

Early turbofan powered airplanes like the Boeing 707 and 727 and the Douglas DC-9 used low-bypass engines. Newer airplanes manufactured by large airliner manufacturers such as Boeing and Airbus, as well as many other regional jet aircraft manufacturers, have engines with a much higher bypass ratio that makes them much more fuel efficient and quieter. Consequently, new airplanes will unlikely use engines with the low-bypass design.

The turbofan core engine compresses, ignites, and discharges air in the same manner as a turbojet engine. The thrust of each gas stream of the fully ducted engine shown in Figure 2-16 has approximately equal airflow, and each delivers approximately the same thrust.

Medium- or intermediate-bypass engines have a mass airflow ratio of 2:1 or 3:1, with a thrust ratio in approximate proportion to the bypass ratio. The fan will be slightly larger in diameter than a low-bypass fan of comparable engine power, and its diameter will determine both the bypass ratio and thrust output of the fan versus the core of the engine.

The high-bypass turbofan engine, with fan ratios of 4:1 to 9:1, have even wider diameter fans in order to move more air. Figure 2-17 shows the design features of current high-bypass turbofans produced by Pratt & Whitney, General Electric, and Rolls-Royce with fans over 100 inches in diameter and representing the current state-of-the-art large engine designs for jumbo-jet aircraft.

Ultra high-bypass turbofan engines with fan ratios of 10:1 and higher are becoming more common. The Rolls Royce Trent 1000 turbofan for the Boeing 787 has a bypass ratio

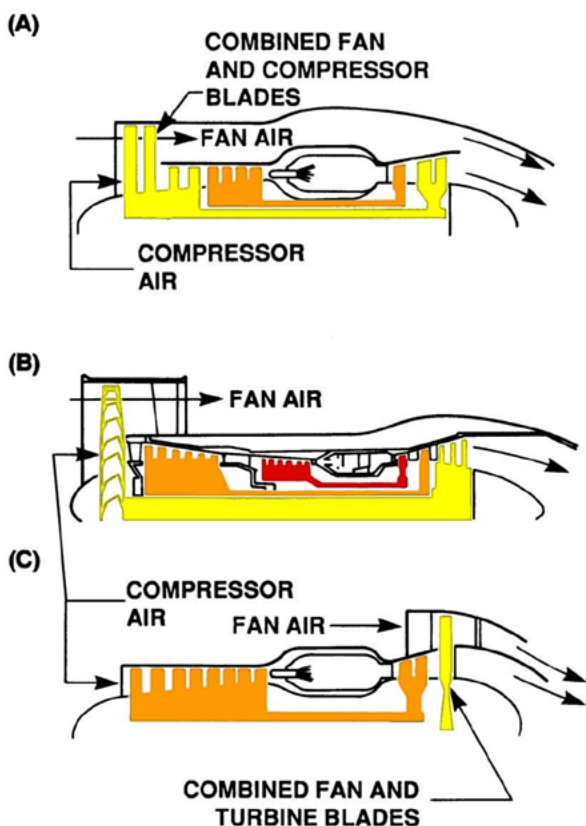


Figure 2-15A. Dual axial flow compressor, forward fan engine with mixed exhaust

Figure 2-15B. Triple-spool front fan engine with unmixed exhaust

Figure 2-15C. Turbofan engine with an aft-fan and unmixed exhaust

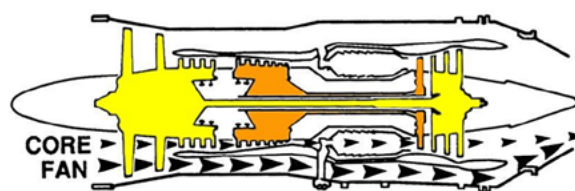


Figure 2-16. Fully ducted low- and medium-bypass turbofan design

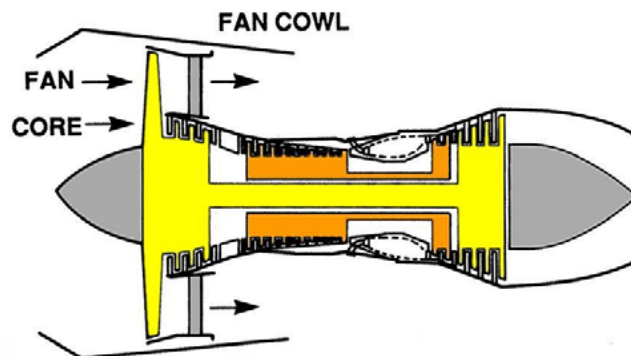


Figure 2-17. High-bypass ratio turbofan

of 10:1, and the Pratt and Whitney geared turbofan for the Airbus A320neo has a bypass ratio of 12.5 to 1. Over time even higher bypass ratios will be developed, because when a greater percentage of the mass airflow is directed out the fan duct the engine can have greater thermal and propulsive efficiency. There is a limit, of course, on how high the bypass ratio can go. It is not possible to send all the air out the fan duct because there would be no air in the core to support combustion and to drive the turbines.

High-bypass and ultra high-bypass engines boast the lowest fuel consumption of the various turbofan engines because of the smaller percentage of air that supports combustion in the core portion of the engine. For example, the Pratt & Whitney PW4000 series turbofans currently have a 5:1 to 9:1 bypass ratio engine with approximately 80 percent of the thrust produced by the fan and 20 percent by the core engine. The thrust percentages vary from engine to engine and are determined by such considerations as fuel economy at altitude, cruise speed, and propulsive efficiency for a particular aircraft design. For these higher bypass engines, the amount of air going out the fan duct falls between 80 and 92 percent of the total mass airflow.

In the past, the fan duct on high-bypass engines typically extended aft only 1/3 to 1/2 of the engine's length, unlike low-bypass engines that typically had full-length fan ducts. Even though the full-length duct provides thrust and drag advantages, the additional weight was a problem for the high-bypass engines. By using lower weight, high strength composites for the fan duct, it is now more common to extend the duct farther aft, and on some airplanes, to use a full-length duct.

Today's high-bypass fan engine has become the most widely used engine type for medium to large aircraft because it offers the best fuel economy by increasing the total mass airflow and decreasing the hot exhaust wake. This conservation of energy keeps more power within the engine to drive the fan and leads to a considerable increase in propulsive and thermal efficiency.

ULTRA HIGH-BYPASS TURBOFAN ENGINES (DUCTED, VARIABLE PITCH)

Another development in turbofans is the variable pitch (variable-bypass ratio) model, which, as of this writing, is being tested for certification. This model is predicted to have the lowest fuel consumption rate per thrust ratio of any turbofan currently in service. It is also expected to have much of the same flexibility of operation that the turboprops enjoy, and it will still be capable of the high subsonic cruising speeds that elude the conventional turboprop. Its bypass ratio will fall somewhere between the high-bypass turbofan and the propfan, and it will likely be fitted with a variable exhaust nozzle. [Figure 2-18]

HYBRID TURBINE-ELECTRIC AIRCRAFT PROPULSION

Airplanes of the future will have the ability to fly utilizing electric motors to power the propeller or ducted fan, and some or all of the electricity to power the electric motors will come from high energy density batteries. Just like many of today's cars are being powered by electric motors and battery packs made up of lithium-ion cells, some airplanes will also have that capability. One inherent problem for the airplane, however, is the battery packs are extremely heavy and the distance the airplane can fly on battery power alone is very limited.

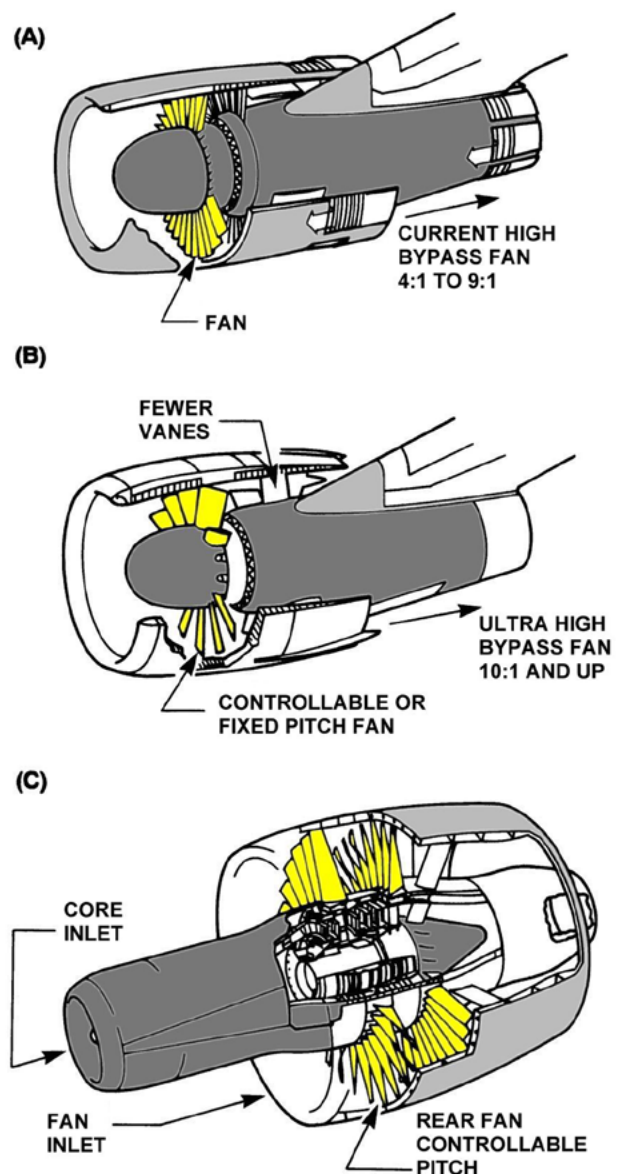


Figure 2-18A. Current technology turbofan engine

Figure 2-18B. Variable pitch front turbofan engine

Figure 2-18C. Variable pitch rear turbofan engine

TURBOGENERATOR

The solution to being able to power the aircraft with electric motors, but not having the inherent limitation of how much energy is stored in the battery pack, is to have a second source of electrical energy that can be used to supplement the batteries. The second source of electrical energy can be a turboshaft engine driving an electrical generator, in other words an auxiliary power unit (APU). Turbine engines operate at various levels of efficiency based on the RPM they are running at, and their RPM varies from ground idle to takeoff thrust. A turboshaft engine being used to solely run a generator at a constant speed can be designed to always operate at its most efficient RPM, and that would allow the combination of the turbine engine and the electric motor to be more efficient. Pictured in Figure 2-19 is a new design from Rolls Royce called a turbogenerator. It is a turboshaft engine of 700 to 1,400 horsepower driving a generator rated



Figure 2-19. Rolls Royce turbogenerator

at 500,000 to 1,000,000 watts. It is being designed to run on sustainable aviation fuel (SAF) and in the future on hydrogen.

SERIES ARCHITECTURE

The airplane's power system shown in Figure 2-20 would be known as a Series Architecture, where there is a single mechanical device that drives the propeller or fan. For this airplane the mechanical device is an electric motor. Figure 2-21 also shows the Series Architecture, with the arrows in red showing the possible direction of electrical current flow. Notice the battery can have current flowing in or out, but the engine generator and the electric motors have current flowing in only one direction.

PARALLEL ARCHITECTURE

Figure 2-22 shows what is known as a Parallel Architecture, where there are two separate mechanical devices that can drive the propeller or fan. The turbine engine has a shaft that drives the gearbox for the propeller/fan, and an electric motor/generator that attaches to the gearbox can also drive the propeller/fan. The aircraft can be operated on the ground with just the electric motor driving the gearbox, and then for takeoff the turbine engine can be started and used to drive the gearbox. If additional power is needed for takeoff, the turbine engine and the electric motor/generator can both be used to drive the gearbox.

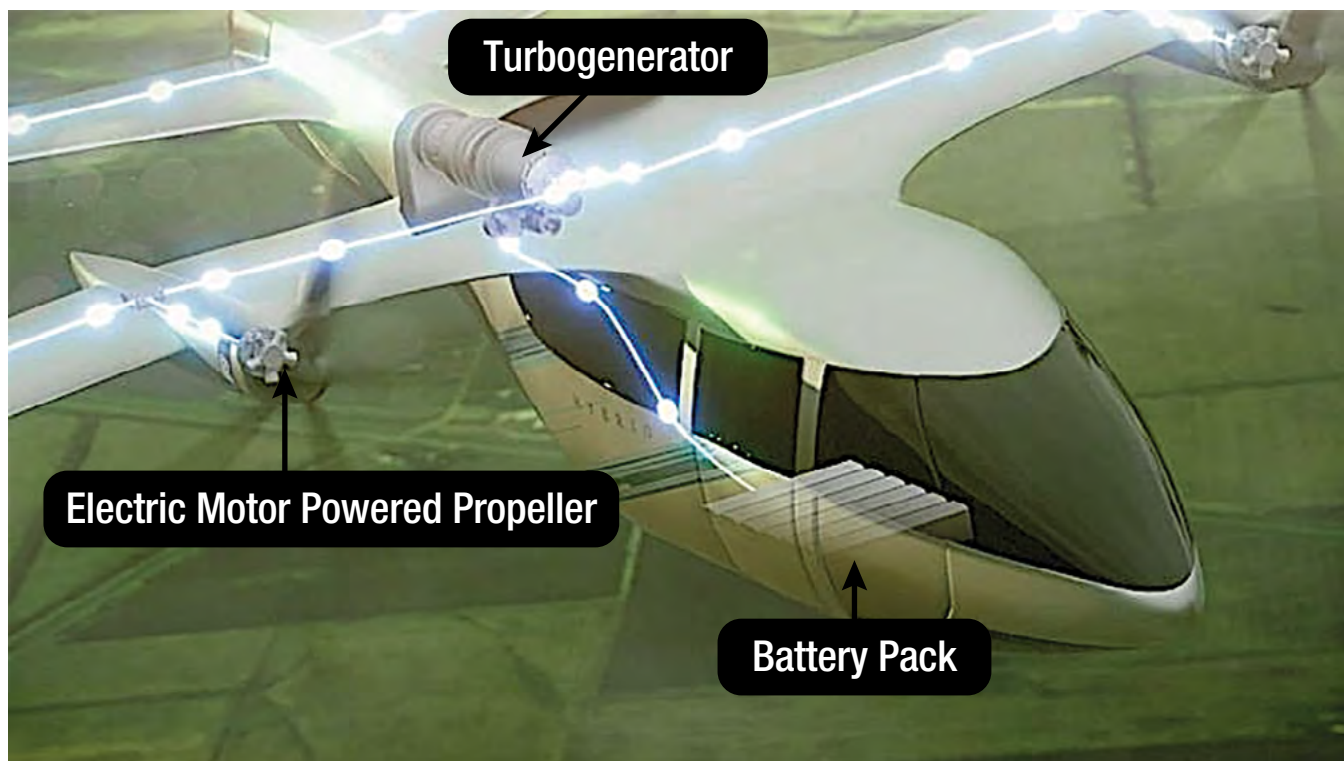


Figure 2-20. Electric airplane with a turbogenerator

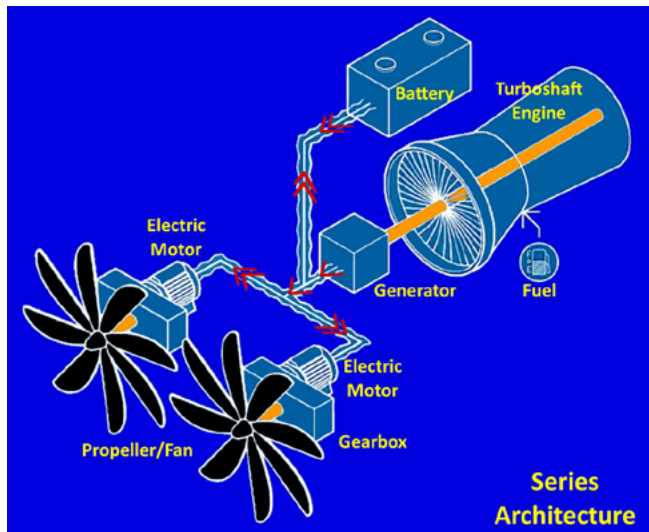


Figure 2-21. Airplane hybrid propulsion with a series architecture

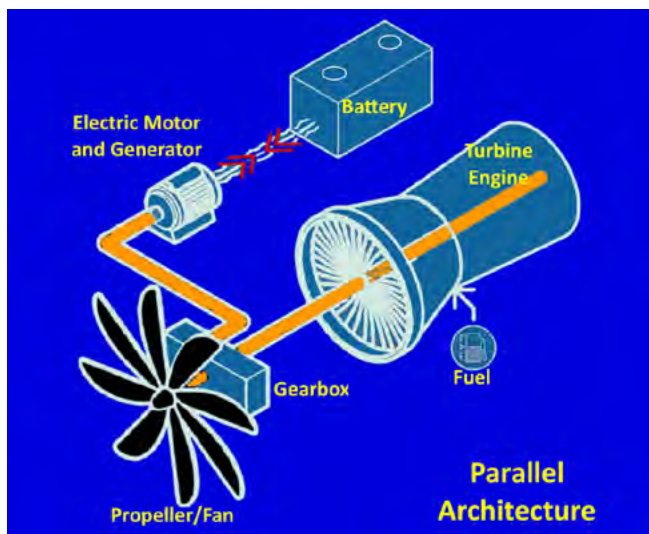


Figure 2-22. Airplane hybrid propulsion with a parallel architecture

PHYSICS OF THE GAS TURBINE ENGINE

A clear understanding of jet propulsion requires understanding the principles of physics that govern the action of mass or matter. The physics described in this section present the basic ideas necessary for understanding the physical relationships of gases and the turbo-machinery within a gas turbine engine.

In a discussion of turbine engines, we are concerned with the mass-flow of atmospheric air, which is compressed and accelerated to create useful work at the turbine wheel and, ultimately, thrust. The thrust is created from either pure reaction to the flowing gases or from a propeller or fan driven by a turbine.

Some of the most important physical properties that apply to the gas turbine engine are weight, density, temperature, pressure, and mass. These properties are useful when applied to formulas such as force, work, acceleration, thrust, and

others that measure certain valuable performance factors. These properties will be described by formula in English Units throughout this text, for example, pounds instead of kilograms

Weight has direction and quantity and is measured in pounds of force. Figure 2-23A shows that weight is one-directional, toward the center of the earth, regardless of the type of material.

Density is the amount of material per unit volume. Figure 2-23B illustrates how two containers with identical contents will have different weights if the contents are packed closer together. The compressor of a gas turbine engine uses this principle by packing more molecules of air into a given space to increase the density and weight of the airflow to create thrust.

For example, at standard day condition the weight of air is 0.076475 pounds/cubic foot. In an engine with an overall compressor pressure ratio of 30:1, the weight of air per cubic foot will be 30 times 0.076475, or 2.295 pounds/cubic foot.

Figure 2-23C illustrates that temperature is the molecular energy of motion due to heat. Molecular motion is low at low temperature, but it increases at higher temperatures. This creates a problem in the compressor of a gas turbine engine because it requires more and more work in terms of compressor speed and fuel consumption to increase density if the air temperature increases.

Pressure is an omni-directional force of motion per unit area. [Figure 2-23D] Air molecules inside a container will rebound off the inner walls with such great rapidity that an essentially even pressure is exerted over all of the inner surfaces. If a pressure gauge were inserted into the closed container, it would produce a steady reading in pounds per square inch.

Figure 2-23E illustrates that mass is the amount of material a body contains. In this respect, it is similar to the description of density. Within a gas turbine engine, the denser the air per unit volume, the more weight it has and the more mass.

FORCE

Force is the capacity to do work or the tendency to produce work. It is also a vector quantity that tends to produce acceleration of a body in the direction of its application. It can be measured in pounds. The formula for force is:

$$\text{Force} = \text{Pressure} \times \text{Area, or } F = P \times A$$

Where:

F = Force in pounds

P = Pressure in pounds per square inch (psi)

A = Area in square inches

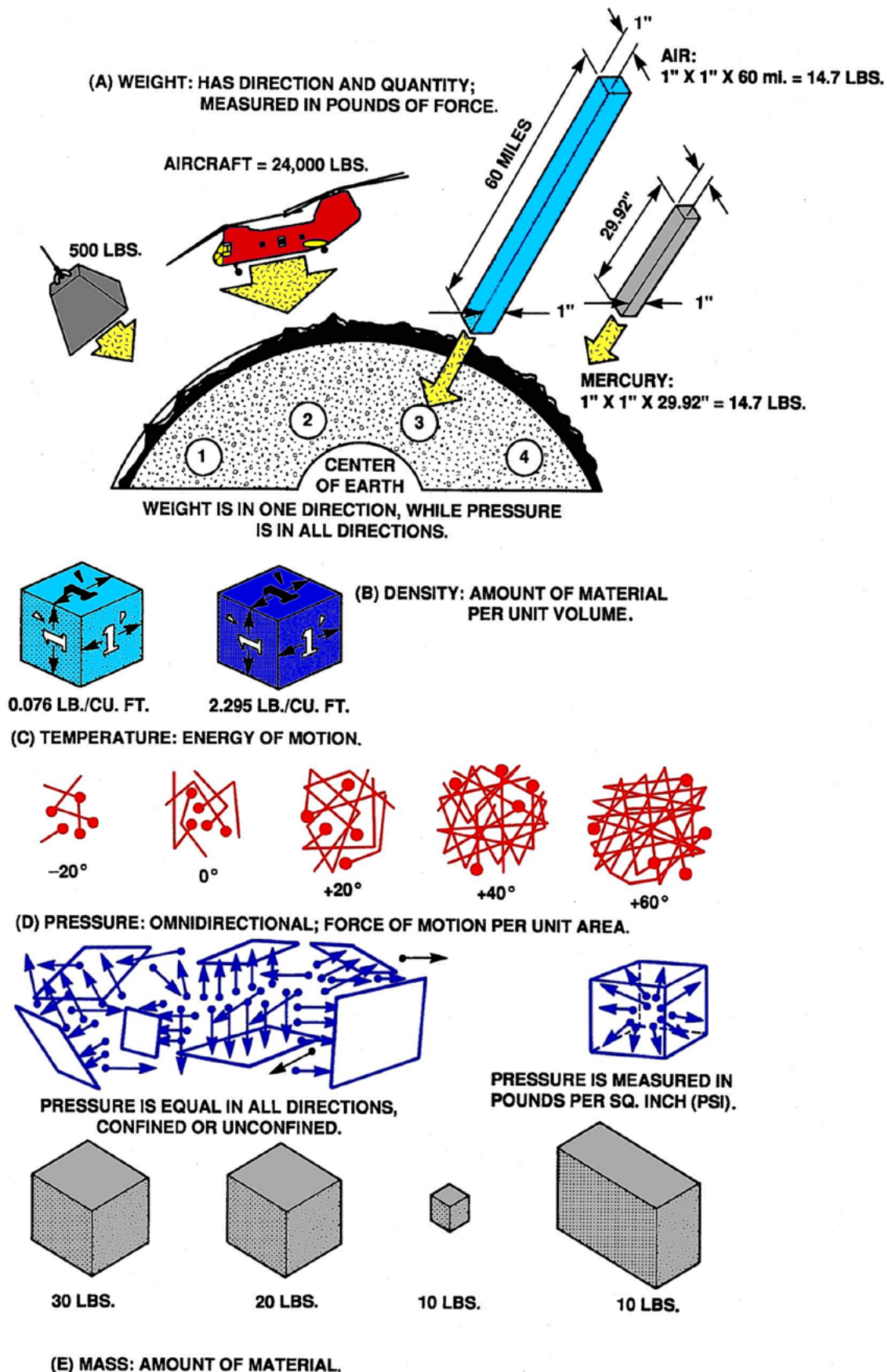


Figure 2-23 A, B, C, D, E. Some important physical properties of matter