STRATOVEC

2025


# USER MANUAL - V1.0

THE ENGINE ANALYSIS MATRIX™

# Engine Analysis Matrix™ - User Manual

**Version 1.0**



## Table of Contents

# 1. Introduction

## 1.1. Purpose of the Software

Welcome to the Engine Analysis Matrix™ (EAM). This software provides a sophisticated yet user-friendly graphical interface for conducting performance analysis on various types of jet engines. It is designed for aerospace students, engineers, and enthusiasts who wish to explore engine characteristics and flight performance metrics.

## 1.2. Key Capabilities

- **Modular Analysis:** Launch dedicated analysis modules for Turbofan, Turbojet, Turbojet with Afterburner, and Turboprop engines.
- **Flight Performance Calculation:** Includes a powerful Flight Range Analysis tool based on the Breguet Range Equation.
- **User-Friendly Interface:** A modern, intuitive GUI designed for efficient workflow and clear visualization of data.

## 1.3. Copyright and Licensing



# 2. Getting Started

## 2.1. System Requirements

To install and run the Engine Analysis Matrix, your system should meet the following minimum requirements:

- **Operating System:** Windows 10 or newer.
- **Disk Space:** Approximately 600 MB of free disk space for installation.
- **Memory (RAM):** 6 GB or more recommended.

## 2.2. Installation and Launch

The Engine Analysis Matrix is distributed as a user-friendly installer.

**Installation:**

1. Locate and double-click the EngineAnalysisMatrix_Setup.exe file.
2. Follow the on-screen instructions of the installation wizard. You may choose the installation directory or use the default location.
3. The installer will create a desktop shortcut and a Start Menu entry for easy access.

**Launching the Application:**
Once installation is complete, you can start the program by:

- Double-clicking the **Engine Analysis Matrix** shortcut on your desktop.

- OR, navigating to it through your Windows Start Menu and clicking on **Engine Analysis Matrix**.
- OR, by running the EngineAnalysisMatrix.exe file directly from the installation folder.

### 2.3. First-Time Setup: License Activation

Upon first launch, if a valid license is not found, you will be prompted with the **License Activation** window.

<!-- Placeholder for an image of the license dialog -->

- **Input Fields:** Enter your 16-digit license key into the four boxes. The format is XXXX-XXXX-XXXX-XXXX. The cursor will automatically advance to the next box after 4 characters are typed.
- **Activate Button:** Click this after entering the key.
  - **Valid Key:** If the key is correct, a success message will appear. The application will create an encrypted license file on your system and then proceed to launch the main program.
  - **Invalid Key:** An error message will be displayed. You must re-enter the correct key to proceed.

You only need to perform this activation once. The application will verify this on all subsequent launches.

## 3. The Main Application Window: GUI Explained

### 3.1. Overview of the Layout

The main window is divided into two primary sections: a **Left Control Panel** for inputs and module selection, and a **Right Display Panel** for immersive visuals.

### 3.2. Left Control Panel

This panel is vertically segmented into three parts.

At the top, an animated GIF of a jet engine cross-section is displayed. This is a decorative element designed to provide a visual reference for the software's subject matter.

This central section contains four buttons, which are the primary entry points to the specialized analysis modules:

- **Turbofan Analysis:** Launches the GUI for analyzing turbofan engines.
- **Turbojet Analysis:** Launches the GUI for analyzing standard turbojet engines.
- **Turbojet (Afterburner) Analysis:** Launches the GUI for analyzing turbojets equipped with an afterburner section.
- **Turboprop Analysis:** Launches the GUI for analyzing turboprop engines.

*Note: The detailed functionality of these modules is documented in Sections 7-10 of this manual.*

This is a powerful tool for estimating the maximum theoretical flight range of an aircraft. It uses the Breguet Range Equation for its calculations.

**Input Fields:**

- **Cruise Velocity (m/s):** The constant true air speed of the aircraft during its cruise phase, in meters per second.

- **TSFC ( kg/N ·h):** Thrust-Specific Fuel Consumption. This is a measure of engine fuel efficiency. It is the rate of fuel consumption (in kg per hour) per unit of thrust produced (in Newtons). **This value must be appropriate for the cruise condition.**
- **Gallons of Fuel:** The total usable volume of fuel on board the aircraft, in US Gallons.
- **Aircraft Empty Weight (kg):** The weight of the aircraft without any usable fuel or payload, in kilograms.
- **Cruise Lift (N):** The aerodynamic lift force generated by the aircraft during cruise, in Newtons. In steady, level flight, this is equal to the aircraft's weight.
- **Cruise Drag (N):** The aerodynamic drag force opposing the aircraft's motion during cruise, in Newtons.

**Action Button:**

- **Calculate Max Breguet Range:** After filling all input fields, click this button to perform the calculation.

**Output Fields (Read-Only):**

- **Fuel Weight (kg):** The calculated mass of the onboard fuel.
- **Gross Takeoff Weight (kg):** The total starting weight of the aircraft (Empty Weight + Fuel Weight).
- **Final (Empty) Weight (kg):** The final weight of the aircraft after all fuel is consumed.
- **Max Range (km):** The calculated maximum theoretical range in kilometers.
- **Max Range (NM):** The calculated maximum theoretical range in nautical miles.

### 3.3. Right Display Panel

This panel features a large, animated GIF depicting a pilot's point-of-view from a cockpit. This element is for aesthetic and immersive purposes.

A small button marked with a **?** is located in the top-right corner of the Cockpit View panel. Clicking this button will open this user manual.

## 4. Core Calculations & Theory

### 4.1. The Breguet Range Equation

The Flight Range Analysis calculator is based on the Breguet Range Equation for jet aircraft. This formula provides an excellent estimation of range for flights with a constant cruise speed and a steady decrease in weight due to fuel burn.

The formula used is:

$$R = (V / (TSFC * g)) * (L/D) * ln(W\_initial / W\_final)$$

### 4.2. Variables and Parameters

- R: Range (in meters)
- V: Cruise Velocity (in m/s)
- TSFC: Thrust-Specific Fuel Consumption (in kg/N ·s). *Note the unit conversion from the input.*
- g: Acceleration due to gravity (in m/s$^2$)

- L/D: The Lift-to-Drag ratio, a measure of aerodynamic efficiency.
- ln: The natural logarithm function.
- W_initial: Gross Takeoff Weight (in kg).
- W_final: Final (Empty) Weight (in kg).

### 4.3. Constants and Conversions

The application uses several built-in constants and performs necessary conversions:

- **TSFC Conversion:** The input TSFC in kg/N·h is divided by 3600 to convert it to kg/N·s for use in the SI unit formula.
- **Fuel Volume to Mass:** The input fuel volume in US Gallons is first converted to Liters, then multiplied by the density of Jet A-1 fuel to find the fuel mass in kilograms.
- **Physical Constants:**
    - GALLONS_TO_LITERS: 3.78541
    - JET_A1_DENSITY_KG_PER_L: 0.804 kg/L
    - GRAVITY_MS2: 9.80665 $m/s^2$
- **Range Conversion:** The final calculated range in meters is divided by 1000 for kilometers and by 1852 for nautical miles.

## 5. Best Practices for Usage

### 5.1. Accurate Data Entry

The principle of "Garbage In, Garbage Out" applies. The accuracy of the calculated range is entirely dependent on the accuracy of your inputs. Use reliable data sources for your aircraft and engine parameters. All inputs must be positive numbers.

### 5.2. Understanding Input Sensitivity

- **TSFC and L/D:** The range is most sensitive to the Thrust-Specific Fuel Consumption (TSFC) and the Lift-to-Drag ratio (L/D). A small improvement in either of these parameters results in a significant increase in range. Ensure the values used are representative of the aircraft's cruise phase.
- **Weight Fraction:** The range is also highly dependent on the ratio of initial to final weight. A higher fuel mass relative to the aircraft's empty mass will yield a longer range.

### 5.3. Interpreting the Results

The Breguet Range is an **idealized, theoretical maximum**. Real-world flight range will be lower due to factors not included in this calculation, such as:

- Fuel used for taxi, takeoff, and climb.
- Fuel reserves required for landing, diversions, and holding patterns.
- Effects of wind (headwinds or tailwinds).
- Non-standard atmospheric conditions (temperature, pressure).
- Changes in flight altitude or speed.

# 6. Troubleshooting

## 6.1. License Errors

- **"Invalid license key. Please try again."**: The key you entered does not match the valid key. Please check for typos and re-enter.
- **"Failed to write license file."**: The application does not have the necessary permissions to create the license.key file in its target directory. Try running the application with administrative privileges ("Run as administrator") for the first-time activation.

## 6.2. Input & Calculation Errors

- **"Please enter valid numbers for all fields."**: This appears if you leave a field blank or enter non-numeric text (e.g., "abc"). Please check all inputs.
- **"All input values must be positive."**: This appears if you enter zero or a negative number. All parameters for this calculation must be greater than zero.
- **Generic Calculation Error**: An unexpected error during calculation will produce a pop-up. This may indicate a highly unusual set of inputs (e.g., fuel weight is zero or negative). Double-check your values.

## 6.3. Visual Glitches or Missing Help File

All necessary visual assets (images, animations) and documentation are bundled within the EngineAnalysisMatrix.exe executable. You should not encounter any "missing file" errors.

If you experience issues such as:

- Visual panels showing text-based errors instead of images or animations.
- The Help button (?) failing to open the user manual.

This indicates that your application installation may be corrupted. Please resolve this by uninstalling the program through the Windows "Add or remove programs" feature and then running the EngineAnalysisMatrix_Setup.exe installer again.

# 7. Turbofan Analysis Module

## 7.1. Overview

This module is dedicated to the comprehensive analysis of two-spool, separate-flow (unmixed) turbofan engines. It follows a robust design and analysis methodology. First, it determines the overall engine size by scaling the inlet area (A0) to meet a specific Target Design Thrust at a given flight condition. Crucially, it also sizes the separate fixed throat areas for both the bypass and core nozzles based on this design point. With this fixed geometry established, the module then performs an extensive off-design analysis, calculating the engine's performance (thrust contributions, TSFC) and detailed station-by-station thermodynamic properties across a user-defined flight envelope of altitudes and Mach numbers.

## 7.2. The GUI Explained

The module window is designed for clarity and ease of use:

- **Media Panel (Left):** A large animated GIF provides a schematic cross-section of a high-bypass turbofan engine, illustrating the fan, core, and separate flow paths.

- **Parameter Panel (Right):** A scrollable frame containing all user-configurable inputs, logically grouped into sections for engine design, flight envelope, geometry, and numerical settings.
- **Action Buttons (Bottom-Center):** The main control buttons to Run Analysis, Show Plots, and Export Results to Excel.
- **Console Output (Bottom):** A detailed text log that provides real-time feedback on the calculation process, including sizing data, progress updates, warnings, and error messages.

This section details every parameter available in the GUI for the turbofan model.

**Engine Design Parameters:**

- **Bypass Ratio (BPR):** The ratio of the mass flow rate of the bypass air stream to the mass flow rate of the core air stream. (BPR = mdot_bypass / mdot_core)
- **Fan Pressure Ratio (FPR):** The ratio of total pressure across the fan stage (P_t2 / P_t1).
- **Overall Pressure Ratio (OPR):** The ratio of the highest pressure in the engine (compressor exit) to the pressure at the fan inlet (P_t4 / P_t1). The core compressor pressure ratio (CPR) is automatically calculated as OPR / FPR.
- **Combustor Exit Temp Tt5 (K):** The total temperature at the inlet of the high-pressure turbine (station 5 in this model's numbering), a critical material and performance limit.
- **Diffuser Efficiency (eta_diff):** Efficiency of the inlet diffuser in recovering pressure from the freestream flow.
- **Fan Polytropic Eff (eta_fan_p):** The polytropic (stage-by-stage) efficiency of the fan.
- **Comp Polytropic Eff (eta_comp_p):** The polytropic efficiency of the high-pressure compressor in the core.
- **Combustion Eff (eta_comb):** The efficiency of the combustor in converting the fuel's chemical energy into heat.
- **Combustor Press Ratio (pi_comb):** The fraction of total pressure retained across the combustor (P_t5 / P_t4), accounting for losses.
- **Turbine Polytropic Eff (eta_turb_p):** The polytropic efficiency of the high-pressure turbine that drives the high-pressure compressor.
- **Nozzle Velocity Eff (eta_nozz):** The efficiency of both the core and bypass nozzles in converting thermal energy into kinetic energy.

**Flight Conditions Range:**

- **Mach Range (Start:Step:End):** Defines the sweep of flight Mach numbers for the off-design analysis.
- **Altitude Range (m) (Start:Step:End):** Defines the sweep of flight altitudes (in meters) for the off-design analysis.

**Reference Area Scaling:**

- **Target Design Thrust (N):** The total desired net thrust (core + bypass) at the specified design point. This parameter drives the overall scaling of the engine.
- **Design Altitude (m):** The altitude for the design point.

- **Design Mach:** The Mach number for the design point.

**Relative Duct Area Ratios (Ax/A0):**
These ratios define the initial internal geometry of the engine relative to the main inlet capture area (A0). These ratios are **fixed** throughout the analysis.

- **A1/A0 (Fan Inlet):** Area ratio at the fan inlet face.
- **A2/A0 (Comp Inlet):** Area ratio at the core compressor inlet.
- **A4/A0 (Comb Inlet):** Area ratio at the combustor inlet.
- **A5/A0 (Turb Inlet):** Area ratio at the turbine inlet.
- **A6/A0 (Core Noz Inlet):** Area ratio at the core nozzle inlet.

**Numerical Parameters:**

- **Mach Convergence Tol / Max Iterations:** Settings for the iterative Mach number solver.
- **Turbine Temp Tol / Max Iterations:** Settings for the iterative work-balance calculation for the turbine.
- **Gas Constant R (J/kg·K) & Fuel LHV (J/kg):** Thermodynamic constants.

## 7.3. The Calculation Process & Theory

The engine is modeled as a two-spool, separate-flow system. After the fan, the flow is split into a bypass stream and a core stream. The analysis uses temperature-dependent gas properties for high accuracy.

- **Station 0:** Freestream / Ambient
- **Station 1:** Fan Inlet (Post-Diffuser)
- **Station 2:** Fan Exit / Flow Splitter
- **Station 3:** Bypass Nozzle Exit (Expanded to Ambient)
- **Station 4:** High-Pressure Compressor (HPC) Inlet
- **Station 5:** Combustor Exit / High-Pressure Turbine (HPT) Inlet
- **Station 6:** HPT Exit / Low-Pressure Turbine (LPT) Inlet
- **Station 7:** LPT Exit / Core Nozzle Inlet
- **Station 8:** Core Nozzle Exit (Expanded to Ambient)

*(Note: The GUI console log may use a slightly different numbering scheme for internal array indexing, which is also documented there for reference.)*

The module employs a direct, two-step calculation method:

**Step 1: Design Point Sizing**
The entire engine's geometry is scaled to meet the performance requirements at the specified **design point**.

1. **Thermodynamic Cycle Analysis:** The model first solves the full thermodynamic cycle at the design point to determine the engine's **specific thrust** (total thrust per unit of core air mass flow) and other key parameters. This involves balancing the work of the turbines with the work required by the fan and compressor.

2. **Mass Flow Calculation:** To achieve the Target Design Thrust, the required core air mass flow (mdot_core) is calculated. The bypass and total mass flows are then determined using the BPR.
3. **Inlet Area (A0) Sizing:** The required inlet capture area A0 is calculated based on the total air mass flow and freestream conditions at the design point.
4. **Internal Duct Sizing:** All other internal duct areas (A1, A2, etc.) are calculated by multiplying A0 by their respective user-defined area ratios.
5. **Nozzle Throat Sizing:** The model calculates the conditions at the inlet of both the bypass and core nozzles. It then determines the separate **fixed throat areas** (At*_bypass and At*_core) required to pass their respective mass flows under choked conditions.

After this step, the engine's physical geometry is completely defined and remains **fixed** for the off-design analysis.

**Step 2: Off-Design Envelope Analysis**
With the fixed engine geometry, the model performs a complete analysis sweep across the entire flight envelope. For each Altitude/Mach point, it solves the system of thermodynamic and fluid dynamics equations to determine the engine's performance, including:

- Core and Bypass Thrust contributions.
- Total Thrust and Thrust-Specific Fuel Consumption (TSFC).
- Detailed thermodynamic properties (T, P, M) at every station in both the core and bypass streams.

## 7.4. Interpreting the Outputs

The console provides a real-time transcript of the calculation. Key items to observe are:

- **Sizing Data:** The log will clearly state the calculated A0 (as A_ref), Fixed_A_bypass_throat, and Fixed_A_core_throat values.
- **Progress Indicators:** Messages will show the progress as the analysis completes each altitude in the flight envelope.
- **Warnings:** The console will flag potential issues like solver non-convergence or choked flow conditions at any of the internal stations.
- **Performance Plots:** These show the overall performance (Total Thrust, TSFC) as a function of Mach number and altitude.
- **Station Plots:** Separate plots for Mach Number, Temperature, and Pressure allow for a deep dive into the engine's internal state. You can visually trace the properties through the core and bypass streams.
- **Nozzle Geometry Plots:** These show the *required* nozzle exit area ratio (Ae/A*) for the core and bypass nozzles to achieve perfect expansion to ambient pressure. This indicates how much the physical nozzle flaps would need to open or close.

The Excel file provides the most granular data for analysis.

- **Performance Summary:** A comprehensive table of all key performance metrics for every flight condition.
- **Station Data Sheets:** Each sheet is dedicated to a specific station (e.g., Fan Inlet, Turb Inlet, Core Exit) and provides the full thermodynamic state across the entire flight envelope.

## 7.5. Model Strengths and Limitations

**Strengths:**

- **Realistic Sizing:** The model sizes the engine based on a real thrust requirement and correctly establishes separate, fixed throat areas for the two distinct exhaust streams.
- **Separate Flow Model:** It correctly models the separate thermodynamics and performance of the bypass and core streams, which is essential for turbofan analysis.
- **Variable Gas Properties:** Using temperature-dependent Cp and gamma for both air and hot gas provides a higher degree of accuracy than simpler models.
- **Comprehensive Diagnostics:** The detailed outputs allow for a thorough investigation of the engine's behavior under all operating conditions.

**Limitations:**

- **No Anti-Choke Correction:** The user-defined Ax/A0 ratios are fixed. If these values are not chosen carefully, internal ducts can choke at off-design conditions. The model will report this, but unlike the advanced afterburner module, it will **not** automatically adjust the geometry to fix it.
- **Fixed Component Efficiencies:** All component efficiencies and the combustor pressure ratio are assumed to be constant. In reality, these parameters vary significantly with engine speed and flight conditions.
- **No Spool Speed (RPM) Model:** The analysis is based on a thermodynamic work balance (LPT work = Fan work, HPT work = HPC work). It does not model physical spool speeds (N1, N2) or use component performance maps, which are features of higher-fidelity simulations.
- **Simplified Nozzle Model:** The model calculates the *ideal* nozzle exit areas (Ae) for perfect expansion. It does not account for the thrust losses that would occur from over- or under-expansion if the physical exit areas were fixed or not perfectly matched.

# 8. Turbojet Analysis Module

## 8.1. Overview

**This module facilitates the design-point and off-design analysis of a conventional, single-spool turbojet engine without an afterburner. The tool first sizes the engine's inlet and nozzle throat areas based on a user-specified thrust requirement at a specific flight condition (the "design point"). It then uses this fixed geometry to calculate the engine's performance metrics (Thrust, TSFC) and detailed thermodynamic properties at each station across a full flight envelope of varying altitudes and Mach numbers.**

**This module is ideal for fundamental jet engine analysis, academic studies, and preliminary performance estimation of non-afterburning turbojet designs.**

## 8.2. The GUI Explained

**The module window is organized for an efficient workflow:**

- **Media Panel (Left):** A large panel displays an animated schematic of a standard turbojet engine, helping to visualize the components and flow path.

- **Parameter Panel (Right):** A scrollable list contains all user-configurable inputs, logically grouped into sections for engine design, flight conditions, geometry, and numerical settings.
- **Action Buttons (Bottom-Center):** Buttons to Run Analysis, Show Plots, and Export Results control the main functions of the module.
- **Console Output (Bottom):** A text box provides a detailed, real-time log of the calculation process, including sizing information, status updates, warnings, and any errors encountered.

**The following parameters control the engine design and analysis.**

**Engine Design Parameters:**

- **Overall Pressure Ratio (OPR):** The ratio of total pressure at the compressor exit to the total pressure at the compressor inlet (P_t3 / P_t2).
- **Turbine Inlet Temp Tt4 (K):** The total temperature of the gas entering the turbine (station 4), a primary determinant of engine performance and a material limit of the hot section.
- **Inlet Recovery (eta_inlet):** Efficiency of the air intake. Represents the fraction of freestream total pressure retained after accounting for external drag and shock losses.
- **Diffuser Efficiency (eta_diff):** Efficiency of the subsonic diffuser in converting kinetic energy to pressure before the compressor.
- **Comp Polytropic Eff (eta_comp_p):** The stage-by-stage efficiency of the compressor, used to calculate the real work required for compression.
- **Combustion Eff (eta_comb):** Efficiency of the combustor in converting the fuel's chemical energy into thermal energy.
- **Combustor Press Ratio (pi_comb):** Total pressure loss across the combustor due to friction and heat addition effects (P_t4 / P_t3).
- **Turbine Polytropic Eff (eta_turb_p):** The stage-by-stage efficiency of the turbine in extracting work from the hot gas.
- **Nozzle Velocity Eff (eta_nozz):** Efficiency of the nozzle in converting thermal energy into exit kinetic energy. (V_actual = V_ideal * sqrt(eta_nozz))

**Flight Conditions Range:**

- **Mach Range (Start:Step:End):** Defines the sweep of flight Mach numbers for the off-design analysis.
- **Altitude Range (m) (Start:Step:End):** Defines the sweep of flight altitudes (in meters) for the off-design analysis.

**Reference Area Scaling:**

- **Target Design Thrust (N):** The desired net thrust of the engine at the specified design point. This is the primary driver for the overall size of the engine.
- **Design Altitude (m):** The altitude at which the engine should produce the target thrust.
- **Design Mach:** The Mach number at which the engine should produce the target thrust.

**Relative Duct Area Ratios (Ax/A0):**
**These ratios define the engine's internal geometry relative to its inlet capture area (A0). Unlike the more**

**advanced Afterburner module, these ratios are fixed and are not automatically adjusted by the software.**

- **A2/A0 (Comp Inlet):** Area ratio at the compressor face.
- **A3/A0 (Comb Inlet):** Area ratio at the combustor entrance**.**
- **A4/A0 (Turb Inlet):** Area ratio at the turbine inlet.
- **A5/A0 (Nozz Inlet):** Area ratio at the nozzle entrance (turbine exit).

**Numerical Parameters:**

- **Mach Convergence Tol / Max Iterations:** Tolerance and iteration limits for the numerical solver that determines the flow Mach number at each station.
- **Turbine Temp Tol / Max Iterations:** Tolerance and iteration limits for the iterative work-balance calculation that finds the turbine exit temperature.
- **Gas Constant R (J/kg·K) & Fuel LHV (J/kg):** Fundamental thermodynamic constants.

## 8.3. The Calculation Process & Theory

**The engine is analyzed as a sequence of thermodynamic processes between stations. The model uses temperature-dependent gas properties (Cp, gamma) for higher accuracy.**

- **Station 0: Freestream / Ambient Conditions**
- **Station 2: Compressor Inlet (Post-Inlet/Diffuser)**
- **Station 3: Combustor Inlet (Post-Compressor)**
- **Station 4: Turbine Inlet (Post-Combustor)**
- **Station 5: Nozzle Inlet (Post-Turbine)**
- **Station 6: Nozzle Exit (Expanded to Ambient Pressure)**

**The module follows a direct, two-step process:**

**Step 1: Design Point Sizing**
**The entire engine geometry is scaled based on the performance requirements at the single design point (Design Altitude, Design Mach, Target Design Thrust).**

1. **The model calculates the engine's thermodynamic cycle at the design point to determine its specific thrust (thrust generated per unit mass flow rate of air, N / ( kg/s )).**
2. **To meet the Target Design Thrust, the required total air mass flow rate (mdot_air) is calculated: mdot_air = Target Thrust / Specific Thrust.**
3. **The required inlet capture area (A0) is then determined from this mass flow rate and the freestream conditions: A0 = mdot_air / (rho_0 * V_0).**
4. **All other internal duct areas (A2, A3, etc.) are calculated by multiplying A0 by the user-provided Ax/A0 ratios.**
5. **Finally, the model calculates the conditions at the nozzle inlet (station 5) and determines the *fixed nozzle throat area (At)** required to pass the gas mass flow at that point.**

**At the end of this step, the engine's geometry (A0, all Ax, and At*) is completely defined and remains fixed for the remainder of the analysis.**

**Step 2: Off-Design Envelope Analysis**
**With the fixed engine geometry, the model iterates through every combination of altitude and Mach number in the specified flight envelope. For each point, it solves the system of thermodynamic equations station-by-station to find the engine's performance and internal state. This includes calculating Thrust, TSFC, mass flow rates, temperatures, pressures, and Mach numbers throughout the engine.**

## 8.4. Interpreting the Outputs

**The console provides a step-by-step narrative of the analysis. It is essential for understanding the model's results.**

- **Sizing Information:** The log will first report the calculated A0 and Fixed_A_throat_engine based on your design inputs.
- **Analysis Progress:** It will show messages as it completes the calculations for each altitude in the flight envelope.
- **Warnings:** Pay close attention to warnings about solver non-convergence or potential choking at internal stations, as these indicate regions where the model is operating at its limits or where the user-defined geometry is problematic.
- **Performance Plots:** Thrust and TSFC are plotted against Mach number or altitude, providing a top-level view of the engine's capabilities.
- **Station Plots:** These plots for Mach Number, Static/Total Temperature, and Static/Total Pressure are crucial for diagnostics. They allow you to trace the fluid properties through the engine. If the (May Choke) warning appears on the title of the "St2_CompInlet" plot, it means that at some point in the flight envelope, the required sonic area exceeded the physical duct area, leading to a choked flow condition.

**The Excel export provides the most comprehensive data set for post-processing.**

- **Performance Summary:** A single sheet containing all key performance metrics for every flight condition, including thrust, TSFC, mass flows, and nozzle geometry requirements.
- **Station Data Sheets:** Individual sheets for each station (St0, St2, St3, etc.) provide a complete thermodynamic state (T, P, M, Cp, Gamma) for every point in the flight envelope.

## 8.5. Model Strengths and Limitations

**Strengths:**

- **Design-Point Sizing:** The model accurately scales the entire engine to meet a specific thrust target, providing a well-grounded starting point.
- **Variable Gas Properties:** The use of temperature-dependent Cp and gamma offers a higher degree of thermodynamic accuracy compared to models that assume constant values.
- **Comprehensive Outputs:** The combination of plots and detailed Excel exports provides deep insight into the engine's performance and internal workings across its entire operational range.
- **Clarity and Speed:** The direct sizing and analysis approach is computationally fast and easy to understand, making it excellent for educational purposes and initial design iterations.

**Limitations:**

- **No Anti-Choke Geometry Correction:** This is the most significant limitation. The user-defined Ax/A0 ratios are treated as fixed and absolute. If these ratios are not well-chosen, the engine may experience physically impossible choking at off-design conditions (e.g., at the compressor inlet, Station 2). The model will flag this condition in the plots, but unlike the more advanced Afterburner module, it will not automatically correct the geometry. The user is responsible for providing viable area ratios.
- **Fixed Component Efficiencies:** All component efficiencies (eta_*) and the combustor pressure ratio (pi_comb) are assumed to be constant across the entire flight envelope. In reality, these values change with engine speed and flight conditions.
- **No Spool Speed (RPM) Model:** The analysis is based on a thermodynamic work balance between the compressor and turbine. It does not model a physical spool speed (RPM) or use component performance maps, which are characteristic of higher-fidelity simulations.
- **Simplified Nozzle Model:** The model calculates the ideal nozzle exit area (Ae) required for perfect expansion to ambient pressure (Pe=P0). It does not account for thrust losses due to over- or under-expansion that would occur if the nozzle exit area were fixed. The nozzle *throat* area, however, is fixed.

# 9. Turbojet (Afterburner) Analysis Module

## 9.1. Overview

**This module provides a powerful and detailed analysis of a single-spool afterburning turbojet engine. Unlike simpler models, this tool performs a multi-stage design and analysis process. It first sizes the engine based on a target thrust requirement and then automatically refines its internal geometry to ensure physical viability across a wide flight envelope. Finally, it calculates the engine's performance (Thrust, TSFC, etc.) and detailed thermodynamic properties at every station throughout the specified altitude and Mach number range.**

**The afterburner (or "reheat") section can be toggled by setting the AB Exit Total Temp to a value higher than the turbine exit temperature.**

## 9.2. The GUI Explained

**The module window is divided into a large media panel on the left and a scrollable parameter panel on the right.**

- **Media Panel:** Displays an animated GIF of an afterburning turbojet engine, providing a visual schematic of the component layout.
- **Parameter Panel:** Contains all user-configurable inputs, grouped into logical sections.
- **Action Buttons:** Below the main panels are buttons to Run Analysis, Show Plots, and Export Results.
- **Console Output:** At the bottom, a text box displays a detailed log of the calculation process, including status updates, warnings, and error messages.

**This section details every parameter available in the GUI.**

**Engine Design Parameters:**

- **Overall Pressure Ratio (OPR):** The ratio of the total pressure at the compressor exit (station 3) to the total pressure at the compressor inlet (station 2). (OPR = P_t3 / P_t2)

- **Turbine Inlet Temp Tt4 (K):** The total temperature of the gas entering the turbine (station 4), in Kelvin. This is a critical design limit for the engine's "hot section".
- **Inlet Recovery (eta_inlet):** The efficiency of the air intake in converting freestream kinetic energy into pressure. It represents the fraction of freestream total pressure available after accounting for external drag and shock losses (for supersonic flight, this is applied *after* the normal shock relation).
- **Diffuser Efficiency (eta_diff):** The efficiency of the subsonic diffuser (internal ducting before the compressor) in recovering pressure. (P_t2 = P_t_inlet * eta_diff)
- **Comp Polytropic Eff (eta_comp_p):** The polytropic (infinitesimal stage) efficiency of the compressor. This value remains constant and is used to calculate the temperature rise across the compressor for a given pressure ratio.
- **Combustion Eff (eta_comb):** The efficiency of the main combustor in releasing the chemical energy of the fuel. (Heat Added = f * eta_comb * LHV)
- **Combustor Press Ratio (pi_comb):** The ratio of total pressure at the combustor exit to its inlet, accounting for losses due to heat addition and friction. This value is typically less than 1. (P_t4 = P_t3 * pi_comb)
- **Turbine Polytropic Eff (eta_turb_p):** The polytropic efficiency of the turbine, used to calculate the temperature drop for a given pressure drop.
- **Nozzle Velocity Eff (eta_nozz):** The efficiency of the nozzle in converting thermal energy into kinetic energy. The actual exit velocity is the ideal exit velocity multiplied by the square root of this efficiency. (V_actual = V_ideal * sqrt(eta_nozz))

**Afterburner Parameters:**

- **AB Combustion Eff (eta_ab):** The combustion efficiency of the afterburner section.
- **AB Pressure Ratio (pi_ab):** The total pressure ratio across the afterburner section, accounting for friction and heat addition losses. (P_t6 = P_t5 * pi_ab)
- **AB Exit Total Temp Tt_ab_max (K):** The target total temperature at the afterburner exit (nozzle inlet, station 6). To activate the afterburner, set this value higher than the turbine exit temperature (approx. 800-1200K). To run the engine "dry" (no afterburning), set this value lower than the expected turbine exit temperature.

**Flight Conditions Range:**

- **Mach Range (Start:Step:End):** Defines the sweep of flight Mach numbers for the analysis.
- **Altitude Range (m) (Start:Step:End):** Defines the sweep of flight altitudes (in meters) for the analysis.

**Reference Area Scaling (Dry Thrust):**

- **Target Design Thrust (N):** The desired net thrust of the engine *without the afterburner engaged* at the specified design point. This is used for the initial scaling of the engine's capture area (A0).
- **Design Altitude (m):** The altitude for the design point.
- **Design Mach:** The Mach number for the design point.

**Relative Duct Area Ratios (Ax/A0):**
**These define the initial internal geometry of the engine as a ratio of the cross-sectional area at a given**

**station (Ax) to the inlet capture area (A0).** ***Note: The analysis may increase these values to prevent internal choking.***

- **A2/A0 (Comp Inlet): Area ratio at the compressor face.**
- **A3/A0 (Comb Inlet): Area ratio at the combustor inlet.**
- **A4/A0 (Turb Inlet): Area ratio at the turbine inlet.**
- **A5/A0 (AB Inlet/Turb Exit): Area ratio at the afterburner inlet.**
- **A6/A0 (Nozz Inlet/AB Exit): Area ratio at the nozzle inlet.**

**Numerical Parameters:**

- **M-Solver Tol / Max Iter:** Tolerance and iteration limits for the numerical solver that finds the Mach number at each station.
- **Turbine Tt Tol / Max Iter:** Tolerance and iteration limits for the iterative calculation of the turbine exit temperature.
- **AntiChoke Max Area Factor:** The maximum factor by which a choked duct's area ratio can be increased relative to its initial user-defined value during the anti-choke search.
- **AntiChoke Max Iter/Point:** The maximum number of geometry modification iterations the anti-choke algorithm will perform.
- **Gas Constant R (J/kg·K) & Fuel LHV (J/kg):** Thermodynamic constants for air and fuel.

## 9.3. The Calculation Process & Theory

**The module employs a sophisticated multi-stage calculation process to design and analyze the engine.**

**The engine is modeled as a series of connected stations. The model uses temperature-dependent specific heat (Cp) and ratio of specific heats (gamma) for both air (stations 0-3) and hot gas products (stations 4-7).**

- **Station 0: Freestream / Ambient Conditions**
- **Station 2: Compressor Inlet (after inlet and diffuser)**
- **Station 3: Main Combustor Inlet (after compressor)**
- **Station 4: Turbine Inlet (after main combustor)**
- **Station 5: Afterburner Inlet (after turbine)**
- **Station 6: Nozzle Inlet (after afterburner)**
- **Station 7: Nozzle Exit (ideally expanded to ambient pressure)**

**The engine is first sized at the specified design point (Design Altitude, Design Mach). This is a crucial two-part process:**

1. **Inlet Area (A0) Sizing:** The model calculates the engine's performance in dry mode (afterburner off). It determines the specific thrust (thrust per kg/s of air). It then calculates the required air mass flow mdot_air to meet the Target Design Thrust, and from this, the required inlet capture area A0.
2. ***Nozzle Throat (At) Sizing***:* Using the mdot_air from the dry sizing, the model then calculates the engine state in wet mode (afterburner on at Tt_ab_max). It determines the total mass flow and

thermodynamic conditions at the nozzle inlet (station 6) and calculates the required choked throat area At* needed to pass this flow.

**This approach results in a realistically sized engine: the core size is based on its primary (dry) thrust requirement, while the nozzle is sized to handle the maximum (wet) exhaust flow. This At* becomes the fixed throat area for the engine in all subsequent calculations.**

**This is an advanced feature that ensures the engine's internal geometry is physically viable. After the initial sizing, the model performs a check across the *entire* flight envelope.**

- **At each Mach/Altitude point, it calculates the required sonic throat area (A*_required) at every station (2, 3, 4, 5, 6).**
- **It compares this A*_required to the station's physical duct area (Ax).**
- **If A*_required > Ax, the station is choked, which is physically impossible.**
- **The model identifies the most severely choked station and increases its Ax/A0 ratio by a small factor.**
- **This process repeats until no choking is detected across the entire flight envelope, or the iteration limit is reached.**
- **This ensures the final engine geometry can operate without unstart or impossible flow conditions. The final, potentially modified, area ratios are used for the rest of the analysis.**

**Because the Anti-Choke stage may have altered the internal area ratios, the engine's dry thrust at the design point may no longer match the user's target.**

- **The model re-calculates the dry thrust at the design point with the final, non-choking geometry.**
- **It compares this new thrust to the Target Design Thrust.**
- **If they don't match (within a tolerance), it iteratively adjusts the *overall engine scale* (both A0 and At* together) up or down and repeats the calculation until the thrust target is met more closely.**

**With a fully defined, physically viable, and correctly scaled engine geometry, the model performs one final sweep of all Mach numbers and altitudes. It calculates the full suite of performance metrics (Thrust, TSFC) and station-by-station thermodynamic properties (T, P, M, etc.) for every point in the operating envelope. These are the final results that are plotted and exported.**

## 9.4. Interpreting the Outputs

**The console provides a rich, real-time transcript of the calculation process. It is crucial for understanding the model's behavior. Pay attention to:**

- **Initial Sizing Values:** Note the calculated A0 and At*.
- **Global Geometry Iterations:** Messages will appear if the anti-choke search modifies the Ax/A0 ratios. This tells you that your initial geometry was not viable.
- **Thrust Matching Iterations:** See how the model refines the engine scale to meet your thrust target.
- **Warnings:** Look for warnings about non-convergence in iterative solvers. While the model proceeds with the last calculated value, it indicates a potential area of numerical instability.
- **Performance Plots:** The Thrust and TSFC plots provide the high-level performance summary.

- **Station Plots (M, T, P):** These are powerful diagnostic tools. You can trace the evolution of Mach number, temperature, and pressure through the engine. Check for unexpected jumps or trends. A "(Duct Choked)" or "(Fixed Throat Choked)" note on a station's title indicates that choking occurred at that location under some flight condition.

**The exported Excel file contains the most detailed output.**

- **Performance Summary:** A flat table of all key performance metrics for every flight condition.
- **Station Data Sheets (St0, St2, etc.):** Each sheet provides a detailed thermodynamic breakdown for a specific station across the entire flight envelope. This is invaluable for in-depth analysis of component performance.

## 9.5. Model Strengths and Limitations

**Strengths:**

- **Sophisticated Sizing Algorithm:** The multi-stage process (dry thrust scaling, wet throat sizing, anti-choke geometry correction, and final thrust matching) provides a robust and physically realistic engine design.
- **Physically Grounded Geometry:** The anti-choke feature prevents the common pitfall of designing an engine that only works at its design point, ensuring it is viable across its full operating range.
- **Fixed-Core, Variable Nozzle Assumption:** The model correctly treats the core engine geometry as fixed while calculating the *required* variable nozzle exit area (Ae) for ideal expansion, which reflects real-world engine operation.
- **Variable Gas Properties:** The use of temperature-dependent Cp and gamma provides higher fidelity than constant-value assumptions.
- **Comprehensive Diagnostics:** Detailed console logs, plots, and Excel exports allow for deep insight into the engine's behavior.

**Limitations:**

- **No Spool Speed (RPM) Model:** The model uses a work-balance approach (Turbine work = Compressor work) but is not based on component performance maps (e.g., compressor/turbine maps). It does not calculate or depend on a physical spool RPM.
- **Fixed Component Efficiencies:** All efficiencies (eta_*) and combustor pressure ratios (pi_*) are assumed to be constant. In reality, these parameters vary significantly with engine RPM and flight conditions. This is the model's most significant simplification.
- **Simplified Nozzle Model:** The model calculates the *ideal* exit area (Ae) required for the exhaust to perfectly expand to ambient pressure (Pe=P0). It does not model the complex mechanics of the convergent-divergent (C-D) nozzle that would be required to achieve this, nor does it account for over- or under-expansion losses if a fixed nozzle were used. The nozzle throat area (At*), however, is fixed after the initial sizing.
- **Ideal Gas Assumption:** The analysis assumes the working fluid behaves as an ideal gas, which is standard for this level of analysis but loses accuracy at extremely high pressures.

# 10. Turboprop Analysis Module

## 10.1. Overview

**This module provides a detailed analysis of a single-spool turboprop engine. In this engine type, the turbine expands the hot gas not only to drive the compressor but also to produce a large amount of excess shaft power. This power is transferred through a gearbox to drive a propeller, which generates the majority of the engine's thrust. A small amount of residual thrust is also generated by the core exhaust jet.**

**The module first sizes the engine's inlet and core nozzle throat based on a Target Design Thrust at a specific flight condition. It then uses this fixed geometry to perform a full off-design analysis across a range of altitudes and Mach numbers, calculating performance metrics like thrust components, shaft power, and fuel efficiencies.**

## 10.2. The GUI Explained

**The module window is structured for an intuitive user experience:**

- **Media Panel (Left):** A large animated GIF displays a schematic of a turboprop engine, illustrating the propeller, gearbox, compressor, combustor, and turbine sections.
- **Parameter Panel (Right):** A scrollable list of all user-configurable inputs, organized into logical groups.
- **Action Buttons (Bottom-Center):** Buttons to Run Analysis, Show Plots, and Export Results control the primary functions.
- **Console Output (Bottom):** A text box that provides a detailed, real-time log of the calculation process, including sizing data, progress, warnings, and errors.

**This section provides an exhaustive explanation of each parameter.**

**Engine Design Parameters:**

- **Overall Pressure Ratio (OPR):** The ratio of total pressure at the compressor exit to the total pressure at the compressor inlet (P_t2 / P_t1).
- **Turbine Pressure Ratio (TPR):** A key parameter for turboprops. It defines the ratio of total pressure at the turbine inlet to the total pressure at the turbine exit (P_t3 / P_t4). This ratio dictates how much the gas expands through the turbine, directly controlling the power split between the compressor and the output shaft. A higher TPR means more expansion and more shaft power.
- **Combustor Exit Temp Tt3 (K):** The total temperature at the turbine inlet (station 3), a critical material and performance limit.
- **Propeller Efficiency (eta_prop):** The efficiency of the propeller in converting shaft power into propulsive thrust power.
- **Gearbox Efficiency (eta_gbx):** The efficiency of the gearbox in transferring power from the turbine shaft to the propeller shaft.
- **Diffuser Efficiency (eta_diff):** The efficiency of the air intake and subsonic diffuser section.
- **Comp Polytropic Eff (eta_comp_p):** The polytropic (infinitesimal stage) efficiency of the compressor.
- **Combustion Eff (eta_comb):** The efficiency of the combustor.

- **Combustor Press Ratio (pi_comb):** Total pressure loss across the combustor (P_t3 / P_t2).
- **Turbine Polytropic Eff (eta_turb_p):** The polytropic efficiency of the power turbine.
- **Core Nozzle Vel Eff (eta_nozz):** The velocity efficiency of the residual thrust nozzle.

**Flight Conditions Range:**

- **Mach Range (Start:Step:End):** Defines the sweep of flight Mach numbers for the analysis.
- **Altitude Range (m) (Start:Step:End):** Defines the sweep of flight altitudes (in meters).

**Reference Area Scaling:**

- **Target Design Thrust (N):** The desired total equivalent thrust (propeller thrust + core jet thrust) at the specified design point. This is the primary driver for scaling the engine size.
- **Design Altitude (m):** The altitude for the design point.
- **Design Mach:** The Mach number for the design point.

**Relative Duct Area Ratios (Ax/A0):**
**These ratios define the engine's internal gas generator geometry relative to the inlet capture area (A0). These ratios are fixed and are not automatically adjusted by the software.**

- **A1/A0 (Comp Inlet): Area ratio at the compressor inlet.**
- **A3/A0 (Comb Inlet): Area ratio at the combustor inlet.**
- **A4/A0 (Turb Inlet): Area ratio at the turbine inlet.**
- **A5/A0 (Noz Inlet): Area ratio at the core nozzle inlet (turbine exit).**

**Numerical Parameters:**

- **Mach Convergence Tol / Max Iterations:** Settings for the iterative solver that finds the flow Mach number at each station.
- **Turbine Temp Tol / Max Iterations:** Settings for the iterative calculation of turbine temperature drop.
- **Gas Constant R (J/kg·K) & Fuel LHV (J/kg):** Thermodynamic constants.

## 10.3. The Calculation Process & Theory

**The engine is modeled as a gas generator that produces shaft power and residual jet thrust. The model uses temperature-dependent gas properties (Cp, gamma).**

- **Station 0: Freestream / Ambient**
- **Station 1: Compressor Inlet (Post-Diffuser)**
- **Station 2: Compressor Exit / Combustor Inlet**
- **Station 3: Combustor Exit / Turbine Inlet**
- **Station 4: Turbine Exit / Nozzle Inlet**
- **Station 5: Core Nozzle Exit (Expanded to Ambient)**

***(Note: The Ax/A0 labels in the GUI correspond directly to these conceptual station numbers.)***

**The module follows a direct, two-step process similar to the standard turbojet module, but with calculations adapted for shaft power production.**

**Step 1: Design Point Sizing**
**The engine's geometry is scaled to meet the performance requirement at the specified design point.**

1. **Thermodynamic Cycle Analysis:** The model solves the gas generator cycle at the design point.
    - It calculates the work required by the compressor based on the OPR.
    - It calculates the total work extracted by the turbine based on the TPR.
    - The excess work (Work_turbine - Work_compressor) is the shaft work available to drive the propeller.
2. **Specific Performance Calculation:** The shaft work is converted to Shaft Power per unit mass flow. This power is then converted to Propeller Thrust per unit mass flow using the propeller and gearbox efficiencies and the flight velocity. The residual Core Jet Thrust per unit mass flow is also calculated. The sum of these is the Total Specific Thrust.
3. **Mass Flow and Area Sizing:** To meet the Target Design Thrust, the required core air mass flow rate (mdot_air) is calculated. From this, the inlet capture area (A0) is determined.
4. **Internal Duct and Nozzle Sizing:** All internal duct areas (A1, A3, etc.) are scaled using the user-provided ratios. The model then calculates the conditions at the core nozzle inlet (station 4) and determines the *fixed core nozzle throat area (At)** required to pass the gas flow.

**At the end of this step, the engine's physical geometry (A0, all Ax, and At*) is completely defined and remains fixed.**

**Step 2: Off-Design Envelope Analysis**
**With the fixed engine geometry, the model performs a full analysis across the specified flight envelope. For each Altitude/Mach point, it solves the thermodynamic equations to find the engine's performance, including:**

- **Shaft Power, Propeller Thrust, and Core Jet Thrust.**
- **Total Thrust.**
- **Thrust-Specific Fuel Consumption (TSFC) and Power-Specific Fuel Consumption (PSFC).**
- **Detailed thermodynamic properties (T, P, M) at every station.**

## 10.4. Interpreting the Outputs

**The console provides a real-time transcript of the calculation. Key items to observe are:**

- **Sizing Information: The log will report the calculated A0 and Fixed_A_core_throat based on your design inputs.**
- **Progress Indicators: Messages will show progress as the analysis completes each altitude.**
- **Warnings: Pay attention to warnings about solver non-convergence or potential choking, which indicate the operational limits of your design.**
- **Performance Overview: This is a 4-panel plot showing:**
    - **Total Thrust:** The sum of propeller and core jet thrust.
    - **TSFC:** A measure of fuel efficiency relative to total thrust.

    - **Shaft Power:** The power (in kW) delivered to the gearbox.
    - **PSFC:** Power-Specific Fuel Consumption ( kg/kW ·h), a key metric for shaft-producing engines.
- **Thrust Components:** A 2-panel plot showing the separate contributions of Propeller Thrust and Core Nozzle Thrust.
- **Station Plots:** Standard plots showing the evolution of Mach Number, Temperature, and Pressure through the gas generator core.
- **Core Nozzle Geometry:** Plots showing the *required* nozzle area ratio (Ae/A*) and throat area (At*) for the core exhaust to achieve ideal expansion.

**The exported Excel file contains the most detailed output.**

- **Performance Summary:** A comprehensive table of all key performance metrics for every flight condition, including all thrust components, power, and fuel efficiencies.
- **Station Data Sheets:** Individual sheets for each station provide a complete thermodynamic state (T, P, M, Cp, Gamma) across the flight envelope.

## 10.5. Model Strengths and Limitations

**Strengths:**

- **Power Split Modeling:** The model correctly uses the Turbine Pressure Ratio (TPR) to analyze the critical split of energy between driving the compressor and producing useful shaft power.
- **Comprehensive Performance Metrics:** It calculates and reports both thrust-based (Thrust, TSFC) and power-based (Shaft Power, PSFC) metrics, which is essential for turboprop analysis.
- **Component Efficiencies:** Includes key efficiencies for the propeller and gearbox, allowing for a more realistic end-to-end performance estimation.
- **Variable Gas Properties:** Utilizes temperature-dependent gas properties for higher thermodynamic accuracy.

**Limitations:**

- **Constant Propeller Efficiency:** The model assumes a single, constant eta_prop. In reality, propeller efficiency is a complex function of flight speed (Mach number), altitude (air density), and propeller RPM. This is a significant simplification.
- **No Anti-Choke Correction:** Similar to the standard turbojet module, the user-defined Ax/A0 ratios are fixed. The model will report if choking occurs at off-design points but will not automatically correct the geometry.
- **Fixed Component Efficiencies:** All gas generator component efficiencies are assumed to be constant, whereas they would vary in a real engine.
- **No Spool Speed (RPM) Model:** The analysis is based on a thermodynamic work balance and does not model a physical spool speed or use component performance maps.
- **Simplified Nozzle Model:** The core nozzle is assumed to be ideally expanded to ambient pressure.

# 11. Introduction to the Nozzle Generator

## 11.1. Overview

adfdf

The Generate Nozzle button is a powerful visualization tool available after a successful engine performance analysis. Its primary purpose is to generate and display a conceptual 3D model of the convergent-divergent (C-D) exhaust nozzle required for the engine to operate optimally at a single, specific flight condition selected from your analysis results.

Because a jet engine operates over a wide range of altitudes and speeds, the ideal shape of its exhaust nozzle changes to remain efficient. This tool calculates the required nozzle geometry (inlet, throat, and exit areas) for any point in your analysis and allows you to visualize it as a 2D profile, a 3D surface, or export it as an STL file for use in CAD or 3D printing software.

Key Concept: The nozzle generated by this tool represents the required variable geometry for a specific point. The inlet area of this generated nozzle corresponds to the fixed duct area you defined in the main parameters (e.g., A6/A0 or A5/A0), while the throat and exit areas are dynamically calculated by the engine simulation for optimal performance at that flight condition.

## 11.2. Prerequisites

The Generate Nozzle button will be disabled (grayed out) until you have successfully run an analysis using the Run Analysis button. You must have a complete set of performance results before you can generate a nozzle.

## 11.3. The Nozzle Generator Window: Common Controls

After clicking Generate Nozzle, a new window will appear. The controls are consistent across all engine types.

Nozzle Selection (Turbofan Only): For the Turbofan engine, you must first select whether you want to generate the Core Nozzle or the Bypass Nozzle.

Select Flight Condition:

Altitude (m): A dropdown menu to select the specific altitude from your analysis range.

Mach Number: A dropdown menu to select the specific flight Mach number from your analysis range.

Length / Exit Radius:

This input controls the overall length of the conceptual nozzle. It is a ratio that defines the nozzle's axial length as a multiple of its calculated exit radius.

A higher value (e.g., 4.0) will produce a longer, more slender nozzle with gradual curves.

A lower value (e.g., 2.0) will produce a shorter, more compact nozzle with more aggressive curves.

The default value is 3.0.

Information Display: This text box shows the key calculated areas and their corresponding radii for the selected flight condition and nozzle type.

Action Buttons:

Generate 2D Profile: Creates a new plot window showing a 2D cross-section of the nozzle profile. This is useful for examining the nozzle's curvature.

Generate 3D Surface: Creates a new 3D plot window showing a rendered surface of the complete nozzle. You can rotate and zoom this view using your mouse.

Export STL: Allows you to save the generated 3D nozzle geometry as an .stl file, a standard format used for 3D printing and in most CAD software. A file-save dialog will appear, letting you choose the location and name for the file.

---

## 11.4. Engine-Specific Nozzle Generation

While the interface is similar, the nozzle being generated is specific to the engine type.

**For the Turbofan Engine**

The Turbofan analyzer is unique as it allows you to generate two separate nozzles.

- **Core Nozzle:**
  - **What it is:** This is the exhaust nozzle for the hot gas stream that has passed through the engine's core (compressor, combustor, turbine).
  - **Inlet Area (A_in):** Corresponds to the fixed duct area at the turbine exit (Station 6).
  - **Throat (A_t) & Exit (A_e) Areas:** These are the *required* throat and exit areas for the core stream to expand efficiently to the ambient pressure at the selected flight condition.
- **Bypass Nozzle:**
  - **What it is:** This is the exhaust nozzle for the cold air stream that was accelerated by the fan and passed through the bypass duct.
  - **Inlet Area (A_in):** This area is conceptually the fan duct exit. Its value is derived from the main fan inlet area (`A1`) and the bypass ratio.
  - **Throat (A_t) & Exit (A_e) Areas:** These are the *required* areas for the cold bypass stream to expand efficiently.

**For the Turbojet Engine (with Afterburner)**

- **What it is:** This tool generates the single, large convergent-divergent nozzle located after the afterburner section. This nozzle must handle both dry (non-afterburning) and wet (afterburning) exhaust streams.
- **Inlet Area (A_in):** Corresponds to the fixed duct area at the afterburner exit (Station 6).
- **Throat (A_t) & Exit (A_e) Areas:** These are the *required* throat and exit areas to handle the high-temperature, high-energy exhaust from the afterburner at the selected flight condition.

**For the Turbojet Engine (Dry / Standard)**

- **What it is:** This generates the C-D nozzle for a standard turbojet without an afterburner.
- **Inlet Area (A_in):** Corresponds to the fixed duct area at the turbine exit (Station 5).

- **Throat (A_t) & Exit (A_e) Areas:** These are the *required* throat and exit areas for the hot exhaust to expand efficiently to ambient pressure.

**For the Turboprop Engine**

- **What it is:** This generator is **only for the core exhaust nozzle**. It does *not* generate the propeller blades. It models the small jet nozzle that produces the residual jet thrust component of the engine.
- **Inlet Area (A_in):** Corresponds to the fixed duct area at the exit of the power turbine (Station 5).
- **Throat (A_t) & Exit (A_e) Areas:** These are the *required* areas for the core's hot gas stream to expand.

### 11.5. Troubleshooting & FAQ

- **Why is the "Generate Nozzle" button disabled?**
  - You must run a successful analysis first. If the analysis fails with an error, the button will remain disabled.
- **Why does the information display show "N/A for selected flight condition"?**
  - This means the engine simulation could not find a valid solution for that specific combination of altitude and Mach number. This often happens at the extreme edges of the flight envelope where the engine cannot operate (e.g., choked flow, insufficient pressure ratios). Try selecting a different flight condition from the middle of your analysis range.
- **What does the nozzle shape look like?**
  - The tool uses two parabolic curves joined at the throat to generate a smooth, continuous C-D nozzle shape based on the calculated inlet, throat, and exit radii.

## 12. Appendix

### 12.1. Physical Constants and Conversions

**The software uses the following built-in physical constants for its calculations. Some constants, like R and LHV, are user-configurable in the GUI but default to these standard values.**

| Constant / Conversion | Symbol / Name | Value | Units | Usage Notes |
|---|---|---|---|---|
| Standard Gravity | g | 9.80665 | $m/s^2$ | Used in the Breguet Range Equation. |
| Gas Constant for Air | R | 287.058 | J/(kg·K) | User-configurable in all engine modules. |
| Lower Heating Value (Jet Fuel) | LHV | 43,000,000 | J/kg | User-configurable in all engine modules. |

| | | | | |
|---|---|---|---|---|
| **US Gallons to Liters** | **GALLONS_TO_LITERS** | **3.78541** | **L/gal** | **Used in the main window's Flight Range Analysis.** |
| **Density of Jet A-1 Fuel** | **JET_A1_DENSITY** | **0.804** | **kg/L** | **Used in the main window's Flight Range Analysis.** |
| **Nautical Mile to Meters** | **NM_TO_METERS** | **1852** | **m/NM** | **Used for range conversion in the main window.** |
| **Standard Sea Level Temp** | **T0_isa** | **288.15** | **K** | **ISA Model base value.** |
| **Standard Sea Level Pressure** | **P0_isa** | **101325.0** | **Pa** | **ISA Model base value.** |

## 12.2. Gas Properties Model (Cp & Gamma)

**To achieve higher fidelity, the analysis models do not assume constant gas properties. The Specific Heat at Constant Pressure (Cp) and the Ratio of Specific Heats (gamma) are treated as functions of temperature. The software uses two distinct models: one for "air" and one for "hot gas" (post-combustion).**

**The models are based on tabulated data points which are linearly interpolated to find the properties at any given temperature.**

- **Air Model:** Used for all stations upstream of the main combustor.
  - **Temperature Range:** 200 K to 1200 K
- **Hot Gas Model:** Used for all stations downstream of the main combustor, including the turbine, afterburner (if applicable), and nozzles.
  - **Temperature Range:** 600 K to 2500 K

**If a calculation requires a property for a temperature outside these ranges, the model extrapolates from the nearest two data points. This approach is significantly more accurate than using a constant gamma of 1.4, especially in the high-temperature sections of the engine.**

## 12.3. Station Numbering Schematics

**The following diagrams illustrate the conceptual station numbering used in each engine analysis module. This is crucial for correctly interpreting the Ax/A0 area ratio inputs and understanding the station-specific data in plots and Excel exports.**

**Turbojet Module**

**<!-- Placeholder -->**

- **0: Freestream**
- **1: Compressor Inlet (after diffuser)**

- **2: Combustor Inlet (compressor exit)**
- **3: Turbine Inlet (combustor exit)**
- **4: Nozzle Inlet (turbine exit)**
- **5: Nozzle Exit (ideally expanded)**

**Turbofan Module (Separate-Flow)**

**<!-- Placeholder -->**

- **0: Freestream**
- **1: Fan Inlet (after diffuser)**
- **2: Fan Exit / Flow Split**
- **Bypass Stream:**
    - **3: Bypass Nozzle Exit**
- **Core Stream:**
    - **4: High-Pressure Compressor (HPC) Inlet**
    - **5: Combustor Exit / High-Pressure Turbine (HPT) Inlet**
    - **6: HPT Exit / Low-Pressure Turbine (LPT) Inlet**
    - **7: LPT Exit / Core Nozzle Inlet**
    - **8: Core Nozzle Exit**

**Turboprop Module**

**<!-- Placeholder -->**

- **0: Freestream**
- **1: Compressor Inlet (after diffuser)**
- **2: Combustor Inlet (compressor exit)**
- **3: Turbine Inlet (combustor exit)**
- **4: Turbine Exit / Nozzle Inlet**
- **5: Core Nozzle Exit (ideally expanded)**
- ***Shaft Power is extracted between stations 3 and 4.***

## 12.4. Glossary of Key Terms & Acronyms

- **BPR (Bypass Ratio):** Ratio of bypass air mass flow to core air mass flow.
- **Choked Flow:** A condition where a duct cannot pass any additional mass flow, regardless of pressure changes. Occurs when the flow reaches Mach 1 at the narrowest point (the "throat").
- **CPR (Compressor Pressure Ratio):** The pressure ratio across the core (high-pressure) compressor in a turbofan. CPR = OPR / FPR.
- **FPR (Fan Pressure Ratio):** The pressure ratio across the fan in a turbofan.

- **Ideal Expansion:** The condition where the nozzle exhaust static pressure exactly equals the ambient atmospheric pressure, maximizing thrust.
- **ISA (International Standard Atmosphere):** A standardized model of how the temperature, pressure, and density of the Earth's atmosphere change with altitude.
- **LHV (Lower Heating Value):** The usable heat energy released per unit mass of fuel during combustion.
- **OPR (Overall Pressure Ratio):** The ratio of the highest pressure in the engine (compressor exit) to the pressure at the engine inlet.
- **Polytropic Efficiency:** A measure of the efficiency of a compression or expansion process that is independent of the pressure ratio, representing the infinitesimal stage efficiency.
- **PSFC (Power-Specific Fuel Consumption):** Fuel flow rate per unit of shaft power produced. The primary efficiency metric for turboprops. Units: kg/(kW ·h).
- **Specific Thrust:** Thrust produced per unit of air mass flow rate (N/( kg/s )).
- **TPR (Turbine Pressure Ratio):** The ratio of total pressure at the turbine inlet to total pressure at the turbine exit. A key design parameter for turboprops.
- **TSFC (Thrust-Specific Fuel Consumption):** Fuel flow rate per unit of thrust produced. The primary efficiency metric for turbojets and turbofans. Units: kg/(N ·h).
- **Work Balance:** The fundamental principle that the power extracted by the turbine(s) must equal the power required by the compressor(s) and/or propeller.

## 12.5. Note on Numerical Solvers

**The analysis modules rely on iterative numerical solvers to calculate the engine's state.**

- **Iterative Mach Solver:** At each station with a defined area (A2, A3, etc.), the flow Mach number is unknown. The software uses an iterative process to find the subsonic Mach number that allows the calculated mass flow to pass through the given physical area at the given total pressure and temperature. The tolerance and max_iter parameters in the GUI control this solver.
- **Iterative Turbine Solver:** In the turbofan and turboprop models, the turbine exit temperature is initially unknown. It is found by an iterative process that balances the work required by the compressor(s)/fan with the work extracted by the turbine(s).
  **The turbine_tol and max_iter_turb parameters control this solver.**

**If the console log shows warnings about "non-convergence," it means one of these solvers reached its maximum iteration limit without reaching the desired tolerance. The analysis proceeds with the last calculated value, but the results in that specific flight condition may have a small error.**

## 12.6. Installation & File Structure (Standalone Application)

**The Engine Analysis Matrix is distributed as a standalone application installed via EngineAnalysisMatrix_Setup.exe.**

- **Executable:** The main program is EngineAnalysisMatrix.exe, located in the installation directory.
- **Bundled Assets:** All necessary files, such as images, schematics, and this user manual, are bundled directly within the executable. There are no external asset files to manage.

- **License File:** Upon successful first-time activation, a license file named license.key is created in a protected user directory (%LOCALAPPDATA%\StratoVec\EngineAnalysisMatrix\ on Windows). This is the only external file created by the application and is required for subsequent launches. Do not delete this file. If you do, you will need to re-enter your license key.