

An Interactive Educational Tool for Turbojet Engines

Thomas J. Benson*
NASA Lewis Research Center
Cleveland, Ohio 44135

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ABSTRACT

A workstation-based interactive educational tool has been developed to aid in the teaching and understanding of turbojet engine design and analysis. The tool solves for the flow conditions through the engine using classical one-dimensional thermodynamic analysis found in various propulsion text books. The student can vary the design conditions through a graphical user interface and the engine performance is calculated immediately. A variety of graphical formats are used to present the results to the student including numerical results, moving bar charts, and student generated T-s, p-v and engine performance plots. The tool provides a series of help screens, which describe the operation of the tool and serve as an on-line user's manual, and an examination screen, which contains a series of questions to be answered by the student using the package. This paper details the numerical methods used in the tool and describes how the tool can be used and modified. The tool employs X-based graphics and has been tested on a wide variety of workstations using the Unix operating system.

INTRODUCTION

The use of personal computers and workstations in undergraduate propulsion engineering is finding wider acceptance in the educational community. Tedious numerical computations associated with many interesting propulsion problems can now be performed on the computer, giving the student time

to explore the propulsion aspects of these problems while minimizing the time spent in arithmetical drudgery. The graphical output from computers present information to the student in a variety of ways which are not available in textbooks. These methods include multiple presentations, the use of color, and animation. Through a graphical user interface, the student can control and interact with the problem to be studied. The computer screen can become a desk top laboratory in which the student studies a physics problem, varies conditions associated with the problem, records data, and evaluates the results.

The use of personal computers or workstations in undergraduate engineering education is a relatively recent development. Earlier efforts (Refs 1-4) have centered around the use of software developed for personal computers, but lacking the graphical interface available on workstations. With these packages, a student enters input conditions at the keyboard and is presented with principally numerical output. More recent efforts (Refs 5-7) have included a graphical user interface to improve the interaction with the software. With these packages, the student uses a mouse to select options or to vary conditions and receives principally graphical output.

This paper will describe a new software package developed at NASA Lewis Research Center to interactively design and analyze a single spool turbojet engine. The package is intended for use in an undergraduate course in mechanical or aerospace engineering as a supplement to formal course work on turbine engine analysis. A guiding principal in the development of this tool is to involve the student in the learning process; to make the student work with the package to achieve a result, not just present the answer to a problem. Some special features

*Research Engineer

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to promote this student interaction are included in this tool and described in this paper. By requiring and emphasizing student interaction, the software package mimics the operation of an engine test cell. Working with the package is much like working in the laboratory, except that the student has the laboratory on his desk top, can use it as often and whenever the computer is available, requires minimal supervision, and endangers no one when the engine blows up.

This desk top laboratory concept can be used in many areas of undergraduate education. The current tool can be rather easily modified to consider additional propulsion problems, such as ramjet analysis, turbojet with afterburner, and two spool turbofan analysis. The basics of the code can be retained and other classes of fluids problems coded, including potential flow, conformal mapping, and basic airfoil theory. Many basic physics problems involving thermodynamics, magnetics, electrostatics and optics would also lend themselves to presentation and study in this way.

ANALYSIS

The thermodynamic analysis of a turbojet engine follows from the classic textbooks of Hill and Peterson, Ref. 8, and Oates, Ref. 9. Fig 1. shows an engine schematic drawing from the view window of the computer program with the numbering convention used in this analysis. The upstream flow conditions,

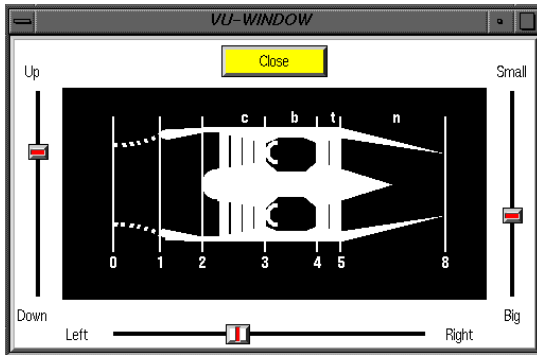


Figure 1: Numbering Convention

station 0, are determined by the flight Mach number and altitude; static conditions are computed for a standard day at the given altitude and total conditions computed using the free stream Mach number.

The air may be either accelerated or decelerated to the inlet, station 1, and is then decelerated to the compressor face, station 2. Across the compressor “c” from station 2 to 3, the air is compressed, work is done on the air and the total temperature is increased. In the burner “b” from station 3 to 4, fuel is added, mixed, and ignited, thus increasing the total temperature. Across the turbine “t” from station 4 to 5, the air is expanded to obtain the power necessary to drive the compressor. The high temperature, high pressure air is then accelerated through a nozzle “n” station 8, to produce thrust. (Station 8 is out of numerical order to allow later introduction of an afterburner and convergent-divergent nozzle.)

In the design of a turbojet, the compressor pressure ratio (CPR) from station 2 to 3 is usually specified at some design flight condition. The magnitude of the CPR will determine the number of compressor and turbine stages required and the overall length and weight of the engine. The temperature at the burner exit or the turbine entrance (T4) is the other major design variable and is usually limited due to materials consideration.

The cycle analysis of the turbojet begins in free stream with the computation of the isentropic total conditions:

$$\frac{T_{01}}{T_a} = 1 + \frac{(\gamma - 1)}{2} M^2 \quad (1)$$

$$\frac{p_{01}}{p_a} = \left(\frac{T_{01}}{T_a} \right)^{\frac{\gamma}{\gamma-1}} \quad (2)$$

where M is the upstream Mach number, γ is the ratio of specific heats, p_a is the ambient static pressure, T_a the ambient static temperature, p_0 the total pressure, and T_0 the total temperature.

From the inlet to the compressor face no work is done on the fluid and the total temperature is constant. Under supersonic free stream conditions there will be total pressure losses associated with shock waves present in the inlet.

$$\frac{T_{02}}{T_{01}} = 1 \quad (3)$$

$$\frac{p_{02}}{p_{01}} = 1.0 - .075(M - 1.0)^{1.35} \quad (4)$$

for M greater than one. For M less than one the standard inlet recovery is one, however the designer

may specify any value less than one to account for boundary layers along the walls or flow separations within the inlet.

Across the compressor,

$$CPR = \frac{p_{03}}{p_{02}} = \text{specified} \quad (5)$$

$$\frac{T_{03}}{T_{02}} = \frac{1}{\eta_c} \left[\left(\frac{p_{03}}{p_{02}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (6)$$

where η_c is the compressor efficiency factor, which is equal to 1.0 for the ideal case. The temperature relation is derived from the work equation across the compressor for a specified CPR.

Within the burner,

$$T4 = T_{04} = \text{specified} \quad (7)$$

$$\frac{T_{04}}{T_{03}} = T_{04} \left(\frac{T_{02}}{T_{03}} \right) \left(\frac{1}{T_{01}} \right) \quad (8)$$

$$\frac{p_{04}}{p_{03}} = \text{specified} \quad (9)$$

the value of T4 is set by the throttle with the maximum T4 determined by material limits. Ideally, the total pressure ratio in the burner is equal to one, but the designer can specify some value slightly less than one.

Across the turbine,

$$\frac{T_{05}}{T_{04}} = 1 - \left(\frac{T_{03}}{T_{02}} - 1 \right) \frac{T_{01}}{T_{04}} \quad (10)$$

$$\frac{p_{05}}{p_{04}} = \left(1 - \frac{1}{\eta_t} \left(1 - \frac{T_{05}}{T_{04}} \right) \right)^{\frac{\gamma}{\gamma-1}} \quad (11)$$

where Eq. 10 expresses the energy balance between the turbine and the compressor and η_t is the turbine efficiency factor which must be specified. Across the entire engine, the engine temperature ratio (ETR) and engine pressure ratio (EPR) can be computed as:

$$ETR = \frac{T_{05} T_{04} T_{03}}{T_{04} T_{03} T_{02}} \quad (12)$$

$$EPR = \frac{p_{05} p_{04} p_{03}}{p_{04} p_{03} p_{02}} \quad (13)$$

From the turbine exit, the high temperature, high pressure flow is expanded through the nozzle to produce thrust. The exit pressure is assumed to be ambient and the nozzle is assumed to be choked at the

minimum area (A8). The exit velocity is then given by

$$u_e = \sqrt{2c_p T_{05} \eta_n \left[1 - \left(\frac{p_a}{p_{05}} \right)^{\frac{\gamma-1}{\gamma}} \right]} \quad (14)$$

where η_n is the nozzle efficiency, T_{05} and p_{05} are derived from the EPR and ETR and free stream conditions, and c_p is the specific heat coefficient. With this value of u_e and the free stream velocity u_0 determined from the Mach number and altitude, the net thrust per unit mass flow, m , is

$$\frac{F_n}{m} = u_e - u_0 \quad (15)$$

The mass flow is determined by the choked nozzle condition. At any given Mach number the corrected mass flow per unit area is given by

$$\frac{m\sqrt{\theta_t}}{\delta_t A} = \sqrt{\frac{\gamma}{R}} \frac{p_0}{\sqrt{T_0}} M \left[1 + \frac{\gamma-1}{2} M^2 \right]^{\frac{-(\gamma+1)}{2(\gamma-1)}} \quad (16)$$

where θ_t is the ratio of total temperature to the reference total temperature T_0 , δ_t is the ratio of the total pressure to the reference total pressure p_0 , R is the gas constant. Using the value of A8 for the nozzle, Mach = 1.0, and θ_t , and δ_t determined by ETR and EPR, the value of m can be computed. The net thrust is then given by Eq. 15. The fuel/air ratio, f , can be found from the following equation:

$$f = \frac{\left(\frac{T_{04}}{T_{03}} \right) - 1}{\left(\frac{Q_R}{c_p T_{03}} \right) - \left(\frac{T_{04}}{T_{03}} \right)} \quad (17)$$

where Q_R is the fuel heating value which must be specified. Finally, the thrust specific fuel consumption is given by:

$$TSFC = \frac{fm}{F_n} \quad (18)$$

The value of A8 which the designer selects will determine the airflow through the engine and the net thrust value at the design condition. However, the designer must also insure that the mass flow through the nozzle can be passed through the compressor face at a moderate speed ($M < .5$). At much higher Mach numbers, the flow may choke in the

compressor with associated high losses due to flow separation. To avoid such non-physical conditions, the engine simulator sets a limit on the magnitude of A_8 relative to A_2 so that, given a choked flow at A_8 , and a chosen size for A_2 , the Mach number at station 2 will not exceed .5. The simulator also calculates a turbine entrance area A_4 which would choke the turbine entrance using Eq. 16 for a given engine airflow. This area is used when evaluating off-design performance. The engine is assumed to be choked at the nozzle exit and at the turbine entrance and these conditions set the work of the turbine and the compressor pressure ratio.

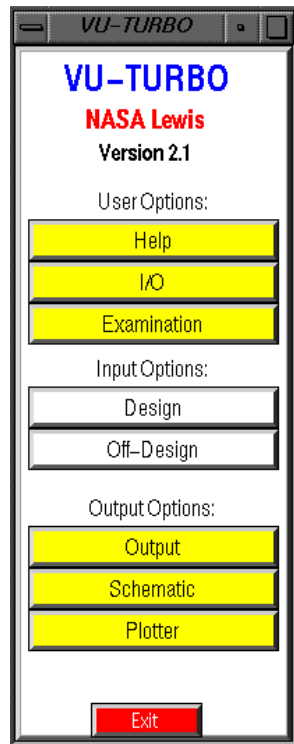


Figure 2: Main Control Panel

DESCRIPTION OF SIMULATOR

Some examples of the graphical user interface for the simulator are given in Figs. 1-7. Each of these figures have been captured from a Silicon Graphics workstation in color and reproduced here in black and white. Since each panel is an X-window, it may be closed, opened, relocated, resized, or iconified at any time without affecting any other panel on

the computer screen. Fig. 2 shows the main control panel of the simulator which is used to invoke the other panels. The main control panel is divided into three groups of buttons, one group to assist the user, one group to control inputs to the package, and one to control outputs from the package. There are three buttons in the user assistance group. The first button invokes the help screen which contains a display window and some choice buttons, as shown in Fig. 3. There is one button corresponding

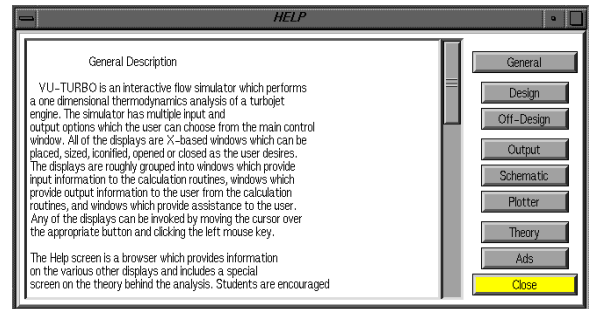


Figure 3: Help Screen

to each of the major buttons on the main control panel. The help screens display text which describe how the simulator works in some detail and serves as an on-line manual for the package. The special button “Theory” provides a brief description of the analysis used and contains references which the student can use for further study.

The “I/O” button on the main control panel will freeze all of the other screens so that graphical output can be made using the “Snapshot” utility of the workstation; there is no printed output from this package. The “Examination” button invokes another window which displays text from an ASCII file containing questions to be answered by the student using the package, as shown in Fig. 4. The

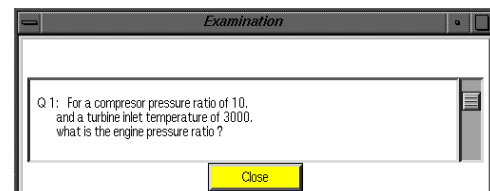


Figure 4: Examination tool

teacher can edit this file and modify it as desired.

The text may contain both questions and answers so that the package can be used like a textbook for simple assignments, or the text may contain only questions and the package used as an examination tool. Later versions of the examination tool will include the option of specifying the data file in which the questions reside, so that multiple files can be created and stored, and, perhaps, a timer can be included to make this panel a true examination tool.

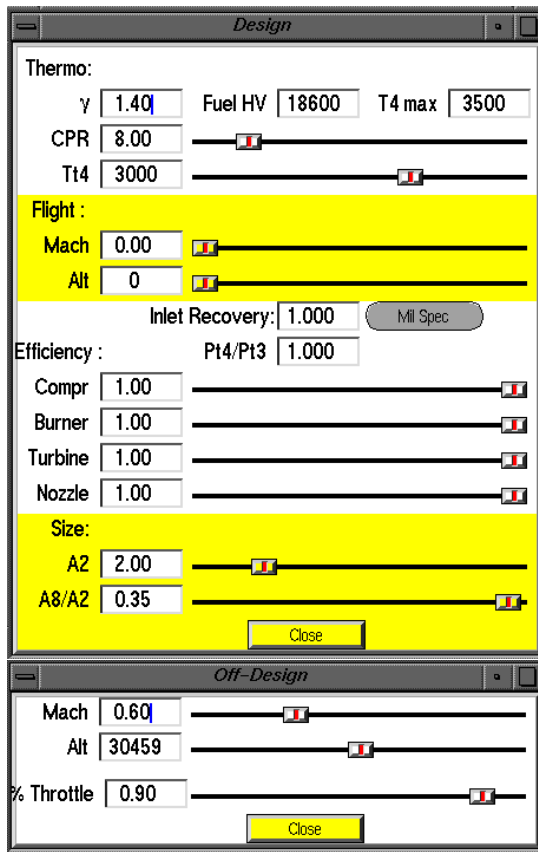


Figure 5: Design and Off-design Input

The main view window has been shown as Fig. 1 and is invoked by the “Schematic” button on the output section of the main control panel. The sliders located to the left, right, and below the main view window allow magnification and repositioning of the engine schematic within the window. As the student increases the compressor pressure ratio, the number of compressor and turbine stages in the schematic will increase. Changing the nozzle area, A8, will also change the schematic. As the airflow through

the engine is changed, the dashed line at the front of the engine changes to indicate the engine mass flow ratio.

Fig 5. shows the design and off-design input panels. The design panel is divided into four sub-panels concerning thermodynamic variables, flight condition variables, efficiency factors, and engine sizing. Most of these variables can be changed by either sliders or type in boxes; the sliders are used for rapid changes and the input boxes for more precise specification. At any time the student can change the value of any variable and the effects on the engine performance will be displayed on the output panel. The dark oval button next to the inlet recovery input box is a choice button which the student uses to select either to type in the recovery or to have the simulator calculate the recovery from Eq. 4. The off-design panel contains only variations in flight conditions and throttle setting.

The computed engine conditions are displayed in the output panel shown in Fig. 6 and invoked by the “Output” button on the main control panel. This

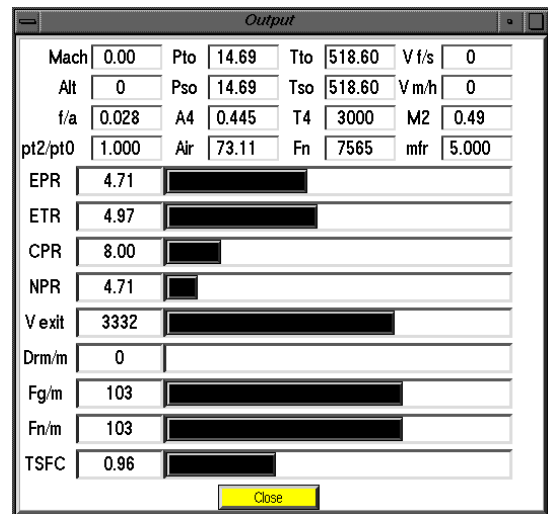


Figure 6: Output Panel

data is displayed in two ways; numerically in the row of boxes at the top and the left, and as bar charts to the right. Each bar is a different color corresponding to a different flow variable. As the design or flight conditions are changed in the input box, the recalculated numbers are displayed and the bar charts move much like a thermometer. This type

of visual output allows the student to immediately sense in what direction the flow variables change and by how much for a given input.

An additional type of output available to the student is performance plots. The plotter package is shown in Fig. 7 and is invoked by the “Plotter” button on the main control panel. The student can

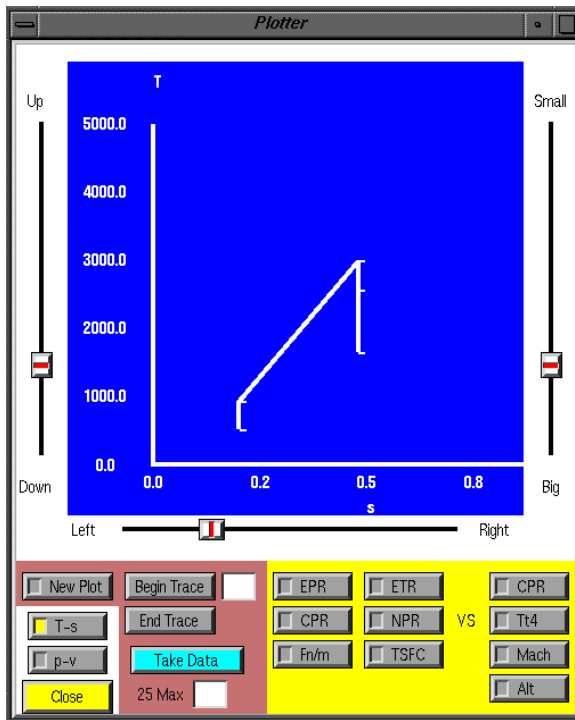


Figure 7: Plotter Panel

control the size and location of the plot within the window by using the sliders located around the window. The type of plot displayed is controlled by the buttons in the lower left corner of the panel. The student can display a T-s or p-v plot by pushing the appropriate button. Fig. 7 shows a T-s plot for the input conditions of Fig. 5. The student can also generate performance plots of the engine by selecting the top button on the left. The generation of a performance plot will be described in the next section.

RESULTS

The simulator can be operated in two modes: design mode, or off-design mode. In the design mode

the student can set the fuel and materials conditions, the design flight conditions, the efficiency of the various components, the engine size, and the design compressor pressure ratio and turbine inlet temperature using the input panel shown in Fig 5. For these specified conditions the simulator will use the equations previously described to perform a thermodynamic cycle analysis and display the results on the output panel. During the design process, the student can vary conditions on the input panel and monitor the effects of different parameters by use of the output panel. For an ideal design, all of the efficiency factors are set to 1.0, for a more realistic design their values are all less than 1.0.

After a design has been developed at some set of design conditions, the performance of the engine at other flight conditions can be evaluated by using the off-design panel. In off-design mode the student can vary the throttle settings, which sets the value of T4, and can vary the flight Mach number and altitude conditions. The simulator will again perform a thermodynamic cycle analysis assuming choked flow at the nozzle and at the turbine inlet using the areas and efficiency factors set in the design mode. The change in performance parameters such as thrust and sfc can again be monitored on the output panel.

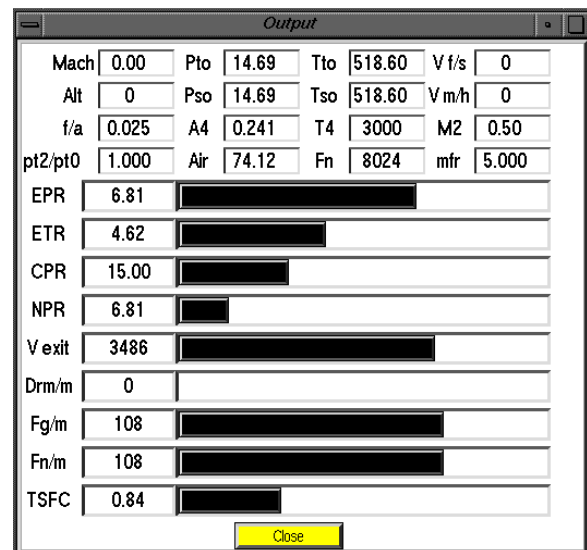


Figure 8: CPR = 15.0 output

Figures 5-13 can be used to demonstrate how a

student might use the simulator. As the input is varied the simulator recalculates the flow conditions and instantly changes the schematic, the T-s diagram, and the output sliders to reflect the new conditions. In Figs. 5 and 6, the default design conditions are presented; CPR equal to 8.0, T4 equal to 3000 degrees Rankine, and a fuel heating value of 18600 BTU/lbm. Design flight conditions are sea level static conditions. The analysis is ideal and all efficiencies are set to 1.0. The T-s diagram shown in Fig. 7 for this ideal design shows vertical legs for the compression and expansion and a maximum temperature of 3000 Rankine. The engine has a compressor face area of 2.0 square feet and develops 7565 pounds of thrust at sea level. Similar results have been checked against designs presented in Hill and Peterson to insure proper coding and operation of the program.

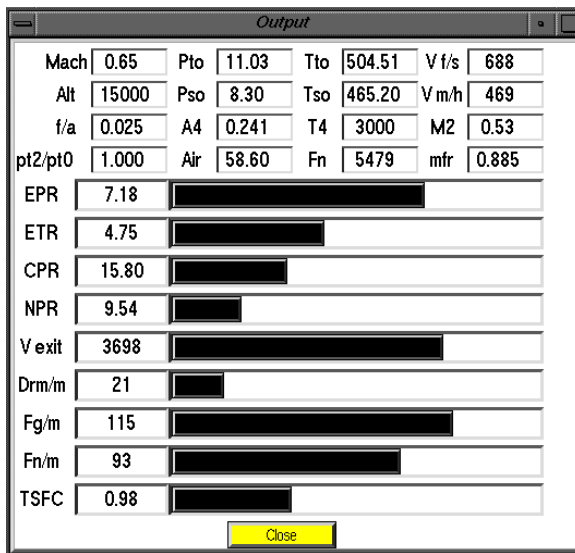


Figure 9: Off-design output

The student then decides to increase the CPR to 15.0 and the output panel changes as shown in Fig. 8. In changing from Fig. 6 to Fig. 8, the output panel shows the student that the overall engine pressure ratio increases, but the engine temperature ratio decreases. This is due to the fixed turbine inlet temperature and the greater temperature loss across the turbine required to drive the compressor at a higher pressure ratio. The net thrust per pound mass is increased about five per cent and the airflow

through the engine is slightly increased resulting in a six per cent increase in net thrust. The sfc decreases due to higher thrust and less fuel burned.

In Fig. 9, the student decides to evaluate the design developed in Fig. 8 at off-design conditions of Mach = .65 and 15000 feet altitude. Comparing the output from Fig. 9 and Fig. 8, it appears that the thermodynamic results at the new flight conditions are very close to the design conditions. The difference in free stream total temperature is quite small, and with a fixed turbine inlet temperature, the ETR and EPR are fairly close to the design values. The net thrust per pound mass is less owing to the ram drag produced at Mach = .65. The net thrust is greatly reduced, however, due to the ram drag and the reduced airflow through the engine because of the change in air density with altitude. The sfc is higher due to the reduced net thrust.

In Fig. 10, the student has returned to the design mode and has reset the efficiency parameters

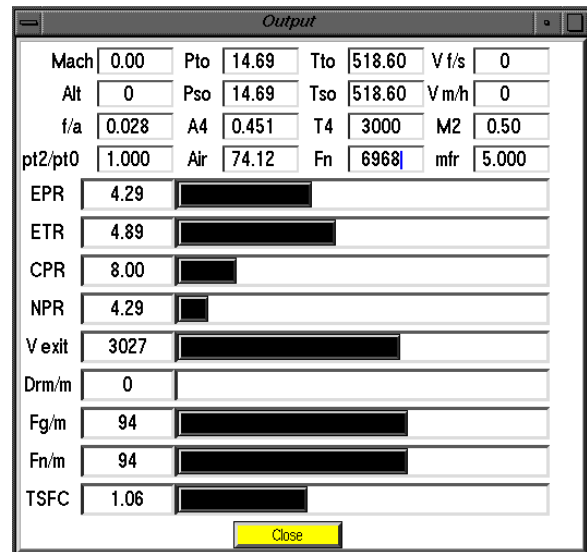


Figure 10: Non-ideal output

from 1.0 to more realistic values, $\eta_c = .90$, $\eta_b = .98$, $\eta_t = .95$, $\eta_n = .88$. Because of the inefficiencies in the engine, all of the engine performance parameters have been decreased except for the fixed values of CPR and T4. The airflow has remained nearly constant, but the thrust per unit airflow has decreased due to the inefficiencies. The net thrust is therefore decreased by about ten per cent and the sfc is

correspondingly higher.

It is also interesting to note the change in the T-s diagram for the real design, as shown in Fig. 11. The compression and expansion legs of the diagram

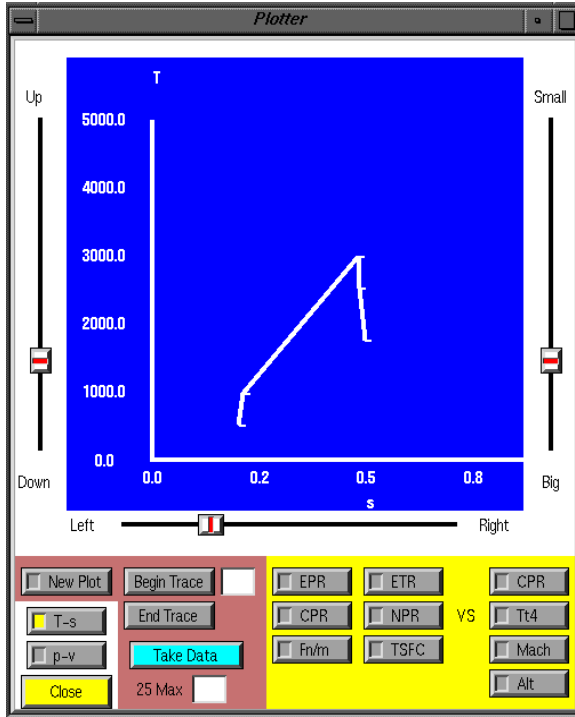


Figure 11: Non-ideal T-s diagram

are no longer vertical as in Fig. 7, but are sloped due to cycle inefficiency. Currently, the student must enter values for the efficiency factors and these values are maintained across the flight envelope. In future upgrades to the package, maps of these factors could be included to produce an interactive cycle deck.

To better record and visualize the change of engine performance with input variables, the student can use the plotter. As previously mentioned, the plotter will display T-s diagrams, p-v diagrams, or performance plots generated by the student. To generate a plot, the student first presses the “New Plot” button at the left. The student then selects which sets of variables to plot by using the buttons in the shaded box at the lower right. In Fig. 12, the student has chosen to plot net thrust per unit mass versus the compressor pressure ratio. As the variable selections are made the axes are automatically labeled and scaled. The student then begins

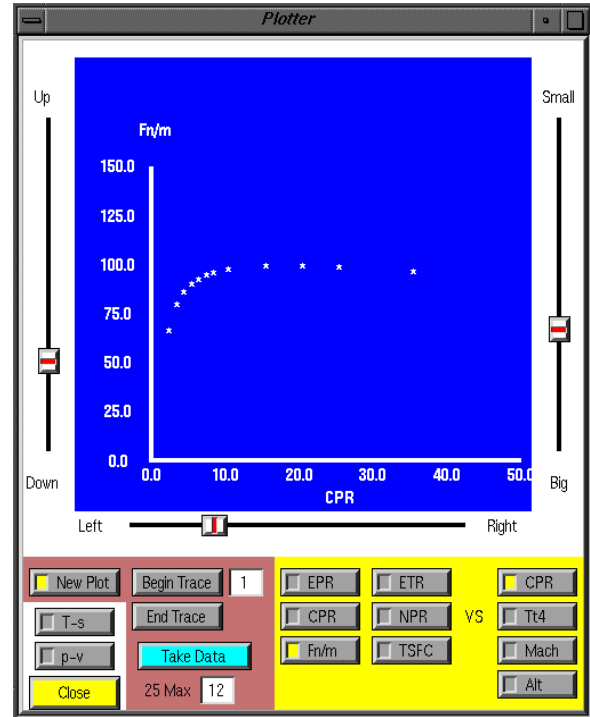


Figure 12: Net thrust versus CPR

a trace by pushing the “Begin Trace” button, and then moves to the input panel. The student varies the CPR on the input panel and can monitor the value of net thrust on the output panel. When the student finds some set of conditions to record, the “Take Data” button is pushed on the plotter panel and a small “*” is automatically marked on the plotter window. The student then changes the CPR and repeats the process. Data may be taken in any order to fill out interesting sections of the plot. In Fig 12, twelve data points have been taken for trace one. When the trace is completed, the “End Trace” button is pushed and a solid color-coded line is automatically drawn through the data. The student can then vary some other condition, such as altitude, or T4, and start a new trace by again pushing the “Begin Trace” button. The student can record up to five traces with up to twenty five data points per trace. Fig. 13 shows the beginning of a second trace of net thrust versus CPR for a higher T4. This plotter package has been designed to require an interaction on the part of the student. The setting of conditions and taking data is meant to mimic the

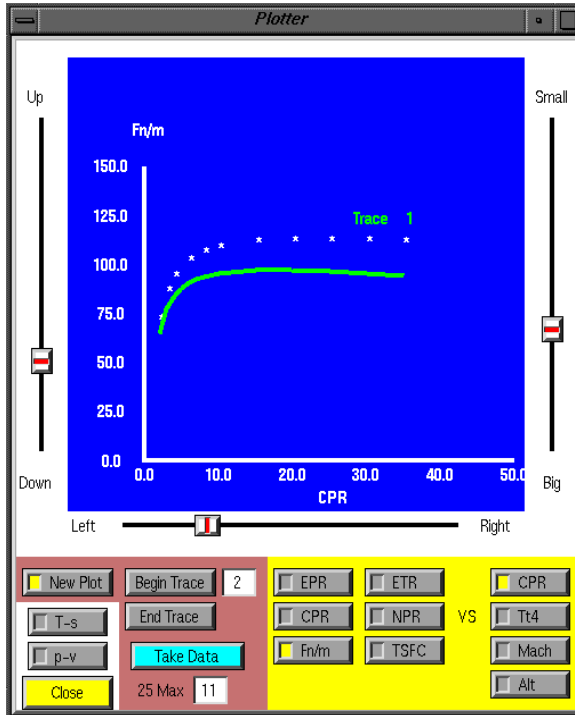


Figure 13: Second trace

operation of an experimental test cell.

SUMMARY

A workstation-based, highly interactive educational tool for turbojet analysis has been developed. The underlying assumptions and equations which form the basis for this tool have been presented in this paper as well as several examples of the results from the simulator. The tool employs two basic ideas to help undergraduates better understand turbojet analysis. First, the student is required to interact with the tool to produce results. The student is in control of the parameters defining the problem and must perform several operations to produce the output. The examination option also requires the student to act and not merely observe. Second, the output results are presented to the student in a variety of forms. For a given flow problem the student can see a schematic drawing of the engine, tabulated numbers for the engine parameters, moving bar charts for the parameters, and plotted data. The tool is currently being extended to solve for a two spool turbofan engine, a turbojet engine with

afterburner, and a simple ramjet. Further extensions of this technology into other flow regimes and other physics problems are planned.

ACKNOWLEDGEMENTS

The current simulator uses the XFORMS library of GUI developed by Mark H. Overmars, Department of Computer Science, Utrecht University, The Netherlands and T.C. Zhao of the University of Wisconsin at Milwaukee. The XFORMS library is copyrighted by T.C. Zhao and Mark Overmars but can be used for non-commercial and non-profit purposes. The software developed by the author is in the public domain and may be copied and also used for non-commercial products, but not resold. Copies of the source are available from the author at the NASA Lewis Research Center.

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