

**T-BEAT: A Conceptual Design Tool for Turbine-Based
Propulsion System Analysis**

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Abstract

The extreme cost, high risk and technological difficulty of access to space are all key factors hindering mankind's continued exploration of the solar system. As a result, safe, low-cost and technically feasible vehicle concepts are constantly being explored. One such concept currently receiving interest is the use of turbine engines as part of a launch vehicle's propulsion system.

These turbine engines may be utilized during the boost phase of a two-stage launch vehicle or part of a combined cycle engine on a single-stage-to-orbit vehicle. Although turbine engines themselves have reached a high level of maturity in the aircraft industry, their use in space launch systems is at a relatively low development level. As a result, much of the inquiry into vehicle types utilizing turbine engines is being performed at the conceptual level. At the conceptual level of design it is possible to explore many options and engine types since costs are relatively low, and design freedom is large. It is therefore helpful to have a design tool that allows rapid analysis of many engine types and configurations over a wide range of operating conditions. The Turbine-Based Engine Analysis Tool, T-BEAT, has been created to fulfill such a need.

T-BEAT was written in C++ and can be run either directly from a UNIX workstation or remotely through the World Wide Web. The program can analyze many configurations including a turbojet, afterburning turbojet, ramjet, and turbine-based combined-cycle engine. T-BEAT provides thrust and Isp for off-design conditions set by the user. The output can be retrieved in the form of a POST engine deck, which helps speed up the design process. Validation for the program was performed using existing codes.

Nomenclature

Combination Propulsion System: A propulsion system comprised of separately installed, usually non-interacting separate engines [3]

Combined Cycle Engine: A single integrated engine capable of operating in two or more different thermodynamic operating modes [3]

GECAT: Graphical Engine Cycle Analysis Tool

Isp: Specific Impulse (seconds)

NPSS: Numerical Propulsion System Simulation

POST: Program to Optimize Simulated Trajectories

SCCREAM: Simulated Combined Cycle Rocket Engine Analysis Module

SCORES: Spacecraft Object-oriented Rocket Engine Simulation

SSDL: Space Systems Design Lab (Georgia Tech)

SSTO: single-stage-to-orbit

TBCC: Turbine-Based Combined-Cycle Engine: A combine-cycle engine in which a turbine based initial acceleration means is incorporated [3]

T-BEAT: Turbine-Based Engine Analysis Tool

TRJ: Turboramjet, an airbreathing-based combined-cycle in which a turbojet initial acceleration mode (usually with afterburning) is followed by a ramjet acceleration/cruise mode [3]

TSTO: two-stage-to-orbit

1.0 Project Motivation

The recent renewal of interest in low-speed propulsion systems for access to space launch vehicles triggered a need for a conceptual design tool to analyze these systems. To understand the interest in such launch systems, it is necessary to summarize the potential gains in using a turbine-based system over all-rocket systems.

Perhaps the most compelling reason to use a turbine-based propulsion system is the simple fact that being an airbreathing system it does not have to carry oxidizer. By getting oxygen from the atmosphere, airbreathing vehicles can potentially be much lighter than all rocket systems. This could result in a lower overall gross weight for the system.

A second major advantage of airbreathing systems is the potential performance gain over all-rocket systems. Much of the predicted performance advantage comes from the higher fuel efficiency of airbreathing propulsion systems. A simple chart illustrating this advantage is shown in Figure 1.

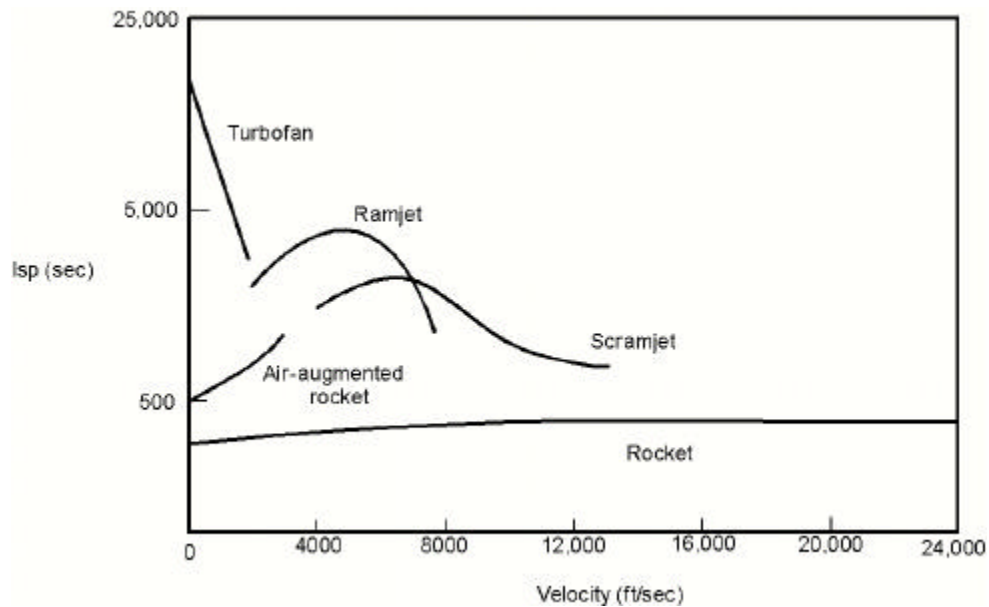


Figure 1: The Advantage of Airbreathing Propulsion [5]

Here we see the much higher specific impulse capable of airbreathing engines compared to an all rocket system. The advantage is especially great in the very low speed region where a turbine system could be utilized. Greater fuel efficiency allows a vehicle to carry less propellant therefore further lowering the vehicle's mass ratio.

Aside from performance gains, a second area in which turbine-based launch vehicles appear attractive is in operability. This area, often neglected by engineers until late in the design process, is often stated as one of the primary reasons the Space Shuttle has failed to meet its price per pound to orbit goal. A turbine-based SSTO vehicle would improve upon or eliminate many of the operability issues plaguing the Space Shuttle. The ability to have a powered descent and landing will allow much more flexibility over the glide-in dead-stick landings required by the shuttle. This will allow for a loiter phase and go-around capabilities making landings much safer. Upon landing, the vehicle will also have self-ferry capability greatly simplifying the ground-servicing operations. Operability gains might also be made with turbine-based propulsion systems being able to start up and shut down gradually [4]. This should prove much safer compared to the abrupt violence of rocket engine start up and shut down. A final operations gain is possible given the extended launch windows provided by airbreathing propulsion systems.

There are many additional safety benefits of a turbine-based system during a launch abort scenario. For example, if a failure occurs that requires the mission to be aborted shortly after take-off, a relatively simple landing of the vehicle will be made. This is unique to turbine-based systems with their powered descent capability. An additional safety benefit is the ability of a turbine-based vehicle to change course if needed to find a suitable landing site. This could occur if unfavorable weather conditions arise at the intended landing site. In this case an unpowered vehicle would have very little cross-range ability.

These potential benefits of using turbine-based launch vehicles show the importance of exploring the design space in which they could be utilized. A propulsion analysis tool geared toward conceptual design would thus prove very useful. But, as important as all the potential benefits of a certain vehicle design are, it is equally important to assess the engineering challenges that must be faced before such an idea can

become a reality. Understanding and organizing these challenges early in the design process can potentially reduce the cost of a design or determine its feasibility. Having a design tool that accurately models these shortcomings as well as the potential gains is very important.

Perhaps the most critical challenge facing turbine-based designs is the transition from various modes of operation. It is not fully known how smoothly an engine will be able to proceed from one mode of operation to another. A very high level of integration is necessary to enable this to occur. Additionally, many moving parts and variable geometry will be required to accommodate each mode.

Another equally pressing concern is protection of the relatively sensitive turbomachinery during the supersonic and hypersonic range. The physical and thermal conditions at these speeds would be severely damaging to the engine's parts, especially the compressor or fan blades. Solving this problem will require isolating the turbomachinery by possibly using a flap system, or greatly increasing the temperature and stress limits of existing materials.

A third challenge facing all combined-cycle or combination propulsion systems is keeping engine weight down. Engines are often the largest percentage of dry weight on a vehicle and can therefore greatly affect the overall size and cost of a vehicle. The use of various engine types or modes as seen in turbine-based systems can result in extremely high engine weights. Solutions to this problem are focused on a very high level of integration between the various modes and sharing such parts as inlets and nozzles. The advantages and disadvantages of turbine-based launch vehicles is summarized in Table 1.

Table 1: Pros and Cons of Turbine-Based Launch Vehicles

Pros	Cons
Increased Performance	Transition Between Modes
Safe Engine Start Up	Protecting Turbomachinery
Powered Landings for Booster	Heavy Engine Weight
Improved Mission Abort Safety	Unproven Technology
Cross Range Ability on Landing	

The potential gain to be had from using turbine-based engines has been shown. The engineering challenges associated with such engines, however, have kept these systems at the conceptual level of design. It is clear then that a tool designed for such a

purpose would prove useful. But before the time and energy was spent into making such a tool, it was necessary to be sure that such a tool did not already exist. There are in fact many programs available that can analyze turbine engines. These codes include GECAT, NPSS and TBCC-X [1]. Although each code has its pros and cons, not one is ideally suited for the conceptual design process followed by the SSDL. This process prefers a code that is robust, allows batch mode operation, has a quick run-time, a user friendly web-interface, written in widely used programming language, ability to analyze many different engine configurations, and has the capability to generate POST engine decks. T-BEAT was created to meet all these requirements. Table 2 summarizes the pros and cons of each code that was investigated.

Table 2: Pros and Cons of Various Turbine Analysis Codes

	GECAT	NPSS	TBCC_X	T-BEAT
Robust	x	x		x
Web-Based				x
Quick Run Time	x		x	x
Batch Mode	x	x		x
POST Deck				x

2.0 Tool Development

Engine Configuration Selection

The first step in the development of T-BEAT was determining which engine configurations to model. Upon investigation of the turbine-based launch vehicle literature, it was found that there exist numerous ways in which such a propulsion system could be utilized. These vehicles could use a turbojet in a "standalone" system where the low-speed turbine system is completely separate from the rest of the vehicle. This architecture would be classified as a combination propulsion system since a separate tail rocket would be needed to reach orbit. A similar architecture would be the case of a turbine powered booster stage on a TSTO vehicle. These two configurations make it necessary for a designer to analyze the engine performance of a standalone turbine system. Therefore it was decided that T-BEAT would include turbojet and after-burning turbojet engines as possible engine configurations.

A second possible engine configuration is the turbine-based combined-cycle engine, TBCC. The TBCC engine takes two forms, the in-line or over-under system. In the in-line TBCC, an afterburning turbojet is used during low-speed operation. At higher Mach numbers, the system then operates as a ramjet with flow bypassing the turbomachinery. Thus the afterburner serves as the ramjet combustor. The J58 engines used on the SR-71 approach this operation, although there is never a ramjet only mode. One disadvantage of this in-line system is that it is difficult to protect the turbomachinery during high Mach number flight. Blocking off the flow path entirely would cause serious losses in performance. Therefore, this configuration is limited to approximately Mach 3.5 flight.

The TBCC can also take form in the over-under configuration. A simple sketch illustrating the over-under concept is provided in Figure 2.

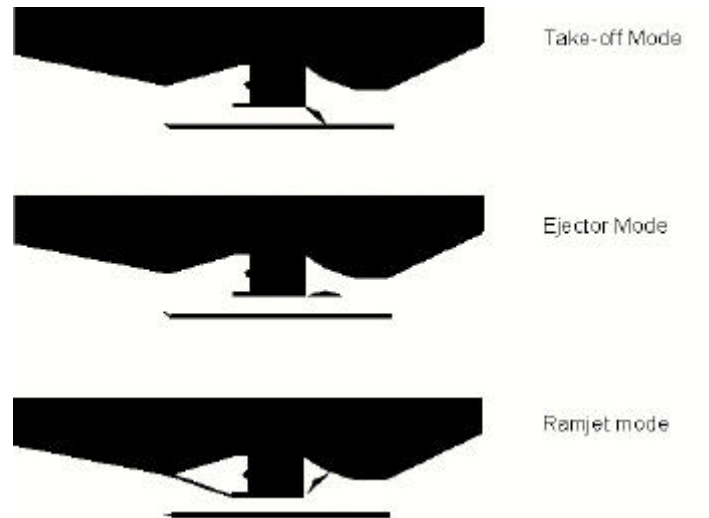


Figure 2: Over-Under TBCC Configuration [7]

The above figure illustrates the high level of integration utilized in this concept. The turbojet and ramjet share an inlet and nozzle. Although the variable geometry was attempted to be minimized, an inlet flap and ejector flap is necessary. During take-off mode, the ramjet flowpath is completely closed by a movable flap and the vehicle relies entirely on the low-speed turbojet system. As the flight speed increases, the vehicle transitions to what is called ejector mode, where both flowpaths are open. During this mode, a small amount of air passes through the ramjet flowpath and is combined with the turbojet exhaust stream. The final mode is the all ramjet mode which occurs when a flap rotates down and shuts off flow to the turbine engine. This configuration solves the problem of the in-line system, in that the use of a flap system could enable the engine to operate at very high Mach numbers without damaging the turbomachinery and without seriously affecting the performance.

In order to capture these two configurations, T-BEAT allows the choice of both the in-line and over-under configurations. Additionally, since modeling the TBCC engine requires ramjet engine modeling, a standalone ramjet analysis has been made available to the user.

Table 3: Engine Configurations Available in Tools Investigated

	GECAT	TBCC_X	T-BEAT
Turbojet	x	x	x
Afterburning Turbojet	x		x
Ramjet	x	x	x
Over-Under TRJ	x	x	x
In-Line TRJ			x
Pre-Cooled Turbojet			x

Table 3 above summarizes the configurations available in T-BEAT as well as the other codes discussed. It should be noted that the configurations listed as available in GECAT are only those that are built in as templates in the program. It is possible to create and design new engine configurations using GECAT.

3.0 Modeling Assumptions

Atmosphere

In order to analyze performance at various altitudes it was necessary to model the atmospheric conditions at these points. This was achieved by incorporating a table look-up code into T-BEAT that contains data from the 1962 Standard Atmosphere. This code was provided by John Bradford, the designer of SCCREAM [2]. This code works by feeding in the altitude and receiving back the corresponding pressure and temperature at that point.

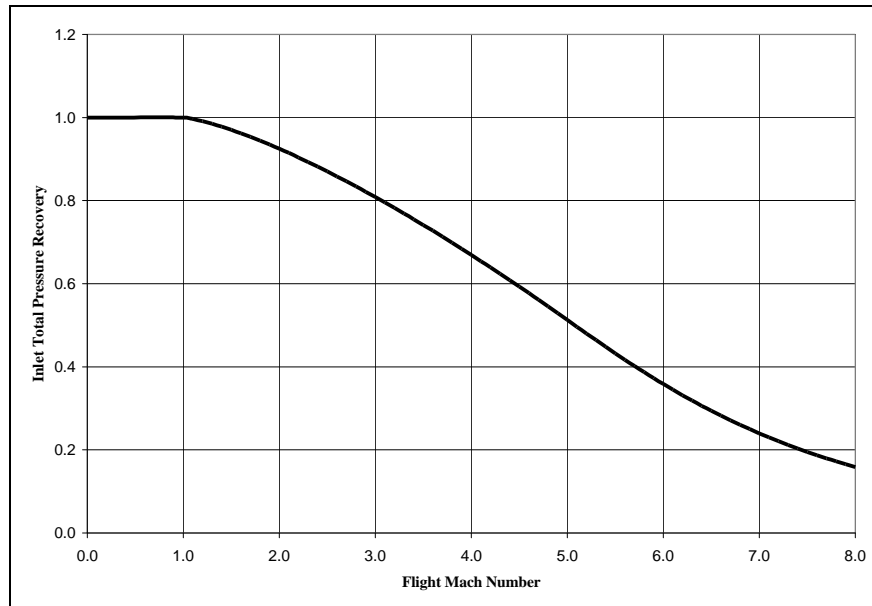


Figure 3: Inlet Total Pressure Recovery

Inlet

Inlet total pressure recovery is modeled using military inlet specifications (MIL-E-5008B). A plot of the pressure recovery given by MIL-E-5008B is shown in Figure 3 above. This military specification represents the pressure recovery that would be achieved by a well designed inlet. It would be possible to design an inlet with better performance at a specific operating point, but over a broad range of flight conditions, the MIL-SPEC inlet represents a good design. It was thought that since these vehicles will

be used as accelerators rather than cruisers, they would not stay at one Mach number for a long time, and therefore this approximation is justified.

Cycle Analysis

The turbojet, afterburning turbojet, and ramjet analyses was accomplished by closely following methods described in Mattingly [6]. Analysis for the TBCC configurations was performed by combining the turbojet and ramjet analyses. This analysis assumes one-dimensional flow at the entrance and exit of each engine component. In order to model realistic performance of these engine cycles, the analysis included component losses for the compressor, burner, turbine and nozzle. The values of these component efficiencies are defaulted to represent the current level of technology, but can be changed by the user to model the increased performance of future designs.

The variation of specific heats through the engine is approximated by assuming the flow is a perfect gas with constant specific heat upstream of the combustor and a perfect gas downstream of the burner but with a different specific heat. Thrust is calculated using a control volume analysis that accounts for the change in fluid momentum through the engine. The equation used to calculate this uninstalled thrust is as follows:

$$T = (\dot{m}_a + \dot{m}_f)u_e - \dot{m}_a u_\infty + A_e(p_e - p_\infty)$$

The Thrust Specific Fuel Consumption, TSFC is calculated by simply dividing the fuel mass flow by the thrust. Isp is then calculated from this since spacecraft designers more commonly use Isp.

In order to size the turbine engines, the user must enter a required thrust, a maximum engine diameter and a maximum Mach number at the compressor face. This max Mach number is defaulted to Mach 0.56, which is representative of modern engines. With this Mach number constraint, the size of the compressor face can be calculated and compared to the maximum engine diameter entered by the user. The code can alert the user if the desired thrust is too high for the given area constraint. For the ramjet portion of the code, the user is asked to enter a maximum cowl area and diffuser area to fix the engine geometry.

Input

At the conceptual design stage, very little is known about how the final product will take form. It is therefore important for a conceptual design tool to allow the user much design freedom. T-BEAT has satisfied this criterion by keeping as many design variables as possible available to change by the user. Default values are also maintained so that an inexperienced user can use the tool more easily. It should be noted that all units in T-BEAT are in the English system. Although many users might find the SI system more convenient, the propulsion field continues to use the English system and it was felt that T-BEAT would be most useful if it followed that tradition.

The first three inputs to T-BEAT are the required thrust, reference point Mach number and reference point altitude. These inputs determine the design point of the engine. The next grouping of inputs is the Mach number and altitude run ranges. Here the user must specify the minimum, maximum and increment for Mach number and altitude. These ranges and increments will determine the off-design points that are analyzed. The next two design variables that can greatly impact the performance of the engine are the compressor pressure ratio and the turbine inlet temperature.

The user can also choose between a hydrocarbon-fueled engine, or a hydrogen-fueled one. The use of different fuels is analyzed by using a different fuel heating value for each. Using hydrogen over hydrocarbon approximately doubles the Isp while thrust remains fairly constant. This is expected because having a much higher fuel heating value, using hydrogen allows the same amount of heat release for a smaller amount of fuel. Since the turbine inlet temperature limits the amount of heat release, the thrust stays the same while the Isp is improved.

The last set of inputs is the component efficiencies for the compressor, turbine and burner. These efficiencies affect the analysis by modifying the total pressure losses occurring in these engine components.

Output

T-BEAT supplies the user with three output formats. The first is appropriately called “Output formatted for plotting.” A sample of this output is provided in Appendix A. This output page provides the reference Mach number and altitude as well as the thrust

and Isp at that point. It also provides a table of Mach number, altitude, thrust and Isp for all of the off-design points specified by the user. This table can easily be copied and pasted into a spreadsheet program such as Excel where plots can be produced.

The second form of output made available by T-BEAT is the “POST engine deck.” This capability is essential for T-BEAT to be used in the Space Systems Design Lab. One of the main goals of the SSDL is to improve the conceptual launch vehicle design process by making it more efficient and creating tools suitable for this purpose. One way in which this is achieved is through the use of Multidisciplinary Design Optimization, (MDO). MDO is the incorporation of various techniques to shorten design times while improving the designs. The Design Structure Matrix (DSM) is one tool that is used in MDO to show the coupling between various engineering disciplines. An example DSM is provided in Figure 4 below with each box representing a unique discipline.

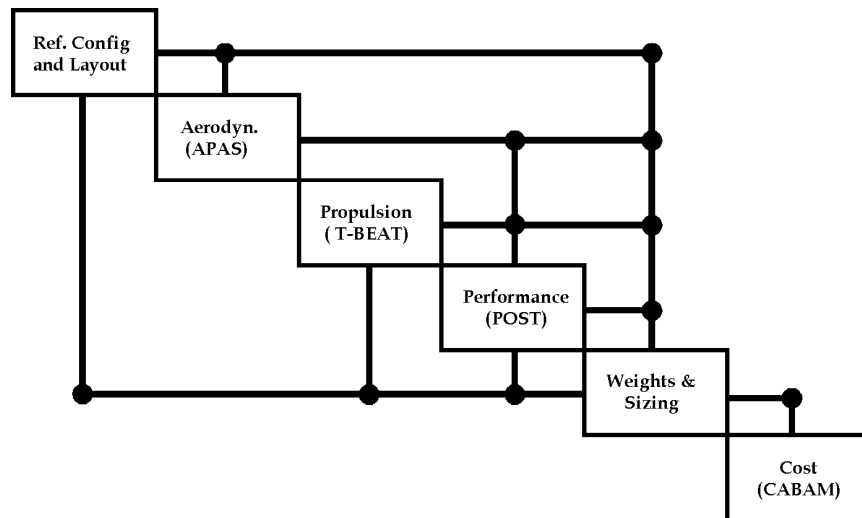


Figure 4: Design Structure Matrix

As evident from the DSM, the results of the propulsion analysis feed forward to the performance discipline. Keeping with the SSDL’s goal to quicken design turn-around times, it would be helpful if this output was provided in a form suitable to the program used by the performance discipline. The performance analysis in the SSDL is executed using the Program to Optimize Simulated Trajectories, POST. This program requires the

engine data to be in a formatted table so that it may be read correctly by the program. If T-BEAT simply provided the performance engineer with a list of data, it would be very time consuming to format this data into the correct form. The time savings can become very significant when engineers are converging a design and a number of iterations are necessary. An example of the POST engine deck provided by T-BEAT is provided in Appendix B.

The final output format given by T-BEAT is labeled “Total output for run.” A sample of this output is provided in Appendix C. This output includes the values of many variables in addition to the thrust and Isp such as temperature and pressure ratios at various stations within the engine. This output can be viewed by a more advanced user to check how the engine is operating internally and thus give insight into how they wish to change their design variables.

4.0 T-BEAT Execution

UNIX Operation

The T-BEAT analysis code was written in C++ and compiled on a UNIX machine. It can be run directly from the UNIX command line by modifying the input files to match the design you wish to analyze and executing the code by typing T-BEAT. The program flow is controlled by the C++ file T-BEAT.cpp. Figure 5 shows how the program is put together.

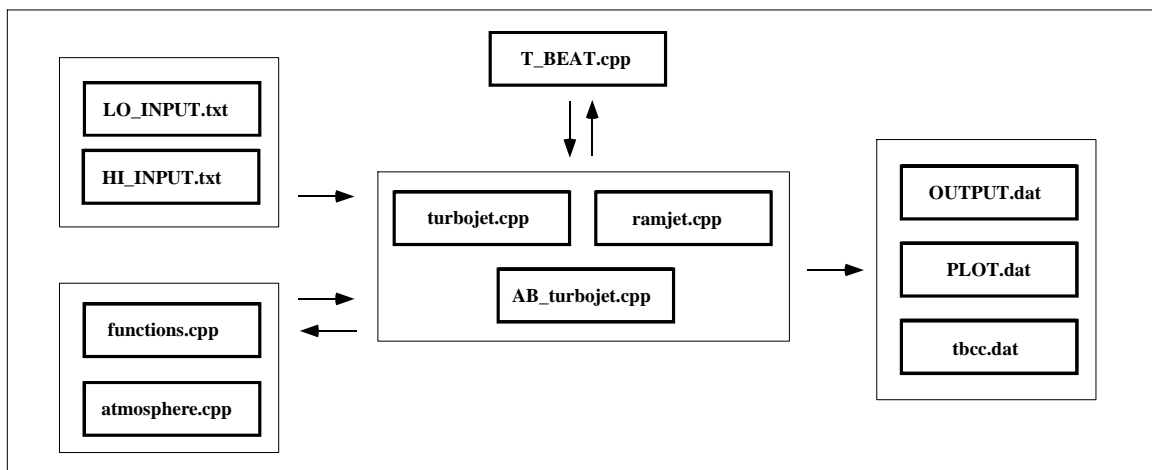


Figure 5: Program Design

When the code is executed it begins by asking the user for the engine configuration. Based on the user's choice, T-BEAT then jumps to the needed subprogram. The user will then be prompted for a required thrust level at a reference altitude and Mach number. Entering these inputs will set the design point of the engine. The program will then run and the user will be notified when execution is complete.

If the user then wishes to change any of the design variables they must open the input files for editing. These files are labeled LO_INPUT.txt and HI_INPUT.txt which correspond to the low speed and high speed inputs respectively. To change the value of an input, the user must simply replace the number with the new value keeping the order of the variables the same. This is necessary so that T-BEAT correctly reads in the variables. Also, because the user is prompted for the engine configuration and required

thrust at a reference condition, the user can ignore the first four inputs of LO_INPUT.txt since they will be overwritten. These variables are included in the input file for execution from the T-BEAT website. The format of the input files is provided in Appendix D.

Web-based Capability

Universities have used the World Wide Web since its creation as a quick and easy way to exchange data and information. In just the past few years this ability has been enhanced so that it is now possible to not only exchange information but also allow programs to be run over the Internet. The SSDL has taken advantage of this revolution by the creation of such tools as SCORES and SCCREAM. Following in this tradition, T-BEAT has been made accessible via the Web. The tool can be currently found at the following URL: <http://atlas.cad.gatech.edu/~rbechtel/T-BEAT.html>

In order to enable this functionality, it was necessary to make a Web page to act as the interface between the remote user and the C++ program located on a local UNIX machine. A CGI script was also needed to bridge the connection. The flow chart in Figure 6 helps describe the process.

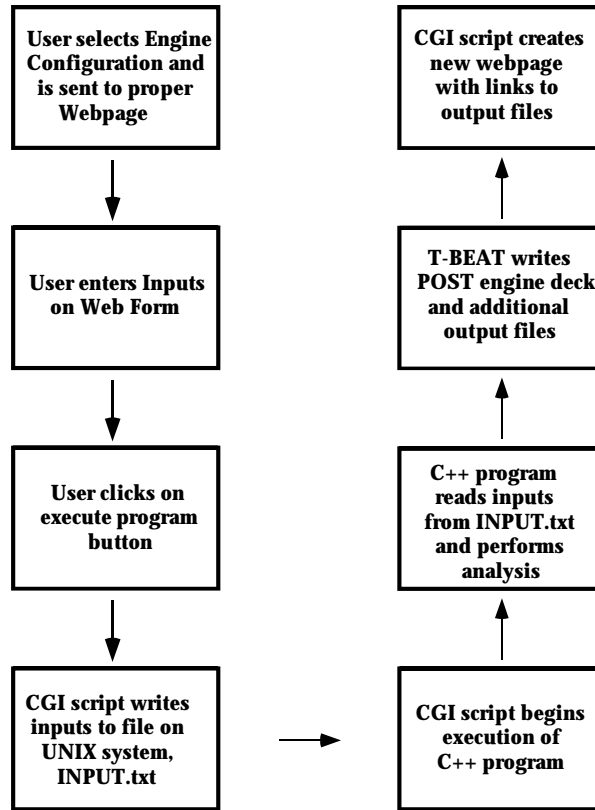


Figure 6: Program Flow from Web

5.0 Tool Validation

Turbojet Validation

Validation of the turbojet was performed by comparing data generated by T-BEAT and GECAT for a similarly designed engine. The design point for this engine comparison was 50,000 lbs of sea-level static thrust. The various other design variables that were matched between programs for the comparison are provided in Table 3.

Table 4: Design Variable Settings for Turbojet Validation Case

Compressor Pressure Ratio	12
Turbine Inlet Temperature	3200 °R
Compressor Efficiency	0.95
Burner Efficiency	0.99
Turbine Efficiency	0.97
Fuel Type	JP-4

Figure 7 shows the thrust data generated during this comparison. As evident from the graph, the data shows very good correlation for the off-design points analyzed below Mach 2. Above Mach 2 the gap widens between the two analyses. After some investigation into this discrepancy it was found that it could be explained by the differing nozzles analyses used by the two codes. In T-BEAT, an efficiency is placed on the nozzle that is constant for all Mach numbers, whereas the nozzle in GECAT does not perform as well at the higher Mach numbers.

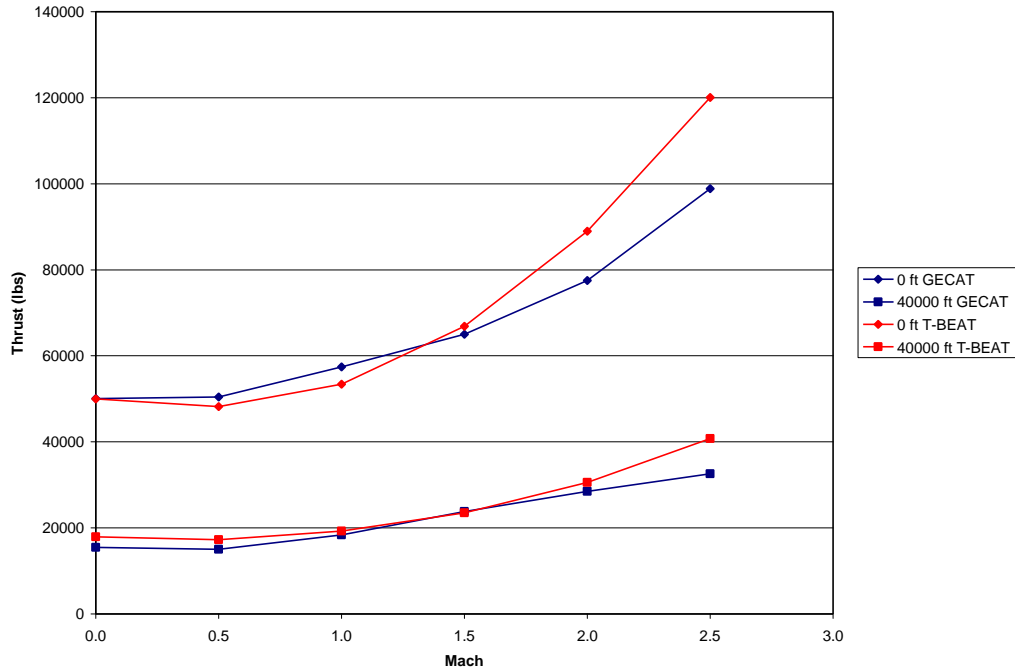


Figure 7: T-BEAT versus GECAT Thrust Data Validation

The Isp comparison given in Figure 8 shows good correlation between the two codes as well however, again there is a slight divergence at very high Mach numbers.

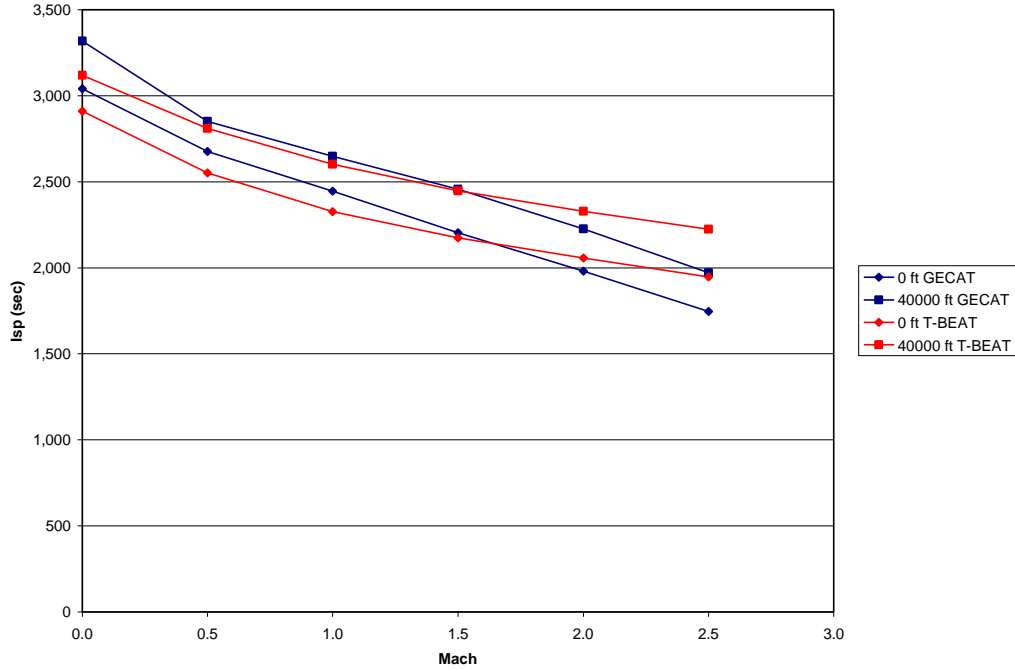


Figure 8: T-BEAT versus GECAT Isp Data Validation

Afterburning Turbojet Validation

In order to achieve more thrust it is possible to burn additional fuel after the turbine. However, this thrust augmentation comes at the price of decreased fuel efficiency. Afterburning typically increases the thrust up to fifty percent while decreasing fuel efficiency by up to a third [6]. In order to validate the T-BEAT afterburner, an engine was designed using the same design variables as the turbojet described above and analyzed at sea-level atmosphere conditions. Output data was then generated for cases with the afterburner on and off and compared to a similar engine modeled using GECAT. The results for the thrust and Isp data are given in Figure 9 and Figure 10 respectively. As evident in the graph, the thrust increased on average by approximately forty percent while the Isp decreased by about forty percent. These numbers appear to be in close agreement with data generated by GECAT.

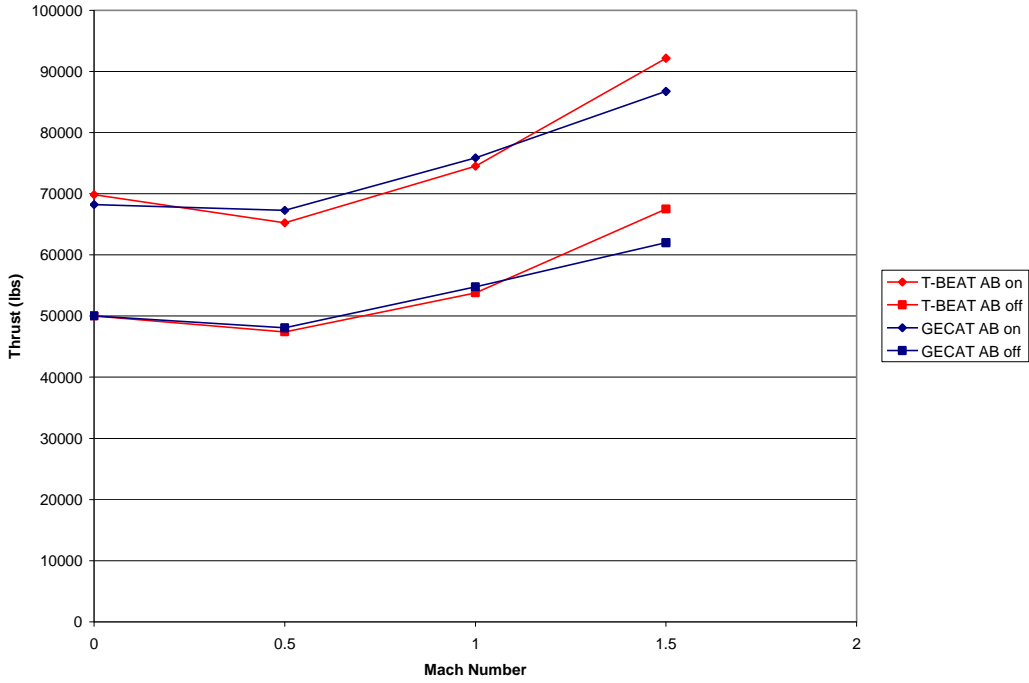


Figure 9: Afterburning Turbojet Thrust Data

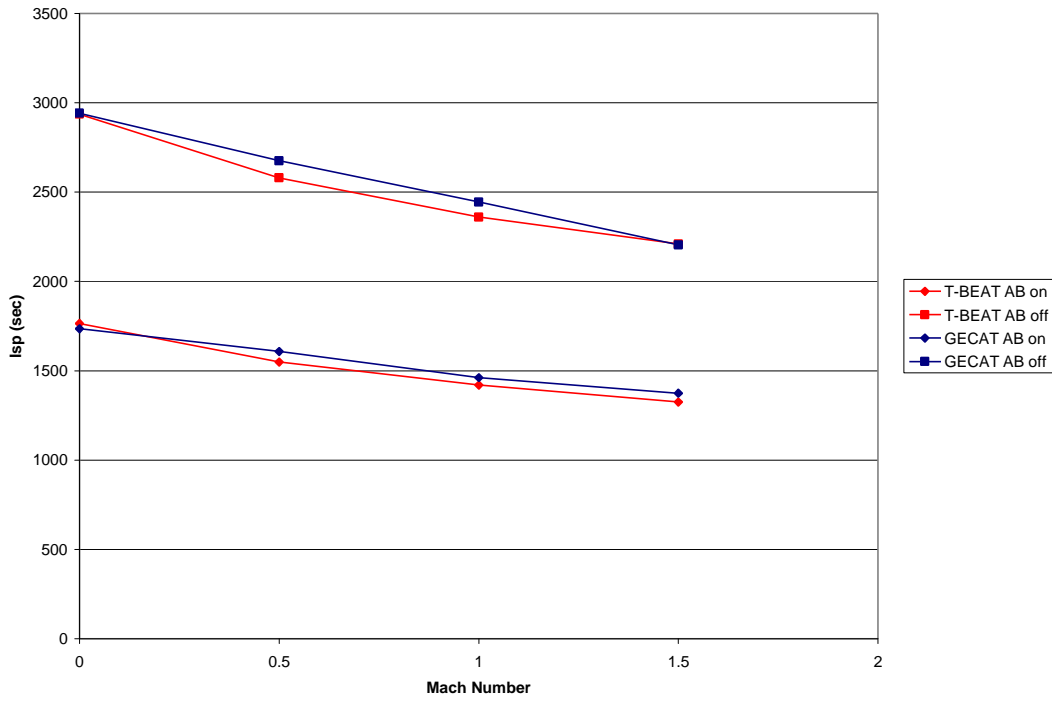


Figure 10: Afterburning Turbojet Isp Data

Ramjet Validation

The program SCCREAM was used in order to validate the ramjet data [2]. SCCREAM was used instead of GECAT because a student version of GECAT was being used and it was not possible to model a hydrogen-fueled ramjet with this version. The thrust data is provided in Figure 11. The thrust coefficients are based on a reference inlet area of fifty square feet.

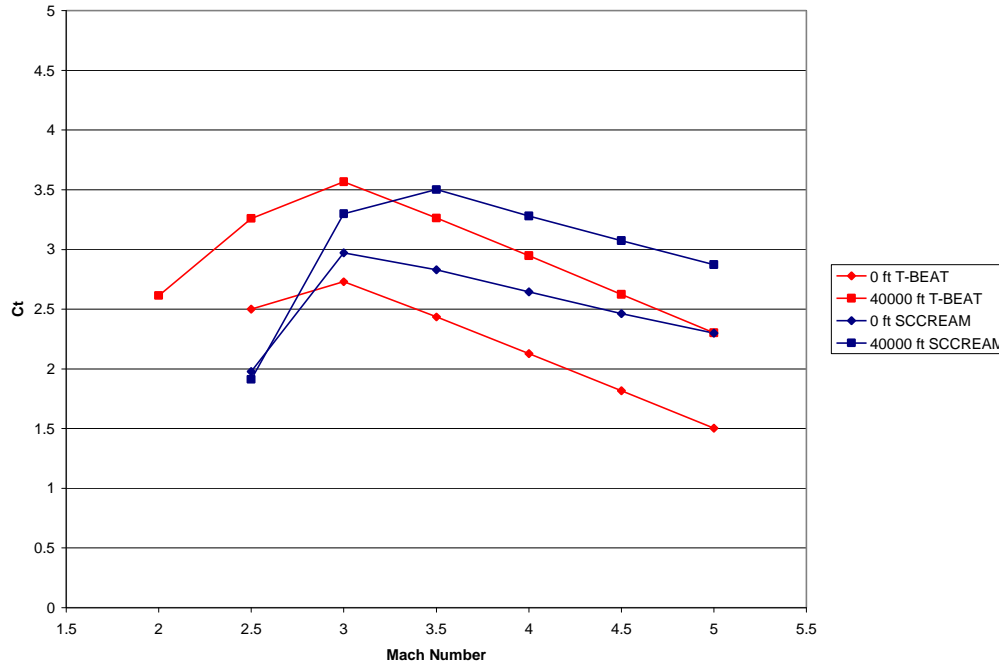


Figure 11: Ramjet Thrust Data

From the general trends in the plot of the thrust data it appears T-BEAT is not exactly matching the results from SCCREAM. The main difference appears in the data below Mach 3 where the engine is unstarted. This discrepancy is due to the fact that T-BEAT uses a simpler method to model the unstarting of the inlet. The difference in the data at higher speeds may be due to SCCREAM allowing the user more freedom in the geometry of the engine and therefore it could not be exactly matched. The same trends appear to be true of the Isp data given in Figure 12.

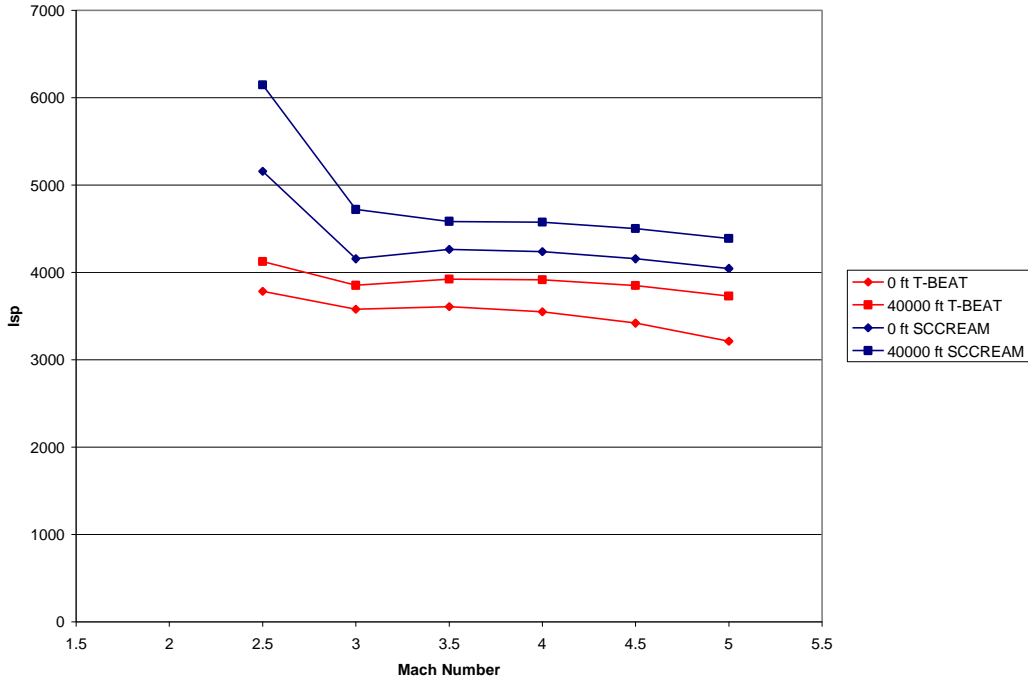


Figure 12: Ramjet Isp Data

TBCC Validation

In order to validate the data for the turbine-based combined-cycle engine it was necessary to use the program TBCC-X [1]. This design tool runs on a UNIX workstation with a graphical user interface. This format allows the user to observe the affect on engine performance by interactively changing design variables. The TBCC-X tool models the TBCC engine in the over-under configuration, and therefore this configuration was run in T-BEAT as well. The design variables held constant between the two engines are provided in Table 4. The ramjet reference area used for the coefficient of thrust calculation is the maximum cowl area.

Table 5: Design Variable Settings for TBCC Validation Case

Low Speed Fuel	Jet-A
CPR	12
Turbine Inlet Temp	3200 R
S.L.S. Thrust	10000 lbs
High Speed Fuel	Hydrogen
Ramjet Ref. Area	50 ft ²

Off-design data was then generated using the two codes for Mach numbers ranging between 0 and 5.5 at altitudes of 0 and 40,000 ft. Thrust data is provided in Figure 13. Note that the low speed data is given as thrust in pounds whereas the high speed data is given in the form of a dimensionless thrust coefficient. As evident from the graph, the low speed data matches fairly well except for a slight dip around Mach 1. This slight deviation was found to be caused by the TBCC_X program modeling some shock interaction not considered by T-BEAT. The high speed data matches fairly well also, although it is noted that the high speed system in TBCC_X appears to be started at a lower Mach number than in T-BEAT.

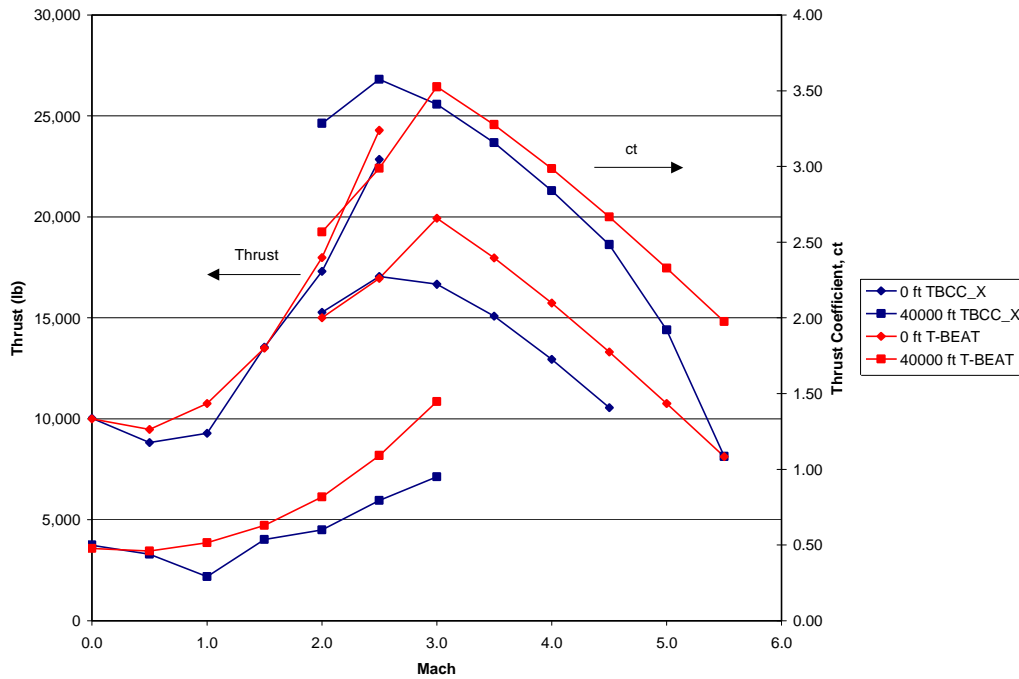


Figure 13: TBCC_X versus T-BEAT Thrust Data Validation

The Isp results for the TBCC comparison are provided in Figure 14. Again the low speed system data shows good agreement. Looking at the high speed data, it may appear strange that the Isp is better than that of the low speed system. This is a result of different fuels being used for each mode. This decision was made based on this design being the default case for the TBCC_X program. The Isp data for the high speed does

not match as well as that of the low system. The Isp for the engine generated by TBCC_X peaks earlier and drops off more quickly than that of the T-BEAT engine. The reason behind this could be that TBCC_X uses a less fuel efficient thermal-choke to regulate the flow whereas T-BEAT assumes variable geometry.

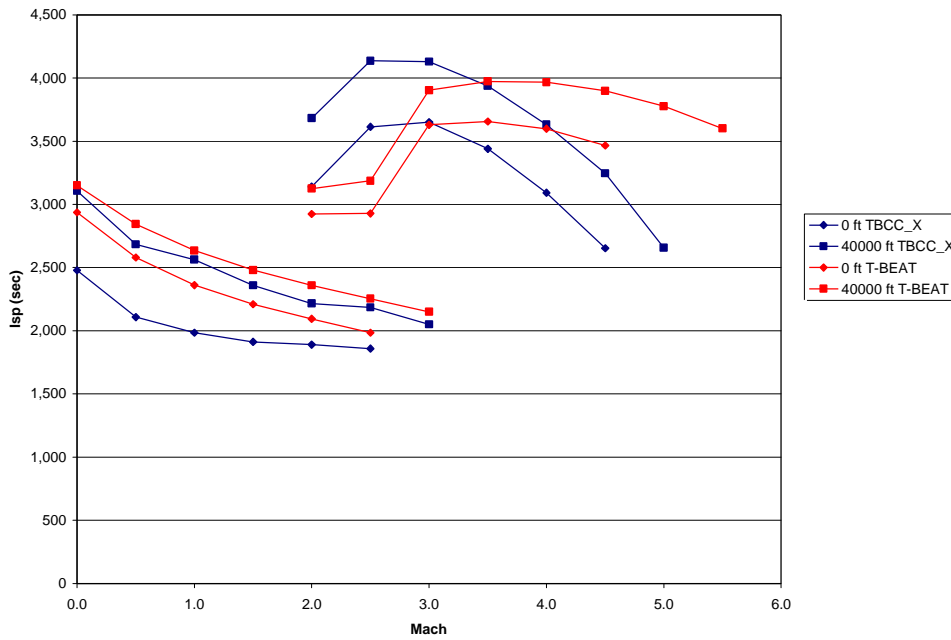


Figure 14: TBCC_X versus T-BEAT Isp Data Validation

Pre-cooled Engine Validation

Current studies are being conducted investigating the use of a pre-cooled turbojet engine for access to space. Much of this work is being done in Japan on the ATREX engine [7]. The idea behind this cycle is to use a cryogenic fuel such as Hydrogen in a heat exchanger to remove heat from the air entering the compressor. This pre-cooled air benefits the engine in two main ways. First, the lower temperature air has a higher density that allows more efficient combustion that leads to higher thrust. Secondly, the higher density air is easier to compress and therefore the load on the compressor is less improving the Isp. One of the disadvantages of such a cycle is that the heat exchanger before the compressor causes a total pressure loss due to skin friction. Another

disadvantage is that the amount of fuel needed for cooling may be more than is necessary for combustion and therefore it may be necessary to carry excess fuel.

In order to model such a cycle, the basic turbojet cycle was slightly modified. The temperature entering the compressor was lowered, and the total pressure loss slightly increased. Also, since this cycle is limited to the use of hydrogen the turbine inlet temperature was increased to represent possible use of the hydrogen to cool the turbine blades. This could be achieved by using the hydrogen to further lower the temperature of the turbine cooling air thus increasing the inlet temperature of the turbine. Data was then generated for this cycle and compared to the basic turbojet in order to see the benefits. The thrust results are provided in Figure 15. In general, the thrust is slightly better for the pre-cooled engine through the lower Mach numbers and then significantly higher at the high Mach number range. This is due to the decreased temperature entering the compressor having a greater effect on performance as the operating conditions become more severe.

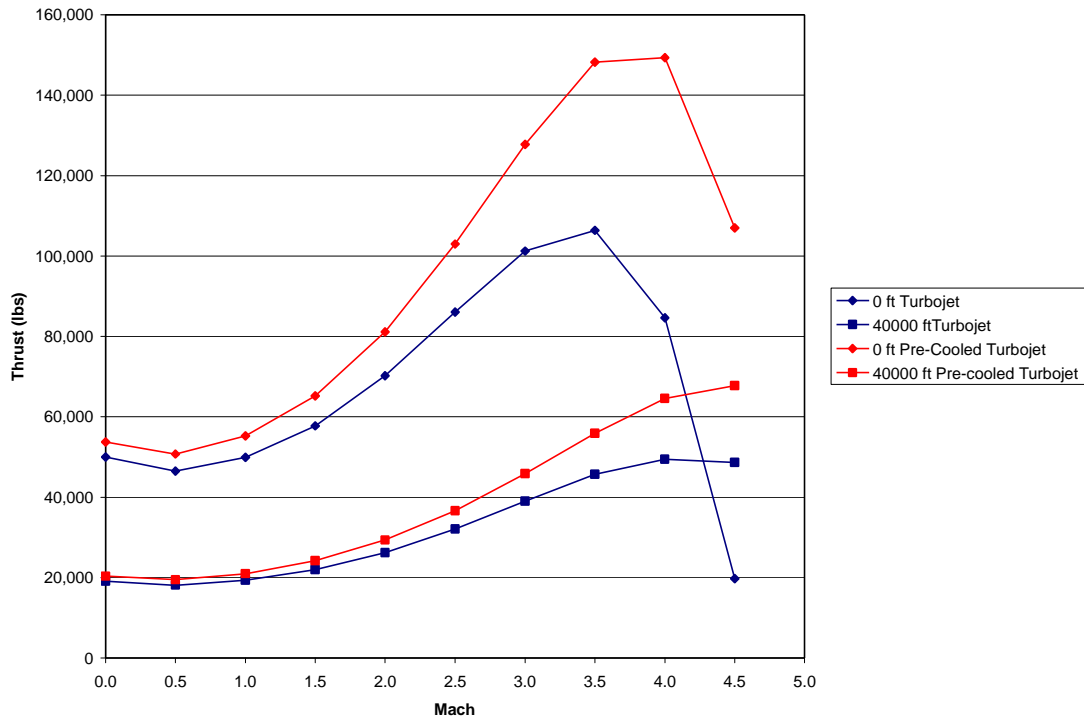


Figure 15: Pre-Cooled Turbojet versus Basic Turbojet Thrust Data

Isp data for the pre-cooled turbojet is provided in Figure 16. This graph shows the Isp practically the same for the two configurations. This trend occurs because allow the work demand on the compressor is lower and Isp could be greater, the extra fuel needed for the heat exchanger cancels out this effect. The only exception is at the extreme operating range which was explained above.

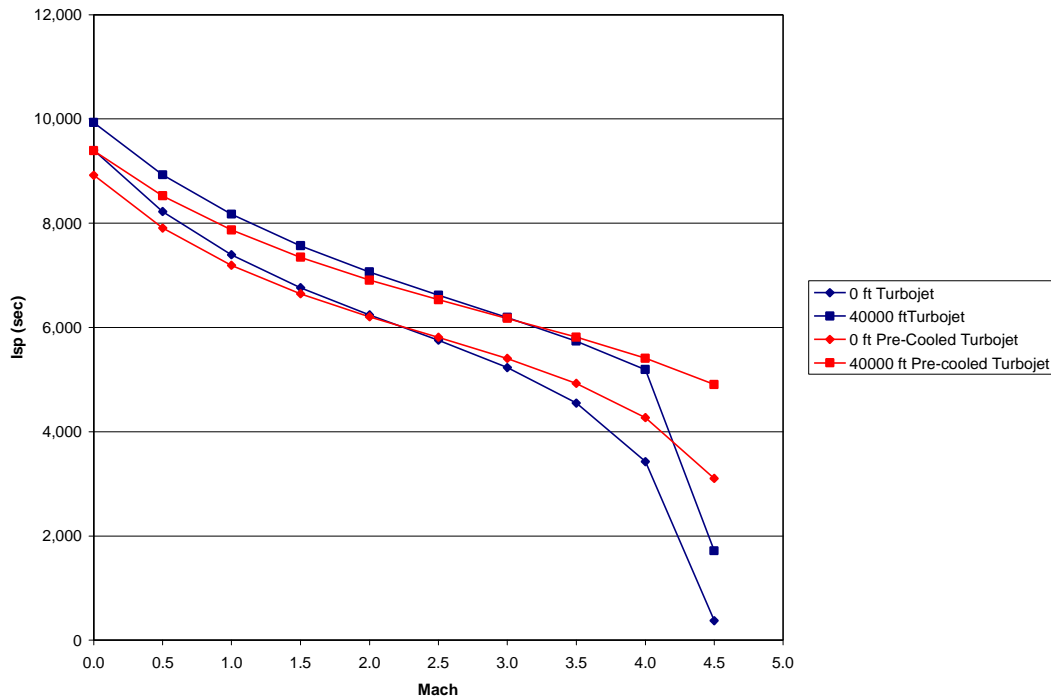


Figure 16: Pre-Cooled Turbojet versus Basic Turbojet Isp Data

6.0 User Guide

Although it was attempted to make T-BEAT as user friendly as possible, a small sample case may be helpful for first-time users. Figure 17 shows a screen capture of the T-BEAT main page where the user must select an engine configuration.

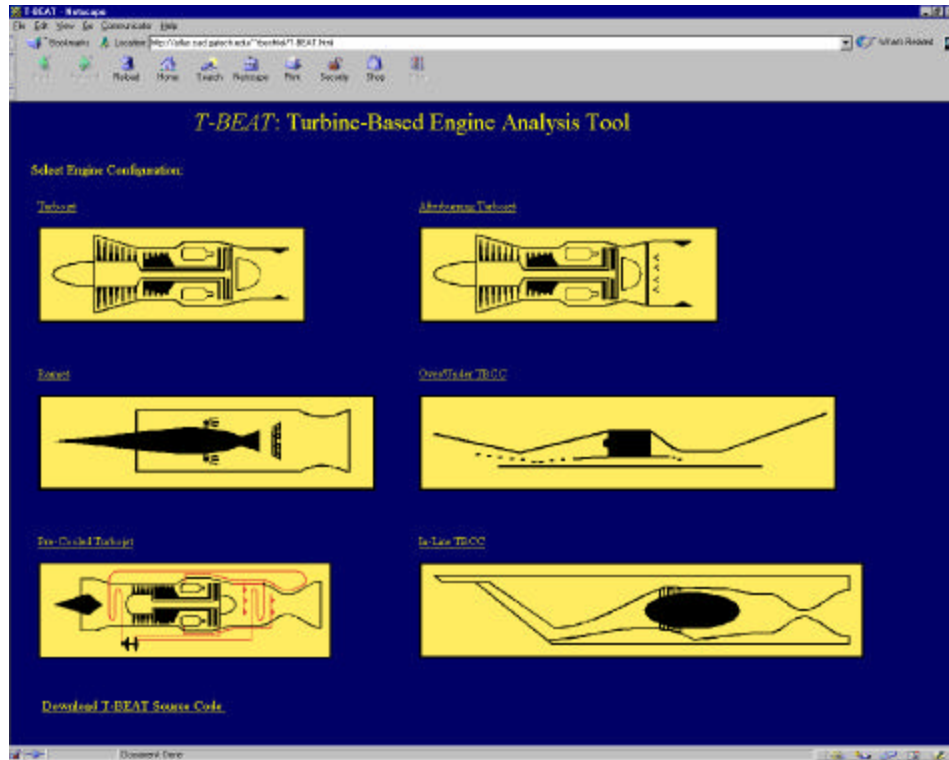


Figure 17: T-BEAT Main Page

In this example the Turbojet configuration is selected by clicking on either the word Turbojet or the picture. Since these are both links, the user is brought to a new webpage where the appropriate inputs may be entered. This page is shown in Figure 18.

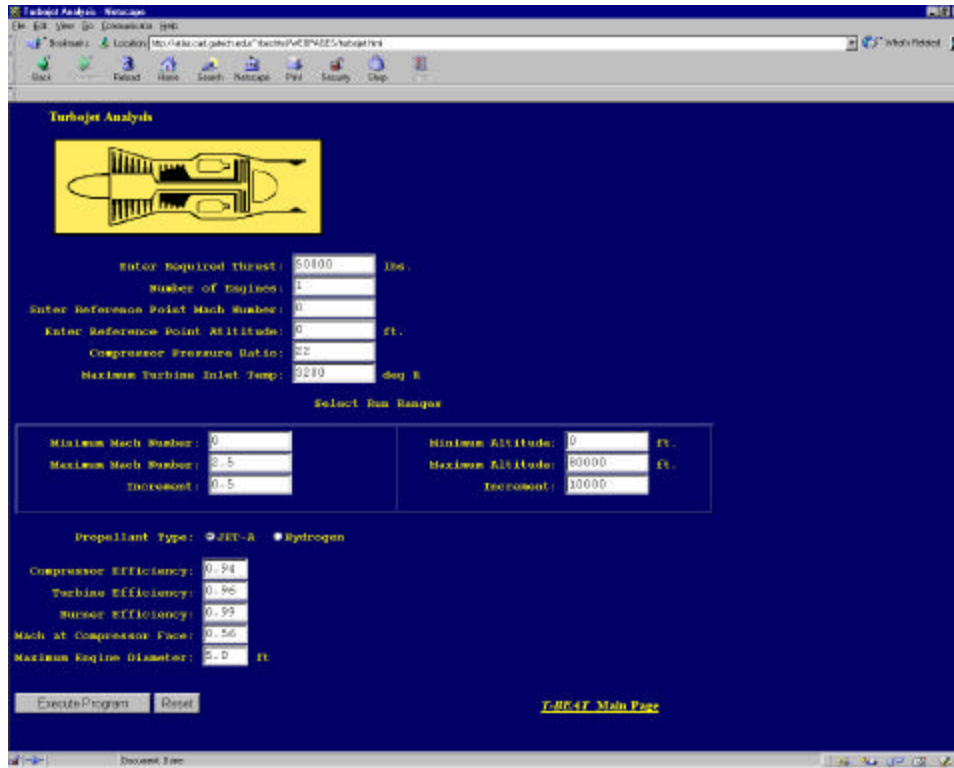


Figure 18: Turbojet Input Screen

As can be seen from the figure, default values for all the inputs are provided. If however, the user wishes to modify them, they must simply click in the box and replace the default value with the value they desire. If the user enters a number outside the range of T-BEAT’s capabilities, they will be asked to re-enter a value. This is achieved using a Javascript. This may also occur if the user accidentally enters a value for the compressor efficiency of 94 instead of 0.94 as intended.

Once all the inputs are entered, the user must click on the box labeled Execute Program found at the bottom left of the screen. Depending on the size of the user’s monitor, it may be necessary to scroll down on the page for the Execute Program button to be in view. If the user decides to analyze a different configuration they may click on the “Back” button on their Web browser, or click on the link labeled “T-BEAT Main Page” found in the bottom right of the screen.

Once the Execute Program button has been clicked, T-BEAT will then analyze the engine design and the user will be sent to the output page shown in Figure 19. The

output page has links to the three output formats that T-BEAT creates. The user may then click on any of these links to access the results of the analysis. If the user wishes to save the data, the best method for doing so is to highlight the desired data and then copy and paste it into a spreadsheet program. It should be noted that on this output page it is suggested to the user to hold down the shift key and click on Refresh or Reload on their browser in order to ensure the data they are seeing is for their current run. Some browsers may load up the output page from cache and the user could mistakenly be looking at data from a previous run.



Figure 19: T-BEAT Output Page

Also found on the output page are links to the two input files used in T-BEAT. The user may save these in order to record the inputs they used in this design for future reference. Finally, if the user wishes to rerun the analysis they can click “Back” on their browser, change the desired input values, and then click on the Execute Program button again.

7.0 Conclusion

The recent renewal of interest in turbine-based launch vehicles has motivated the development of the low speed propulsion system analysis tool T-BEAT. Because of the low maturity level of turbine-based space access vehicles, this tool was geared toward conceptual design. In order to meet this goal, T-BEAT allows the user much control over engine configuration, design variables and operating points. T-BEAT creates output in a POST engine deck format to allow quick exchange between design disciplines. Additionally, T-BEAT can be executed from the command line of a UNIX system or remotely via the World Wide Web. This feature allows designers with different computing platforms and geographic locations to use the tool. Validation of the tool has been completed using GECAT, SCCREAM and TBCC-X. This validation shows good correlation between the codes and verifies that T-BEAT is working as expected.

8.0 References

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2. Bradford, J. E., Olds, J. R., "SCCREAM v.5: A Web-Based Airbreathing Propulsion Analysis Tool," AIAA 99-2104, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, June 20-24, 1999.
3. Escher, W., "Proposed Lexicon for Combined-Cycle Hypersonic Propulsion Systems," May 20, 1996.
4. Escher, W., "Spaceliner class operability gains via combined airbreathing/rocket propulsion," AIAA 99-2355, AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 35th, June 20-24, 1999, Los Angeles, CA.
5. Martin, J.A., "A Tutorial: Airbreathing and Rocket-Based Combined Cycle (RBCC) Propulsion," The University of Alabama, Tuscaloosa, AL.
6. Mattingly, Jack D., *Elements of Gas Turbine Propulsion*, McGraw-Hill, Inc., 1996.
7. Taguchi, H., Futamura, H., Yanagi, R., Maita, M., "Performance Analysis on Pre-Cooled Turbojet Engine for TSTO Spaceplane," IAF-00-S.5.03, 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2, 2000.
8. Trefny, C.J., Benson, T.J., "An Integration of the Turbojet and Single-Throat Ramjet," NASA Technical Memorandum 107085, Airbreathing Propulsion Subcommittee Meeting, Dec. 5-9, 1995, Tampa, FL.

Appendix A: Example of Output Formatted for Plotting

TURBOJET

Reference Mach: 0.5
Reference Altitude: 20000
Reference Isp: 3054
Reference Thrust: 50000

Altitude	Mach	Thrust	Isp
0	0	80211.4	3319.80
0	0.5	75335.2	2918.67
0	1	82484.5	2647.37
0	1.5	98241.1	2445.58
0	2	123391	2283.72
0	2.5	156810	2134.83
20000	0	52705	3423.74
20000	0.5	50000	3054.46
20000	1	54535.2	2793.89
20000	1.5	64273.7	2594.48
20000	2	79969.8	2434.01
20000	2.5	101639	2291.53
40000	0	29951.6	3516.54
40000	0.5	28619.8	3173.89
40000	1	31061.4	2923.38
40000	1.5	36184.4	2726.64
40000	2	44464.2	2566.84
40000	2.5	56113.8	2427.32
60000	0	11433.6	3516.09
60000	0.5	10924.9	3173.31
60000	1	11857.2	2922.75
60000	1.5	13813.7	2725.99
60000	2	16975.7	2566.19
60000	2.5	21424.4	2426.65
80000	0	4185.16	3502.87
80000	0.5	3995.19	3156.38
80000	1	4339.53	2904.35
80000	1.5	5064.53	2707.18
80000	2	6236.11	2547.29
80000	2.5	7880.97	2407.44

Appendix B: POST Deck Example

```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c   POST engine deck for Over/Under TBCC Configuration
c               Generated by T-BEAT
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

l$tblmlt genv6m= 0.0, tvclm=1, tvc3m=1, 5hgenv3,
$
c Thrust values
l$tab table=5htvc1t,2,4hmach,5hgdalt,6,3,8*1,
0,
      0,        50000,
      0.5,      46509.1,
      1,        49876.4,
      1.5,      57734.8,
      2,        70160.7,
      2.5,      86015.2,
40000,
      0,        19085,
      0.5,      18088.7,
      1,        19289.1,
      1.5,      21925.9,
      2,        26181.6,
      2.5,      32044.7,
80000,
      0,        2662.71,
      0.5,      2521.02,
      1,        2689.95,
      1.5,      3062.46,
      2,        3663.34,
      2.5,      4488.68,
$end
c Isp values
l$tab table=5hispl1t,2,4hmach,5hgdalt,6,3,8*1,
0,
      0,        9403.78,
      0.5,      8224.49,
      1,        7397.68,
      1.5,      6762.5,
      2,        6240.58,
      2.5,      5756.35,
40000,
      0,        9931.59,
      0.5,      8927.9,
      1,        8173.62,
      1.5,      7566.89,
      2,        7064.13,
      2.5,      6620.51,
80000,
      0,        9895.13,
      0.5,      8879.96,
      1,        8120.52,
      1.5,      7511.61,
      2,        7007.73,
      2.5,      6562.35,
$end
c Ramjet Mode Ct values
l$tab table=5htvc3t,2,4hmach,5hgdalt,7,3,8*1,
40000,
      2,        2.61104,
      2.5,      3.25752,
      3,        3.56348,
      3.5,      3.25994,
      4,        2.94363,
      4.5,      2.62192,
      5,        2.29836,
80000,

```

```
      2,      2.56939,
    2.5,      3.19873,
      3,      3.49881,
    3.5,      3.19589,
      4,      2.88033,
    4.5,      2.55944,
      5,      2.23672,
120000,
      2,      2.39647,
    2.5,      2.95468,
      3,      3.23029,
    3.5,      2.92996,
      4,      2.61754,
    4.5,      2.30004,
      5,      1.98084,
$end
c Isp values
l$tab table=5hisp3t,2,4hmach,5hgdalt,7,3,8*1,
40000,
      2,      3275.35,
    2.5,      4050.88,
      3,      3770.18,
    3.5,      3852.97,
      4,      3863.56,
    4.5,      3818.19,
      5,      3725.39,
80000,
      2,      3263.76,
    2.5,      4030.33,
      3,      3753.71,
    3.5,      3834.14,
      4,      3842.24,
    4.5,      3794.09,
      5,      3697.94,
120000,
      2,      3213.18,
    2.5,      3940.21,
      3,      3681.68,
    3.5,      3751.52,
      4,      3748.37,
    4.5,      3687.37,
      5,      3575.33,
$end
c Ramjet Mode Inlet Area
l$tab table=4hae3t,0,50 $
```

Appendix C: Total Output for Run Example

Turbojet	Mode Mach:	0.5	
	Altitude:	0	ft
<hr/>			
	speed_of_Sound:	1116.53	ft/s
	flight_Velocity:	558.267	ft/s
	Tt0_over_T0:	1.05	
	Pt0_over_P0:	1.18621	
	P0:	2116.25	psf
	T0:	518.67	R
	q0:	370.391	psf
	inlet_Eff:	1	
	Pt2_over_Pt0:	0.99	
	Pt2:	2485.22	psf
	Tt2:	544.603	R
	Area 2:	11.4397	ft^2
	velocity 2:	606.488	ft/s
	Tt3_over_Tt2:	2.48454	
	Pt3:	49514.1	psf
	Tt3:	1353.09	R
	comp_Eff:	0.910024	
	fuel_to_air_Ratio:	0.0348544	
	Tt5_over_Tt4:	0.799437	
	Pt5_over_Pt4:	0.364065	
	Pt4:	48028.7	psf
	Tt4:	3200	R
	Pt5:	17485.6	psf
	Tt5:	2558.2	R
	turb_Eff:	0.964316	
	Pt9_over_P9:	7.7709	
	Pt9:	17310.7	psf
	P0:	2116.25	psf
	P0_over_P9:	0.95	
	M9:	2.00843	
	T9_over_T0:	3.07291	
	V9_over_a0:	3.38039	
	Vexit:	3774.32	ft/s
	thermal_Eff:	0.437469	
	propulsive_Eff:	0.261899	
	overall_Eff:	0.114573	
	mass_flow:	444.092	lbm/s
	Thrust:	46720.3	lbf
	Isp:	3018.39	sec

Appendix D: Input files Example

LO_INPUT.txt

```
config      4
required_Thrust  50000
ref_M0      0
ref_Alt     0
comp_press_Ratio  22
turb_inlet_Temp  3200
AB_throttle_Temp  3700
minMach     0
maxMach     2.5
incMach     0.5
minAlt      0
maxAlt      80000
incAlt      10000
comp_eff    0.94
turb_eff    0.96
burn_eff    0.99
M2          0.56
max_dia     5.0
prop_type   2
num_Engines 1
```

HI_INPUT.txt

```
minMach     2.0
maxMach     5.0
incMach     0.5
minAlt      0
maxAlt      80000
incAlt      20000
burn_eff    0.99
prop_type   1
A1          50
A3          42
num_Engines 1
```


Appendix E: Source Code

The following pages contain all the files used for the T-BEAT program. These include:

T-BEAT.cpp	// main program source code
turbojet.cpp	// turbojet mode source code
AB_turbojet.cpp	// afterburning turbojet mode source code
ramjet.cpp	// ramjet mode source code
atmosphere.cpp	// atmosphere model source code
functions.cpp	// function file source code
turbojet.h	// turbojet mode header file
AB_turbojet.h	// afterburning turbojet mode header file
ramjet.h	// ramjet mode header file
atmosphere.h	// atmosphere model header file
functions.h	// function header file
constant.h	// contains include files and constants
makefile	// used to compile program
firstCGI.cgi	// cgi script for web page
T-BEAT.html	// main program web page
turbojet.html	// turbojet mode web page
AB_turbojet.html	// afterburning turbojet web page
over_under.html	// over-under TBCC web page
in_line.html	// in-line TBCC web page
pre_cool.html	// pre-cooled turbojet web page