



# Smooth T 8.2





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## Preparing Turbine Maps for Gas Turbine Performance Modeling

*GasTurb GmbH*

## **Smooth T 8.2**

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Printed in Germany

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# Foreword

Computer programs that calculate the performance of gas turbines or piston engines with turbocharger need as input a description of the turbine maps (sometimes called also turbine characteristics). These maps are either calculated or derived from a turbine rig test.

The accuracy of the turbine map representation is very important for precise cycle calculations . Remember, that 1% error in low pressure turbine efficiency efficiency can mean - dependent on engine type - up to more than 1% error in specific fuel consumption. It can easily happen, that such an error is introduced into the cycle calculation by use of a low quality turbine map. Both in case the data are scattered or if there are not enough speed lines in the map the interpolation of data is prone to errors .

The turbine characteristics are needed in performance calculation programs in a special format. To produce this format "by hand" is a cumbersome task that takes quite much time because of the scatter in the data. Moreover the data from the turbine rig test usually are not evenly distributed over the tested speed range or the distance between speed lines is big. Interpolation and extrapolation of the measured data are required.

The program Smooth T is a tool that quickly produces high quality turbine characteristics from measured data. Such characteristics can be used not only for performance calculations. One can also evaluate small differences between different turbine versions, for example the effects of Reynold's number, tip clearance, restaggered blades and vanes etc.

However, Smooth T is not only a valuable tool for dealing with measured data. It can also be used to check the quality of any turbine map. One can use, for example, existing turbine maps as input. Various cross plots offered by the program allow a judgment whether the map is a reasonable description of turbine physics or not. Deficiencies can be corrected and physical meaningful interpolations and extrapolations of the map are possible.

Instead of genuine measured data - which seldom are available outside industry and research facilities - one can also take data from figures published in literature. Even relativized turbine map data can be used as input.

The output of the program is tabulated data with the same number of equally spaced points for all speed lines. These data are suited as input into performance programs simulating gas turbines or turbocharged piston engines.

Dachau 2014

Joachim Kurzke

# 1 What You Can Do with Smooth T

Computer programs that calculate the performance of gas turbines or piston engines with turbocharger need as input a description of the turbine maps (sometimes called also turbine characteristics). These maps are either calculated or derived from a turbine rig test.

The accuracy of the turbine map representation is very important for precise cycle calculations. Remember, that 1% error in turbine efficiency can mean - dependant on engine type - up to 1% error in specific fuel consumption. It can easily happen, that such an error is introduced into the cycle calculation by use of a low quality turbine map. Both in case the data are scattered or if there are not enough speed lines in the map the interpolation of data is prone to errors.

The turbine characteristics are needed in performance calculation programs in a special format. To produce this format "by hand" is a cumbersome task that takes quite much time because of the scatter in the data. Moreover the data from the turbine rig test usually are not evenly distributed over the tested speed range or the distance between speed lines is big. Interpolation and extrapolation of the measured data are required.

The program Smooth T is a tool that quickly produces high quality turbine characteristics from measured data. Such characteristics can be used not only for performance calculations. One can also evaluate accurately small differences between turbines, for example the effects of tip clearance, re-staggering blades and vanes, cooling air injection, Reynold's number, etc.

However, Smooth T is not only a valuable tool for dealing with measured data. It can also be used to check the quality of any turbine map. One can use, for example, existing turbine maps as input. Various cross-plots offered by the program allow a judgment whether the map is a reasonable description of turbine physics or not. Deficiencies can be corrected and physical meaningful interpolations and extrapolations of the map are possible.

Instead of genuine measured data - which seldom are available outside industry and research facilities - one can also take data from figures published in literature. Even relativized turbine map data can be used as input.

The output of the program is tabulated data with the same number of points for all speed lines. These data are suited as input into performance programs simulating gas turbine or turbocharged piston engine performance.

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## 2 Installing the Program

### Requirements

For running the program Smooth T 8.2 you need a PC with a color monitor which has a screen resolution of 1024x768 or better. Windows 2000, Windows XP, Windows Vista, Windows 7 and 8 are suitable operating systems. The license server, used for Floating and Site Licenses, can run on Windows, Max OS, Linux or Solaris.

### Installation

Run setup for installing the program. A wizard will lead you through the details of the installation. Install Smooth T 8.2 in its own, new directory and do not install it in the directory of any previous program version you may have. Some of the files delivered with Smooth T 8.2 have the same file name as those of previous versions, but different file contents. Mixing the files from different versions of Smooth T will cause a program crash.

### Installation on a Network

On a network you can store the program in a directory which everybody can access. The different users should store their private data in their own directories for maps. Note that the example maps delivered with the program must reside in the same directory as the program. You can store a copy of these files in any private component map directory.

A Microsoft security patch now prevents HTML Help .CHM files from being opened on network drives. When you call help, "Action canceled!" will be displayed instead of the topic text. This will happen with all HTML Help files that you open over a network connection (note, that local HTML Help files will not be affected).

The reason for this error is a new and more strict security policy for Microsoft Internet Explorer. Microsoft is permanently updating MSIE to fix potential or real security threats. In case of this error, the Microsoft Security Bulletin MS05-026 disables HTML Help files opened from a network drive. Learn more about the security threat in the Microsoft Knowledgebase Article KB896358.

When you install the program on a network, please ensure that the help file (file extension .CHM) gets installed on the local C: drive (this is recommended by Microsoft). If this is not possible or not desirable, you can explicitly register individual help files and folders to allow viewing them over the network or edit the Windows registry to make the security settings less strict in general. Microsoft describes the necessary steps in detail in the knowledge base article KB 896054.

### Using a Working Directory

If you want to store your files in a directory different from the program, you need to start Smooth T 8.2 with a command line parameter. After the program call (separated by a space) add the path to your data. If your path name contains blanks, then you must enclose the path name with quotation marks.

If you have stored the program in directory C:\Program Files\GasTurb\Smooth T, for example, and want your data stored in directory C:\My Documents\Smooth T\Data, then you must start the program by the following command sequence:

```
C:\Program Files\GasTurb\Smooth T\Smooth_T82.exe "C:\My Documents\Smooth T\data"
```

## 2.1 License software

Additionally to Smooth T 8.2, you have to install a license software called CodeMeter Control Center©. This will be done automatically, if you check the respective box during the setup of Smooth T 8.2.

Moreover, in case you have a Floating or Site License, a license server has to be installed somewhere in your local network. Details about the installation of the license server and the activation of licenses can be found in a guide you have received together with your license information via email.

If you experience any kind of problems during the installation, please contact the support.

### 3 Data Input

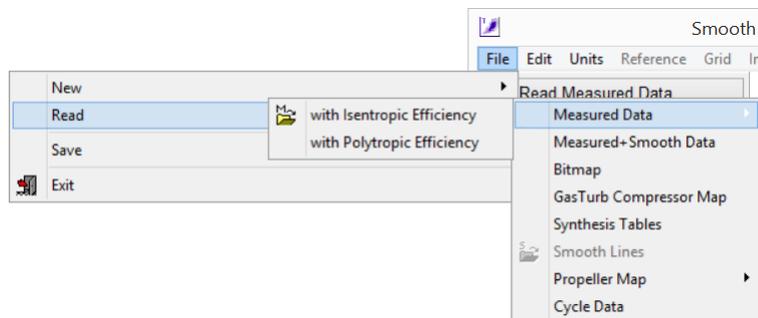
#### 3.1 Input Options

You can select between several input options from the menu option *File|New*:



Selecting *File|New|Measured Data* opens the data input editor window in which you can [enter your data manually](#).

If you want to read data from file then select *File|Read*:



Selecting *File|Read|Measured Data* allows reading the input data, for which a smooth map is to be created, from file. [Measured Data](#) are stored in a file with the file name extension MEA and may contain isentropic or polytropic efficiency values. Polytropic efficiency data will be converted to isentropic efficiency immediately after the data input process.

If the option *Measured+Smooth Data* is selected, then first a file with measured data is read and second the file with [Smooth Lines](#) (file name extension SMO).

If instead of numerical data only a picture of the map is available, then scan it and store it as a Windows bitmap (file name extension BMP). With Smooth T 8.2 you can read numbers from such a [Bitmap](#).

[Synthesis Tables](#) contain turbine map data in a special format which is required by some gas turbine performance simulation programs (file name extension SYN). A [GasTurb Map](#) has the format as required by the GasTurb program (file name extension MAP).

A file with [Smooth Lines](#) does not contain measured data but the result of the map smoothing process. If you want to read a file with smooth lines as measured data, you can cheat the program: Modify the [map type indicator](#) in such a way, that the smooth data are marked as measured data. Furthermore it is recommended to change the file name extension to MEA.

Measured Data, Synthesis Tables, Cycle Data and Smooth Lines can be read in non-relativized and in relativized form. [Relativized](#) data will be converted to non-relativized data before the map smoothing process commences.

[Cycle Data](#) are data from a gas turbine cycle calculation that can be viewed during the map smoothing process.

## 3.2 Units

The system of units that you select in the program main window affects directly the numbers for the corrected specific work and velocity:

	SI system	US system
Corrected Specific Work $H/T_1$	J/(kg*K)	BTU/(lbm*R)
Velocity	m/s	ft/s

The units for corrected speed and corrected mass flow are arbitrary. However, the numbers for all quantities which are derived from corrected speed or corrected mass flow depend on the units chosen:

Quantity	Formula	Units
Corrected Specific Work	$H/T_1$	ch
Corrected Mass Flow	$W*\sqrt{T_1}/P_1$	cw
Corrected Speed	$N/\sqrt{T_1}$	cn
Torque / [ $W*\sqrt{T_1}$ ]	$H/T_1 / N/\sqrt{T_1}$	ch / cn
Torque / $P_1$	$W*\sqrt{T_1}/P_1 * H/T_1 / N/\sqrt{T_1}$	cw * ch / cn

The program writes a neutral text near to the x- and y-axes of the graphs. You can [edit the text](#) and add the units that apply to your special map, for example.

## 3.3 Measured Data

A turbine rig test is run in such a way, that with a fixed throttle position the spool speed is set to a certain value, say 100% of the design speed. Then a scan is taken and all measured data are stored in a file. With the help of a test analysis program the overall pressure ratio  $P/P$ , the total corrected mass flow  $W_{corr}$ , the specific work, the efficiency, the exit flow angle and other quantities are evaluated.

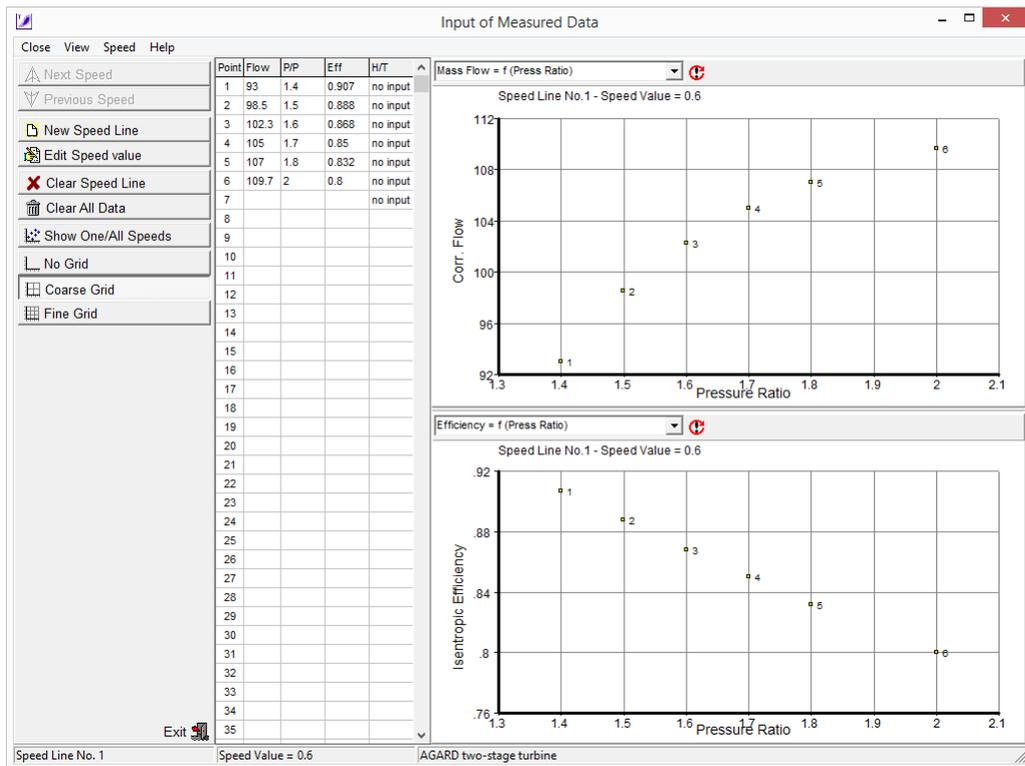
A data point of a turbine map to be read by Smooth T is composed of a selection from the following six numbers:

1. Speed
2. Pressure ratio
3. Mass flow
4. Efficiency
5. Specific work
6. exit flow angle

### 3.3.1 Manual Input

Before entering the data points some general information is requested. Mass Flow is always an input parameter, additionally there are two of the three parameters Pressure Ratio, Efficiency and Specific Work needed. The input of the flow Exit Angle is optional.

Entering data manually is straightforward. Just type the measured values in the corresponding column. The sequence of the data is of no relevance. You can start with the data group for any speed value. Within a data group you can commence with the lowest, the highest or a medium pressure ratio point, for example. Check the graphics for detecting typing errors before closing the window.



### 3.3.2 Reading from File

Usually you will get your data stored in a file which has been created by a turbine test analysis program. Instead of true measured data you can use also the results from a turbine map calculation program as input to Smooth T 8.2.

The first line of a file with measured data must begin with an integer number which indicates the file contents. This is the **map type indicator**.

After the map type indicator there must be at least one blank space. The rest of the line is reserved for the **map title**.

The **second line** in the file must contain the keywords for the input. Valid keywords are:

Mass_Flow	(mandatory)
Pressure_Ratio	(optional)
Efficiency	(optional)

Work	(optional)
Angle	(optional)

Two out of the three keywords *Pressure\_Ratio*, *Efficiency*, *Work* must be used. The sequence of the keywords defines the sequence of the data columns that follow.

The **third line** contains the gas property information, either

- the isentropic exponent gamma and the gas constant in J/(kg\*K)
- the turbine inlet temperature and the fuel-air-ratio

With the second option it is assumed that the fuel is a hydrocarbon similar to Kerosene and Diesel.

The **forth line** must begin with an integer. This gives the number of speed lines to follow. After the number of speed lines there must be at least one blank space. Then either the word *relativized* or *non-relativized* must follow.

After that line there follow the data groups for the various speeds. Each data group consists of a speed line header and a number of data lines. The speed line header contains as the first number the speed value. The second number is the number of data lines to follow.

A data line for a turbine map contains the numbers corresponding to the keywords given on the second line. The sequence of the data is the same as the sequence of the keywords. Note that efficiencies for a non-relativized map must be a number lower than 1 (except for pressure ratios below 1).

The sequence of the data groups within a file with measured data is of no relevance. You can start with the data group for any speed value. Within a data group you can commence with the lowest, the highest or a medium pressure ratio point. You find an example file with measured data of a [turbine map](#) in the appendix.

### 3.4 Smooth Data

The file format for smooth data is very similar to that for measured data, but the [map type indicator](#) is 3 and there are two more data groups.

The first additional group contains the parabola coefficients that define the beta-line grid and the second group contains the coordinates of the [map reference point](#) (speed and beta) and the work and flow coefficients of the map reference point. The map reference data group exists only if the file was written by Smooth T 8.2. Previous versions of Smooth T did not write these lines; if they do not exist then you will be asked to enter reference point data before you can work with the program.

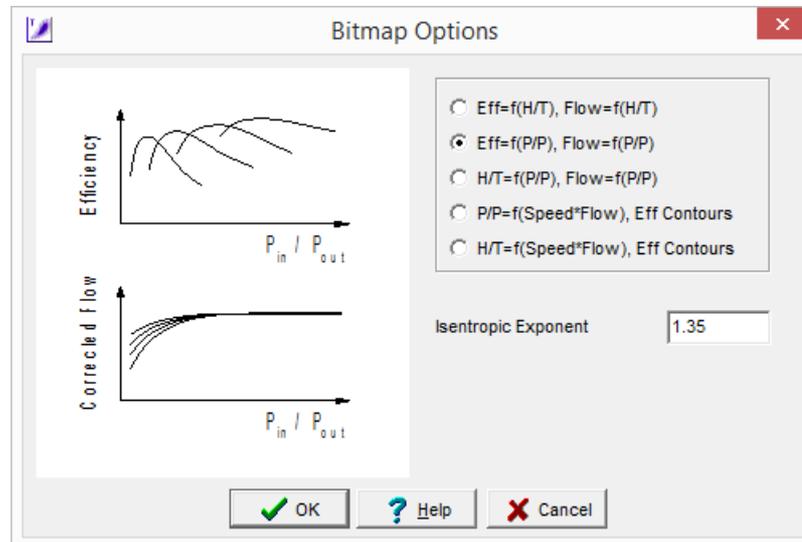
If the pressure ratio is in the range from 0.999 to 1.001 then the efficiency values [are not suited](#) for fully describing the turbine operating point. In this special case instead of efficiency the torque value is written to file. The corresponding number is marked with the letter **T**.

Have a look at the example for a [smooth turbine map](#) in the appendix.

### 3.5 Reading a Bitmap

For reading a bitmap choose the menu option *File|Read|Bitmap* from the program opening window.

In literature, maps are presented in many different forms. You must tell the program, which form your map has. Select from the following options:



If in your map representation the corrected specific work is used, then you must tell the program somehow in which units the specific work is given. The units for specific work will be determined from the data for a single point:

- Efficiency
- Pressure Ratio
- Work

You can take these numbers from the turbine design point, for example. The program will use the numbers for efficiency and pressure ratio to calculate the specific work in SI units. This allows correlating the user input for work with the program internal units for the specific work.

#### 3.5.1 Reading Efficiency from a Bitmap

For the following explanations let us assume, that the map is given as two pictures with both corrected flow and efficiency as a function of pressure ratio.

In the window that opens after loading the bitmap there are two triangles and a square blinking. Click on the square with the left button of your mouse, keep the button pressed and move the square to the origin of the graph showing efficiency over pressure ratio. When you release the button, the origin is fixed and a window opens in which you can enter the values for pressure ratio and efficiency. Note that Smooth T 8.2 requires efficiency values as relative numbers normally in the range from 0 to 1.0. Do not use percentage, even if the picture shows percentage numbers. Click OK to store the data of the origin.

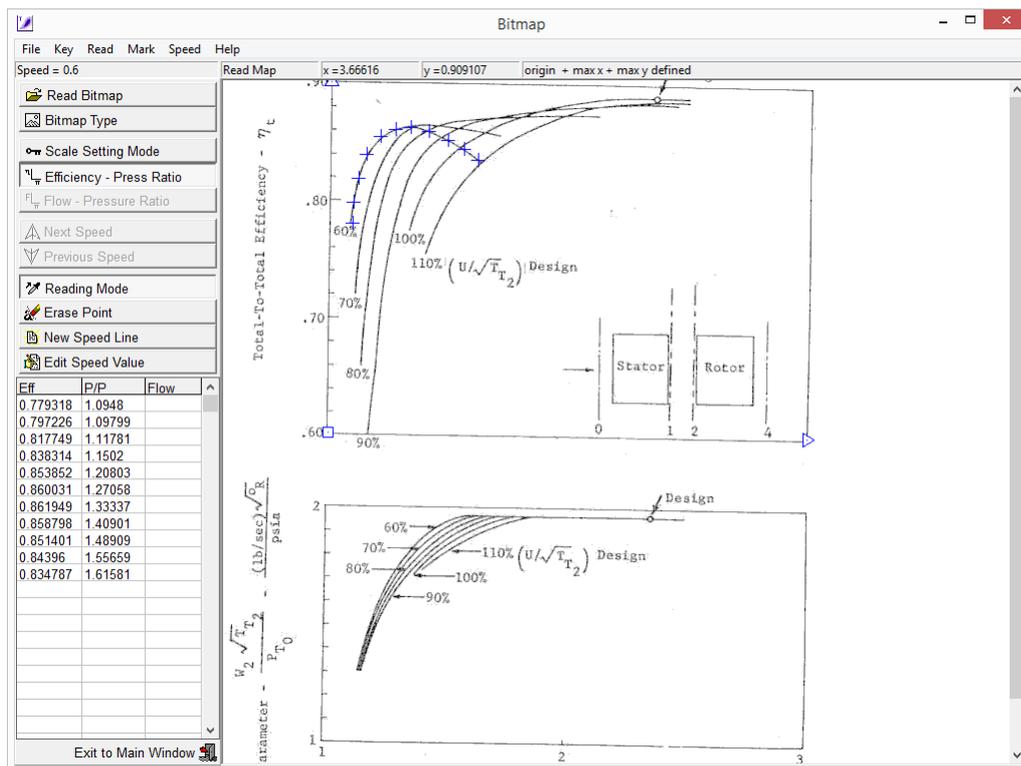
Next click the triangle pointing to the right and move it to a point on the x-axis. After releasing the button, you will be asked for the value of the pressure ratio. The efficiency value is the same as for the origin.

Last click the triangle pointing upwards and move it to a point on the y-axis. Release the button when the triangle is at the right place, then you will be asked for the value of the efficiency. The pressure ratio value is the same as for the origin.

Actually it does not matter which of the blinking symbols you move first to the proper location. You can move the symbols in several steps, and use the scrollbars of the window in between, for example, before you click the OK button.

As soon as you have set all three symbols, you will be asked for the speed value of the first line. After this number has been entered, you can move around with the cross-hair cursor in the bitmap. In the status line the true coordinates are shown as evaluated from the mouse pointer position.

Move the mouse to a point on the first speed line and click. The coordinates of this point will show up in the table on the left. Add the next point to the table by clicking another point on the speed line. The sequence of the points on a speed line is of no importance.



If you have placed a point by accident incorrectly, then you can delete this point by clicking the Erase Point button. Note, however, that you can only delete the latest point.

When you are finished with the first speed line, click the New Speed Line button or *Speed/New Line*. Enter the next speed value and proceed. The sequence of the speed lines is of no importance.

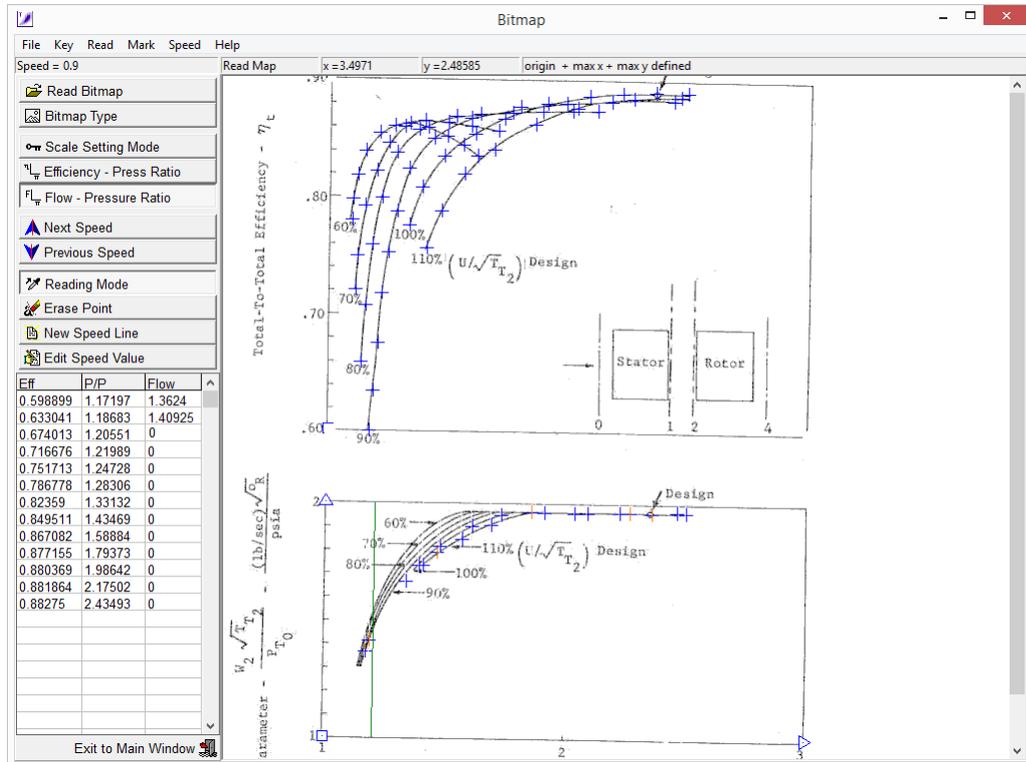
### 3.5.2 Reading Mass Flow from a Bitmap

After all efficiency values have been read from the bitmap, then reading corrected flow values can follow. Click on the menu option *Key* or the Scale Setting Mode button to redefine the system of coordinates.

Again the three symbols for the definition of the origin and the maximum values of the x- respectively y-axis will appear and blink. Place these symbols as required and enter the corresponding values.

## Reading a Bitmap

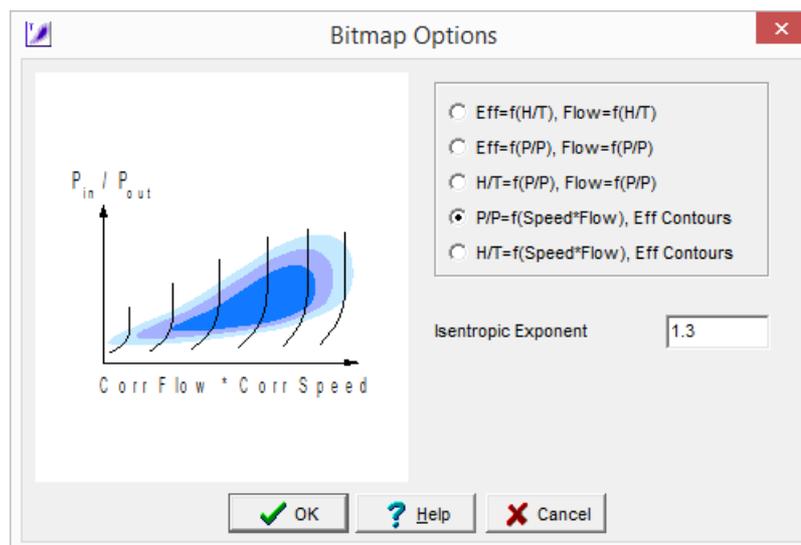
After the coordinates have been set, then click a line in the table on the left. This will draw a vertical line for the corresponding pressure ratio into the efficiency graph. Next move the cross-hair cursor to the bitmap and pick the corrected flow value by clicking at the right place.



Click one table line after the other and pick the corrected flow values from the bitmap. Go also to the other speed lines and complete the map reading.

### 3.5.3 Reading Efficiency from a Map with Contour Lines

For the following explanations let us assume, that the map is given in this format:



Set the blinking symbols for the x- and y-axis as described in the previous section.

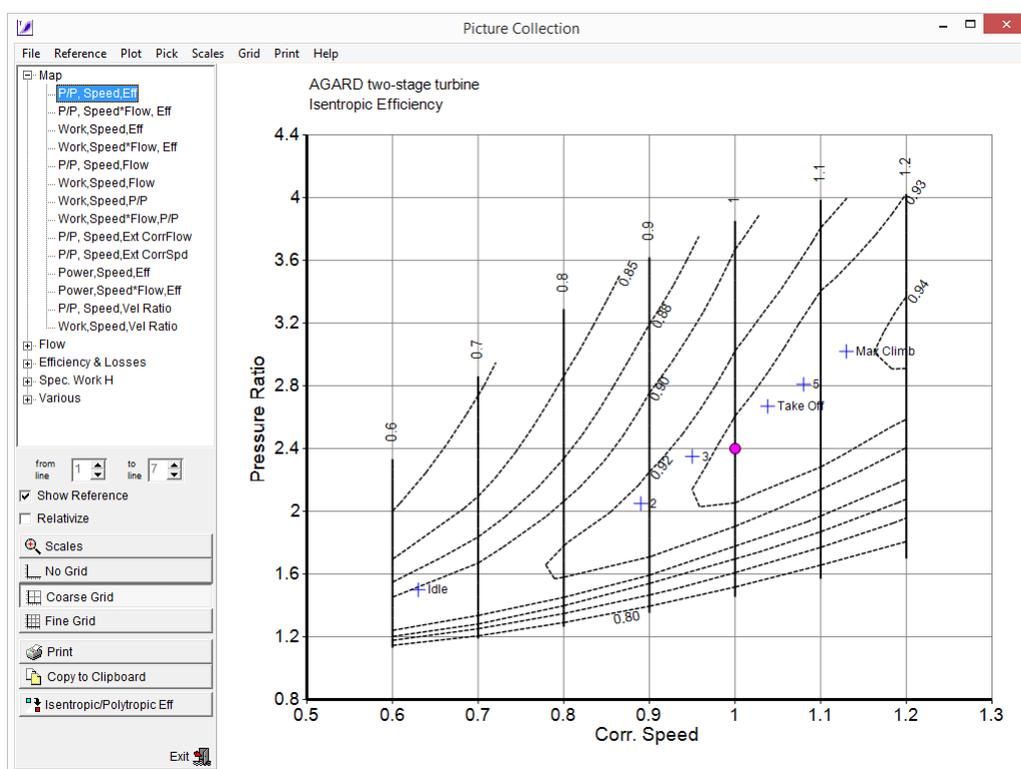
Move the mouse to a point on the first speed line where it crosses an efficiency contour line and click. The coordinates of this point will show up in the table on the left. Then move your mouse to the column with the heading Efficiency and type the efficiency value into the table.

### 3.6 Cycle Data

You can plot data that were calculated with a cycle program, for example, in many graphs. The cycle data may be entered manually (choose *File/New/Cycle Data*) or they can be read from a file (choose *File/Read/Cycle Data*). For the file format please look at the [example](#) in the appendix.

In the picture collection you can switch between graphs with or without the cycle data points. Select *Plot/Cycle Data* in the menu to toggle between the options.

While you are working on the speed lines or the efficiency there will be one or several of the cycle data points shown as a blue crosses. These points have speed values near to the speed you are working on. The deviation between the cycle data and the map will be shown in the mass flow and efficiency definition windows below the working panel.



### 3.7 File Reading Error

If something in your data input file format is incorrect then an editor will open. You can correct the error, and write back the file to disk. After saving try again to read the file. If you are unclear about the error message then have a look at the [keyword](#) definitions and the file format description for measured data respectively smooth data.

Problems may be caused by normally invisible symbols like tabulators instead of blank spaces and special end of line markers.

## 4 Smoothing a Map

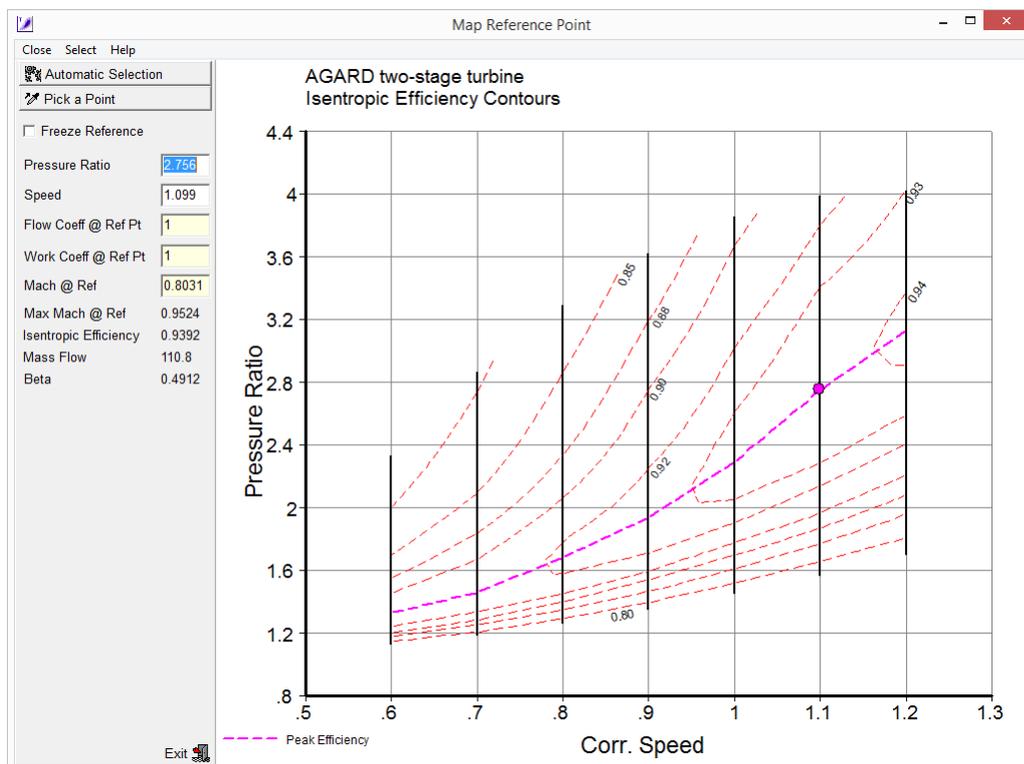
### 4.1 Map Reference Point

In Smooth T 8.2 a map reference point must be selected before smoothing the map can begin. For this reference point the Mach number at the exit of the first stator of the turbine (the Nozzle Guide Vane NGV) must be given as well as values for the flow and work coefficients. It is desirable to use the true turbine design point as map reference point, however, that is not mandatory. A reasonable estimate for the flow Mach number is sufficient if an exact number is not known and for the work and flow coefficients  $\eta_{ref}=1$  and  $C_{ref}=1$  can be used.

Assigning a Mach number to the corrected flow value of the map reference point allows calculating the stator throat Mach number for every other point in the map. Additionally, the axial component of the rotor inlet flow velocity  $V_{ax}$  can be calculated. This velocity, divided by speed, yields a number proportional to the flow coefficient. If an absolute number for the flow coefficient at the map reference point is known, then the true flow coefficient can be evaluated for every point in the map. If the true flow coefficient at the reference point is not known and  $\eta_{ref}$  is set to 1.0, then one can observe at least how the flow coefficient varies throughout the map.

Similarly, the true work coefficient can be found if its value at the map reference point is known. Relative values for  $\eta$  are produced if  $\eta_{ref}=1$  is used.

While smooth data are not available, the reference point can be selected from the available measured data points. After having at least a first guess of the smooth lines the map reference point can be set without restrictions.



The reference point coordinates can be selected automatically employing the following rules:

- If one of the speed lines is labeled 1 in the original map, then this speed is selected.
- Otherwise, the speed with 90% of the highest speed value in the map will be chosen.

Alternatively to the automatic selection of the map reference point you can pick a point from the map with your mouse or enter numbers for Pressure Ratio and Speed to fix a point. If you are working on a map to be used with GasTurb for creating a model that fits to given data, then you should use the map scaling point of GasTurb as the reference point.

If the **Freeze Reference** box is checked then the smooth lines cannot be unintentionally modified in close vicinity to the reference point.

### 4.1.1 Why Freeze the Reference Point ?

Freezing the reference point is helpful if this point is employed in GasTurb as the map scaling point which is the location of the GasTurb cycle design point in the map. If the reference point is frozen during the map smoothing process, then the map scaling factors employed in GasTurb will remain unaffected by the modifications made in other parts of the map. This makes it easier adapting a map to given off-design data.

Map scaling in GasTurb is done in such a way, that Pressure Ratio, Mass Flow and Efficiency are factored with the aim that at the map scaling point the respective values of the cycle design point are equal to those read from the map. Moreover, all speed values are factored to such an extent that the speed value for the map scaling point is equal to 1.0.

For a more detailed explanation of the problem let us assume, for example, that the cycle efficiency is 0.85 and the efficiency in the unscaled map is at the reference point equal to 0.83. While in GasTurb the map is scaled, all efficiency values in the map are factored up by  $f = 0.85/0.83 = 1.024$ .

Let us further assume that from the scaled map at the off design point "A" an efficiency value of 0.9 is read, but the given data to be reproduced with GasTurb say that efficiency there is only 0.89.

In this case the unscaled map must be modified in such a way, that after scaling the efficiency at point "A" is 0.89. In the unscaled map the efficiency at this point is  $0.9/1.024 = 0.879$ . For getting there in the scaled map  $=0.89$  the efficiency in the unscaled map must be reduced to  $0.89/1.024 = 0.869$  which is easily done with Smooth T.

However, that yields the desired effect only if the data of the reference point remain unchanged, i.e. the reference point is frozen. If the reference point is not frozen and the efficiency at the reference point would be changed to 0.825, then the efficiency scaling factor (which is applied in GasTurb to all values in the map) would become  $f = 0.85/0.825 = 1.03$ . The efficiency at point "A" would be affected as every point and the scaled map would show at point "A" the value  $0.869*1.03 = 0.895$  instead of the desired value of 0.89.

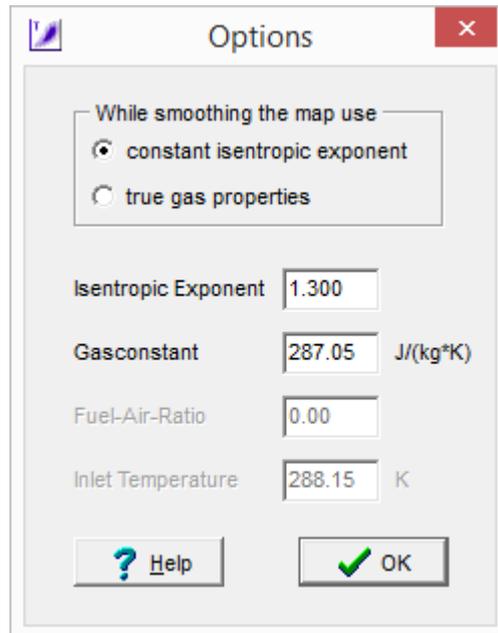
The described unpleasant side effect of modified reference point data can be avoided by "freezing" it.

## 4.2 Gas Property Options

For calculating specific work or torque from pressure ratio and efficiency the gas properties are required. There are two options for the gas properties:

1. constant isentropic exponent and gas constant
2. properties of combustion gases as a function of turbine inlet temperature and fuel-air-ratio

Switching between these options will affect the graphical and the table output for specific work and for torque.



Early versions of Smooth T have used option 1 with gas constant = 287 J/[kg\*K] while the isentropic exponent was an input property.

## 4.3 Defining the Beta Line Grid

After reading the measured data the so-called beta-line grid must be defined which is a net of equally spaced auxiliary coordinates. In this program the beta lines are composed of parabolas.

The beta line grid can be defined [graphically](#) or by the input of the [parabola coefficients](#).

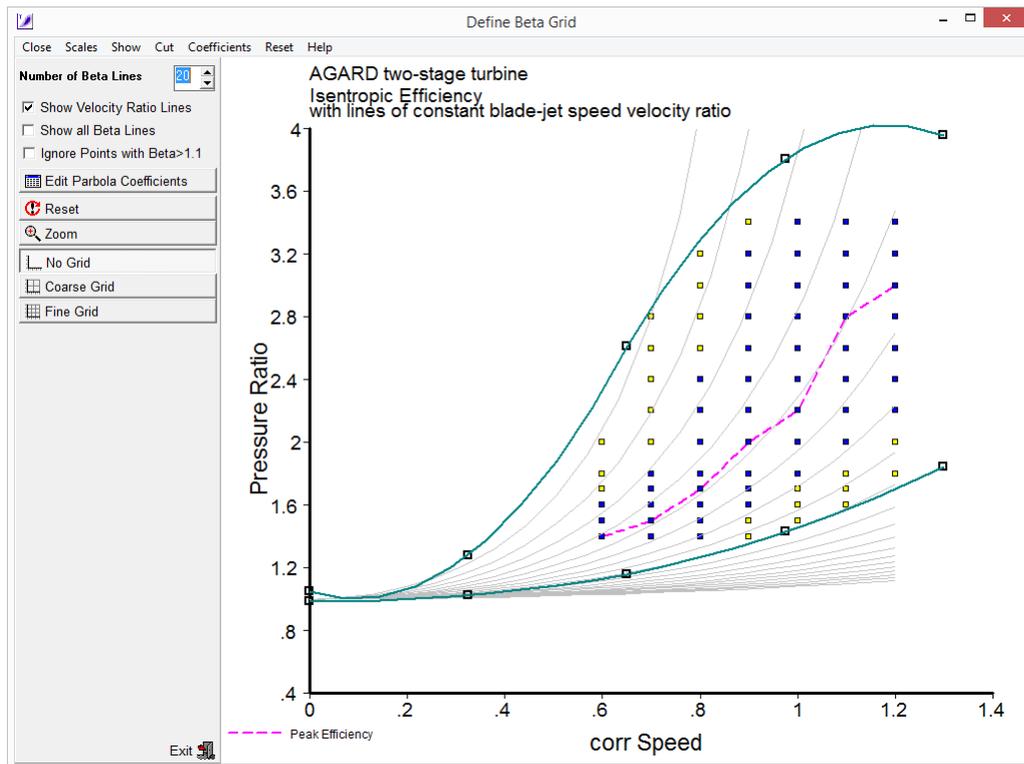
### 4.3.1 Define Beta Line Grid Graphically

You get a proposal for the auxiliary coordinates on your screen with the two lines for beta=0 and beta=1. In the background there are lines with constant blade-jet speed ratio and the peak efficiency line.

You can modify the shape of these two lines easily with your mouse. On both lines you see five squares which define two connected parabolas, one for the lower speed range and one for the upper speed range. From school you will remember, that a parabola is fully defined by three points. If you change the position of one of the points, then the shape of the parabola passing through that point will be modified. Click one of the squares and move it while holding the mouse button down. After you have released the button, the beta lines will be redrawn.

The final map will contain only data on and between the lowest (Beta=0) and the highest (Beta=1) line. Make sure that the line for Beta=0 is below the other line.

From principle the beta lines have no physical meaning. However, if you make your beta lines follow the lines of constant velocity ratio, then they will be correlated with turbine physics.



In the low speed range the efficiency changes rapidly with pressure ratio. There the beta lines should be near to each other and follow approximately the lines of constant velocity ratio because only then you will catch the efficiency values accurately with a dense beta line grid. Following this advice will minimize the [interpolation errors](#) that happen when reading data from the map.

Be careful and enclose all your important data points between the two parabolas. Measured data points that are intentionally outside the beta line grid should be eliminated by selecting the menu command *Cut* respectively by clicking the Ignore Points with Beta > 1.1 button.

If you are not interested in the map region with turbine pressure ratios below unity, then you should select the Beta=0 line in such a way that pressure ratio is everywhere greater than 1. Since for pressure ratio 1 the isentropic specific work is zero, working with efficiency in [the region around pressure ratio 1](#) is not practical. Smooth T 8.2 can handle pressure ratios below 1.0, however, smoothing the lines in that part of the map is more difficult than smoothing other parts of the map.

### 4.3.2 Input of Parabola Coefficients

You can define and edit the beta line parabola coefficients directly after clicking the Edit Parabola Coefficients button.

Parabola Coefficients  $y = a \cdot x^2 + b \cdot x + c$

	lower speed range			upper speed range		
	a	b	c	a	b	c
beta = 0	0.4178	-8.8634E-18	0.98105	0.67103	-0.25654	1.0408
beta = 1	5.206	-0.98157	1.0474	-4.9185	11.667	-2.8964

The input of the parabola coefficients is convenient if you want to use the same beta line grid for two or more maps. Employing the same beta line grid makes it easy to evaluate the differences between two maps.

## 4.4 Smoothing the Mass Flow Lines

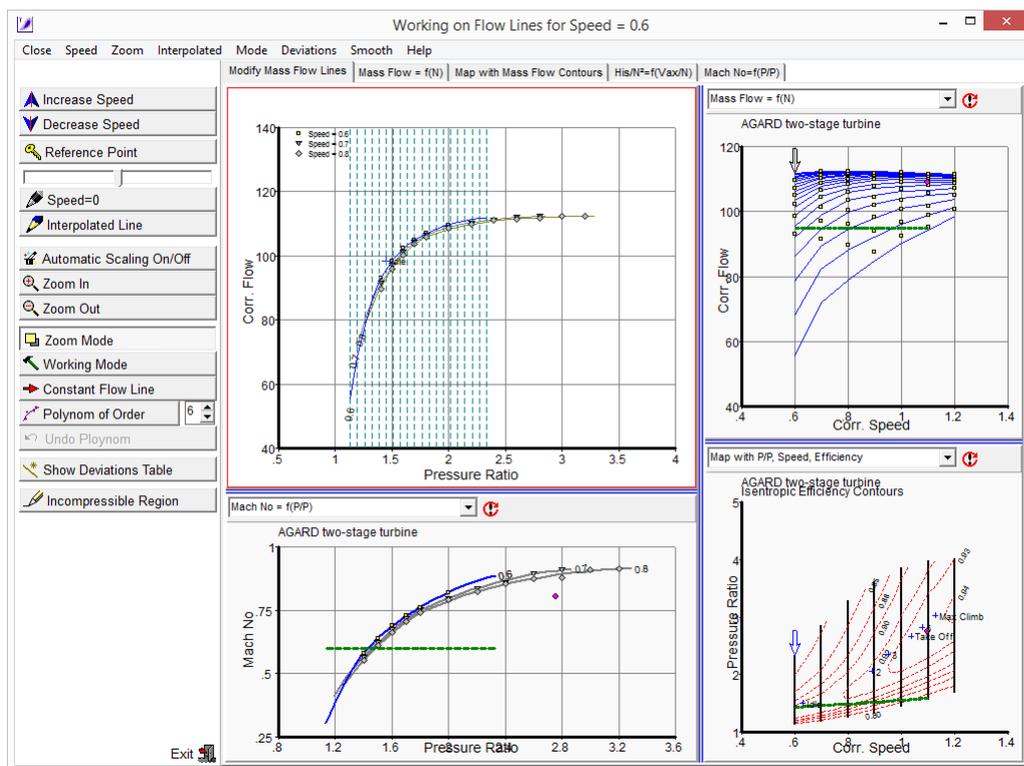
After you have fixed the beta line grid and the Map Reference Point, you can make the mass flow lines smooth.

Click in the program main window the Work on Mass Flow button or select the menu option *Smooth/ Mass Flow* to open the mass flow smoothing window. This window shows in the top left figure the data points of the first three mass flow lines and all beta lines. The beta lines are vertical because the pressure ratio of any beta line is fixed by the intersection of the beta line with the speed line in the [beta line grid definition](#) window.

The line for the lowest speed is illuminated which indicates, that this line is now the active one. The other two mass flow lines are shown for cross reference and comparisons.

The other three figures show alternative views on the data that can be selected from the selection boxes above the figures.

Clicking the tabs below the main menu line will show the most important correlations in full size. Note that you can resize the individual pictures on the Modify Mass Flow Lines page with your mouse: click one of the small blue bars between them, hold the mouse button down and move it as required. After releasing the button all figures will be refreshed.

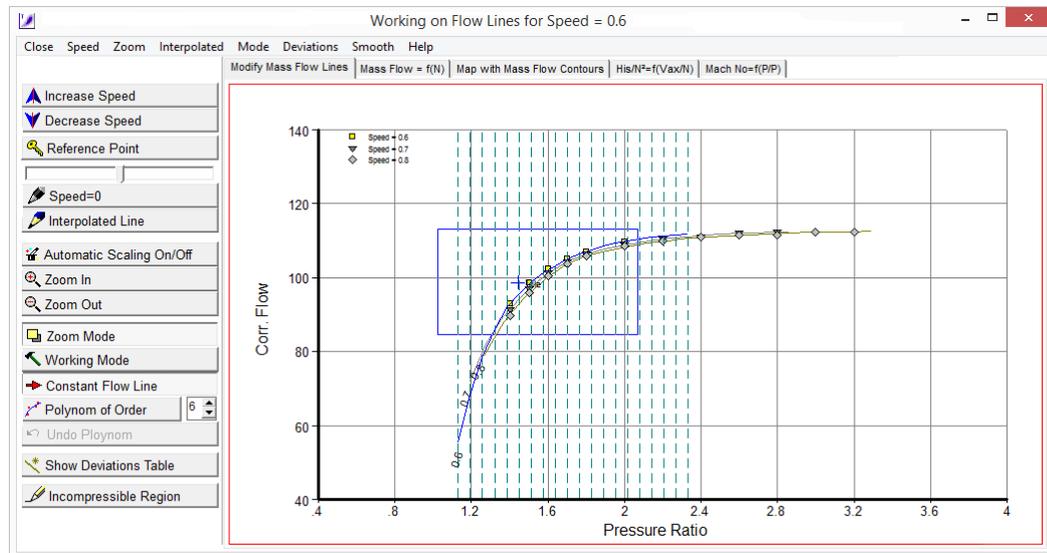


There are two operating modes in this window: the [Zoom Mode](#) and the [Working Mode](#).

### 4.4.1 Zoom Mode

In Zoom Mode you can change the viewport. Zooming out will give you a better overview while zooming in will give you more details. Note that the cursor will indicate that you are in zoom mode by adding a little rectangle to the mouse pointer.

While the pointer has the zoom shape you can draw a rubber rectangle (press the left button and hold it down while selecting an area) to enlarge a part of the map. Another way to change the view is by selecting from the menu option *Zoom|In* or *Zoom|Out*.



The scale for the y-axis in the top left figure is selected automatically according to the corrected flow range of the active line. If you do not want that the flow scales change when the speed is increased or decreased then select *Zoom|Auto Scale* or click the *Automatic Scaling On/Off* button to toggle between automatic scaling on and off.

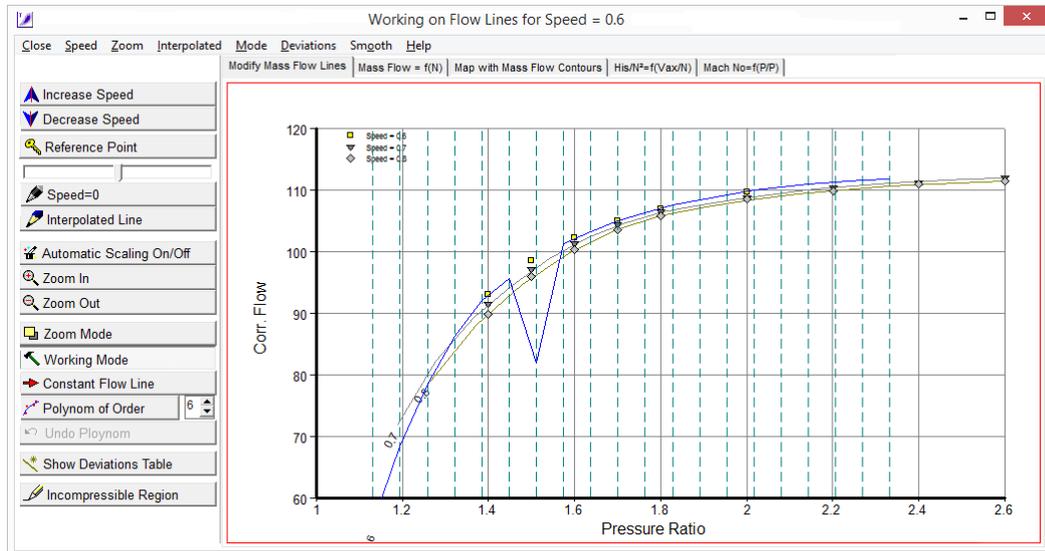
While modifying the mass flow line in the upper left graphic you can simultaneously look at the implications which your modification has on other views. Select between different options from the drop down boxes above each graph. If you move your mouse away from the top left graph then the cursor is configured as zooming tool: you can draw a rubber rectangle to enlarge a part of the graphic. To go back to the default view, click the *Reset Scale* button above the respective graph.

If you have difficulties restoring the normal size then switch to a different speed line and back to the speed line you want to deal with. To do this select the menu option *Speed|Incr* or *Speed|Decr* to increase respectively decrease the speed value. Alternatively you can click the *Increase Speed* or *Decrease Speed* button.

Click the right mouse button while pointing to the top left picture for a popup menu which allows you to switch to *working mode*.

### 4.4.2 Working Mode

In Working Mode you can modify the map in the top left graph. Move your mouse pointer to the location where you want to modify, press the left mouse button and hold it down while modifying the line. Note that the selected point of the smooth line moves along the beta line to which it belongs. Release the button when the line is at the right place. In the example figure below the active line has been distorted intentionally for demonstration purposes.



While you are modifying a speed line, the new numbers for mass flow and pressure ratio are derived from the pixel coordinates on the screen. If the graph in which you are working is small, then the number of pixels that make the x-axis, for example, is also small. The conversion process from the pixel coordinates to the true mass flow numbers is not very accurate in such a case. Therefore it is recommended to make the graph in which you are working as big as practical.

While modifying a speed line you can employ as guide a line which is linearly interpolated between the two neighboring speed lines. Click the Interpolated Line button to make it visible. Since turbine physics is a non-linear science, the true mass flow line will not be identical to this guide line. Nevertheless the interpolated line can be of help for shaping the true line, especially if only a few measured data points are available.

You need not to make the shape of a line very smooth manually. You can use for the final smoothing the menu option *Smooth|Poly Line* or click the button titled Polynom of Order and a best fit polynomial will be found based on the breakpoints of the speed line. Note that the measured data are not taken into account for finding this polynomial. Try with different order polynomials (the order is selected with the spin box to the right of the Polynom of Order button) if the shape of the smoothed line does not satisfy you. Use the Undo Polynom button or the menu option *Smooth|Undo Line* to go back if necessary.

At high pressure ratios the corrected flow can be constant which makes the speed line horizontal. There is a tool which makes drawing a horizontal line easy: While in working mode click the Constant Flow Line button or select the menu option *Smooth|Const Flow*. The cursor will change its shape to a double headed arrow. Now move it to the pressure ratio above which the corrected flow is constant, press the left button and move the mouse while holding the button down. Release the button when you have found the best place of the horizontal part of the mass flow line.

A smooth line represents measured data that have some scatter. Most of the measured data will not be part of the smooth line, there will be deviations. Click the Show Deviations Table button or select the menu option *Deviations|Show* to get a table with numbers for the deviations of the measured data from the smooth line. Deviations lower than the threshold - which you can select depending on the scatter in your data - will not be listed.

### 4.4.3 Some Advice

In the drop down box of the lower left figure you can select the plot Mach No =  $f(P/P)$ . Since the stator throat Mach number can not exceed 1.0, all corrected flow values of the smooth lines must remain below that limit.

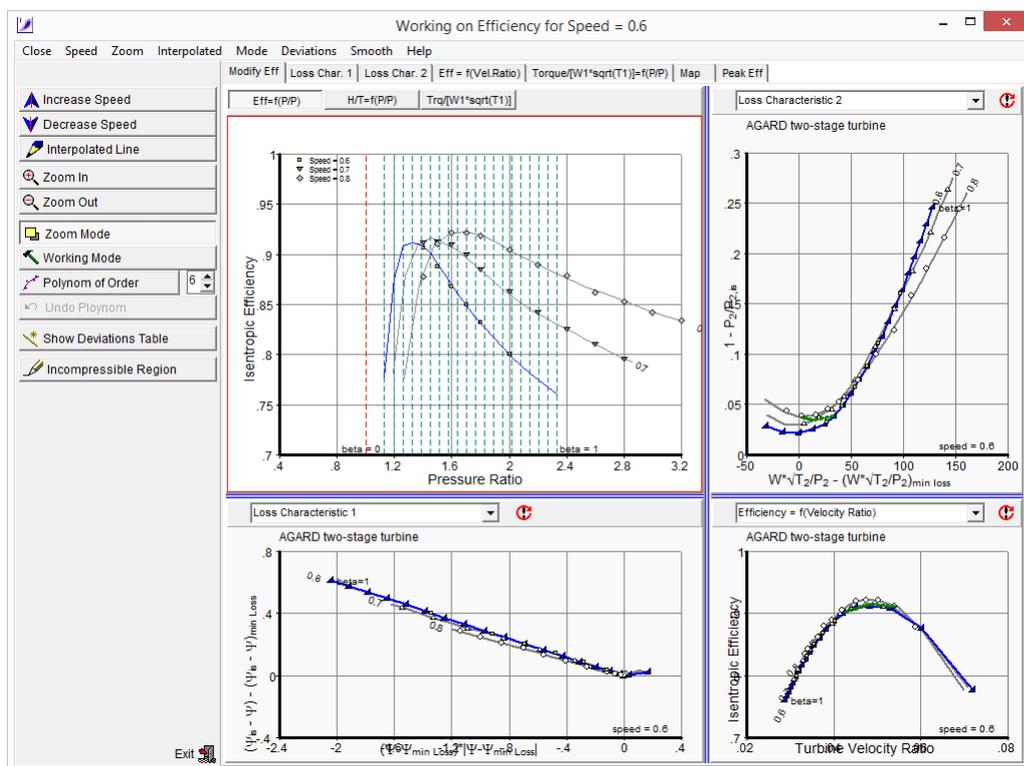
Remember that the content of this plot depends on the data of the [Map Reference Point](#). If you increase the highest value of the corrected flow found in the map while smoothing a flow line, then this can invalidate the input data for the map reference point.

Click the Incompressible Region button to see in many plots a green line which connects points with a NGV throat Mach number of 0.6. This line is an indication where in the map the incompressible flow region approximately ends.

## 4.5 Smoothing Efficiency Lines

It is strongly recommended to begin with smoothing efficiency lines only after the mass flow lines are smooth, otherwise you are unable to make the efficiency and the specific work lines smooth at the same time.

Click the Work on Efficiency button or select the menu option *Smooth|Efficiency* in the program main window to see in the top left figure the data points of the first three efficiency lines and all beta lines. One of the lines is illuminated which means that this line is now the active one.



There are three versions of the top left picture in which the beta lines are vertical. This is because the position of any beta line is fixed by the intersection of the beta line with the speed line.

## Smoothing Efficiency Lines

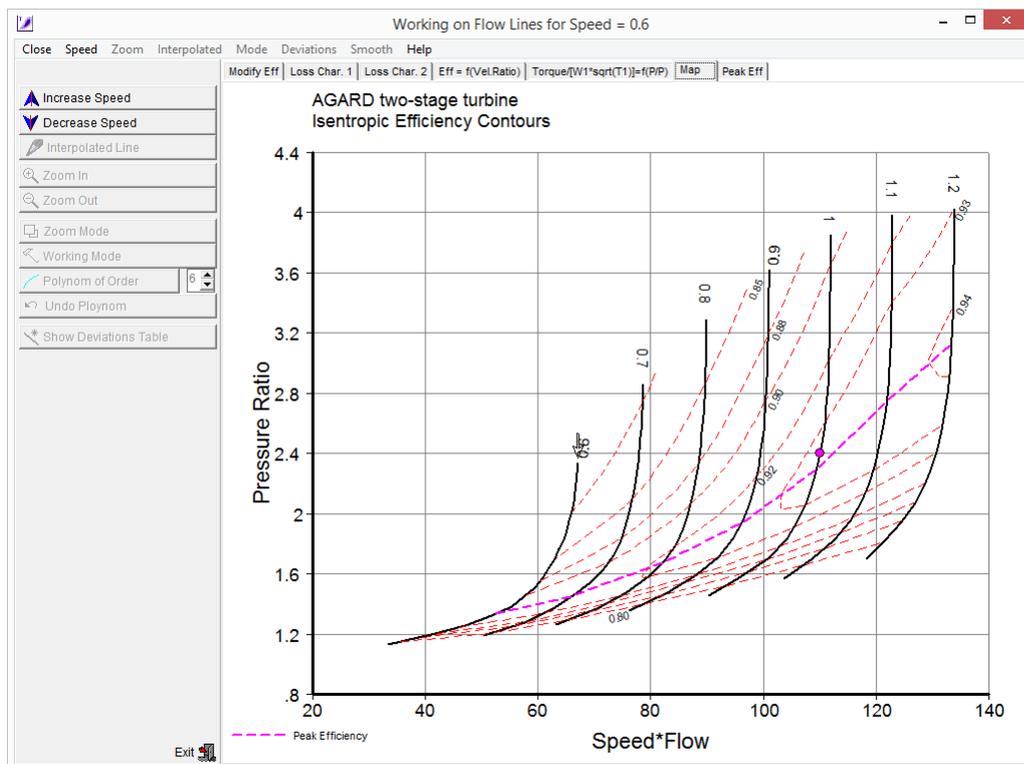
It depends on the shape of the speed lines which of the three graphs is most convenient for smoothing the efficiency line. You can switch between the various graphs at any time. For getting a line roughly right use specific work  $H/T=f(P/P)$  or torque  $Trq/[W\sqrt{T_1}]=f(P/P)$ . For the fine trim smoothing efficiency is more convenient.

As in the mass flow smoothing window there are two operating modes: the Zoom Mode and the Working Mode. You can switch between them by clicking the corresponding button or by selecting from the pop up menu that opens with a click of the right mouse button.

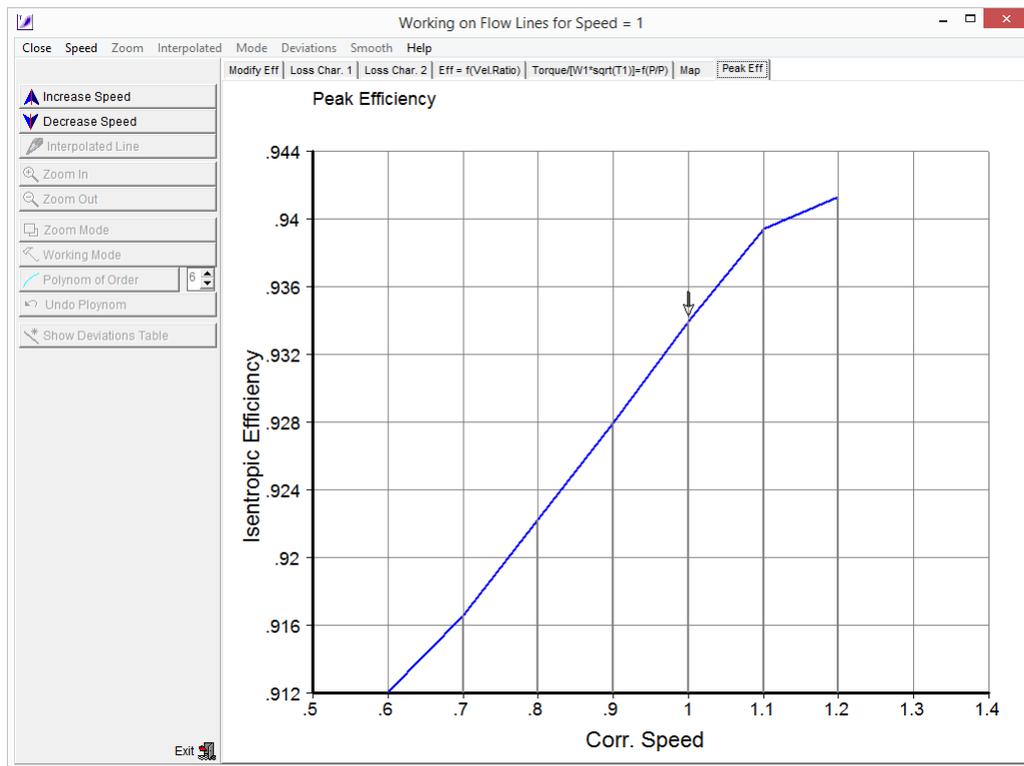
If there are **cycle data** available then those cycle data points that have a speed value near to the one you are working on will be shown as blue crosses. Note that not the true cycle data values are shown in the top left picture, the values shown are from points that are shifted along a line of constant beta to the point where the beta line crosses the speed line in the pressure ratio - mass flow picture.

### 4.5.1 Peak Efficiency

The Peak Efficiency Line is a line which connects the points with the highest efficiency on each speed line. This line is also called the Backbone of the map.



In the *Peak Eff* plot the efficiency along the backbone of the map is shown over speed:



#### 4.5.2 Finetuning Efficiency

For many problems, and especially the interpolation and extrapolation of a map, the specific work is a very helpful parameter to use. However, because of the limited resolution on the screen, the required accuracy in efficiency cannot be achieved in all cases by using the specific work alone.

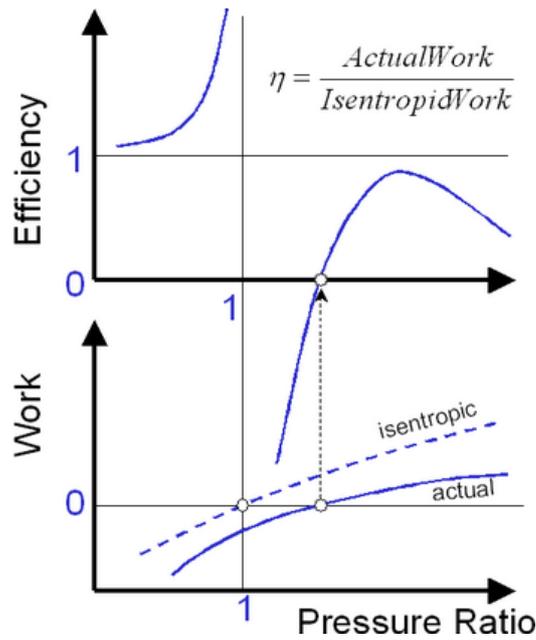
You need not to make the shape of the efficiency respectively specific work line very smooth manually. You can use for the final smoothing the menu option *Smooth|Poly Line* and a best fit polynomial will be found based on the breakpoints of the smooth line. Note that the measured data are not taken into account for finding this polynomial. Try with different order polynomials (the order is selected with the spin box to the right of the *Polynom of Order* button) if the shape of the smoothed line does not satisfy you. Use the *Undo Polynom* button or the menu option *Smooth|Undo Line* to go back if necessary.

After smoothing specific work it is a good idea to check the different efficiency plots and the loss characteristics. Fine-tuning efficiency will not change specific work significantly, but is worthwhile doing it.

#### 4.5.3 Pressure Ratio 1

Drawing efficiency along a speed line becomes difficult where the line work over pressure ratio passes through pressure ratio = 1. At the location where the isentropic specific work is zero, the efficiency changes from  $+\infty$  to  $-\infty$ . In this part of the map it is better to work with the lines for specific work or torque and use the plots specific work over pressure ratio or torque over pressure ratio for defining efficiency implicitly. Make sure, that the effective specific work is always lower than the isentropic specific work. Otherwise, you imply a drop in entropy and thus violate the second law of thermodynamics.

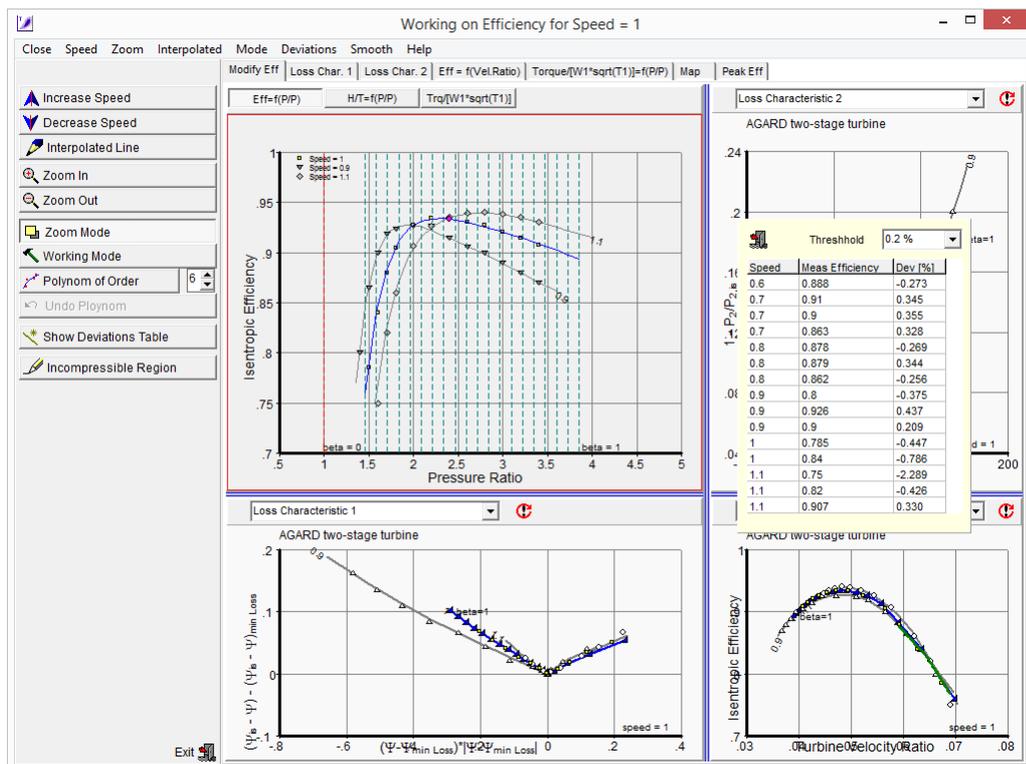
## Smoothing Efficiency Lines



For extrapolation of the map to very low speeds you should consider the similarity of those speed lines to the shape of the speed line for speed = 0. This specific speed line must pass through the point {pressure ratio = 1, mass flow = 0} and will in all other parts have a pressure ratio above one. Specific work is exactly = 0 along all of the line. The mass flow range is from negative choking mass flow to positive choking mass flow. The speed line in terms of flow over pressure ratio will not be symmetrical around the point {pressure ratio = 1, mass flow = 0}.

### 4.5.4 Deviations

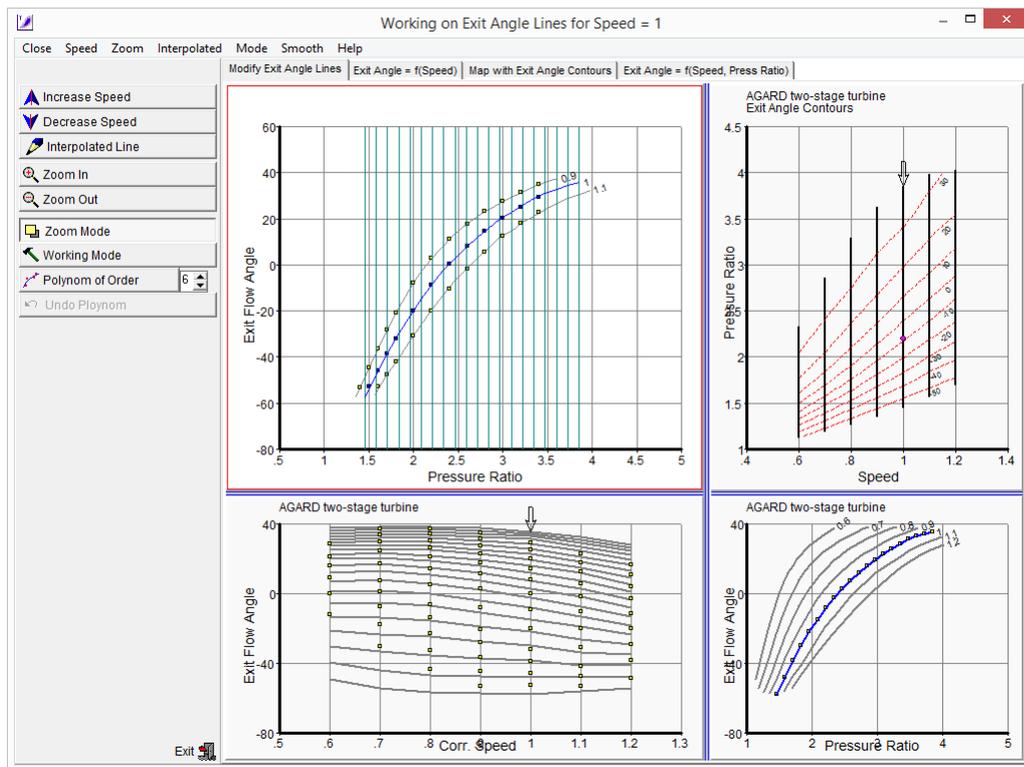
You can check easily the magnitude of the deviations between the smooth lines and the measured data, click the Show Deviations Table button for that and adjust the threshold as required.



## 4.6 Exit Flow Angle

If measured numbers for the turbine exit flow angle are available, then smooth lines can be produced. Turbine exit flow angle is of interest in a performance program if the losses of the component downstream of the turbine depend on the flow angle. An example are the losses of struts after the power turbine in a helicopter engine because there the flow angle can vary over a very wide range.

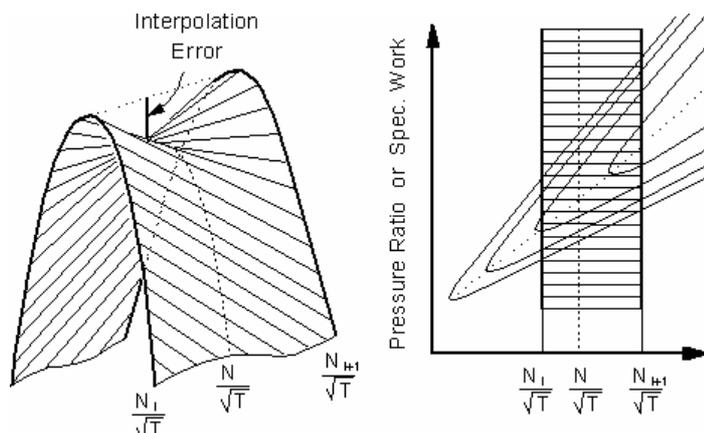
In the top left figure you can modify the lines, check the other three graphs if your modification makes sense.



## 4.7 Extending the Map

### 4.7.1 Interpolation and Extrapolation

If the speed lines are not narrowly spaced and if the beta lines are not approximately parallel to the peak efficiency line then a linear interpolation of the final map in the program that employs the smooth map can result in a significant interpolation error:



One solution to the problem is to interpolate additional speed lines with the help of Smooth T 8.2. Select the menu option *Interpolate* from the program opening screen and enter the desired speed values. You should first smooth all the mass flow and efficiency lines before you do that. The automatically generated speed line proposal will have a poor quality if the lines from which it is derived are not smooth.

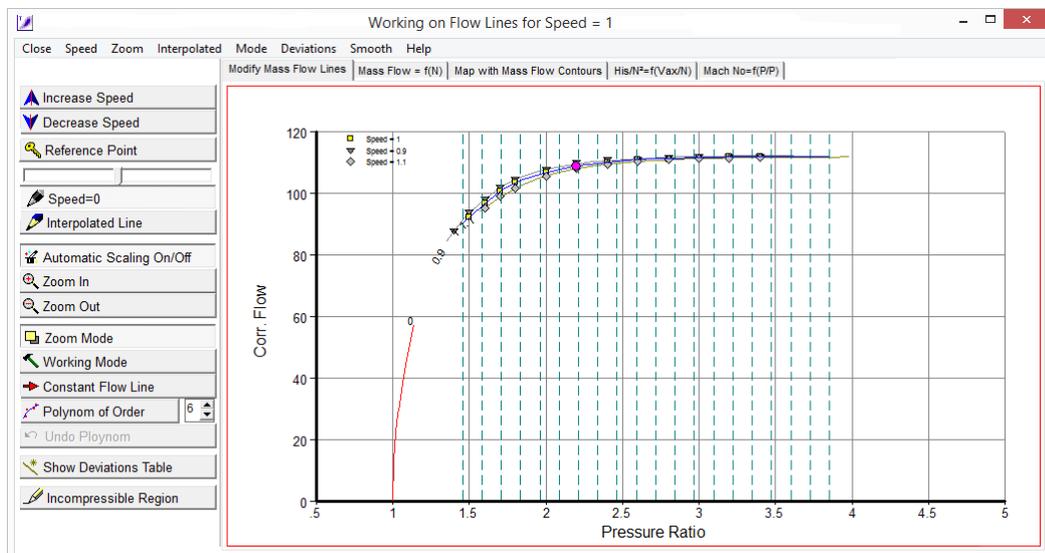
### 4.7.2 Speed Line Zero

The speed line zero has several interesting features which make it very interesting for the extrapolation of a turbine map towards very low speeds. The line passes through the point {Pressure Ratio = 1, Mass Flow = 0}. Blowing through the turbine will yield a corrected mass flow  $> 0$  and requires a pressure ratio  $P_1/P_2 > 1$ . The specific work remains zero for any value of mass flow and pressure ratio, but there will be some force (torque) required to prevent the rotor from turning if the mass flow is not zero.

For moderate corrected flow, if the Mach number is everywhere in the turbine lower than say 0.6, the pressure loss through the turbine will be proportional to dynamic head. Since density and the gas constant  $R$  are invariable it holds

$$\frac{P_2}{P_1} = 1 - k_p \cdot \left( \frac{W \cdot \sqrt{T_1}}{P_1} \right)^2$$

Thus for moderate corrected flow the speed line zero is a parabola passing through the point {Pressure Ratio = 1, Mass Flow = 0}.



In the mass flow definition window click the Speed=0 button to get a parabola which shows how the speed line zero could look like. Reshape it employing the slider above the button to make it consistent with your map. Note that the actual speed line zero will deviate from the parabola at high flow values respectively Mach numbers.

Between the line for the lowest speed for which you have data and the speed line zero proposal you can interpolate additional speed lines. Note that you can not create a line for exactly speed=0 in Smooth T 8.2 because efficiency and other quantities like work and flow coefficients are unsuitable if  $N=0$ .

Torque divided by pressure  $P_1$  is a quadratic function of corrected flow for the speed line zero. Therefore the speed line zero will be linear if plotted as  $\text{Trq}/(W\sqrt{T_1})$  over corrected flow.

Note that the considerations above are only strictly valid as long as the Mach number remains moderate everywhere within the turbine. If the flow is increased more and more by, for example, decreasing the turbine exit pressure with constant  $P_1$ , then the Mach numbers will increase until finally somewhere in the turbine, the flow becomes sonic. Further decreasing the exit pressure will no longer increase the mass flow, the speed line plotted as the mass flow over pressure ratio will become horizontal.

## 4.8 Adapting a Map to Cycle Data

You cannot only use Smooth T 8.2 for drawing smooth lines through measured or calculated turbine data points. It is also feasible to adapt an estimated turbine map to the data you might have from a cycle calculation program or from the output of a computer deck as delivered to customers by an OEM. Thus you can re-engineer the map which was used with the cycle code.

Often the turbine operating points from a full engine simulation do not cover all regions of the map. However, it is most important and often sufficient to get only the given turbine operating points right in a re-construction of the cycle model of interest.

### 4.8.1 Mass Flow

The cycle data points are shown as blue crosses in the working panel. Only those cycle data are visible that have approximately the same speed as the one you are working on.

With the default picture selection the deviation between the given cycle data and the values read from the map are shown in the lower left picture while in the lower right picture the cycle points are shown in the map. It is not difficult to shape the speed line in such a way that the given mass flow values are in line with those read from the map.

### 4.8.2 Efficiency

In the efficiency definition window again the cycle data points are shown as blue crosses. Note that not the true cycle data values are shown in the top left picture, the values shown are from points that are shifted along a line of constant beta to the point where the beta line crosses the speed line in the pressure ratio - mass flow picture.

## 4.9 General Rules

There is an old Latin wisdom which states: "natura non fecit saltas" (nature does not jump). This holds also for the normal operating range of turbo machines, where the flow pattern changes gradually from subsonic over transonic to supersonic. Therefore all aero-thermodynamic parameters in the map of a turbine will be smooth when plotted over speed or  $\beta$ .

It depends on the design of the turbine, whether the maximum corrected flow  $W^*\sqrt{T_1}/P_1$  is dependent on corrected speed  $N/\sqrt{T_1}$  or not. Highly loaded single stage turbines do often operate at design pressure ratio with a choked stator and in this case obviously the maximum corrected flow remains constant in a significant part of the map. In the case of an un-choked first stator of a turbine, the maximum corrected flow is a weak function of corrected speed and  $W^*\sqrt{T_1}/P_1$  decreases when  $N/\sqrt{T_1}$  increases.

## General Rules

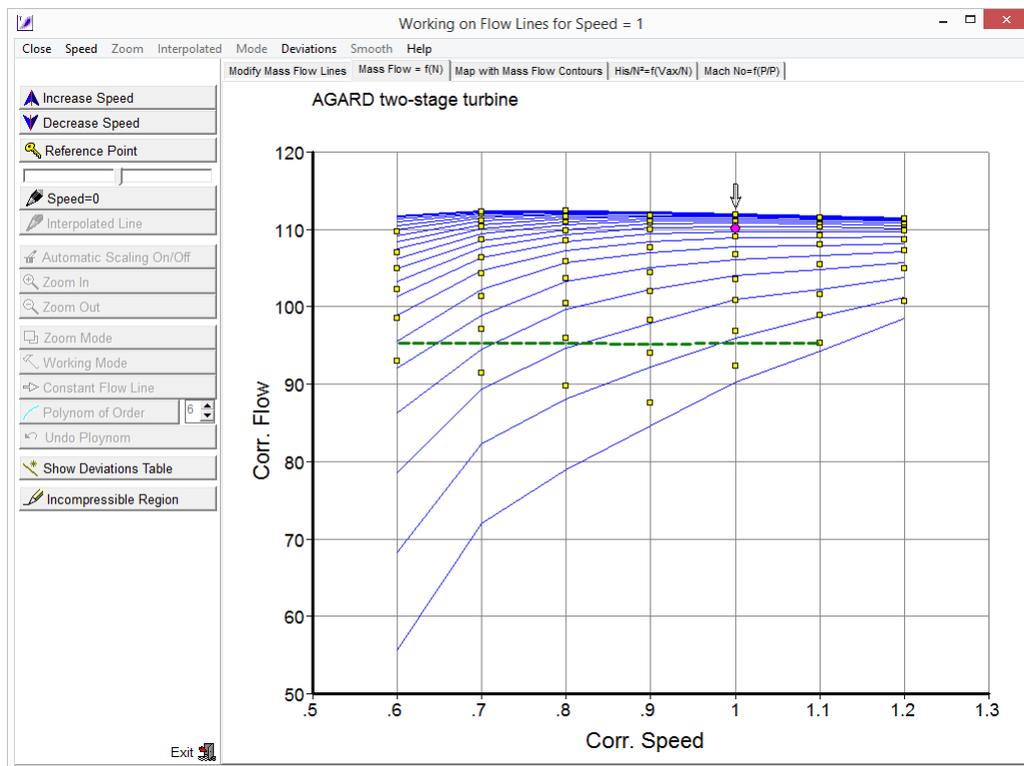
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It is general practice to plot the corrected flow over pressure ratio or specific work. In a plot of mass flow over speed with lines of constant  $\beta$  one can check the consistency of trends both for maximum flow and the partload range.

One can see from a turbine map plot with "efficiency islands" whether the map data are smooth or not. However, one cannot see whether the data makes sense physically. For that purpose it is much better to look at the shape of the lines  $(H - H_{is})/N^2 = f(H/N^2)$  (loss characteristic 1) or the lines  $1 - P_2/P_{2,is} = f(\text{Exit Corrected Flow})$  (loss characteristic 2). These lines look like a bucket with a consistent trend of the minimum loss location with speed.

## 5 Checking a Map

### 5.1 Flow-Speed Relationship

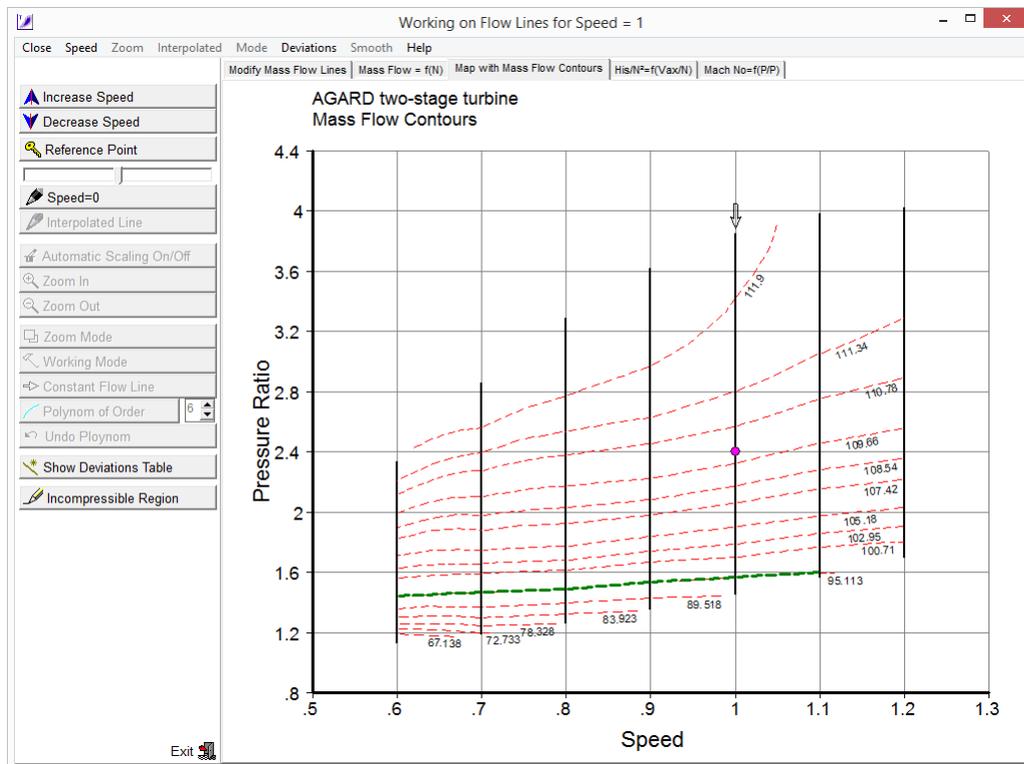


Often the upper beta lines collapse in this plot. This represents the choking mass flow as a function of corrected speed. When the flow through the first vane of the turbine - the Nozzle Guide Vane - is sonic, then the choking mass flow will be independent from corrected speed.

The green line limits the subsonic part of the map.

## 5.2 Map with Mass Flow Contours

The dashed lines are lines of constant corrected flow, the green line limits the subsonic part of the map.



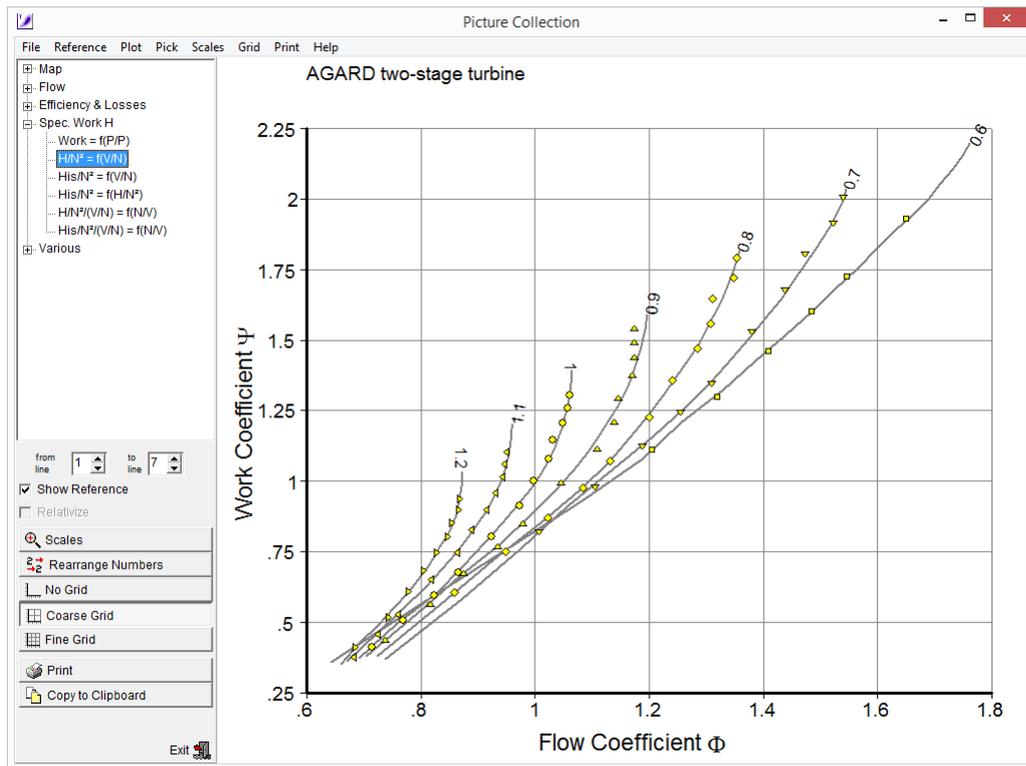
## 5.3 Work and Flow Coefficients

For a single stage turbine it can be concluded from a velocity diagram analysis that in the ideal case the relationship between the **work coefficient** and **flow coefficient** is linear:

$$\Psi = k \cdot \Phi$$

The magnitude of the constant **k** depends on the vane and blade exit flow angles that are assumed to be constant because the flow will essentially follow the respective profile geometry.

In the subsonic flow regime the axial velocity can increase proportional to the circumferential speed. At higher Mach numbers this is no longer possible because the axial velocity component achieves a maximum value due to choking of a vane or blade passage.



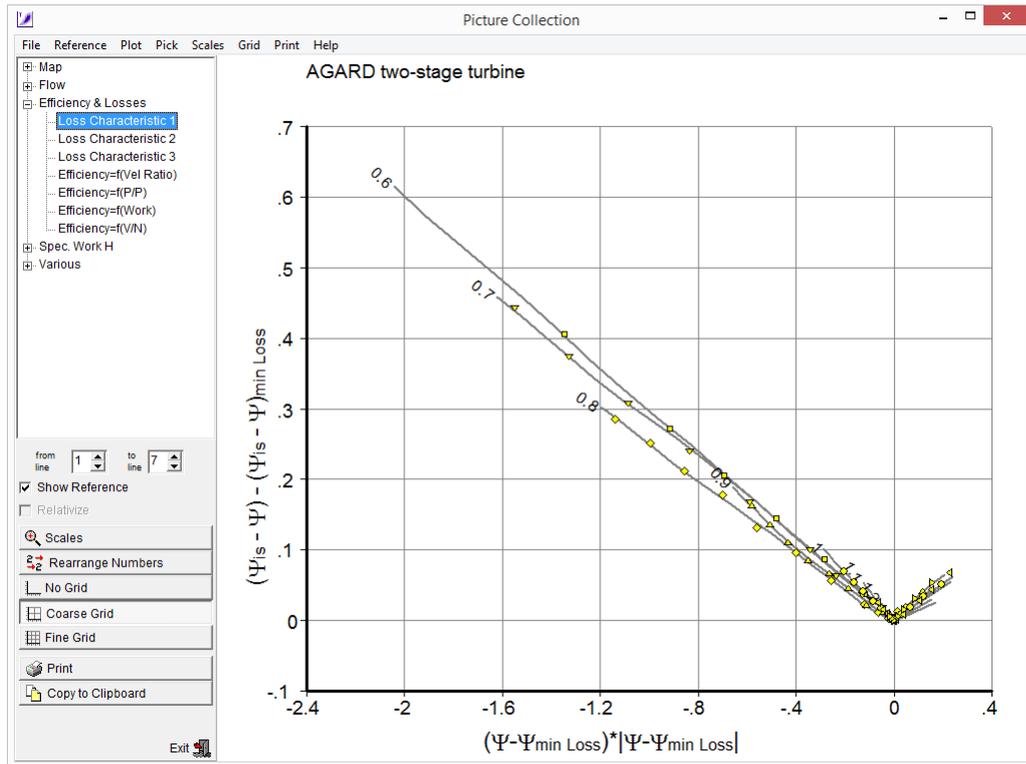
In the user interface of Smooth T 8.2 Greek symbols are employed for the work coefficient which can be identified as  $\psi$  or as  $H/N^2$  and the flow coefficient as  $\phi$  respectively  $V_{ax}/N$ .

In addition to the plots with  $\psi$  there are alternative plots employing  $1/\psi$  as x-axis. These are useful at extremely low speeds where the numbers for  $\psi$  become very big; In contrast, the numbers for  $1/\psi$  remain in a reasonable range.

## 5.4 Loss Characteristics

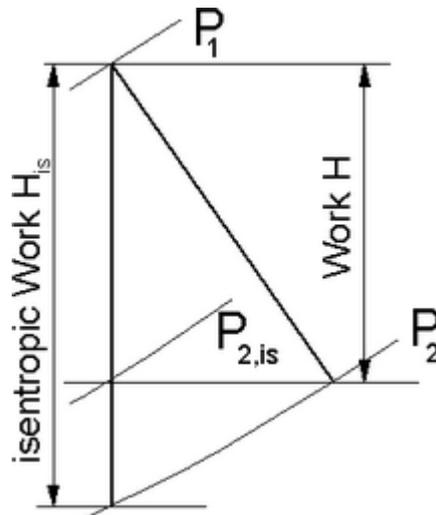
### 5.4.1 Loss Characteristics 1

In the first loss characteristic the x-axis values are a measure of the distance from the peak efficiency point, expressed as difference in  $\psi$  values squared. On the y-axis there are the losses  $1 - \eta$ , compared to those of the point with the minimum losses. This loss characteristic is very well suited for the normal speed range. However, for low speed values it becomes extremely sensitive to small changes.

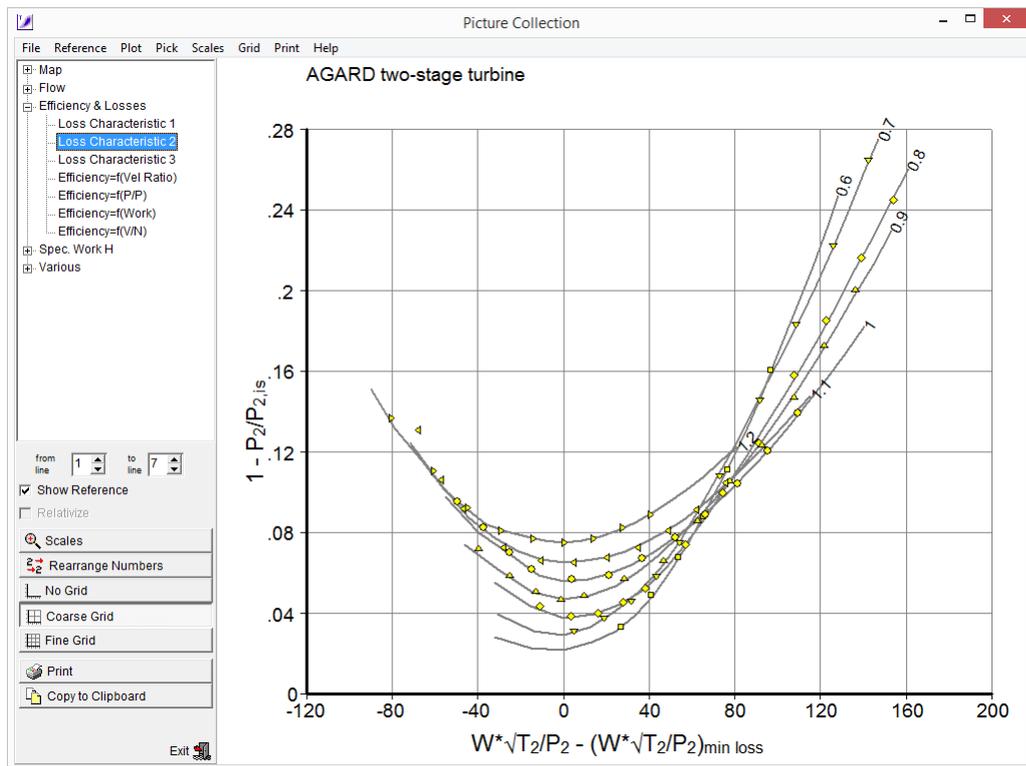


### 5.4.2 Loss Characteristics 2

The second option for describing the losses works very well over the full speed range. Here the losses are described as a total pressure loss from the pressure  $P_{2,is}$  - which would be achieved by an isentropic expansion process with the actual work output - to the real exit pressure  $P_2$ .

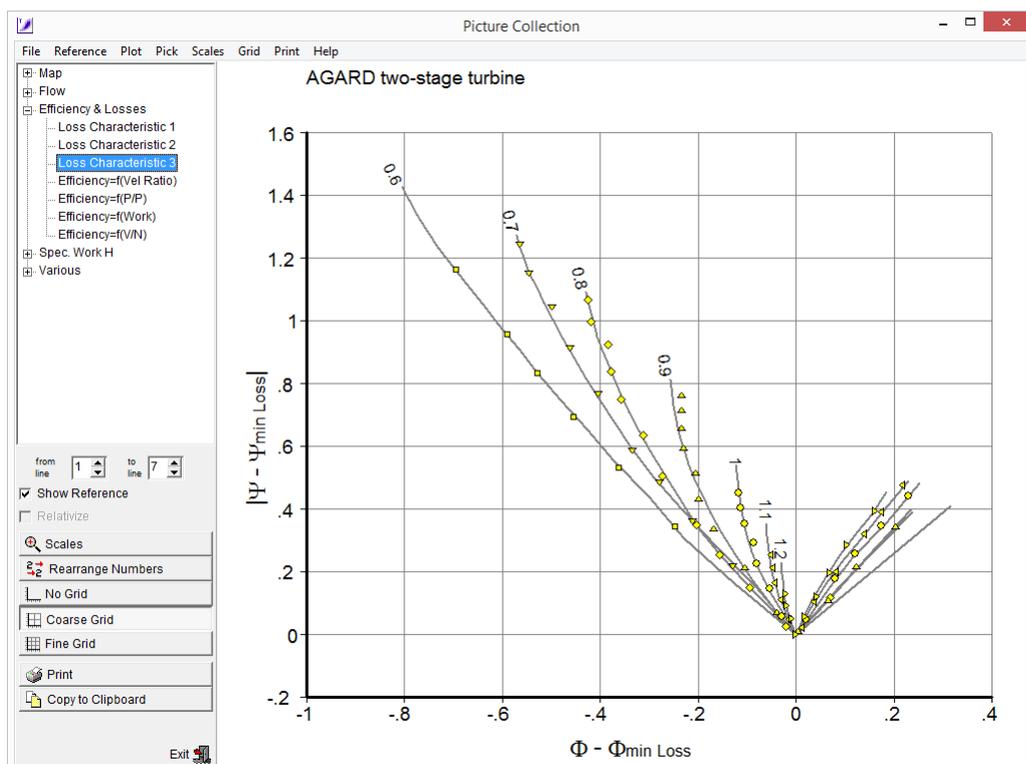


A typical example for this loss characteristic is this:



### 5.4.3 Loss Characteristics 3

The third method of describing the losses shows  $|\Psi - \Psi_{\min \text{ Loss}}|$  which is flow coefficient difference from the location with minimum losses:

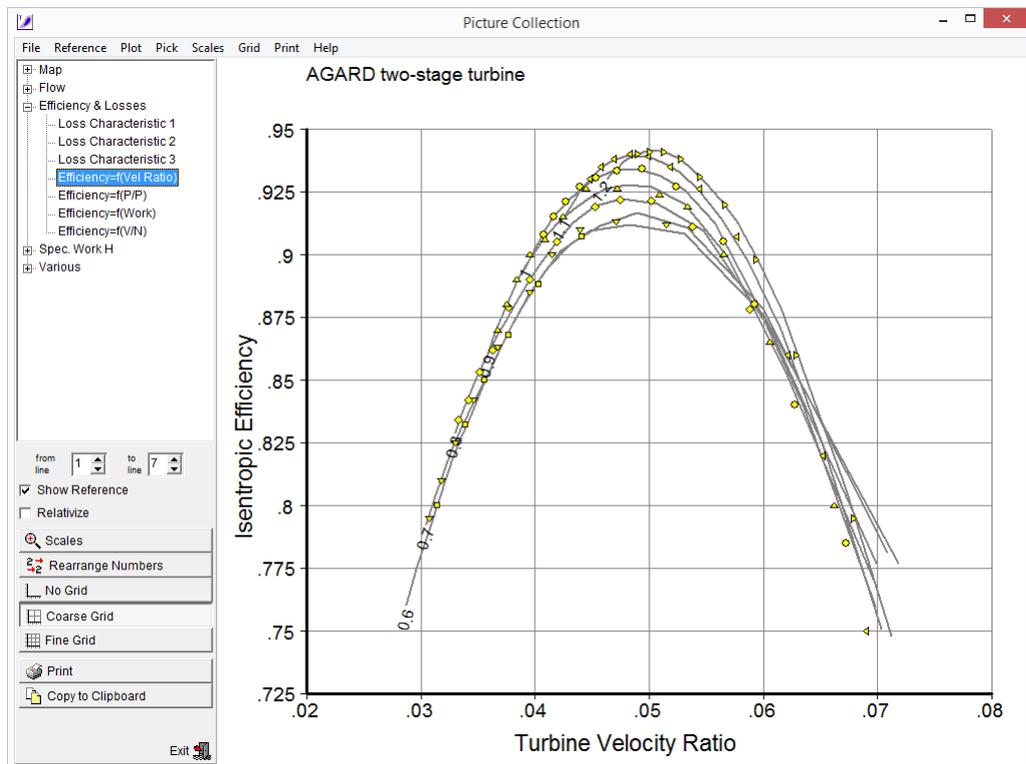


### 5.4.4 Turbine Velocity Ratio

The turbine velocity ratio, also called the **blade - jet speed ratio**, is defined as the ratio of circumferential speed and the jet velocity corresponding to an ideal expansion from inlet total to exit static conditions. In Smooth T the turbine velocity ratio is calculated as

$$V_r = \frac{N/\sqrt{T_1}}{\sqrt{2 \cdot \Delta H_{is}/T_1}}$$

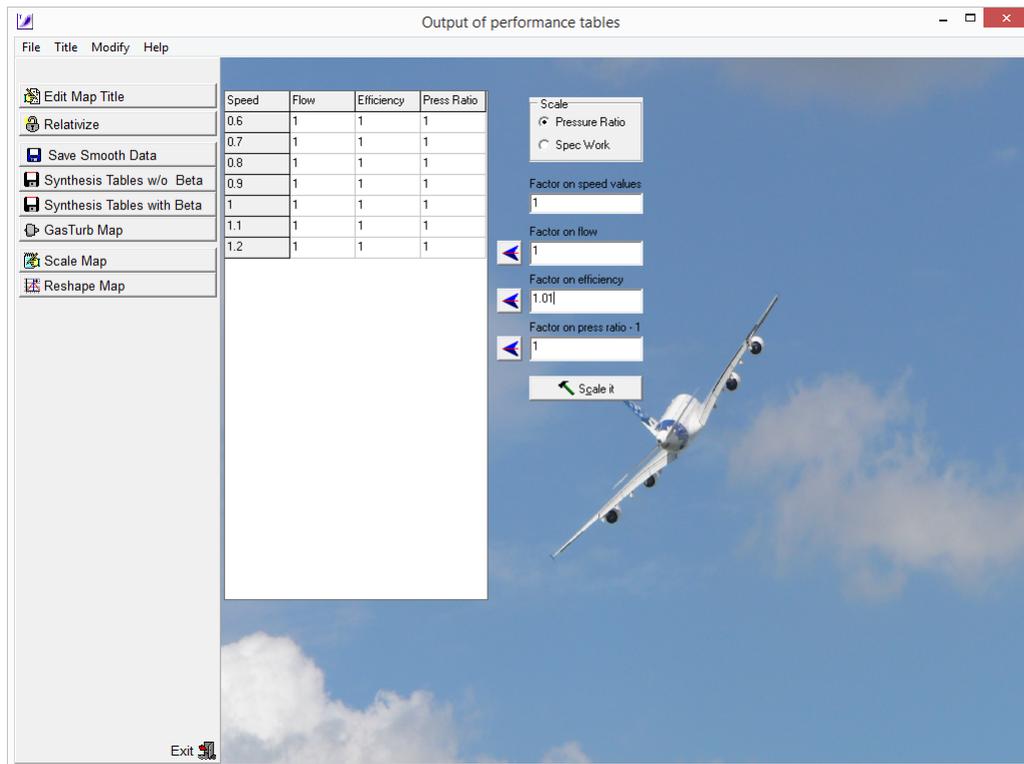
In Reference 1 it is shown for an idealized case of a single stage turbine how static efficiency can be related mathematically to the blade-jet speed ratio. The static efficiency variation is parabolic and reaches its maximum at a blade-jet speed ratio which depends only on the turbine stator exit angle. The conclusion from Reference 1 is that also for a real case the blade-jet speed ratio is a very good correlating parameter for both static and total efficiency.



## 6 Scaling and Reshaping a Map

### 6.1 Map Scaling

Map scaling is selectable from the menu option *Modify/Scale Map* in the program output window. For the scaling method you can decide between pressure ratio scaling and specific work scaling. Often you will scale the map with constant factors. Enter these factors in the boxes to the right of the table and transfer the numbers to the table by clicking the buttons with the arrows, and finally click the Scale It button.



For each of the speed lines you can apply a different scaling factor by editing the numbers in the table. Note, however, that by doing that you can easily produce a map which violates the laws of physics.

GasTurb accepts only maps with relative speed, and all speed values must be lower than 1.5. If you have used absolute speed values or speed in percentage during the map smoothing process then you can convert the speed numbers by scaling them before clicking the GasTurb Map button.

Map scaling is performed in the following sequence of steps:

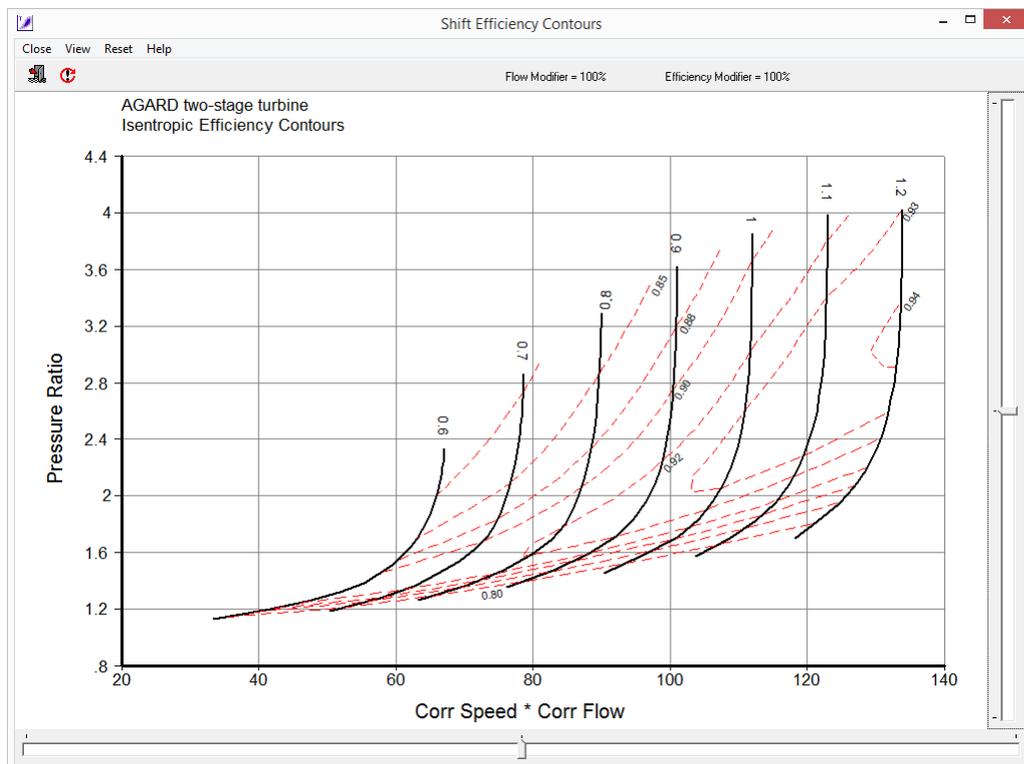
1	Speed	
2	Mass flow	
3	Efficiency	
4	Pressure ratio - 1 scaling	Specific work scaling
	Scale P/P - 1	Scale specific work
	Calculate specific work from pressure ratio and scaled efficiency	Calculate pressure ratio from specific work and scaled efficiency
5	Calculate torque from new specific work and scaled speed	

Consequently scaling speed affects also torque, and scaling specific work affects also pressure ratio and torque. It is highly recommended to go again through the picture collection after scaling a map.

## 6.2 Reshaping a Map

Reshaping a map can be useful if a performance model of a turbofan is to be matched with measured values in the low speed range. In such a case it can be necessary to adapt efficiency and corrected flow of the low pressure turbine independently from each other.

The menu option *Modify/Shift Efficiency* opens a window in which you can shift the efficiency islands up and down in pressure ratio. Furthermore you can modify the slope of the corrected flow versus pressure ratio - see what happens when you move the vertical respectively horizontal slider.



Note that using this feature has nothing to do with the laws of physics; it is pure manipulation of data. Check your results carefully before using a manipulated map in any gas turbine performance simulation program.

## 7 Data Output

### 7.1 Output Options

A list of predefined graphics is offered in the picture catalog for printing and copying to the Windows clipboard. If you do not find your favorite graph there, then you can create it as a [special plot](#).

The program produces three types of output data files:

File content	File extension
Smooth data	*.SMO
Synthesis tables	*.SYN
GasTurb map	*.MAP

The file format for smooth data is nearly the same as that of measured data. The decimal separator which is used as default for file output depends on your country settings in the Windows environment. Synthesis tables and GasTurb tables use always . as decimal separator.

You can save the smooth lines by clicking on the Save Smooth Data button or from the menu *File|Save|Smooth Data* in the program opening window. Synthesis tables and GasTurb maps are only produced from the output window (activate it from the menu option *Output* or with a click on the Output Map button in the program opening window). Before writing output files you have the option to scale the map either manually or automatically.

### 7.2 Relativizing a Map

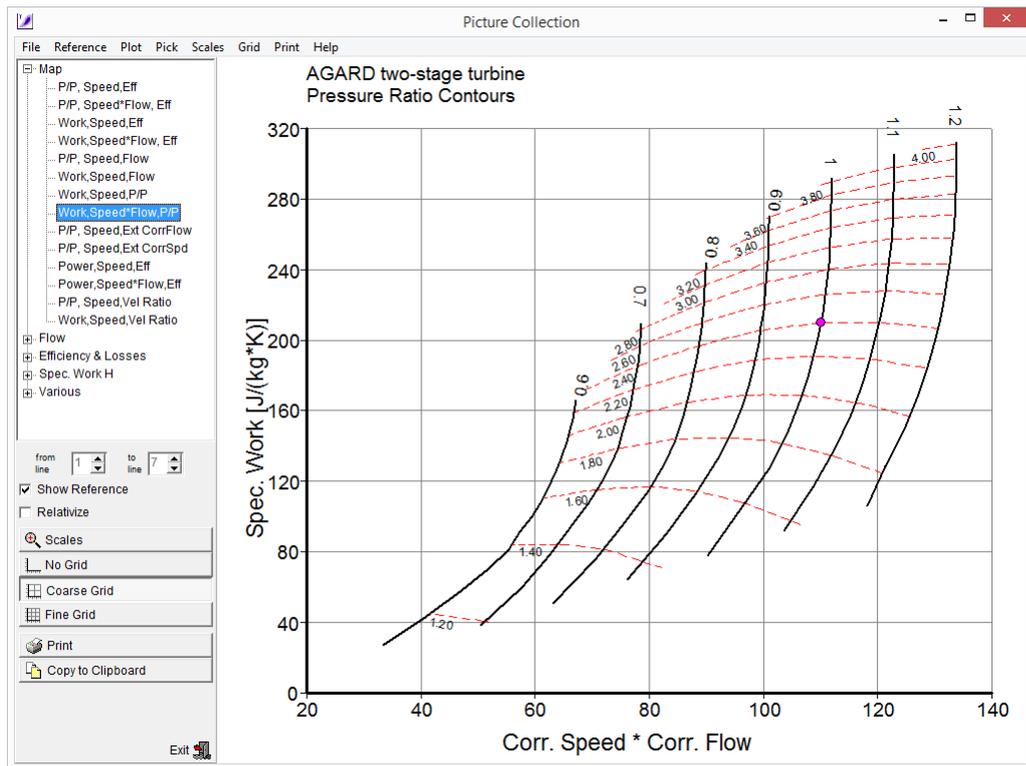
You can relative the map which means that you replace in the output the pressure ratio  $P_2/P_1$  by the relative pressure ratio  $(P_2/P_{1-1}) / [(P_2/P_{1-ref}) - 1]$ , the mass flow by the relative mass flow  $W/W_{ref}$ , the speed by  $N/N_{ref}$  and the efficiency by  $\eta / \eta_{ref}$ . The reference values are those of the [map reference point](#).

Note that you cannot use relativized maps with GasTurb. If you have only relativized data of a turbine, then read the relativized map into Smooth T, guess the turbine design data, and output the map in non-relativized format as GasTurb map.

### 7.3 Graphical Output

The Picture Collection offers many pre-defined views on the data. If you do not find what you are interested in, then select *Plot|Special* from the menu to define your own x and y axes.

If you need numbers, select *Pick* from the menu in the picture collection and you can read data from the graph. Picking in Smooth T employs a linear interpolation between the speed and  $\beta$  lines.



### 7.3.1 Scales in Graphics

The program selects the scales of the graphics automatically with round numbers on both the x- and y-axis. You can easily modify the scales by using the menu option *Scale*. In this way, you can produce a series of plots with the same scale. If you modify the scale of a plot, the program will accept your input only if your wish implies round numbers for the x and y-axis.

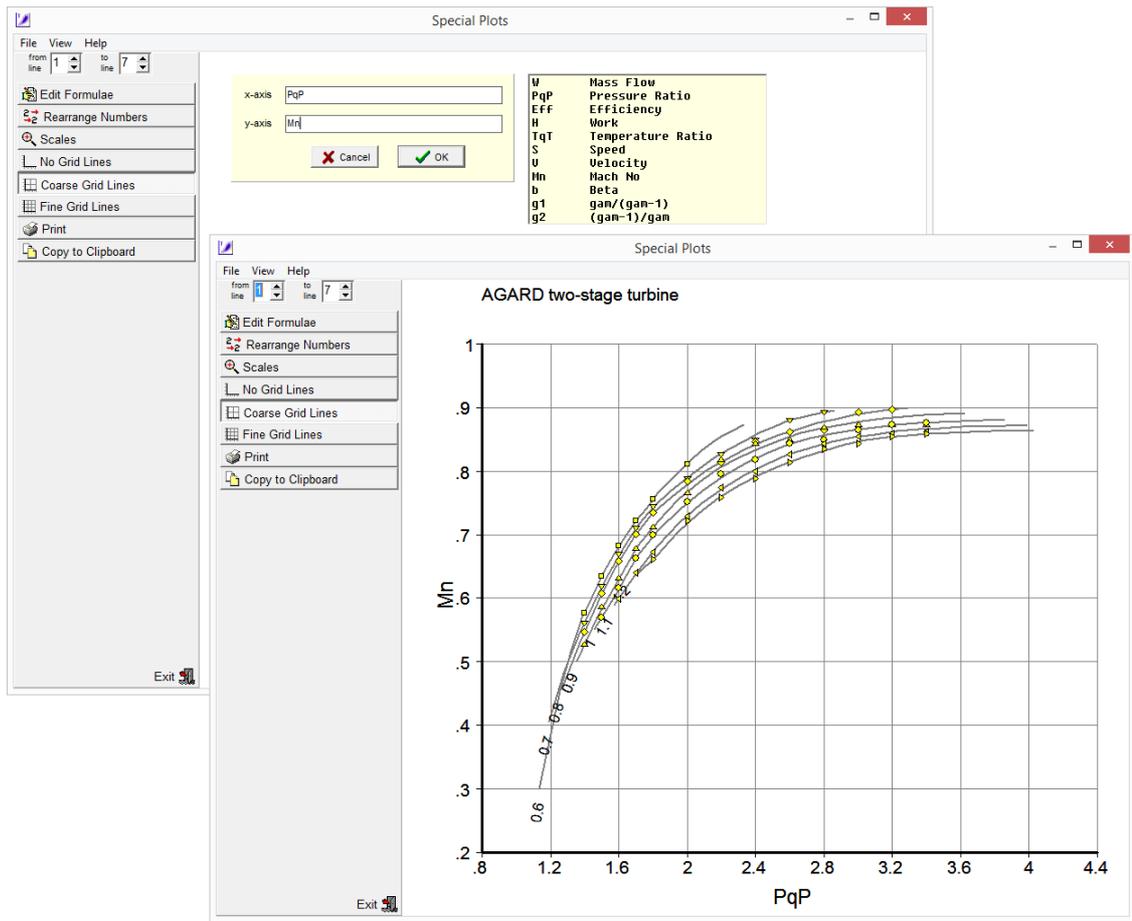
In many places you can zoom into a picture: Press the left mouse button and hold it down while moving the mouse. Enclose with the rubber rectangle the region you are interested in and release the button to initiate repainting the figure. With a click of the right button of your mouse you will zoom out to the standard scaling.

If the range of values is very small, an appropriate number will be subtracted from the values and noted separately at the axis. If for example all values are between 32000.3 and 32000.4 the scale will begin with 0.3 and end with 0.4. Near to the axis the string +32000 will be written.

You can produce graphs with or without grid lines. From a figure with fine grid lines you can read numbers without the help of a ruler. Reading numbers from a plot without grid lines is a cumbersome task because the spacing between grid lines on paper will not be even centimeters or inches. While running Smooth T you can easily read numbers from a map: Go to the picture catalog and select *Pick* from the menu.

### 7.3.2 User Defined Graphs

If you are missing a special plot in the picture collection, then you can define yourself a graph. Select **Plot|Special** from the menu in the picture catalog and enter formulae for the x and the y axes. The list of property names which may be used in the formulae is shown to the right of the input window. You can use the operators +, -, \*, / and ^ in the formula, and also brackets.



### 7.3.3 Text on Axes

You can edit most of the text which is written near to the x- and y-axes. You can add the unit for the corrected mass flow, for example. Store your modifications in a file if you want to reuse them.

Be careful with your modifications: the program will not check whether the text on an axis is according to the content of the graph or not.

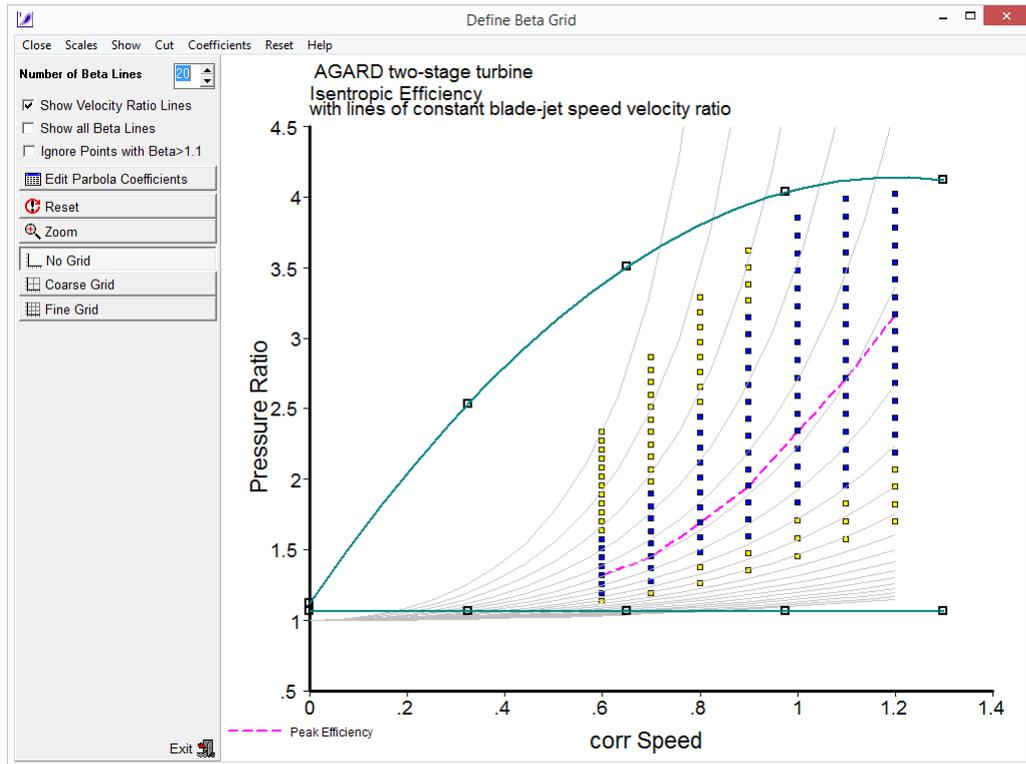
## 7.4 Synthesis Tables

A turbine map as produced by Smooth T consists of several tables stored in one file. The default extension to the file name is "SYN".

The program offers a selection of tables, choose what you need for your purpose. Mass Flow is always an output, the other tables are optional. If you want to read later the synthesis tables produced as "measured data" with Smooth T 8.2, then make sure that the set of tables is consistent with the requirements for the [keywords](#).

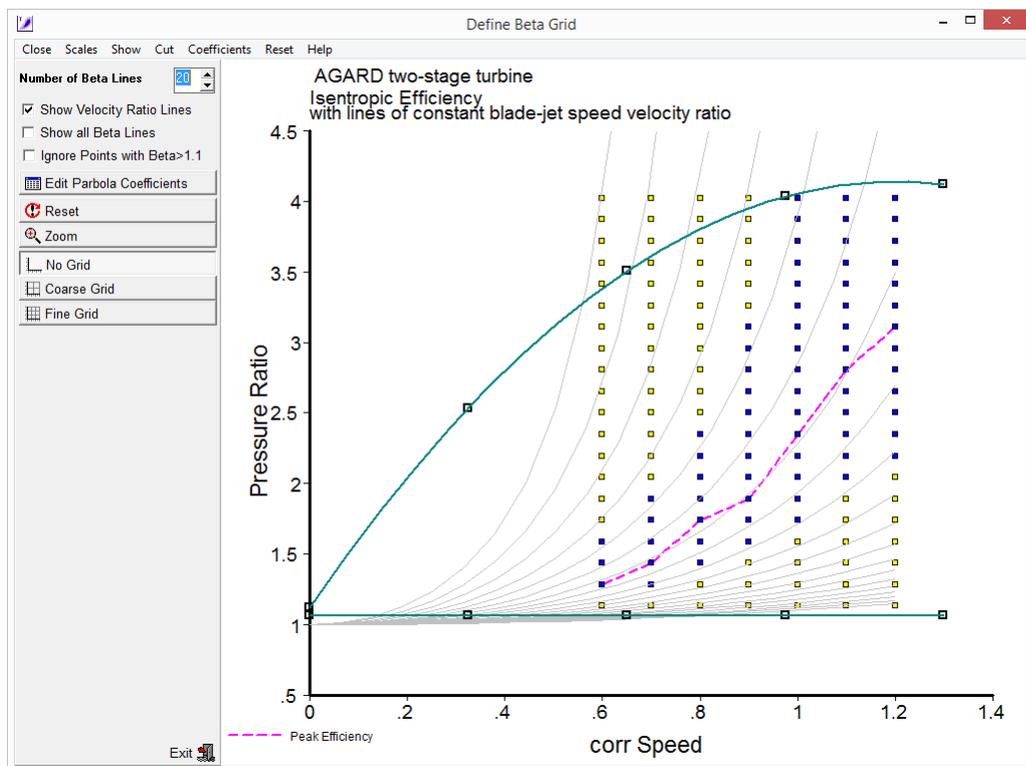
Synthesis tables that employ  $\beta$  as auxiliary coordinates and also tables without  $\beta$  can be produced as output.

In a map employing  $\beta$  the distance between the data points increases with speed. Thus the distance is small in regions where efficiency changes rapidly with pressure ratio. In the upper speed range there are no rapid efficiency changes and the distance between the points can be bigger without losing accuracy.



Map with auxiliary coordinates  $\beta$

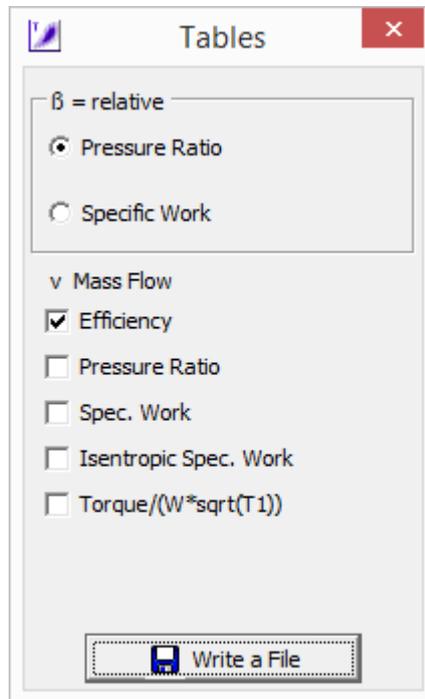
In a map without auxiliary coordinates the distance between the data points is independent from speed. The number of data points must be selected in such a way that the map reading accuracy requirements are met everywhere. Usually synthesis tables without auxiliary coordinates will be much bigger than those with  $\beta$  for a given accuracy. Moreover, there will be many useless data points in the map region where low speed is combined with high pressure ratio.



Map without auxiliary coordinates

### 7.4.1 Synthesis Tables with $\beta$

The following tables are offered for output with auxiliary coordinates.  $\beta$  can mean a relative pressure ratio or a relative specific work.



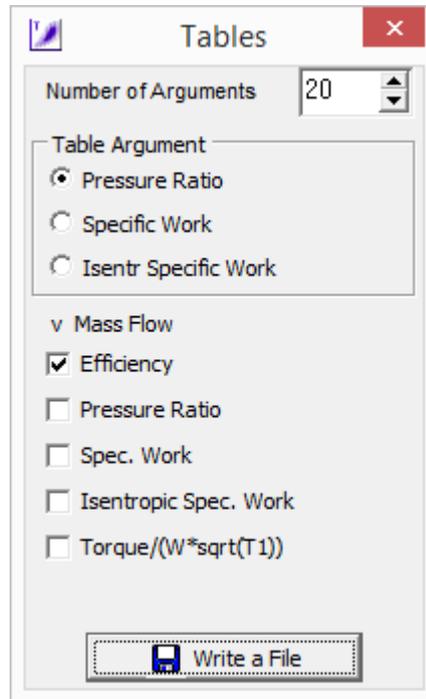
In the program in which you are using the synthesis tables with  $\beta$  as relative pressure ratio, for example, read first the Min and Max Pressure Ratio tables which yields  $P_1/P_{2,\min}$  and  $P_1/P_{2,\max}$ . Then calculate  $\beta$  as

$$\beta = (P_1/P_2 - P_1/P_{2,\min}) / (P_1/P_{2,\max} - P_1/P_{2,\min})$$

Now you are ready to read the data from the other tables.

### 7.4.2 Synthesis Tables without $\beta$

The following tables are offered for output without auxiliary coordinates.



The table argument can be specific work, isentropic specific work or pressure ratio. The number of argument values is selected in the top right corner, a number of 50 or more is required for adequate efficiency accuracy in the low speed region of the map.

## 7.5 GasTurb Tables

GasTurb tables are essentially synthesis tables employing  $\beta$  as auxiliary coordinates. Note that the *speed* values in a GasTurb table must be numbers in the range 0...1.5, i.e. you must use relative speed values. Moreover, the number of speed lines is limited depending on the GasTurb program version.

GasTurb tables can be read by Smooth T as "measured data". The Reynolds correction data are described in detail in the GasTurb manual; They are of no relevance for Smooth T.

A GasTurb turbine map is described with a set of 4 or 5 *tables* stored in one file. The extension to the file name is "MAP". The table with the turbine exit angle is optional.

Note: the explanations (text in blue/italic) are not part of an actual file and tables are abbreviated by the *<Table: ...>* statement, followed by the argument, the parameter and finally the function value!

```

Map Type      Map Title
99              Arbitrary Text
Reynolds correction data:
Reynolds: RNI=x1 f = y1 RNI = x2 f = y2
    
```

*Table Content Keyword*

Min Pressure Ratio

*<Table:  $\beta$ , 1.0, Min Pressure Ratio>*

Max Pressure Ratio

*<Table:  $\beta$ , 1.0, Max Pressure Ratio>*

Mass Flow

*<Table:  $\beta$ , Speed, Mass Flow>*

Efficiency

*<Table:  $\beta$ , Speed, Efficiency>*

Angle

*<Table:  $\beta$ , Speed, Angle>*

---

## 8 References

[1] Turbine Design and Application, Volume 1  
Arthur J. Glassman  
NASA SP-290, 1972

## 9 Appendix

### 9.1 Nomenclature and Definitions

#### 9.1.1 Symbols

a	Velocity of sound
A	Area
H	Specific work
Mn	Mach number
N	Spool speed
$N/\sqrt{\theta_1}$	Standard day corrected spool speed
P	Total pressure
P <sub>s</sub>	Static pressure
P <sub>w</sub>	Power
R	Gas constant
T	Total temperature
Trq	Torque
T <sub>s</sub>	Static temperature
U	Circumferential speed
V <sub>ax</sub>	Axial velocity
W	Mass flow
$\gamma$	Isentropic exponent
$\delta$	$P / 101.325\text{kPa}$
$\theta$	$T / 288.15\text{K}$
$\rho$	Density
$\Phi$	Flow coefficient
$\Psi$	work coefficient

#### 9.1.2 GasTurb

GasTurb is a cycle program for design and off-design performance of many gas turbine configurations, see [www.gasturb.de](http://www.gasturb.de). With the help of Smooth T 8.2 you can produce the component map format which is needed by GasTurb.

#### 9.1.3 Map Type Indicator

The map type indicator is an integer number which indicates numerically the contents of a file. The following map type indicators are defined:

1	measured data
2	smooth data (retained for consistency with previous versions)
3	smooth data
20	cycle data without turbine exit angle data
21	cycle data with turbine exit angle data

any map:

99	GasTurb tables or synthesis tables
----	------------------------------------

### 9.1.4 Map Title

The map title is an arbitrary text which describes the map. It will be printed with any graphical output and also stored with all files produced from Smooth T 8.2.

### 9.1.5 Keywords

In a file with measured or smooth data the following keywords are valid:

- Mass\_Flow (mandatory)
- Pressure\_Ratio (optional)
- Efficiency (optional)
- Work (optional)
- Angle (optional)

Two out of the three keywords Pressure\_Ratio, Efficiency, [Work](#) must be used.

In a file with [GasTurb tables](#) the following keywords are used:

- Min Pressure Ratio
- Max Pressure Ratio
- Mass Flow
- Efficiency

### 9.1.6 Speed

A speed line in Smooth T 8.2 is a line of constant corrected spool speed in a plot with Pressure Ratio over Mass Flow.

The term speed is actually a shortcut for the corrected spool speed  $N/\sqrt{T_1}$  which is a measure of the circumferential Mach number at the inlet to the compressor:

$$Mn_u = \frac{u}{a} = \frac{const \cdot N}{\sqrt{\gamma \cdot R \cdot T_s}} = \frac{const \cdot N}{\sqrt{\gamma \cdot R \cdot T} \cdot \sqrt{T_s/T}}$$

As can be seen from the formula above - since  $T_s/T$  is only a function of Mach number and isentropic exponent - it holds:

$$\frac{N}{\sqrt{T}} = f(\gamma, Mn_u)$$

Instead of using  $N/\sqrt{T_1}$  it is more convenient to use the standard day corrected speed  $N/\sqrt{\Theta_1}$  which is expressed in rpm (revolutions per minute).

Actual numbers for  $N/\sqrt{\Theta}$  are often very big and this can cause undesired effects (overlapping of numbers, for example) in the graphical output of Smooth T 8.2. Therefore it is recommended to use relative corrected speed values as they are also used in GasTurb:

$$\left(\frac{N}{\sqrt{\Theta}}\right)_{rel} = \frac{N}{\left(\frac{N}{\sqrt{\Theta}}\right)_{ref}}$$

### 9.1.7 Mass Flow

In Smooth T 8.2 the term mass flow stands for the corrected mass flow which is a measure of the axial Mach number at the inlet to the compressor.

$$Mn_{ax} = \frac{V_{ax}}{a} = \frac{W}{A \cdot \rho \cdot \sqrt{\gamma \cdot R \cdot T_s}} = \frac{W \cdot R \cdot T_s}{A \cdot P_s \cdot \sqrt{\gamma \cdot R \cdot T_s}} = \frac{W \cdot \sqrt{R \cdot T / \gamma} \cdot \sqrt{T_s / T}}{A \cdot P \cdot (P_s / P)}$$

As can be seen from the formula above - since  $T_s/T$  and  $P_s/P$  are only functions of Mach number and isentropic exponent - it holds:

$$\frac{W \cdot \sqrt{R \cdot T}}{A \cdot P} = f(\gamma, Mn_{ax})$$

A frequently used shortcut of this formula is  $W\sqrt{T}/P$ . When using numbers then this term has units unfamiliar to most people. It is better to use standard day corrected mass flow which has in the SI system the unit kg/s:

$$\frac{W \cdot \sqrt{\Theta}}{\delta} = \frac{W \cdot \sqrt{T/288.15K}}{P/101.325kPa}$$

Note that Smooth T 8.2 works with both  $W\sqrt{T}/P$  and  $W\sqrt{\Theta}/\delta$ , the units employed can be freely chosen.

### 9.1.8 Efficiency

Within Smooth T 8.2 normally the efficiency values are interpreted as isentropic efficiency.

$$\eta = \frac{H_{is}}{H}$$

The isentropic work  $H_{is}$  is calculated from the pressure ratio.

You can use polytropic efficiency while reading measured data from a file, a bitmap, or while you enter the data manually. The polytropic efficiency data will be converted to isentropic efficiency immediately after the data input process. In some of the plots in the picture catalog you can choose between polytropic and isentropic efficiency.

### 9.1.9 Pressure Ratio

The pressure ratio  $P/P$  is defined as the total pressure  $P_1$  at the inlet of the turbine divided by the total pressure  $P_2$  at the exit of the turbine.

### 9.1.10 Specific Work

In Smooth T 8.2 the terms Specific Work and Work are in many places used as abbreviation for the Corrected Specific Work  $H/T_1$  or  $H/ \sqrt{T_1}$  which is a measure of the work per unit of mass flow divided by turbine inlet temperature.

During the map smoothing process the actual corrected specific work  $H/T_1$  is calculated from the total pressure ratio  $P_1/P_2$  and the efficiency. The isentropic corrected specific work  $H_{is}/T_1$  is calculated from the total pressure ratio  $P_1/P_2$ .

### 9.1.11 Torque

The compressor shaft power  $PW$  is

$$PW = c \cdot N \cdot Trq = W \cdot \Delta H$$

with  $c$  as an unit conversion constant. This formula can be converted to

$$\frac{Trq}{W \cdot \sqrt{T_1}} = \frac{\Delta H/T_1}{c \cdot N/\sqrt{T_1}}$$

or

$$\frac{Trq}{P_1} = \frac{\frac{W \cdot \sqrt{T_1}}{P_1} \cdot \frac{H}{T_1}}{c \cdot \frac{N}{\sqrt{T_1}}}$$

### 9.1.12 Power

The true shaft power is the product of mass flow and specific work:

$$PW = W \cdot \Delta H$$

The corrected power is the product of corrected mass flow and corrected specific work:

$$PW_{corr} = \frac{W \cdot \sqrt{T_1}}{P_1} \cdot \frac{\Delta H}{T_1} = PW \cdot \frac{P_1}{\sqrt{T_1}}$$

Shaft power can also be expressed as the product of torque and speed:

$$PW = Trq \cdot N$$

This yields another expression for corrected power:

$$PW_{corr} = Trq \cdot P_1 \cdot \sqrt{T_1}$$

### 9.1.13 Flow Coefficient

The flow coefficient  $\phi = V_{ax}/U$  and the work coefficient  $\psi = H/U^2$  are useful for describing turbine performance in the map region where the Mach numbers are low. The axial component of the first stator exit flow velocity  $V_{ax}$  can be calculated at any point in the map from the Mach number which in turn can be found from the correlation between corrected flow and the first stator exit Mach number at the [map reference point](#).

Note that in previous versions of Smooth T 8.2 corrected mass flow divided by corrected speed was used as an expression for the flow coefficient. This was an approximation for  $\phi$  which is valid for low Mach numbers only. The graphs created by Smooth T 8.2 show valid values for the flow coefficient over the full Mach number range.

Instead of circumferential speed  $U$  the speed value  $N$  may be employed for calculating a number which is proportional to the flow coefficient  $\phi$ . If the true flow coefficient is known for the map reference point, then  $\phi$  can be calculated for any point in the map. Setting  $\phi_{ref}=1$  at the map reference point yields plots with relative  $\phi$  values that are nearly as useful as those with the true data.

### 9.1.14 Work Coefficient

The parameters flow coefficient  $\phi = V_{ax}/u$  and work coefficient  $\psi = H/u^2$  are useful for describing the off-design performance of a compressor in the low Mach number region because there the influence of compressibility becomes negligible.

A number proportional to the work coefficient can be calculated as  $H/N^2$  and the isentropic work coefficient  $\psi_{is}$  is proportional to  $H_{is}/N^2$ .

$$\frac{\Delta H_{is}/T_1}{\left(N/\sqrt{T_1}\right)^2} = \frac{\Delta H_{is}}{N^2} \cong \frac{\Delta H_{is}}{u^2} = \psi_{is}$$

If at the map reference point a value for the work coefficient is known, then  $\psi$  and  $\psi_{is}$  can be calculated for any point of the map.

### 9.1.15 Format of a Table

A table is a set of numbers and contains argument values (A), parameter values (P) and function values (F):

Key	A[1]	A[2]	A[3]	A[4]	A[5]
P[1]	F[1,1]	F[1,2]	F[1,3]	F[1,4]	F[1,5]
P[2]	F[2,1]	F[2,2]	F[2,3]	F[2,4]	F[2,5]
P[3]	F[3,1]	F[3,2]	F[3,3]	F[3,4]	F[3,5]

The first number of a table is the table key which is composed from the number of rows and columns of the table:

$$\text{key} = \text{number of rows} + \text{number of columns}/1000$$

The number of rows is one more than the number of parameter values in the table and the number of columns is one more than the number of arguments in the table. The key for the table above would be 4.006, for example.

A table starts always on a new line and begins with the key. After the key follow the first four argument values, separated by at least one "blank" from each other. The rest of the argument values are on additional lines (five numbers per line). Only on the last line with argument values there may be less than five numbers.

Parameter values must always begin a new line and the first four function values follow on the same line. The rest of the function values are arranged as described for the argument values.

The data need not be in specific columns, but there must be at least one blank between each number. The length of the lines must not exceed 79 columns.

## 9.2 File Format Examples

### 9.2.1 Example File with Measured Turbine Map Data

**Note:** the explanations (text in blue) are **not** part of an actual file!

```
Map Type      Map Title  
1              AGARD two-stage turbine
```

```
Keywords  
Mass_flow      Pressure_Ratio  Efficiency
```

```
One of the two following lines:  
Gamma=1.3      Gasconstant=287.05  
Tref=500       far=0.023
```

```
# of Speed Lines  keyword (relativized or non-relativized)  
7                Non-Relativized Map
```

```
Speed           # of Points  
0.70000         10  
Mass_flow      Pressure_Ratio  Efficiency  
91.40000        1.40000          0.91200  
97.10000        1.50000          0.91300  
101.30000       1.60000          0.91000  
104.30000       1.70000          0.90000  
106.40000       1.80000          0.88500  
108.70000       2.00000          0.86300  
110.30000       2.20000          0.84200  
111.10000       2.40000          0.82500  
112.00000       2.60000          0.81000  
112.30000       2.80000          0.79500
```

```
Next Speed Line  
0.90000         13  
111.80000       3.40000          0.87000  
111.80000       3.20000          0.88000  
111.80000       3.00000          0.89000  
111.70000       2.80000          0.90000  
111.10000       2.60000          0.90600
```

110.90000	2.40000	0.91500
110.00000	2.20000	0.92600
107.60000	2.00000	0.92600
104.40000	1.80000	0.92400
102.00000	1.70000	0.91900
98.20000	1.60000	0.90000
94.00000	1.50000	0.86500
87.60000	1.40000	0.80000
0.80000	12	
89.80000	1.40000	0.87800
96.00000	1.50000	0.91100
100.40000	1.60000	0.92150
103.60000	1.70000	0.92170
105.80000	1.80000	0.91900
108.50000	2.00000	0.90500
109.80000	2.20000	0.89000
111.00000	2.40000	0.87900
111.50000	2.60000	0.86200
111.60000	2.80000	0.85300
112.30000	3.00000	0.84200
112.40000	3.20000	0.83400
1.20000	9	
109.80000	2.60000	0.93100
105.00000	2.00000	0.86000
111.40000	3.40000	0.94020
111.30000	3.20000	0.94100
100.70000	1.80000	0.79500
110.60000	2.80000	0.93800
107.20000	2.20000	0.89800
110.90000	3.00000	0.94100
108.70000	2.40000	0.92000
1.00000	12	
111.90000	3.40000	0.90800
111.60000	3.00000	0.92100
110.90000	2.60000	0.93050
109.00000	2.20000	0.93400
103.50000	1.80000	0.90500
96.80000	1.60000	0.84000
111.80000	3.20000	0.91500
111.10000	2.80000	0.92700
110.00000	2.40000	0.93350
106.80000	2.00000	0.92700
100.80000	1.70000	0.88000
92.30000	1.50000	0.78500
1.10000	11	
95.30000	1.60000	0.75000
98.90000	1.70000	0.82000
101.60000	1.80000	0.86000
105.50000	2.00000	0.90700
108.00000	2.20000	0.92600
109.20000	2.40000	0.93500
110.30000	2.60000	0.93920

## File Format Examples

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110.90000	2.80000	0.94000
111.30000	3.00000	0.93800
111.40000	3.20000	0.93500
111.50000	3.40000	0.93000
0.60000	6	
93.00000	1.40000	0.90700
98.50000	1.50000	0.88800
102.30000	1.60000	0.86800
105.00000	1.70000	0.85000
107.00000	1.80000	0.83200
109.70000	2.00000	0.80000

### 9.2.2 Example File with Smooth Turbine Data

**Note:** the explanations (text in blue) are **not** part of an actual file!

*Map Type*      *Map Title*  
3                AGARD two-stage turbine

*Keywords*  
Mass\_flow      Pressure\_Ratio      Efficiency

*One of the two following lines:*

Gamma=1.3      Gasconstant=287.05  
Tref=500      far=0.023

*Beta Grid Constants:*

1.311333333 -1.494800000 1.657570000  
0.000000000 0.000000000 0.000000000 2.400000000  
-9.166666667 18.833333333 -5.891670000  
0.000000000 0.000000000 0.000000000

*Map reference point data:*

RefSpeed=1.1030000      RefBeta=0.5576342  
RefMach=0.6449000      RefPsi=1.0000000      RefPhi=1.0000000

*# of Speed Lines*      *Keyword (relativized or non-relativized)*  
7                        Non-Relativized Map

<i>Speed</i>	<i># of Points</i>		
0.60000	15		
<i>Mass_flow</i>	<i>Pressure_Ratio</i>	<i>Efficiency</i>	
65.80644989	1.232769966	0.878737569	
81.00357819	1.295310020	0.906146169	
89.03225708	1.357850075	0.908800006	
94.19355011	1.420390010	0.906343281	
97.63440704	1.482930064	0.894089997	
100.2150497	1.545470119	0.879850745	
102.4372787	1.608010054	0.866129994	
104.2293930	1.670550108	0.854659975	
105.6630783	1.733090162	0.843656719	
106.9175568	1.795630097	0.833208978	
107.9211502	1.858170152	0.822761178	
108.8387070	1.920710087	0.813805997	
109.5698929	1.983250141	0.804480016	

110.1290283	2.045790195	0.795159996
110.5591431	2.108330250	0.786559999

*Next Speed Line:*

0.699999988	15	
73.83512878	1.253763318	0.849667788
88.63799286	1.364208579	0.901993334
96.41577148	1.474653840	0.916112959
100.8243713	1.585098982	0.912010014
103.8709717	1.695544243	0.900259972
106.1648712	1.805989504	0.885479987
107.8136215	1.916434765	0.870429993
108.8888931	2.026880026	0.858959973
109.7849503	2.137325287	0.847490013
110.5878067	2.247770309	0.838169992
111.1254501	2.358215570	0.828140020
111.5197067	2.468660831	0.820249975
111.8422928	2.579106092	0.812370002
112.0573502	2.689551353	0.804480016
112.2365570	2.799996614	0.796589971

0.800000012	15	
80.75269318	1.300983310	0.828849971
93.47669983	1.444365263	0.900539994
100.1075287	1.587747216	0.921329975
104.2293930	1.731129050	0.922760010
106.8906784	1.874511003	0.914160013
108.6379929	2.017892838	0.903410017
109.7168503	2.161274910	0.893369973
110.4695282	2.304656744	0.883329988
111.0250931	2.448038578	0.874010026
111.3978500	2.591420412	0.864700019
111.6845932	2.734802485	0.856090009
111.9390717	2.878184319	0.848919988
112.1147003	3.021566153	0.841759980
112.2580566	3.164947987	0.835300028
112.3297501	3.308330059	0.829569995

0.899999976	15	
86.09319305	1.374429941	0.789430022
96.16487122	1.535779953	0.885479987
102.0788498	1.697129965	0.919889987
105.5914001	1.858479977	0.927779973
107.9569931	2.019829988	0.927779973
109.4444427	2.181180000	0.925629973
110.2957001	2.342530012	0.919889987
110.8817215	2.503880024	0.912720025
111.3261566	2.665230036	0.904839993
111.5985718	2.826580048	0.897669971
111.7706070	2.987930059	0.889779985
111.8673782	3.149279833	0.881900012
111.9211502	3.310629845	0.874729991
111.9390717	3.471979856	0.867560029
111.9390717	3.633329868	0.861109972

## File Format Examples

---

1.000000000	15	
90.89605713	1.474103332	0.768999994
98.20789337	1.638452888	0.852330029
103.5125427	1.802802444	0.908779979
106.5233002	1.967151880	0.927600026
108.2437286	2.131501436	0.932969987
109.3906784	2.295850992	0.933870018
110.2509003	2.460200548	0.932969987
110.8243713	2.624550104	0.930289984
111.2042999	2.788899660	0.926699996
111.5268784	2.953248978	0.922219992
111.7204285	3.117598534	0.917739987
111.8279572	3.281948090	0.912370026
111.8924713	3.446297646	0.906989992
111.8924713	3.610646963	0.901610017
111.8924713	3.774996758	0.897130013

1.100000024	15	
95.28674316	1.600003362	0.748390019
100.1254501	1.752383828	0.845160007
103.7992783	1.904764295	0.889959991
106.3082428	2.057144880	0.915950000
108.1003571	2.209525347	0.926699996
109.1756287	2.361905813	0.933910012
109.9068069	2.514286280	0.938210011
110.5519714	2.666666746	0.939930022
110.9820786	2.819047213	0.939930022
111.2688217	2.971427679	0.938780010
111.4121933	3.123808146	0.936559975
111.4838715	3.276188612	0.932969987
111.5197067	3.428569078	0.929030001
111.5555573	3.580949545	0.924009979
111.5555573	3.733330011	0.918420017

1.200000048	15	
99.05017850	1.752130032	0.777059972
102.5447998	1.877572894	0.823660016
104.9641571	2.003015757	0.861289978
106.5770569	2.128458500	0.890860021
107.8315430	2.253901482	0.907890022
108.6738434	2.379344225	0.918640018
109.3906784	2.504787207	0.926699996
109.9641571	2.630229950	0.932969987
110.3942719	2.755672932	0.937099993
110.7526932	2.881115675	0.939779997
110.9677429	3.006558418	0.941039979
111.1111069	3.132001400	0.941399992
111.1828003	3.257444143	0.941039979
111.1828003	3.382886887	0.940140009
111.2544785	3.508329868	0.938709974

### 9.2.3 Example File with Cycle Data

The sequence of the data lines in a file with cycle data is of no importance. The comment is optional. Points without a comment will be marked with numbers in the graphics.

Cycle data may be with or without exit angle information. Use **20** as File Type Indicator if no turbine exit angle information is available:

**Note:** the explanations (text in blue) are **not** part of an actual file!

```

File Type      File Title
20             Turbine Operating Line Data Points

# of (not empty) lines with data to follow
6

Press Ratio    Mass Flow    Efficiency    Speed    Comment
1.5            98.5         0.8980        0.63     Idle
2.05           109.1        0.9218        0.89
2.35           109.9        0.925         0.95
2.67           109.8        0.9302        1.038    Take off
2.81           110.0        0.933         1.08
3.02           111.6        0.943         1.13     Max Climb

```

If your cycle data include the turbine exit angle then use **21** as File Type Indicator and add the angle information after the Speed information and before to optional comment:

```

File Type      File Title
21             Turbine Operating Line Data Points

# of (not empty) lines with data to follow
6

Press Ratio    Mass Flow    Efficiency    Speed    Angle    Comment
1.5            98.5         0.8980        0.63     25       Idle
2.05           109.1        0.9218        0.89     15
2.35           109.9        0.925         0.95     8
2.67           109.8        0.9302        1.038    -5       Take off
2.81           110.0        0.933         1.08     -8
3.02           111.6        0.943         1.13     -12      Max Climb

```

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