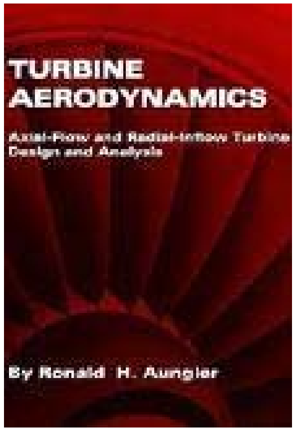
AXIAL-FLOW TURBINE AERODYNAMIC DESIGN AND ANALYSIS WITH THE TURBAERO SOFTWARE SYSTEM



TurbAero **is an aerodynamic design and analysis software system for axial-flow and radial-inflow turbines for personal computers. It implements methods described in the following book:**

Aungier, R. H., *Turbine Aerodynamics: Axial-Flow and Radial-Inflow Turbine Aerodynamic Design and Analysis* (ASME Press, New York, 2006).

Note: a user's guide (TurbAero.pdf) will be installed with the software to bridge the gap between this book and the TurbAero software system.

By Ronald H. Aungier
September 15, 2011

OVERVIEW OF THE PROGRAMS IN TURBAERO

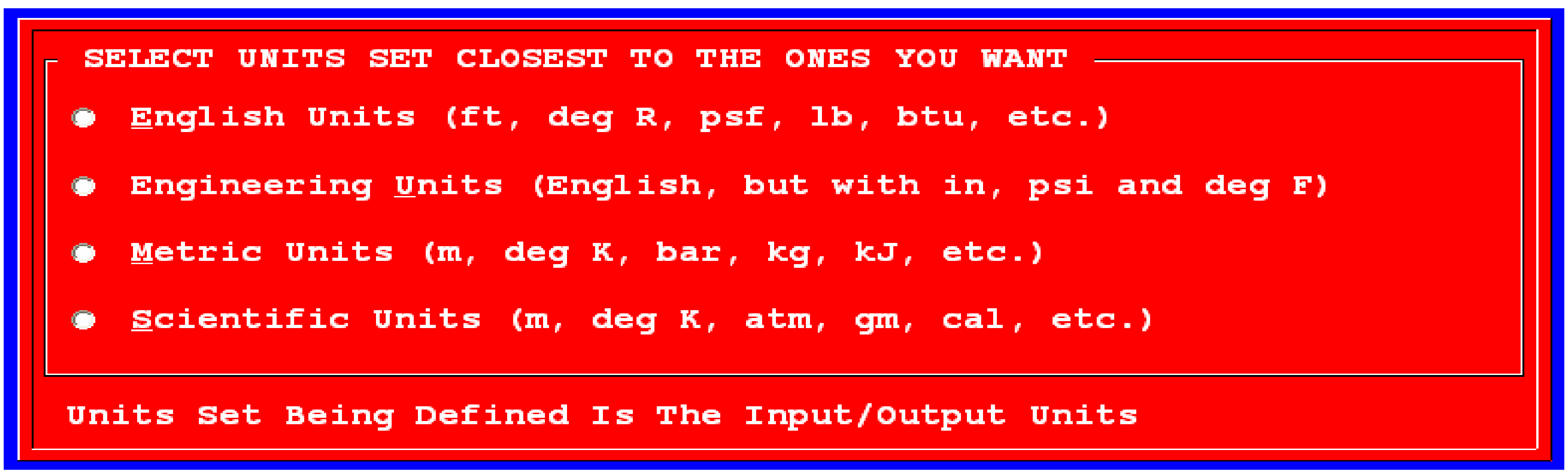
- **TURBAERO: a menu program to control the system and conveniently navigate among the other programs.**
- **AFTSIZE: an axial-flow turbine stage preliminary aerodynamic design program.**
- **AXTURB: an aerodynamic performance analysis for axial-flow turbines.**
- **RIFTSIZE: a radial-inflow turbine stage preliminary aerodynamic design program**.
- **RIFT: an aerodynamic performance analysis for radial-inflow turbines.**
- **GASPATH: a general gas path (end-wall contours and blades) detailed design program.**
- **RIFTNOZ: a radial-inflow turbine nozzle detailed aerodynamic design program.**
- **AIRFOIL: an airfoil detailed design program for axial-flow turbine blade-geometry..**
- **FLOW3D: a quasi-three-dimensional inviscid flow field analysis with supporting boundary layer analyses.**
- **B2B2D: a two-dimensional (subsonic) blade-to-blade flow analysis with supporting boundary layer analysis.**
- **TDB2B: a time-marching (any Mach no.) blade-to-blade flow analysis with supporting boundary layer analysis.**
- **RKMOD: an ideal/non-ideal fluid equation-of-state package for a variety of thermodynamic property calculations (this equation of state is used by many of the other programs).**
- **GASDATA: a gas property database maintenance program to support RKMOD and the other programs that use its equation of state (including a current database of over 100 compounds).**
- **RIGPAC: (Radial Impeller Geometry PACkage): a general geometry package primarily for impellers, but suitable for other vaned components also. It performs many operations and geometry calculations commonly used in centrifugal compressor and radial-inflow turbine design and implementation (e.g., scaling, tip trims, imposing new profiles for different capacities, etc.). Conceptually, it is similar to GASPATH, except that it starts from known geometry. Hence, it is often used to introduce existing component designs into the TurbAero system to apply the other programs for troubleshooting or upgrade activity.**
- **BEZIER: a program to generate the curves used by GASPATH to construct the end-wall contours and blades.**
- **EXHAUST: an exhaust diffuser aerodynamic performance analysis (including a scroll or collector).**
- **VOLUTE: a detailed geometry design program for volutes in radial turbomachinery.**
- **BLADE: an axial-flow compressor standard blade geometry program. Sometimes useful for wind turbine and wave turbine blade design.**

USING THE TURBAERO MENU PROGRAM

- **The Menu Program (Turbaero.exe) Is Highly Recommended.**
- **It Simplifies The Navigation Among Programs Required For Design & Analysis.**
- **It Provides For General Application Setup (Printer, Monitor Screen Font, Default Input/Output Units, Etc.).**
- **It Offers Several Taskbar Styles And Startup Options To Suit User Preferences.**
- **Typically, The Menu Program Is Launched From A Shortcut On Your Desktop.**

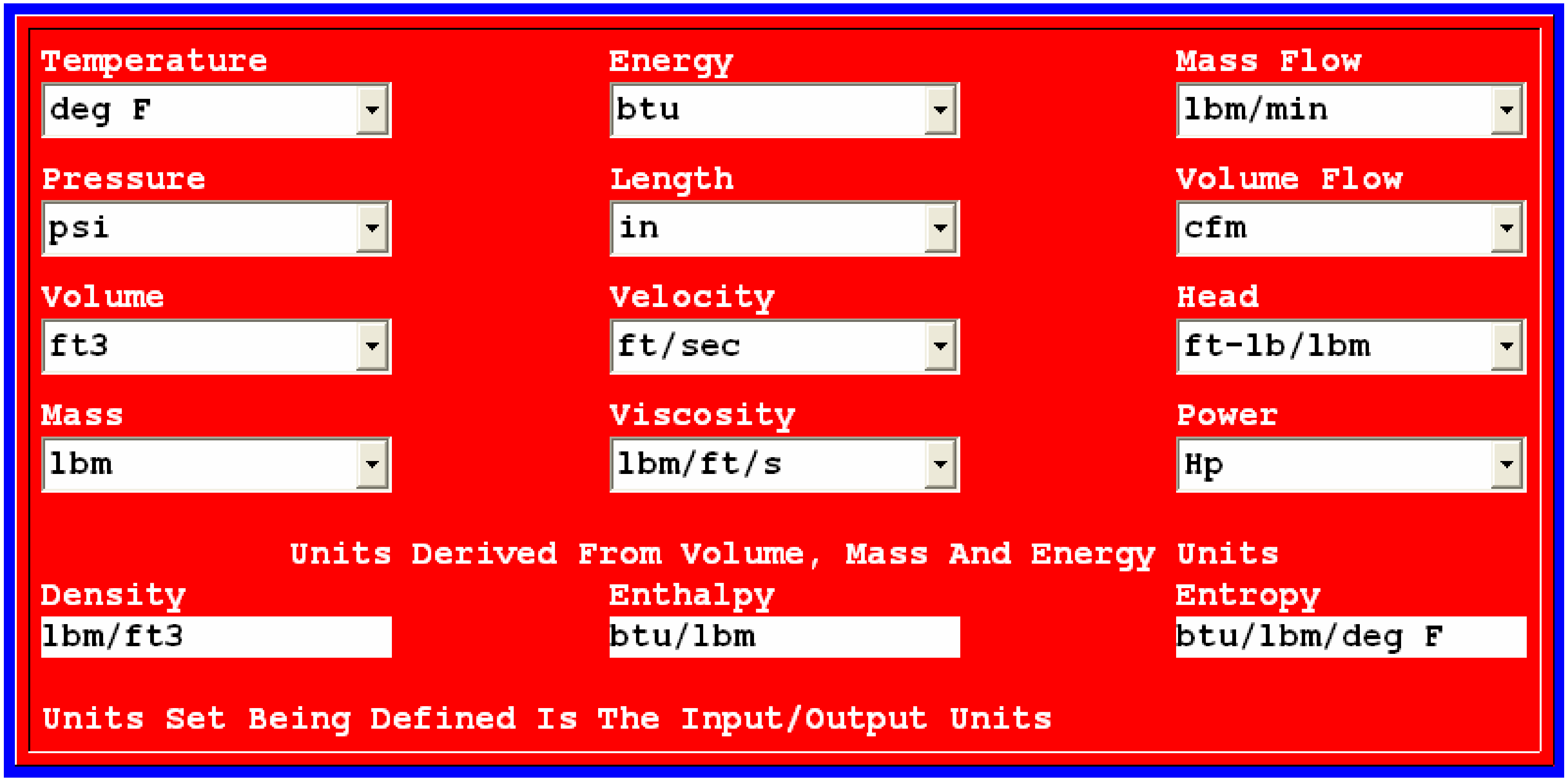
INPUT & OUTPUT UNITS FOR TURBAERO PROGRAMS

- **Programs That Use Dimensional Data Offer A Wide Range Of Input/Output Units.**
- **A Default Set Of Units (Defined By The User) Is Assumed For New Problems.**
- **The User Can Change The Units Used For Any Problem As Appropriate.**
- **Actual Units Used Are Always Saved In The Input Files For Use On Future Runs.**
- **Caution: Changing The Units Does Not Convert Input Data Already Loaded.**
- **To Set The Input/Output Units, First Select A Basic Set From The Choices Below.**



INPUT & OUTPUT UNITS, CONTINUED

- Then, You Can Customize Individual Units From The Dropdown Lists Below.
- Note That Some Units Are Derived From Your Specified Units.



IDEAL & NON-IDEAL FLUID EQUATION-OF-STATE PACKAGE

- **Available Models:**
  - **Aungier's Modified Redlich-Kwong Equation Of State.**
  - **Original Redlich-Kwong Equation Of State.**
  - **Ideal (Thermally Perfect) Gas Equation Of State.**
  - **Pseudo-Perfect Gas Equation Of State.**

- **Applicable To Pure Fluids And Fluid Mixtures.**

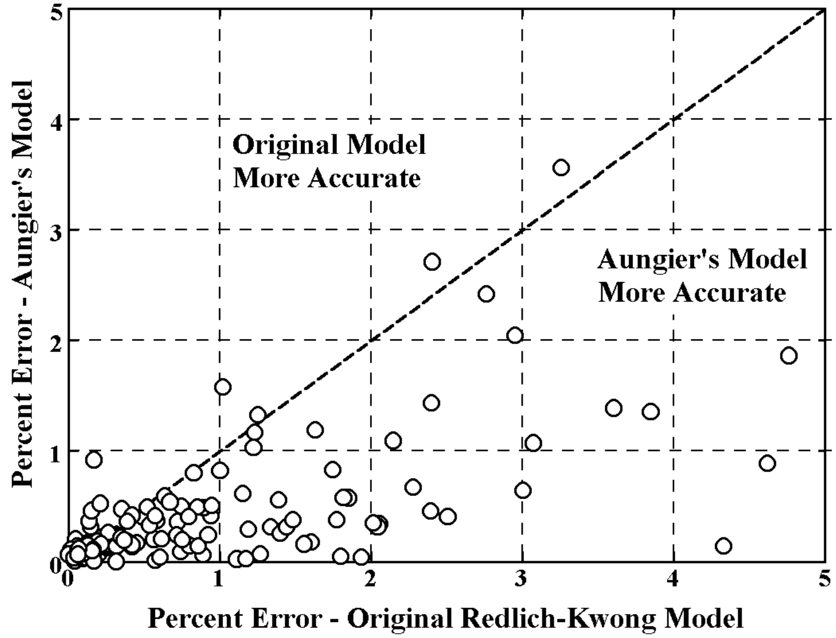
- **In General, Internal Flow Programs Are Valid For The Vapor Phase <u>Only</u>. RKMOD Can Handle Two-Phase Flows For Phase Checking, Liquid Knockout, Etc. Performance Analysis programs (AXTURB & RIFT) Also Treat Two-Phase Flows.**

- **GASDATA Contains An Initial Gas Property Database (Over 100 Compounds) To Get Users Started. <u>But No Gas Property Database Can Be Accurate For All Possible Applications</u>. Users Are Responsible For Establishing A Database Suitable For Their Applications.**

- **Some Good Sources Of Gas Property Data For TurbAero Are:**
  - **Ried, R. C., Prausnitz, J. M., and Sherwood, T. K., *The Properties Of Gases And Liquids* (McGraw-Hill, New York, 1977).**
  - **Ried, R. C., Prausnitz, J. M. and Poling, B. E., *The Properties Of Gases And Liquids*, Fourth edition (McGraw-Hill, New York, 1987).**
  - **Yaws, C. L., *Chemical Properties Handbook* (McGraw-Hill, New York, 1999).**

NON-IDEAL GAS EQUATION-OF-STATE ACCURACY

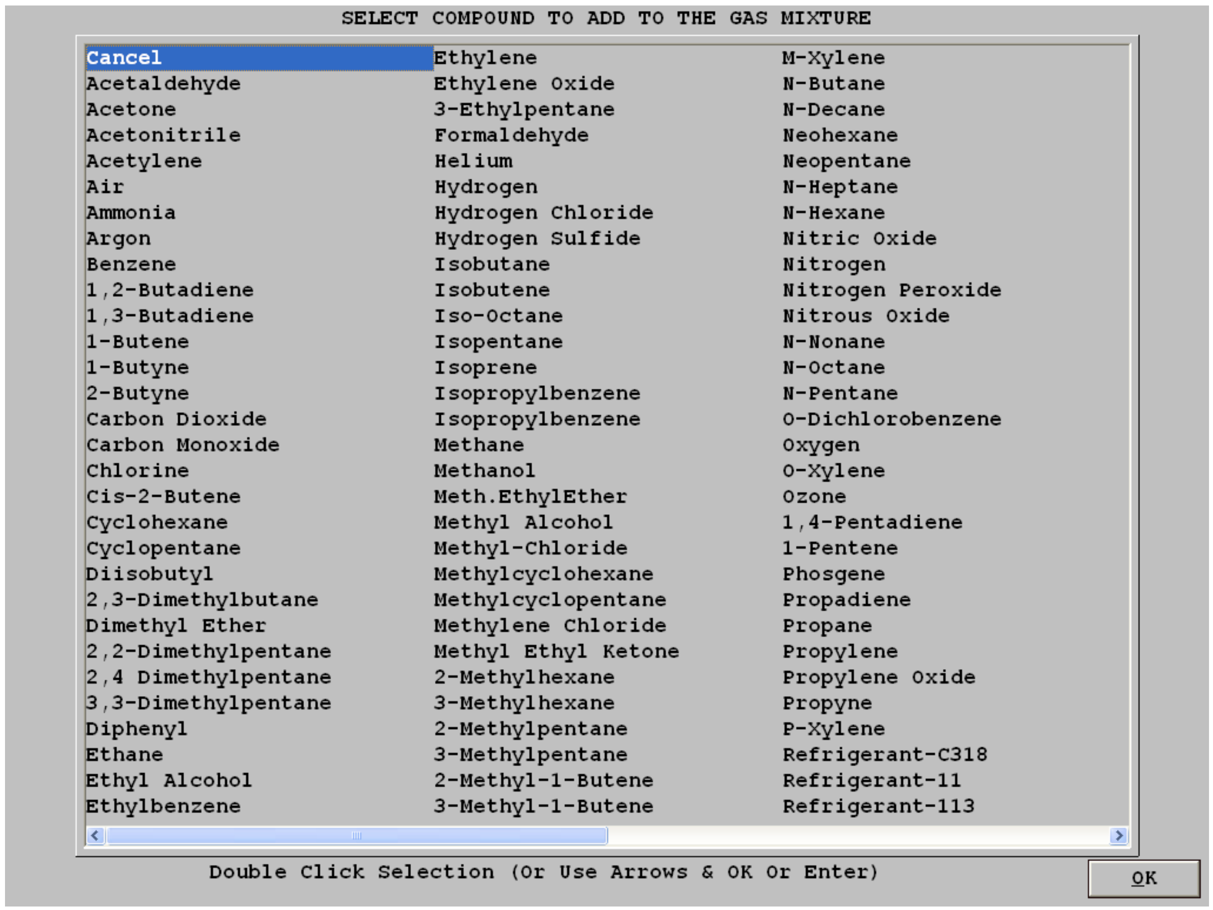
- **Accuracy Is Quite Sufficient For All Aerodynamic Design And Analysis Activity.**
- **Aungier's Modified Redlich-Kwong Equation Of State Is The Better Choice.**
- **These Equations Of State Are Not Recommended For Critical Applications Such As Performance Test Data Reduction Or Low-Tolerance Performance Guarantees.**
- **The Figures Below Compare Predictions With Experiment For Commonly-Used Compounds Over a Wide Range Of Pressure, Temperature And Acentric Factor.**



COMPOUND	ω
Ammonia	0.2550
Carbon Dioxide	0.2250
Ethylene	0.0868
Helium	-0.464
Hydrogen	-0.220
I-Butane	0.1848
Methane	0.0080
N-Pentane	0.2539
Nitrogen	0.0400
Propane	0.1520
Refrigerant R134a	0.3254
Steam	0.3440

SELECTING COMPONENTS FOR A GAS MIXTURE

- **Double-Click A Compound To Add It To The Mixture.**
- **Double-Click Cancel When The Mixture Definition Is Complete.**



SPECIFYING COMPOUND MOLE FRACTIONS FOR A MIXTURE

- **Enter The Mole Fraction Of Each Compound In The Mixture**
- **The Programs Will Let You Edit These Values Later If Needed.**
- **The Programs Always Normalize The Sum Of The Mole Fractions To Unity**

```
SET MOLE FRACTIONS OF THE MIXTURE COMPONENTS

Methane: Mole fraction = 0.6
 Ethane: Mole fraction = 0.3
Propane: Mole fraction = 0.1
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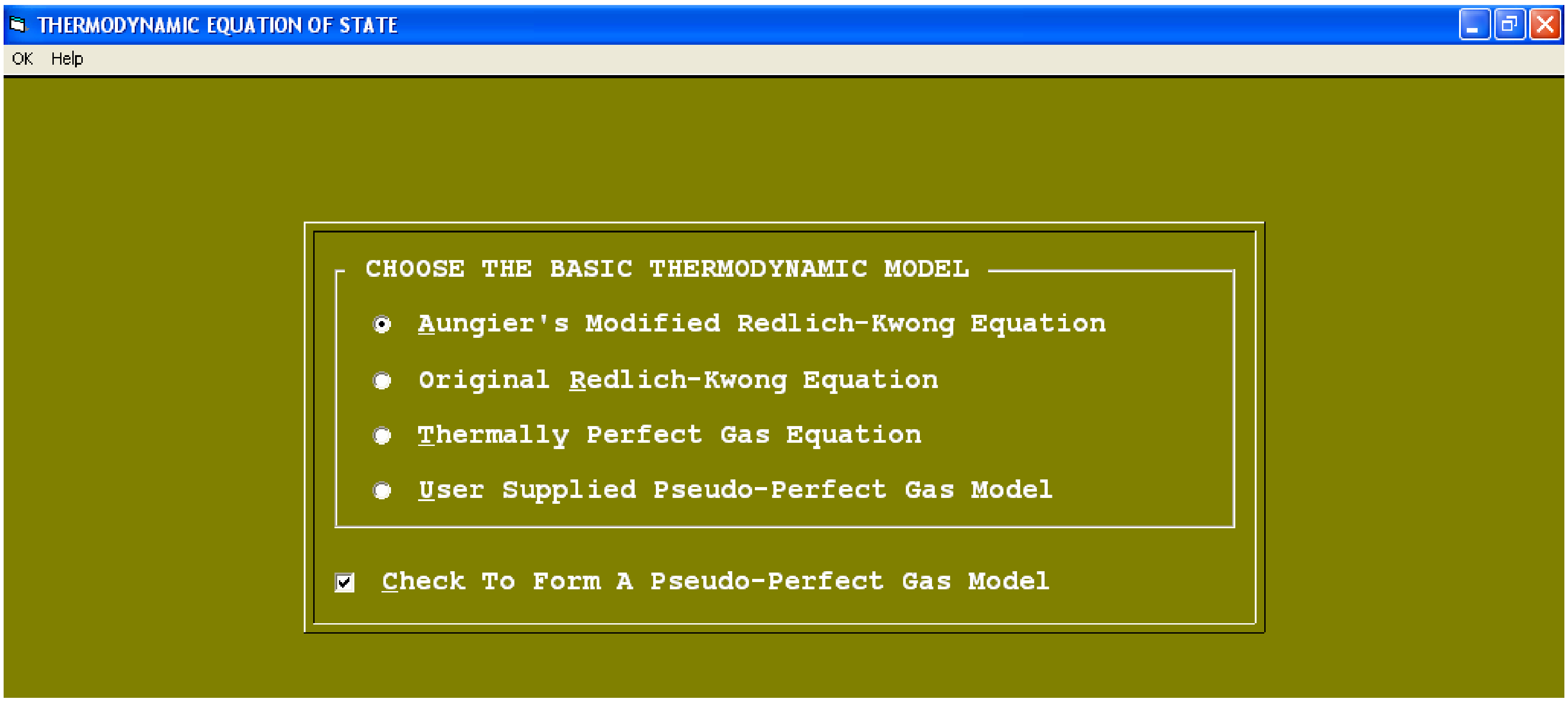
SELECTING THE EQUATION OF STATE

- **Select The Equation Of State To Be Used.**
- **Check The Box To Have The Program Form A Pseudo-Perfect Gas Model.**



OTHER USEFUL EQUATION-OF-STATE INFORMATION

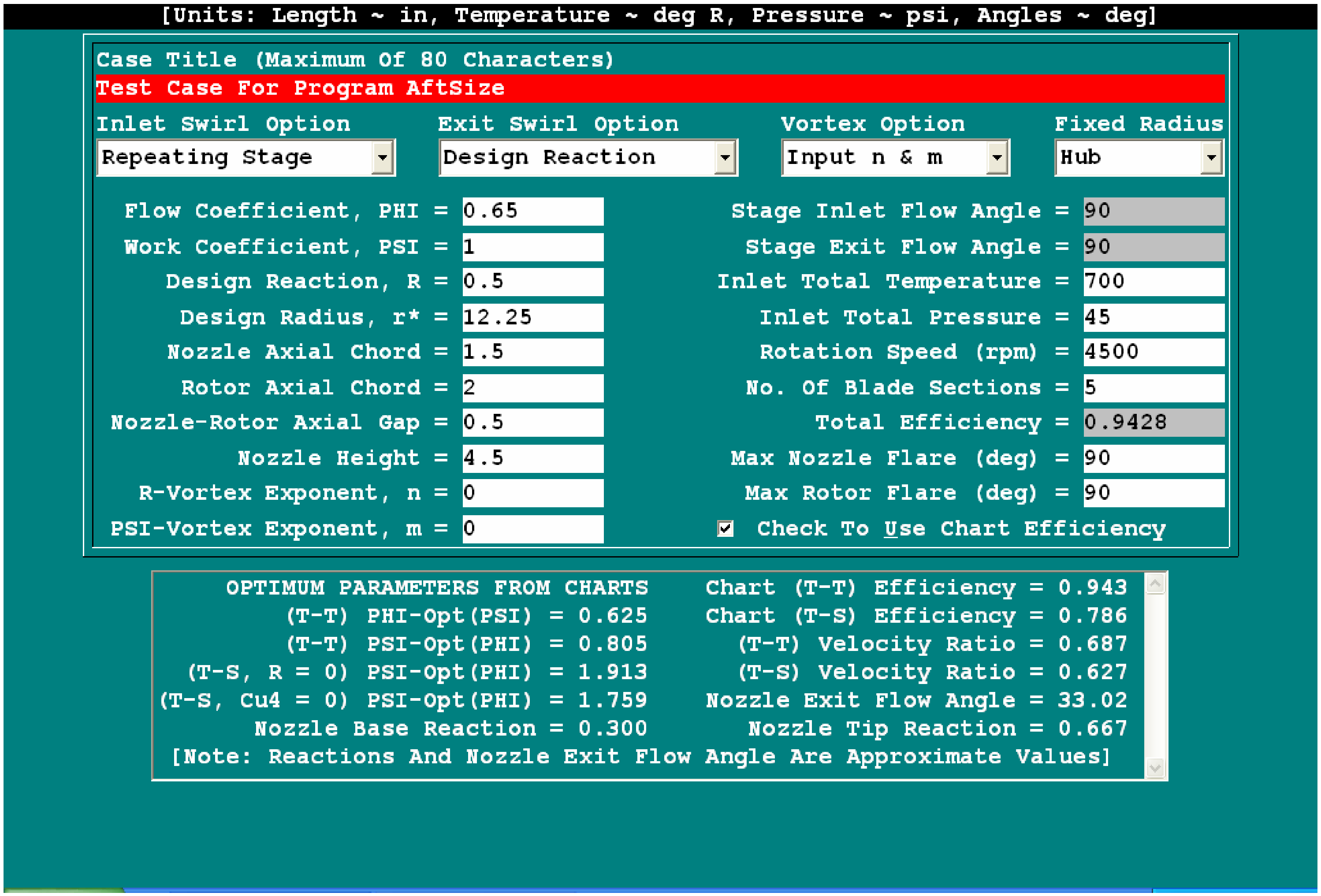
- **The Various Programs Will Let You Edit An Existing Gas Model. You Can Change The Equation Of State, Edit The Mole Fractions Of A Mixture, And Add Or Delete Compounds In A Mixture.**
- **The Equation-Of-State Package Also Contains A Generalized Model For Gas Viscosity That Can Be Applied Using The Same Data Required For The Ideal And Non-Ideal Gas Models. For The Rarely Used User-Supplied Pseudo-Perfect Gas Model, You Will Have To Supply Viscosity Values At Two Temperatures As Input.**
- **Due To An Oversight, My Centrifugal Compressor Book Does Not Describe The Viscosity Model. It Is described In My Axial-Flow Compressor Book And In My Turbine Aerodynamics Book (ASME Press, 2006).**
- **Turbine Aerodynamics Requires Treating Two-Phase (Liquid-Gas) Flows. The Modeling Of The Liquid And Vapor Saturation Lines Includes Some Minor Improvements Not Described In Either Of My Compressor Books. They Are Described In My Turbine Book, If You Need That Information.**
- **When In Doubt, Use RKMOD To Estimate The Vapor Saturation Line Data To Be Sure Your Inlet Conditions Are In The Vapor Phase. Remember, Except For RKMOD, AXTURB and RIFT, The Programs Are Valid For Vapor Phase Flow Only.**

STAGE PRELIMINARY AERODYNAMIC DESIGN

- **Program AFTSIZE Develops Preliminary Stage Designs From Performance Specifications And Empirical Correlations, With Minimal Input By The User.**
- **It Also Permits the User To Modify Many Of The Default Values To Refine The Design To Better Match Actual Design Requirements And Performance Predictions.**
- **They Can Export a Complete Input File For A Performance Analysis By Program AXTURB To More Accurately Assess The Stage's Performance And To Provide Improved Estimates Of The Modifiable Default Values.**
- **Its Stage Component Designs Are Well-Matched And Sufficiently Complete To Assure The User That Their Detailed Design Will Be Successful.**
- **The Program Can Export Component Preliminary Design Geometry To The Various TurbAero Detailed Design Programs To Supply Their Initial Input Files.**
- **Extensive Comparison Of The Empirical Performance Estimates For The Default Designs With AXTURB Performance Predictions Consistently Show Good Agreement Over A Wide Range Of Design And Operating Conditions.**
- **It Provides A Dramatic Reduction In Engineering Design Time And Improves Design Quality By Its Ability To Rapidly Explore Many Design Alternatives Before Starting The More Time-Consuming Detailed Aerodynamic Design Process.**

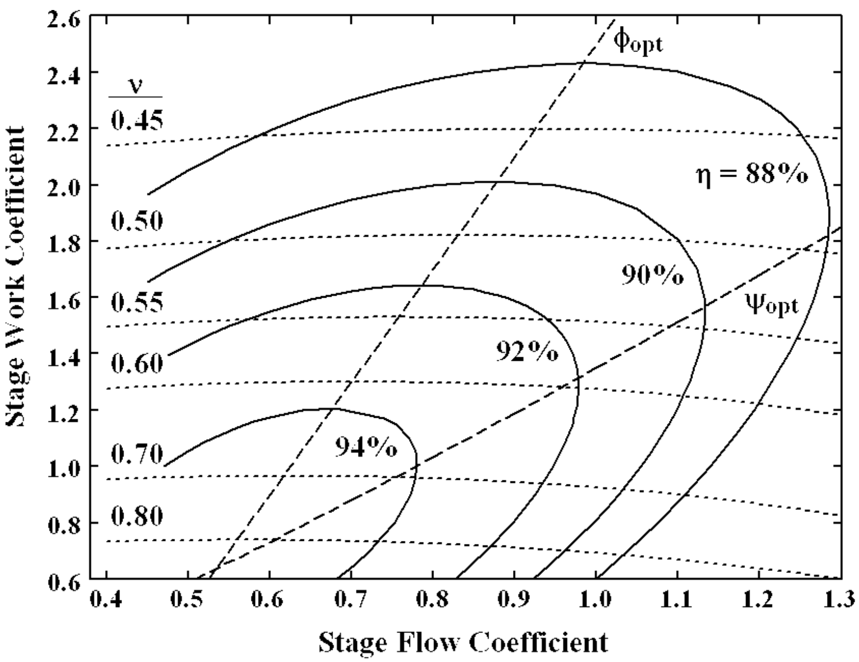
AXIAL-FLOW TURBINE STAGE PRELIMINARY DESIGN

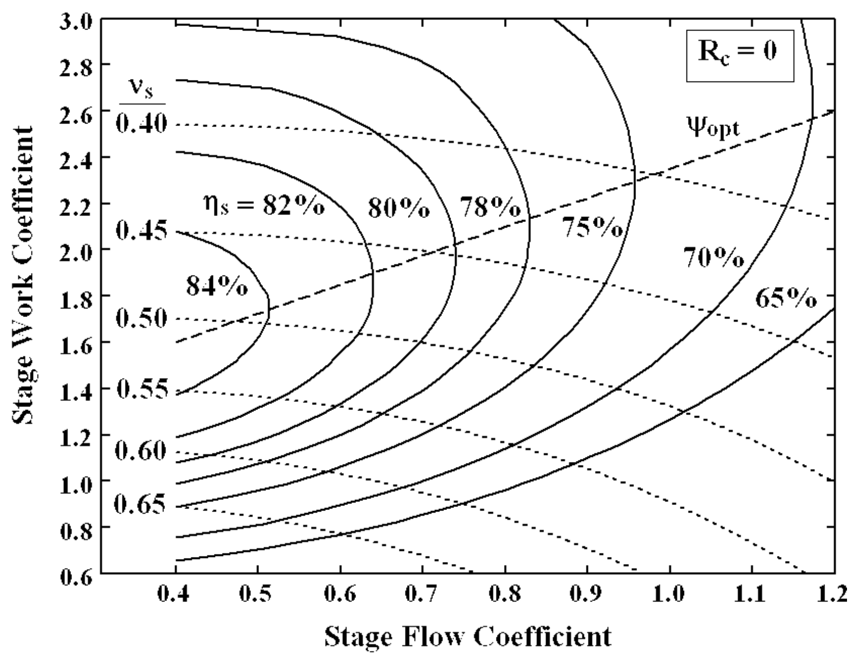
This Picture Shows The Basic Stage Design Specifications Required To Define The Stage Configuration To Be Designed By AFTSIZE And The Stage Inlet conditions.



AXIAL-FLOW TURBINE STAGE PRELIMINARY DESIGN, CONTINUED

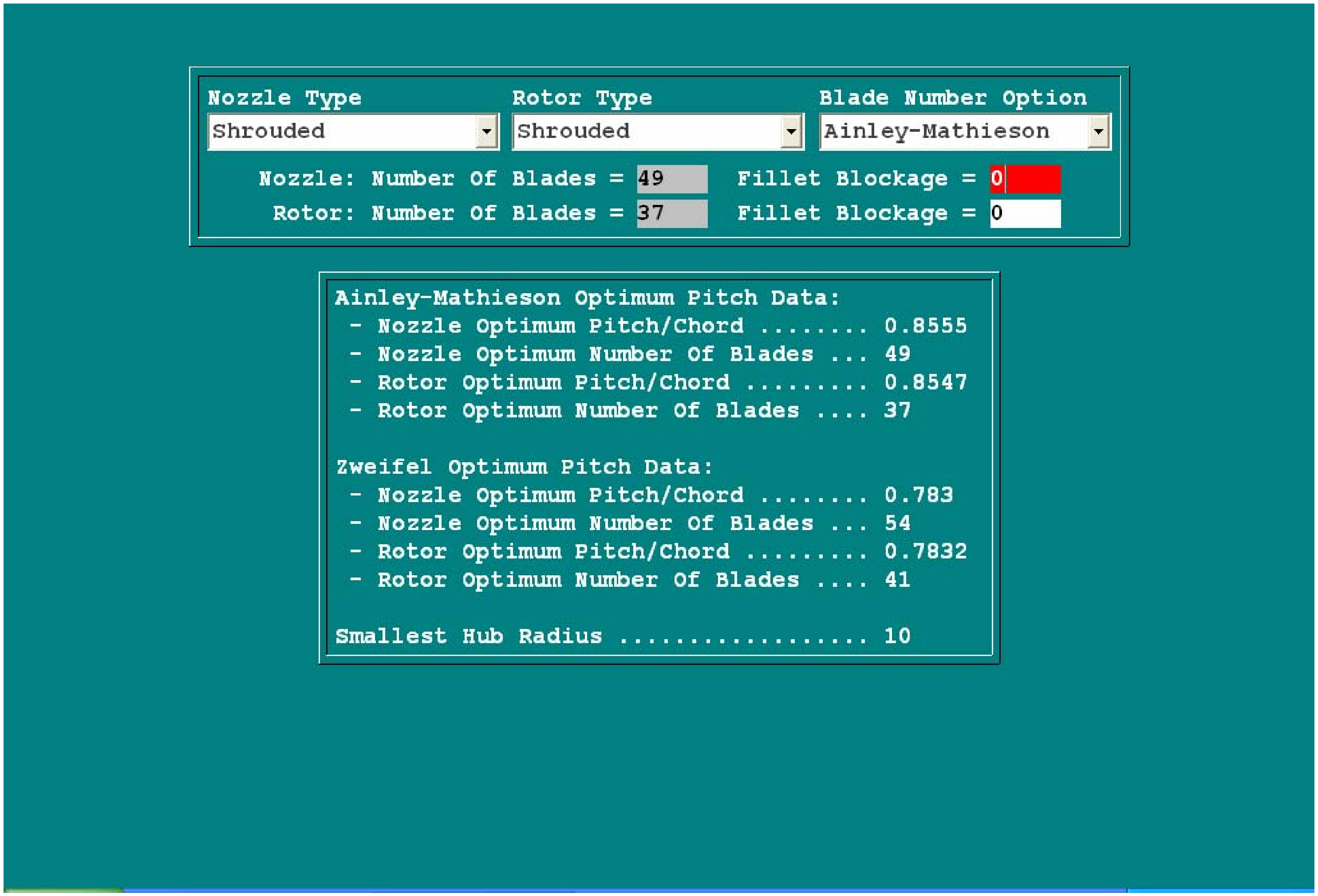
- **The Basic Configuration And Principal Options Are Selected From Drop-Down Lists**
- **Performance Goals Are Referenced To Various Generalized Efficiency Charts From My Turbine Book Such As The Stage Total Efficiency And Impulse Stage Static Efficiency Charts Shown Below For Initial Guidance In Selecting Realistic Goals As Near-To-Optimum as Possible For The Application.**
- **AFTSIZE Can Export An AXTURB Input File For A Performance Analysis To Refine These Performance Estimates For The Resulting Preliminary Design Configuration.**





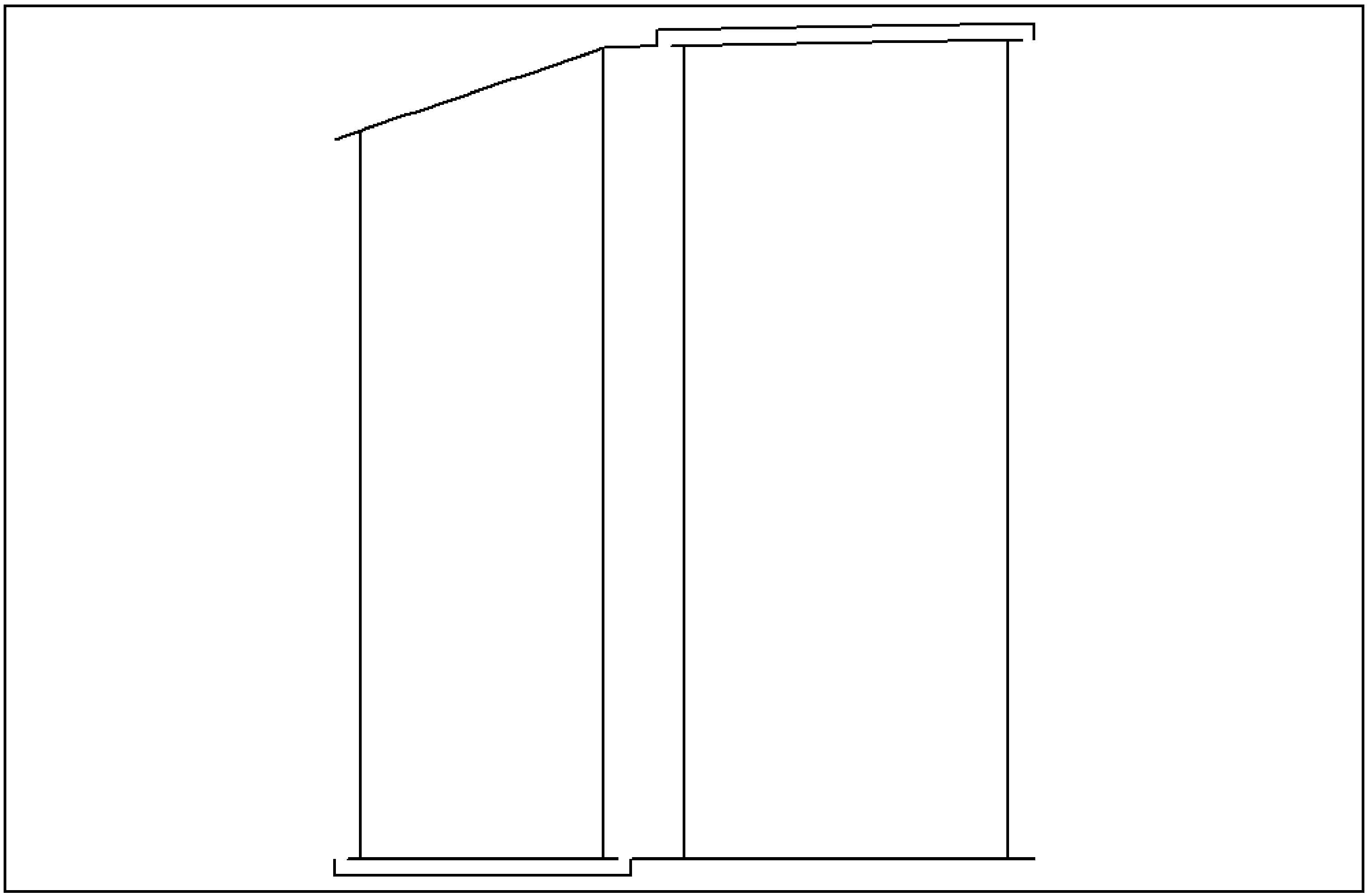
AXIAL-FLOW TURBINE BLADE SPECIFICATIONS

This Picture Shows the Blade Geometry Specification Window. Popular Correlations For The Optimum Number Of Blades Are Listed To Provide Guidance.



AXIAL-FLOW TURBINE STAGE CROSS-SECTION

This Picture Shows A Cross-Section Plot After AFTSIZE Has Sized The Stage.



PROGRAM AXTURB AERODYNAMIC PERFORMANCE ANALYSES

Program AXTURB Provides Aerodynamic Performance Predictions For Axial-Flow Turbines. A Multiple Streamline Analysis Is Used To Include The Effect Of Hub-To-Shroud Incidence Variation On Overall Performance.

It Treats Both Single-Stage And Multistage Turbines. Also Single-Row Turbines (Wind Turbines And Wave Turbines). Stage Components Considered Include

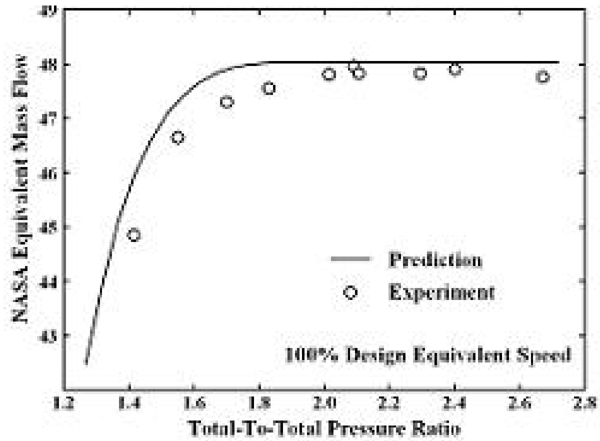
- **Nozzles**
- **Rotors**
- **Reversing Rows (Curtis Stages)**
- **Guide Vanes**
- **Turbine End-Seal Leakage**
- **Control Valve Losses**

It Can Consider Two-Phase, Condensing Flow. It Is Applicable To Both Solid (Drum) Rotors And Diaphragm-Disk Arrangements. It Also Predicts The Rotor Axial Thrust Forces.

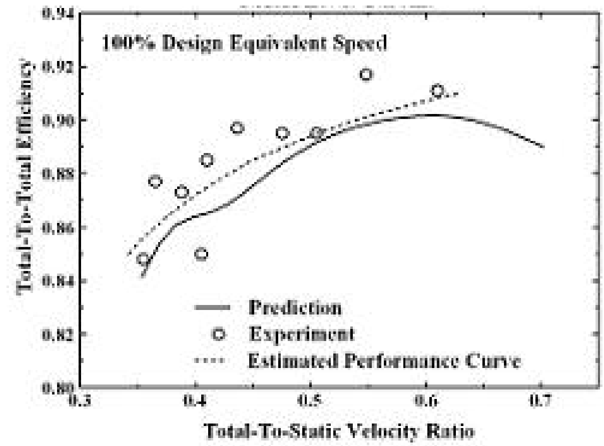
It Includes A General Map Utility To Allow The User To Generate A Wide Variety Of Performance Map Types For Review And Documentation.

QUALIFICATION OF AXTURB'S PREDICTION ACCURACY

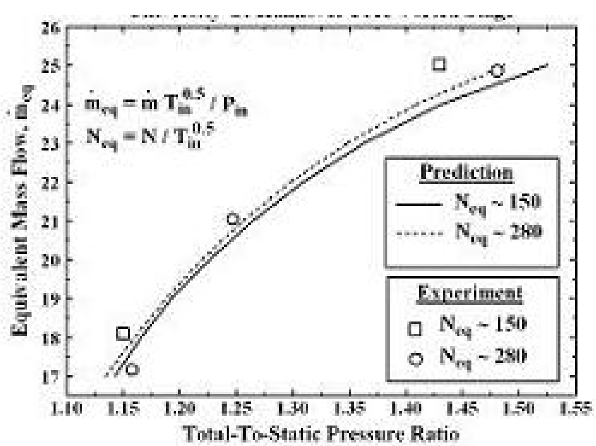
These Pictures Compare AXTURB Predictions With Experimental Data



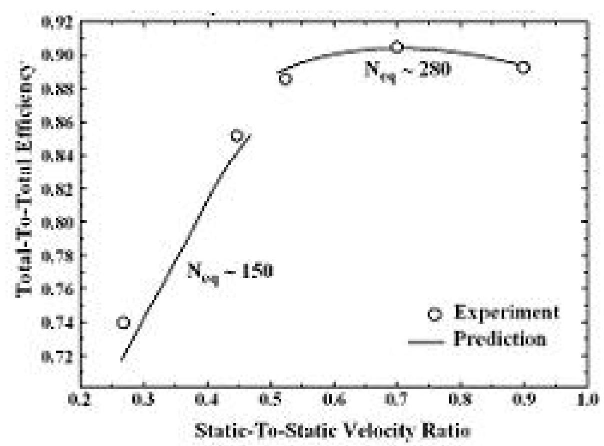
NASA Lewis Axial Flow Turbine Mass Flow



NASA Lewis Axial Flow Turbine Efficiency



University Of Hannover Turbine Mass Flow



University Of Hannover Turbine Efficiency

PROGRAM AIRFOIL DETAILED AIRFOIL GEOMETRY DESIGN

AIRFOIL Is A General Axial Flow Turbine Airfoil Geometry Detailed Design Program. It Can Design A Series Of Blade Profiles On Several Constant-Radius Sections To Design A Complete Blade Row.

The Typical Design Process Starts By Exporting An Initial AIRFOIL Input File From AFTSIZE Corresponding To Its Preliminary Design.

Program AIRFOIL Can Export The Geometry Portion Of Input Files For A 2D Blade-To-Blade Flow Analysis in B2B2D Or TDB2B To Evaluate The Blade Loading Distributions.

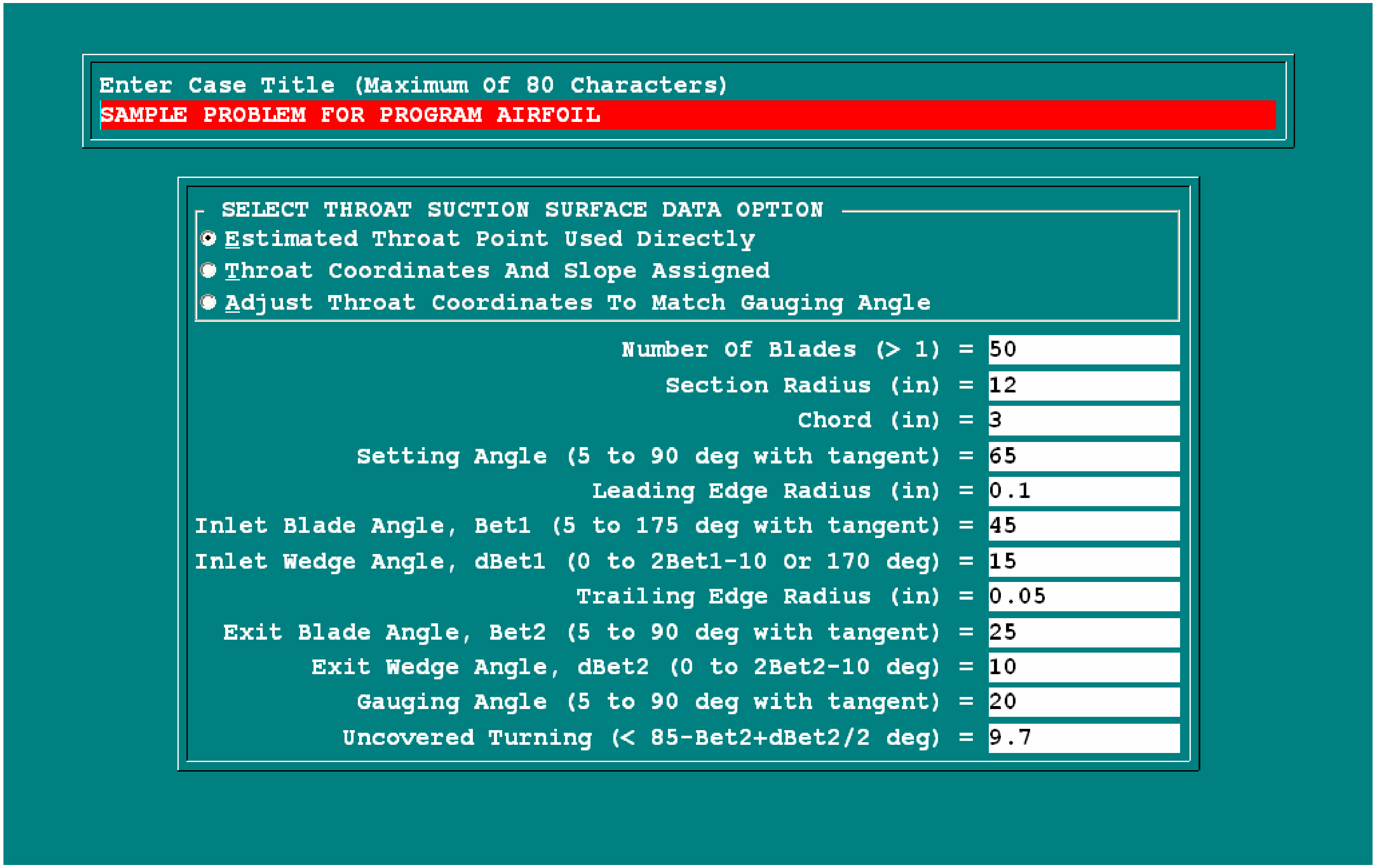
The Refined Airfoil Design Developed Here Can Be Imported by Program AXTURB To Check On The Aerodynamic Performance. When The Blade Row Performance And Blade Loading Distributions Are Satisfactory, The Blade Design Is Complete.

AIRFOIL Can Export Detailed Geometry Data to A Text File To Be Used By Other Software For Drafting, Manufacturing, Spreadsheets, Etc.

AIRFOIL Seeks To Match Key Inlet and Discharge Velocity Triangle Information And Uses A Series Of Surface Reference Points To Control The Airfoil Shape.

BASIC DESIGN SPECIFICATIONS FOR AIRFOIL

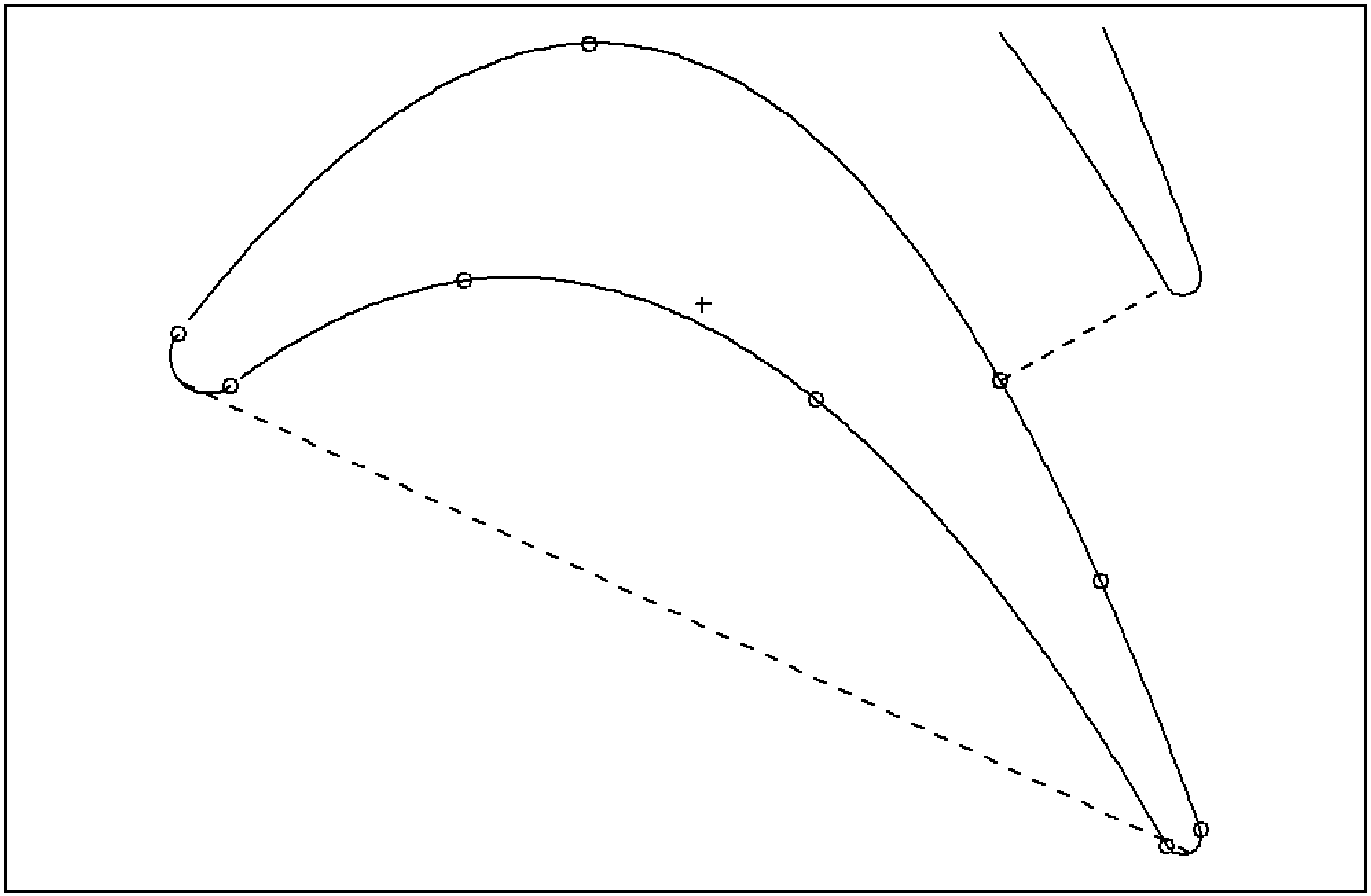
This Picture Shows The Basic Design Input Data Specification Window For AIRFOIL.



THE SURFACE REFERENCE POINTS USED BY AIRFOIL

This Picture Illustrates The Reference Points, Stacking Axis And Throat Width Specifications Used By AIRFOIL.

SECTION 1 AIRFOIL DESIGN VIEW PLOT (+ = STACKING AXIS)



PROGRAMS EXHAUST AND VOLUTE

Program EXHAUST Is A Performance Analysis For The Exhaust-End Components Of Axial-Flow Turbomachines. This Can Include Several Component Types.

- **An Axial Diffuser**
- **An Axial-To-Radial Diffuser (90 Degree Bend).**
- **An Exhaust Volute Or Collector.**

One Common Application Is To Calculate An Exhaust Loss Coefficient To Be Input To AXTURB. That Allows The Exhaust End Performance To Be Included In The Overall Turbine Performance Predictions.

When A Volute Or A Collector Is Present, Program VOLUTE Can be Used To Accomplish A Detailed Design Of The Passage Cross-Section Contours At Several Circumferential Locations. It Offers Several Commonly Used Options For Passage Contour Shapes, Component Sizing, Internal or External Components, Etc.