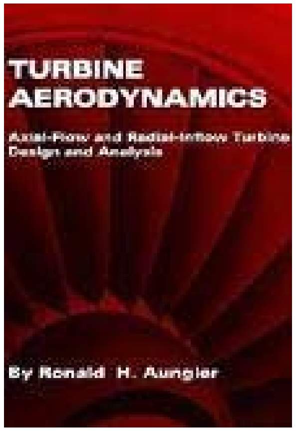
RADIAL-INFLOW TURBINE AERODYNAMIC DESIGN AND ANALYSIS USING THE TURBAERO SOFTWARE SYSTEM



***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

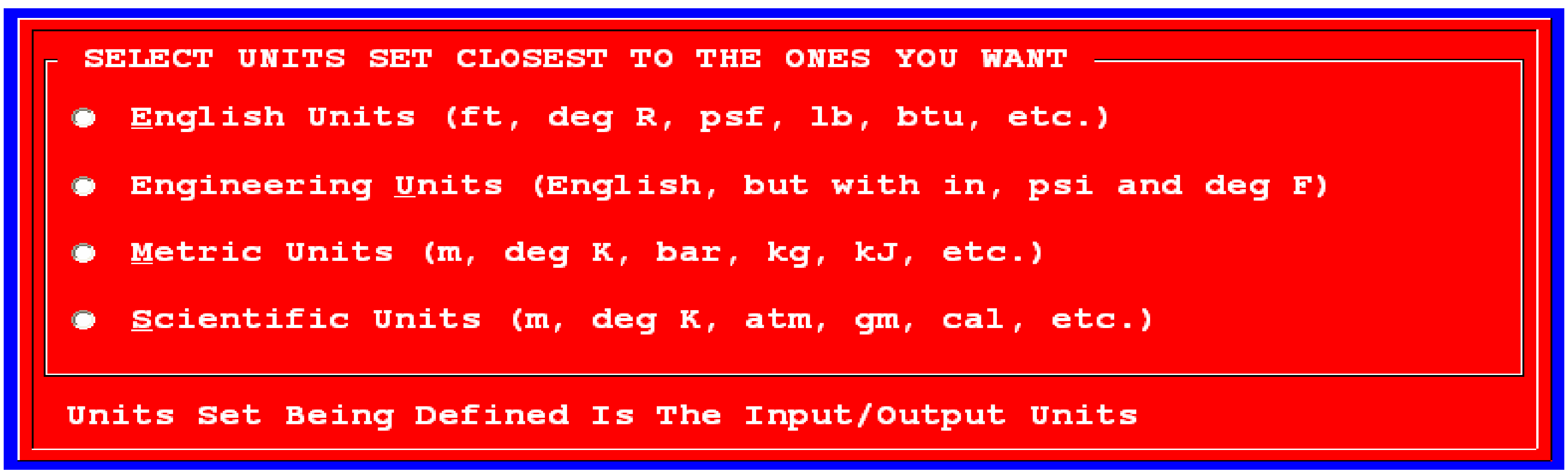
- **TURBAERO: a menu program to control the system and conveniently navigate among the other programs.**
- **AFTSIZE: an axial-flow turbine stage preliminary aerodynamic design program.**
- **AXTURB: an aerodynamic performance analysis for axial-flow turbines.**
- **RIFTSIZE: a radial-inflow turbine 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.**

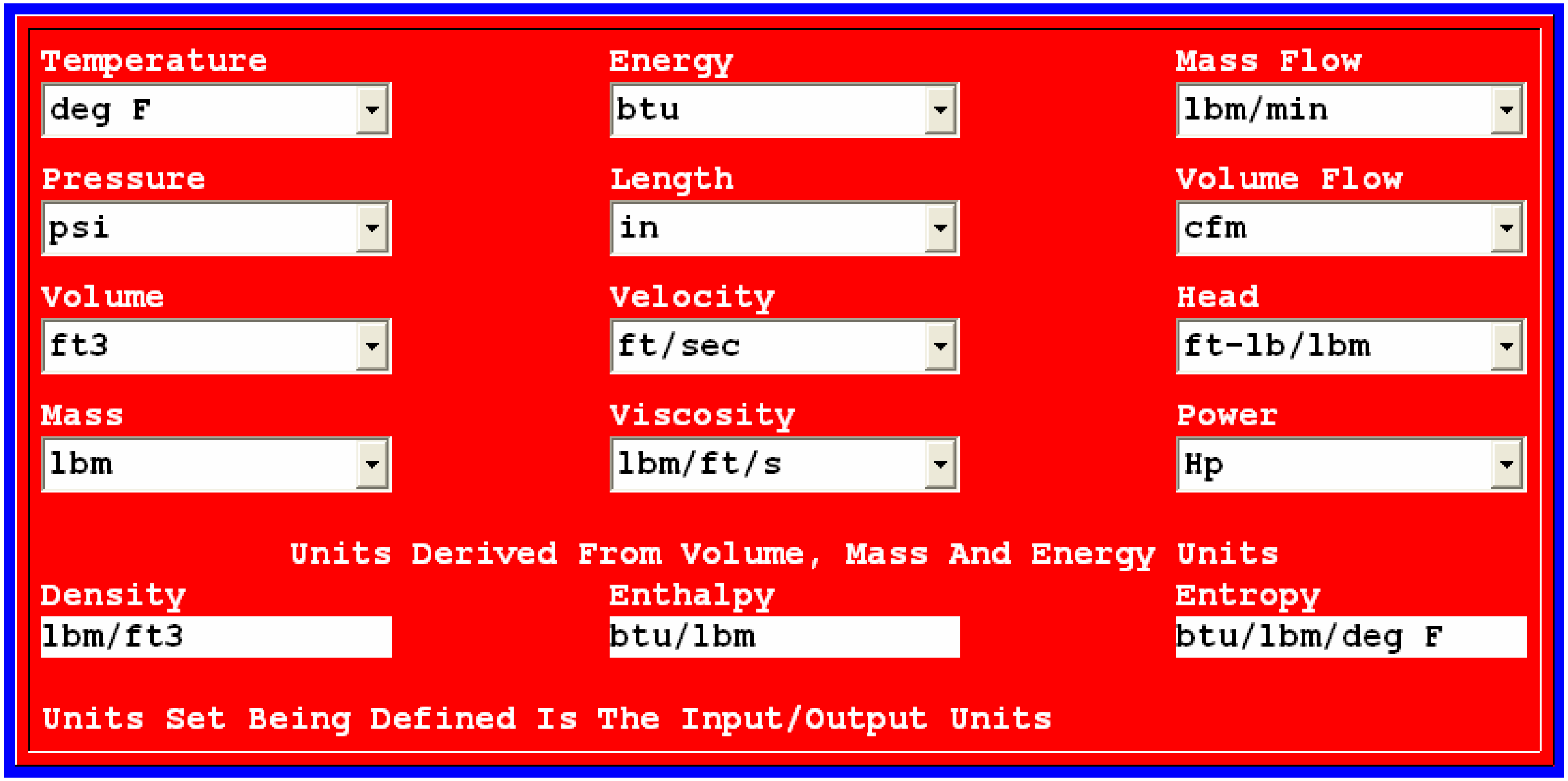
INPUT & OUTPUT UNITS FOR TURBAERO PROGRAMS

- **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.**

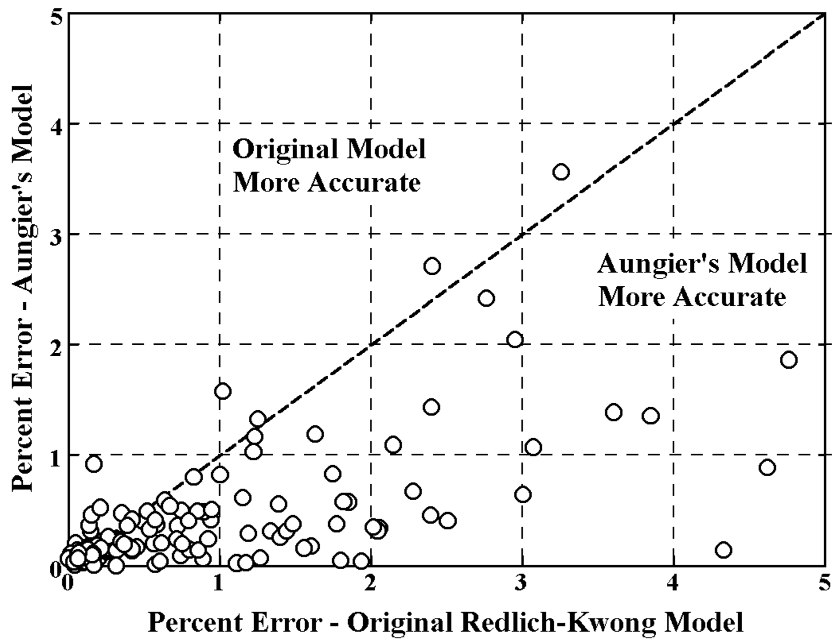
- **In General, Internal Flow Programs Are Valid For The Vapor Phase <u>Only</u>. RKMOD Can Handle Two-Phase Flows For Phase Checking, Liquid Knockout, Etc. Performance Analysis programs (AXTURB & RIFT) Also Treat Two-Phase Flows.**

- **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

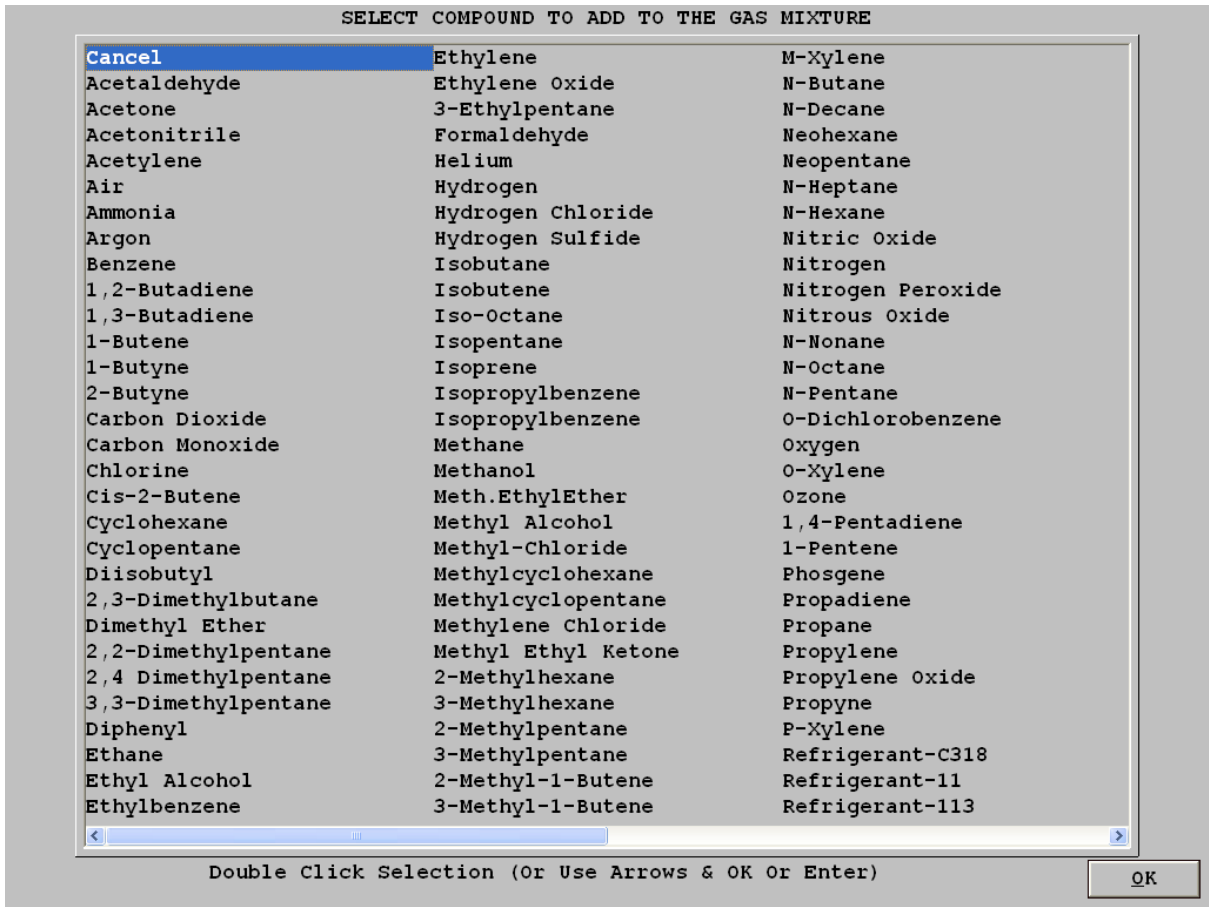
- **Accuracy Is Quite Sufficient For All Aerodynamic Design And Analysis Activity.**
- **Aungier's Modified Redlich-Kwong Equation Of State Is The Better Choice.**
- **These Equations Of State Are Not Recommended For Critical Applications Such As Performance Test Data Reduction Or Low-Tolerance Performance 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

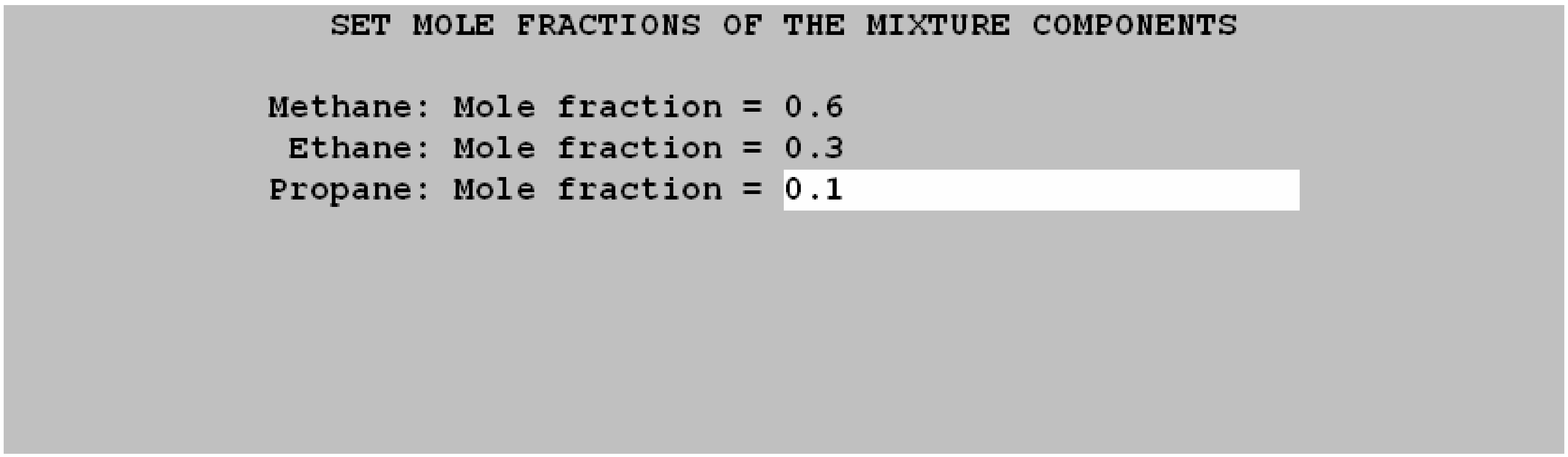
SELECTING COMPONENTS FOR A GAS MIXTURE

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



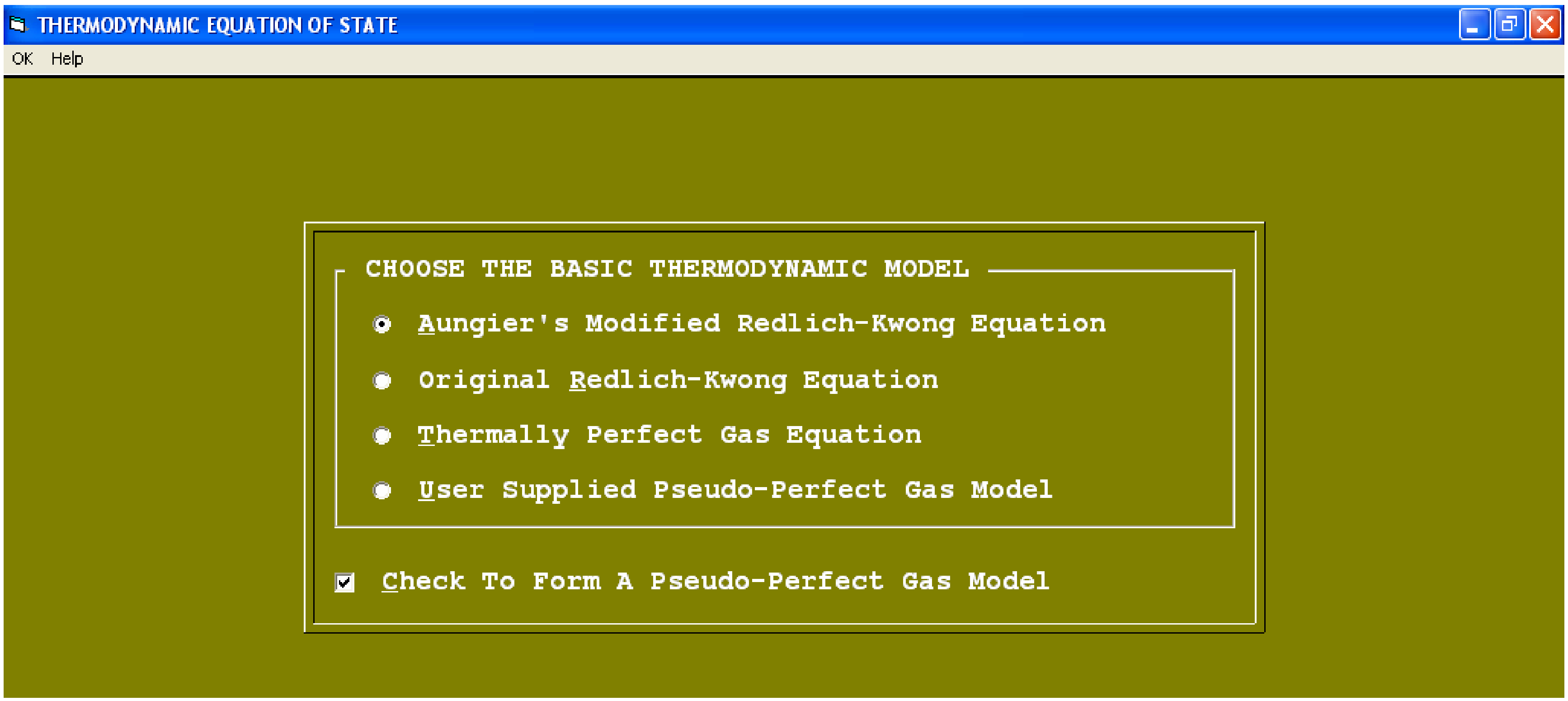
SPECIFYING COMPOUND MOLE FRACTIONS FOR A MIXTURE

- **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**



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 RIFTSIZE 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 RIFT 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.**

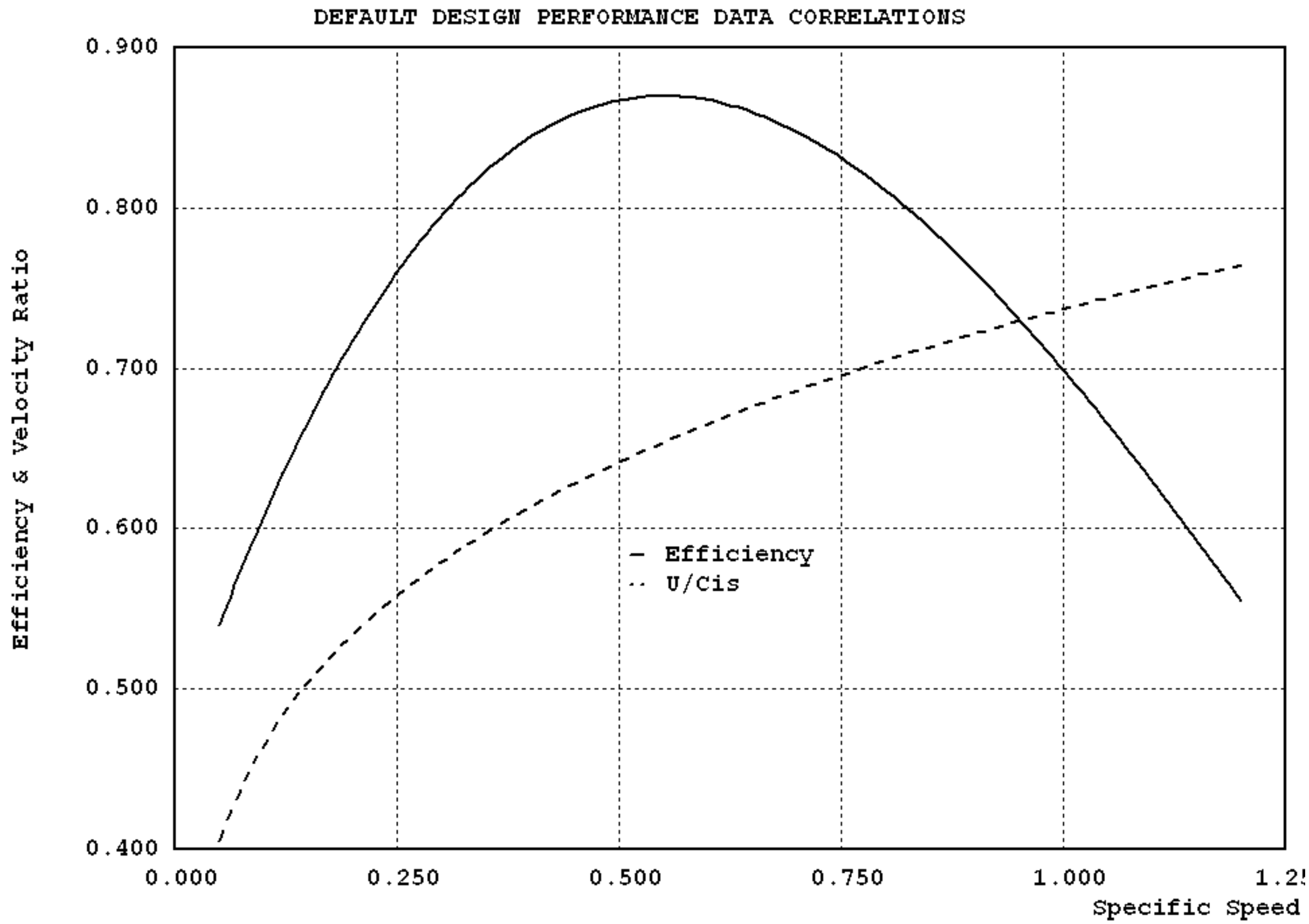
- **The Program Can Export Component Preliminary Design Geometry To The Various TurbAero Detailed Design Programs To Supply Their Initial Input Files.**

- **Extensive Comparison Of The Empirical Performance Estimates For The Default Designs With RIFT 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 Improve Design Quality By Its Ability To Rapidly Explore Many Design Alternatives Before Starting The More Time-Consuming Detailed Aerodynamic Design Process.**

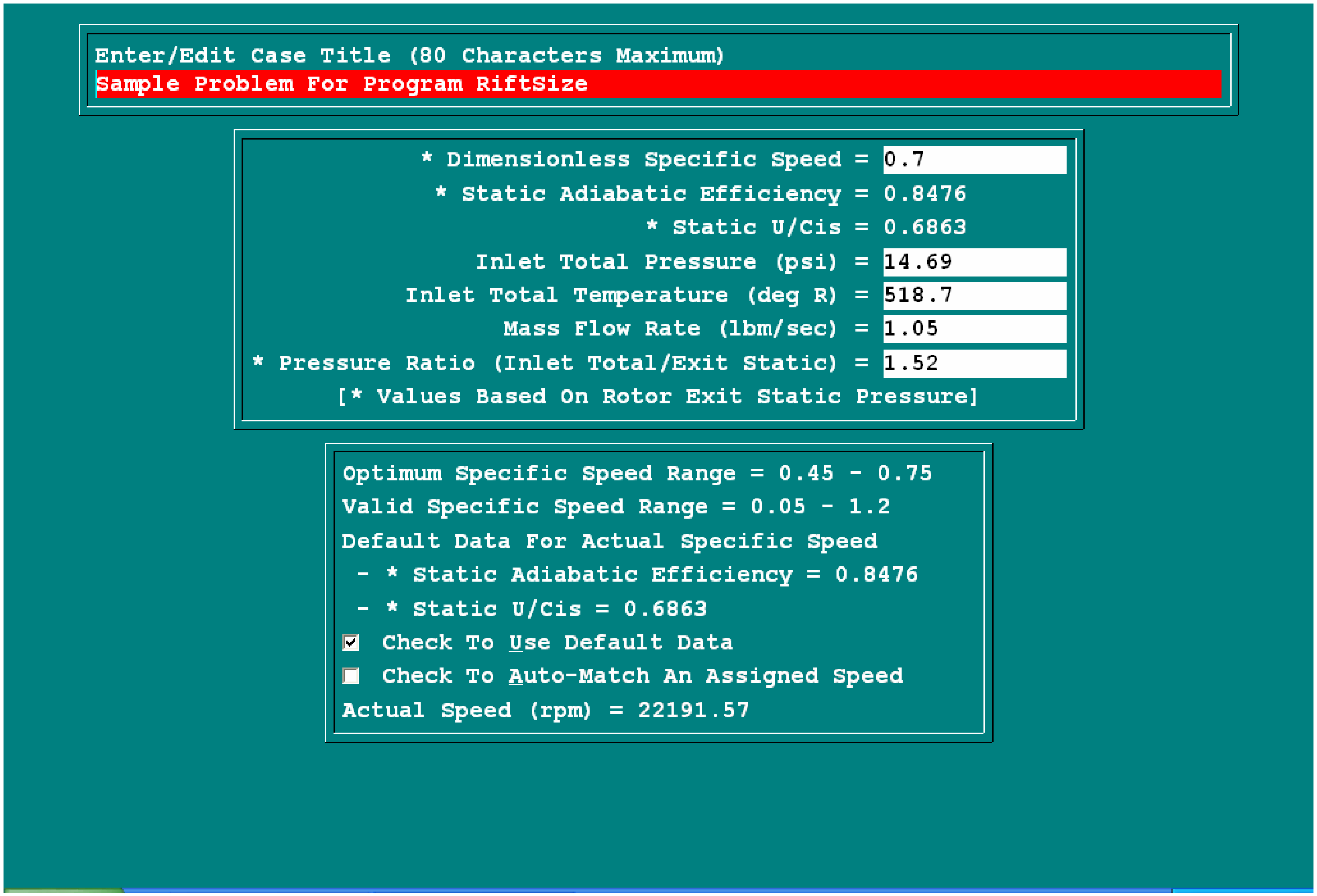
RADIAL-INFLOW TURBINE PRELIMINARY DESIGN WITH RIFTSIZE

- **RIFTSIZE Uses Generalized Specific Speed Charts To Guide The Designer In Selecting Near-Optimum But Realistic Design Goals For The Application.**
- **RIFTSIZE Can Export An Input File For A RIFT Performance Analysis Of The Resulting Stage Preliminary Design To Refine These Performance Estimates.**



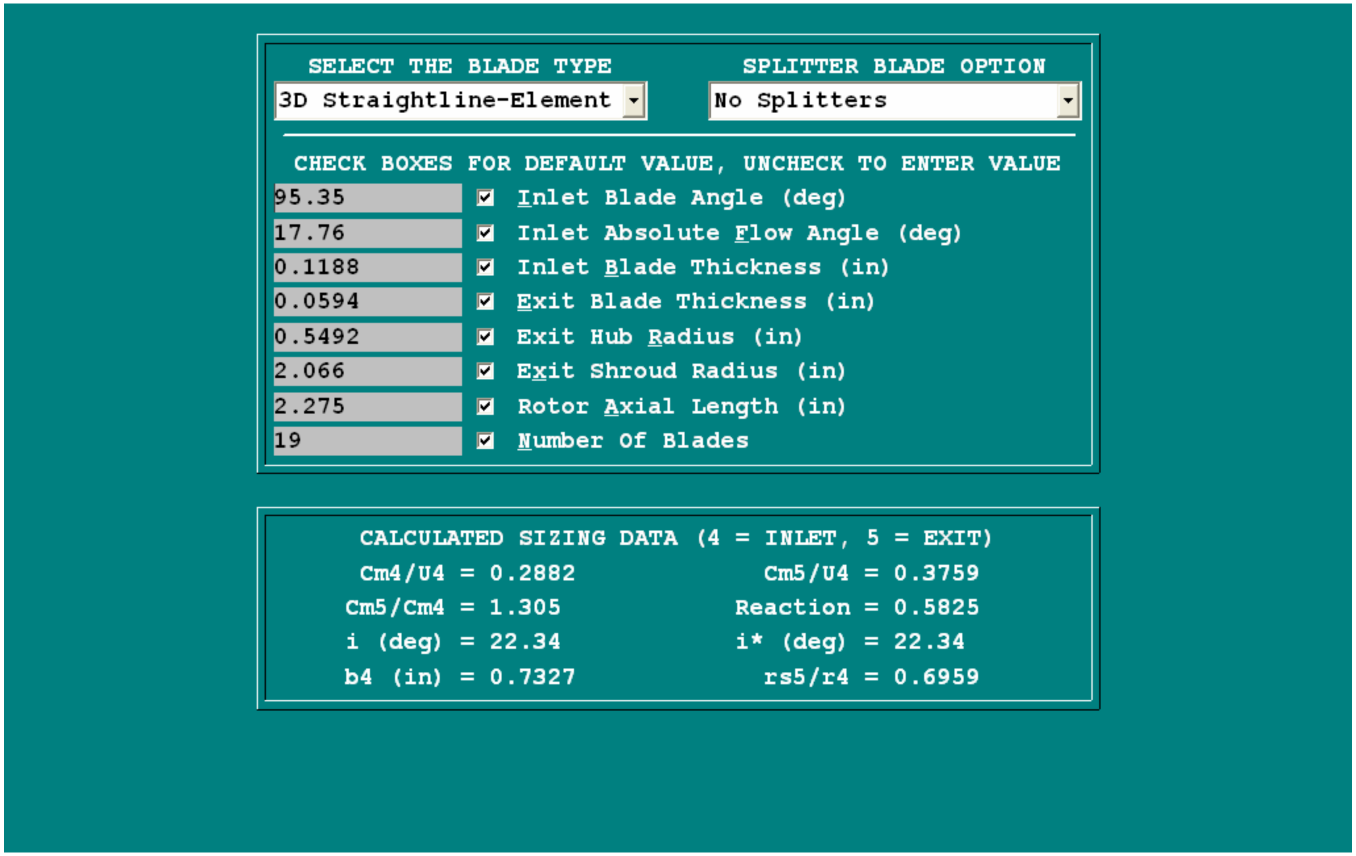
BASIC DESIGN SPECIFICATIONS FOR RIFTSIZE

This Picture Shows The Design Specifications Window For RIFTSIZE. Default Specifications From The Generalized Specific Speed Chart Are Listed For Guidance.



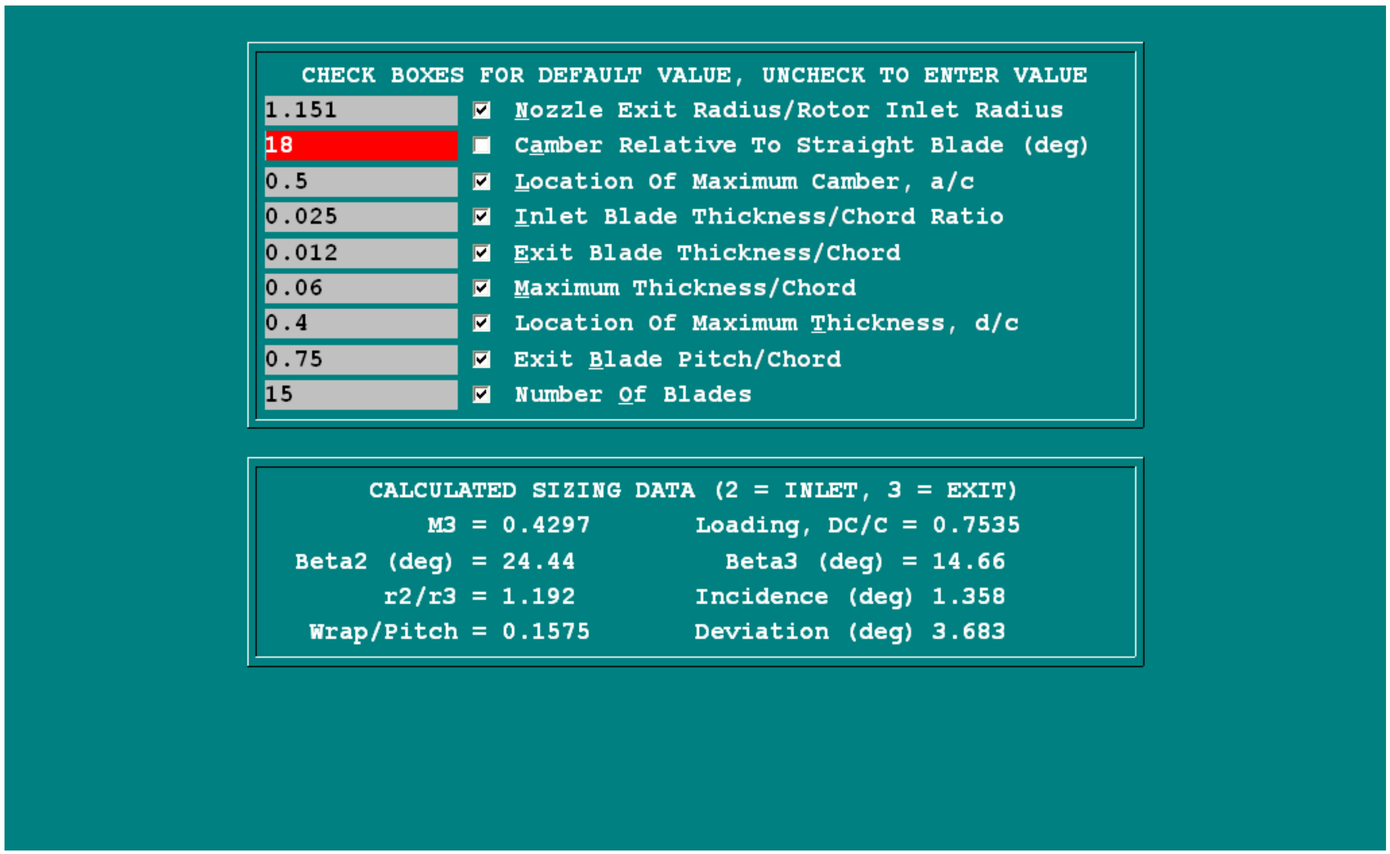
RIFTSIZE ROTOR SIZING SPECIFICATIONS

This Picture Shows The Rotor Sizing Design Specifications Window. Default Values From The Literature Are Used Initially, But The User Can Substitute Other Values As Found Necessary. Key Dimensions Resulting From The Choices Made Are Shown For Guidance.



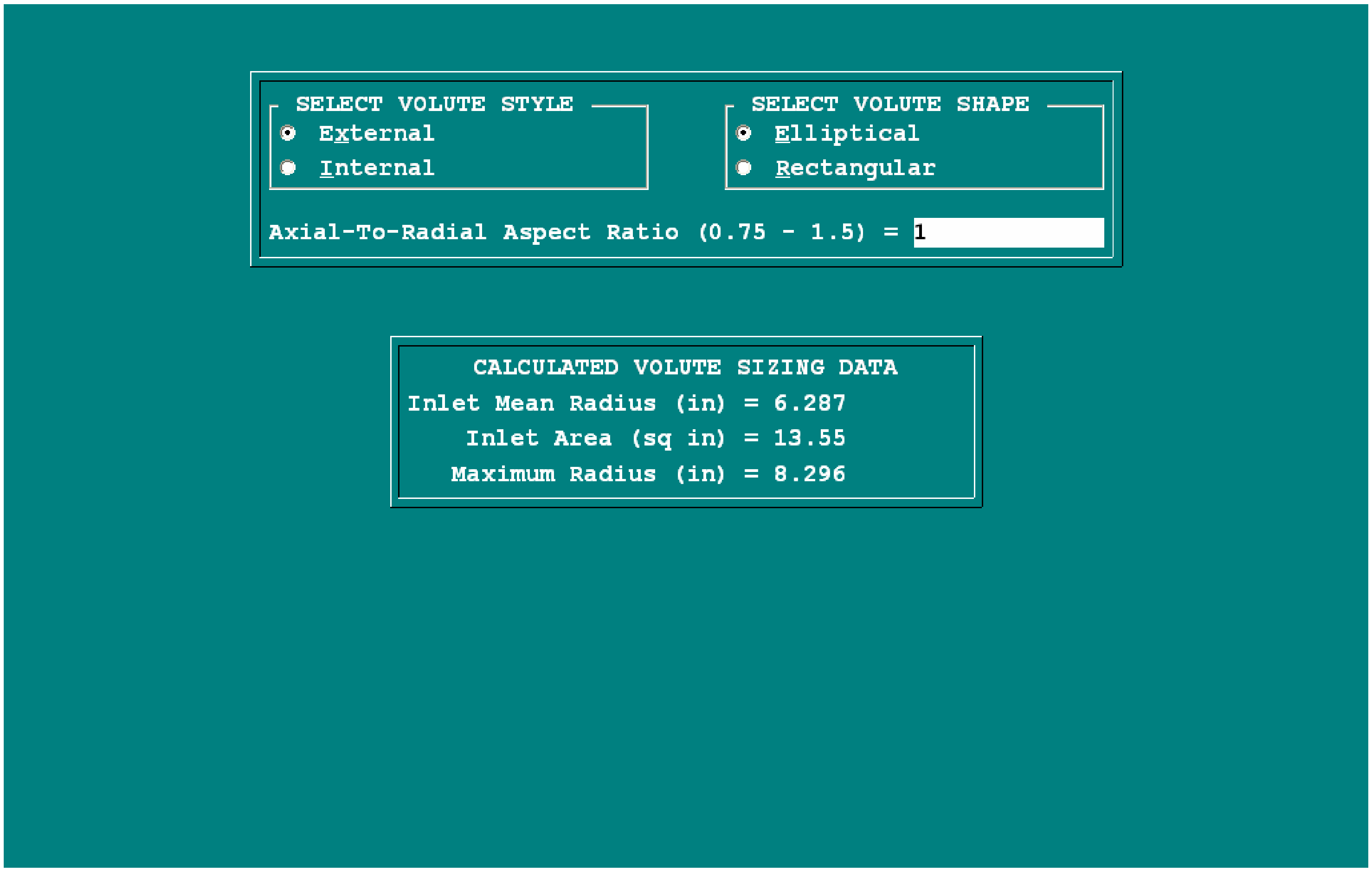
RIFTSIZE NOZZLE SIZING SPECIFICATIONS

This Picture Shows The Nozzle Sizing Design Specifications Window. Default Values From The Literature Are Used Initially, But The User Can Substitute Other Values As Found Necessary. Key Dimensions Resulting From The Choices Made Are Shown For Guidance.



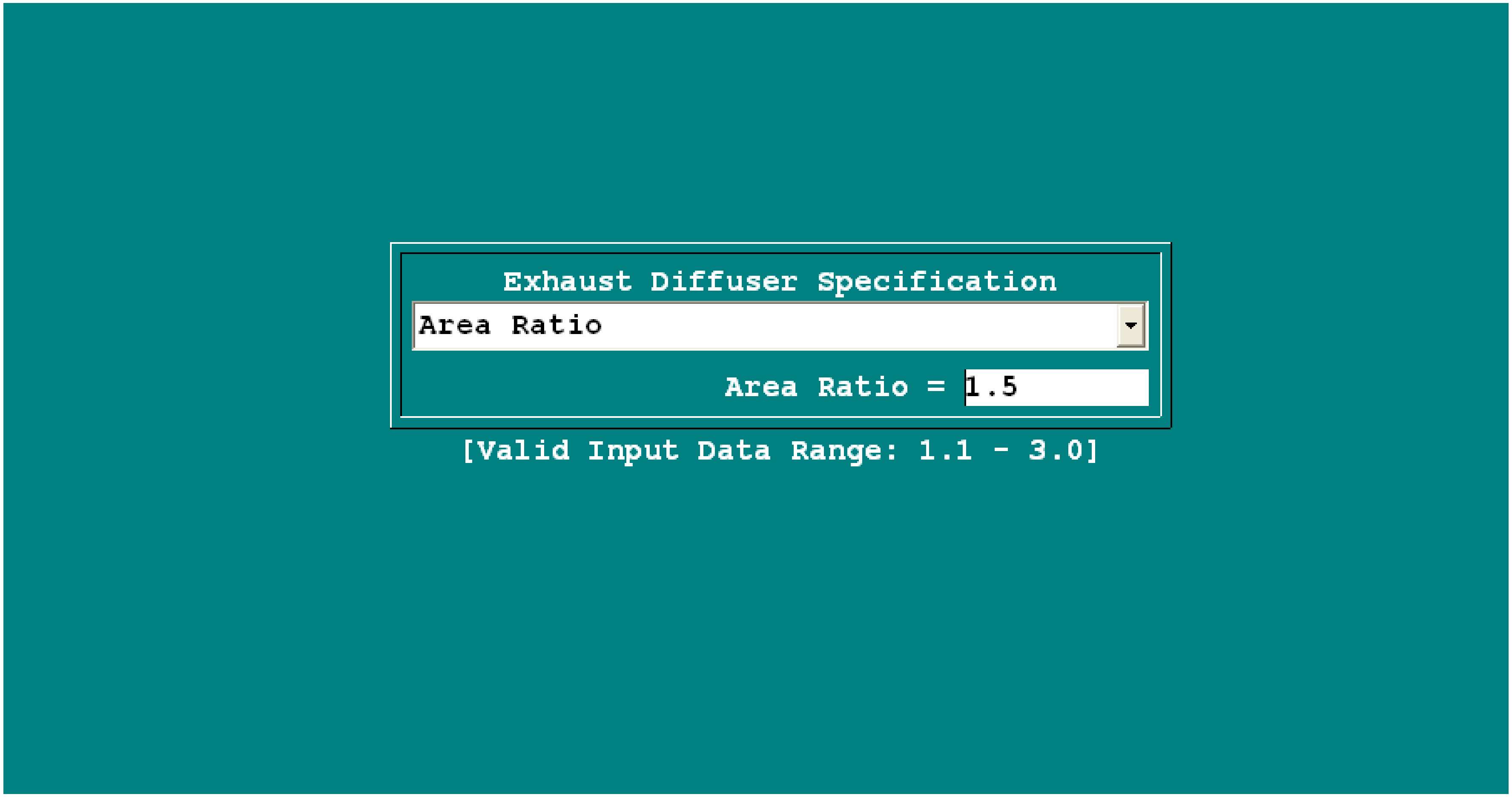
RIFTSIZE INLET VOLUTE SIZING SPECIFICATIONS

This Picture Shows The Inlet Volute Sizing Design Specifications Window. This Includes The Style And Shape To Be Used. Key Dimensions Resulting From The Choices Made Are Shown For Guidance.



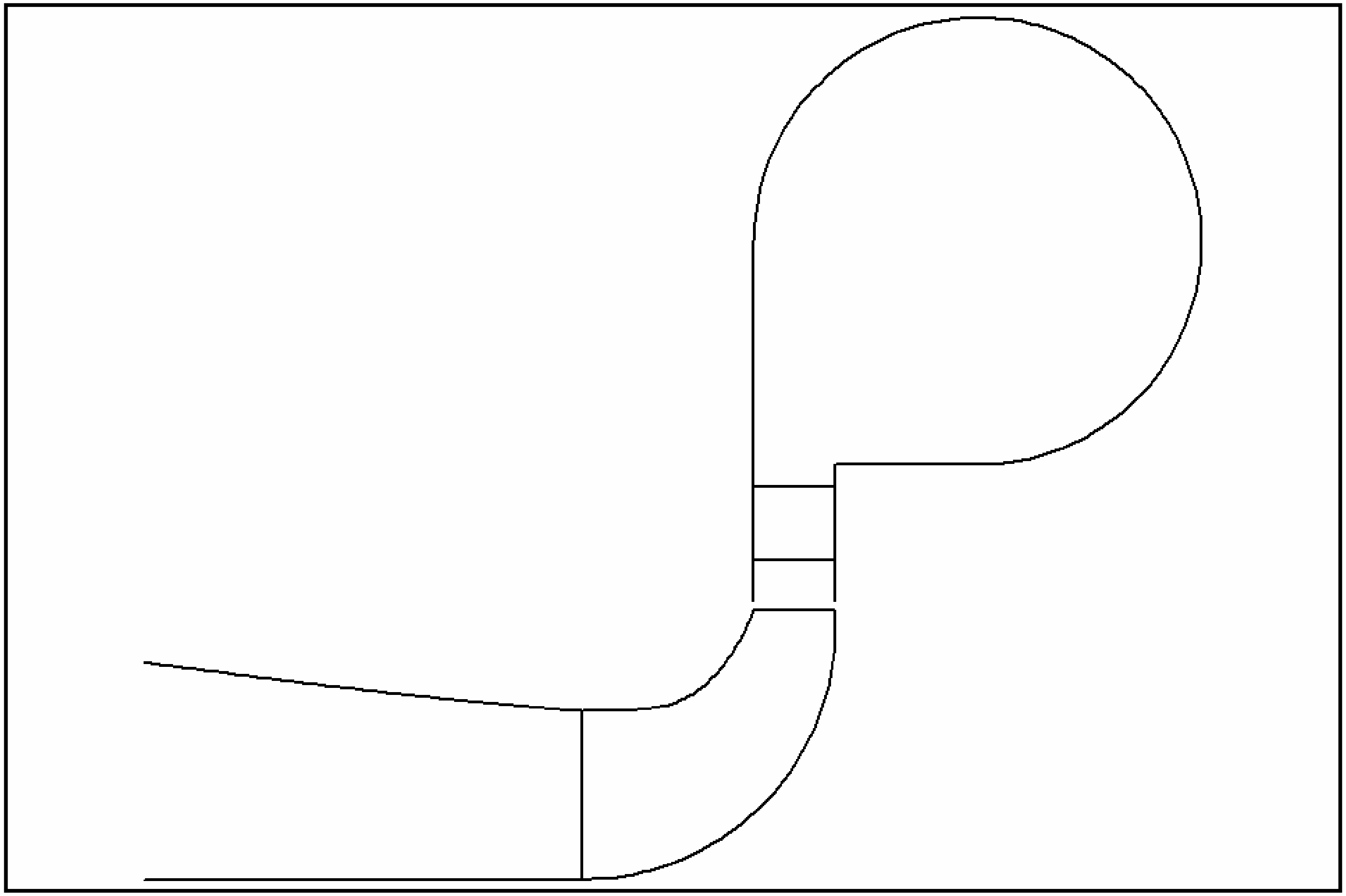
RIFTSIZE EXHAUST DIFFUSER SPECIFICATION

This Picture Shows The (Optional) Exhaust Diffuser Design Specification Window. Either Area Ratio Or The Length-To-Width Ratio Can Be Specified



CROSS-SECTION PLOT OF THE STAGE PRELIMINARY DESIGN

The Picture Below Is A Stage Cross-Section Plot Supplied By RIFTSIZE After All Components Of The Radial-Inflow Turbine Stage Have Been Sized



PROGRAM RIFT AERODYNAMIC PERFORMANCE ANALYSIS

Program RIFT Provides Aerodynamic Performance Predictions For Single-Stage And Multistage Radial-Inflow Turbines

It Is A Mean-Streamline Analysis. Components that Can Be Considered Are

- **Inlet Volutes**
- **Nozzles**
- **Rotors**
- **Exhaust Diffusers**
- **Rotor Seal Leakage**
- **Vaneless Annular Passages**

Two-Phase, Condensing Flow Can Be Considered

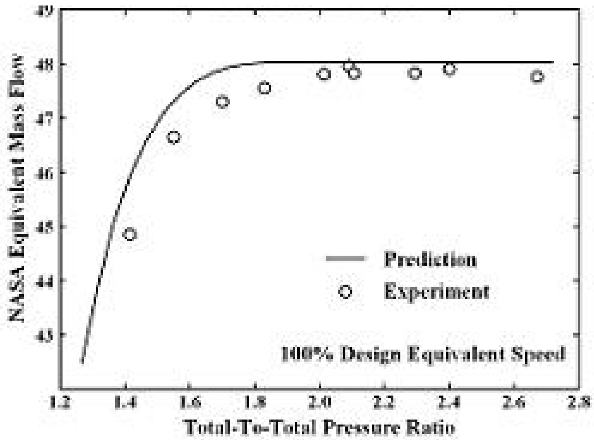
RIFT Includes A General Map Utility To Allow The User To Generate A Wide Variety Of Performance Map Types For Review And Documentation.

It Also Provides Prediction Of Rotor Axial Thrust Forces.

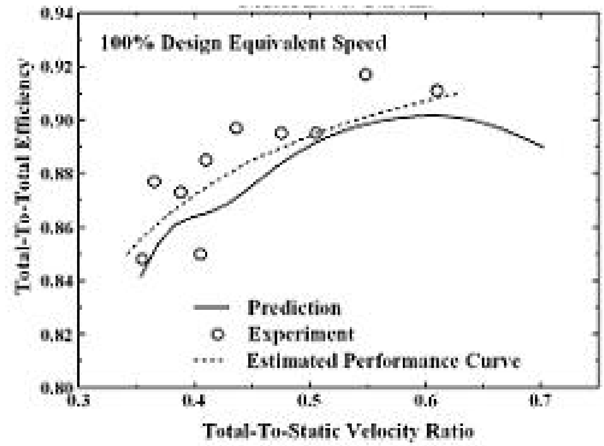
RIFT Can Export Flow Conditions To Update Input Files For Several Other TURBAERO Design And Analysis Programs (B2B2D, TDB2B, FLOW3D & VOLUTE)

QUALIFICATION OF RIFT PREDICTION ACCURACY

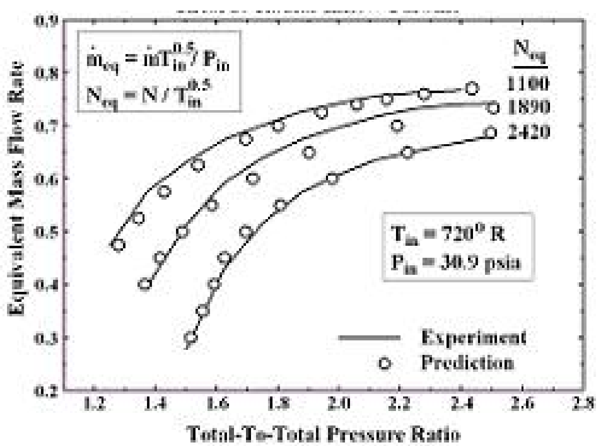
These Pictures Compare RIFT Predictions With Experimental Data



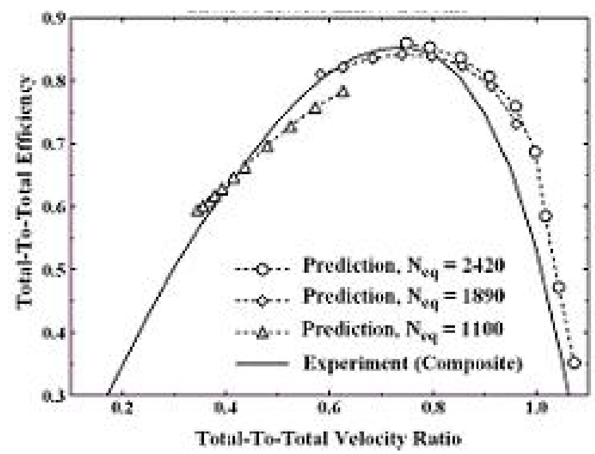
NASA Lewis Radial-Inflow Turbine Mass Flow



NASA Lewis Radial-Inflow Turbine Efficiency



Ricardo Radial-Inflow Turbine Mass Flow



Ricardo Radial-Inflow Turbine Efficiency

PROGRAM RIFTNOZ - DETAILED AERODYNAMIC DESIGN

Program RIFTNOZ Accomplishes The Detailed Aerodynamic Design Of Nozzles

It Uses A Standard Airfoil Family Adjusted To Match The Nozzle Row Inlet & Discharge Velocity Triangles

Normally, Its Initial Input File Is Created by RIFTSIZE From The Preliminary Design

It Contains An Internal Linearized Blade-To-Blade Flow Analysis To Provide Approximate But Continual Blade Loading Evaluation To The Designer

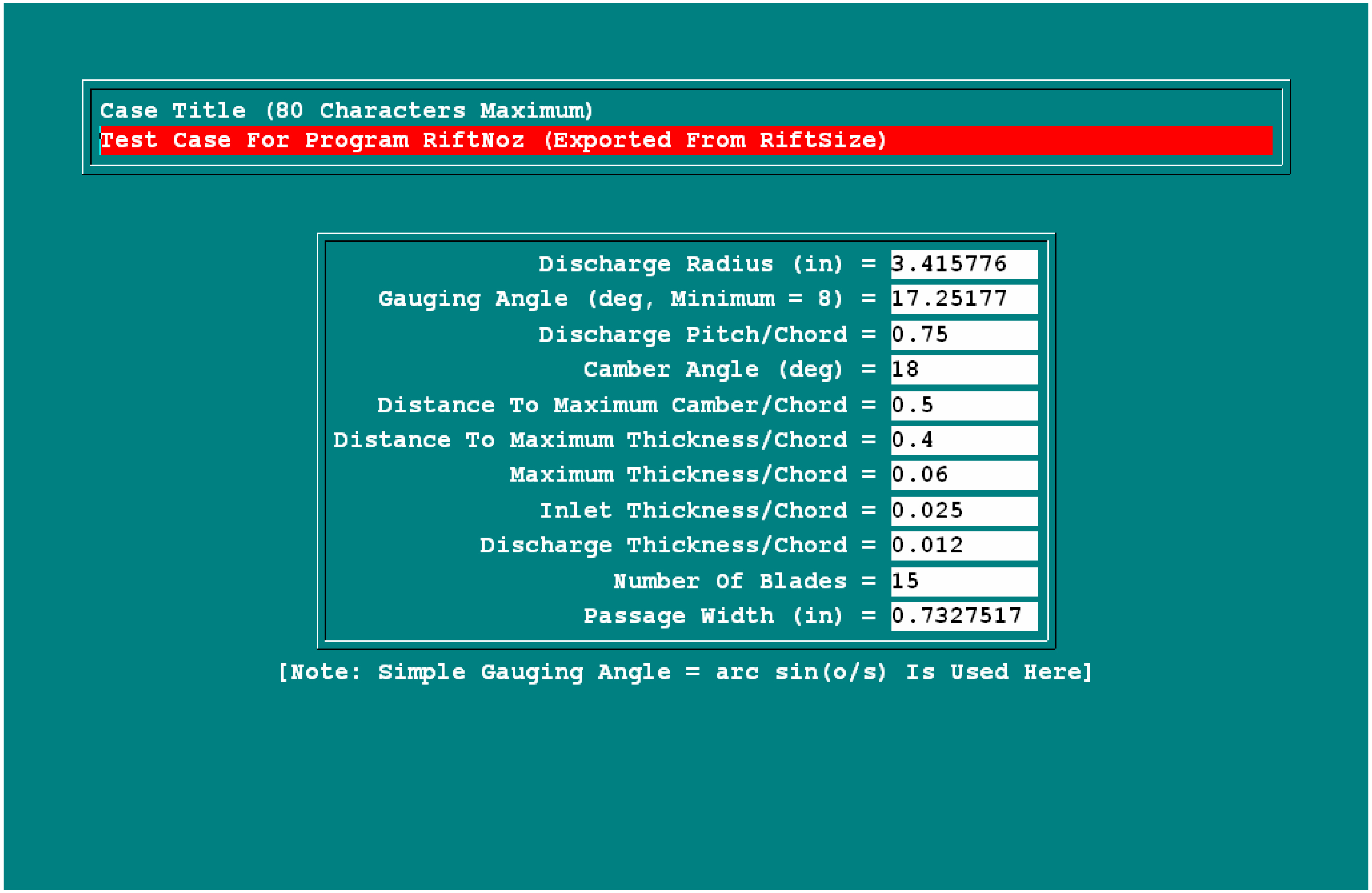
It Can Export The Geometry To RIFT, B2B2D And TDB2B To Update The Performance Predictions And For A More Exact Blade Loading Evaluation

It Can Export detailed Geometry to Text Files For Use In Spreadsheets, CAD Systems, Manufacturing Software, Etc.

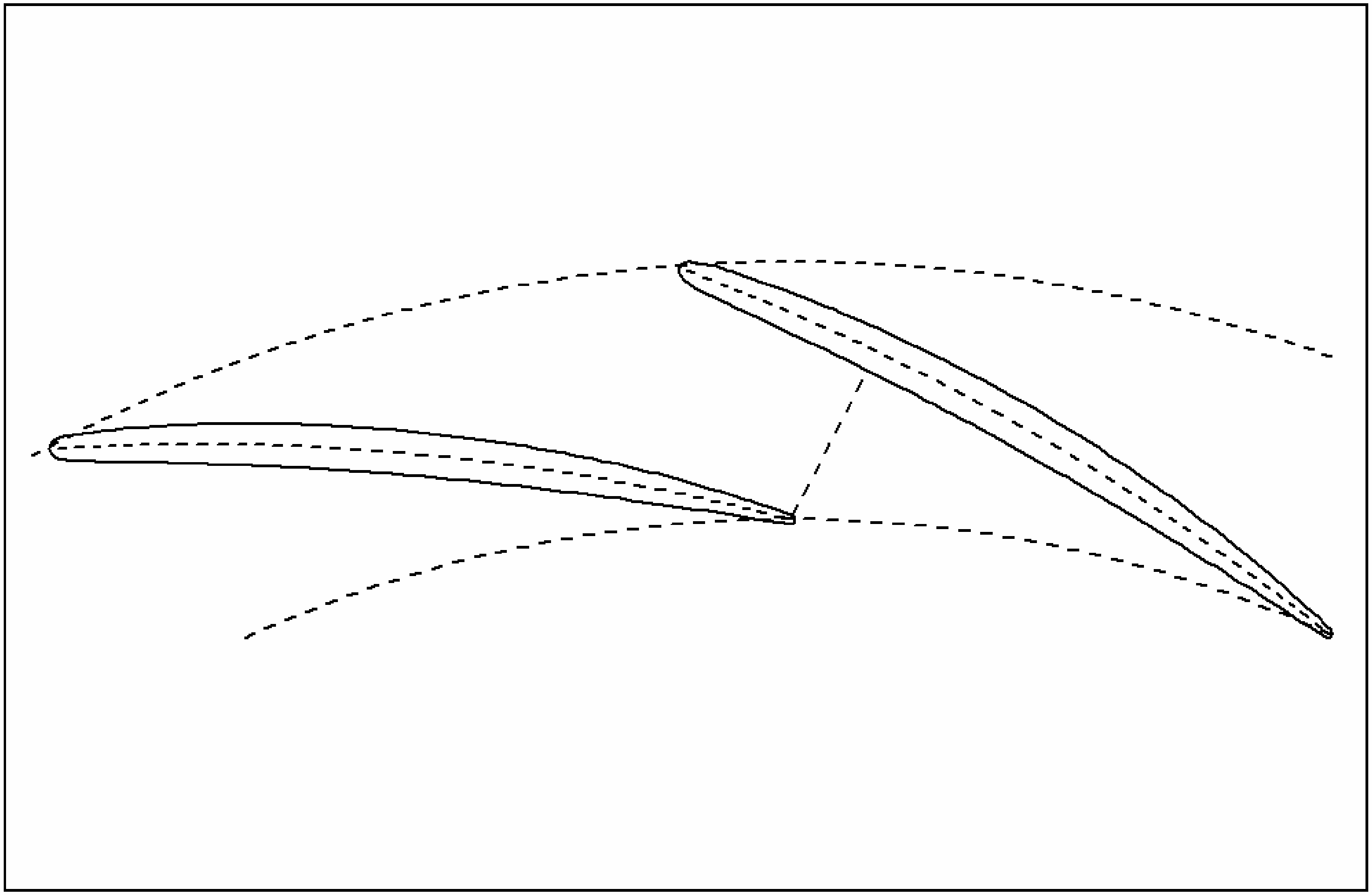
In The Rare Cases Where Greater Generality Is Needed, Detailed Design Programs GASPATH And BEZIER Can Also Be Used For Nozzle Detailed Design

RIFTNOZ BASIC DESIGN DATA

This Picture Shows The RIFTNOZ Basic Design Data Input Window



A CASCADE PLOT OF THE RIFTNOZ DETAILED NOZZLE DESIGN



IMPELLER DETAILED AERODYNAMIC DESIGN

- **Detailed impeller Design Uses COMPAERO Centrifugal Compressor Programs GASPATH, BEZIER And FLOW3D, Modified To Reverse The Flow Direction.**
- **Impeller Blade Types Available**
  - **Two-Dimensional, Axial-Element.**
  - **Two-Dimensional, Radial-Element.**
  - **Three-Dimensional, Straight-Line-Element (Ruled Surface).**
  - **Circular-Arc Camberline (Special Two-Dimensional, Axial-Element)**
- **Curves Required By GASPATH From BEZIER.**
  - **End-Wall Contours.**
  - **Camberline Blade Angle Distributions.**
  - **Blade Thickness Distributions.**
- **Curve Types Available In BEZIER**
  - **Bezier Polynomial Curves (The Most General).**
  - **Circular-Arc Curve (Minimum Curvature).**
  - **Three-Point Cubic-Spline Curves.**
  - **Third-Order Polynomial Curves.**
  - **Curve Defined By User Supplied Points (Which Are Curve Fit).**
  - **Composite Curve (Two Or More Curves Combined).**

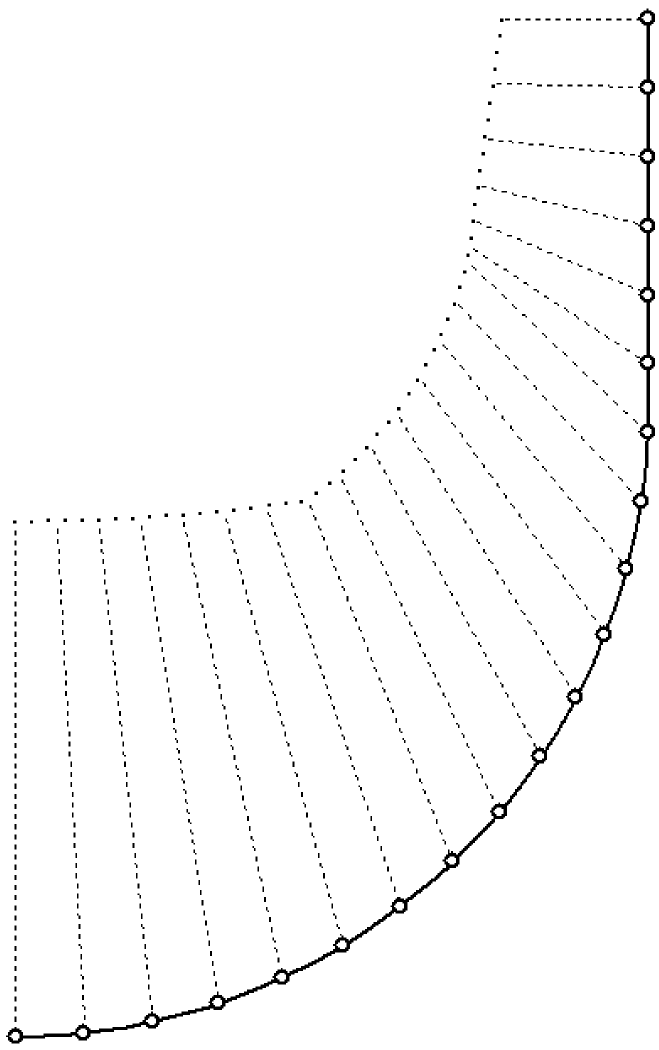
<u>Note</u>: The First Four Curve Types Require That The End-Point Slopes Be Specified. A Liner Segment Will Be Included At One End If Needed. User Can Require Linear Segments (Of Specified Minimum Lengths) On Both Ends

INITIALIZING THE REQUIRED INPUT FILES

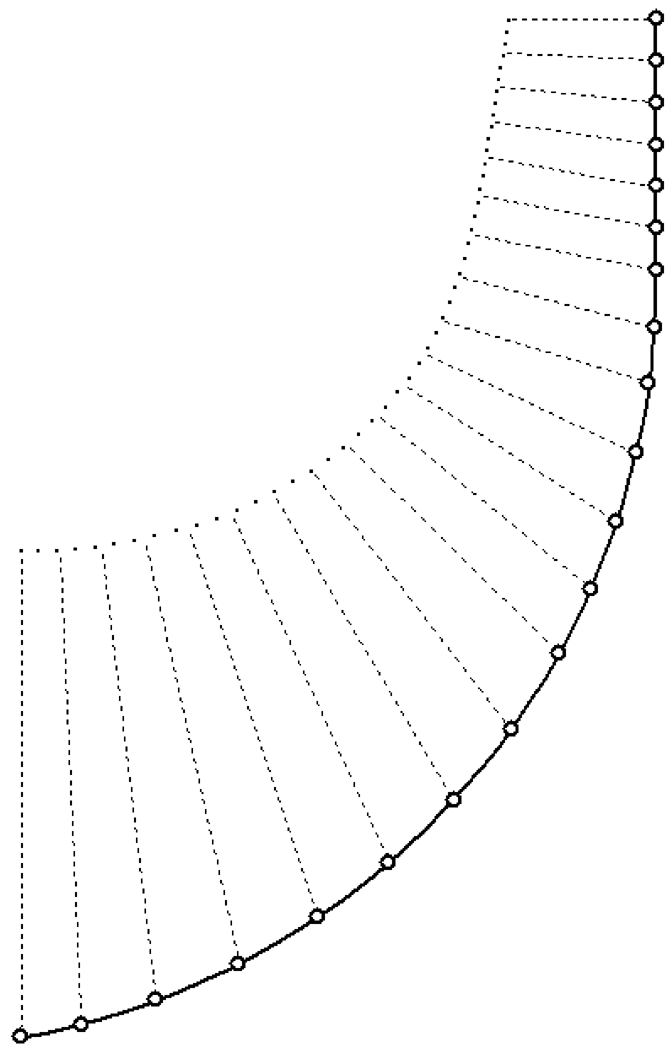
- **Initialize Input Files For GASPATH And BEZIER From RIFTSIZE (Preliminary Design Results Are Used).**
- **FLOW3D Requires Hub And Shroud Vaneless Extensions On Each End Of The Blade Row. RIFTSIZE Can Include Them Or Omit Them When Initializing BEZIER.**
- **Including Them Will Require Readjusting The Leading And Trailing Edge Points Every Time You Change A Contour,**
- **Omitting Them Requires Defining The Extensions As Separate Curves And Forming A Composite Curve For GASPATH To Use. Since End Points And Their Slopes Normally Are Fixed, The Extensions Usually Need Only Be Designed Once. And BEZIER Can Reform A Previously Defined Composite Curve For You.**
- **I Find The Second Approach More Convenient, But Some Designers Prefer The First. It's Really Just A User Preference.**
- **Create The Initial Input File For FLOW3D With GASPATH Or RIGPAC. Then Update It With RIFT To Add The Units, Stage Operating Conditions And Equation Of State.**

REFINING THE PRELIMINARY DESIGN

- **The Preliminary Design Will Be Sized About Right, But Almost Always Will Have Unacceptable Features.**
- **The Spline Curve Used For The Shroud Contour Is Rarely Acceptable. You May Be Able To Edit It, But Usually You Have to Replace It.**
- **The Blade Angle Distributions Are Sets Of Points, Which Are Not Easily Edited. Usually You Will Just Replace Them.**
- **Many Designers Replace These Unacceptable Curves Using An Option In BEZIER To Fit A Bezier Curve To An Existing Curve. The Bezier Curve Is Very General And Easily Modified To Correct Any Deficiencies.**
- **You Will Usually Find That The Quasi-Normals From Hub To Shroud Do Not Approximate Normals As Recommended. The Distributions Of The Points On One Or Both Contours Will need Adjusting to Fix That.**
- **See A Typical Before-And-After Simple Adjustment Example On The Next Page.**



Preliminary Design From RIFTSIZE



Adjusted Preliminary Design

SOME HINTS FOR USING BEZIER EFFECTIVELY

- **BEZIER Stores All Curves You Have Created Unless You Delete Them. Use This Feature To Enable Returning To An Earlier Version When Appropriate. Use Curve Captions That Help With This (For Example, Bezier Shroud #2). You Can Copy A Curve, Rename It And Modify It Without Losing The Original.**

- **Curve Types Are Either Geometric Contours Or General Curves. When Editing, You Can View A Second Curve Of The Same Type As A Background Curve.**

- **BEZIER Displays And Plots Key Data (Curvature, Area Distributions, Etc.) To Provide Useful Guidance Before Actually Constructing The Impeller In GASPATH.**

- **The Circular-Arc Curve (With Linear Extensions) Is The most Common Choice For Hub Contours (To Minimize Passage Curvatures).**

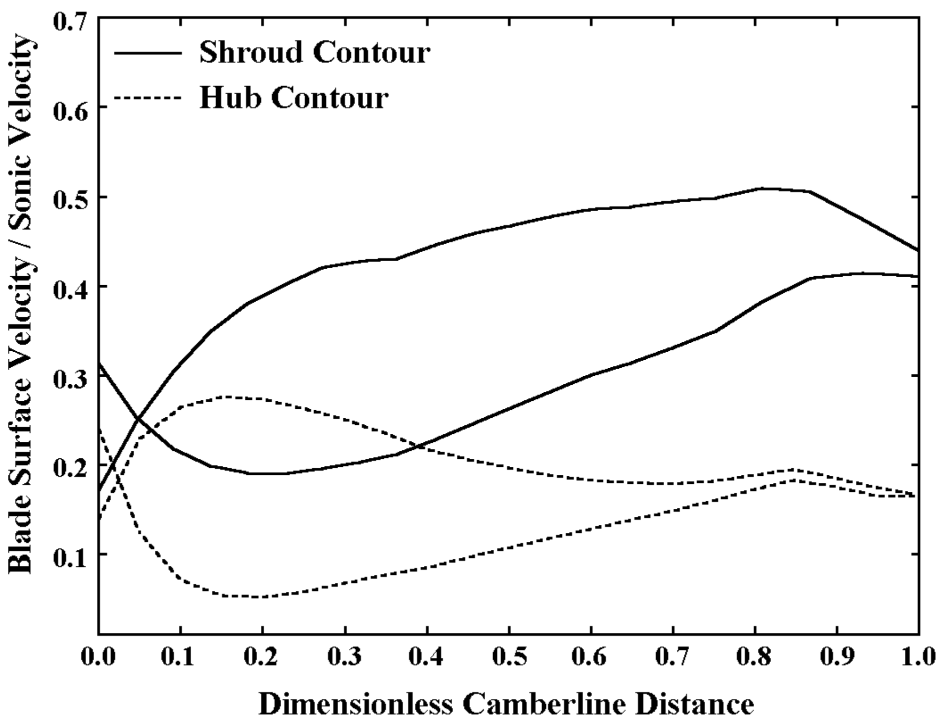
- **Some Designers Use the Same Form For Shroud Contours Quite Successfully. But The Bezier Curve Is The More Common Choice.**

- **Equal Spaced Quasi-Normals On The Shroud Contour Is Often A Good Choice And Always A Good Starting Point. Quasi-Normals Are Usually Refined Primarily By Adjusting The Point Spacing On The Hub Contour.**

- **Interactive Adjustment Is Usually Done By Moving 2 Or 3 Key points And Using BEZIER's Option To Equal-Space Points Between Two Specified Points.**

GASPATH AND FLOW3D INTERACTION

- **Many Aero Design Features Will Be Already Set Via CENCOM (Inlet & Discharge Geometry, Overall Impeller Diffusion, Average Blade Loading, Etc.).**
- **It Remains To Achieve Good Velocity Distributions On Blade And End-Wall Surfaces, The Required Throat Area, Structural Integrity And Manufacturability.**
- **GASPATH Exports Input Files For FLOW3D To Assess The Velocity Distributions As Illustrated In The Blade Loading Diagrams, Below.**



AFTERMARKET APPLICATIONS WITH RIGPAC

- **RIGPAC Was Developed To Implement Centrifugal Compressor Prototype Stages Into Practical OEM Product Lines. Many Of Its "Operations" Are Well Suited To Rerate Activity. It Can Reverse The Flow Direction For Radial-Inflow Turbine Impeller Applications**
- **RIGPAC Can Import Impeller Geometry From Text Files Obtained By Reverse-Engineering, Or Via CAD/CAE Systems. The Process Is Deceptively Simple, But Oversights Are Common, Mainly Because We Do It So Infrequently (Even I Often Don't Get It Right The First Time). The On-Line Help Explains the Process, But You Must Get The Text Import File Right And Not Overlook Anything.**
- **Some Rerates Can Be Accomplished Using RIGPAC, RIFT And FLOW3D, Only. RIGPAC Can Supply (Or Update) Impeller Geometry Data To RIFT And FLOW3D.**
- **In many Cases, Using A Modification Of Existing Impeller Contours And Blades Is The Simplest Approach And Has The Lowest Risk. RIGPAC Can:**
  - **Trim Or Extend The Impeller Tip To Modify The Impeller Head.**
  - **Adjust The Gross Passage Area Distribution To Increase Or Decrease The Flow Capacity.**
- **It Can Also Export The Defining Curves Needed By BEZIER For A More Fundamental Impeller Redesign Via GASPATH.**
- **It Is Often A Very Good Way To Introduce The Geometry Of An Existing Impeller Into The TurbAero System For Other Design And Analysis Activity.**

INLET VOLUTE DETAILED DESIGN

Program VOLUTE Accomplishes The Detailed Design Of The Flow Passage Contours For Volutes. RIFTSIZE Can Create Its Initial Input File And RIFT can Update Its Flow Specifications From Its Performance Prediction. The Picture Below Is The Program's Main Window Where the Design Data Is Specified And Passage Cross-Sections Are Displayed At Several Circumferential Locations. VOLUTE Can Update The Geometry In A RIFT Input File And Export It To A Text File For Subsequent Import Into Drafting Or Manufacturing Software.