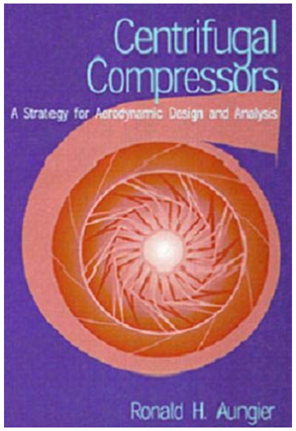
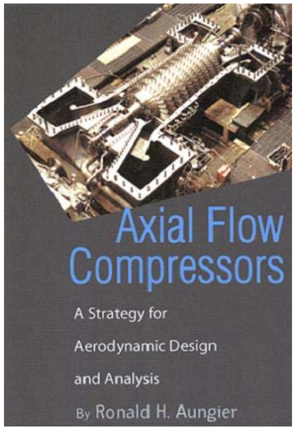
CENTRIFUGAL COMPRESSOR AERODYNAMIC DESIGN AND ANALYSIS USING COMPAERO

CompAero **is an aerodynamic design and analysis software system for centrifugal and axial-flow compressors for personal computers. It implements methods described in the following two books:**





Aungier, R. H., *Centrifugal Compressors: A Strategy for Aerodynamic Design and Analysis* (ASME Press, New York, 2000)

Aungier, R. H., *Axial-Flow Compressors: A Strategy for Aerodynamic Design and Analysis* (ASME Press, New York, 2003)

Note: a user's guide (CompAero.pdf) will be installed with the software to bridge the gap between these books and the CompAero software system.

By Ronald H. Aungier
September 14, 2011

OVERVIEW OF THE PROGRAMS IN COMPAERO

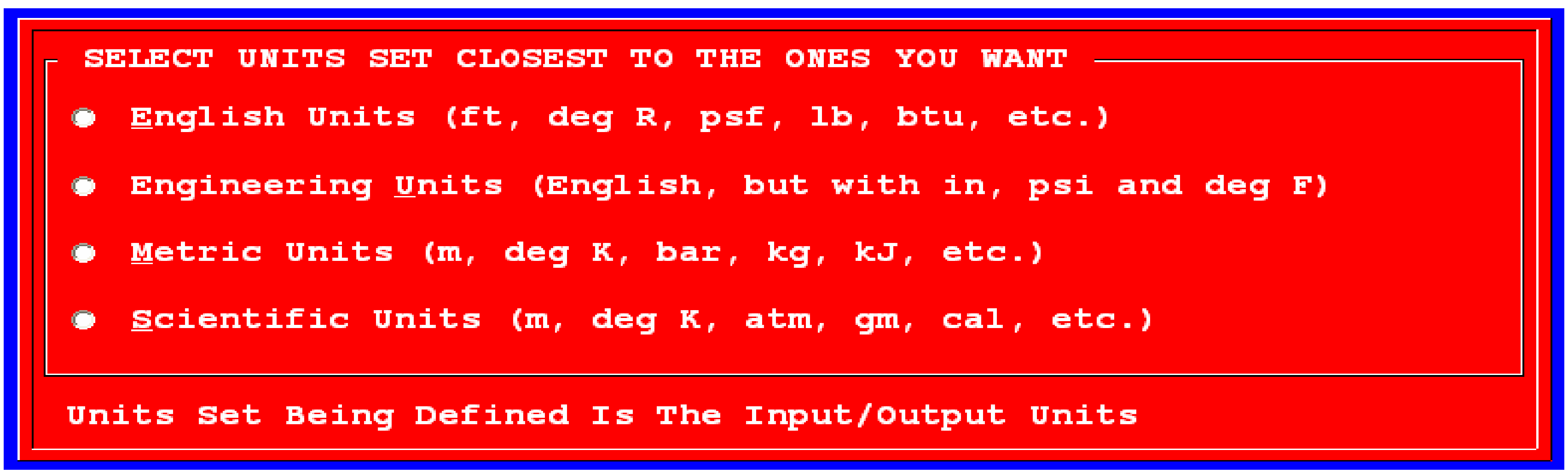
- **COMPAERO: a menu program to control the system and conveniently navigate among the other programs.**
- **SIZE: a centrifugal compressor stage preliminary aerodynamic design program.**
- **CENCOM: an aerodynamic performance analysis for single-stage or multistage centrifugal compressors.**
- **GASPATH: a general gas path (end-wall contours and blades) design program.**
- **VLDESIGN: a vaneless diffuser detailed aerodynamic design and performance analysis program.**
- **VDDESIGN: a vaned diffuser detailed aerodynamic design, performance analysis and blade-to-blade flow analysis program.**
- **RCDESIGN: a crossover-bend and return channel detailed aerodynamic design, performance analysis and blade-to-blade flow analysis program.**
- **FLOW3D: a quasi-three-dimensional inviscid flow field analysis and surface boundary layer analyses.**
- **B2B2D: a two-dimensional blade-to-blade potential flow analysis with supporting boundary layer analysis.**
- **TDB2B: a time-marching 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: (<u>R</u>adial <u>I</u>mpeller <u>G</u>eometry <u>PAC</u>kage): 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 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 COMPAERO 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.**
- **AXCOM: an aerodynamic performance analysis for single-stage or multistage axial-flow compressors.**
- **AXSTAGE: an axial-flow compressor stage design program.**
- **AXDESIGN: a multistage axial-flow compressor design program.**
- **EXHAUST: an exhaust diffuser aerodynamic performance analysis (including a scroll or collector).**
- **BLADE: a blade-section geometry program for the various standard axial-flow compressor airfoils.**
- **VOLUTE: a detailed geometry design program for volutes in radial turbomachinery.**
- **PTC10: corrects compressor test performance data to design conditions per ASME PTC 10-1997.**

USING THE COMPAERO MENU PROGRAM

- **The Menu Program (Compaero.exe) Is Highly Recommended.**
- **It Simplifies The Navigation Among Programs Required For Design & Analysis.**
- **It Offers Several Taskbar Styles And Startup Options To Suit User Preferences.**
- **Typically, The Menu Program Is Launched From A Shortcut On Your Desktop.**
- **The Picture Below Shows The Balanced Rows & Columns Taskbar Style.**

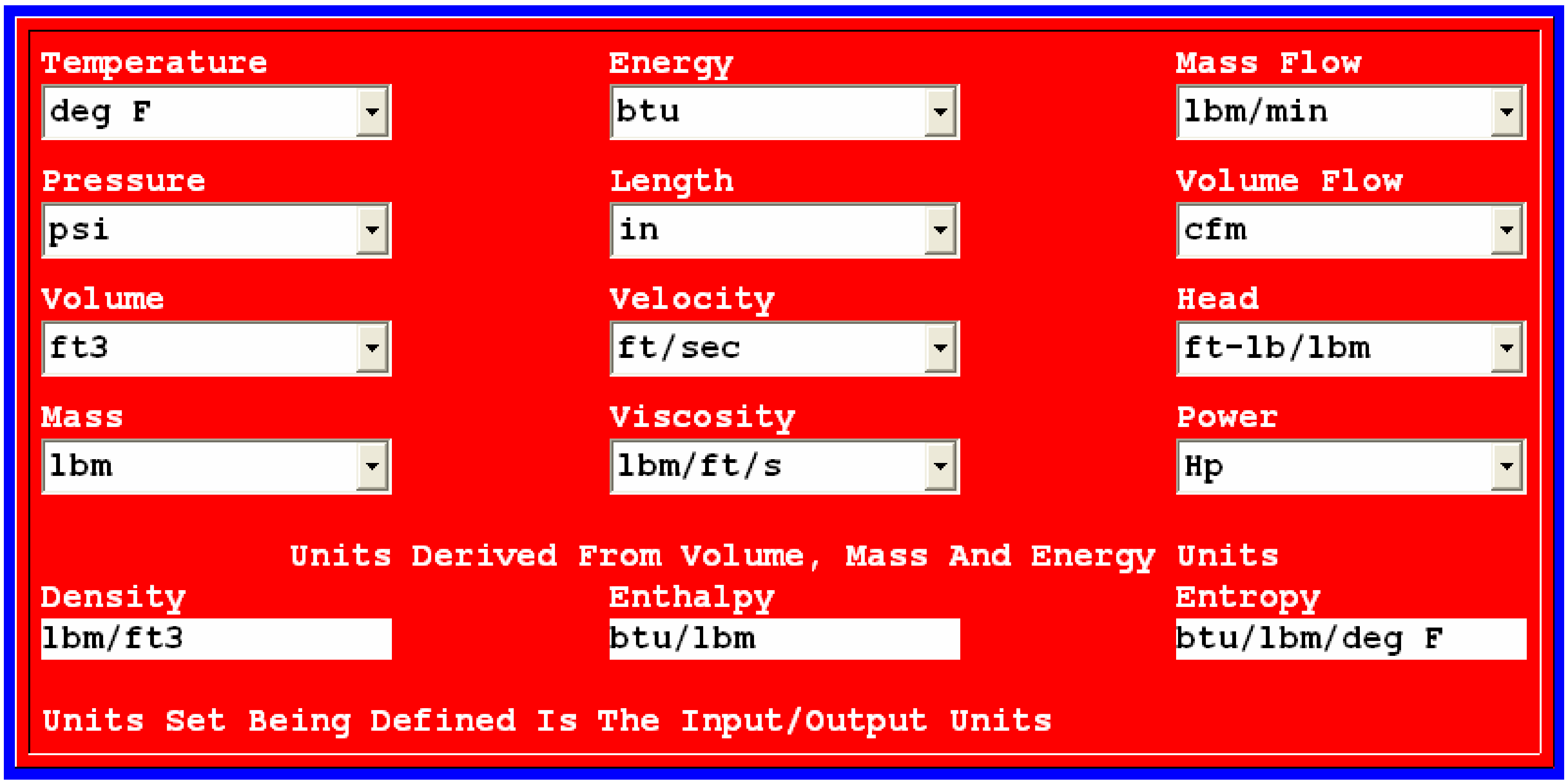
INPUT & OUTPUT UNITS FOR COMPAERO PROGRAMS

- **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.**
- **<u>Caution</u>: Changing The Units Does <u>Not</u> 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.**

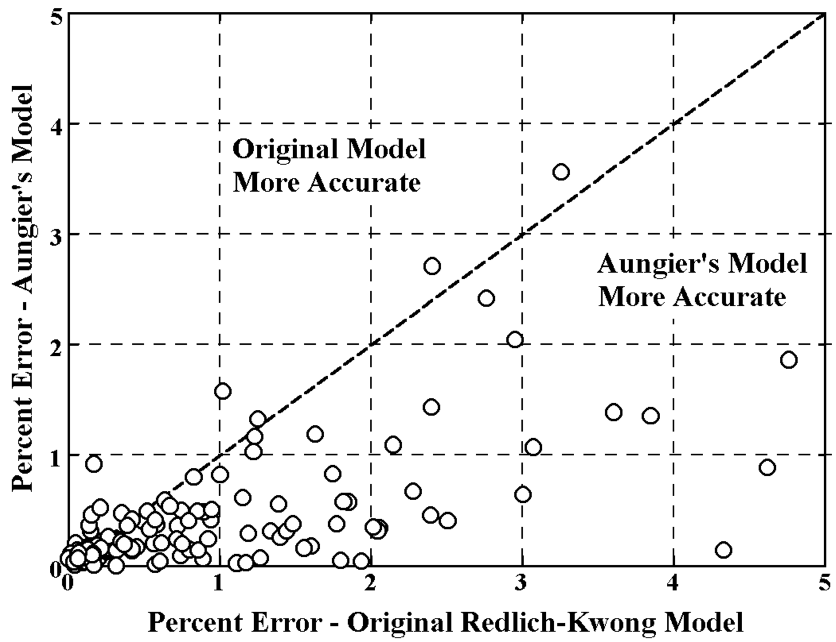
- **In General, Compressor Programs Are Valid For The Vapor Phase <u>Only</u>. RKMOD Can Handle Two-Phase Flows For Phase Checking, Liquid Knockout, Etc.**

- **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 CompAero 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

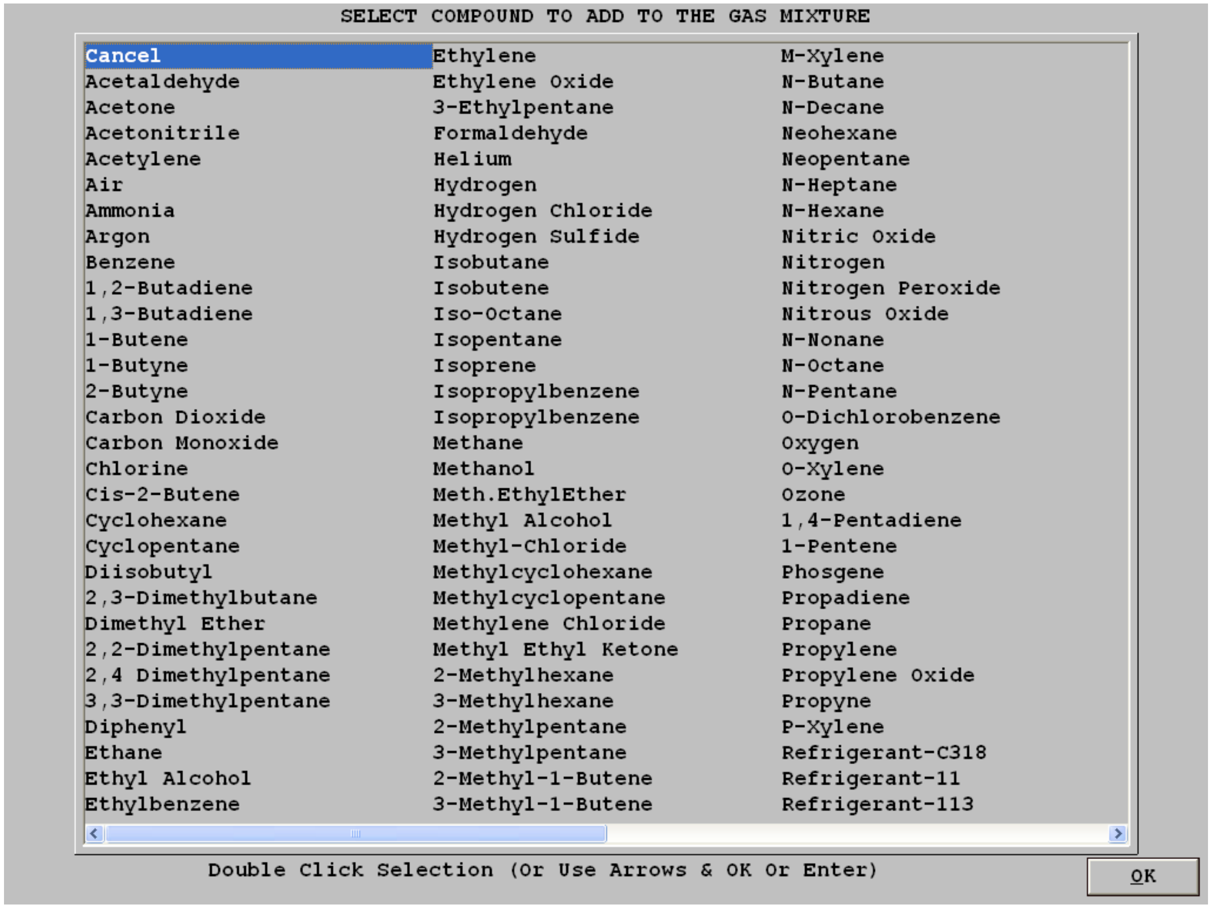
- **Accuracy Is Quite Sufficient For All Aerodynamic Design And Analysis Activity.**
- **Aungier's Modified Redlich-Kwong Equation Of State Is The Better Choice.**
- **These Equations Of State Are Not Recommended For Critical Applications Such As Performance Test Data Reduction Or Low-Tolerance Performance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

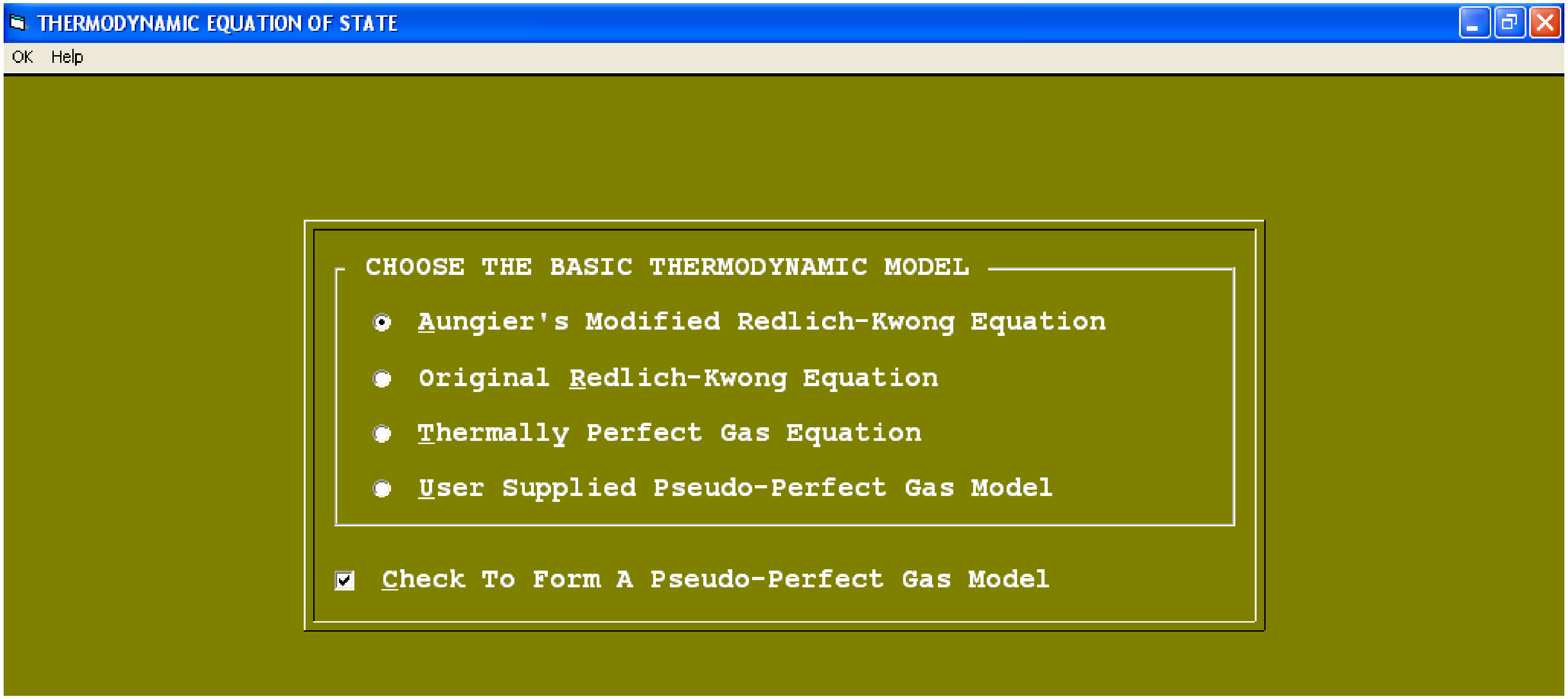
- **Enter The Mole Fraction Of Each Compound In The Mixture**
- **The Programs Will Let You Edit These Values Later If Needed.**
- **The Programs Always Normalize The Sum Of The Mole Fractions To Unity**

```
SET MOLE FRACTIONS OF THE MIXTURE COMPONENTS

Methane: Mole fraction = 0.6
 Ethane: Mole fraction = 0.3
Propane: Mole fraction = 0.1
```

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

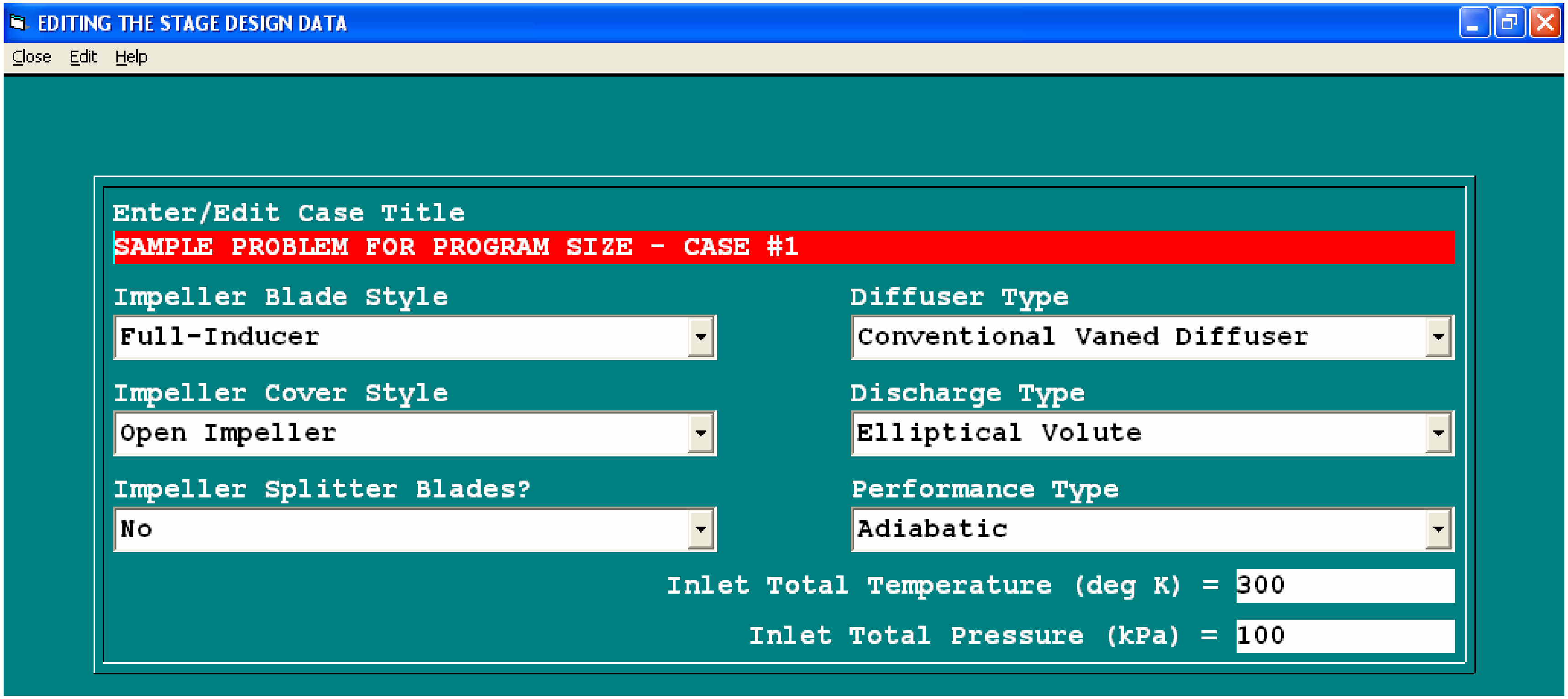
- **The Various Programs Will Let You Edit An Existing Gas Model. You Can Change The Equation Of State, Edit The Mole Fractions Of A Mixture, And Add Or Delete Compounds In A Mixture.**
- **The Equation-Of-State Package Also Contains A Generalized Model For Gas Viscosity That Can Be Applied Using The 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 Ever Need That Information.**
- **When In Doubt, Use RKMOD To Estimate The Vapor Saturation Line Data To Be Sure Your Compressor Inlet Conditions Are In The Vapor Phase. Remember, Except For RKMOD And The Liquid-Knockout Calculation In CENCOM, <u>The Compressor Programs Are Valid For Vapor Phase Flow Only</u>.**

STAGE PRELIMINARY AERODYNAMIC DESIGN

- **Program SIZE 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 Its Default Values To Refine The Design To Better Match Actual Design Requirements And Performance Predictions.**
- **It Can Export a Complete Input File For A Performance Analysis By Program CENCOM 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 CompAero Detailed Design Programs To Supply Their Initial Input Files.**
- **Extensive Comparison Of Its Empirical Performance Estimates For Its Default Designs With CENCOM 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.**

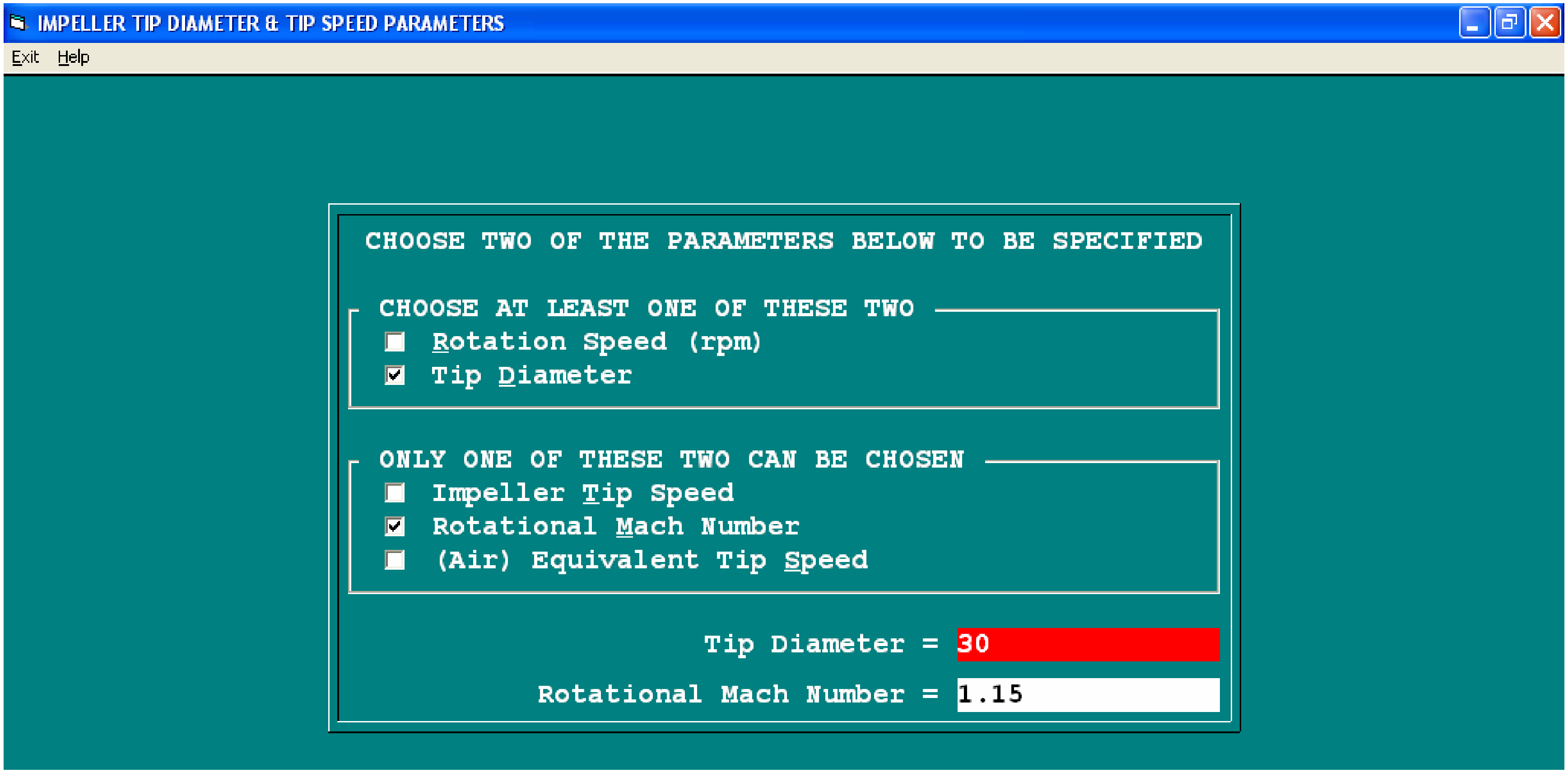
BASIC STAGE DESIGN SPECIFICATIONS

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



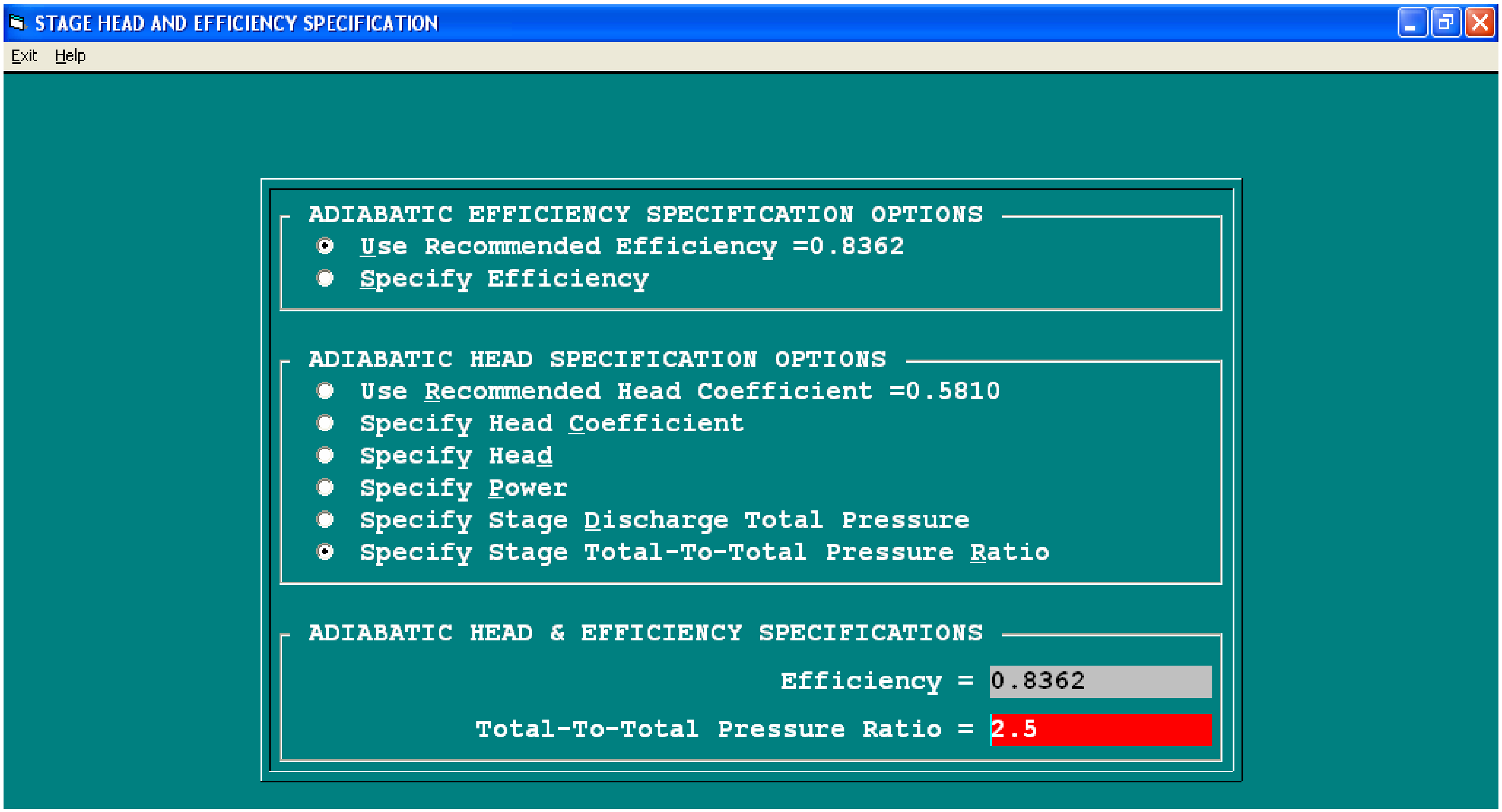
IMPELLER DIAMETER & SPEED SPECIFICATIONS

- **There Are Several Alternative Methods To Specify Impeller Speed & Diameter.**
- **You Select From The Available Choices To Best Match Your Objectives.**



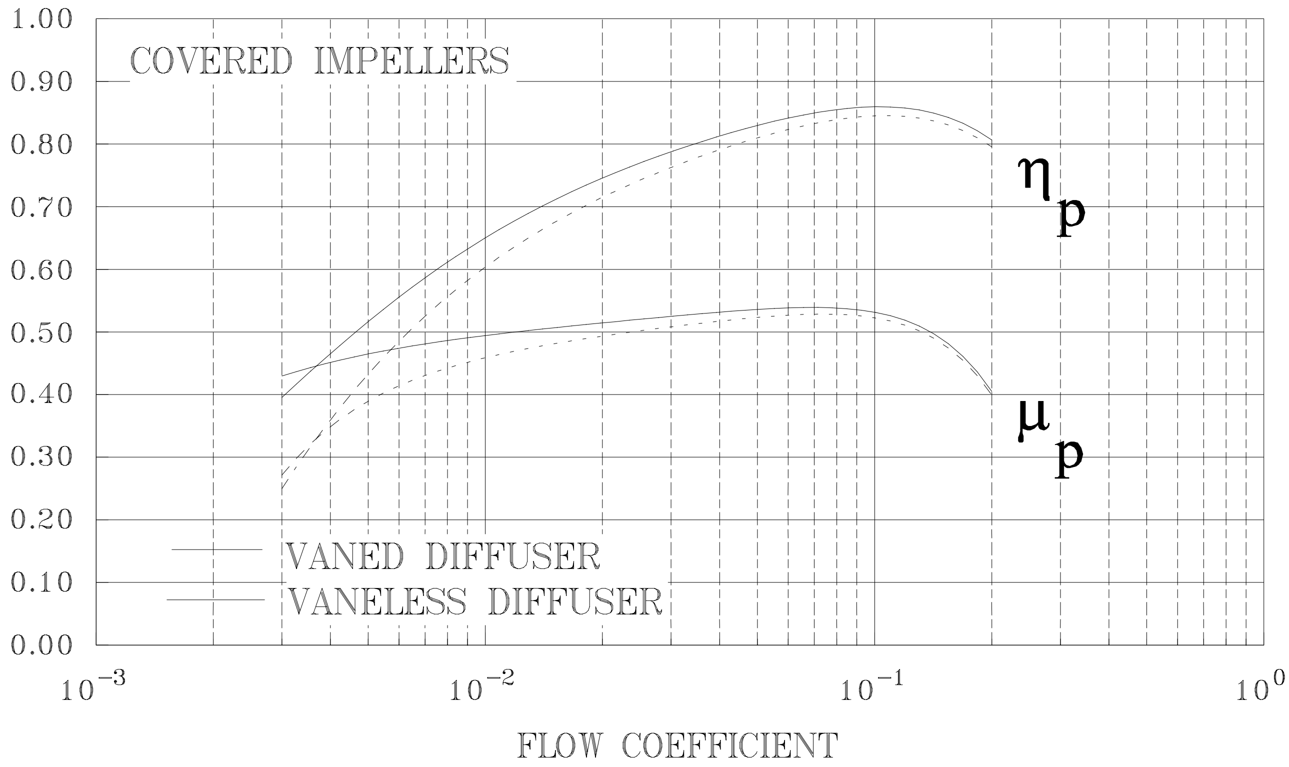
STAGE HEAD & EFFICIENCY SPECIFICATIONS

- **There Are Also Several Alternative Methods To Specify Head & Efficiency.**
- **You Select From The Available Choices To Best Match Your Objectives.**



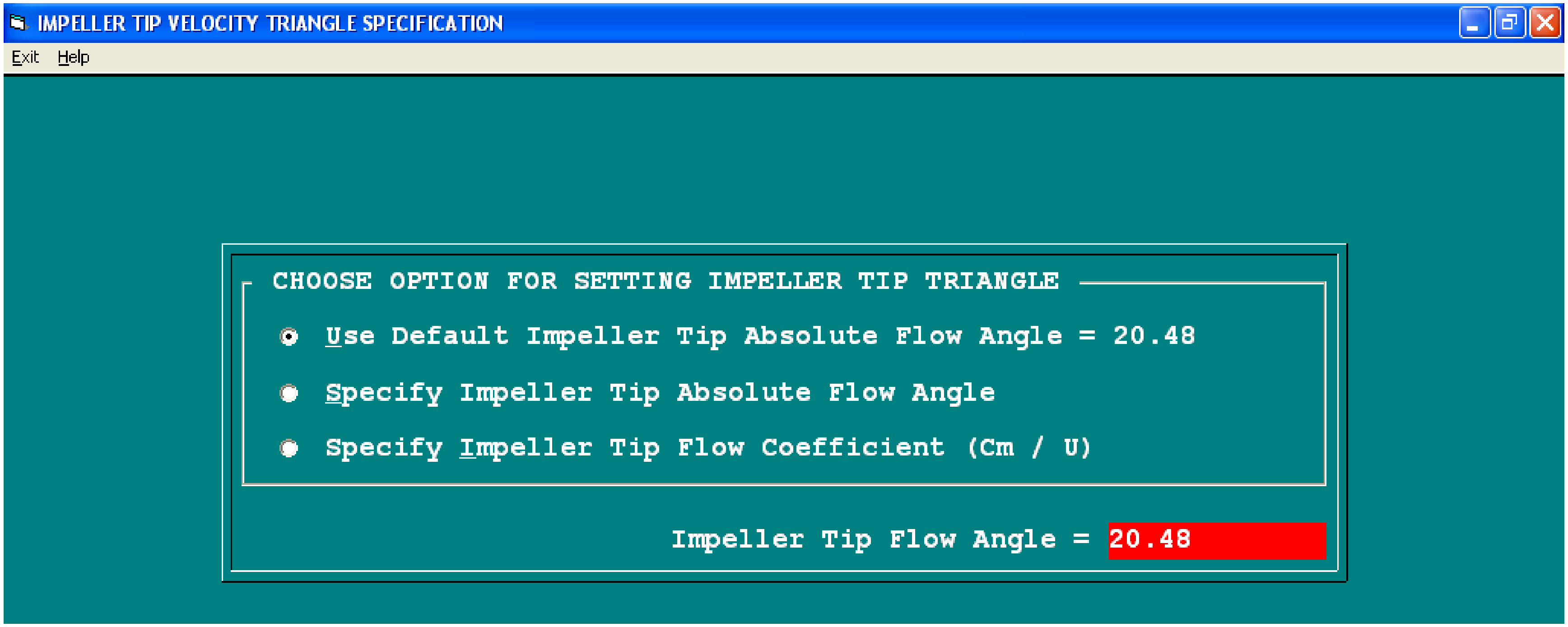
THE DEFAULT (RECOMMENDED) HEAD & EFFICIENCY

The Program's Default Performance Specifications Are Based On Empirical Correlations Of Polytropic Head Coefficient And Efficiency As A Function Of Stage Flow Coefficient Developed From A Number Of "Successful" Development Programs For Open And Covered Impellers. The Covered Impeller Correlation Is Shown Here.



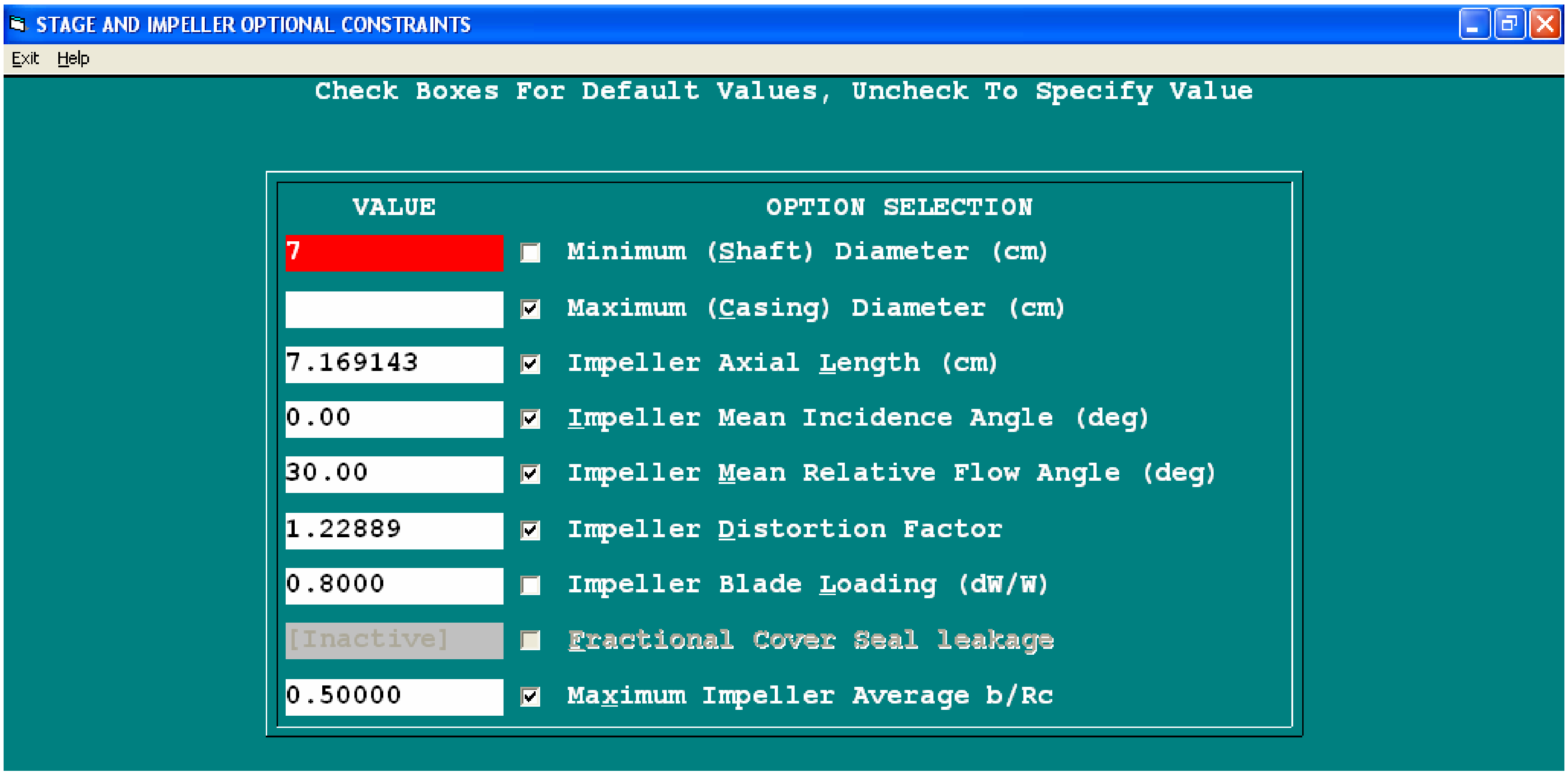
IMPELLER TIP VELOCITY TRIANGLE SPECIFICATION

The User Can Accept the Program's Recommended Impeller Tip Velocity Triangle Or Modify It.



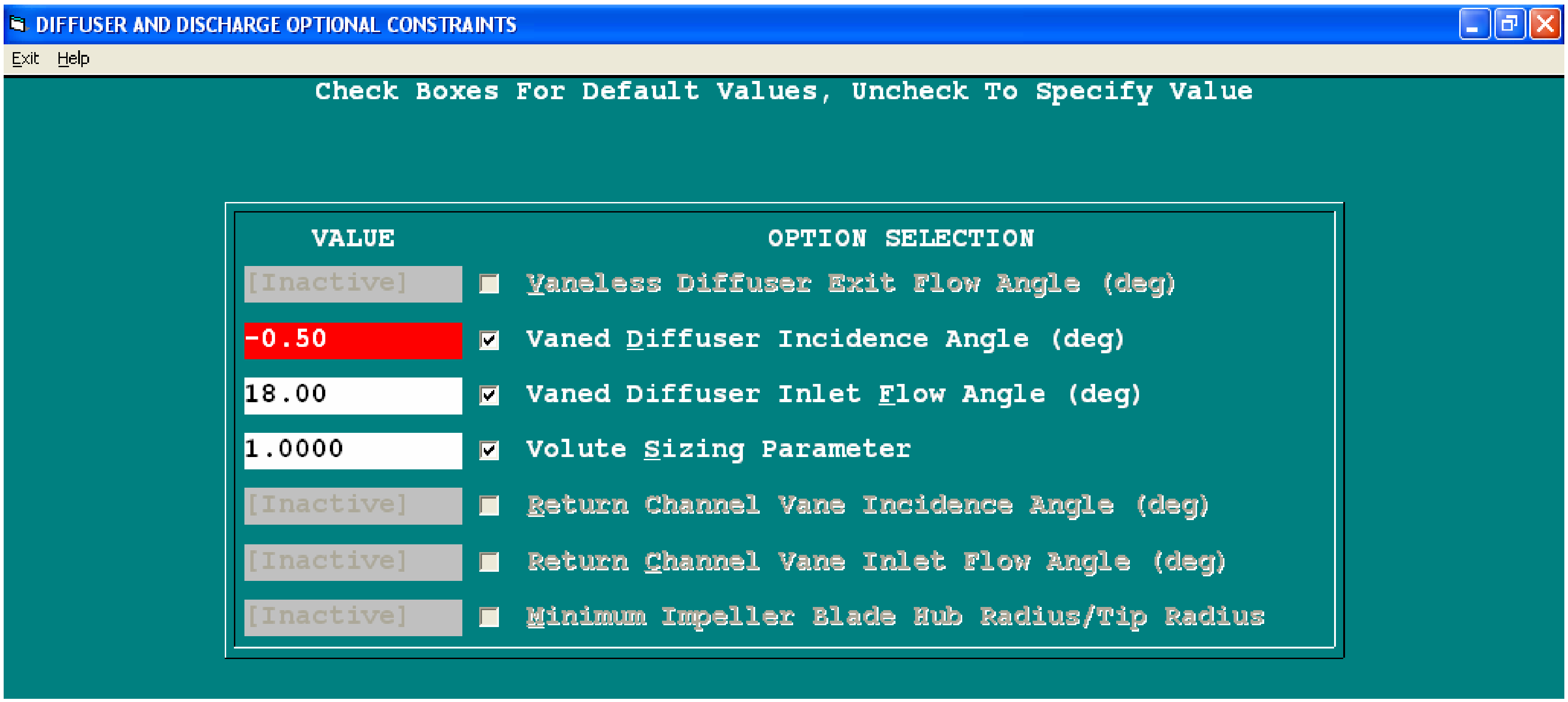
USER-MODIFIED DEFAULT PARAMETERS

The User Can Also Modify Several Of The Program's Default Specifications.



MORE USER-MODIFIED DEFAULT PARAMETERS

The User Can Also Modify These Program’s Default Specifications.



SOME USEFUL HINTS ON PROGRAM SIZE

- **SIZE Has Been Referred To By Some As "The Nintendo Game For Centrifugal Compressor Engineers." It Can Be A Little Addictive, But I Don't Know Of Any Case Where I Considered Users Were Wasting Their Time. You Can Learn A Lot About Design Alternatives By Using It. In Fact, It Can Be Rather Educational.**

- **Designers Should Make Full Use Of Its Ability To Export The Initial Input Files For The Detailed Design Programs. It Can Supply The Units, Stage Operating Conditions And The Equation Of State As Well As The Initial Geometry.**

- **It Is Always Faster To Improve An Initial Component Design Than To Create A Totally New Design. Initial Design Data From SIZE Is A Little Crude, But Close Enough To Save The Designer A Lot Of Time.**

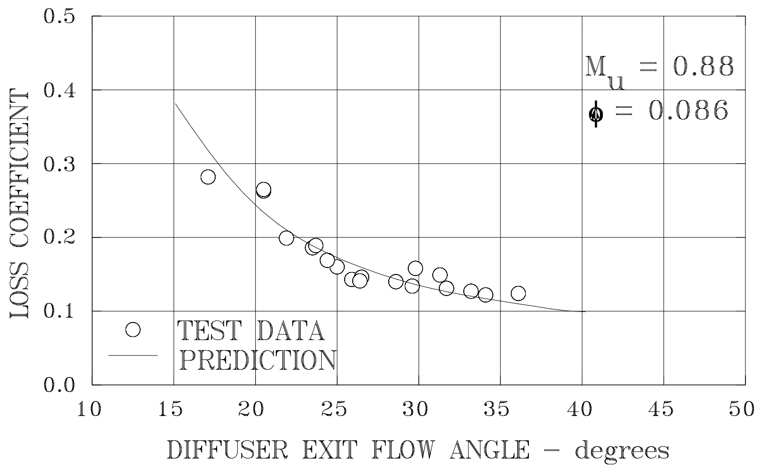
AERODYNAMIC PERFORMANCE ANALYSIS (CENCOM)

- **CENCOM Is A Mean-Line Aerodynamic Performance Analysis For Single-Stage And Multistage Centrifugal Compressors.**
- **Its Primary Emphasis Is On Providing True Predictions Based On Geometry.**
- **A Few Multistage Compressor Inter-Stage Components Require User-Input Performance Data (Such As Inter-Cooler Loss), But They Are Rare Exceptions.**
- **Available Stage Components Include:**

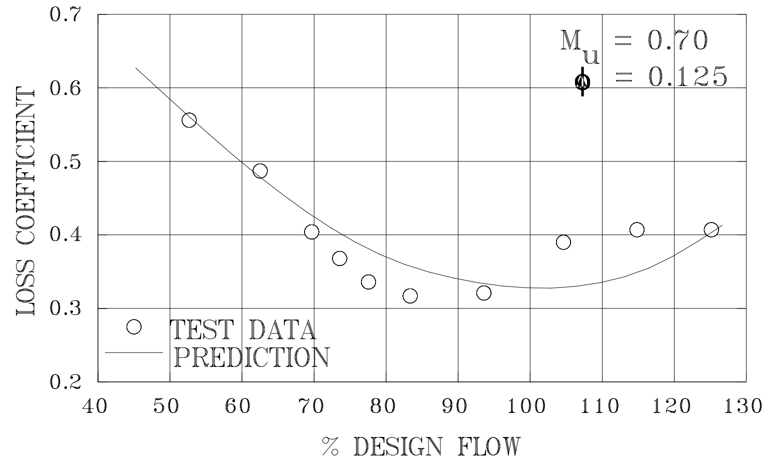
Inlet Guide Vanes	**Return Channels**	**Side-Load Flows**
Impellers	**Scrolls (Volutes)**	**Extraction Flows**
Vaneless Diffusers	**Collectors**	**Stage Inlet Stations**
Vaned Diffusers	**Vaneless Passages**	**Local Assigned Loss**
Crossover Bends	**Inter-Coolers**	**Local Liquid Knockout**
Labyrinth Seals		

- **A Fairly Sophisticated Compressor Performance Map Utility Is Included To Display A Variety Of Performance Map Styles.**
- **CENCOM Benefited From Validation On A Very Large Number Of Tested Stages Of Widely Varying Types (Elliott, Carrier, NREC, MAN-GHH, Ebara, Etc.).**
- **Few Commercial Codes Can Come Even Close To Its Prediction Accuracy And I Know Of None That Can Surpass It.**

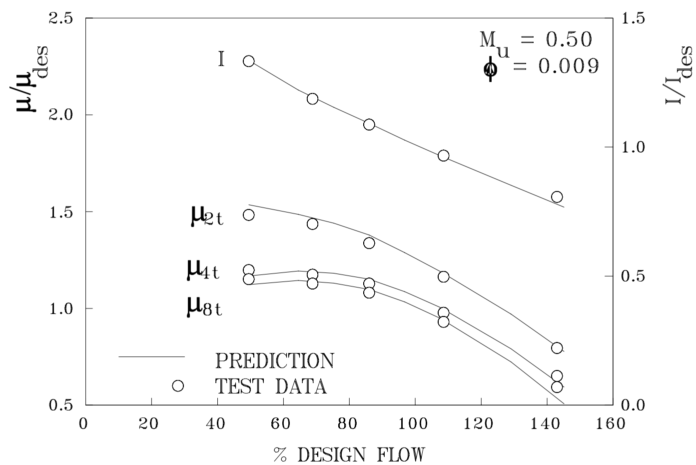
CENCOM VALIDATION WITH EXPERIMENT



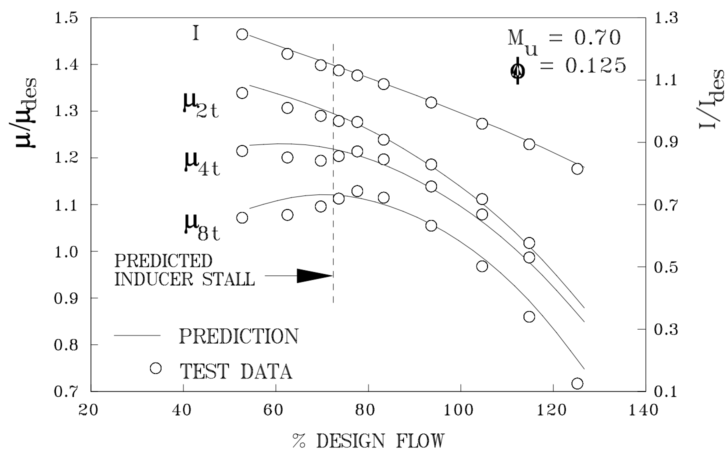
Vaneless Diffuser Performance



Return Channel Performance



Low-Flow Stage Performance



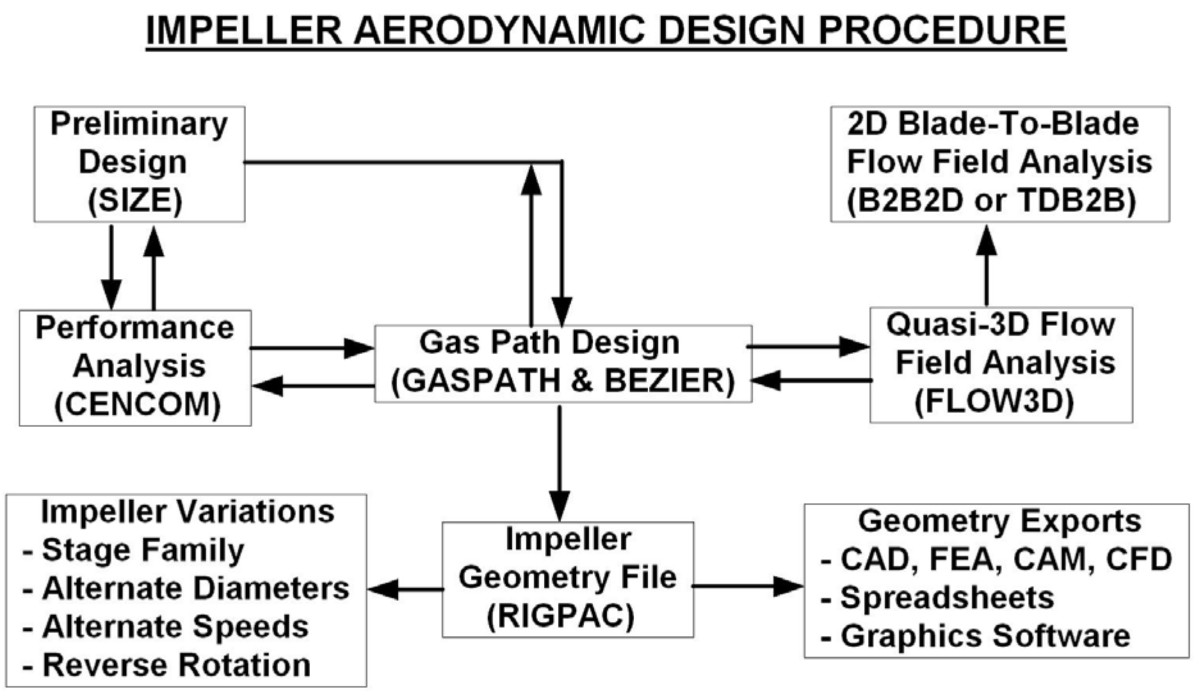
High-Flow Stage Performance

EFFECTIVE USE OF PROGRAM CENCOM

- **With The Exception Of Reverse-Engineered Compressors, Users Often Edit CENCOM Input Files But Rarely Have To Create One From Scratch.**
- **In Design Work, SIZE Provides Its Initial Input File And The Detailed Component Design Programs Provide Updates To It During The Design Process.**
- **Even For Reverse-Engineered Compressors, The Impeller Geometry Is Usually Entered Into RIGPAC For Processing And Export To CENCOM.**
- **CENCOM Is Easily The Most Often Used Program In The CompAero System But Probably Has The Fewest User-Generated Input Files.**
- **My Website (http://turbo-aero.com) Provides General Input Data Forms For CENCOM And RIGPAC That Are Convenient When Collecting Geometry For Aftermarket Applications.**
- **Vaned Diffuser Validation Was For The Parallel-Walled, Conventional (Airfoil) Type. But It Has Also Been Used Effectively For Vane-Island And Low-Solidity Types.**
- **I Advise Users To Use CENCOM For Evaluation And The Design Programs For Design As Much As Possible. Designing With CENCOM Can Add Some Risk Of Finding The Weaknesses In The Empirical Models By Precisely Optimizing Based On Them. That Advice Cannot Always Be Followed, But It Is A Good Target.**

IMPELLER AERODYNAMIC DESIGN WITH COMPAERO

This Flowchart Illustrates The Basic Process Used For Impeller Aerodynamic Design With The CompAero System.



Notes:

- Internal Flow Field Analyses Are Valid Through Transonic Flow
- SIZE Supplies Initial Input Files For CENCOM & GASPATH
- GASPATH Supplies/Updates Input Files For CENCOM & FLOW3D
- GASPATH Supplies Input Files For RIGPAC
- FLOW3D Supplies Input Files For B2B2D & TDB2B

IMPELLER GEOMETRY CONSIDERATIONS

- **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).**

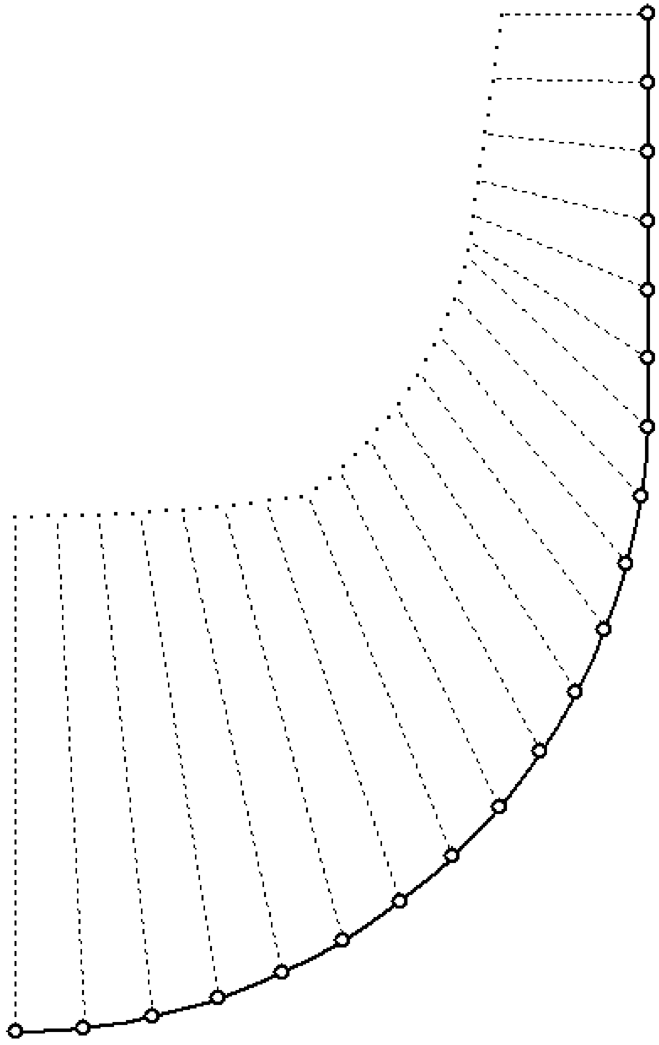
Note: The First Four Curve Types Require That The End-Point Slopes Be Specified. A Liner Segment Will Be Included At One End If Needed. User Can Require Linear Segments (Of Specified Minimum Lengths) On Both Ends.

INITIALIZING THE REQUIRED INPUT FILES

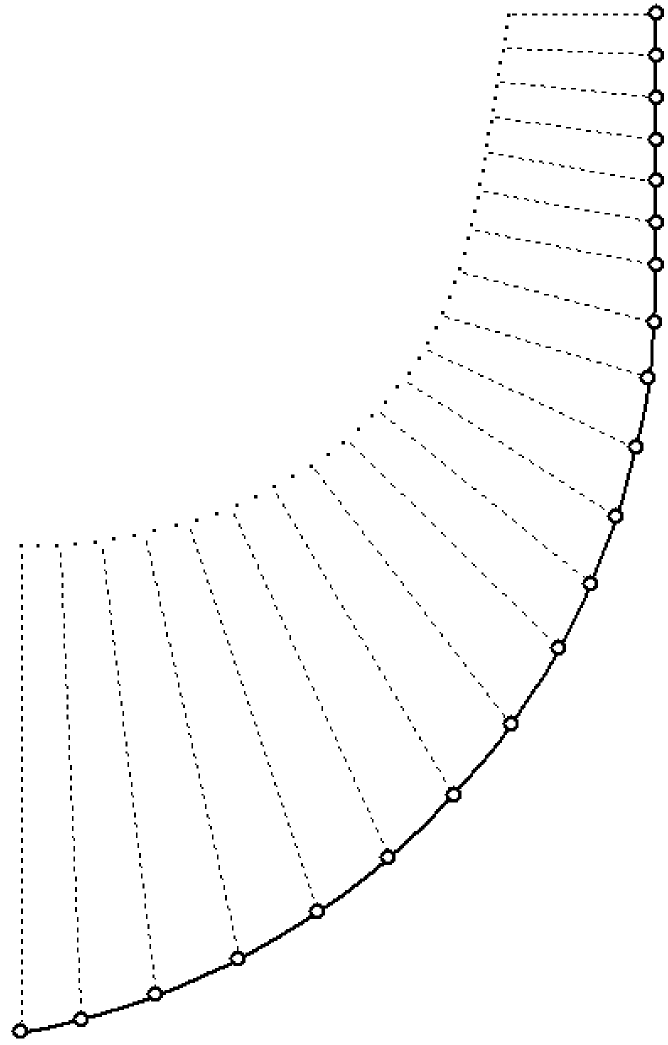
- **Initialize Input Files For GASPATH And BEZIER From SIZE (Preliminary Design Results Are Used).**
- **FLOW3D Requires Hub And Shroud Vaneless Extensions On Each End Of The Blade Row. SIZE Can Include Them Or Omit Them When Initializing BEZIER.**
- **Including Them Will Require Readjusting The Leading 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 CENCOM 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 SIZE



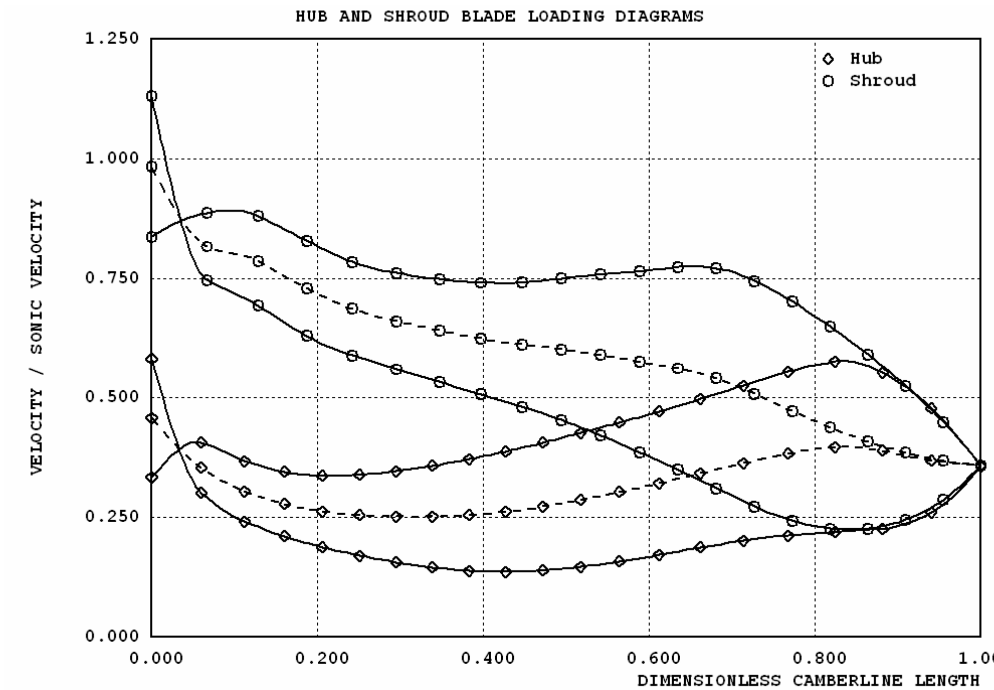
Adjusted Preliminary Design

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 Prototype Stages Into Practical OEM Product Lines. Many Of Its "Operations" Are Well Suited To Rerate Activity.**
- **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, CENCOM And FLOW3D, Only (I Have Done Several Rerates That Way). RIGPAC Can Supply (Or Update) Impeller Geometry Data To CENCOM 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 CompAero System For Other Design And Analysis Activity.**