

Marshall Space Flight Center Fluids Workshop

Turbine Aerodynamic

Design System Improvements

F.W. Huber
L.W. Griffin
S.P. Simpson

April 22-24, 2003
UAB Birmingham, Huntsville, Alabama

Turbine Aerodynamic Design System Improvement*

Presentation Outline

- Volute Manifold Design and Analysis Methodology
- Meanline Modifications for Compatibility with Engine Analysis Code

* Efforts funded by MSFC

Volute Design and Analysis Methodology

Objective

Develop a manifold design methodology for turbines and pumps

Enable rapid screening of candidate flow paths

Features

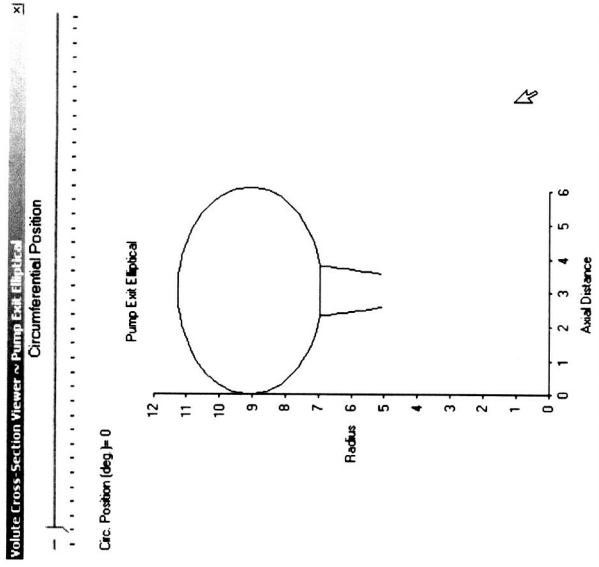
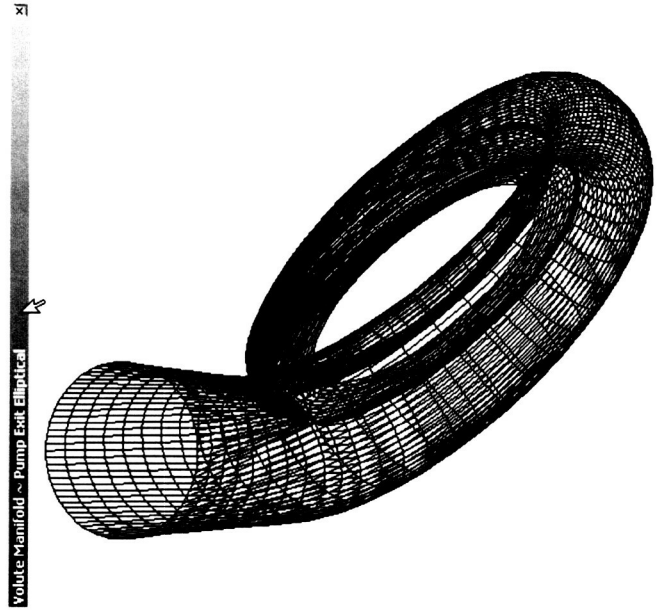
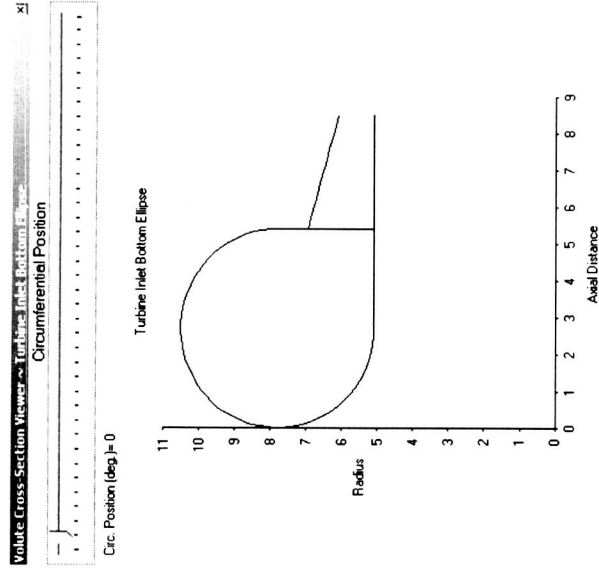
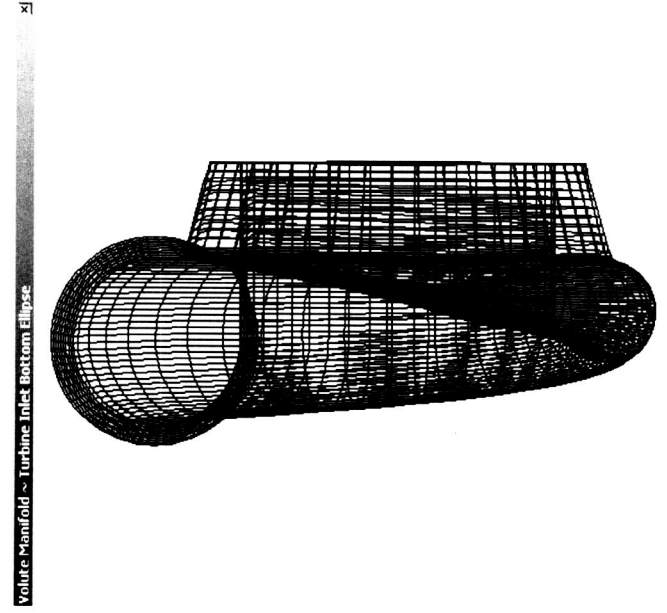
- Geometry Generator
- Graphical Interface - GUI
- Meanline Analysis
- Output Geometry for Grid Generation

Volute Design and Analysis Methodology

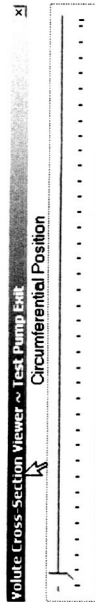
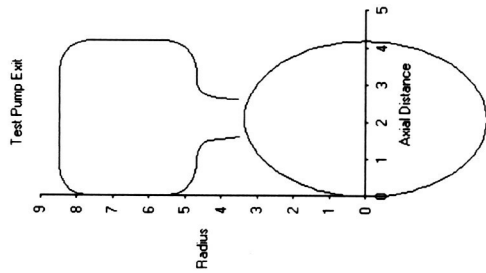
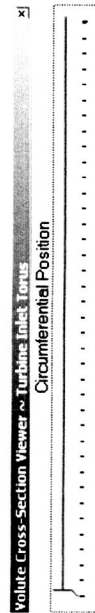
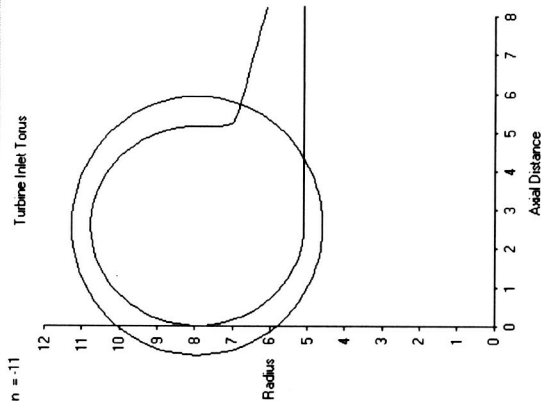
General Description

- Application to Pumps & Turbines - Inlets and Exits
- Manifold types: Circular, Elliptical, Rectangular cross-section
- Area distributions: Constant torus, linear, specified variable
- Single tongue
- 1D Meanline analysis: Predict avg. gas conditions and performance
- Output includes: Meanline results and Geometry Definition

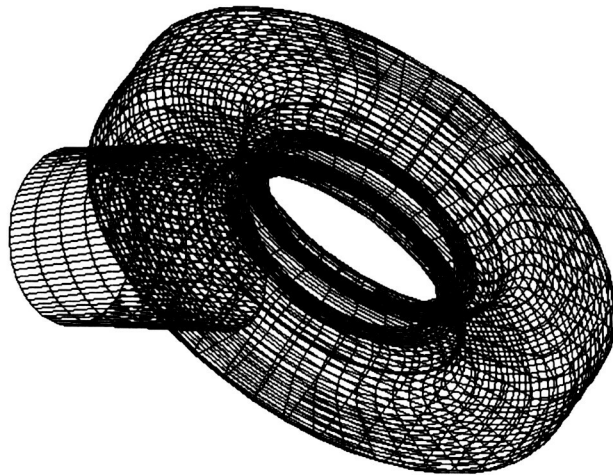
Sample Manifold Types



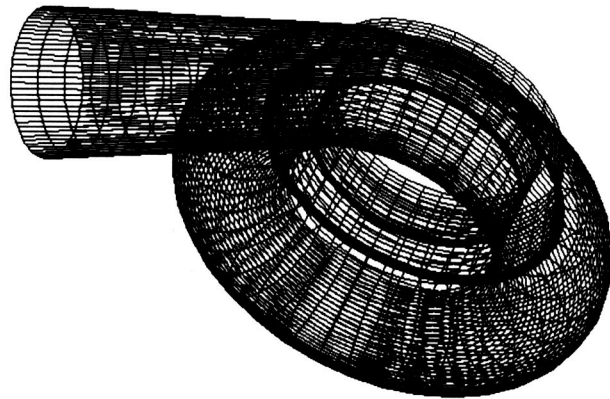
Sample Manifold Types



Volute Manifold ~ Test Pump Exit



Volute Manifold ~ Turbine Inlet Torus

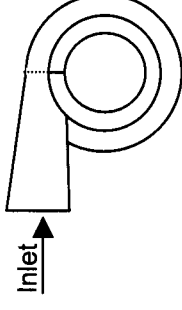


Volute Design and Analysis Methodology

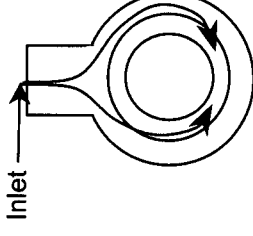
General Approach to Meanline Analysis

4 Modes / Analyses depending on geometry and inlet location:

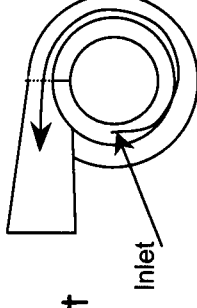
- Tangential duct inlet with variable or constant manifold area



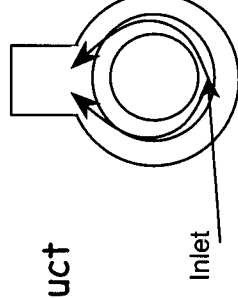
- Perpendicular duct inlet with constant area torus



- Component inlet with variable or constant manifold area & tangential exhaust duct



- Component inlet with constant area torus & perpendicular exhaust duct



Volute Design and Analysis Methodology

General Approach to Meanline Analysis Continued

Specify:

- Flow entry to manifold (Duct or Component Interface)
- Gas properties
- Inlet gas conditions: Flow, T_t , P_t , and swirl angle

Calculations assume circumferentially uniform flow at component inlet

User Interface - Main Window

File

Vol Area Dist

Cross-Section

View Volume

Mainline

ML Plots

Case Title

Component Type

☐ Turbine / Pump Inlet

☐ Turbine Exit

☐ Pump Exit / RIT Inlet

Transition Location

☐ Bottom

☐ Mid Height

☐ Top

☐ Left

☐ Middle

☐ Right

Inlet Gas Conditions

Flow rate ~ lbs/sec

Pt Inlet ~ psia

Tt Inlet ~ deg R

Swirl Angle ~ deg

Gas Constant

Gamma

Coef. Viscosity

Flow enters from

☐ Pipe

☐ Component Interface

Overall Geometry Input

A Pipe / A Comp. Interface

A Pipe Torus / A Comp. Interface

Pipe Length ~ in.

A Vol Max / A Comp Interface

Tongue thickness ~ in.

Blend Arc ~ circumfer. degrees

A Trans. Max / A Comp Interface

Transition Length ~ in.

Transition Fillet Radius ~ in.

Component Int. Hub Rad. ~ in.

Component Flow Path Ht ~ in.

Volume Manifold Circumferential Area Variation

☐ Linear

☐ Const A Torus w Tang Pipe

☐ Non Linear

☐ Const A Torus w Perp Pipe

Cross-Section Detail

☐ Rectangular

☐ Elliptical

Manifold Shape Factor

Rect. Max Fill Rad. ~ in

Rect. Min Fill Rad. ~ in

of Circ. Cross-Sections

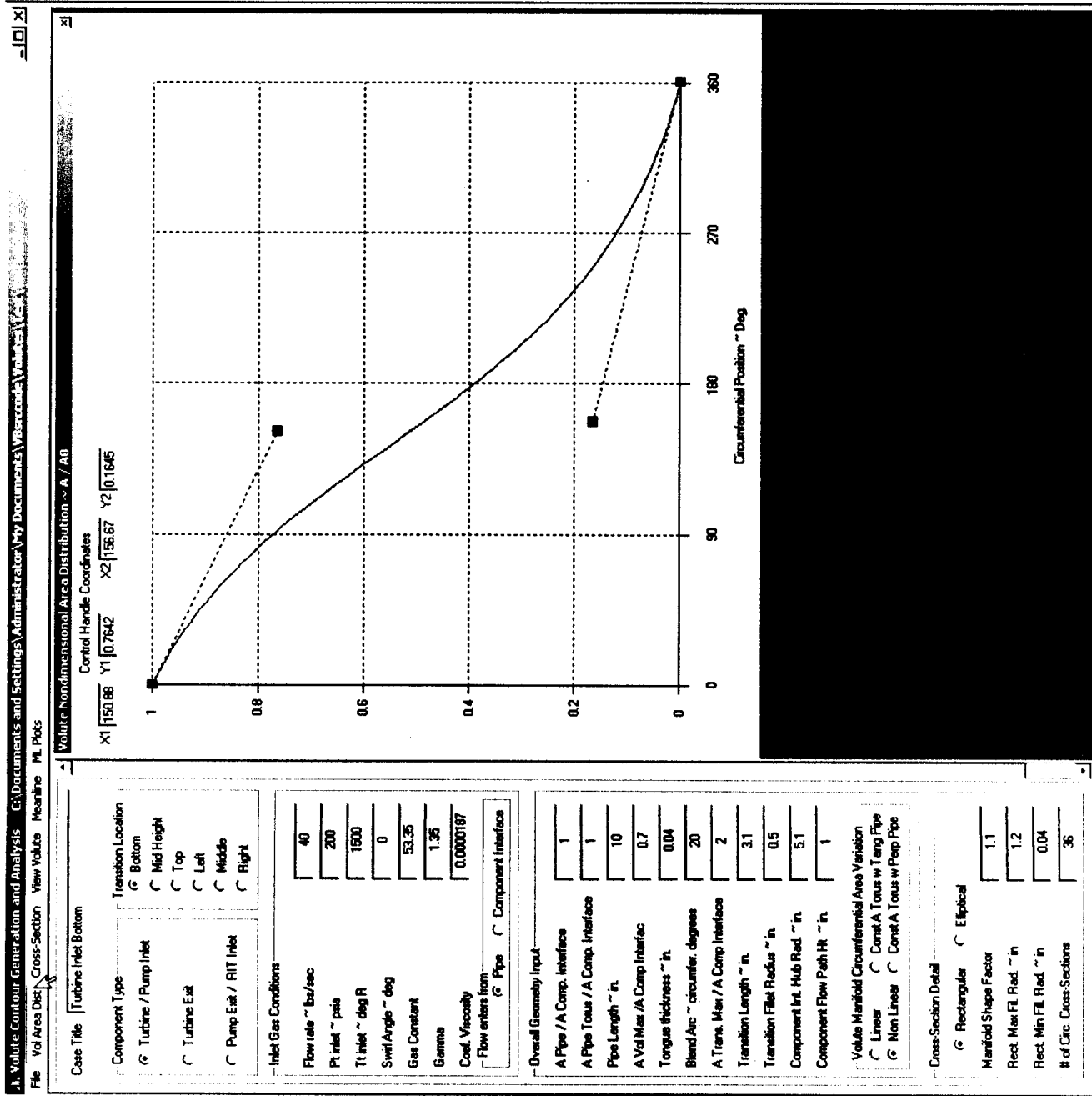
User Interface - File Menu Items

New <input type="button"/> Open Input <input type="button"/> Save Input As <input type="button"/> Save XYZ Coords <input type="button"/> Save ML Results <input type="button"/> Copy ML Results <input type="button"/> Print ML Results <input type="button"/> Exit		File Vol Area Dist Cross-Section View Volume Mainline ML Plots	
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Inlet Gas Conditions Flow rate ~ lbs/sec _____ P inlet ~ psia _____ T inlet ~ deg R _____ Swirl Angle ~ deg _____ Gas Constant _____ Gamma _____ Cool Viscosity _____ Flow enters from ☐ Pipe ☐ Component Interface		Transition Location ☒ Bottom ☐ Mid Height ☐ Top ☐ Left ☐ Middle ☐ Right	
--	--	---	--

Overall Geometry Input A Pipe / A Comp. Interface _____ A Pipe Torus / A Comp. Interface _____ Pipe Length ~ in. _____ A Vel Max / A Comp Interface _____ Tongue thickness ~ in. _____ Blend Ang ~ circular degree _____ A Trans. Max / A Comp Interface _____ Transition Length ~ in. _____ Transition Flat Radius ~ in. _____ Component Int. Hub Rad. ~ in. _____ Component Flow Path Ht ~ in. _____ Volume Manifold Circumferential Area Variation ☐ Linear ☐ Const A Torus w Tang Pipe ☐ Non Linear ☐ Const A Torus w Perp Pipe		Cross-Section Detail ☐ Rectangular ☐ Elliptical Manifold Shape Factor _____ Rect. Max Fil Rad. ~ in _____ Rect. Min Fil Rad. ~ in _____ # of Circ. Cross Sections _____	
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User Interface - Volute Manifold Area Distribution



[J. Volume Contour Generation and Analysis](#)
[C:\Documents and Settings\Administrator\My Documents\Wbrcode\Volume\Contour](#)
[File](#)
[Vol Area Dot](#)
[Cross Section](#)
[View Volume](#)
[Mainline](#)
[HL Plots](#)

Case Title **Turbine Inlet Bottom**

Component Type

☒ Turbine / Pump Inlet

☐ Turbine Exit

☐ Pump Exit / RIT Inlet

Transition Location

☒ Bottom

☐ Mid Height

☐ Top

☐ Left

☐ Middle

☐ Right

Inlet Gas Conditions

Flow rate ~ lbs/sec **40**

Pt inlet ~ psia **200**

T inlet ~ deg R **1500**

Swirl Angle ~ deg **0**

Gas Constant **53.35**

Gamma **1.35**

Cost Viscosity **0.0000187**

Flow enters from ☒ Pipe ☐ Component Interface

Overall Geometry Input

A Pipe / A Comp. Interface **1**

A Pipe Torus / A Comp. Interface **1**

Pipe Length ~ in **10**

A Vol Max / A Comp Interface **0.7**

Tongue thickness ~ in **0.04**

Blend Arc ~ circumfer. degrees **20**

A Trans. Max / A Comp Interface **2**

Transition Length ~ in **3.1**

Transition Fillet Radius ~ in **0.5**

Component Int. Hub Rad. ~ in **5.1**

Component Flow Path Ht ~ in **1**

Volume Manifold Circumferential Area Variation

☐ Linear ☒ Const A Torus w Tang Pipe

☒ Non Linear ☐ Const A Torus w Perp Pipe

Cross-Section Detail

☒ Rectangular ☐ Elliptical

Manifold Shape Factor **1.1**

Rect. Max Fil Rad. ~ in **1.2**

Rect. Min Fil Rad. ~ in **0.04**

of Circ. Cross-Sections **36**

Volume Cross Section Viewer ~ Turbine Inlet Bottom

Circ. Position (deg) ~ 0

User Interface - Volute Geometry Window

1. Volute Contour Generation and Analysis C:\Documents and Settings\Administrator\My Documents\Vblcode\Volute Geometry Window

File Vol Area Dist Cross-Section View Volute Mainline M Plots

Volute Manifold ~ Turbine Inlet Bottom

Case Title Turbine Inlet Bottom

Component Type

☒ Turbine / Pump Inlet

☐ Turbine Exit

☐ Pump Exit / PIT Inlet

Transition Location

☒ Bottom

☐ Mid Height

☐ Top

☐ Left

☐ Middle

☐ Right

Inlet Gas Conditions

Flow rate ~ lbs/sec 40

Pt inlet ~ psia 200

Tt inlet ~ deg R 1500

Swirl Angle ~ deg 0

Gas Constant 53.35

Gamma 1.35

Coef Viscosity 0.0000187

Flow enters from ☒ Pipe ☐ Component Interface

Overall Geometry Input

A Pipe / A Comp. Interface 1

A Pipe Torus / A Comp. Interface 1

Pipe Length ~ in 10

A Vol Max / A Comp Interface 0.7

Tongue thickness ~ in 0.04

Blend Arc ~ circumfer. degrees 20

A Trans. Max / A Comp Interface 2

Transition Length ~ in 3.1

Transition Fillet Radius ~ in 0.5

Component Int. Hub Rad. ~ in 5.1

Component Flow Path Ht ~ in 1

Volute Manifold Circumferential Area Variation

☐ Linear ☐ Const A Torus w Tang Pipe

☒ Non Linear ☐ Const A Torus w Perp Pipe

Cross-Section Detail

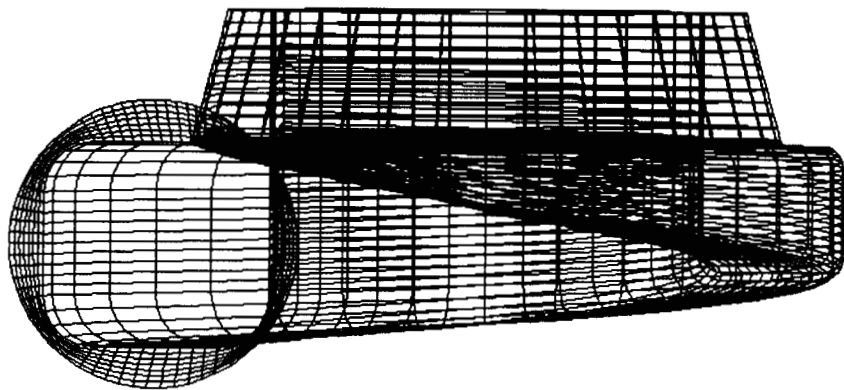
☒ Rectangular ☐ Elliptical

Manifold Shape Factor 1.1

Rect. Max Fil. Rad. ~ in 1.2

Rect. Min Fil. Rad. ~ in 0.04

of Circ. Cross Sections 36



J. Volume Contour Generation and Analysis (C:\Documents and Settings\Administrator\My Documents\VBARcode\Volume\Task11\

Case Title

Turbine Inlet Bottom

Component Type

☒ Turbine / Pump Inlet
☐ Turbine Exit
☐ Pump Exit / RIT Inlet

Transition Location

☒ Bottom
☐ Mid Height
☐ Top
☐ Left
☐ Middle
☐ Right

Inlet Gas Conditions

Flow rate ~ lbs/sec

40

P inlet ~ psia

200

T inlet ~ deg R

1500

Swirl Angle ~ deg

0

Gas Constant

53.35

Gamma

1.35

Cost Viscosity

0.0000167

Flow enters from

☒ Pipe
☐ Component Interface

Overall Geometry Input

A Pipe / A Comp. Interface

1

A Pipe Torus / A Comp. Interface

1

Pipe Length ~ in

10

A Vol Max / A Comp Interface

0.7

Tongue thickness ~ in

0.04

Blend Arc ~ circular, degrees

20

A Trans. Max / A Comp Interface

2

Transition Length ~ in

31

Transition Flat Radius ~ in

0.5

Component Int. Hub Rad. ~ in

5.1

Component Flow Path Ht ~ in

1

Volume Manifold Circumferential Area Variation

☒ Linear
☐ Const A Torus w Tang Pipe
☐ Non Linear
☐ Const A Torus w Perp Pipe

Cross-Section Detail

☒ Rectangular
☐ Elliptical

Manifold Shape Factor

1.1

Rect. Max FL Rad. ~ in

1.2

Rect. Min FL Rad. ~ in

0.04

of Circ. Cross Sections

35

1. Volume Meanline Output ~ Turbine Inlet Bottom

Turbine Inlet Bottom

Volume Manifold Summary

Pipe Inlet Tongue

90 Deg.

180 Deg.

270 Deg.

Static

181.544

181.293

183.878

Total

200.000

199.663

198.756

Tstatic

1483.295

1462.931

1478.097

Tot. Vel.

470.4

700.7

538.6

Length

0.0

10.0

33.0

Rey=10-3

0.0

10445.0

18049.3

Flow Area

35.1

24.6

14.0

Wet Perim.

21.0

16.7

17.3

Hyd. Dia.

6.7

5.3

3.2

Component Interface Summary

0 Deg.

90 Deg.

180 Deg.

270 Deg.

Static

155.706

170.589

168.410

172.779

Total

199.663

198.756

197.737

196.449

Mass Avg DelPt/Pt

0.0120

Component Interface Data at Midspan

Circ.

Alpha

Pt

delPt/Pt

0

0.617

29.447

155.706

199.663

0.0017

10

0.519

33.380

167.130

199.555

0.0022

20

0.511

33.763

167.839

199.450

0.0027

30

0.503

34.147

168.431

199.348

0.0033

40

0.499

34.455

168.985

199.247

0.0038

50

0.494

34.783

169.460

199.147

0.0043

60

0.490

35.066

169.860

199.049

0.0048

70

0.486

35.306

170.189

198.952

0.0052

80

0.483

35.540

170.416

198.854

0.0057

90

0.481

35.670

170.589

198.756

0.0062

100

0.479

35.787

170.654

198.657

0.0067

110

0.479

35.836

170.630

198.556

0.0072

120

0.479

35.859

170.484

198.452

0.0077

130

0.480

35.818

170.253

198.345

0.0083

140

0.482

35.676

169.974

198.234

0.0088

150

0.485

35.591

169.589

198.118

0.0094

160

0.488

35.435

169.192

197.997

0.0100

170

0.490

35.280

168.787

197.870

0.0107

180

0.493

35.152

168.410

197.737

0.0113

190

0.495

35.073

168.095

197.599

0.0120

200

0.495

35.041

167.929

197.456

0.0127

210

0.495

35.146

167.856

197.309

0.0135

220

0.492

35.324

168.063

197.160

0.0142

230

0.487

35.696

168.429

197.009

0.0150

240

0.479

36.196

169.113

196.860

0.0157

250

0.469

36.947

170.064

196.716

0.0164

260

0.455

37.809

171.323

196.577

0.0171

270

0.440

39.126

172.779

196.449

0.0178

280

0.424

40.556

174.201

196.332

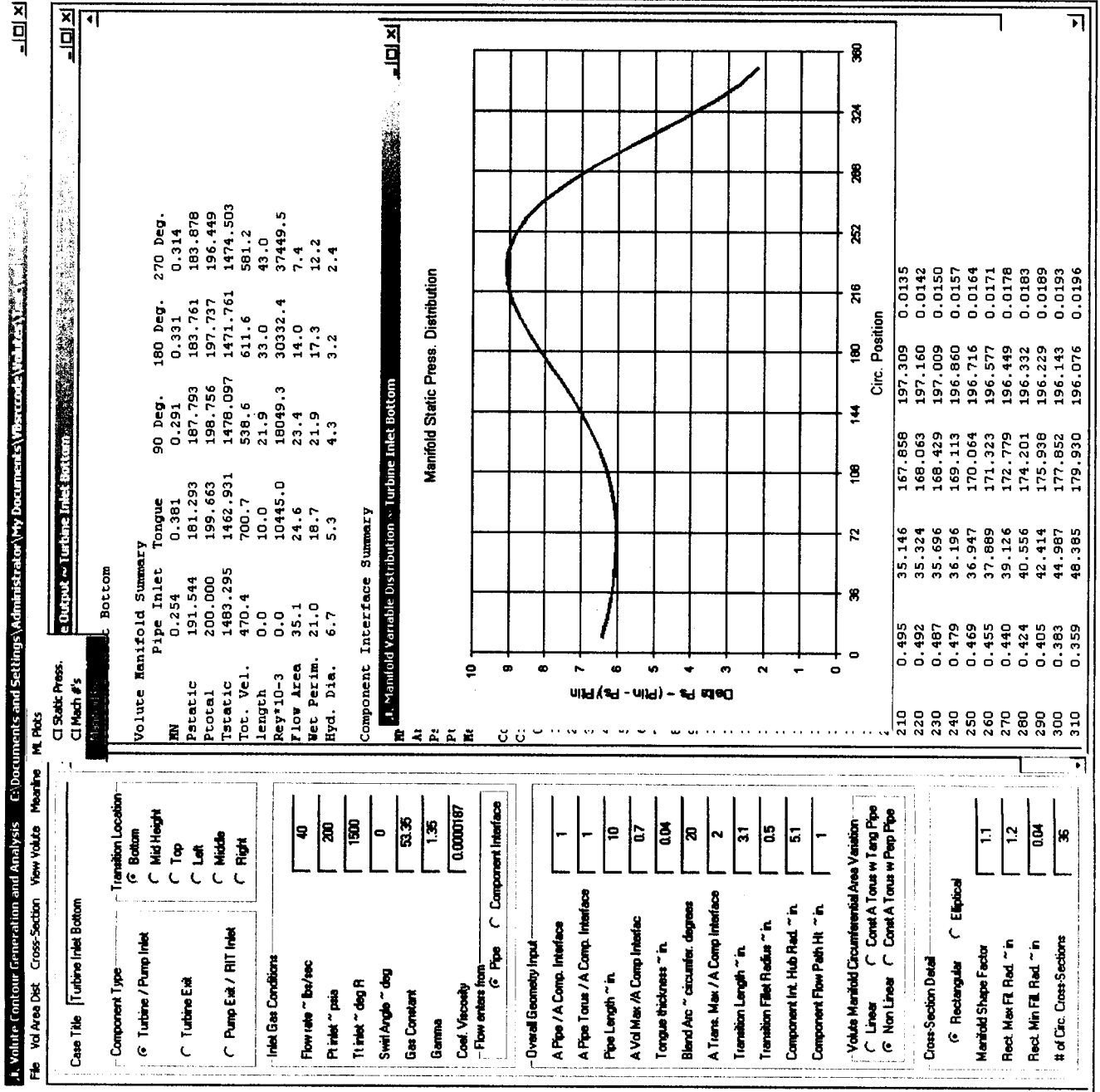
0.0183

290

0.405

42.414

User Interface - Meanline Plots



Volute Design and Analysis Methodology

Future Direction / Effort

Output specific geometry files to be use for CFD grid generation

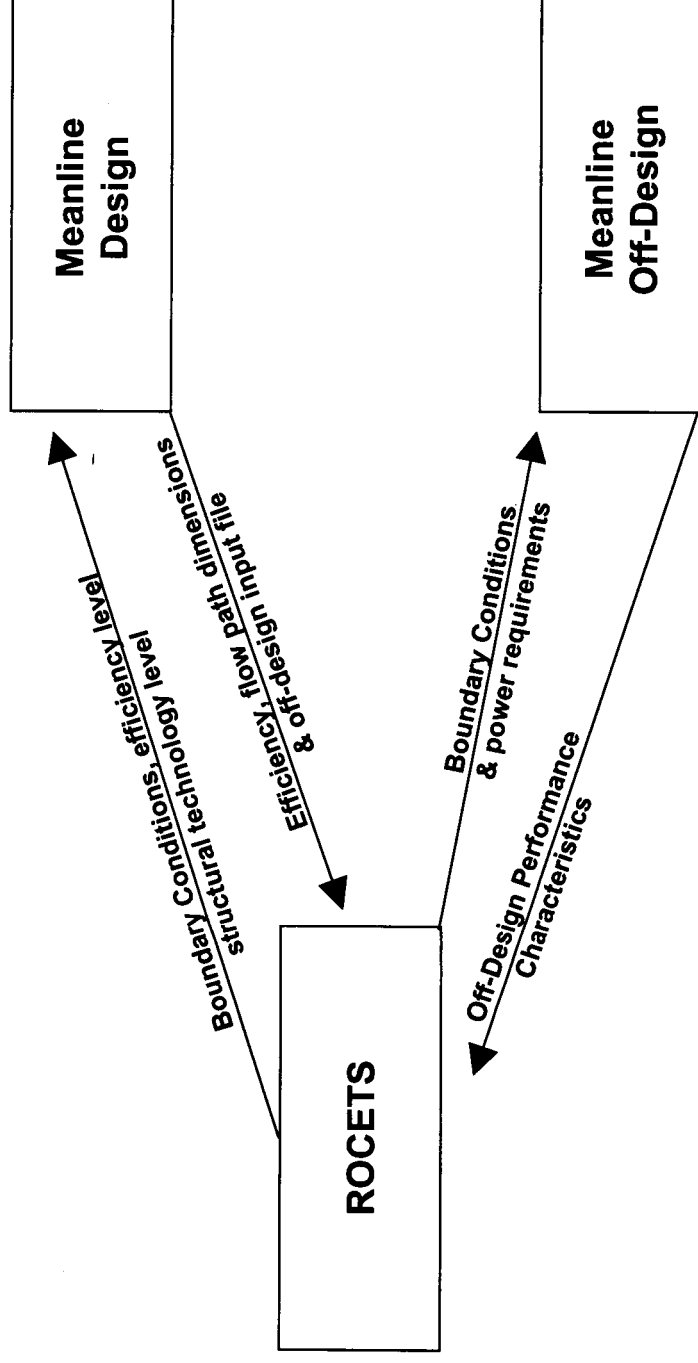
Coupling of volute and component meanlines for 1st pass estimate of interactions

Meanline Modifications for Engine Analysis Code

Objective:

Restructure existing turbine meanline design and off-design codes for use as modules in the Rocket Engine Transient Simulation (ROCETS) code

- Provide performance estimates consistent with current ROCETS cycle requirements



Meanline Modifications for Engine Analysis Code

Requirements:

Convert from GUI to Batch codes

Batch codes (DLL's) callable from ROCETS using minimal input

Generation of remaining design input based on design assumptions

Add partial admission analysis capability to both sets of design and off-design codes

Existing Meanline Code

Spindle Cap Feed

USE Test

SPOOL SUMMARY

Efficiency	0.8543 t-t	Spool 1	0.8140 t-s
P/P	1.4631 t-t	1.4919 t-s	
U/C actual	0.4779 t-t	0.4857 t-s	
U/C actual	24.023 btu/s	33.562 exit	
Weight (T/H)/P	165.9 btu/s	230.4 hp	
Power - Total	165.9 btu/s		
Power - Shaft	142.91 btu/s		
Torque	171.4 ft-lbs		

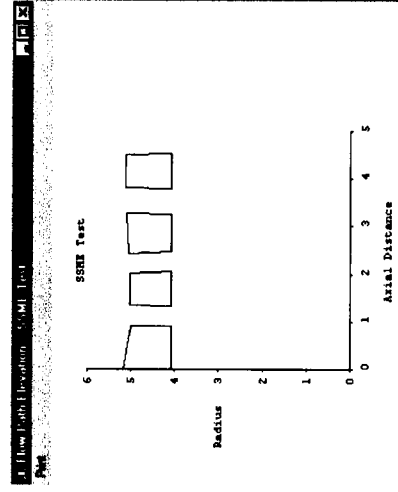
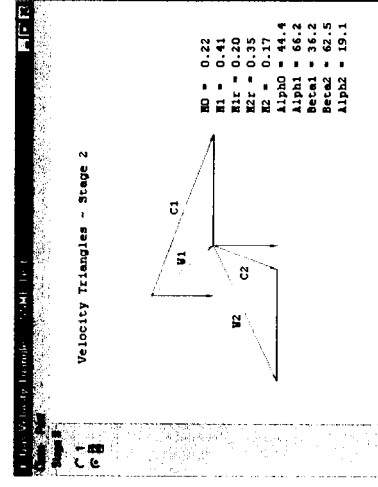
STAGE SUMMARY

Efficiency	0.8433 t-t	Stage 1	0.7565 t-s
P/P	1.2348 t-t	1.2745 t-s	
U/C actual	0.4624 t-t	0.4770 t-s	
C/Lbm	0.598 bld in	0.618 bld ex	
Reaction	0.467 Ps	0.465 Ts	
Work	6.51 btu/lbm	132.1 hp	
Power - Tot.	65.1 btu/s	129.1 hp	
Power - Shaft	91.3 btu/s		
PFE	5982.0		
AN-2 E-8	13.3		

Spool 2

Efficiency	0.8404 t-t	Stage 2	0.7718 t-s
P/P	1.3848 t-t	1.2882 t-s	
U/C actual	0.5141 t-t	0.4875 t-s	
U/C actual	0.5342 t-t	0.435 bld ex	
Reaction	0.398 Ps	0.428 Ts	
Work	5.11 btu/lbm		
Power - Tot.	71.8 btu/s	101.3 hp	
Power - Shaft	71.8 btu/s	101.3 hp	
PFE	5982.0		
AN-2 E-8	14.6		

AIRFOIL ROW SUMMARY									
Stage 1					Stage 2				
Stator (abs)		Rotor (rel)		Stator (abs)		Rotor (rel)		Stage	
Inlet	Exit	Inlet	Exit	Inlet	Exit	Inlet	Exit	Inlet	Exit
MM									
0.114	0.418	0.203	0.441	0.213					
Camber	86.94	44.33	49.37	76.82					
Percent	99.0	88.1	90.8	89.7					
Preval	100.0	99.2	90.8	89.7	81.0				
Throat	546.6	531.6	531.9	516.2	510.1				
Total	550.0	550.0	536.3	532.9					
Top Vel.	130.4	468.7	229.1	490.9	237.9				
Ang Vel.	0.0	437.4	158.7	460.0	173.4				
Tang Vel.	130.4	171.1	165.3	171.4	162.8				
Down			277.4	277.4					
Root rad.	4.076	4.076	4.076	4.076					
Tip rad.	4.422	4.422	4.422	4.422					
Wing Area	5.169	5.001	5.000	5.000					
Tip Rad	31.73	26.38	27.28	27.28					
Ann. Area	14.02	14.02	14.02	13.32	14.02				
Flow									
gamma	1.400	1.400		1.400					
Cp	0.240	0.240		0.240					
Reyn	53.35	53.35		53.35					
ROW OVERALL					Rotor (rel)				
Pairs/Pax	Stator (abs)		Rotor (rel)		Rotor (rel)		Stage		
Turning	66.64	1.125	115.40	1.125					
CR	3.302	2.066							
Re based on bx	1303813.								
Divis	0.00001228								
No. airfoils	52								
TE Affix	9.609								
TE Affix	23.84								
TE Affix	27.45								
Coape Angle	69.632								
Coape Flow	14.02								
Coape Pt	99.78								
Coape Tc	550.0								



Meanline Modifications for Engine Analysis Code

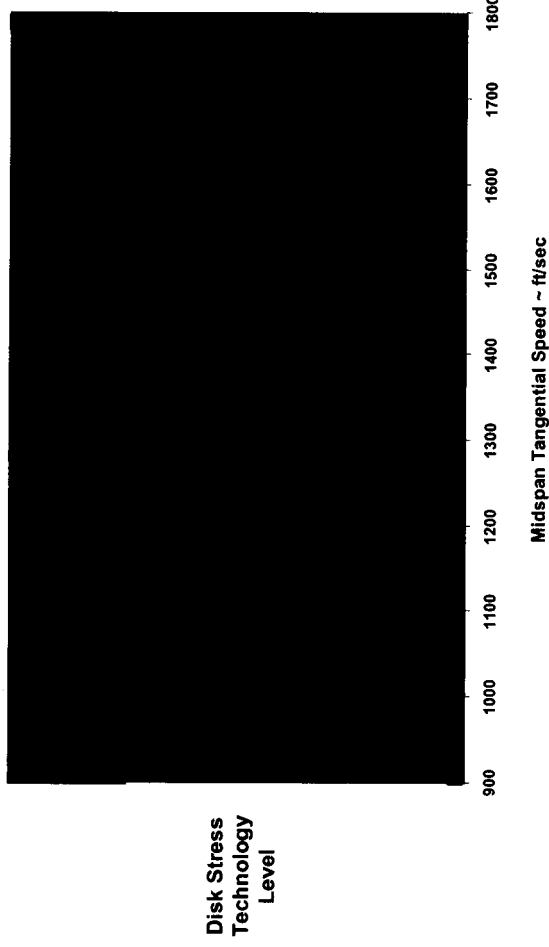
Batch Meanline

- GUI removed
- 80% source code modules common to both versions
- Main subroutine accepts argument list from ROCETS:
 - Case Title
 - Inlet Pt, Tt, Flow
 - Pressure ratio, RPM
 - Number of stages or desired efficiency level
 - Mean tangential speed of last stage
 - Annulus area * RPM^2 of last stage
 - Percent flow admission
 - Option to specify how stage work split and reaction are determined
 - Gas properties
 - 4 file flags

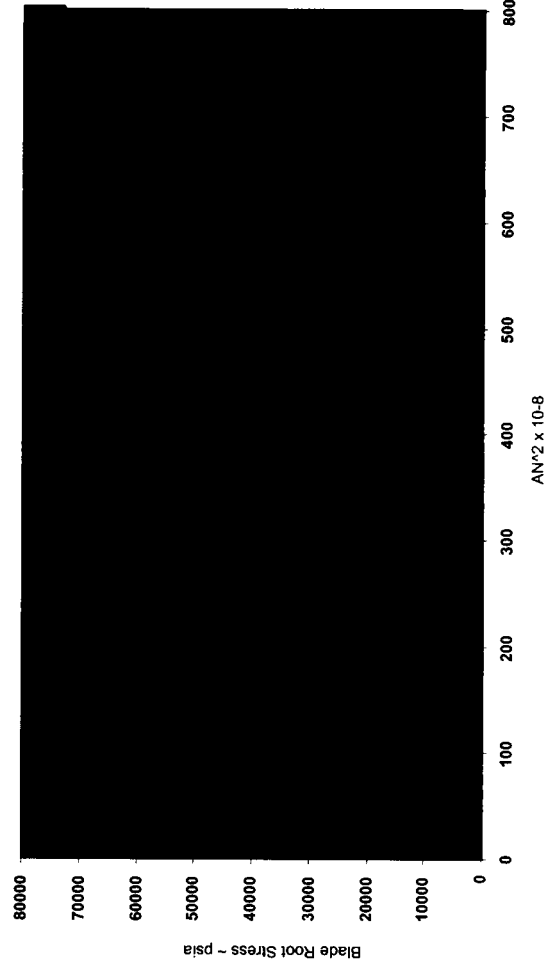
Meanline Modifications for Engine Analysis Code

Guidelines for selection of turbine structural technology levels

Turbine Blade Speed vs Technology Levels



Turbine Blade Stress vs AN2



Meanline Modifications for Engine Analysis Code

GUI Meanline modified to maintain compatibility with ROCETS version

Dialog box for ROCETS input

J. ROCETS Input	
Case Title	Sample 2 Stage Turbine
Tt inlet ~ deg R	2200.
Pt inlet ~ psia	2250.
Flow inlet ~ lbs/sec	65.1
Press. Ratio ~ Pt inlet / Ps exit	8.71
RPM	33000
# Stages or Eta ts Range	.68
Mean Wheel Speed ~ ft / sec	1600
AN^2 ~ 10^-8 ~ in^2 RPM^2	600
Percent Admission	1.
Opt Velocity Compounded	0
R gas ~ ft lb / lbm deg R	342.
Cp gas ~ btu / lbm deg R	1.69
gamma gas	1.36
Viscosity ~ lb / ft sec	.000024
Edit input file before running	1
Run ML from existing input file	0
Write standard output file	1
Write off-design input file	0
Run	Cancel

Meanline Modifications for Engine Analysis Code

GUI Version Main Input Window with calculated input & flow path

Meanline Analysis

File Stage Input ROCETS Input Draw Run MixRun ParaRun CtrlWordRun

Input Parameters

Case Title Sample 2 Stage Turbine

Analysis Options

Working Fluid: ROCETS

Admission Fraction: 1

Inlet Conditions

No. of Spools: 2

Total Temp. deg R: 2200

Total Press. psia: 2250

Flow ~ lbs/sec: 65.1

Gas Angle ~ deg: 0

Gas Constant: 342

Gamma: 1.35

Coef. of Viscosity: 0.000024

Specific Heat: 1.63

Spool Input

No. of Stages: 2

RFM: 33000

Pressure Ratio: 8.71

P/P Code TS = 0, TT = 1: 0

Last Blade Aaam ~ in ~ 2: 55.096

First Blade Exit Dim ~ in: 9.5336

First Vane LE In / TE In: 1

1st V/B Overlap %tb: 0.05

Stage Input

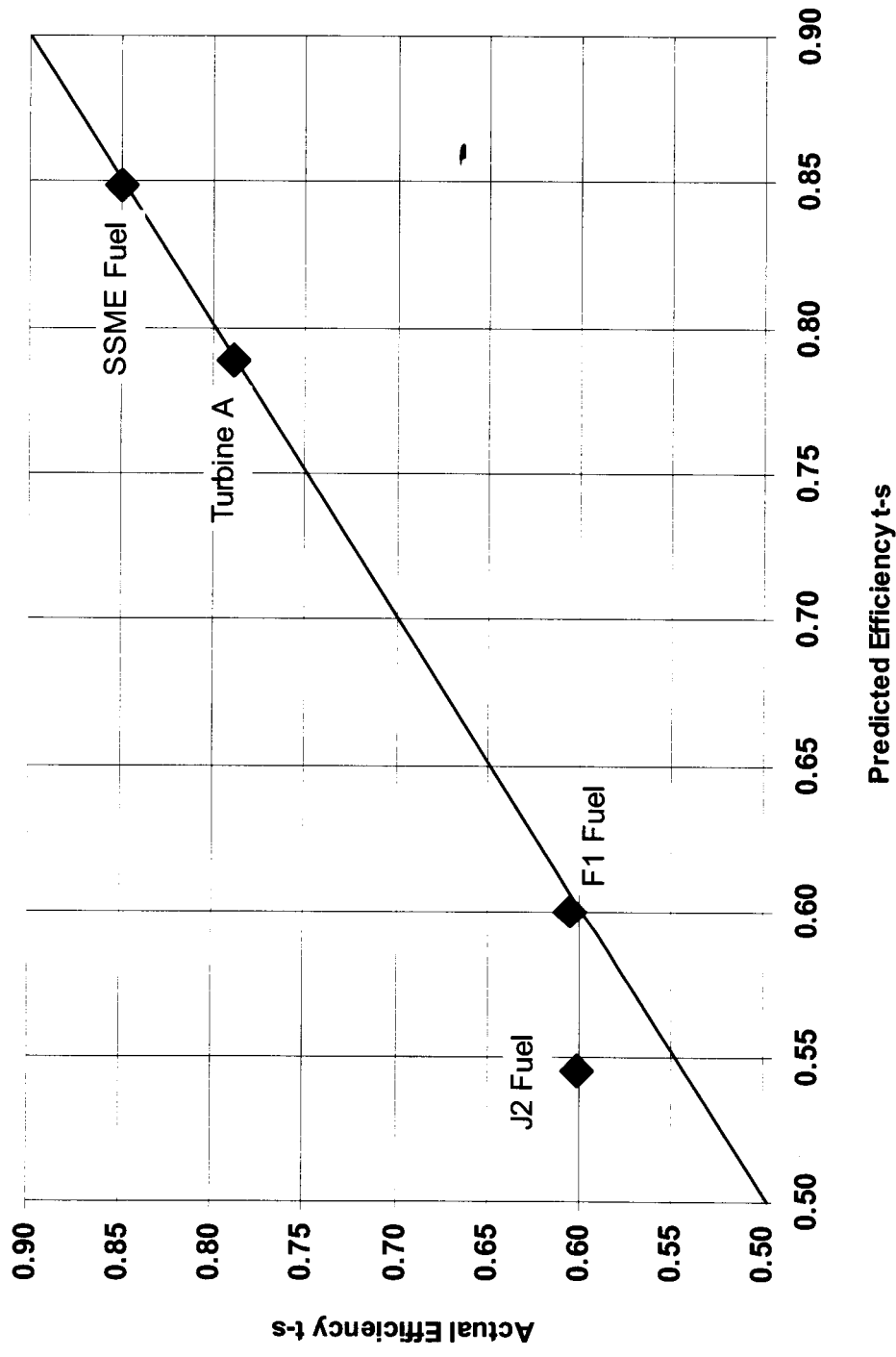
	Stg 1	Stg 2
T-S Work Split Fract ~ Stg/Ovrl Spl	0.84	0.16
Stage Reaction ~ Ps	0.09	0.09
Vane bx mean ~ in	1.4572	1.2682
Vane Taper Factor ~ bx tip/bx root	1	1.1
Vane TE Thickness ~ in	0.03	0.03
Vane ID Flow Path Angle	0	0
Vane Zweifel Load Coef.	0.9	0.7
Vane Spcrg ~ % upstm blade bx	0.4	0.4
Vane Loss Adder ~ DP/Pr	0	0
Blade bx mean ~ in	1.5339	1.3488
Blade Taper Factor ~ bx tip/bx root	0.9	0.9
Blade TE Thickness ~ in	0.03	0.03
Blade ID Flow Path Angle	0	0
Blade Height ~ % last blade in spool	0.9116	1
Blade Zweifel Load Coef.	0.7	0.7
Blade Spcrg ~ % upstm axial bx	0.4	0.4
Blade Loss Adder ~ DP/Pr	0	0
Tip Clearance ~ in	0.0192	0.0197
Shroud Code	0	0

Flow Path Elevation ~ Sample 2 Stage Turbine

Print

Meanline Modifications for Engine Analysis Code

Comparison of calculated and actual turbine performance



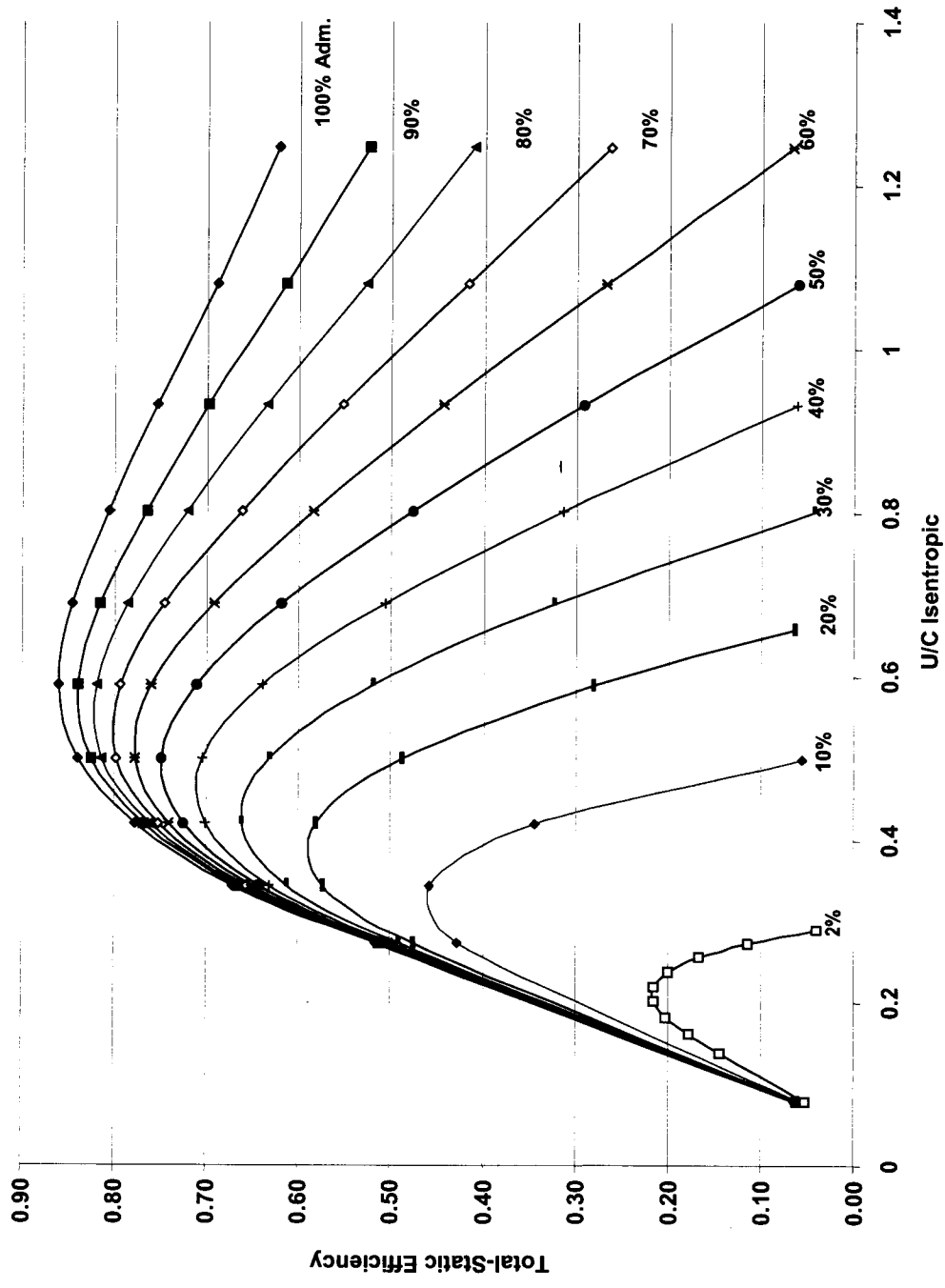
Meanline Modifications for Engine Analysis Code

Partial Admission Turbine Analysis Modifications

- Stator flow path annulus area and flow area book-keeping
- Additional performance losses
 - Windage / pumping (Suter and Traupel)
 - Expansion / filling & emptying (Stenning)

Meanline Modifications for Engine Analysis Code

Predicted effect of percent admission on turbine design point efficiency



Meanline Modifications for Engine Analysis Code

Future Direction / Effort

Compile additional data for calibration / verification

- Supersonic turbine performance prediction
- Partial admission turbine performance prediction