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Abstract

Prediction of Incidence and Surface Roughness Effects on Turbine Performance

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The results of a Navier-Stokes analysis for predicting the change in turbine efficiency due to a change in either incidence or surface roughness is discussed. It was experimentally determined by Boynton, Tabibzadeh, and Hudson that polishing the SSME high pressure fuel turbine blades improved turbine efficiency by about 2 points over a wide range of operating conditions. These conditions encompassed the range of incidence seen by the turbine blading during flight. It is also necessary to be able to predict turbine performance at various operating points for future rocket turbopump applications. The code RVCQ3D, developed by Rod Chima, was used to determine the effects of changes in incidence angle on turbine blade row efficiency. The midspan Navier-Stokes results were used in conjunction with an inviscid flow analysis code to predict the efficiency of the two stage SSME over a wide range of operating conditions for smooth and rough turbine blades. The use of the Navier-Stokes analysis to predict changes in turbine efficiency due to variation in incidence angles was found to be superior to other incidence loss correlations available in the literature. The sensitivity of the Navier-Stokes results to grid parameters is discussed.

The effects of the surface roughness were accounted for using the Cebeci-Chang rough wall turbulence model. This model was implimented in the code RVCQ3D. The implimentation of this model for predicting the change in efficiency is also discussed.

PREDICTION OF INCIDENCE and SURFACE ROUGHNESS EFFECTS ON TURBINE PERFORMANCE

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OBJECTIVES

- IMPROVE TURBINE PERFORMANCE PREDICTION CAPABILITY
  - INCIDENCE EFFECTS
  - SURFACE ROUGHNESS EFFECTS

MOTIVATION

- INCIDENCE EFFECTS IMPORTANT
  - DURING ENGINE START
  - WHEN ENGINE IS THROTTLED
- ROUGHNESS EFFECTS IMPORTANT
  - WHEN PROTECTIVE COATINGS ARE USED

INCIDENCE and SURFACE ROUGHNESS ?

- DIFFERENT QUESTIONS BUT SIMILAR APPROACHES

- RELATIVE CHANGE IMPORTANT

  RELATIVE GRID SENSITIVITY

  RELATIVE LOSS LEVEL

COMPUTATIONAL APPROACH

- USE INVISCID AND VISCOUS ANALYSES
- RELATIVELY QUICK ANALYSIS NEEDED

  MANY CASES NEEDED TO VERIFY APPROACH
- INVISCID - MTSB - QUASI-3D
- VISCOUS - RVCQ3D - MIDSPAN

MTSB - INVISCID + LOSSES

- FLOW ANALYSIS
  - HUB-TO-SHROUD - MERIDL
  - BLADE-TO-BLADE - TSONIC
- LOSS ANALYSIS
- BOUNDARY LAYER - BLAYER
  - PROFILE
  - ENDWALL
- CORRELATIONS
  - TIP CLEARANCE
  - SECONDARY FLOW
  - INCIDENCE

VISCOUS SOLVER

- MIDSPAN - BLADE-TO-BLADE ANALYSIS
- EXISTING SOLVER - RVCQ3D
  - EXPLICIT
  - TIME MARCHING
  - RESIDUAL SMOOTHING
- TURBULENCE MODEL
  - MIXING LENGTH
  - MODIFIED FOR ROUGHNESS EFFECTS
    CEBECI-CHANG MODEL

INCIDENCE

- COMPARE NAVIER-STOKES INCIDENCE LOSS MODEL WITH EMPIRICAL CORRELATIONS
- EMPIRICAL MODELS

  GLASSMAN'S

  MOUSTAPHA et al.

  TRAN et al. - SSME HPFT
- NAVIER-STOKES DERIVED CORRELATION

  CURVE FIT MIDSPAN NAVIER-STOKES RESULTS & USE IN PLACE OF EMPIRICAL MODEL IN PERFORMANCE CALCULATION (MTSB)

INCIDENCE LOSS COMPARISONS

- MSFC BLOWDOWN TEST – 2 STAGE TURBINE

  SSME HPFT – $U/V_{IDEAL} = 0.37$(DESIGN)

  $0.25 < U/V_{IDEAL} < 0.65$

- LEWIS 30in DIA TURBINES – 1 & 2 STAGES

  DESIGN POINTS – NO INCIDENCE EFFECTS

  40% SPEED LINE vs PRESSURE RATIO

DOES ONE CORRELATION FIT ALL CASES?

- COMPARISON WITH DIFFERENT TURBINES TESTS:

  UNIVERSALITY OF NAVIER-STOKES DERIVED INCIDENCE LOSS CORRELATION

- SSME HPFT - LOW PRESSURE RATIO

- 30 in DIAMETER TURBINES

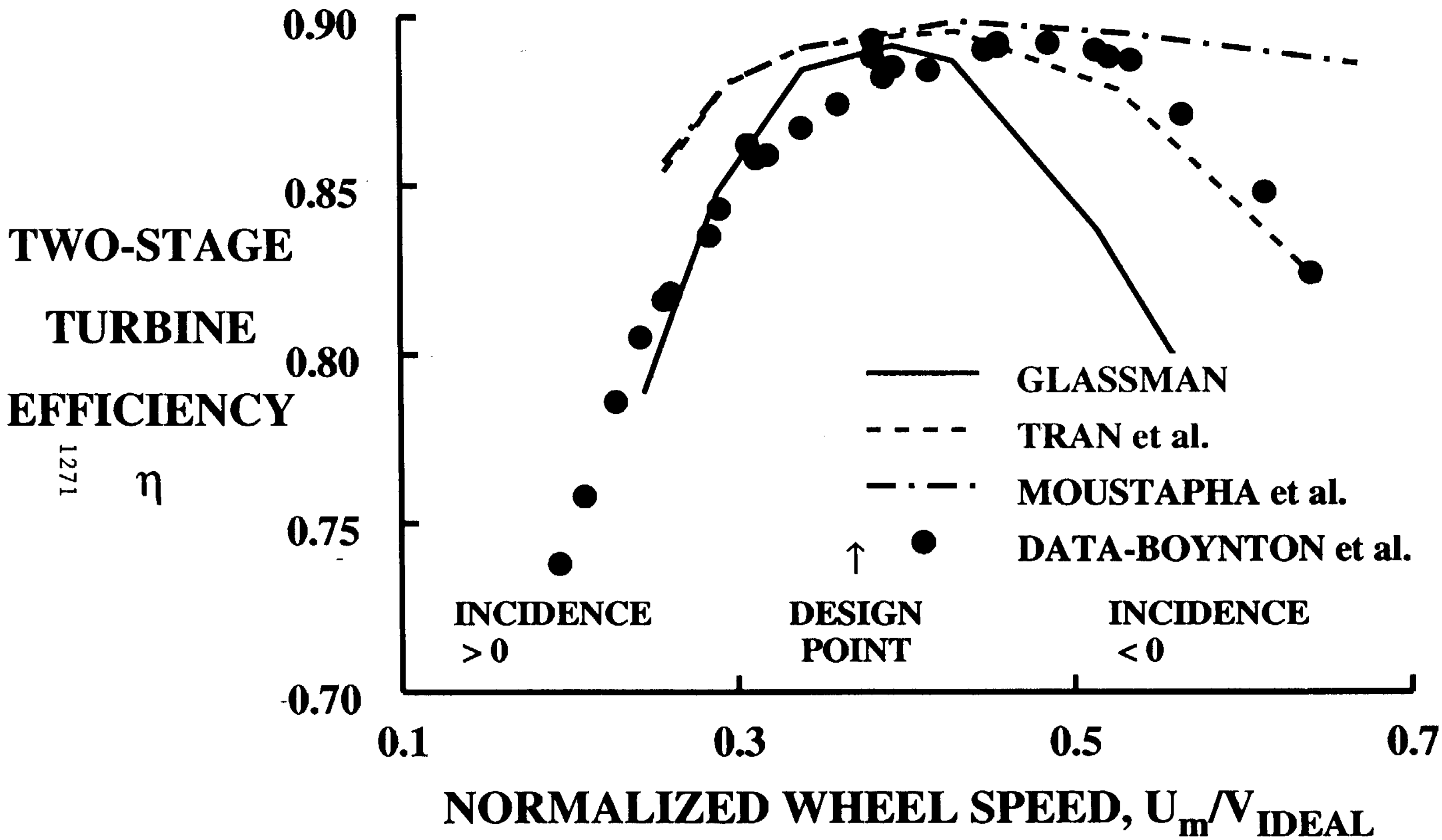
  HIGH PRESSURE RATIO

  TRANSONIC FLOW CONDITIONS

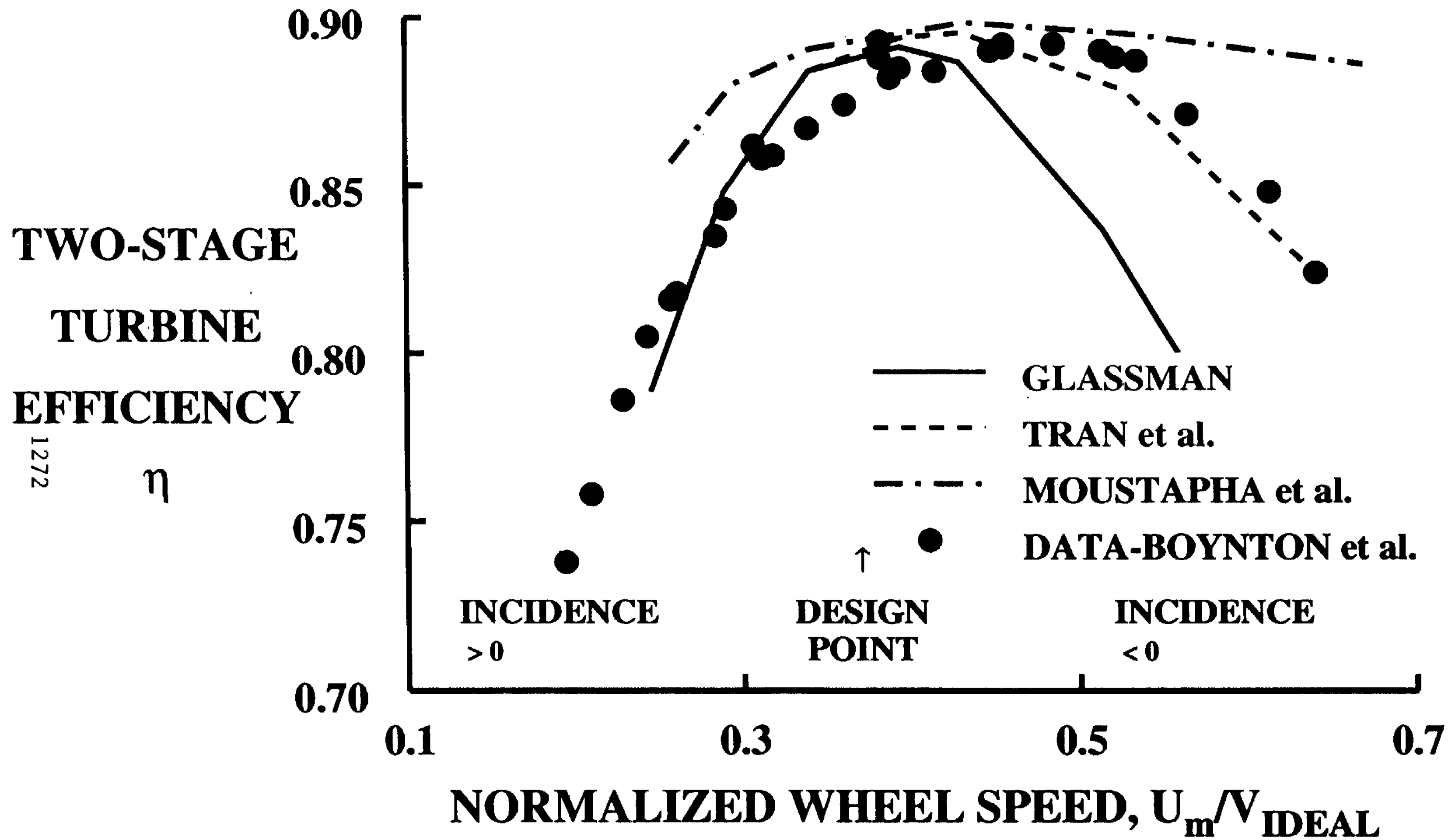
SENSITIVITY OF ROTOR LOSS TO GRID PARAMETERS

Grid	y_1^+	$\bar{e}$
145×54	0.6	0.0509
291×54	0.6	0.0423
291×70	0.6	0.0438
291×54	1.2	0.0375
291×54	0.3	0.0321
291×70	0.3	0.0441
MTSB		0.0351

EFFICIENCY FOR SMOOTH BLADED SSME HPFT

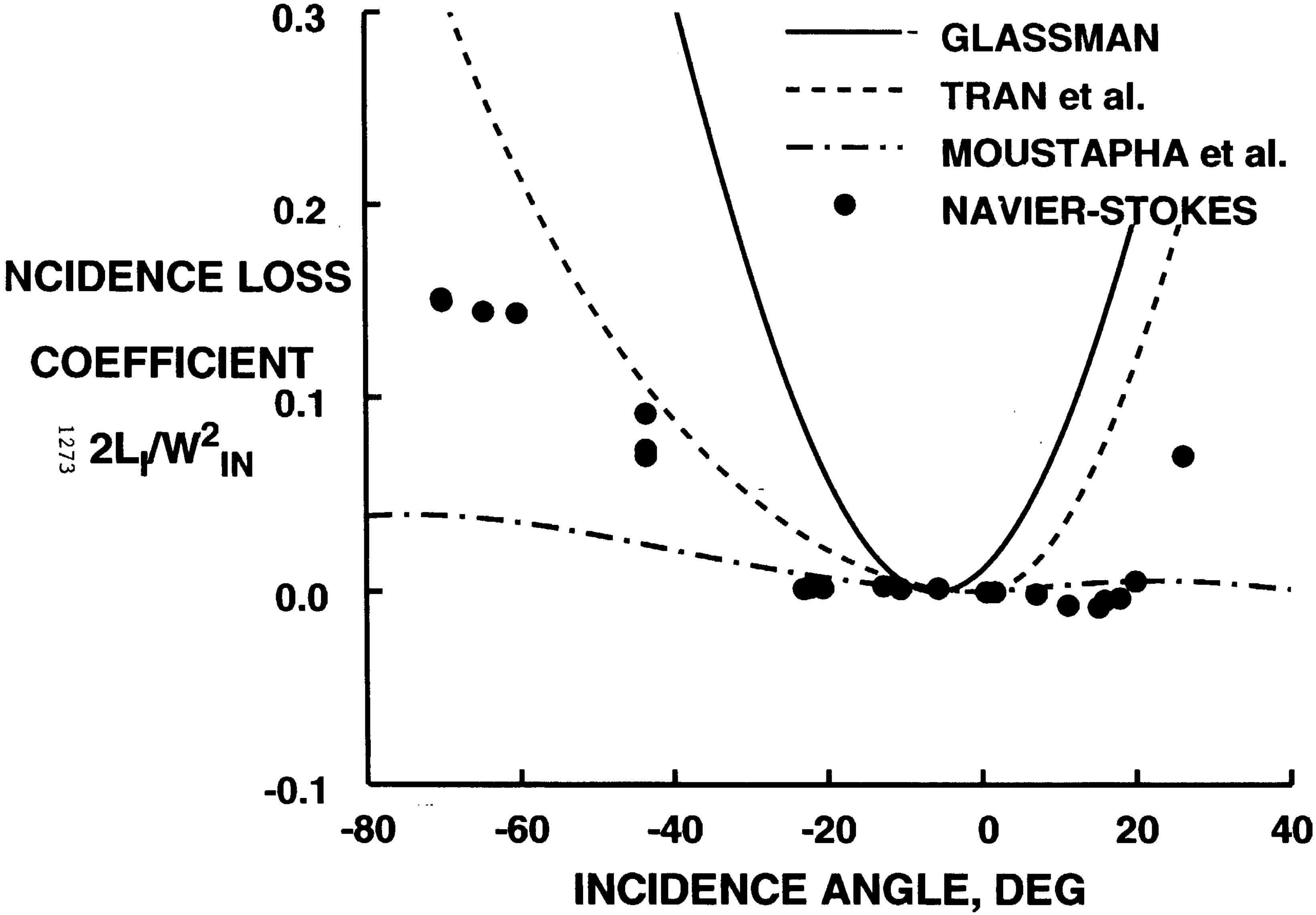


EFFICIENCY FOR SMOOTH BLADEDED SSME HPFT

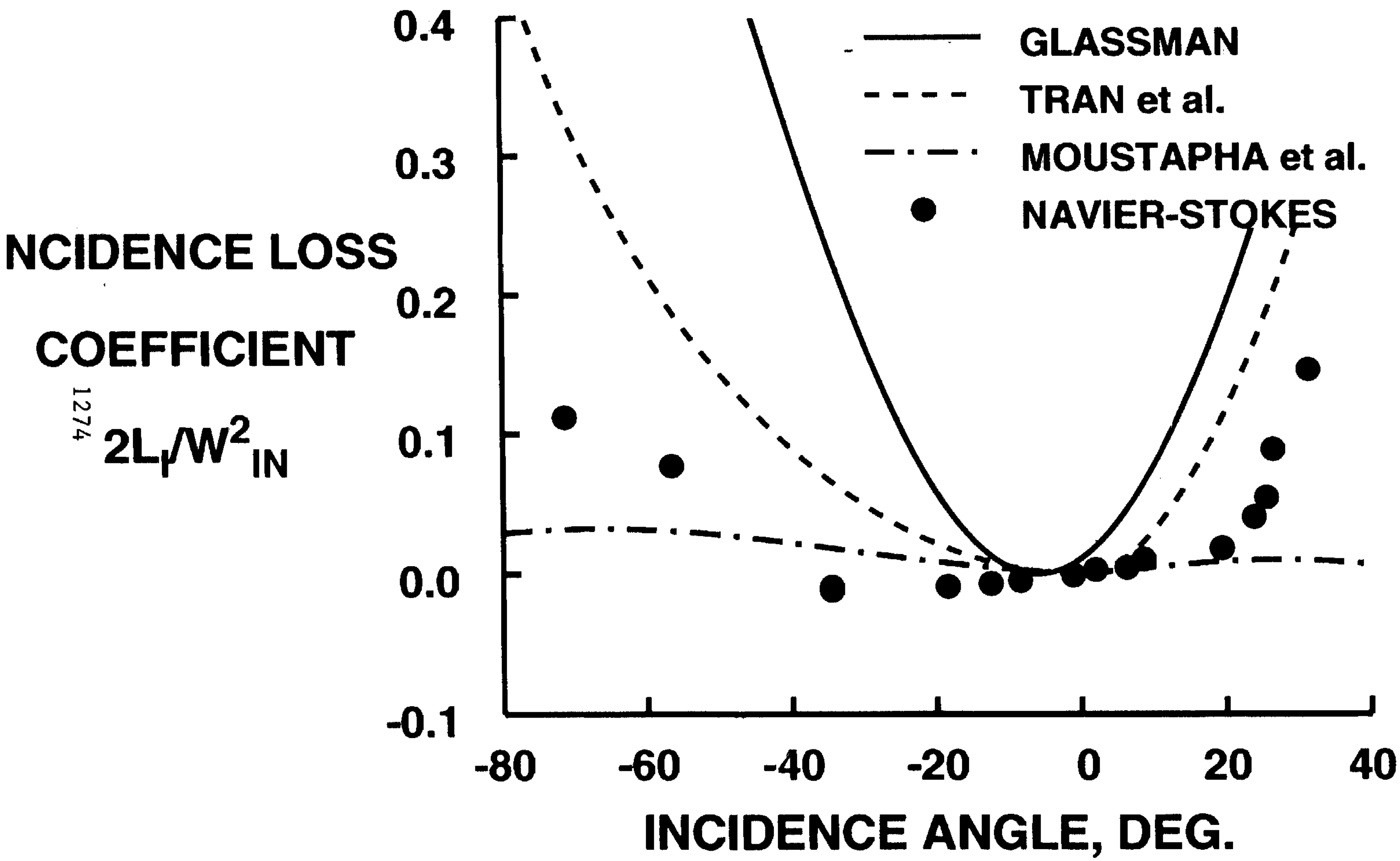


LOSS PREDICTIONS - NAVIER-STOKES & CORRELATIONS

SSME HPFT FIRST STAGE ROTOR

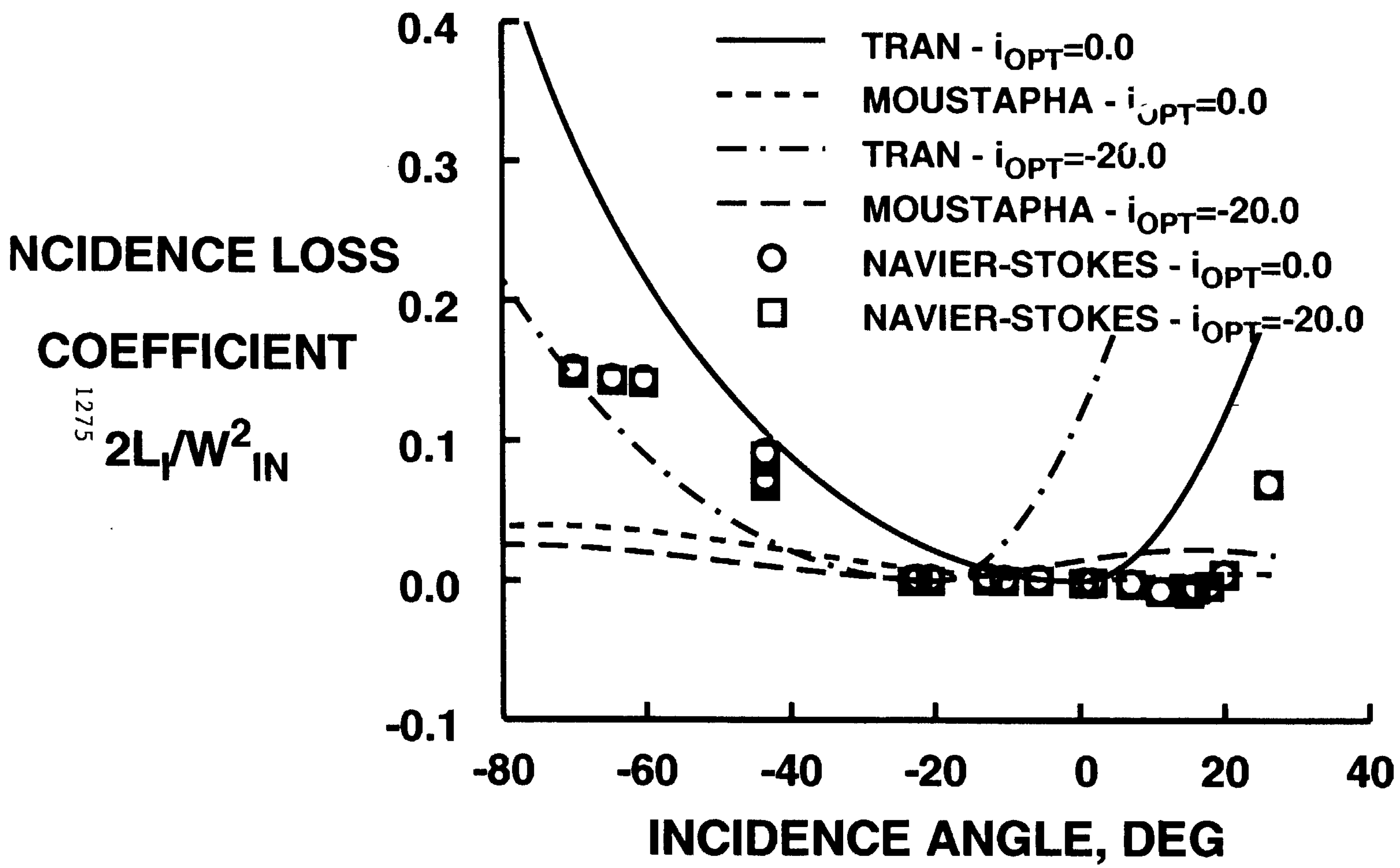


LOSS PREDICTIONS - NAVIER-STOKES & CORRELATIONS
SSME HPFT SECOND STAGE STATOR



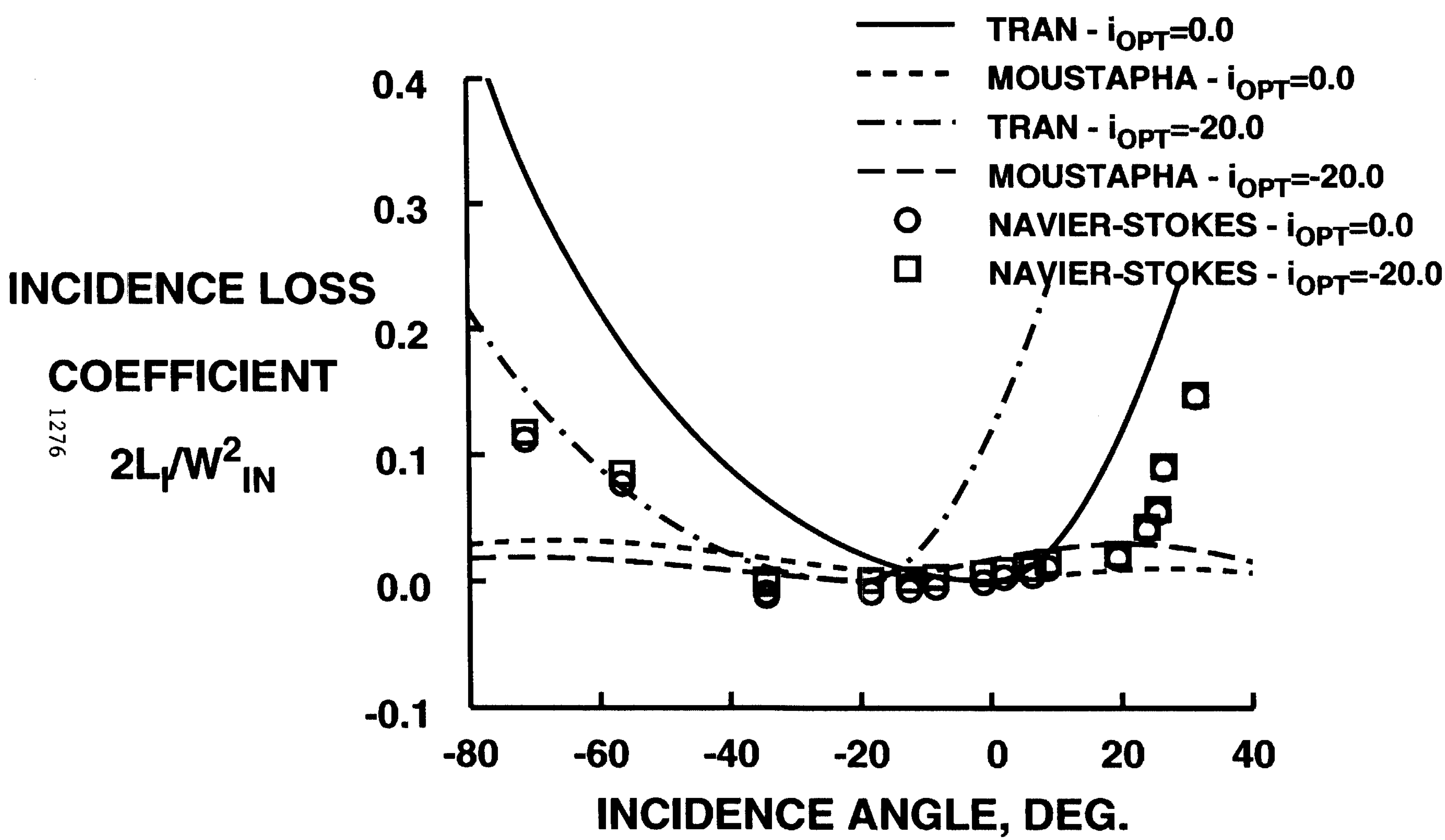
EFFECT OF OPTIMUM INCIDENCE ANGLE ON LOSS

SSME FIRST STAGE ROTOR

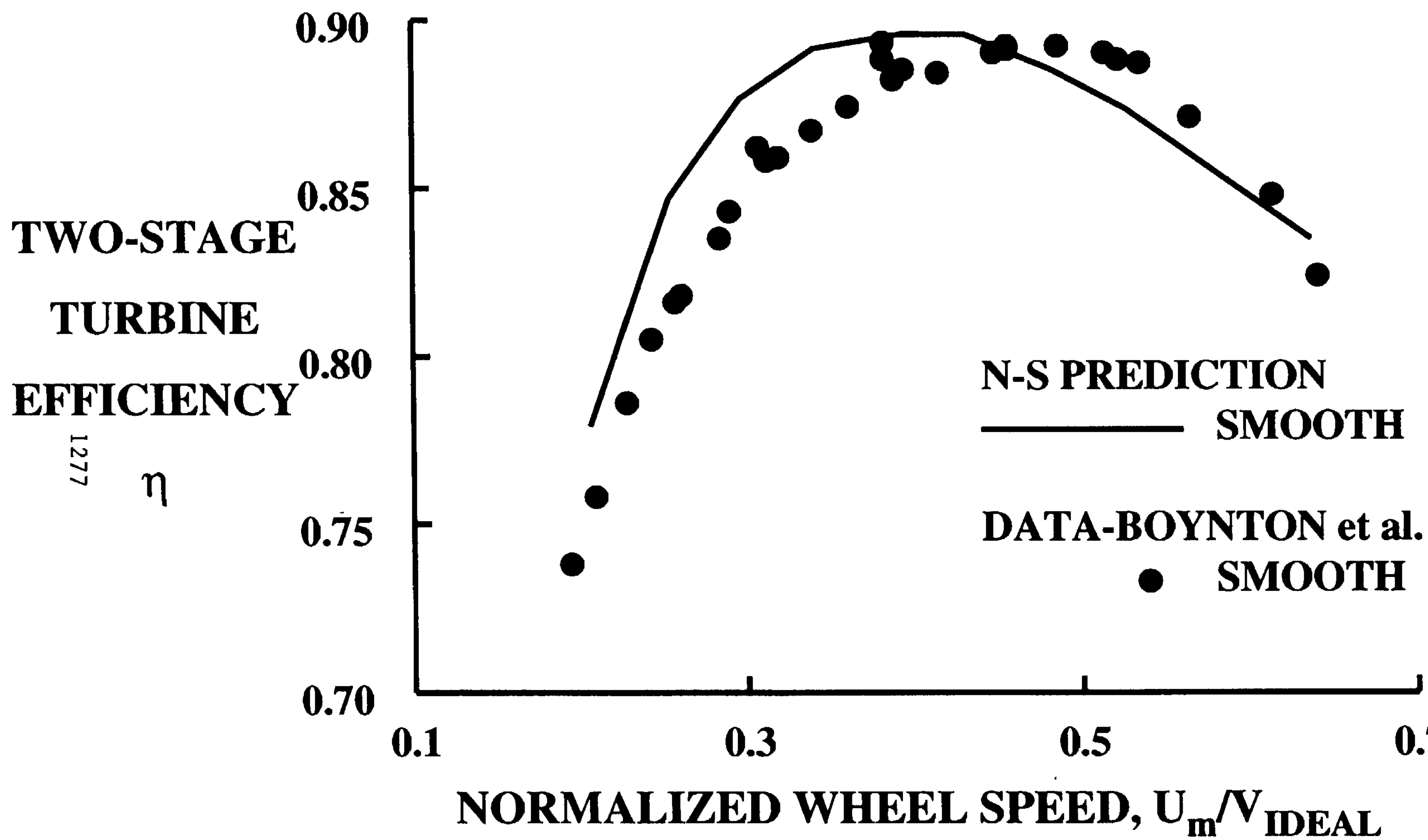


EFFECT OF OPTIMUM INCIDENCE ANGLE ON LOSS

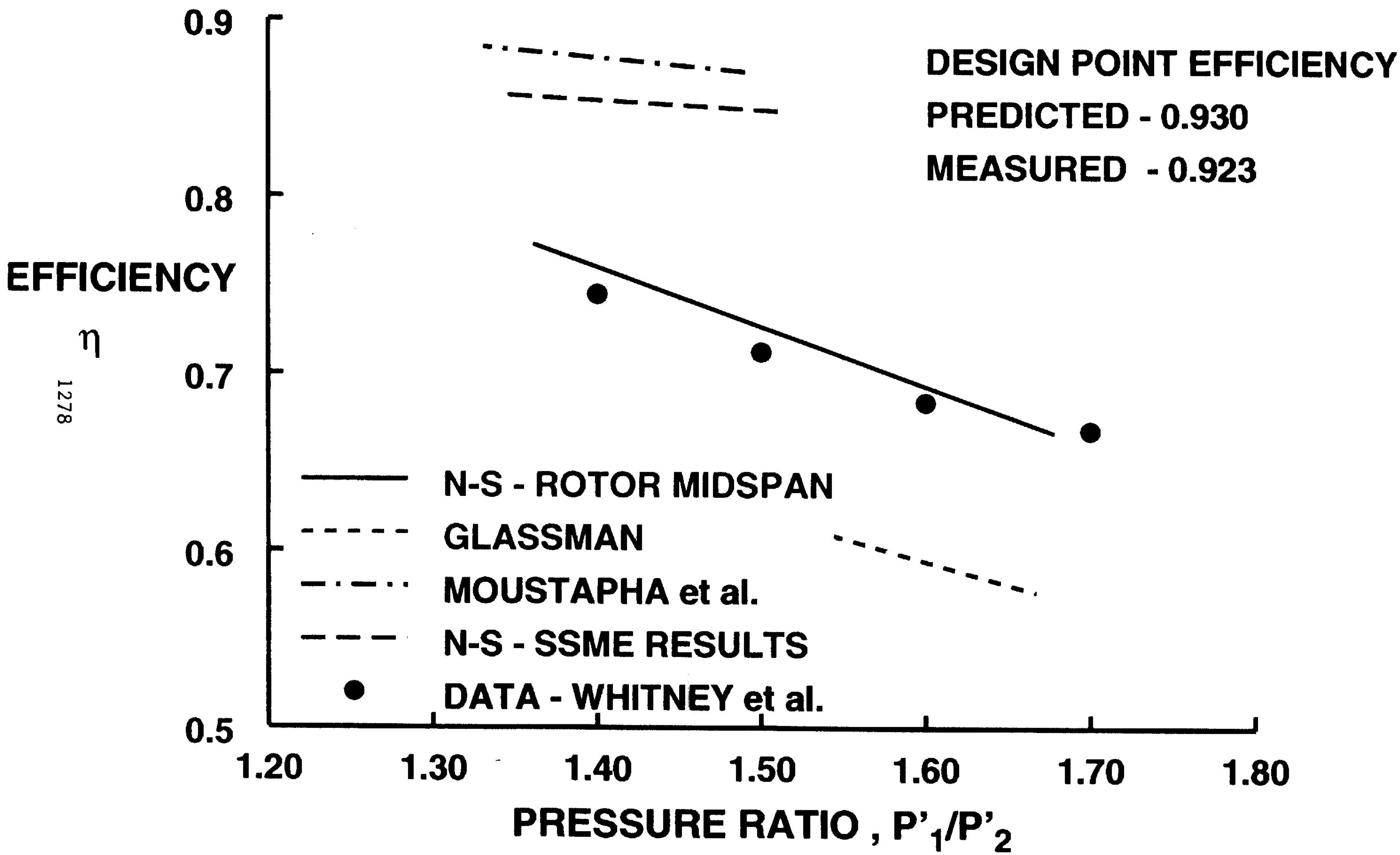
SSME HPFT SECOND STAGE STATOR



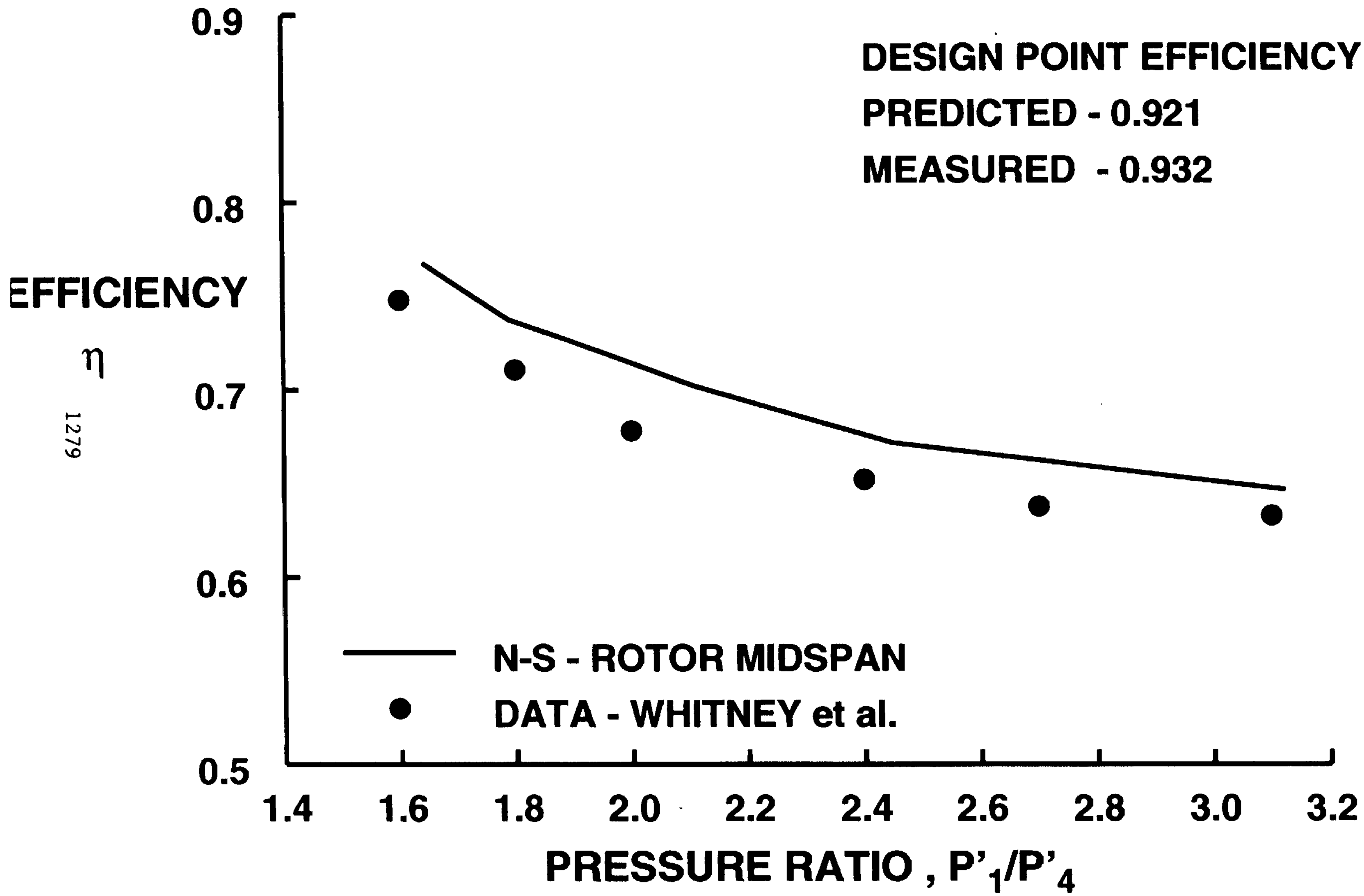
EFFICIENCY OF SMOOTH BLADED SSME HPFT
NAVIER-STOKES DERIVED INCIDENCE LOSS MODEL



EFFICIENCY FOR SINGLE STAGE 30in TURBINE - 40% SPEED



EFFICIENCY FOR TWO STAGE 30in TURBINE - 40% SPEED



INCIDENCE LOSS CONCLUSIONS

- INCIDENCE LOSS WELL PREDICTED BY NAVIER-STOKES MIDSPAN ANALYSIS
- NAVIER-STOKES APPROACH DOES NOT RELY ON A PRIORI KNOWLEDGE OF OPTIMUM INCIDENCE ANGLE
- BEST AGREEMENT WHEN USING NAVIER-STOKES RESULTS FOR SIMILAR CONFIGURATION

  NOT A SIGNIFICANT DISADVANTAGE
- IMPROVED INCIDENCE LOSS CORRELATION VIA VARIATION OF NAVIER-STOKES PARAMETERS

  NOT ALWAYS CONVENIENT IN EXPERIMENTS

SURFACE ROUGHNESS

- CEBECI-CHANG ROUGHNESS MODEL IMPLEMENTED IN MIDSPAN NAVIER-STOKES CODE

  MIXING LENGTH TURBULENT EDDY VISCOSITY MODEL FOR BOTH SMOOTH AND ROUGH SURFACES

  INCREASE IN MIXING LENGTH TO ACCOUNT FOR ROUGHNESS

  INCREASE IS A FUNCTION OF ROUGHNESS HEIGHT AND DENSITY

- NEAR WALL DAMPING (A^+) PART OF TURBULENT EDDY VISCOSITY MODEL

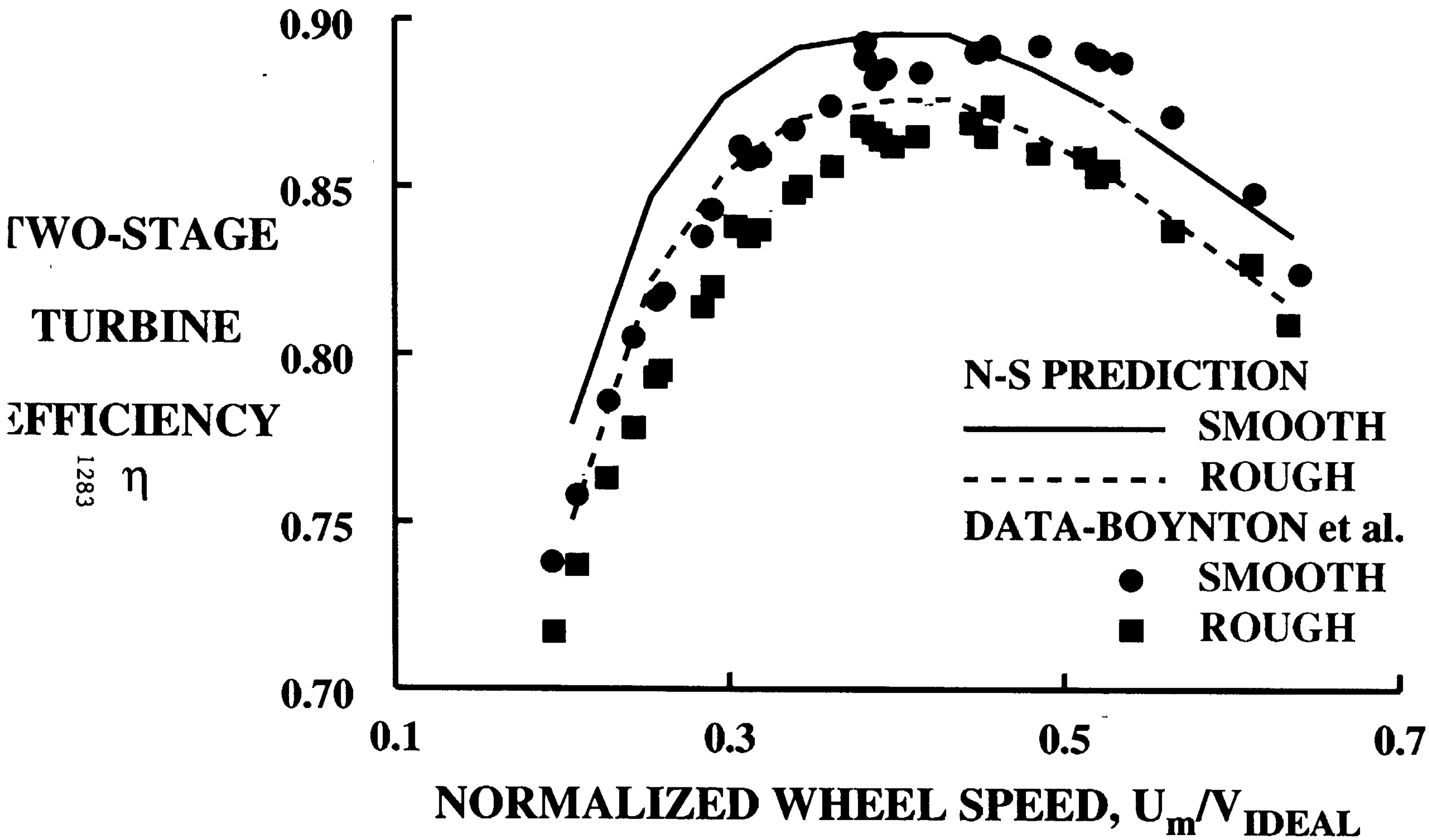
EFFECT OF GRID AND SURFACE ROUGHNESS ASSUMPTIONS ON EFFICIENCY

h =15 micrometers

Grid	y_1^+	K	A^+	$\bar{e}_{2D}$	$\Delta\eta$
291×54	0.3	0.0	26.0	0.0321	
		0.0	1.0	0.0483	0.011
		0.3	26.0	0.0348	0.002
		0.3	1.0	0.0550	0.015
		0.7	1.0	0.0656	0.022
		1.0	26.0	0.0455	0.009
		1.0	1.0	0.0703	0.025
291×54	0.6	0.0	26.0	0.0423	
		0.0	1.0	0.0570	0.010
		0.3	26.0	0.0449	0.002
		0.3	1.0	0.0654	0.015
		0.7	1.0	0.0726	0.020
		1.0	26.0	0.0546	0.008
		1.0	1.0	0.0767	0.023

Grid	y_1^+	K	A^+	$\bar{e}_{2D}$	$\Delta\eta$
291×54	1.2	0.0	26.0	0.0375	
		0.0	1.0	0.0531	0.010
		0.3	26.0	0.0402	0.002
		0.3	1.0	0.0586	0.014
		0.7	1.0	0.0686	0.021
		1.0	26.0	0.0502	0.008
		1.0	1.0	0.0730	0.024
291×70	0.3	0.0	26.0	0.0441	
		0.0	1.0	0.0564	0.008
		0.3	26.0	0.0462	0.001
		0.3	1.0	0.0623	0.012
		0.7	1.0	0.0720	0.019
		1.0	26.0	0.0581	0.009
		1.0	1.0	0.0760	0.021
Experimental					0.021

EFFICIENCY FOR SMOOTH AND ROUGH BLADED HPFT



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SURFACE ROUGHNESS CONCLUSIONS

- CEBECI-CHANG ROUGHNESS MODEL PREDICTS CHANGE IN TURBINE PERFORMANCE DUE TO ROUGHNESS

  $\Delta \eta$ = 2 POINTS

- USABLE FOR RANGE OF INCIDENCES

- TURBULENCE MODEL NEEDS IMPROVEMENT

  INCONSISTENCY BETWEEN ASSUMPTIONS NEEDED FOR ACCURATE LOSS & HEAT TRANSFER PREDICTIONS

OVERALL CONCLUSIONS

- MIDSPAN NAVIER-STOKES ANALYSIS USEFUL FOR PREDICTING OFF-DESIGN POINT PERFORMANCE AND ROUGHNESS EFFECTS

- MIDSPAN NAVIER-STOKES CODE(RVCQ3D) & PERFORMANCE CODE(MTSB) TOGETHER GIVE ACCURATE TURBINE EFFICIENCY PREDICTION