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OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

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This paper discusses the procedure, approach and Rocketdyne CFD results for the optimization of the NASA consortium impeller design. Two different approaches have been investigated. The first one is to use a tandem blade arrangement, the main impeller blade is split into two separate rows with the second blade row offset circumferentially with respect to the first row. The second approach is to control the high losses related to secondary flows within the impeller passage. Many key parameters have been identified and each consortium team member involved will optimize a specific parameter using 3-D CFD analysis. Rocketdyne has provided a series of CFD grids for the consortium team members. SECA will complete the tandem blade study, SRA will study the effect of the splitter blade solidity change, NASA LeRC will evaluate the effect of circumferential position of the splitter blade, VPI will work on the hub to shroud blade loading distribution, NASA Ames will examine the impeller discharge leakage flow impacts and Rocketdyne will continue to work on the meridional contour and the blade leading to trailing edge work distribution. This paper will also present Rocketdyne results from the tandem blade study and from the blade loading distribution study. It is the ultimate goal of this consortium team to integrate the available CFD analysis to design an advanced technology impeller that is suitable for use in the NASA Space Transportation Main Engine (STME) fuel turbopump.

OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

BY

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PRESENTED AT NASA MARSHALL SPACE FLIGHT CENTER

11TH WORKSHOP FOR CFD APPLICATIONS IN ROCKET PROPULSION

APRIL 20-22. 1993

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OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

- OBJECTIVES
  - DEVELOP ADVANCED CONCEPT HIGH HEAD COEFFICIENT IMPELLER DESIGN WITH MINIMIZED EXIT FLOW DISTORTION
  - DESIGN HIGH HEAD COEFFICIENT IMPELLER AND REDUCE 3 STAGES STME FUEL PUMP TO 2 STAGES
- APPROACH
  - INCORPORATE CFD AS DESIGN TOOL AND OPTIMIZE IMPELLER DESIGN THROUGH CFD ANALYSIS
  - WATER TEST TO CONFIRM IMPELLER PERFORMANCE

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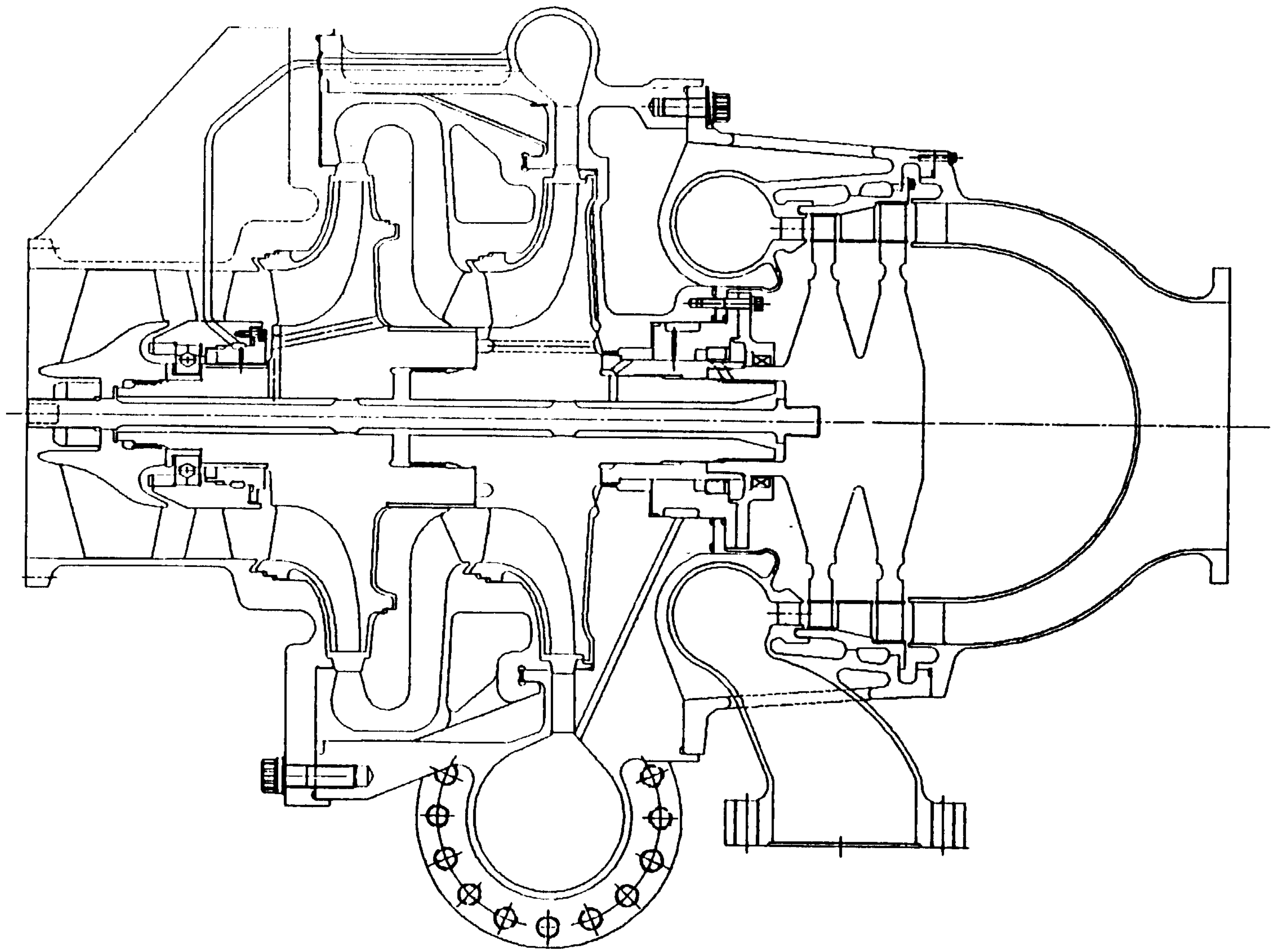
CONSORTIUM 2STAGE FUEL PUMP



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OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

- EXISTING BASELINE DESIGN
  - SUCESSFULLY COMPLETED WATER TEST
    - TEST RESULTS PRESENTED IN SEPARATE PAPER
  - ACHIEVED REQUIRED HEAD
  - GOOD AGREEMENT BETWEEN CFD RESULTS AND LASER MEASUREMENT
    - PRESENTED IN JAN. 1993 NASA PUMP CONSORTIUM MEETING
  - MINOR REVERSE FLOW AND FLOW SEPARATION NEAR SUCTION SIDE SHROUD REGION
- BASELINE DESIGN OPTIMIZED THROUGH CFD ANALYSIS BY ALL CONSORTIUM MEMBERS
- ROCKETDYNE CONTRIBUTION
  - TANDEM BLADE APPROACH
  - CONTROL IMPELLER BLADE LOADING FROM L.E. TO T.E.

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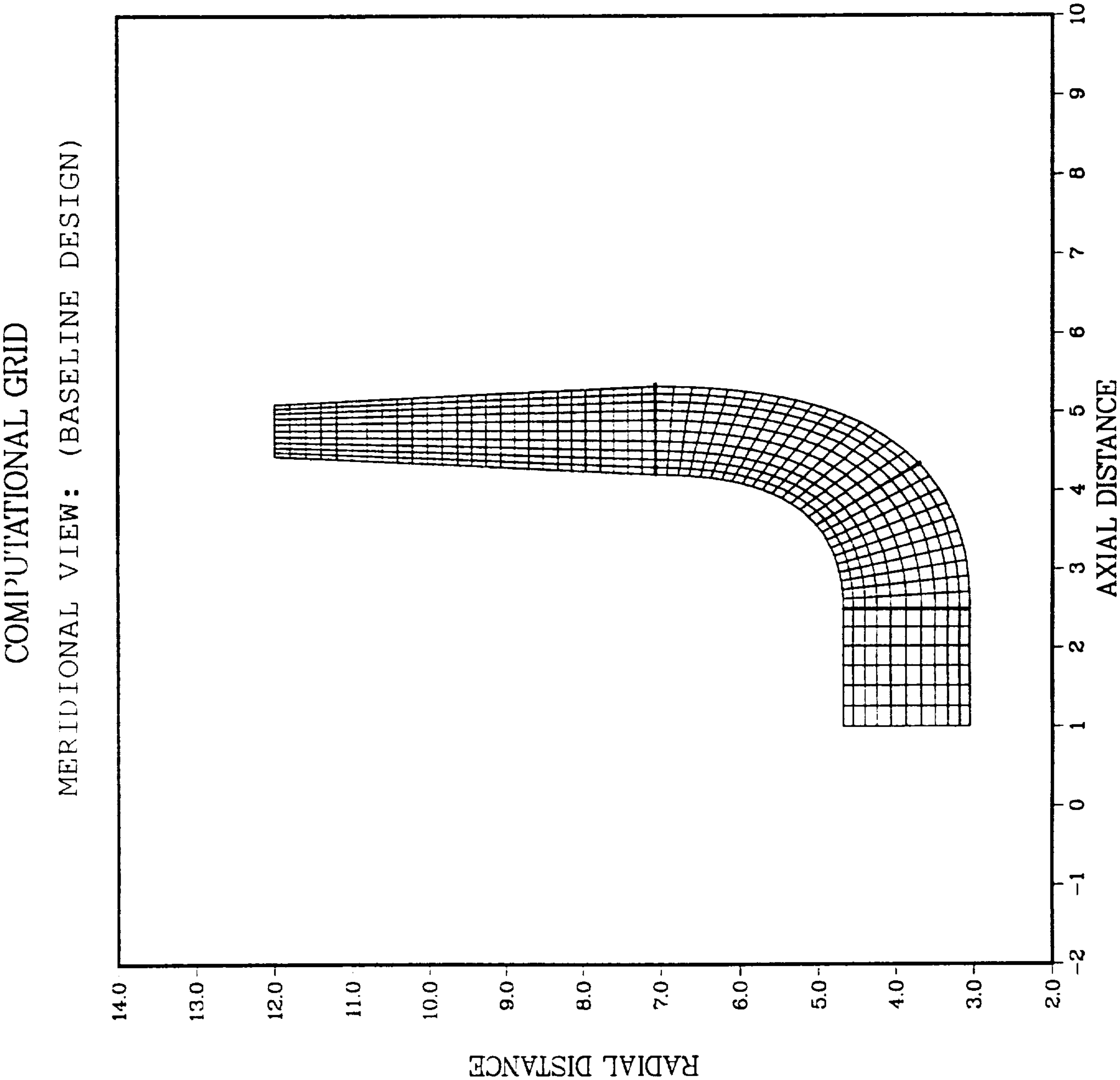

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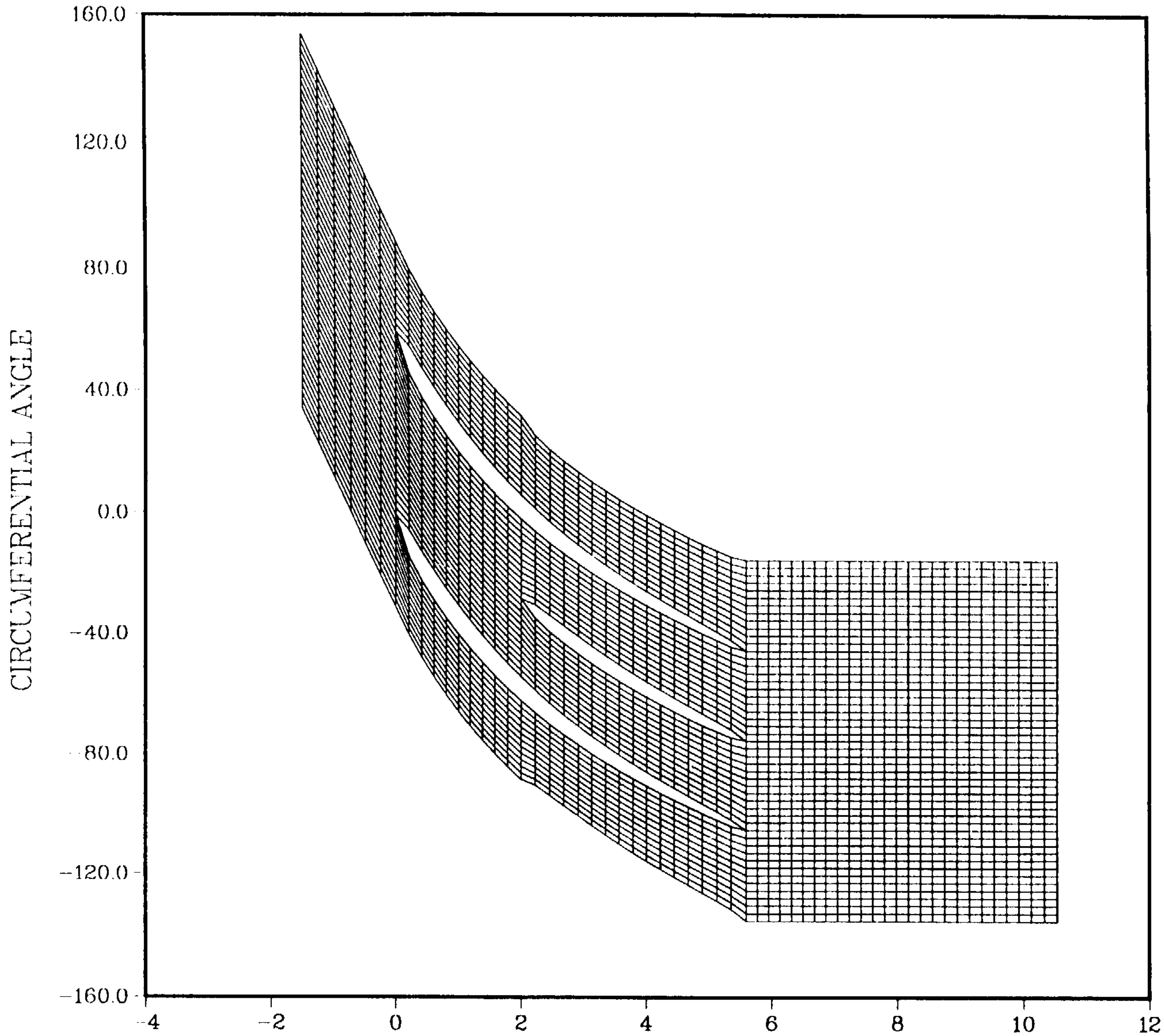
COMPUTATIONAL GRID

BASELINE DESIGN



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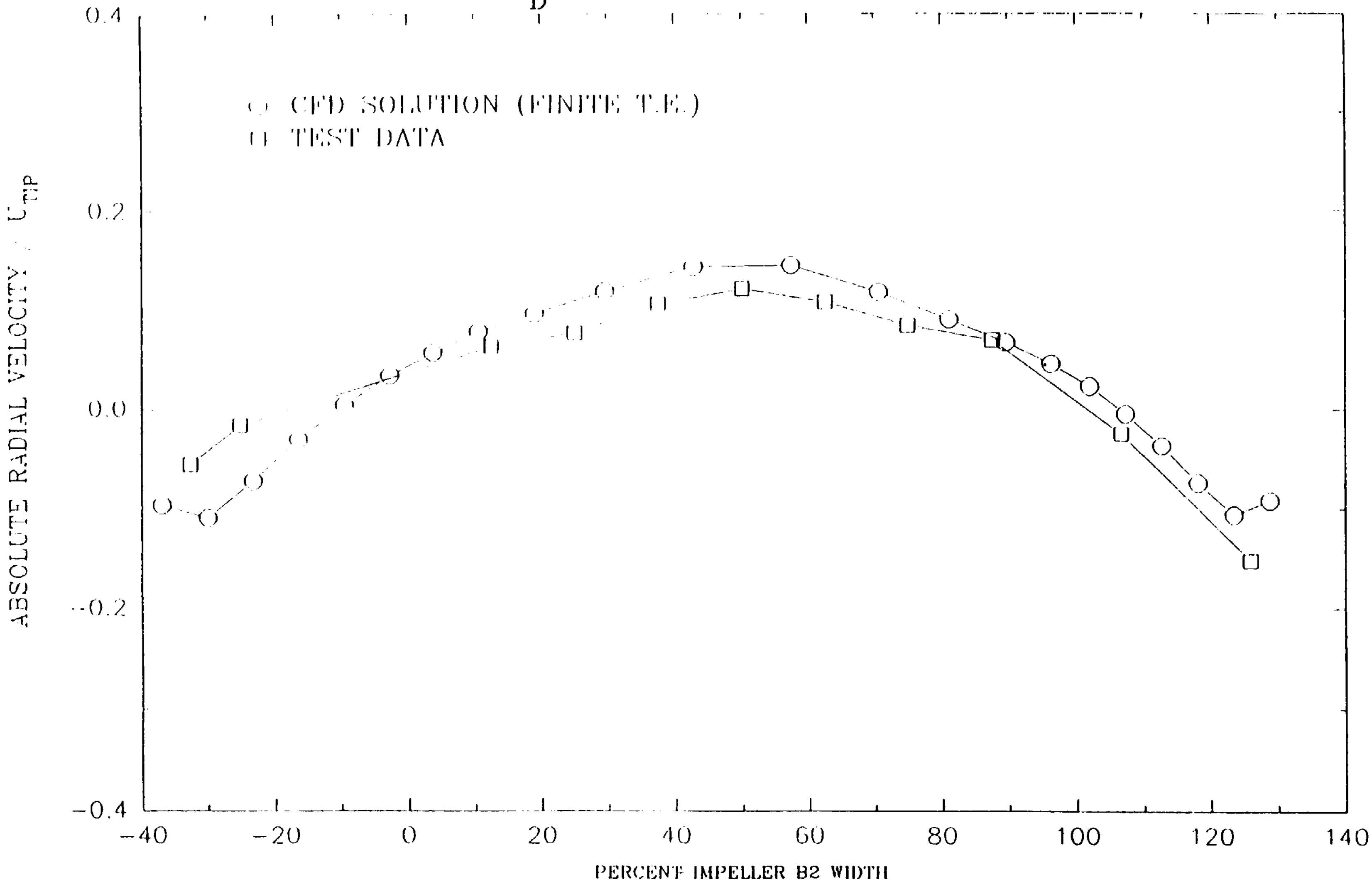
COMPARISON OF CFD SOLUTION TO TEST DATA
AVERAGED ABSOLUTE RADIAL VELOCITY
PLANE 1, $Q_D = 100\%$, RADIUS=4.700 INCH



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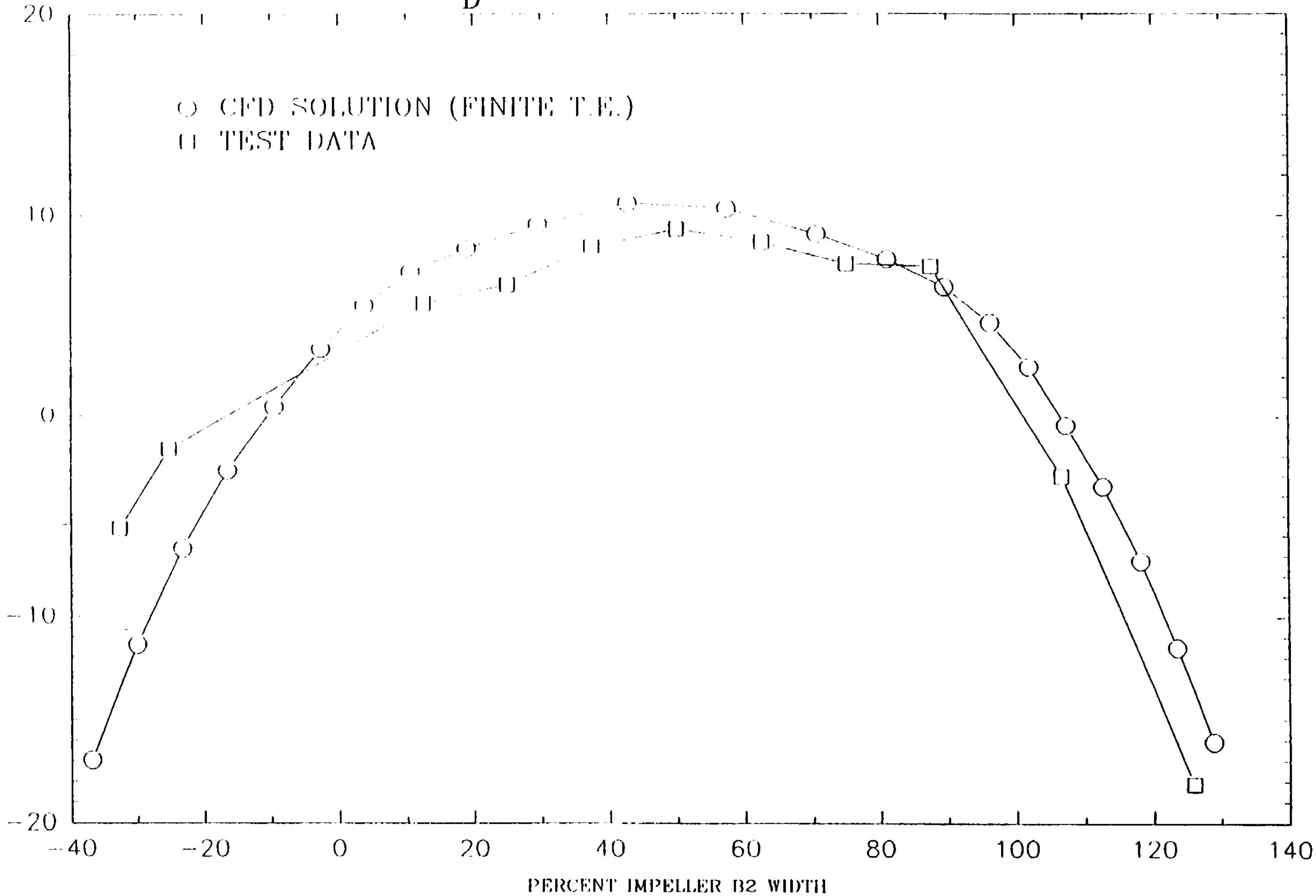
COMPARISON OF CFD SOLUTION TO TEST DATA
AVERAGED ABSOLUTE FLOW ANGLE
PLANE 1, Q_D=100%, RADIUS=4.700 INCH



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OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

- TANDEM BLADE APPROACH
  - CUT 1 (TANDEM LOCATE AT BLADE L.E.)
  - CUT 2 (TANDEM LOCATE AT MIDSECTION OF BLADE)
  - CUT 3 (TANDEM LOCATE NEAR T.E. OF BLADE)

- TANDEM BLADE CFD RESULTS
  - MINIMUM PERFORMANCE IMPROVEMENT WITH LARGE ADDITIONAL BLADE FABRICATION COMPLEXITY
  - CUT 1 MORE EFFECTIVE THAN CUT 2 AND CUT 3 TO CONTROL FLOW
  - SMALL CLOCKING ANGLE MORE BENIFICIAL THAN LARGE CLOCKING ANGLE
  - DETAILED CFD RESULTS PRESENTED IN OCTOBER, 1992 NASA CONSORTIUM MEETING
  - INDEPENDENT ANALYSIS IN WORK TO CONFIRM RESULTS

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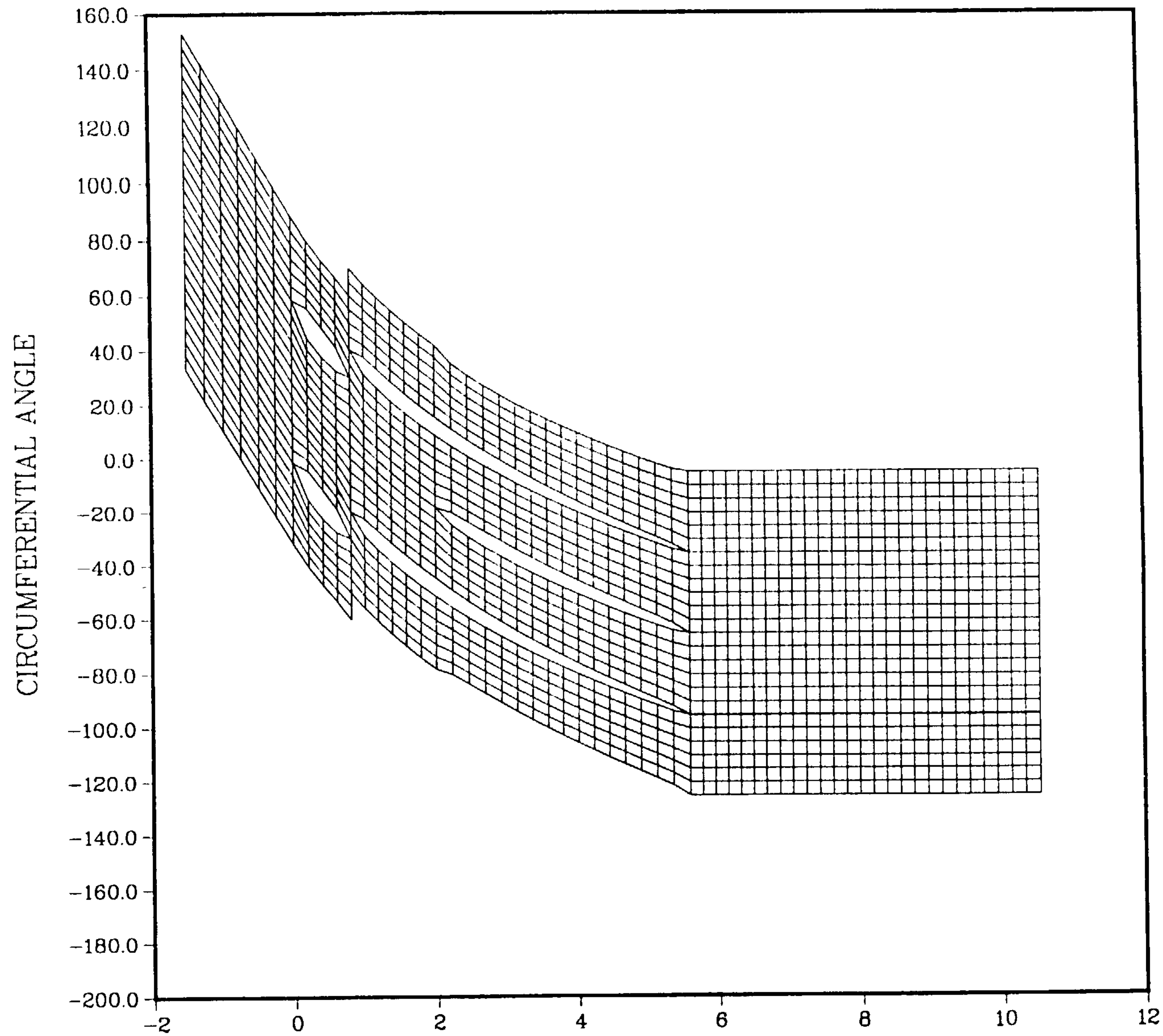
TANDEM BLADE: (CUT 1)



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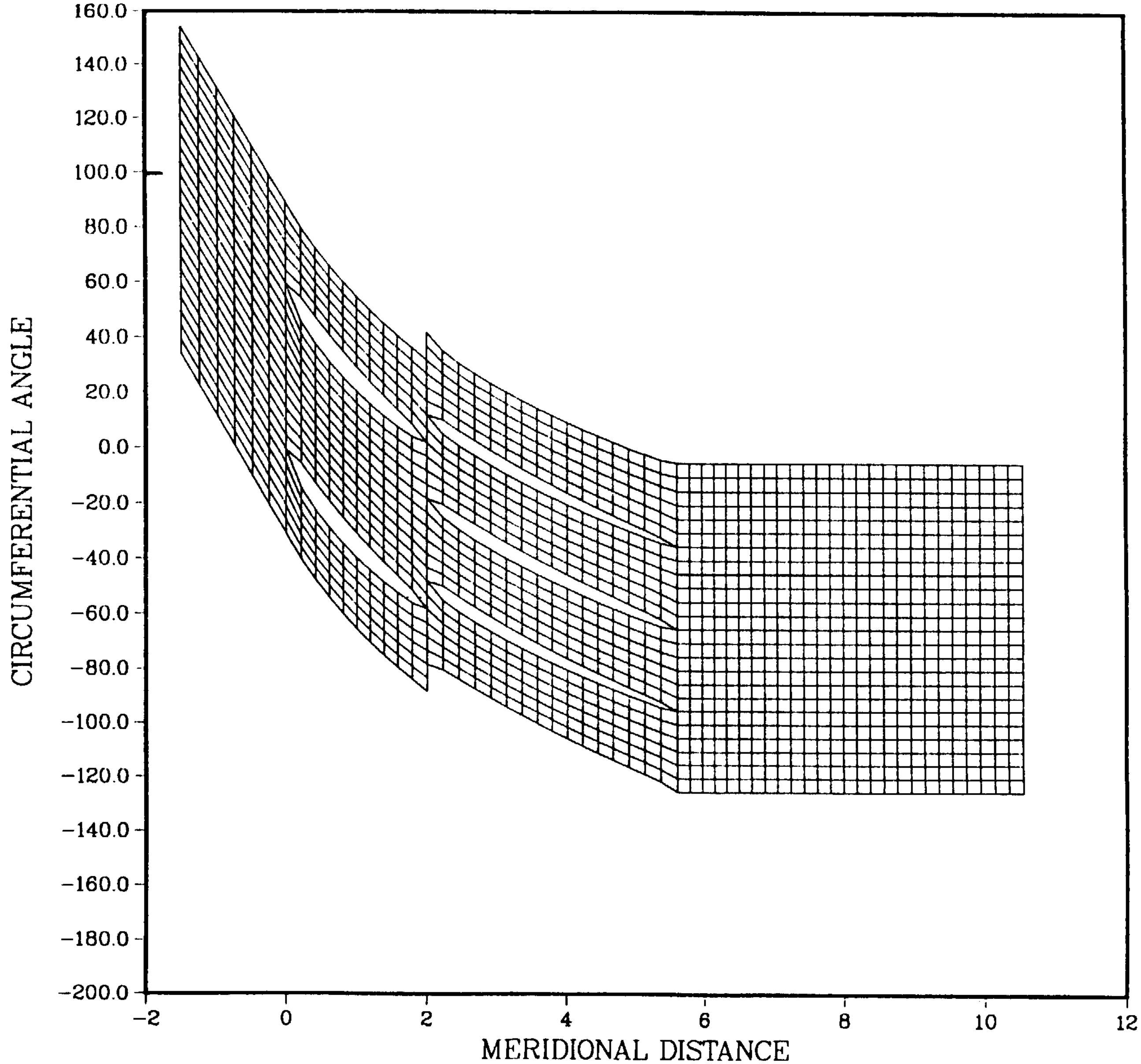
TANDEM BLADE: (CUT 2)



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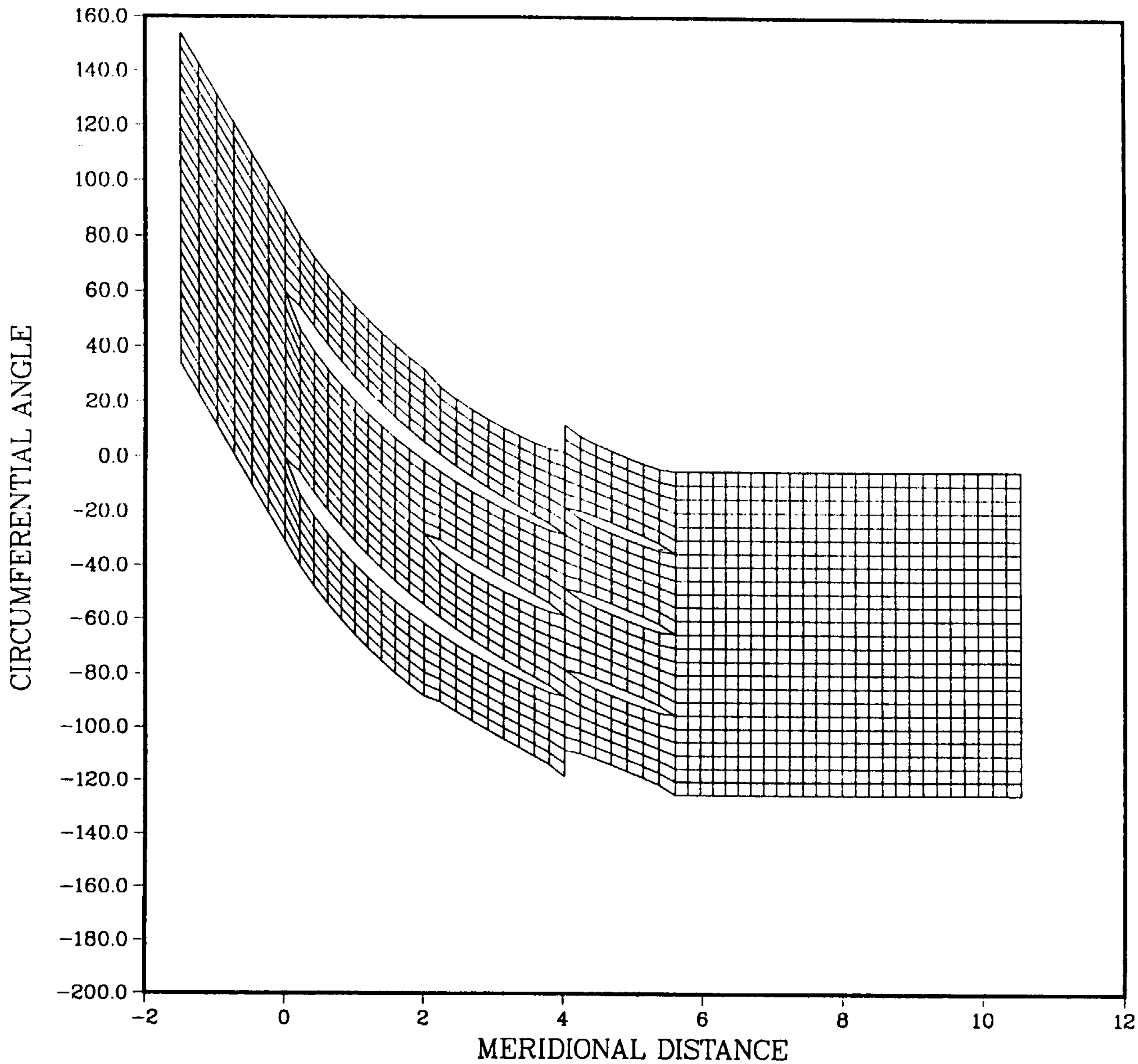
COMPUTATIONAL GRID

TANDEM BLADE: (CUT 3)



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OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

- CONTROL OF IMPELLER BLADE LOADING FROM L.E. TO T.E.
  - REDISTRIBUTE BLADE LOADING BUT PRESERVE BASELINE BLADE CONTOUR
    - BASB, UNLOAD AT L.E. AND T.E. BUT INCREASE LOADING AT MID-SECTION
    - BASC, INCREASE BLADE LOADING AT L.E. AND T.E. BUT UNLOAD AT MID-SECTION
    - BASG, L.E. LOADED
    - BASH, T.E. LOADED
  - CHANGE IMPELLER MERIDIONAL CONTOUR WITH B2 WIDTH REDUCED BY 20%
    - 3 AXIAL LENGTHS (3.87, 3.40, 2.82) ALL WITH DISCHARGE BLADE ANGLE 41.5 (GOOX, GOOY, GOOZ)
    - 3 AXIAL LENGTHS (3.87, 3.40, 2.82) ALL WITH DISCHARGE HUB BLADE ANGLE 50 DEGREE AND TIP BLADE ANGLE 35 DEGREE (GOOF, GOOH, GOOK)

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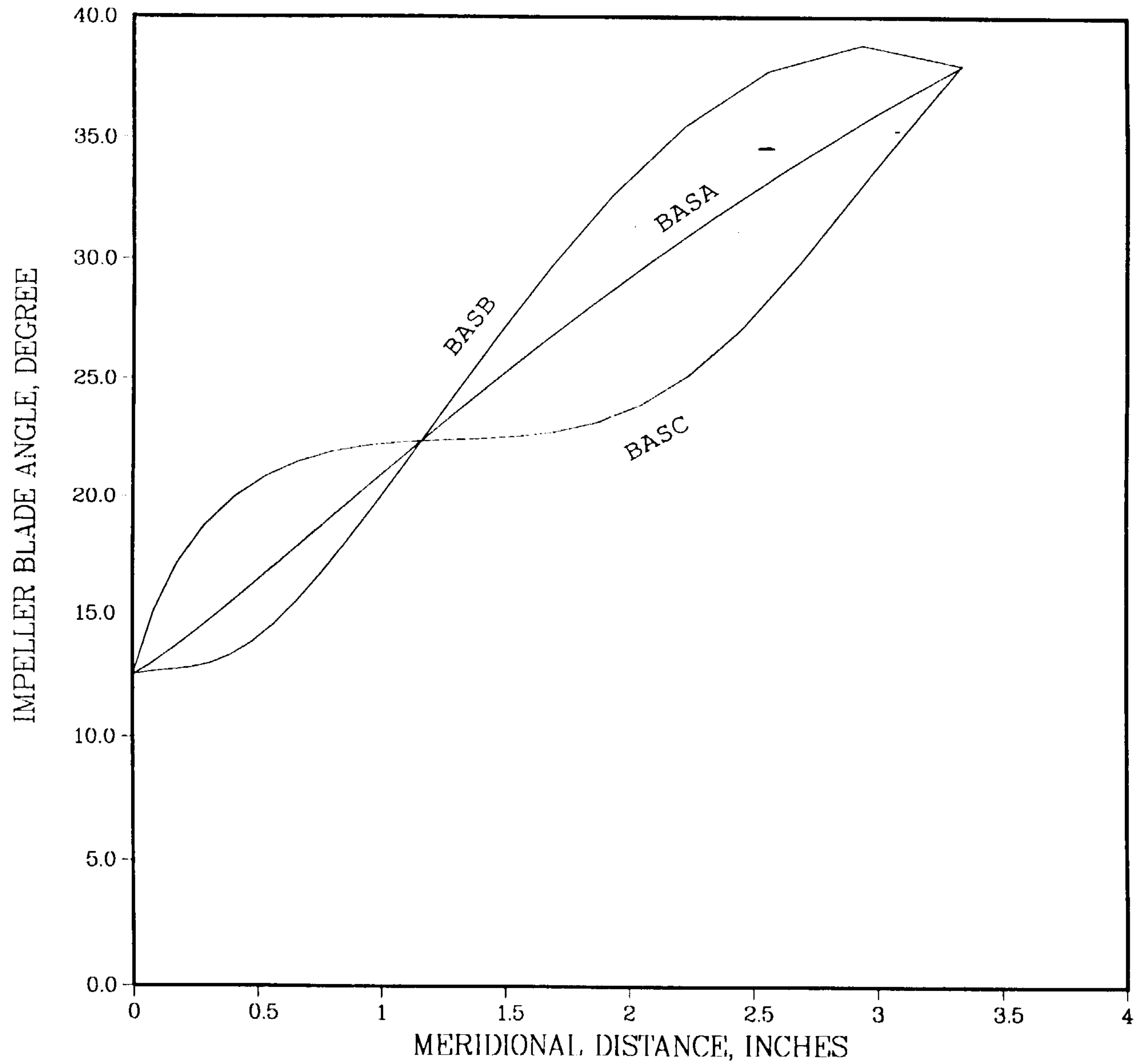
NASA CONSORTIUM IMPELLER



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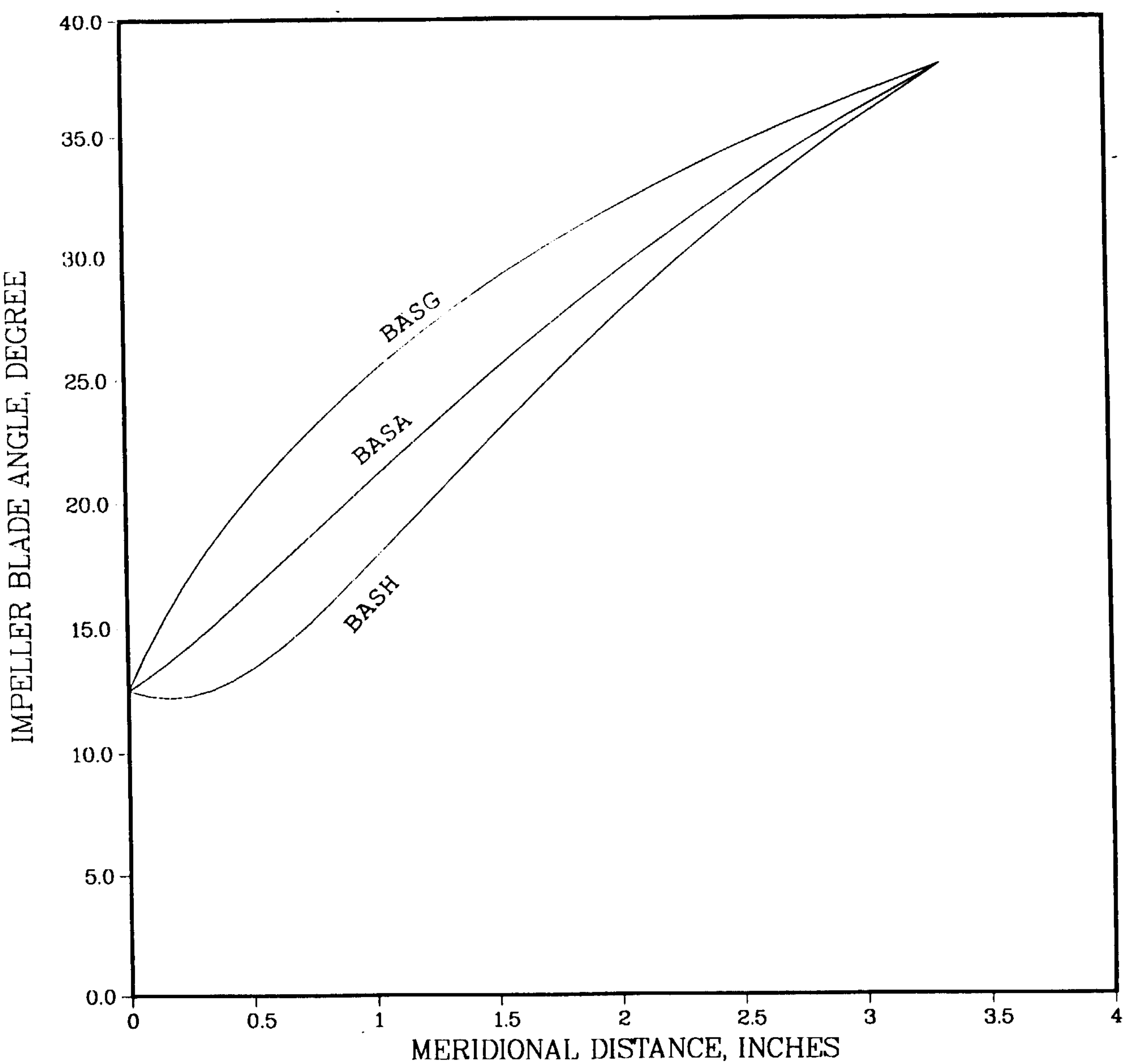
NASA CONSORTIUM IMPELLER



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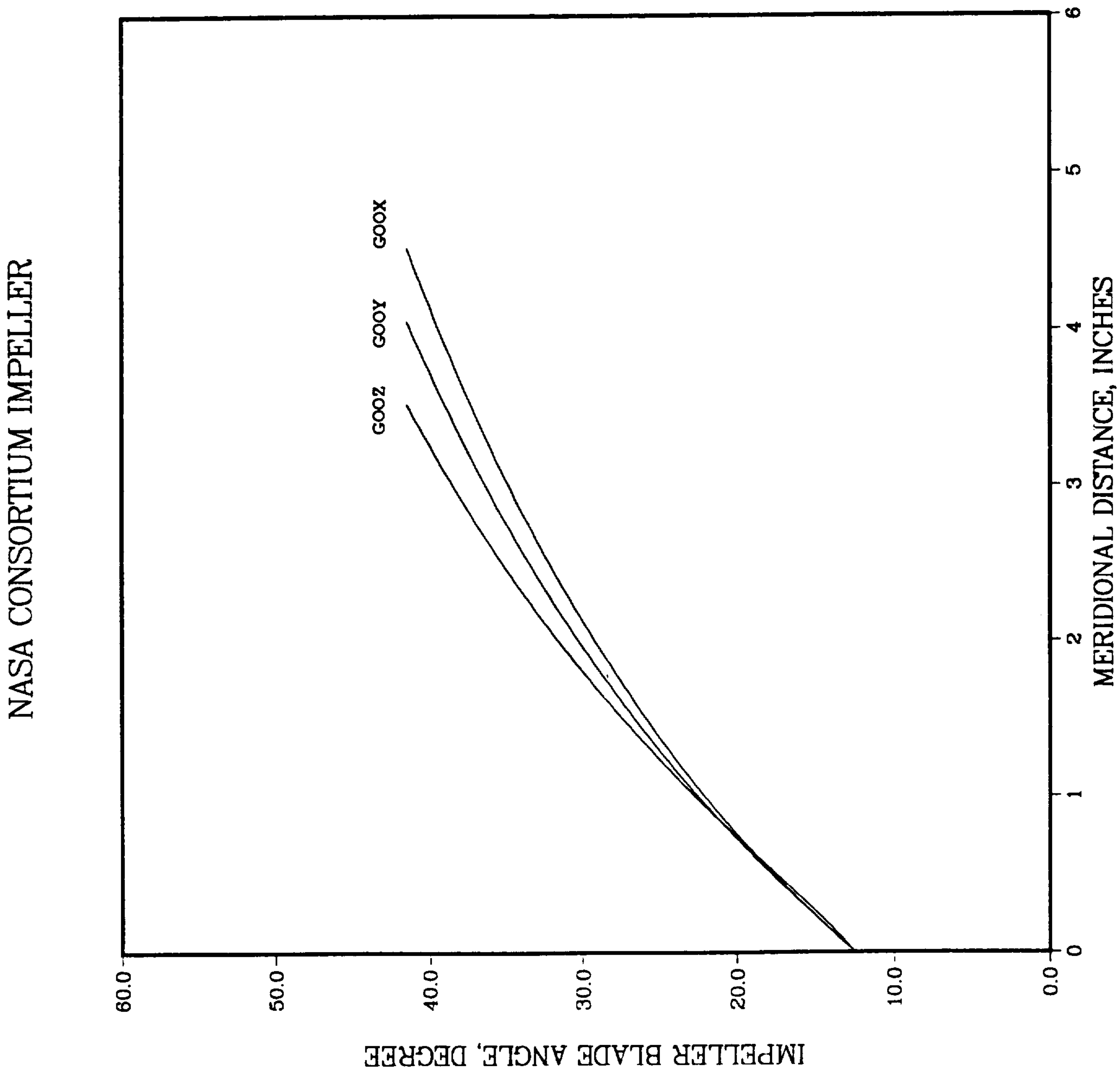

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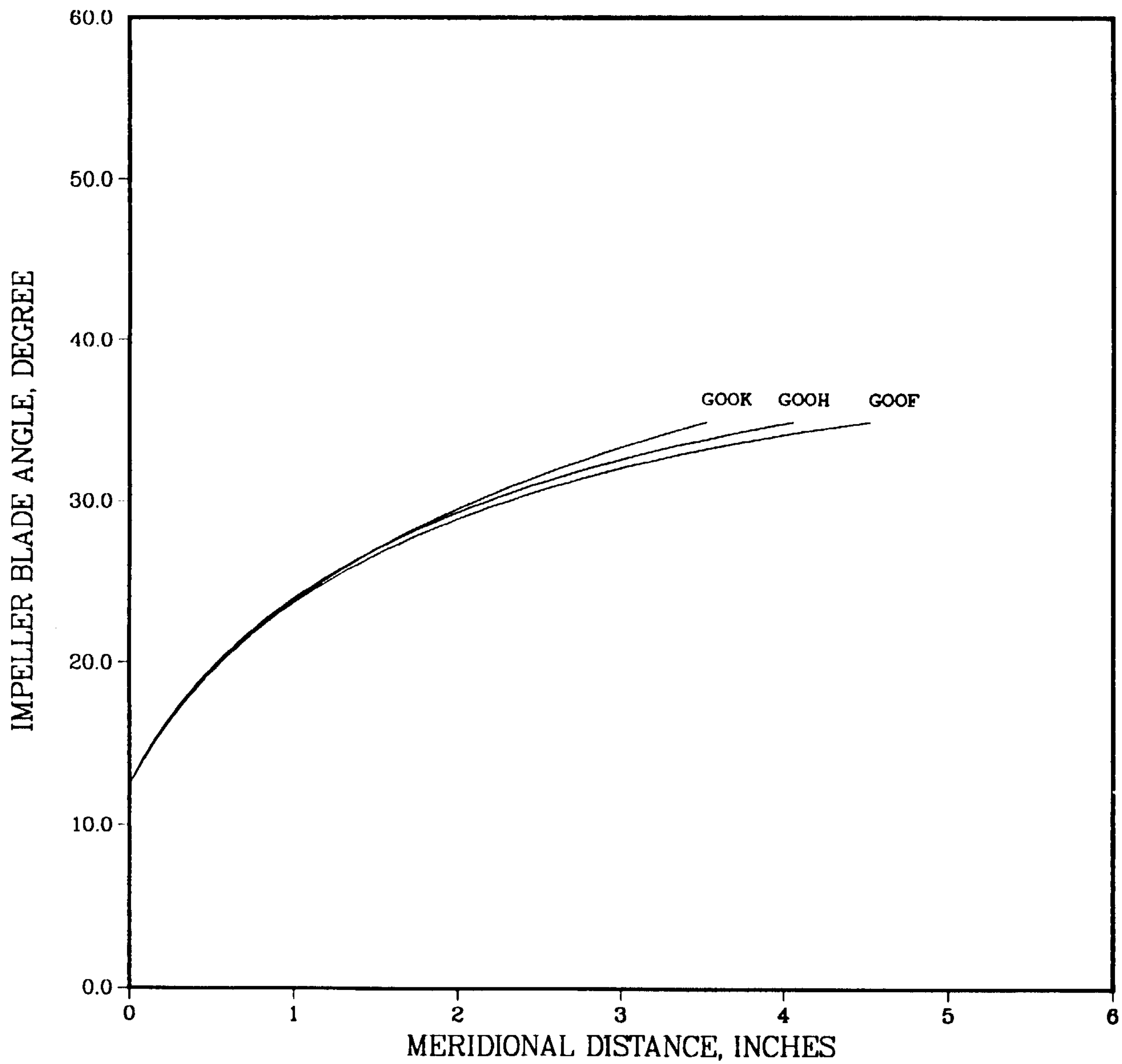
NASA CONSORTIUM IMPELLER



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OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

- RESULTS OF CFD ANALYSIS
  - NO SIGNIFICANT IMPACT ON IMPELLER OVERALL PERFORMANCE BY REDISTRIBUTING L.E. TO T.E. BLADE LOADING
  - REDUCED B2 INCREASES OUTLET RADIAL VELOCITY AND ELIMINATES REVERSE FLOW AND BLADE SUCTION SIDE SEPARATION
  - INCREASED AXIAL LENGTH IMPROVE IMPELLER EFFICIENCY UP TO 1% AND REDUCES BLADE TO BLADE DYNAMIC LOADING UP TO 18%
  - VARYING OUTLET BLADE ANGLE SLIGHTLY IMPROVES HUB TO TIP FLOW DISTORTION WITH NO IMPROVEMENT OF BLADE TO BLADE NONUNIFORMITY

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NASA CONSORTIUM IMPELLER PERFORMANCE

CASE / PERFORMANCE	BASA	BASB	BASC	BASG	BASH	GOOF	GOOH	GOOK	GOOX	GOOY	GOOZ
EFFICIENCY (%)	95.1	95.1	95.0	95.1	95.1	96.0	95.5	95.4	95.95	95.7	95.2
EULER HEAD (FT)	1329.8	1320.7	1337	1342.8	1329.2	1332.5	1332.9	1321.5	1336.3	1334.9	1326.4
INLET PT (PSI)	29.2	29.2	29.2	29.2	29.1	29.7	29.7	29.5	29.7	30.0	29.9
OUTLET PT (PSI)	576.1	572.4	578.7	581.5	575.5	582.9	580.2	571.7	584.1	582.3	576.3
HUB TO TIP FLOW DISTORTION (DEGREE)	3.00	3.08	3.15	1.80	3.00	2.72	2.46	2.39	3.53	2.94	2.53
BLADE TO BLADE DYNAMIC LOAD	0.78E4	0.77E4	0.79E4	0.81E4	0.74E4	0.71E4	0.75E4	0.79E4	0.64E4	0.68E4	0.77E4
FLOW SPLIT ZONE II, ZONE III	54.7 45.3	55.2 44.8	53.5 46.5	58.8 41.2	51.0 49.0	53.3 46.7	55.0 45.0	55.6 44.4	53.6 46.4	55.3 44.7	57.2 42.8
IMPELLER HEAD COEFF.	0.653	0.649	0.656	0.66	0.653	0.661	0.657	0.651	0.662	0.660	0.653
OUTLET FLOW SEPARATION	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO
OUTLET FLOW RECIRCULATION	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO

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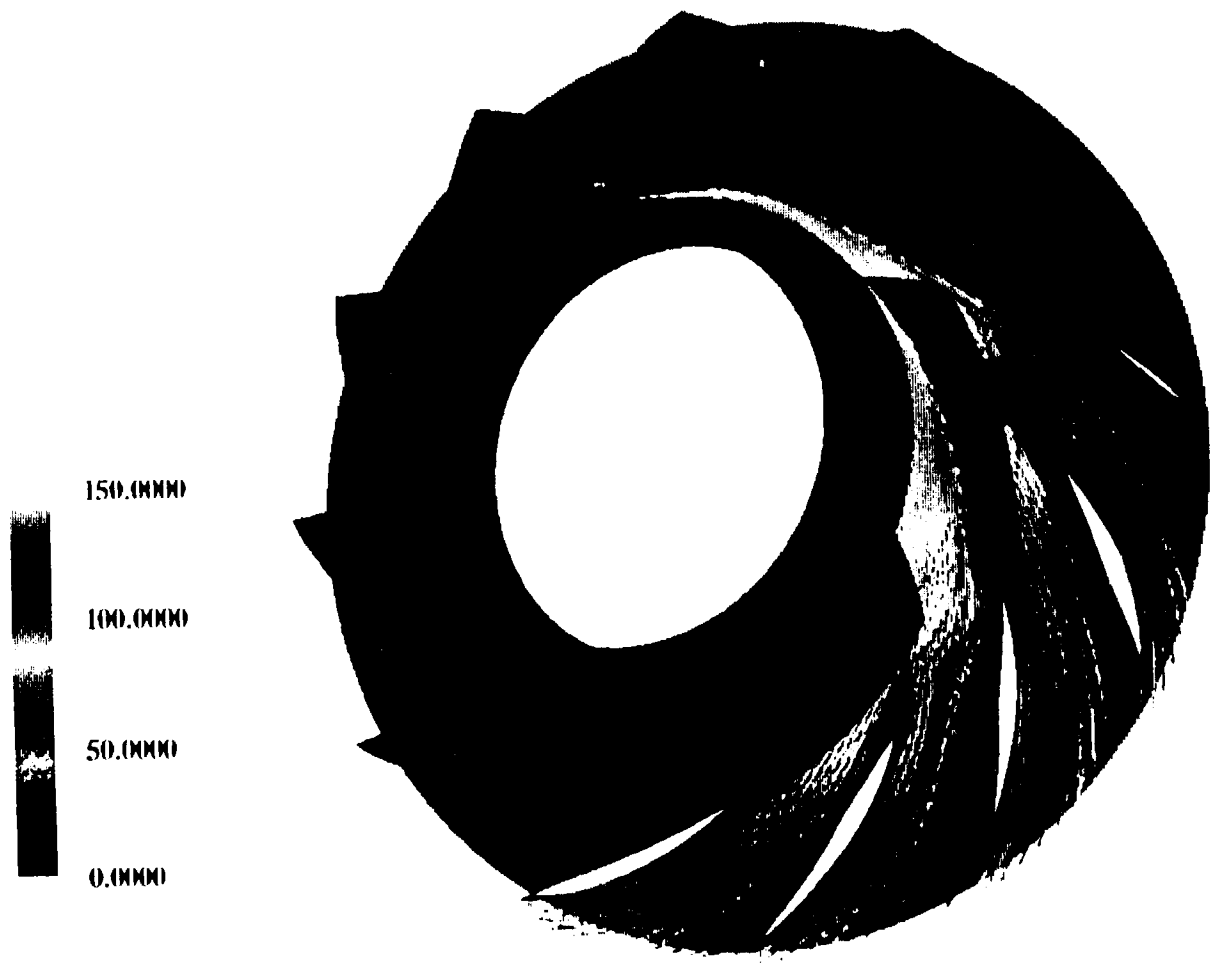
NASA CONSORTIUM IMPELLER

BASA

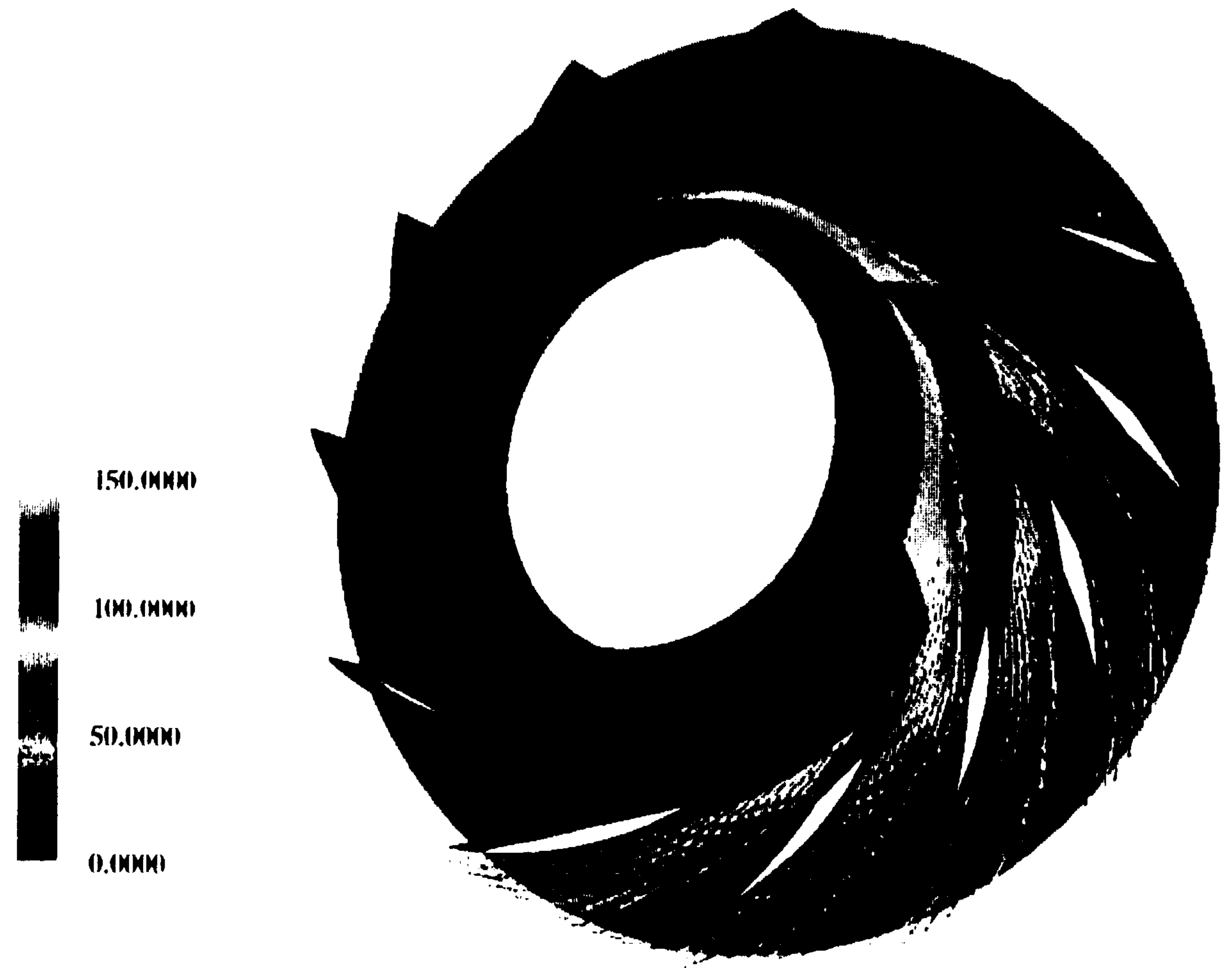
VELOCITY VECTORS IN MIDPLANE



NASA CONSORTIUM IMPELLER

BASH

VELOCITY VECTORS IN MIDPLANE



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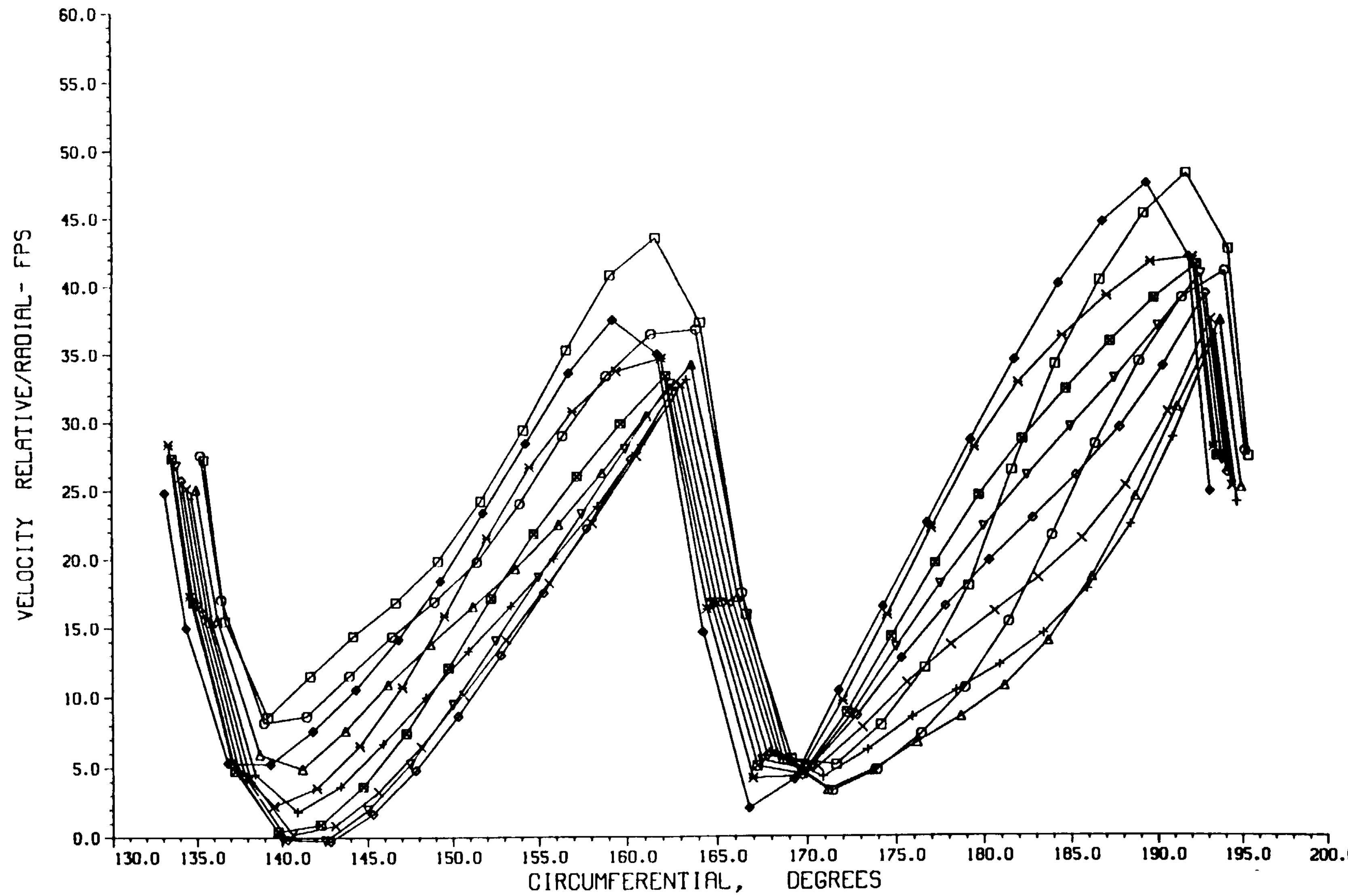
IMPELLER DISCHARGE RADIAL VELOCITY:

(BASELINE DESIGN)



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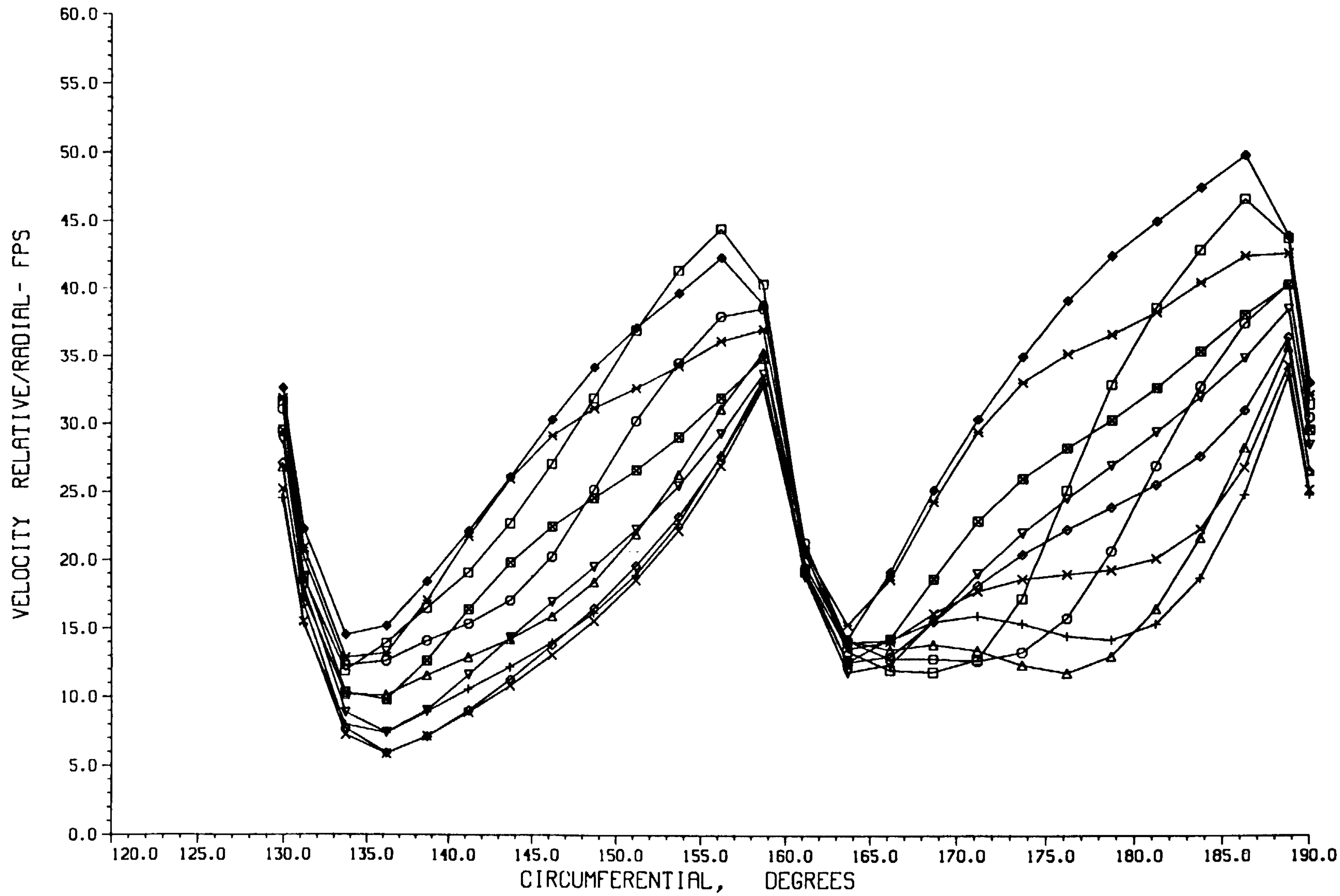
IMPELLER DISCHARGE RADIAL VELOCITY: (GOOX DESIGN)



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NASA CONSORTIUM IMPELLER PERFORMANCE

PERFORMANCE \ CASE	BASA	BASB	BASC	BASG	BASH	GOOF	GOOH	GOOK	GOOX	GOOY	GOOZ
EFFICIENCY (%)	$\boxed{95.1}$	95.1	95.0	95.1	95.1	96.0	95.5	95.4	$\boxed{95.95}$	95.7	95.2
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IMPELLER HEAD COEFF.	0.653	0.649	0.656	0.66	0.653	0.661	0.657	0.651	0.662	0.660	0.653
OUTLET FLOW SEPARATION	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO
OUTLET FLOW RECIRCULATION	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO

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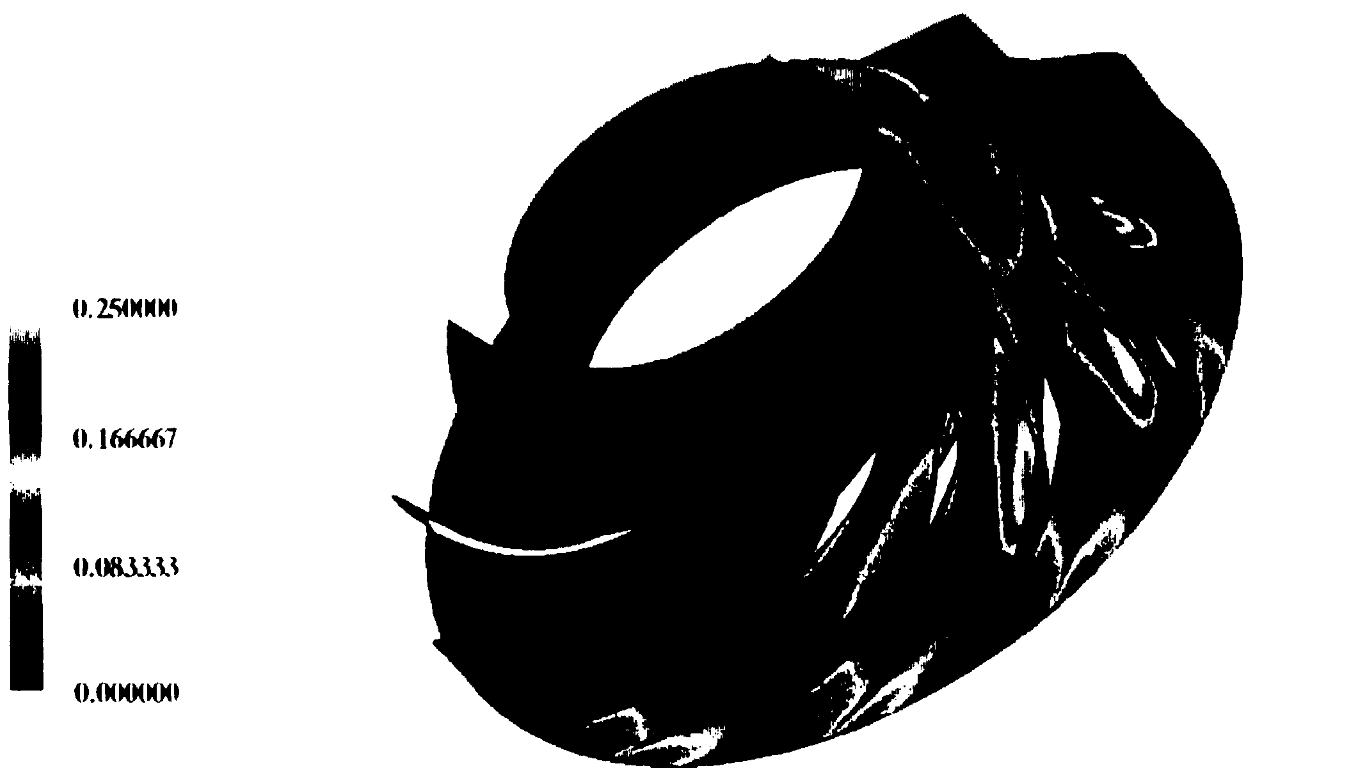
NASA CONSORTIUM IMPELLER

BASA

ROTARY STAGNATION PRESSURE   REDUCED STATIC PRESSURE



NASA CONSORTIUM IMPELLER

GOOF

ROTARY STAGNATION PRESSURE   REDUCED STATIC PRESSURE

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NASA CONSORTIUM IMPELLER PERFORMANCE

CASE PERFORMANCE	BASA	BASB	BASC	BASG	BASH	GOOF	GOOH	GOOK	GOOX	GOOY	GOOZ
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IMPELLER HEAD COEFF.	0.653	0.649	0.656	0.66	0.653	0.661	0.657	0.651	0.662	0.660	0.653
OUTLET FLOW SEPARATION	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO
OUTLET FLOW RECIRCULATION	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO

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OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

- CONCLUSION
  - CFD RESULTS SHOW MINIMAL PERFORMANCE IMPROVEMENT OF TANDEM BLADE CONFIGURATION FOR THIS HIGH HEAD COEFFICIENT AND HIGH EYE TO TIP RATIO
  - IMPELLER DISCHARGE REVERSE FLOW CAN BE CONTROLLED BY THE B2 WIDTH
  - THE IMPELLER EFFICIENCY AND EXIT FLOW DISTORTION CAN BE IMPROVED BY CONTROL OF THE IMPELLER AXIAL LENGTH
  - BASELINE DESIGN CAN BE FURTHER OPRIMIZED TO MEET STRUCTURAL AND HYDRODYNAMIC REQUIREMENT
    - PARTIAL BLADE SOLIDITY, PARTIAL BLADE POSITION, T.E. BLADE LEAN PENDING OTHER CONSORTIUM TEAM MEMBER RESULTS

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OPTIMIZATION OF A CENTRIFUGAL IMPELLER DESIGN THROUGH CFD ANALYSIS

TABLE I : DESCRIPTION OF CHANGES FOR EACH CASE

BASA: EXISTING BASELINE DESIGN WITH WATER TEST RESULTS

BASB: SAME BLADE ENVELOPE AS BASA WITH LARGER LOAD AT BLADE L.E. AND T.E. BUT SMALLER LOAD AT MID-SECTION

BASC: SAME BLADE ENVELOPE AS BASA WITH LARGER LOAD AT MID-SECTION, BUT SMALLER LOAD AT L.E. AND T.E.

BASG: SAME MERIDIONAL CONTOUR AS BASA WITH HEAVY LOAD AT L.E. AND GRADUAL UNLOADING TOWARD T.E.

BASH: SAME MERIDIONAL CONTOUR AS BASA WITH VERY SMALL LOAD AT L.E. AND GRADUAL INCREASE IN LOADING TOWARD T.E.

GOOF: INCREASE AXIAL LENGTH BY 37%, REDUCE B2 BY 20% AND CHANGE OUTLET BLADE ANGLE FROM HUB=50 TO TIP=35

GOOH: INCREASE AXIAL LENGTH BY 20%, REDUCE B2 BY 20% AND CHANGE OUTLET BLADE ANGLE FROM HUB=50 TO TIP=35

GOOK: NO CHANGE OF AXIAL LENGTH, REDUCE B2 BY 20% AND CHANGE OUTLET BLADE ANGLE FROM HUB=50 TO TIP=35

GOOX: INCREASE AXIAL LENGTH BY 37%, REDUCE B2 BY 20% AND USE CONSTANT OUTLET BLADE ANGLE 41.5

GOOY: INCREASE AXIAL LENGTH BY 20%, REDUCE B2 BY 20% AND USE CONSTANT OUTLET BLADE ANGLE 41.5

GOOZ: NO CHANGE OF AXIAL LENGTH, REDUCE B2 BY 20% AND USE CONSTANT OUTLET BLADE ANGLE 41.5

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NASA CONSORTIUM IMPELLER GEOMETRY

CASE / GEOMETRY	BASA	BASB	BASC	BASG	BASH	GOOF	GOOH	GOOK	GOOX	GOOY	GOOZ
AXIAL LENGTH (INCH)	2.82	2.82	2.82	2.82	2.82	3.87	3.40	2.82	3.87	3.40	2.82
B2 WIDTH (INCH)	1.12	1.12	1.12	1.12	1.12	0.90	0.80	0.90	0.90	0.90	0.90
HUB WRAP (DEGREE)	0~105	0~105	0~105	0~91	0~114	0~100	0~90	0~80	0~100	0~90	0~80
TIP WRAP (DEGREE)	20~103	20~103	20~103	20~91	20~114	0~100	0~90	0~80	0~100	0~90	0~80
OUTLET LEAN (DEGREE)	16	20	14	0	0	0	0	0	0	0	0
HUB OUTLET BLADE ANGLE	38	38	38	38	38	50	50	50	41.5	41.5	41.5
TIP OUTLET BLADE ANGLE	38	38	38	38	38	35	35	35	41.5	41.5	41.5
HUB INLET BLADE ANGLE	20	20	20	20	20	20	20	20	20	20	20
TIP INLET BLADE ANGLE	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5

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