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REDESIGN AND TEST OF AN SSME TURBOPUMP FOR THE LARGE THROAT MAIN COMBUSTION CHAMBER

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Abstract

The preburner oxidizer turbopump for the Space Shuttle Main Engine (SSME) was successfully redesigned for use with the Large Throat Main Combustion Chamber (LTMCC) and tested in air utilizing rapid prototyping. The redesign increases the SSME's operating range with the current Main Combustion Chamber (MCC) while achieving full operational range with the LTMCC. The use of rapid prototyping and air testing to validate the redesign demonstrated the ability to design, fabricate, and test designs rapidly and at a very low cost.

Nomenclature

A	Area
b_2	Impeller discharge axial width
C_m	Meridional velocity
D_t	Impeller discharge diameter
H	Shape factor
N	Turbopump Speed
Q	Flow rate
U_t	Impeller tip speed
ϕ	Impeller discharge flow parameter
ϕ_{cr}	Impeller discharge flow parameter at stall
$\Delta\phi_{MCC}$	Decrease in design flow parameter due to change in MCC
$\Delta\phi_{MFG}$	Decrease in design flow parameter due to manufacturing variations
σ_1	Boundary layer displacement thickness
σ_2	Boundary layer momentum thickness

Background

The SSME utilizes a staged combustion cycle in order to maximize the engine's specific impulse (Figure 1). A preburner provides high temperature, high pressure fluid to drive the High Pressure Fuel and High Pressure Oxidizer Turbopumps (HPFTP and HPOTP respectively). The oxidizer for the preburners is provided by a preburner pump (PBP) which increases the HPOTP discharge pressure to the preburner inlet pressure. On the SSME, the preburner pump is attached to the shaft of the HPOTP (Figure 2). Therefore, the PBP flow rate is linked to the HPFTP and HPOTP power requirements and its speed is determined by the HPOTP.

The throat area of the current Phase II MCC is being enlarged to reduce the SSME's chamber pressure while maintaining its thrust capability. Increasing the throat area results in lower turbomachinery discharge pressures while maintaining the current flow rate requirements. Therefore, the HPFTP and HPOTP operate at lower speeds and require less power with the LTMCC than with the Phase II MCC. This results in lower PBP flow rates and lower speeds for the same engine thrust level.

During the shuttle ascent, each SSME is throttled from 65% to 104% of the designed thrust level. While hot fire testing of a SSME engine with a LTMCC, a bi-stable operation occurred at a power level of 67%. Bi-stability results in rapid changes in the chamber pressure (Figure 3); has been observed with the current MCC at power levels of 65%; and has been attributed to a preburner pump stall condition. Bi-stability occurs when the MCC pressure rapidly oscillates. The source of this oscillation is stalling of the PBP.

When the preburner pump stalls, its discharge pressure suddenly decreases. This decreases the power to the high pressure turbopumps which decreases the combustion chamber pressure. Attempting to maintain the thrust requirements, the SSME controller (which controls the engine valve positions) increases the preburner flow rate to increase the high pressure turbopump's input power and discharge pressure (Figure 4). The increase in

PBP flow rate causes the PBP to unstall which rapidly increases the PBP discharge pressure; the high pressure turbopump power; and the chamber pressure. The chamber pressure increases beyond the desired value and the controller responds by decreasing the PBP flow rate. This causes the PBP to resume a stalled condition. This cycle is known as bi-stability.

Air testing of several preburner turbopumps in the early 1980's demonstrated that the cause of the turbopump stall is the preburner pump diffuser. Therefore, a task to eliminate the stall over the range of the LTMCC by redesigning the preburner pump diffuser was initiated.

Redesign Objectives

The design objectives were to operate the preburner pump at the 63% power level for the LTMCC while maintaining the current turbopump operating characteristics at the 109% power level for the Phase II MCC. The 63% power level objective is based on the requirement that the SSME engine operate on a test stand with 2% power level margin from the minimum mission power level of 65%. In addition, the SSME engine must be able to operate at 109% power level in the case of an engine shut-down during ascent.

Analytical Approach

Although the vaned diffuser had been identified as the source of stall, the stall mechanism had not been determined. Two possible sources of stall were considered: 1) leading edge stall and 2) stall due to boundary layer separation. Both stall mechanisms were analyzed and used to determine new diffuser designs.

The leading edge stall model used was developed for vaned diffuser and anchored to experimental data for conical diffusers. [1] The incidence angle at which stall occurs is a function of the leading edge blade angle (Figure 5). Calculating the diffuser incidence angle requires knowing the impeller discharge absolute flow angle, and determining the effects of boundary layer blockage and blade blockage on the diffuser inlet flow area. Calculation of these parameters is performed with Rocketdyne's proprietary centrifugal pump performance code. This program was used to design the diffuser's leading edge blade angle, inlet blade height, and leading edge blade thickness. Also, the effect of the trailing edge thickness and discharge blade height on performance is determined with this code.

The second stall mechanism was analyzed using a potential flow method to predict the velocity profile adjacent to the airfoil and a boundary layer code to determine if boundary layer separation has occurred. [2,3] Since the PBP diffuser includes an increase in axial length from the inlet to the discharge, a streamtube thickness distribution was used to perform a quasi 3-D analysis. The boundary layer was defined as separated when the shape factor was greater than 2.4 at a distance less than 90% of the blade surface length. The shape factor is defined as follows:

$$H = \frac{\sigma_1}{\sigma_2}$$

A vane geometry profile code generated the vane designs and was rapidly analyzed with the potential flow code to determine the pressure distribution and the boundary layer code to determine if the flow separated. Since the PBP performance and operating point where leading edge stall occurs is a function of the blade leading edge thickness, an iteration between the resulting vane geometry and the performance code was required.

Redesign Requirements

The SSME engine system model calculates the operating parameters for the entire engine system for each power level. This model was used to evaluate the impact on the preburner pump of using the LTMCC. From the engine system model, it was determined that the preburner pump must operate at a lower impeller discharge flow parameter. The impeller discharge flow parameter is defined as:

$$\phi = \frac{C_m}{U_t} = \frac{Q}{AU_t}$$

where $A = \pi D_t b_2$
$U_t = ND_t$

Therefore:

$$\phi \propto \frac{Q}{N}$$

The operating requirements at the 63% and 109% for both the current Phase II MCC and the LTMCC are listed in Table 1.

	Phase II MCC		Large Throat MCC	
	63% Thrust	109% Thrust	63% Thrust	109% Thrust
Q (GPM)	291.3	699.0	270.2	657.2
N (RPM)	18,923	29,141	18,643	28,969
ϕ	0.058	0.090	0.054	0.085

Table 1 - Operating Requirements of the Preburner Turbopump

This results in the following redesign requirements:

Power Level	Phase II MCC	LTMCC	$\Delta\phi$
63%	0.058	0.054	0.004
109%	0.090	0.085	0.005

Table 2 - Impeller Discharge Flow Parameter, ϕ

In order to achieve the design objectives, the impeller flow parameter at which stall occurs (ϕ_{cr}) must be decreased by 0.004 for the 63% power level. A value of 0.005 was used for the redesign to provide margin. Based on engine test data and prior air test experience, an additional 0.005 decrease in ϕ_{cr} is required to account for manufacturing variations. Thus, the redesign requirement is:

$$\Delta\phi_{CR} = \Delta\phi_{MCC} + \Delta\phi_{MFG} = 0.005 + 0.005 = 0.010$$

Baseline Impeller Diffuser Design

Two diffuser designs were completed and tested for use with the baseline 5.0" diameter impeller. The diffuser inlet geometry was designed using the performance analysis program. For the first diffuser redesign, the leading edge blade angle was decreased by 1° and the inlet blade height was decreased until ϕ_{cr} was decreased by 0.010. This resulted in a 0.218" inlet blade height compared to 0.250" for the baseline diffuser design. Then the potential flow and boundary layer codes were used to determine the blade thickness profile. The blade profile for the first redesign is thicker than the current diffuser design and the wrap angle is slightly larger (Figure 6). The pressure (Figure 7) and shape factor distributions (Figure 8) for $\Delta\phi_{cr}$ of 0.010 give an attached boundary layer on both the pressure and suction surfaces.

For the second diffuser design, the inlet blade height was held at 0.250" and the inlet blade angle was decreased until ϕ_{cr} was decreased by 0.010. Again, the leading edge blade thickness and blade thickness distribution were increased over the current diffuser design (Figure 9). Similar to redesign #1, the potential flow and boundary layer analysis codes were used to obtain this blade profile.

Parameter	Current Design	First Redesign	Second Redesign
Leading Edge Radius from centerline	2.712"	2.710"	2.710"
Inlet Blade Angle (from tangential)	9.92°	8.92°	8.15°
Inlet Blade Height	0.250"	0.218"	0.250"
Inlet Blade Thickness	0.050"	0.058"	0.061"
Wrap Angle	52.3°	55.7°	54.8°
Throat Area	0.0686 in^2	0.0550 in^2	0.0535 in^2
Trailing Edge Radius from centerline	3.41"	3.41"	3.41"
Discharge Blade Angle (from tang.)	10.8°	10.8°	10.8°
Discharge Blade Height	0.345"	0.345"	0.345"
Discharge Blade Thickness	0.100"	0.128"	0.106"
Blade Number	11	11	11

Table 3 - Preburner Turbopump Diffuser Design Parameters

Increasing the operating range of the PBP required redesigning the diffuser with zero incidence at a lower ϕ (engine thrust level) than the baseline diffuser design (Figure 10). This causes an increase in incidence at the higher thrust levels; an increase in diffuser pressure loss; and a lower pump discharge pressure. This was confirmed with the performance analysis code. Thus, the penalty of wide flow operation is larger diffuser pressure losses at the higher flow rates.

Currently, there is an engine system requirement of 7515 psia PBP discharge pressure at the Phase II MCC 109% power level. This requirement is occasionally violated with the current design and requires analysis of the pressure drop in the preburner valves before the turbopump is accepted. Since a single-component (diffuser only) design change minimizes the cost to implement the design change, the redesigned diffusers were tested to quantify the impact of the redesign on the engine system.

Air Test Approach

Air testing was selected as a method of validating the redesigned diffusers performance with respect to the stall point and pressure rise at Phase II MCC 109% power level. The current diffuser and the redesigned diffusers were fabricated using rapid prototyping in order to reduce fabrication time and lower testing cost.[4] These diffuser were tested using a metal volute and impeller. The air test results confirmed that diffuser redesigns #1 and #2 shifted ϕ_{cr}. They also showed that the pressure at the Phase II MCC 109% power level decreased (Figure 11).

Modified Impeller Diffuser Design

Based on the test data, the redesigned diffusers required changing the engine system requirements. Therefore, alternative designs were evaluated. Obtaining the same PBP discharge pressure as the baseline design required increasing the impeller tip diameter and designing a third diffuser (a two-component change).

The gap between the impeller discharge and the diffuser inlet acts as a mixing zone for the impeller blade wakes.[3] This mixing can significantly suppress pressure-perturbation effects caused by passage of the impeller past the stationary diffuser vanes. The diffuser leading edge radial location was determined to maintain the dynamic pressure environment and achieve the pressure rise of the current impeller/diffuser. The performance code determined that a 0.125" increase in diffuser inside diameter and a 0.145" increase in impeller diameter would achieve the current impeller/diffuser discharge pressure at the Phase II MCC 109% power level (Figure 12).

By using rapid prototyping, a polycarbonate ring was manufactured and epoxied to the baseline impeller providing an innovative, low cost method of increasing the impeller diameter. Again, the resulting design has a blunt leading edge and an increased blade thickness distribution compared to the baseline diffuser

(Figure 13). Since the diffuser leading edge was radially increased, the axial length from the inlet to the discharge was reduced to achieve the required pressure and boundary layer profile. Table 4 compares the baseline design to the final diffuser redesign configuration.

Parameter	Baseline Design	Final Redesign
Leading Edge Radius from centerline	2.712"	2.774"
Inlet Blade Angle (from tangential)	9.92°	8.35°
Inlet Blade Height	0.250"	0.250"
Inlet Blade Thickness	0.050"	0.080"
Wrap Angle	52.3°	54.1°
Throat Area	0.0686 in^2	0.0509 in^2
Trailing Edge Radius from centerline	3.41"	3.41"
Discharge Blade Angle (from tang.)	10.8°	10.8°
Discharge Blade Height	0.345"	0.335"
Discharge Blade Thickness	0.100"	0.100"
Blade Number	11	11

Table 4 - Preburner Turbopump Diffuser Redesigns

The final diffuser redesign with the 5.145" diameter impeller meet all design objectives (Figure 14). The impeller discharge flow parameter at which stall occurs was decreased by 0.008-0.013 versus the targeted value of 0.010 and the pressure rise at the Phase II MCC 109% power level matched the baseline impeller/diffuser design. This also demonstrated the centrifugal pump performance program's capability to determine turbopump performance.

Conclusion

A total of three diffuser were designed, analyzed, manufactured using rapid prototyping and testing in air. The design requirements of being able to operate the PBP at the 63% power level for the LTMCC and maintain the current impeller/diffuser design pressure rise at the Phase II MCC 109% power level was meet. The dynamic pressure environment for the resulting redesign is not increased from the baseline impeller/diffuser design.

References

[1] Meng, S. Y., Jackson, E. D., "The Continuous Diffusion Crossover System Design," Fluid Machinery Spring Conference, Houston, Texas, June 1983.

[2] McFarland, E. R., "A Rapid Blade-to-Blade Solution for Use in Turbomachinery Design," ASME Paper No. 83-GT-67, March 1983

[3] Crawford, M. E., Kays, W. M., "STAN5 - A Program For Numerical Computation of Two-Dimensional Internal and External Boundary Layer Flows", NASA CR-2742, Dec. 1976

[4] Lee, G. A., Lunde K. J., Williams R., "Air Testing of an SSME Turbopump Using Rapid Prototyping," AAIA 94-3152

[5] Furst, R., "Liquid Rocket Engine Centrifugal Flow Turbopumps," NASA SP-8109, Dec. 1973

SSME ENGINE SYSTEM

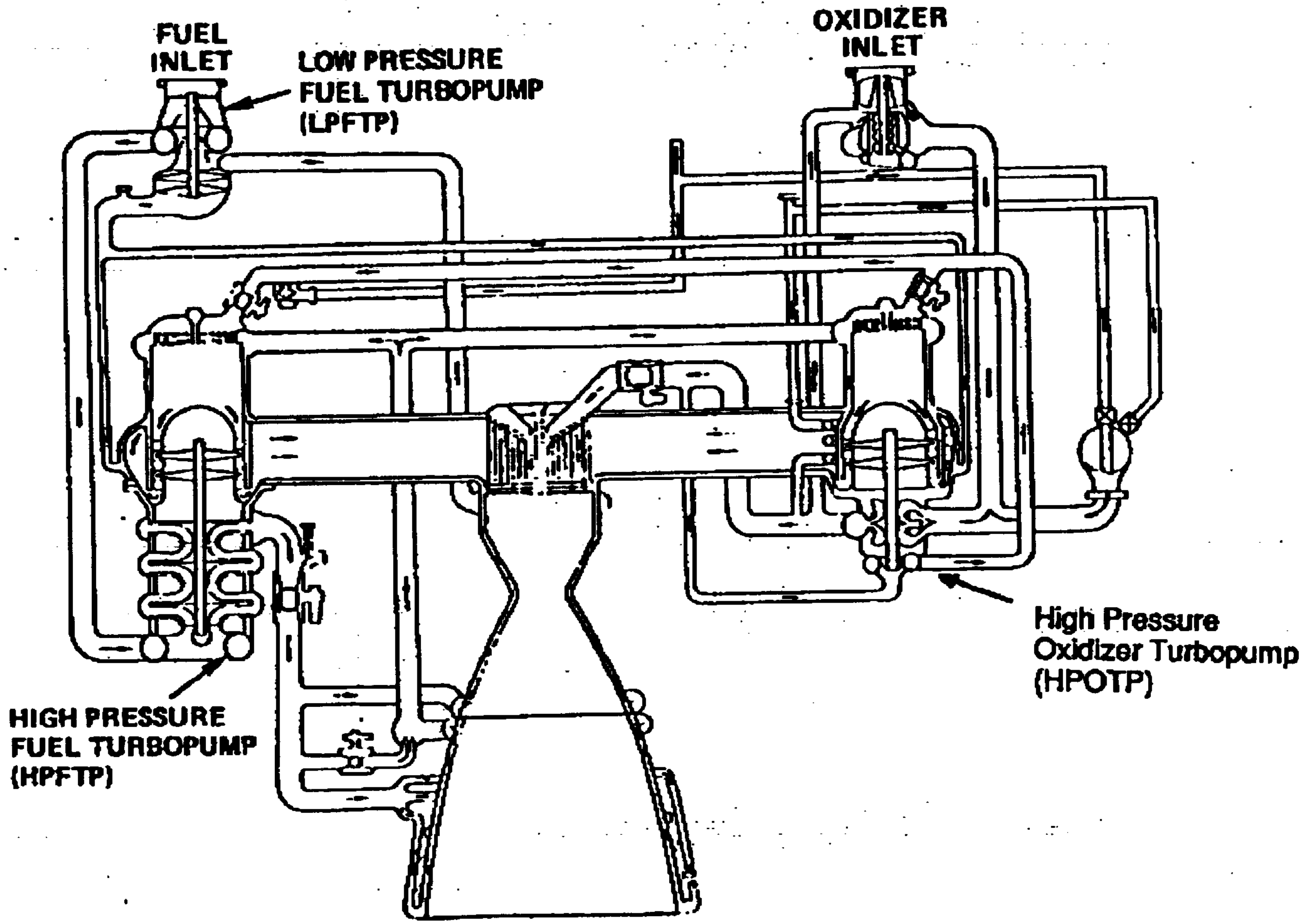

FIGURE 1

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PHASE II
HIGH PRESSURE OXYGEN TURBOPUMP

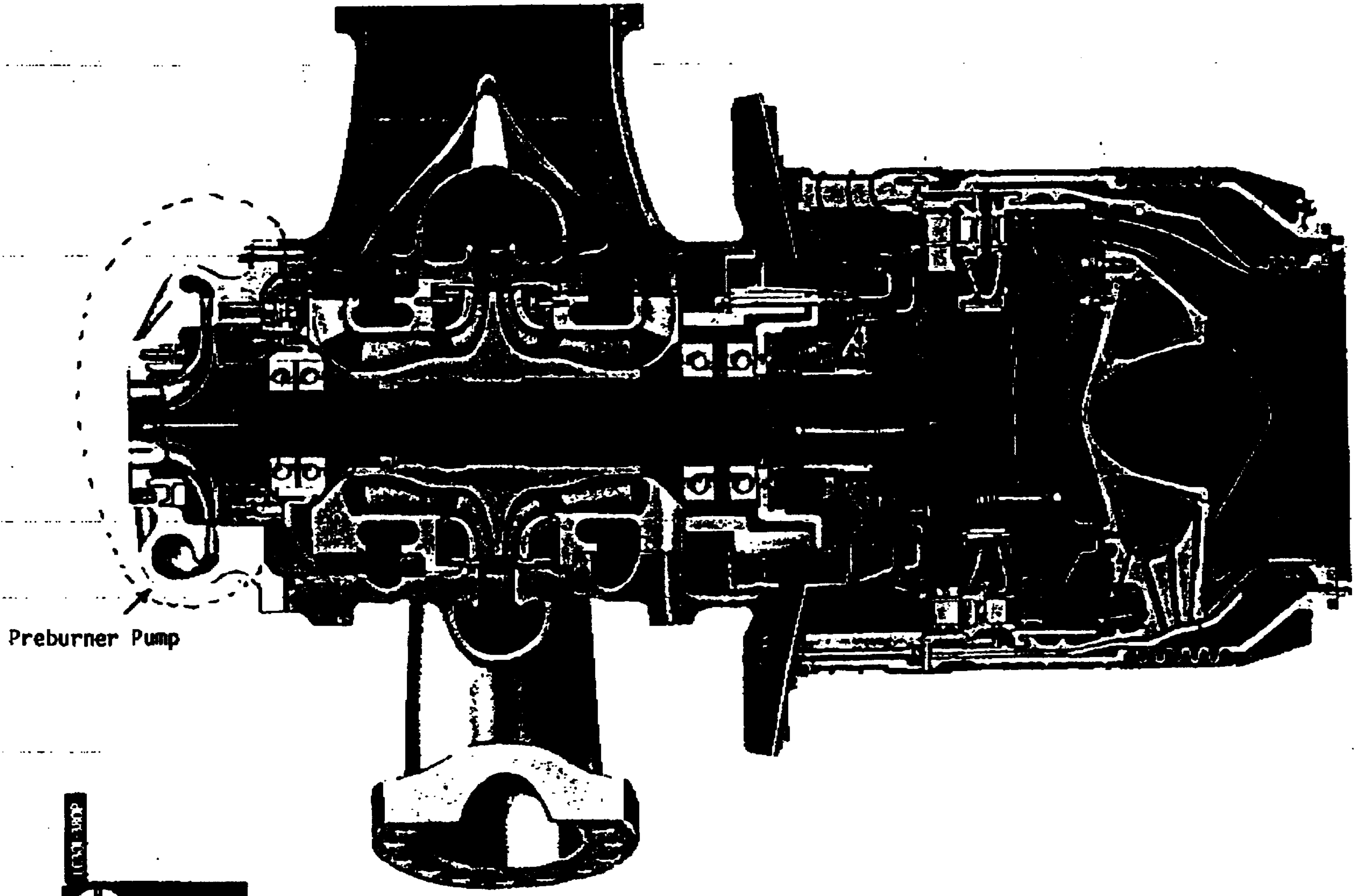

FIGURE 2

HPOTP PREBURNER PUMP BI-STABILITY

BI-STABLE EXAMPLE VS NOMINAL

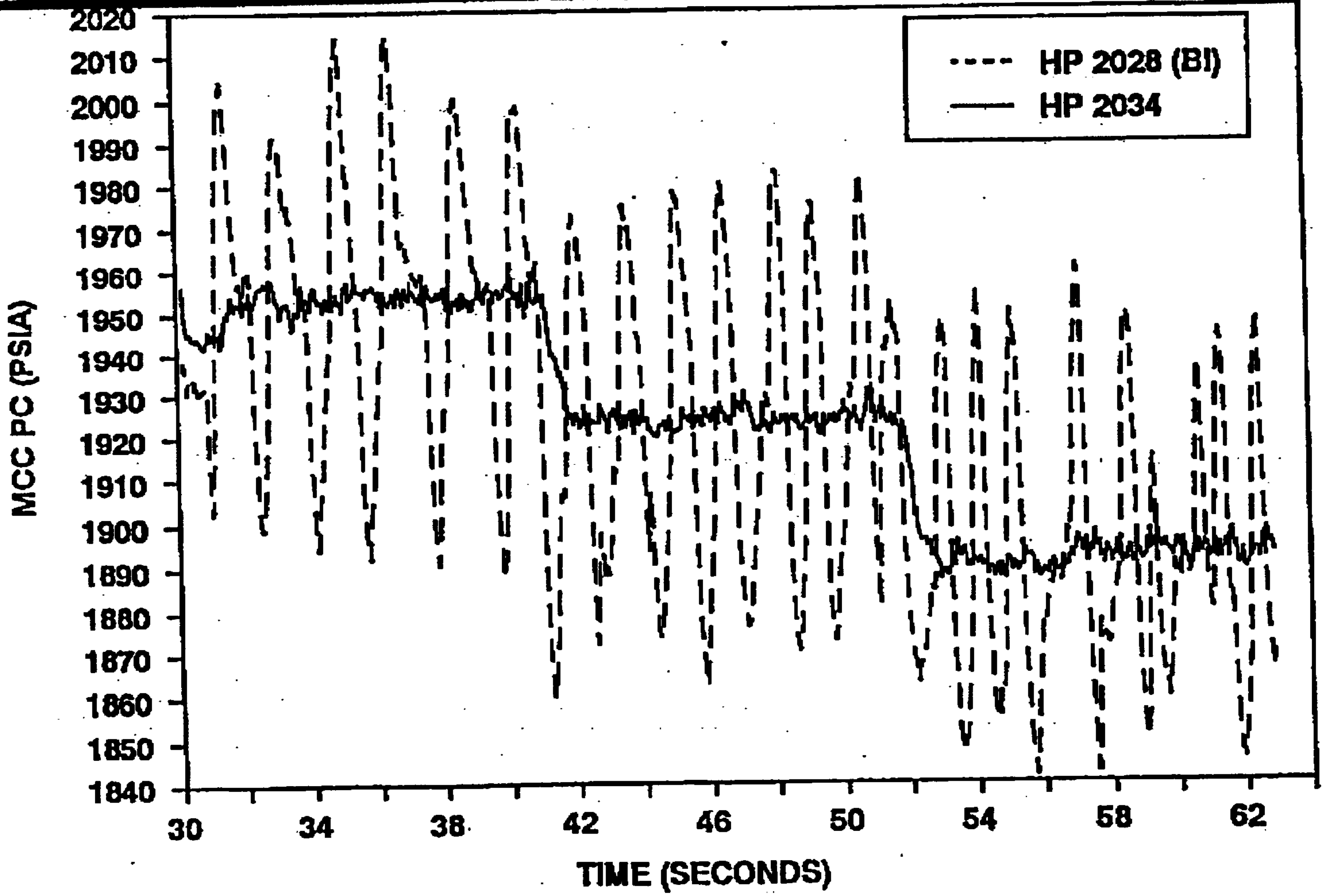

FIGURE 3

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PREBURNER PUMP REDESIGN FOR LARGE THROAT MCC ENGINE

HPOTP PREBURNER PUMP (PBP) BI-STABILITY

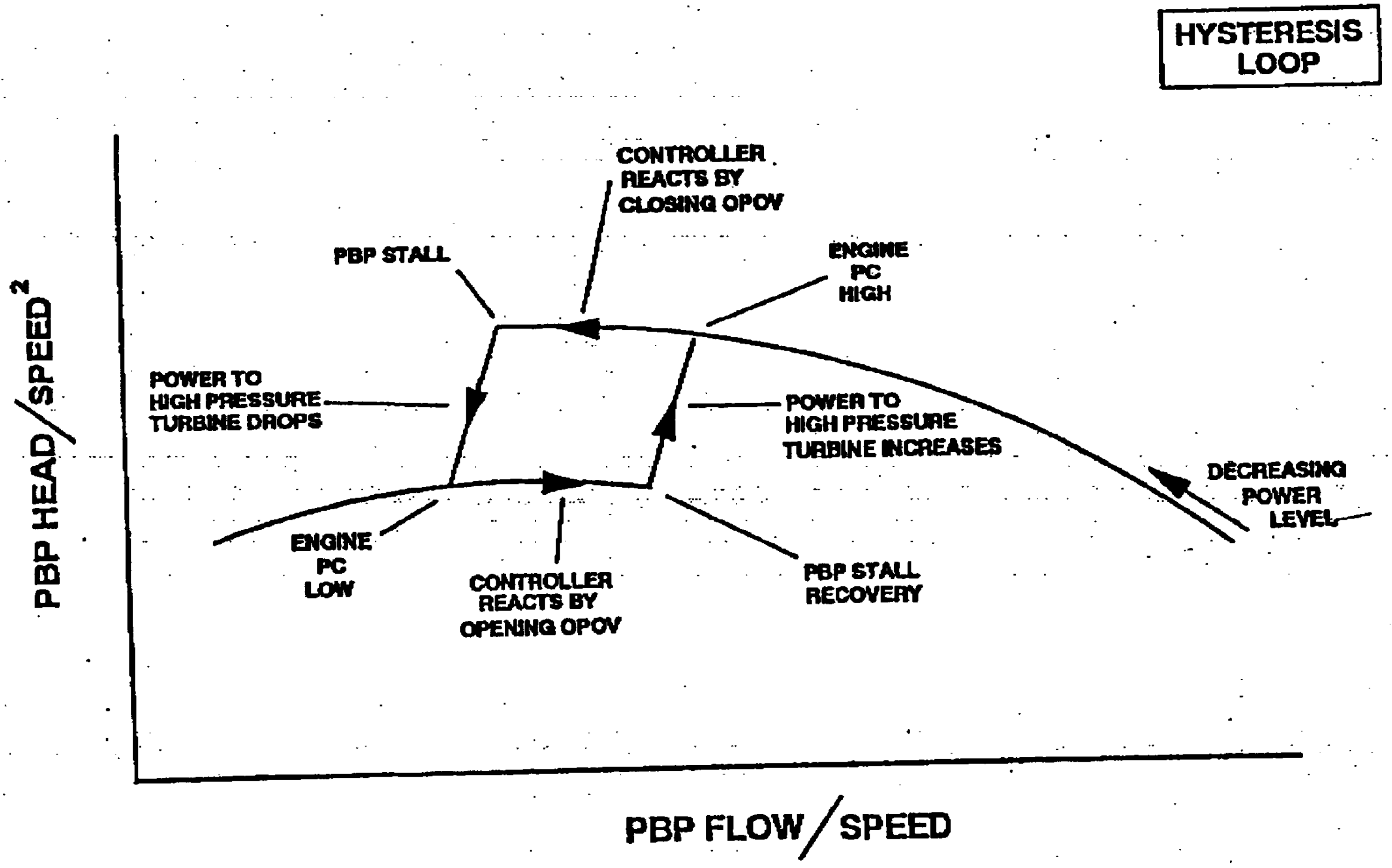

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FIGURE 4

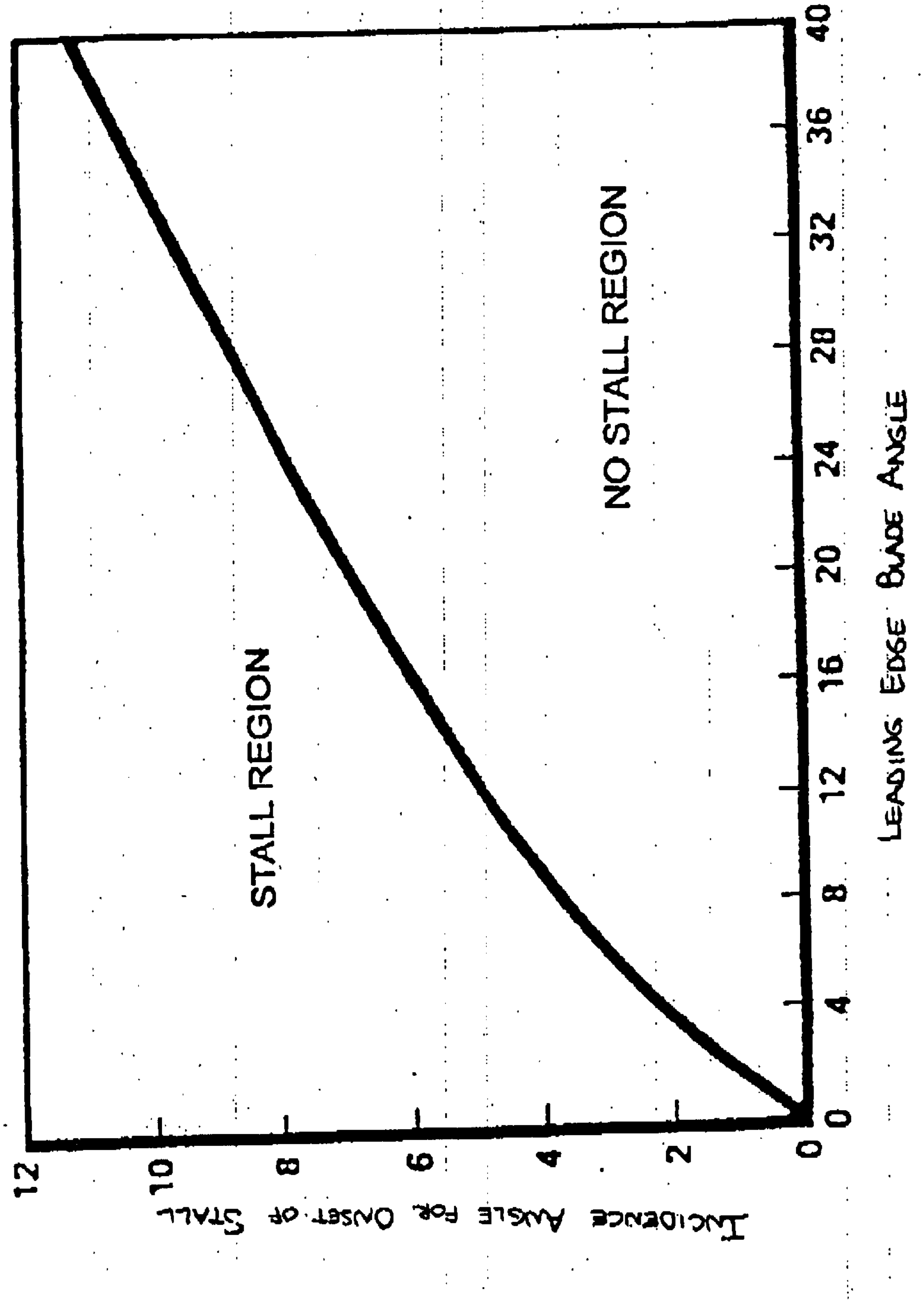


Figure 5: Onset of Stall Due to Leading Edge Incidence

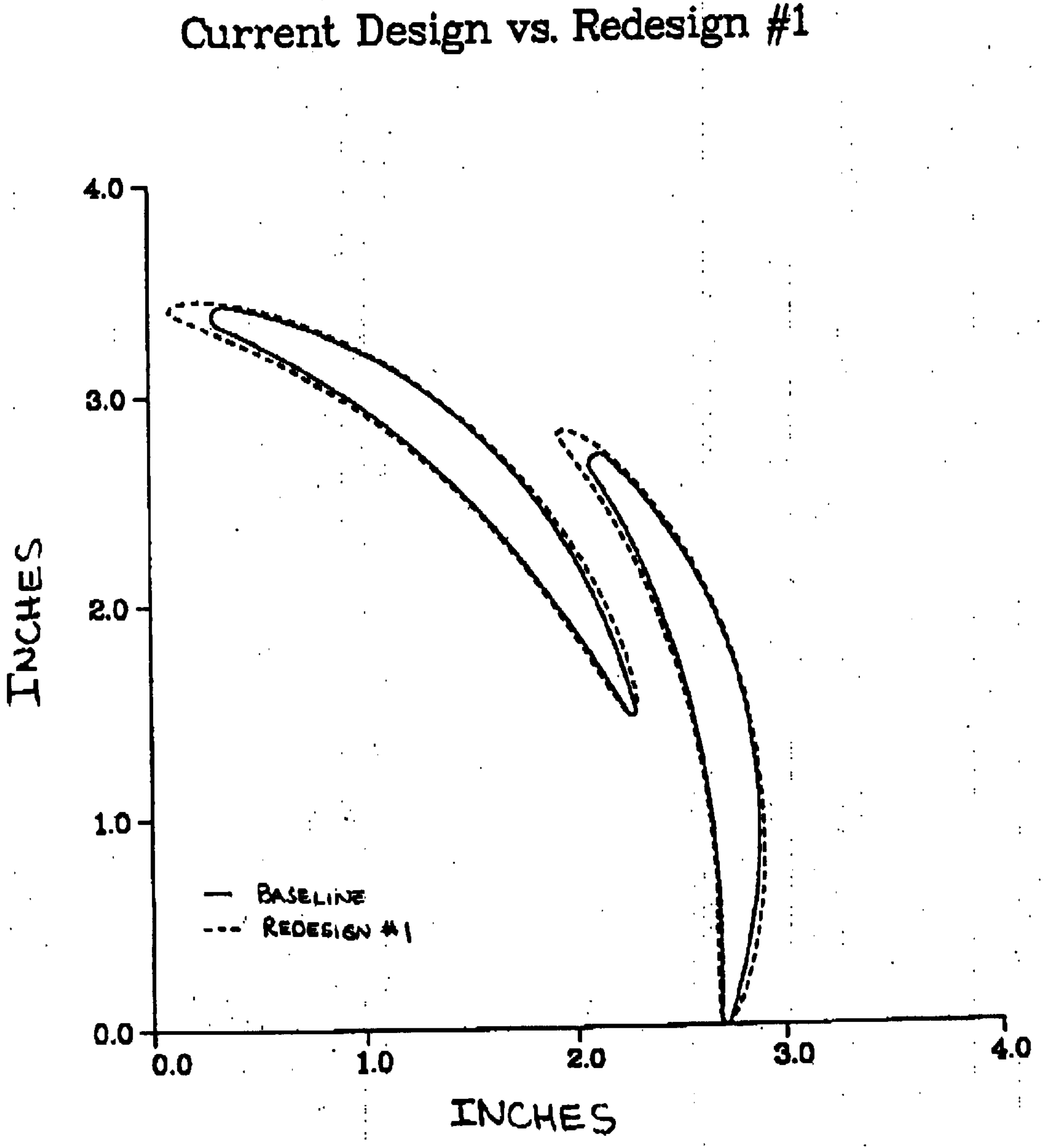


FIGURE 6: DIFFUSER REDESIGN #1 GEOMETRY

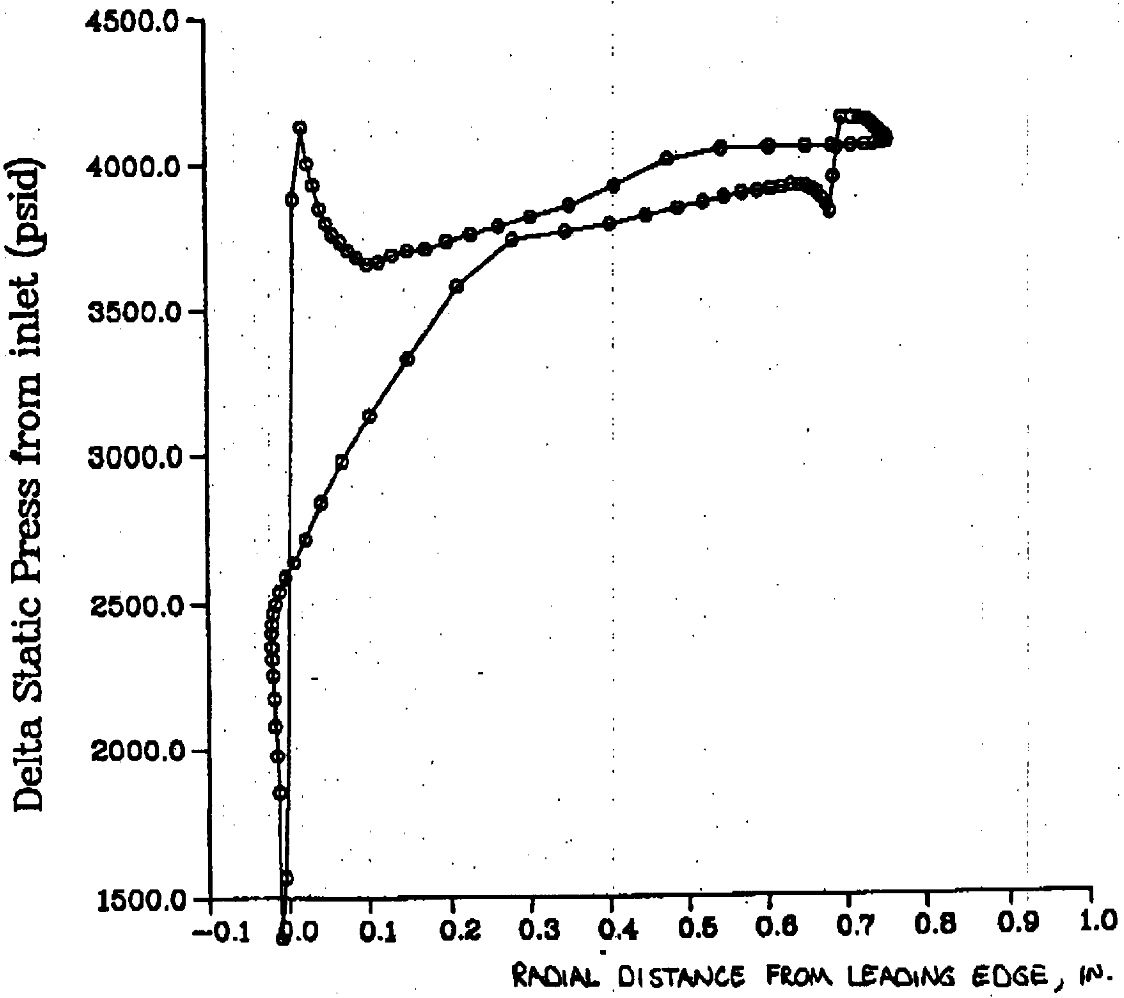


FIGURE 7: REDESIGN #1 STATIC PRESSURE DISTRIBUTION

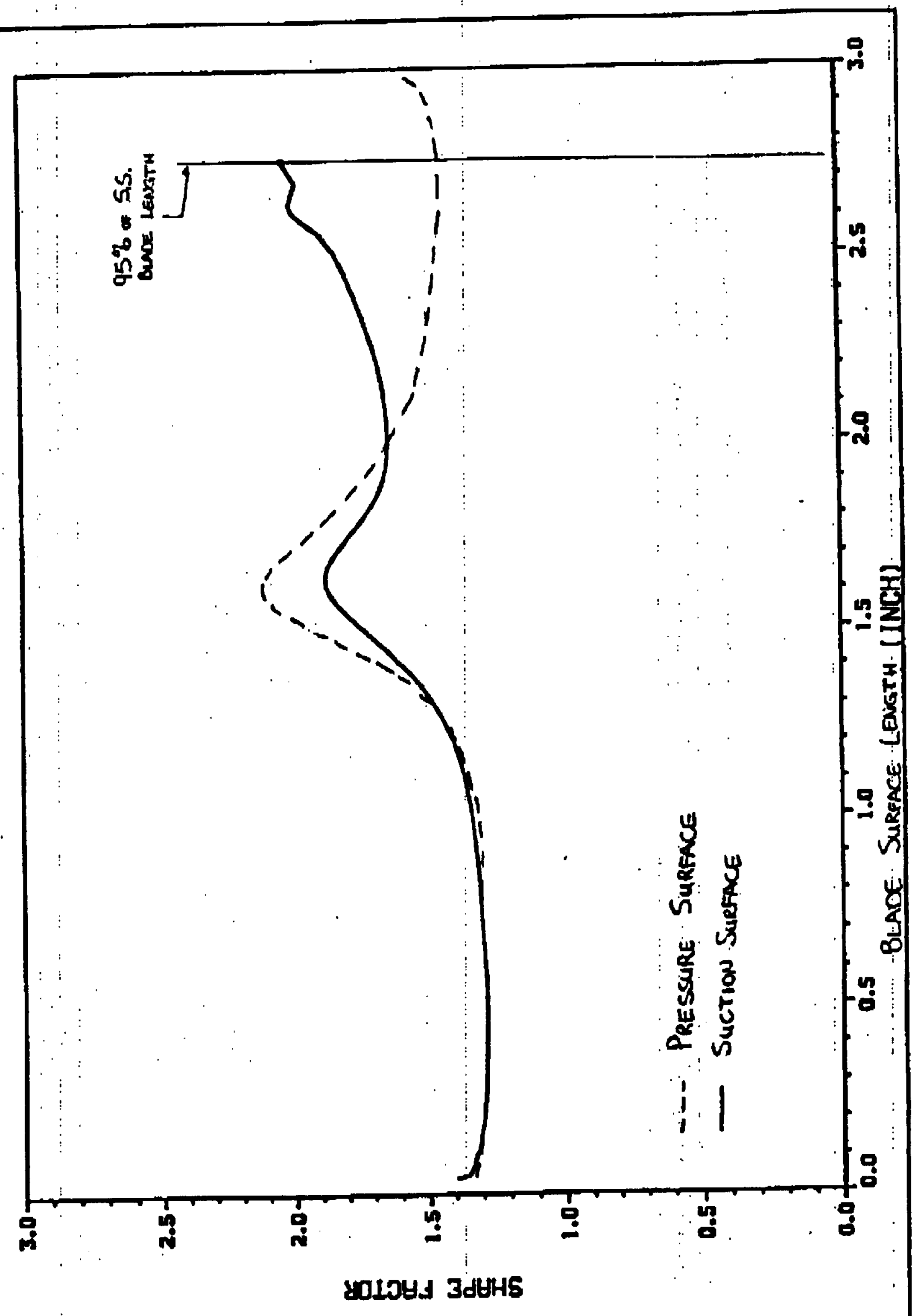


Figure 8 Diffuser Redesign #1 Shows Attached Boundary Layer @ $\Delta\Phi_{CR}$ = 0.010

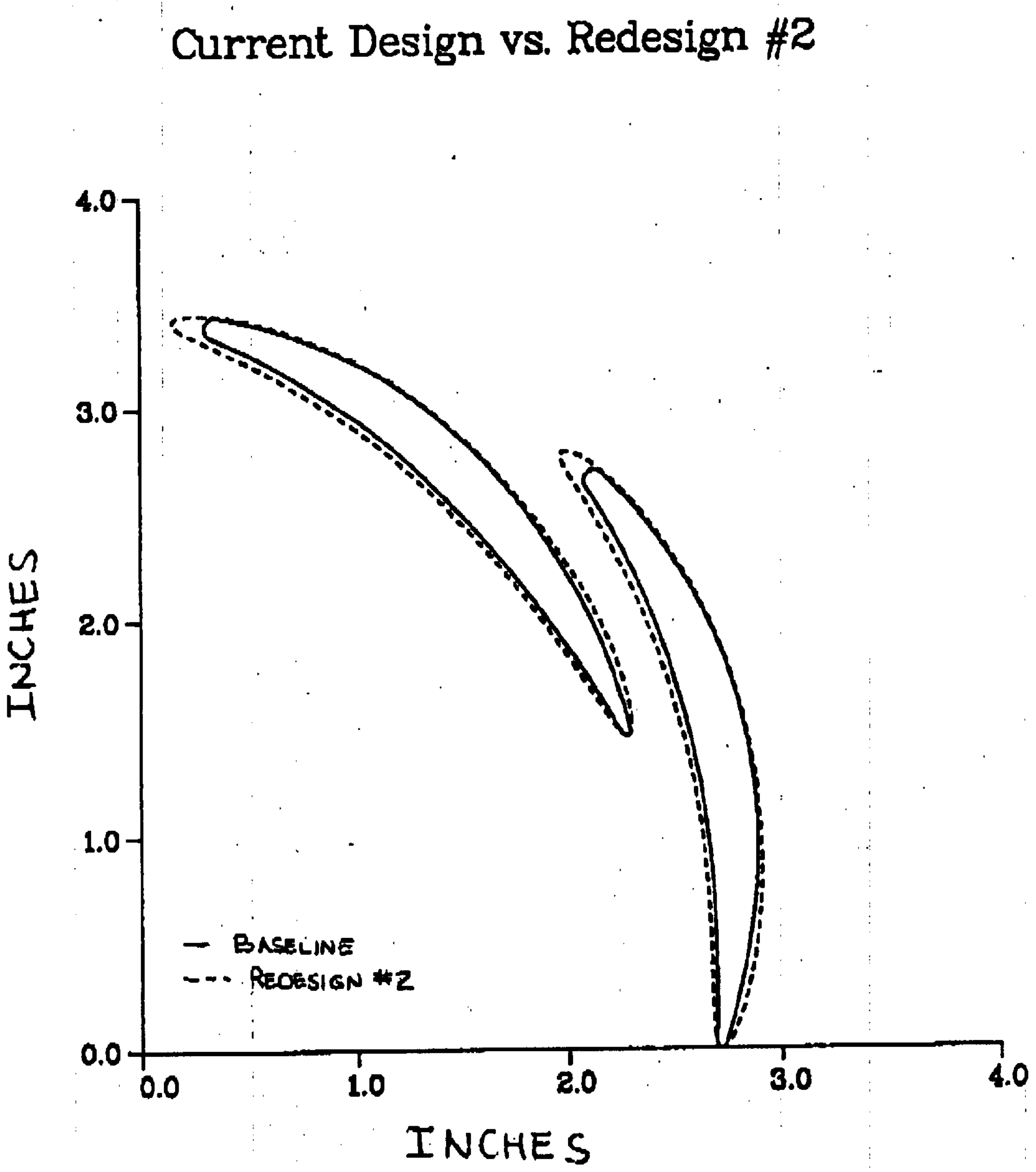


FIGURE 9: DIFFUSER REDESIGN #2 GEOMETRY

HPOTP PBP Redesign for LTMCC

Larger Incidence @ Higher Thrust Level

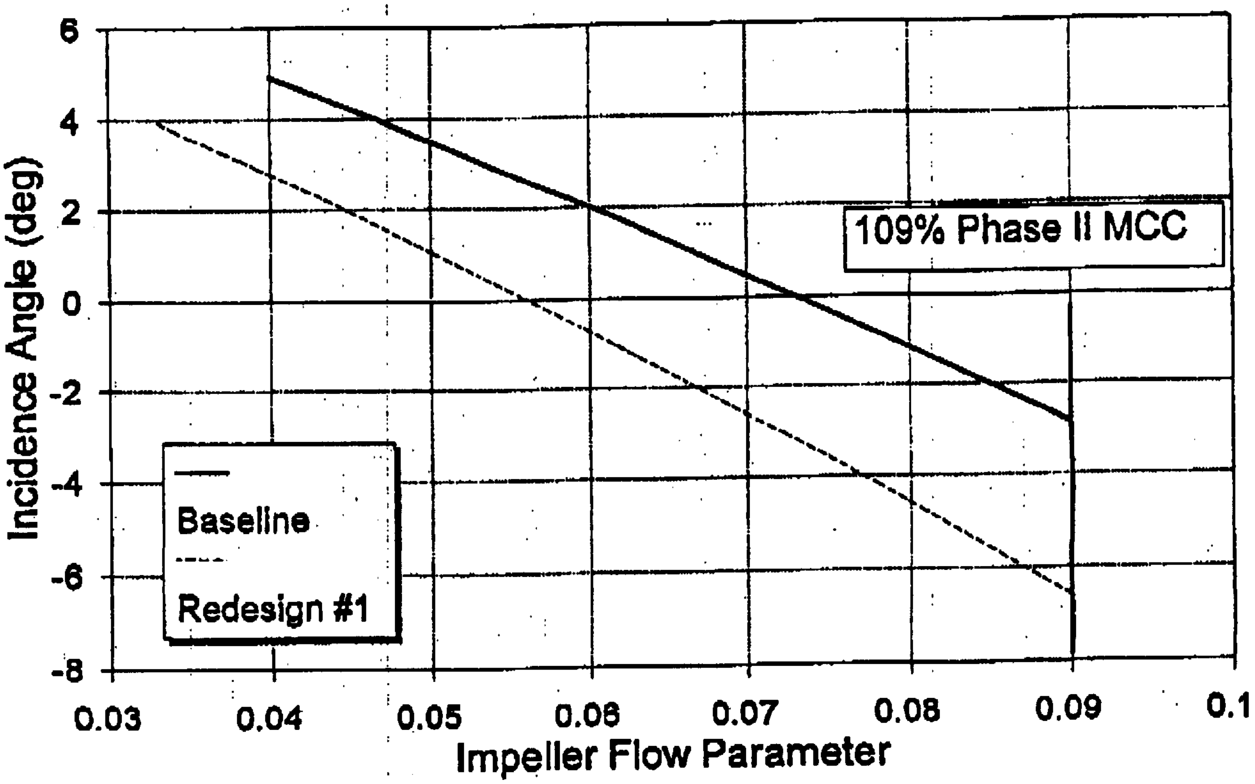


Figure 10:

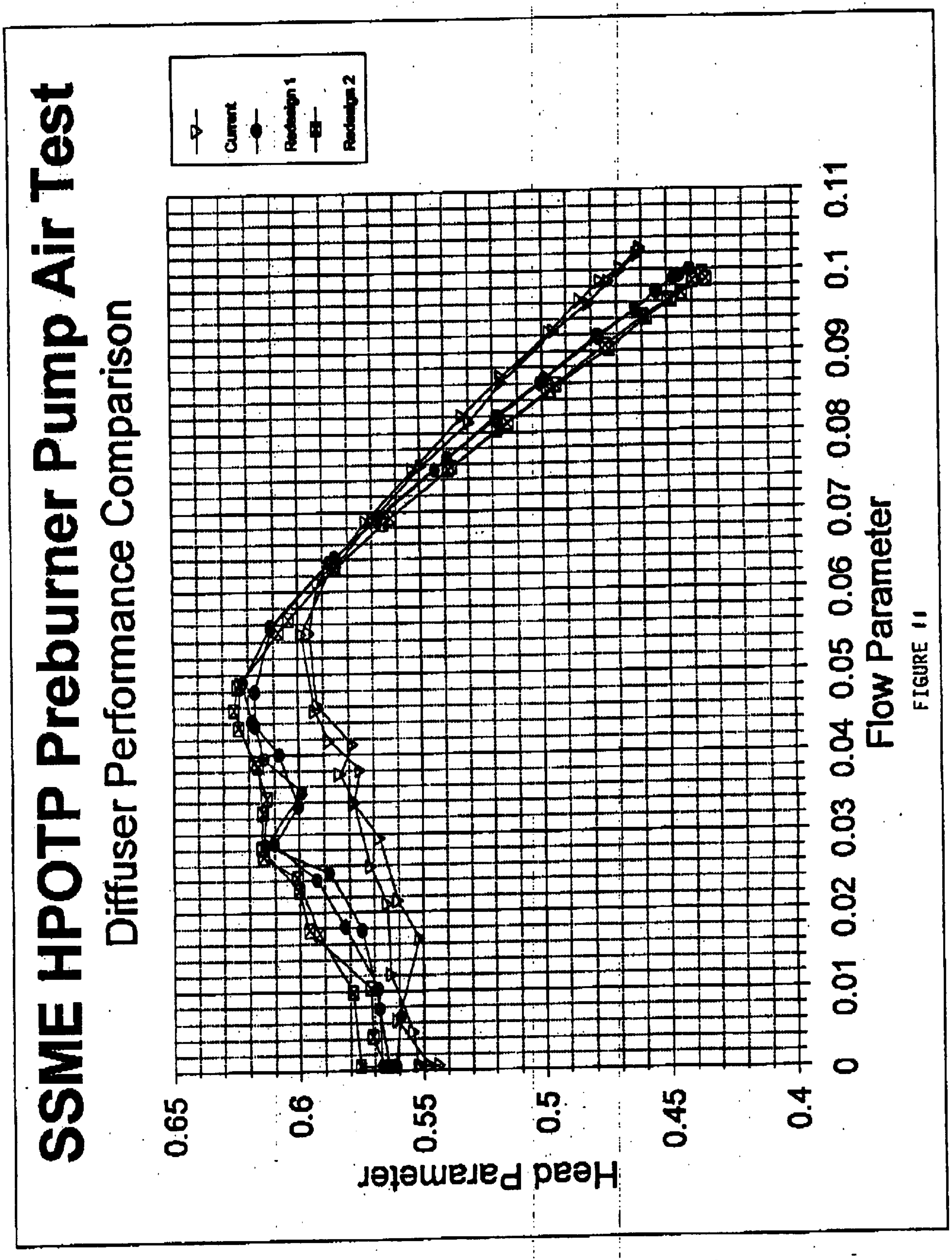
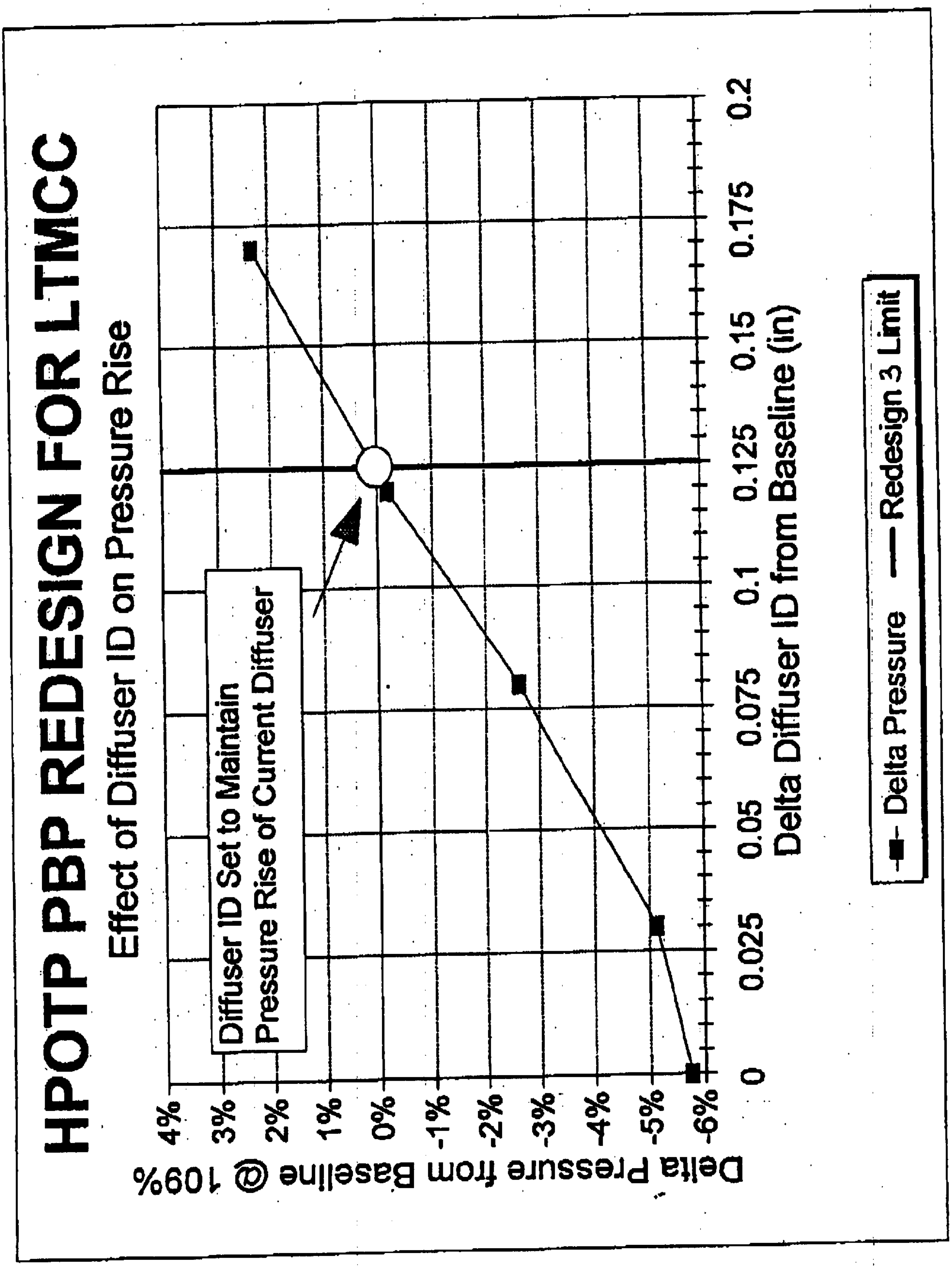

SSME HPOTP Preburner Pump Air Test
Diffuser Performance Comparison
Current
Redesign 1
Redesign 2
Head Parameter
0.65
0.6
0.55
0.5
0.45
0.4
Flow Parameter
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11

FIGURE 11


HPOTP PBP REDESIGN FOR LTMCC

Effect of Diffuser ID on Pressure Rise

Figure 12

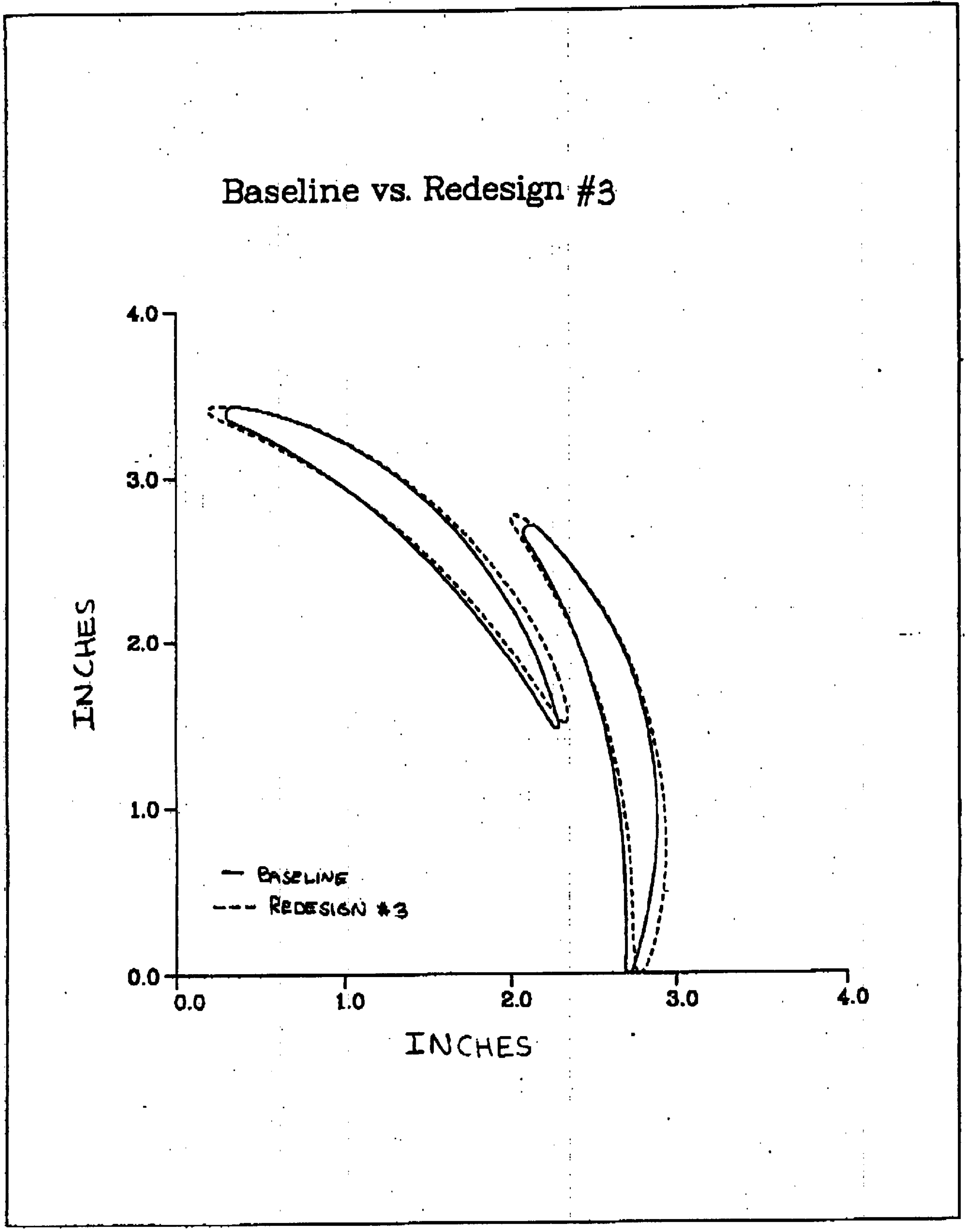


FIGURE 13: DIFFUSER REDESIGN #3 GEOMETRY

Preburner Pump Redesign for LTMCC

Head-Flow Performance

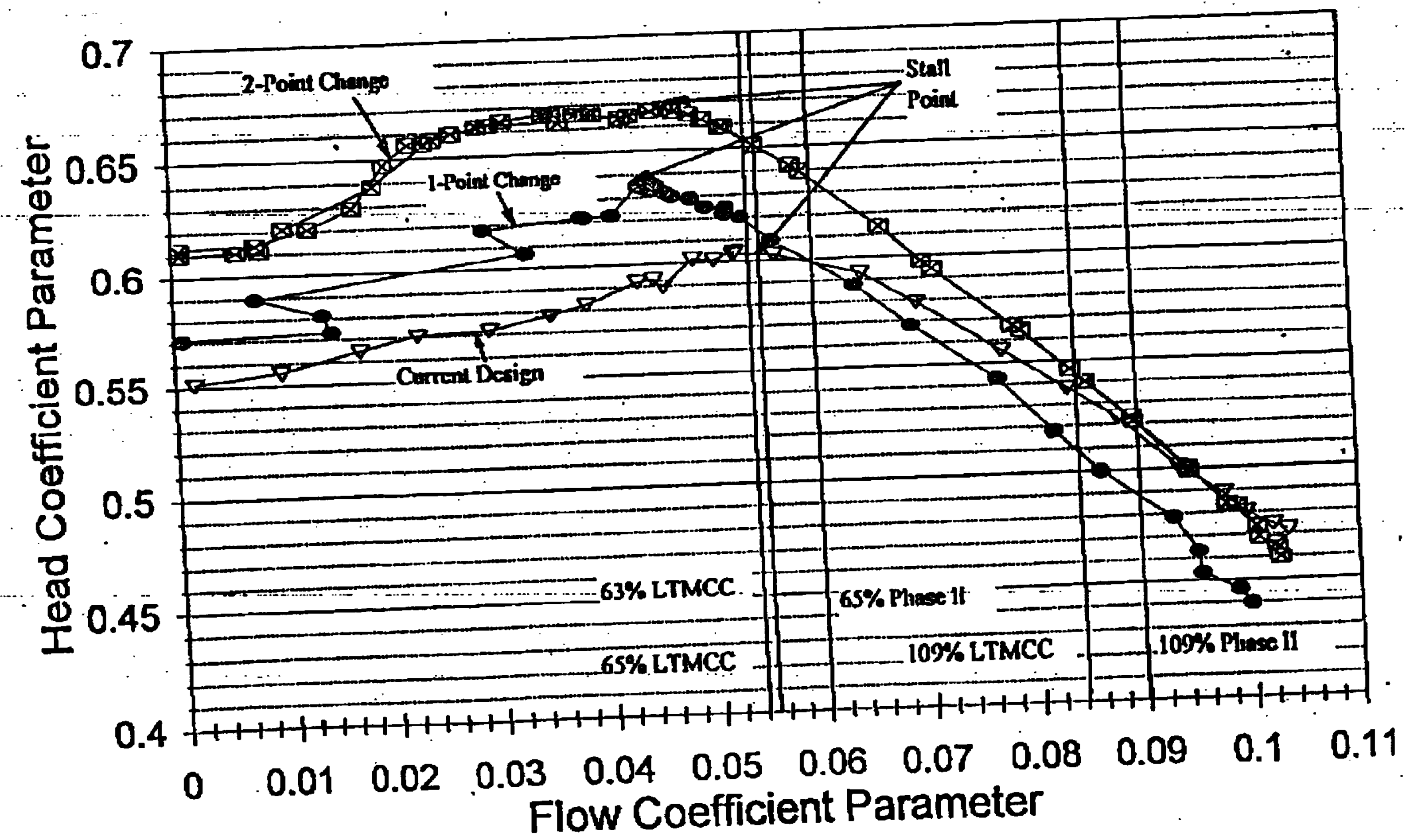


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FIGURE 14