SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
400 Commonwealth Drive, Warrendale, Pa. 15096

The Use of Variable Inlet Guide Vanes for Automotive Gas Turbine Engine Augmentation and Load Control

R. C. Pampreen
Research Engineer
Chrysler Corporation

SOCIETY OF AUTOMOTIVE ENGINEERS

Automotive Engineering Congress and Exposition
Detroit, Michigan
February 23-27, 1976

760285

760285

The Use of Variable Inlet Guide Vanes for Automotive Gas Turbine Engine Augmentation and Load Control

Ronald C. Pampreen
Chrysler Corporation

THE Chrysler Corporation is currently engaged in a government sponsored program for the Energy Research and Development Administration (ERDA) to improve gas turbine engine fuel economy and emission control. One means of improving fuel economy is engine power augmentation. The use of augmentation permits the engine to be designed for a smaller size than that of an unaugmented engine. The losses associated with part-power engine operation in the steady-state driving range are consequently reduced by the smaller size, while augmentation permits attainment of the maximum power required during vehicle acceleration.

The types of augmentation being investigated in the program are variable inlet guide vanes (VIGV) and water injection. This paper describes the experiences encountered to date with VIGV augmentation. Discussions are presented on 1) compressor and turbine matching requirements, 2) compressor performance with VIGV, and 3) engine and turbine performance characteristics under augmentation conditions. In addition to augmentation, discussions are included on the use of VIGV for low-power and idle engine operations.

To carry out the goals of the program, an upgraded version of the current Chrysler engine has been designed. The current engine is referred to as the Baseline Engine. The design and development work on the VIGV has been carried out on Baseline Engine hardware, through compressor rig and engine testing.

ENGINE OPERATION WITH VIGV

In the past, the use of VIGV on the automotive gas turbine engine has been primarily for the purpose of minimizing engine acceleration time. In Ref. (1), a high value of idle speed was obtained by simulating the pressure ratio characteristic of a lower speed with large values of positive preswirl (in the direction of engine rotation). The study conducted in Ref. (2) also employed this technique for the same reason, and, in addition, considered the use of water injection for power boost during acceleration. In Ref. (3) VIGV were considered for use, not only at idle, but also at maximum speed. As in Refs. (1) and (2), positive preswirl was used at idle speed, but, differing from Ref. (2), negative swirl was employed near maximum speed. This simulated the pressure ratio characteristic of maximum speed at a lower speed, thus reducing the difference in engine speed between idle and maximum power.

In the ERDA program, VIGV are being used to improve fuel economy and emission control. This is illustrated in Fig. 1, which shows the engine operating lines at 50% and 100% speeds on partial compressor maps.

Differing from Ref. (3), negative preswirl is employed at maximum speed, not to minimize acceleration time but to augment engine power. Additional augmentation is provided by water injection at maximum negative VIGV travel, again, not to minimize acceleration time as in Ref. (2), but to improve fuel economy in the vehicle driving range. This is accomplished by referencing the engine size to the

ABSTRACT

This paper presents the results of the design and development work on variable inlet guide vanes (VIGV) for use in the ERDA Upgraded Automotive Gas Turbine Engine. The feasibility of the concept of VIGV augmentation was carried out on ERDA Baseline engine hardware in compressor rig and complete engine testing.

Included in the paper are discussions of this VIGV design philosophy, development logic and test results, and the critical areas of gas generator compressor and turbine matching combined with variable-nozzle power turbine and vehicle matching.

FIGURE 1
CHANGES IN ENGINE OPERATING LINE ON COMPRESSOR MAP WITH VIGV APPLICATION

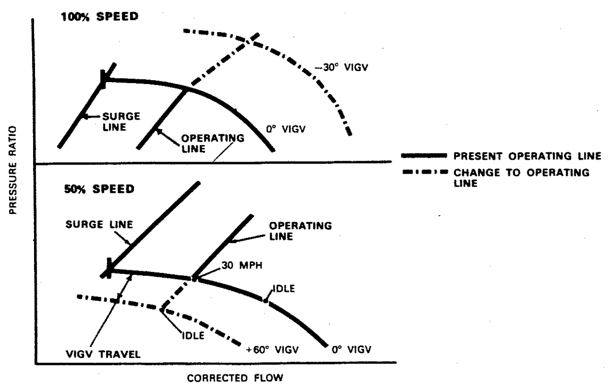
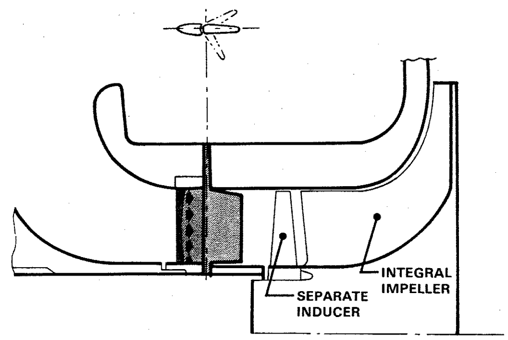


FIGURE 2
VARIABLE INLET GUIDE VANES ON COMPRESSOR ASSEMBLY



unaugmented power at maximum gas generator speed. The power losses at any given part-power condition are reduced if the aerodynamic components have been sized for a smaller reference power.

To improve fuel economy still further, VIGV are used at 50% speed. Similar to Refs. (1)-(3), positive preswirl is used at idle speed, not, however, to achieve a high value of idle speed, but to lower the flow and pressure ratio at a low idle speed for better fuel economy, as suggested in Ref. (3). Without VIGV, the baseline engine operation at 50% gas generator speed between peak power and idle power is achieved by reducing the turbine inlet turbine. This changes the match between the compressor and turbine to a higher airflow, as shown in Fig. 1. For the Upgraded Engine, the power turbine exit temperature will be held constant for all power levels at 50% speed. This will reduce idle pressure ratio and airflow. It is hoped that idle fuel flow can also be reduced. This will depend on how well compressor and turbine efficiencies are maintained in this power range. Of particular concern, at the beginning of the program, was the uncertainty of the maintenance of good compressor efficiency over the VIGV angle range from 0° to +60°.

It was also hoped that added fuel economy would come from maintaining a constant power turbine exit temperature. This would avoid the cyclic heating and cooling of the regenerator and associated engine parts between peak power and idle. Lastly, it was expected that the hydrocarbon and CO emissions would be reduced by maintaining at higher value of power turbine exit temperature at idle than that of the Baseline Engine.

Hardware was designed, procured and tested to investigate operation with VIGV on the Baseline Engine. Preliminary testing was conducted on a compressor test rig with a Baseline Engine compressor. These tests provided the initial experience for obtaining the best trade-off between positive preswirl at 50% speed and augmentation at 100% speed. This was followed by engine testing to confirm the test rig results and provided component matching data. Each of these activities are discussed in the following sections.

VIGV DESIGN

The variable inlet guide vane used in the ERDA program is an articulated design as shown in Fig. 2. This type of design provides a wider range of minimum-loss operation over a wider range of deflection angles than does an integral vane which is simply pivoted to produce the required swirl. This is supported by the work reported in Ref. (4). Similar approaches have been taken in Ref. (5) and (6), but the forward section of the vane in these references is movable as well as the rear. The configuration in Fig. 2 was selected because the data shown in Ref. (4) indicates the possibility of having a stationary forward section and, thus, a more economical VIGV configuration over a wide range of low-loss deflection angle.

The vane section is an NACA 0010 Profile, modified for a trailing edge thickness/chord ratio of .016. The maximum-thickness/chord ratio used in Ref. (4) was .05. A value of 0.10 was used in the VIGV design in anticipation of structural integrity.

The chord length of the vanes in Ref. (4) was varied from hub to tip to give a nearly constant solidity between 1.07 and 1.08. The VIGV configuration used on the Baseline Engine has a variable solidity from hub to tip. This was the result of selecting a constant chord length for manufacturing simplicity. To insure the attainment of the desired turning at the tip, the tip solidity was specified to be 1.0. The low Hub/Tip ratio (.46) of the Baseline Engine impeller resulted in mean and hub solidities of 1.45 and 2.54, respectively. Differing from Ref. (4), the hub flowpath was cylindrical. It was hoped that the large value of hub solidity would counter the adverse effect of clearance of 60° flap angle as the edge of the flap moved away from the hub.

The axial spacing from the impeller leading edge was selected to be 5/8 of the vane chord length. Data presented in Ref. (7) from a number of blade sections shows that wakes are dissipated at about 5/8 chord. It was hoped that this would be true for the VIGV at zero degrees flap angle. This would be the flap direction for most of the vehicle driving range.

COMPRESSOR RIG TESTING

Two compressor configurations were investigated in the compressor rig tests. One configuration consisted of the Baseline Engine compressor with the rotor as shown in Fig. 2. It is identified as a B-52 compressor. The second test configuration was identical to the first except that the separate inducer was removed. In addition, the leading edge of impeller's inducer was bent closed 4°. This latter configuration is identified as a B-36 compressor. The latter configuration was tested to evaluate the need to have a separate inducer with VIGV. The intent of the separate inducer is to obtain as high a range of flow as possible between rotor stall at 50% speed and rotor choke at 100% speed, with a fixed geometry compressor. It seemed that the use of VIGV might preclude the need for the separate inducer. The inlet guide vane assembly with actuator is shown in Fig. 3. An overall view of the compressor and the test rig instrumentation is shown in Fig. 4.

Figure 5 shows the test results obtained on the Baseline compressor configuration. Data was taken with positive guide vane deflection angles of 0° and 60° at 50%, 60%, and 70% speeds. The test results in Fig. 5 show an efficiency drop from 0 ° to 60 ° vane angle change. This could be due to operating the separate inducer at high-loss negative incidence angles. The average blade angle is about 60° for the separate inducer and about 55° for the B-36 inducer. The separate inducer has an inlet blade angle which is conductive to low incidence angles at low speeds in order to provide good rotor stall margin. Since positive swirl reduces rotor incidence angle, it is possible that the separate inducer is not ideally suited to the vector diagram changes affected by the guide vanes.

Fig. 6 shows the test results obtained with the B-36 compressor configuration. Fig. 7 shows a performance comparison with and without the separate inducer for guide vane deflection angles of 0° and +60°. The comparison shows that the maximum stage efficiency rose from 0.71 to 0.725 for the B-36 compressor as the guide vane was deflected from 0° to 60°. At the same speed, the maximum efficiency dropped from 0.73 to 0.70 for the Baseline compressor as the guide vane was deflected from 0° to maximum travel. The reduction in efficiency is consistent with the lower values of choke flow. The data indicates the sensitivity of the matching of the preswirl delivered by the VIGV and the inducer inlet blade angle.

The compressor test rig results at 100% speed are shown in Figures 8 and 9, for tests with and without the separate inducer, respectively. The compressor must be augmented 8.5% in pressure ratio and flow, with little or no reduction in efficiency, in order to achieve the required 12% power augmentation. Along a constant turbine inlet temperature line, the augmentation of compressor airflow and pressure ratio is 1.5% for the B-36 compressor and 3.7% for the B-52 compressor with 30° of negative guide vane angle. The B-52 compressor shows a drop of about 2 points in maximum efficiency, and the B-36 compressor shows about 4 points drop in maximum efficiency.

FIGURE 3
VARIABLE INLET GUIDE VANE ASSEMBLY

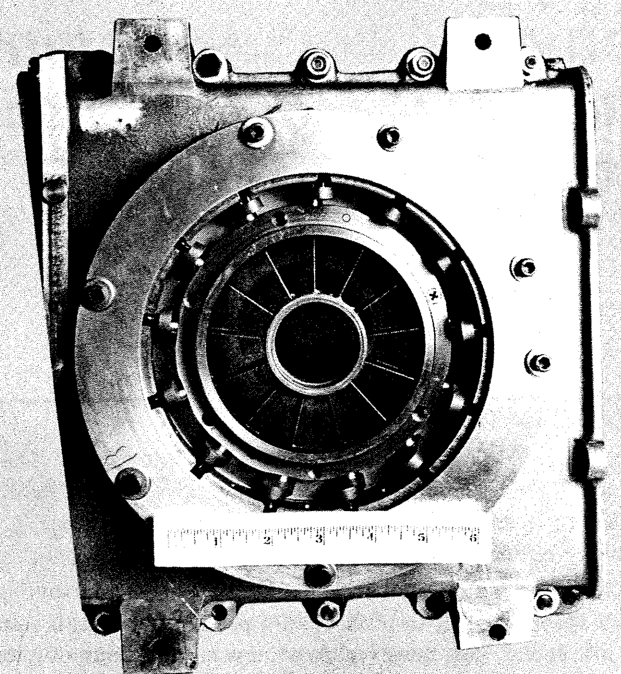


FIGURE 4
BASELINE ENGINE COMPRESSOR TEST RIG COMPRESSOR & DIFFUSER ASSY.

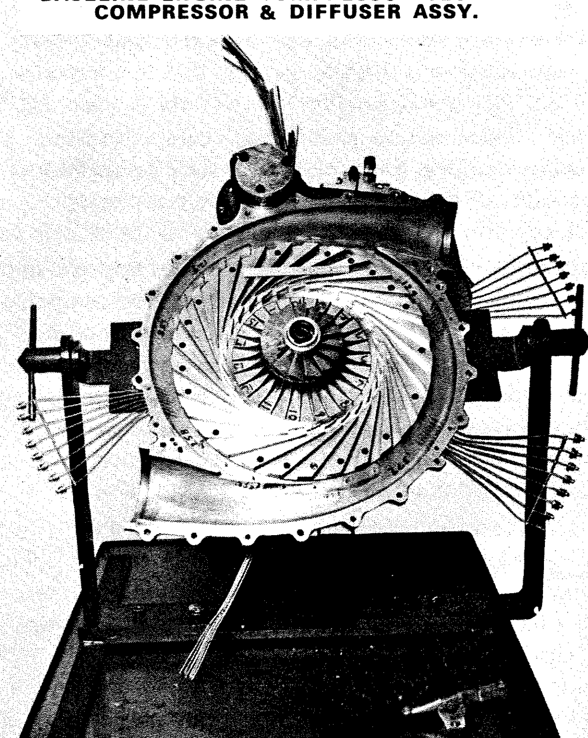


FIGURE 5

B-52 COMPRESSOR PERFORMANCE WITH VIGV

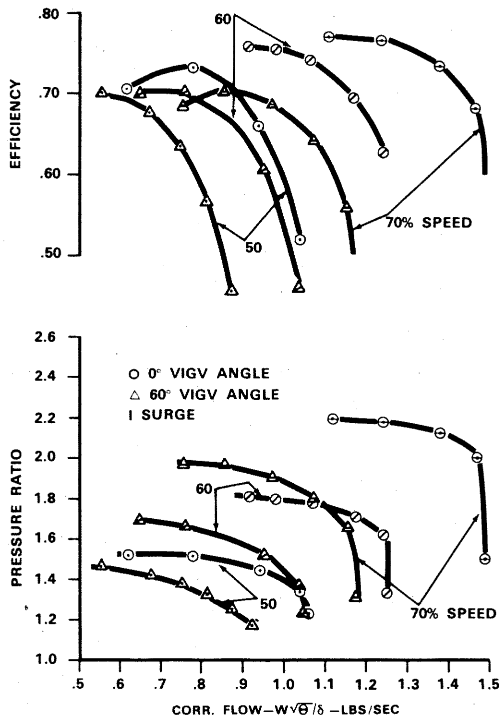


FIGURE 7

PERFORMANCE COMPARISON OF B-52 AND B-36 COMPRESSORS WITH VARIABLE INLET GUIDE VANES

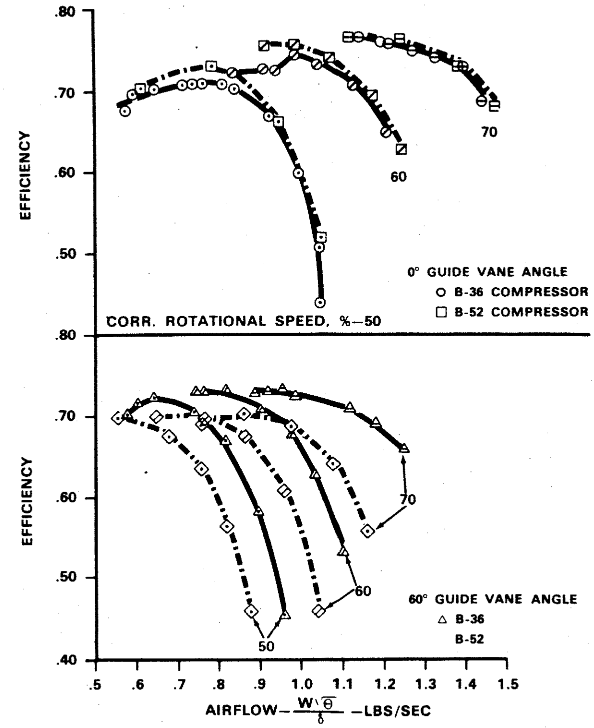


FIGURE 6

B-36 COMPRESSOR WITH VIGV

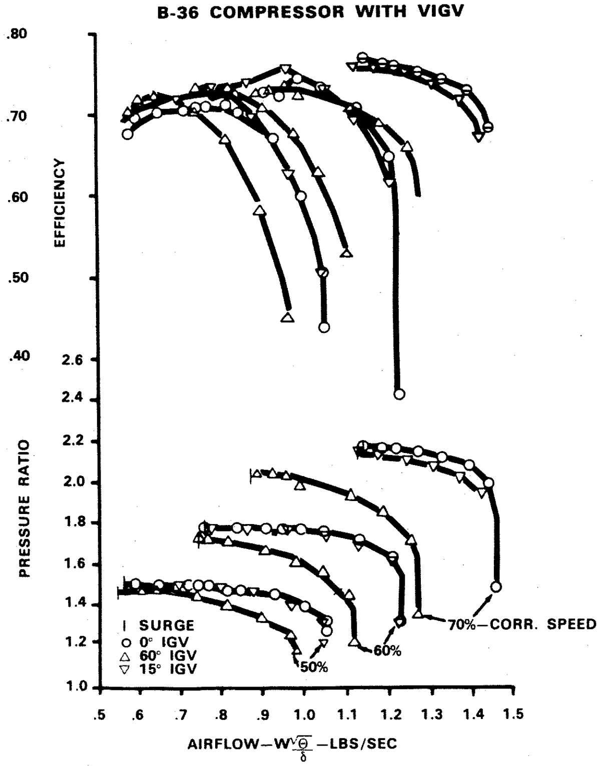


FIGURE 8

B-52 COMPRESSOR CHARACTERISTICES AT 100% CORR. SPEED WITH VARIABLE INLET GUIDE VANES

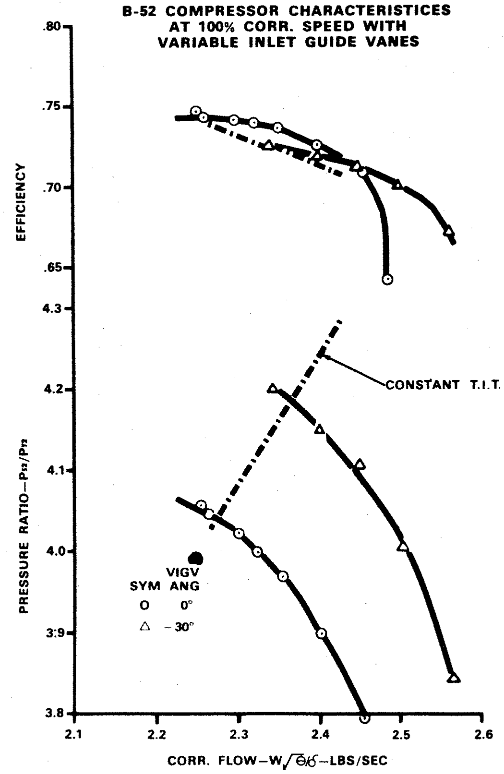


FIGURE 9

B-36 COMPRESSOR CHARACTERISTICS AT 100% CORR. SPEED WITH VARIABLE INLET GUIDE VANES

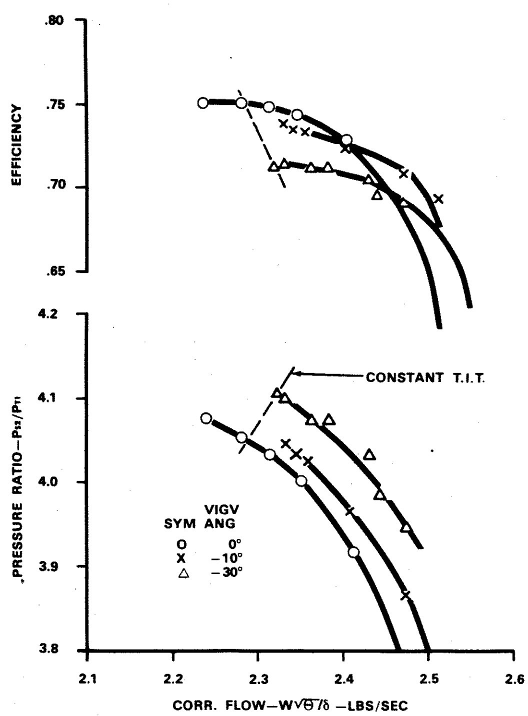
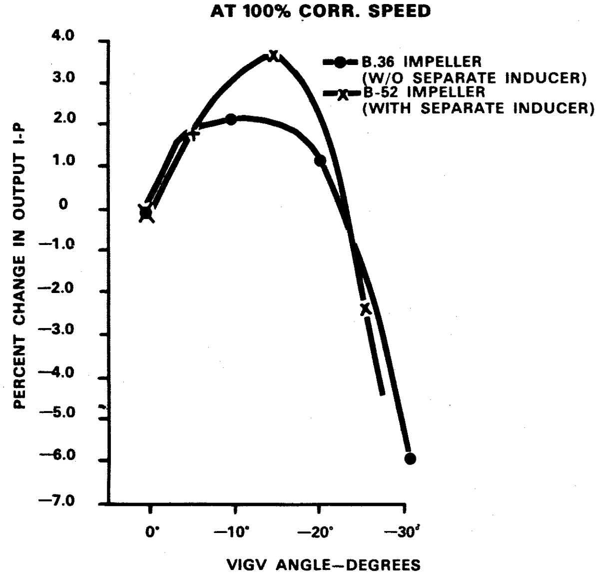


FIGURE 10

EFFECT OF VIGV ANGLE ON PEAK POWER AT 100% CORR. SPEED



In summary, then the rig data showed that the separate inducer with its higher inlet blade angle configuration would be better suited to engine augmentation. However, a further increase in blade angle by a revision, such as a blade twist, might be necessary to minimize the efficency reduction at −30° and to achieve the required increases in flow and pressure ratio.

COMPRESSOR RESULTS FROM ENGINE TESTING

Engine testing began with an initial confirmation of the rig performance results with and without the separate inducer. Instrumentation which duplicated that of the test rig was installed so that a direct comparison of engine and rig data could be made. Tests were conducted at 100% and 50% speeds. At 100% speed, data was taken at a power turbine exit temperature of 1350°F over guide vane angles from 0° to −30°. At 50% speed, data was taken at idle and peak power for power turbine exit temperatures ranging from 1100°F to 1350°F over guide vane angles from 0° to +60°.

The power augmentation results are shown in Fig. 10 for tests with and without the separate inducer, respectively. With the separate inducer, 3.6% power augmentation was achieved; without the separate inducer, 2.0% power augmentation was achieved. The augmentation is less than expected from compressor test rig results. With the separate inducer, there should have been 6% power augmentation, and without the separate inducer there should have been 3% augmentation.

It was assumed that the lack of power augmentation was due to a lack of compressor augmentation. The test rig results showed that the compressor augmentation goals were not met with either inducer-impeller configuraton. However, the augmentation was better with the rotor with the separate inducer. It was presumed that this was due to more favorable incidence-angle matching with the larger inlet blade angle of the separate inducer. Consequently, it was assumed that an additional increase in inlet blade angle might yield further improvement in augmentation. Accordingly, a separate inducer was twisted closed approximately 2.5 degrees.

Test results showed very little difference in the augmentation of compressor flow and pressure ratio with the twisted inducer. Fig. 11 shows the variation of compressor flow and pressure ratio along the engine operating line with guide vane angle for each compressor configuration tested. The plot shows little difference in performance with the standard or twisted separate inducer. The plot also shows little difference in performance without the separate inducer. This result differs from the test rig data which showed less compressor augmentation without the separate inducer. To illustrate this, Fig. 12. shows a comparison between engine and rig data. The performance difference between rig and engine data is unexplained at present.

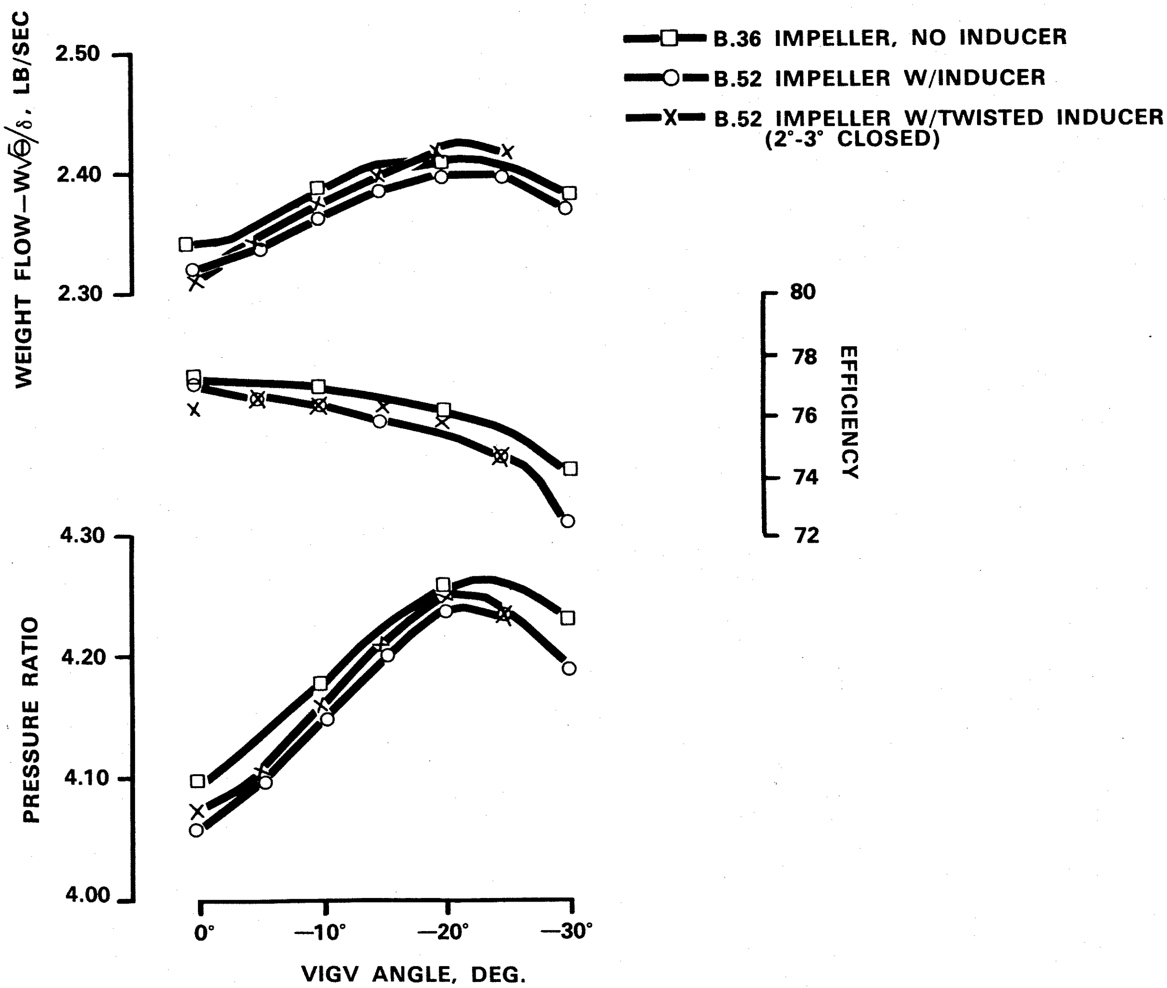
The plots in Fig. 11 show that the augmentation of compressor flow and pressure ratio is insensitive to the

FIGURE 11

VARIABLE INLET GUIDE VANE TESTS

POWER AUGMENTATION AT 100% CORR. SPEED

COMPRESSOR TEST RESULTS



changes of inlet blade angle (and hence to incidence angle) for the rotors tested. The inability to accomplish the required compressor augmentation needed to achieve the program engine augmentation goal must therefore be due to a deficiency in the VIGV performance or a performance coupling between VIGV and compressor. The data of Fig. 11 implies that the sharp rise in VIGV loss with deflection angle occurs at a smaller value of deflection angle than indicated in Ref. (4), which was used for design and performance background. Calculations were performed to deduce the VIGV loss characteristic from the engine compressor data. This was accomplished by altering the VIGV loss versus deflection angle characteristic in combination with the known zero-swirl compressor map until the compressor augmentation test data was matched. The results are shown in Fig. 13 in a comparison with the data of Ref. (4). the deduced loss characteristic shows the sharp rise in loss to occur at about 20° deflection angle instead of 35° as indicated by the data of Ref. (4).

Several courses of action were considered. First, it could be possible that the clearance spaces are producing significant end-wall losses and affecting rotor inlet conditions. To confirm this, a test was conducted to evaluate the effect of VIGV clearance on compressor performance. The guide vane flaps were set to −30°, and the clearance gaps were filled. Test results showed no change in compressor performance. This indicates that clearance losses and their effect on the rotor inlet are small compared to the profile losses. Secondly, the VIGV assembly could be tested on a flow rig to confirm the deduced loss characteristic. This confirmation is necessary in order to isolate performance coupling between the VIGV and the compressor. The deduced VIGV performance was obtained on the assumption of no change in compressor performance. It could be possible that the discharge conditions from the VIGV affect compressor efficiency and work. To obtain a quick and simple evaluation of the loss characteristic, it was decided to install a wake-rake between the guide vanes and the rotor inlet at the arithmetic mean radius. (See Fig. 14).

The rake had equally spaced tubes with an overall width equivalent to the VIGV circumferential blade spacing. The longitudinal axis of the rake is coincident with the VIGV axis at −20° and is radially located at the arithmetic mean radius. During the test, the guide vane flap was varied until a definite wake was established, rather than recording data at specified flap angles. Because there were only ten elements in the wake-rake (cf. Fig. 14) there were only five flap angles between +4° and −30° at which a definite wake could be defined. These, however, were sufficient to establish the shape of the loss curve.

The wake-rake data is shown in Fig. 15 in terms of total pressure drop parameter and pitch spacing. The flap angles at which a definite wake was found are +4°, −3.5°, −11.4°, −21.5° and −25 °. The wake changes very little between −25° and −30°. This is probably due to the fact that the next valid wake definition is beyond −30°. At +4°, the misalignment of the flow direction with the fixed probe is beginning to cause less that full impact total pressure to be recorded outside of the wake. This affects the validity of the loss coefficient computed at this flap angle. The loss coefficients computed from these data points are compared with the deduced characteristics in Fig. 16.

The results in Fig. 16 show that the guide vane loss begins to rise at about −15°. The loss characteristic is much closer to the deduced estimate that to the data of Ref. (4). The conclusion is that the lack of continued augmentation of compressor pressure ratio and flow beyond −20° VIGV angle is primarily due to high guide vane loss. The possibility still exists for a contribution to loss due to an interaction between the guide vane and the rotor. However, it must either be of secondary importance as a direct increment of loss, or it is the reason for the difference from the data of Ref. (4). No in-depth analysis has been performed yet.

For the third course of action, the stationary forward section of the guide vane could be re-staggered to impose an initial bias of −10° swirl as shown in Fig. 17. This gives an initial −10° bias, due to angle of attack, before the rear section is activated relative to the forward section. The −30° preswirl should then be achieved with aerodynamic loading shared by both the forward and rearward sections instead of completely on the rear section.

The compressor test results are shown in Fig. 18. The plot shows that the −10° stators brought the compressor augmentation closer to program goals. The original 0° stator

FIGURE 12
VARIABLE INLET GUIDE VANE TESTS
B.36 COMPRESSOR CHARACTERISTICS

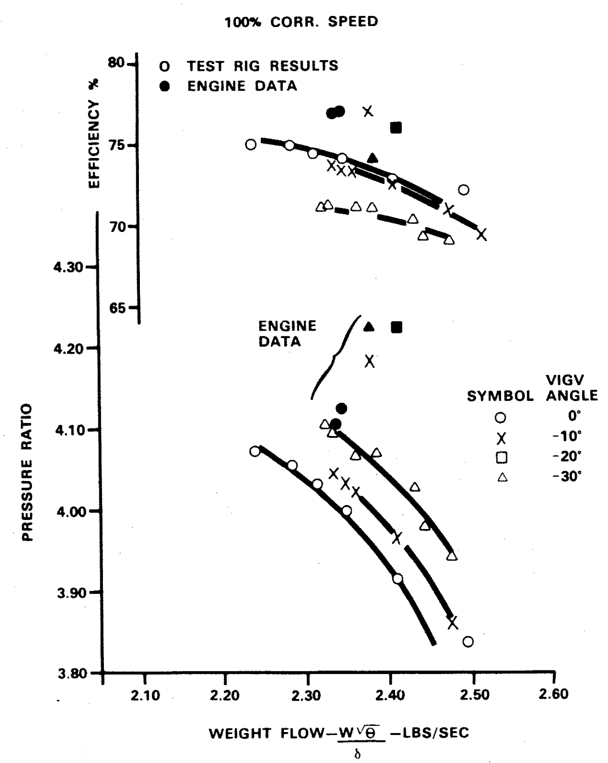


FIGURE 13
VIGV LOSS CHARACTERISTICS

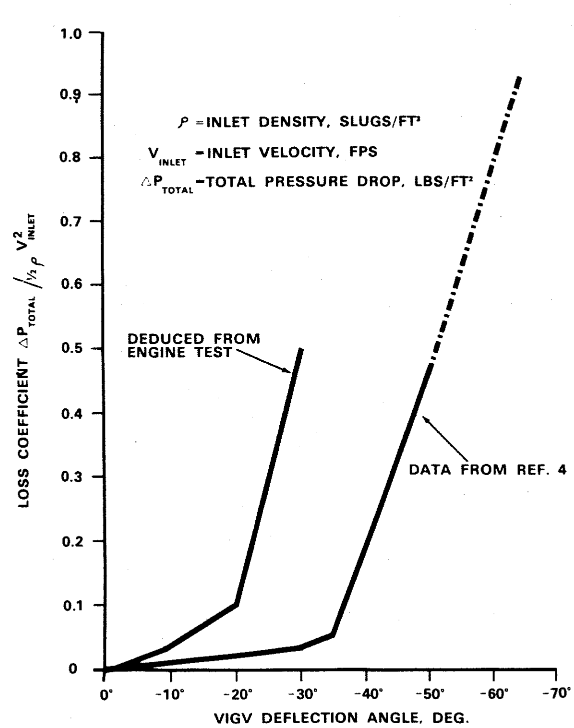


FIGURE 14

INSTRUMENTATION BEHIND VARIABLE INLET GUIDE VANES ON BASELINE ENGINE

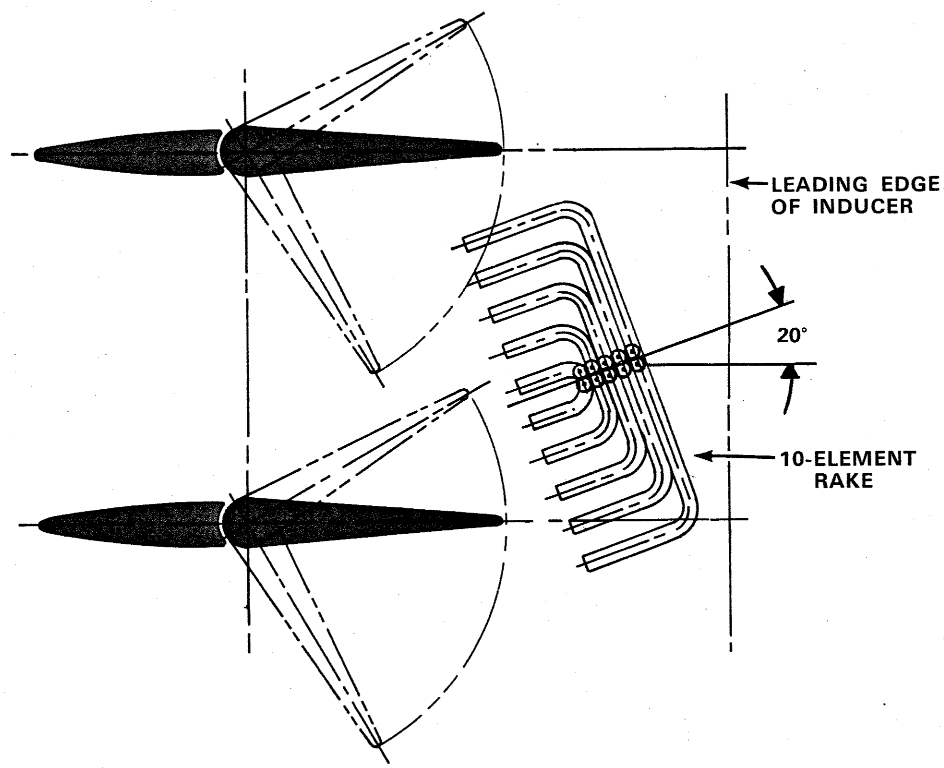
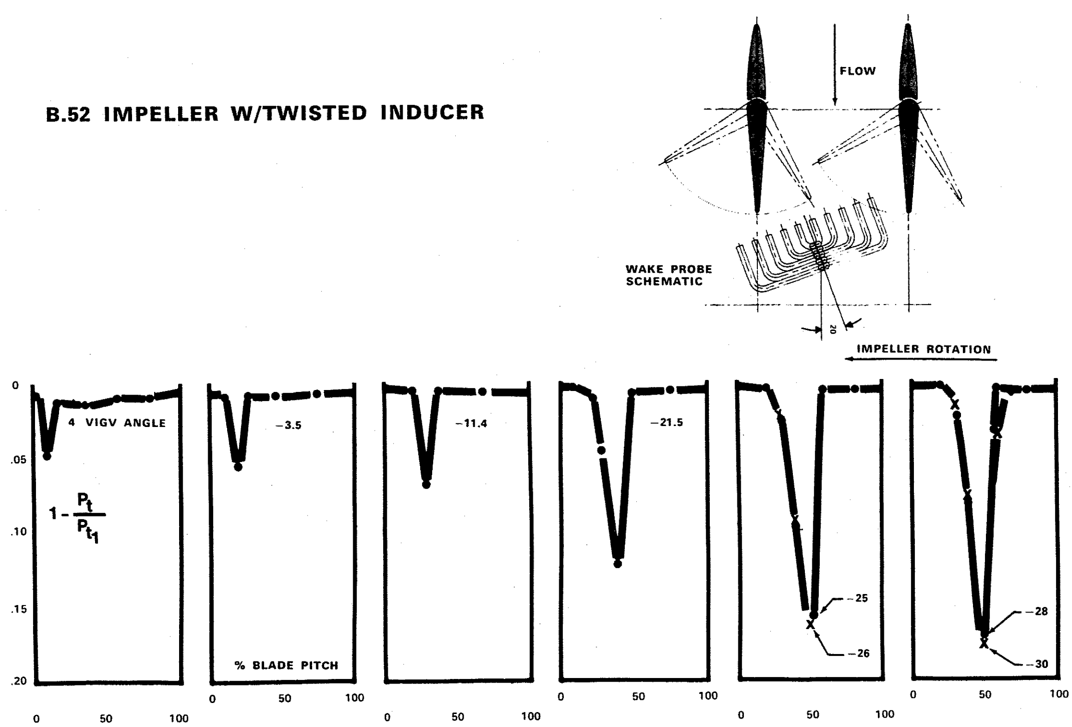


FIGURE 15

VARIABLE INLET GUIDE VANE WAKE SURVEYS AT 100% CORRECTED SPEED



design met the augmentation goal up to about −20° VIGV angle. The −10° stators met the goal up to about −27°. It may be possible to meet the goals at higher values of negative VIGV angle with higher values of negative stator stagger angle. However, as shown in Fig. 19, twisting the stators from 0° to −10° resulted in 50% speed compressor efficiency dropping one to three points over the raange of VIGV operation. Consequently, additional negative bias on the stator could be expected to degrade compressor efficiency further at the low speeds.

The engine augmentation results are shown in Fig. 20. Maximum power augmentation did not increase although the power level did not increase at VIGV angles greater than −20°. The engine results do not reflect the increase in compressor performance. At −25° VIGV angle, the pressure ratio (Fig. 18) increased 1.5%, the flow increased 2.3% and the compressor efficiency increased about one point. Collectively, this should have amounted to a 6% increase in power. The data shows only a 2.5% increase in power over the results obtained with the 0° stator at −25° VIGV angle. Consequently, the engine data was reviewed for turbine performance parameters to explain the lack of engine augmentation.

TURBINE ANALYSIS FROM ENGINE TESTING

The efficiencies and pressure ratios across the gas generator and power turbines are shown in Figs. 21 and 22, respectively. The gas generator turbine efficiency begins to drop at about −20° VIGV angle. To accommodate the compressor work, the pressure ratio across this turbine rises sharply. Fig. 22 shows a slight drop in power turbine efficiency within the data scatter and a significant drop in power turbine pressure ratio beyond −20° VIGV angle.

These results showed that the lack of engine augmentation was due to reduction in available pressure ratio across the power turbine. This could be due to progressive reduction in gas generator turbine efficiency beyond −20° VIGV angle. As efficiency drops, the pressure ratio available for the power turbine is reduced. Also, as compressor work increases with augmentation, the Mach Number increases into the interstage duct between turbines. This increases the interstage duct diffusion losses,

FIGURE 16

VARIABLE INLET GUIDE VANE LOSS CHARACTERISTICS

COMPARISON OF EXPERIMENTAL PITCH-LINE LOSS COEFFICIENTS WITH CASCADE DATA AND DEDUCED VALUES FROM BASELINE ENGINE COMPRESSOR TEST DATA

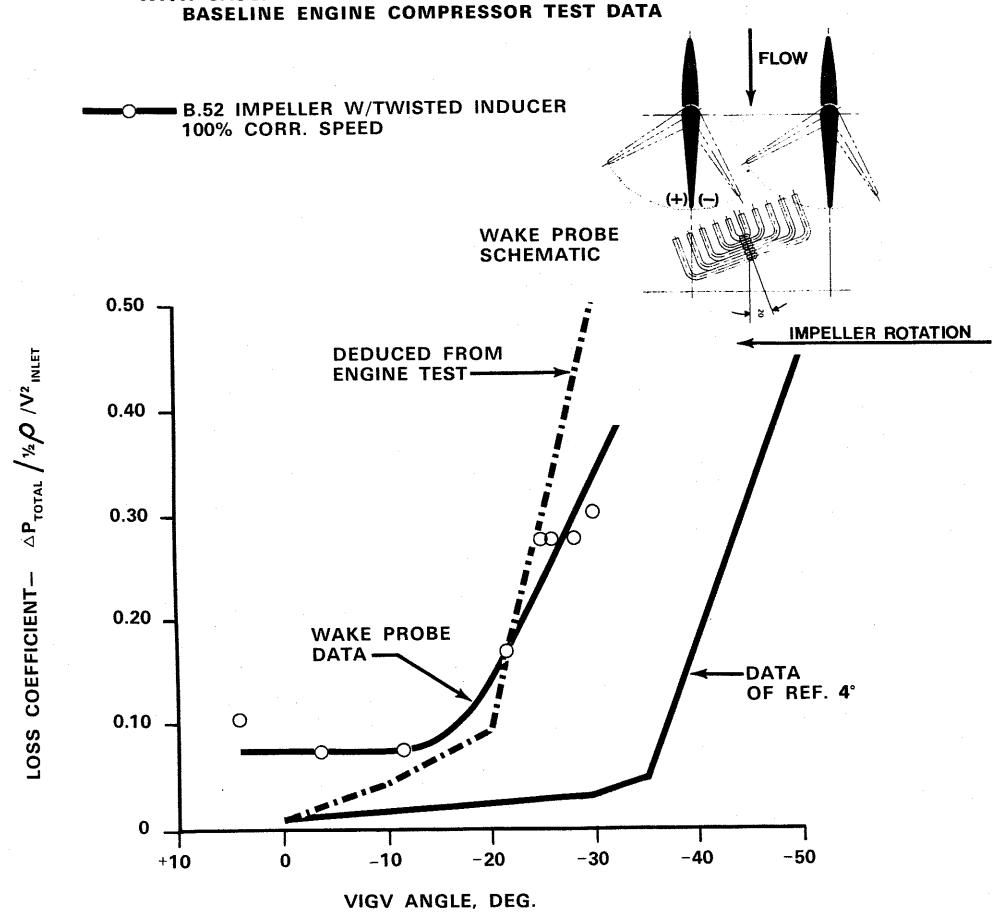
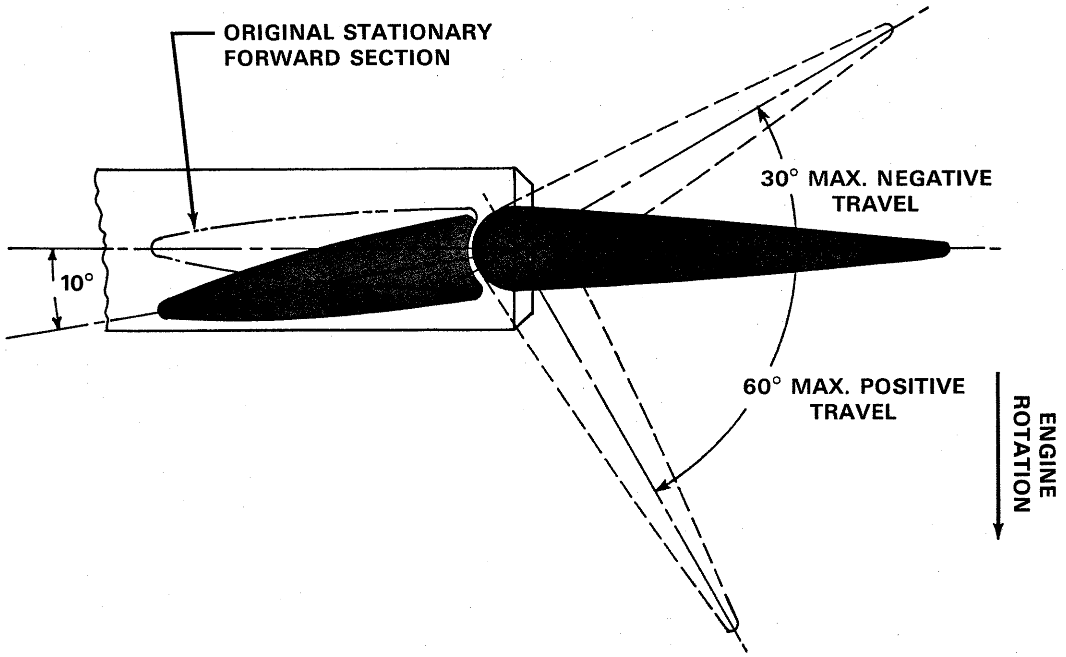


FIGURE 17

COMPARISON OF ORIGINAL VS. REVISED VIGV FORWARD SECTION ON BASELINE ENGINE



which also reduces the available pressure ratio across the power turbine.

A study was conducted to determine the reasons for the lack of Baseline Engine power augmentation in constrast to the performance augmentation of the baseline compressor with variable inlet guide vanes. The study consisted of computing the performances and aerodynamic states of the compressor turbine and power turbine under augmented conditions of 0°, −15° and −25° VIGV angles. The intention was to try to duplicate the engine results computationally and then examine the component performances and the vector diagram data for the cause. The calculations were performed with turbine off-design computer programs which estimate performance based on pitch-line vector diagram parameters and aerodynamic models of loss, blockage and deviation angle. The loss model accounts for profile, mixing, endwall and clearance losses with a correction for Reynolds number.

A comparison of the computed versus the experimental power augmentation is shown in Fig. 23. There is good agreement between calculated and test results. The calculated results, however, show larger reductions in power turbine efficiency with VIGV angle than indicated by the data. This is illustrated in Fig. 24. The efficiency levels are different, but the trends are similar up to about −15° VIGV angle. Beyond this value, the estimated efficiency for the power turbine reduced much faster than the values computed from the data. It should be recognized that the probe sampling to obtain the component turbine data from

FIGURE 18

ENGINE PARAMETER CHARACTERISTICS WITH VIGV AUGMENTATION AT 100% CORR. SPEED

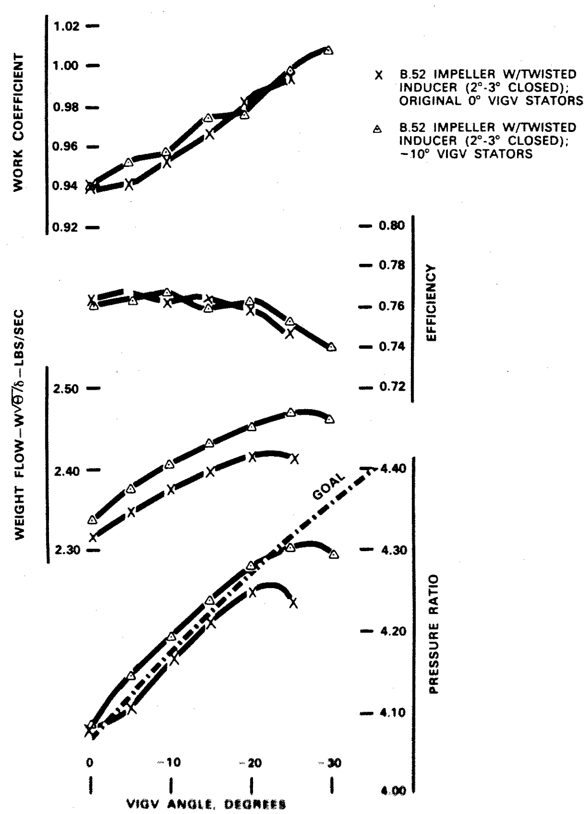


FIGURE 19

VARIABLE INLET GUIDE VANE TESTS
COMPRESSOR EFFICIENCY AND PRESSURE RATIO AT 50% CORR. SPEED
PEAK POWER POINTS

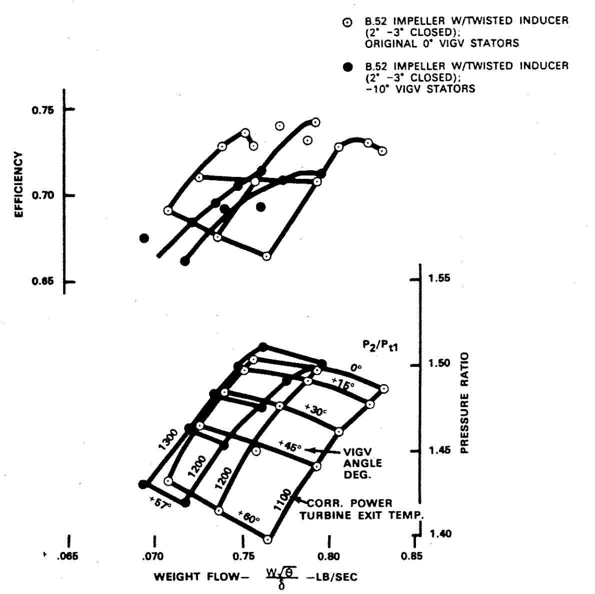


FIGURE 20

EFFECT OF VIGV ANGLE ON
PEAK POWER AT 100% CORR. SPEED

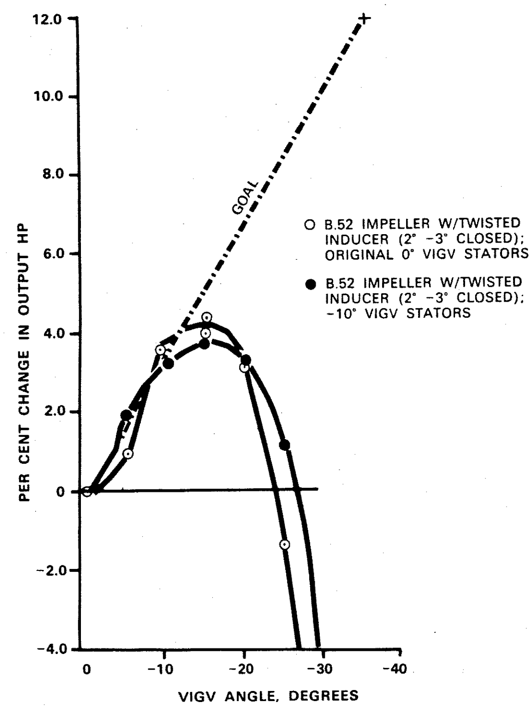


FIGURE 21

GAS GEN. TURBINE CHARACTERISTICS WITH VIGV AUGMENTATION
AT 100% CORR. SPEED

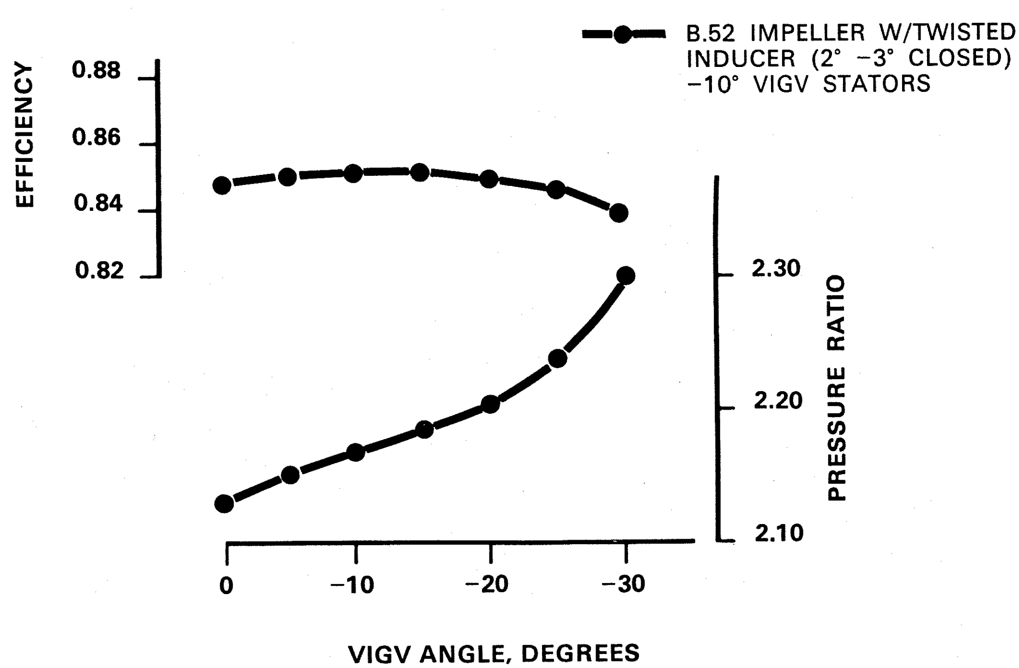
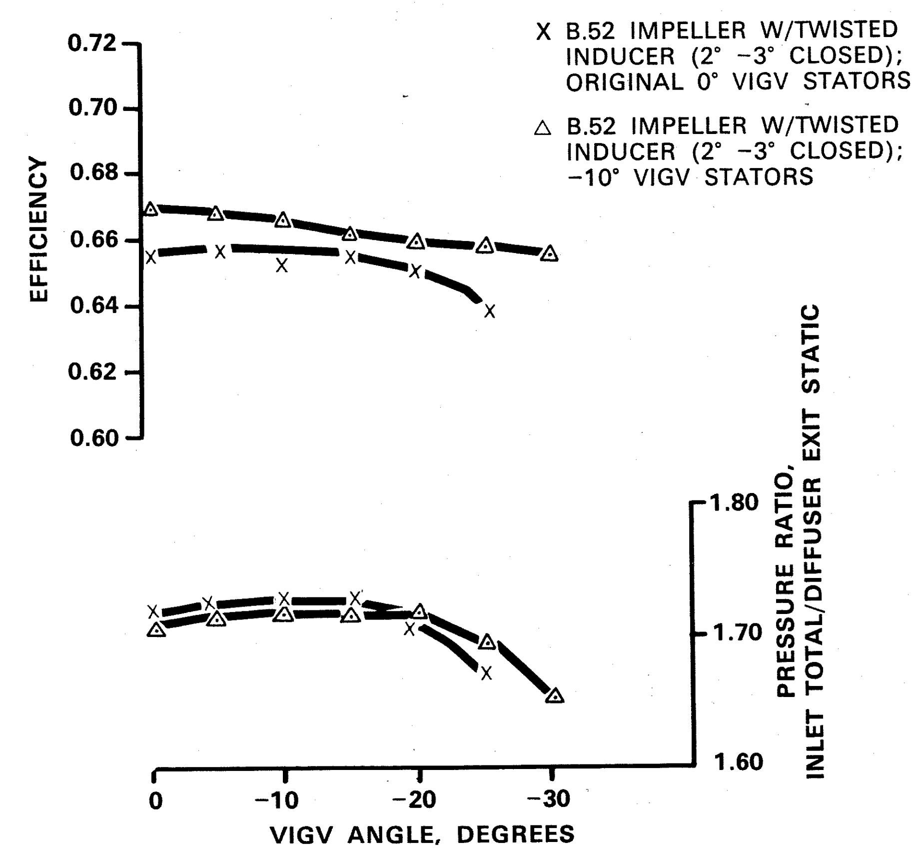


FIGURE 22

POWER TURBINE CHARACTERISTICS WITH VIGV AUGMENTATION AT 100% GAS GENERATOR SPEED

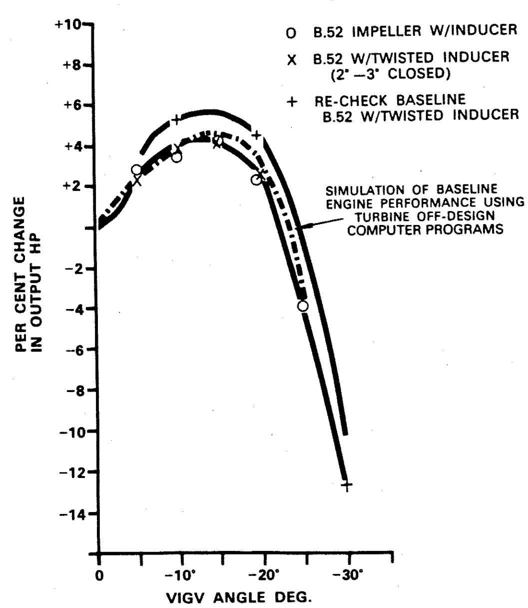


engine tests was quite small and that a certain amount of imprecision can exist in the test results.

The sharp decrease in calculated power turbine efficiency is due to increased loss in the interstage duct due to increased Mach Number at the exit of the gas generator turbine (GGT). This is a consequence of trying to extract extra work out of a turbine which was designed for a work coefficient of 2.4 and consequently was designed with a high rotor exit Mach Number with significant exit swirl.

FIGURE 23

EFFECT OF VIGV ANGLE ON PEAK POWER AT 100% SPEED CONSTANT TURBINE INLET TEMPERATURE



GENERAL APPLICATION TO POWER AUGMENTATION AND PART-POWER FUEL ECONOMY

The development work on the VIGV and the turbine performance results from engine testing have shown the aerodynamic requirements needed for engine power augmentation. In this work, a compromise was taken in compressor efficiency at part-power in order to come sufficiently close to to the required increase in compressor pressure ratio and flow. Steps have been taken in the

Upgraded Engine design to try to reduce the compromise with part power fuel economy. The Baseline Engine testing also showed the need to design the gas generator turbine with lower rotor exit Mach Number and swirl. In the Upgraded Engine, the work coefficient has accordingly been reduced to enhance augmentation.

With regard to the VIGV development, the stationary forward section had to be staggered $-10°$ to achieve the required augmentation in concert with the loss characteristic of the VIGV. In so doing, there were 1-3 points lost in compressor efficiency at 50% speed over the 60° range of positive preswirl. Additional development work is needed to eliminate this compromise on part-speed performance. This compromise would not be needed if the VIGV loss characteristic were similar to that of Ref. (4). It has been conjectured that the proximity of the rotor has partially contributed to this. When the vanes are deflected opposite engine rotation, the close proximity of the rotor suggests that the rotor could be inducing the flow to deviate from the suction surface. It is also hoped that use of a backswept rotor will enhance the aerodynamic matching of the VIGV to the rotor. The Upgraded Engine impeller will have 30° of backsweep.

The Baseline Engine results showed that, in order to achieve successful augmentation, the gas generator turbine should not be designed for too high a work coefficient or the rotor exit conditions will tend to deteriorate interstage duct recovery during augmentation. The Upgraded Engine gas generator turbine has a work coefficient of 2.1 compared to the Baseline Engine value of 2.4. This is expected to prevent such deterioration because of lower rotor exit Mach number and swirl values than those of the Baseline Engine. However, it is also necessary for the gas generator turbine to achieve its design efficiency. Fig. 25 shows the computed values of rotor exit absolute Mach Number and swirl angle for the Baseline and Upgraded Engine. The latter is presented for two values of turbine efficiency - program goals and 2 points below. The increase in Mach number beyond $-15°$ VIGV angle has been sharply reduced by the lower work-coefficient of the Upgraded Engine. Note, however, the increase in Mach Number and swirl with a 2-point miss in target efficiency.

The result of turbine performance uncertainties on augmentation is shown on Fig. 26. To meet program goals, the target efficiency must be met, and the interstage duct must have an effectiveness of 0.78. The plot shows the variation of power augmentation with a 5-point difference in diffuser effectiveness. The miss in augmentation is more serious if the gas generator turbine misses its target by 2 points. The available pressure ratio across the power turbine is reduced not only by the miss in gas generator turbine efficiency, but also by increased interstage duct losses due to increases in rotor exit Mach Number and swirl. In general, then, VIGV augmentation can be achieved if the gas generator efficiency is sufficiently high and if the interstage diffusion is not seriously degraded over the required range of VIGV angle.

At part-power at 50% speed, the turbine efficiencies increase with positive preswirl on the compressor, as shown

FIGURE 24

VARIATION OF TURBINE EFFICIENCIES WITH VIGV AUGMENTATION AT 100% GAS GENERATOR SPEED

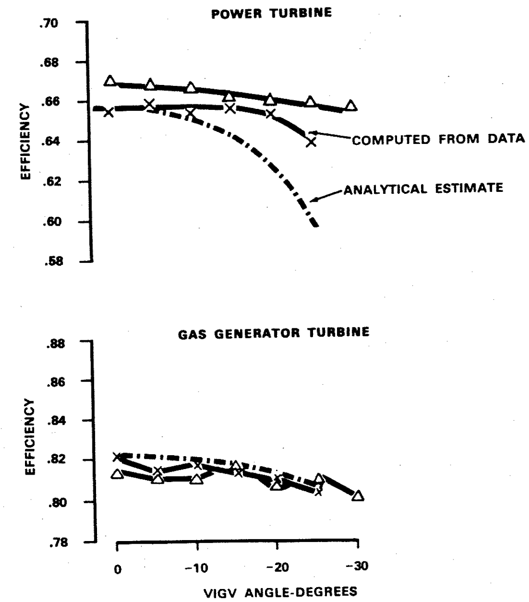
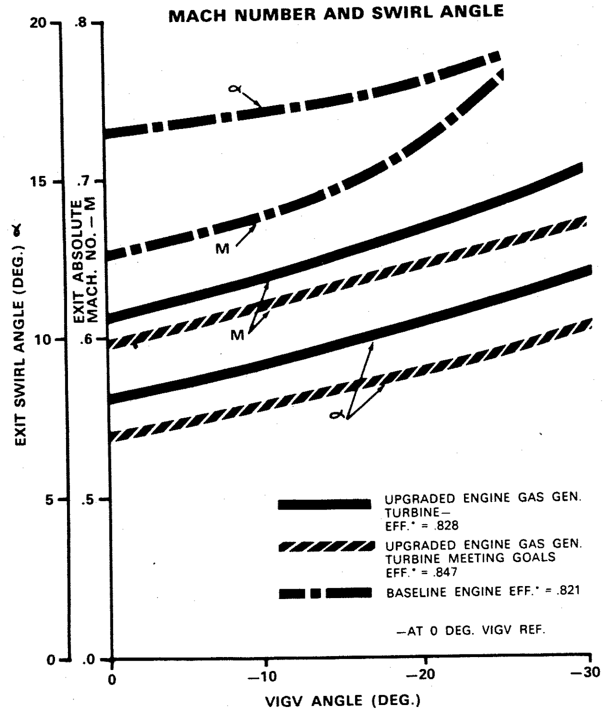


FIGURE 25

GAS GENERATOR TURBINE EXIT MACH NUMBER AND SWIRL ANGLE



in Fig. 27. The difference in gas generator turbine efficiency between the two sets of data has not been explained. The increases in efficiency are a result of maintaining high turbine inlet temperature and reducing compressor work.

FIGURE 26
ESTIMATED UPGRADED ENGINE POWER TURBINE RESPONSE TO VIGV AUGMENTED COMPRESSOR

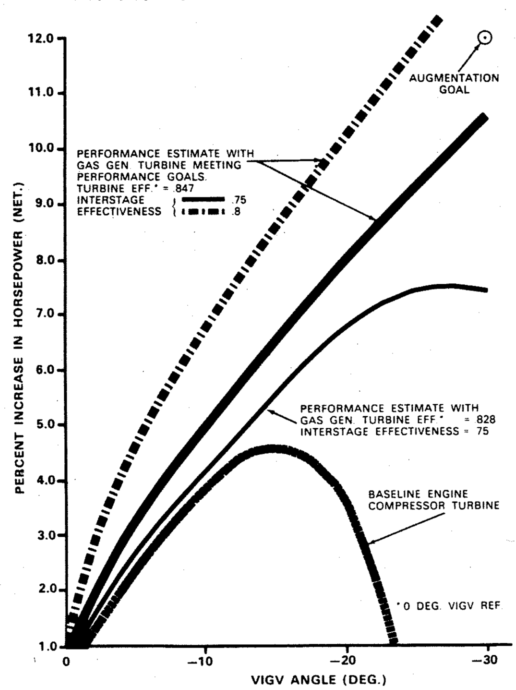
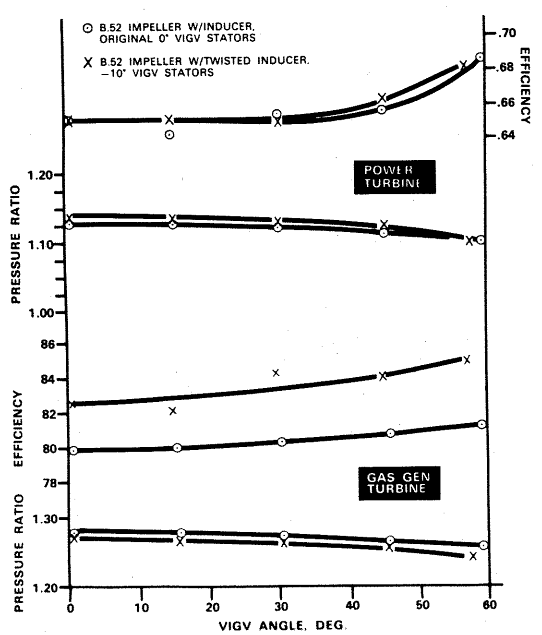


FIGURE 27
TURBINE PERFORMANCE AT 50% GAS GEN. SPEED—MAX. POWER POINTS
CONSTANT POWER TURBINE EXIT CORR. TEMP. = 1300° F.



This combination yields reduced corrected turbine work and, hence, increased efficiency.

CONCLUSION

This paper has presented the results of the design and development work on variable inlet guide vanes (VIGV) for use in the ERDA Upgraded Automotive Gas Turbine Engine. The feasibility of the concept of VIGV augmentation was carried out on ERDA Baseline engine hardware in compressor rig and complete engine testing.

The design and development work has identified problem areas which must be addressed in order to achieve successful augmentation with VIGV. It was found necessary to bias the stator of an articulated VIGV to achieve increases in compressor flow and pressure ratio up to −27° flap angle. It was also found that the gas generator turbine must have satisfactorily high efficiency and sufficiently low exit Mach Number and swirl angle in order not to significantly degrade the interstage duct diffusion during augmentation. High recovery is needed in the interstage duct and therefore, care must be taken in the design of the interstage duct to achieve high values of effectiveness.

ACKNOWLEDGMENTS

Acknowledgment is made to D. S. Musgrave, who performed the analytical work for the compressor; C. H. Mader, who conducted the compressor rig tests and performed the turbine analytical work, and to J. V. Gross, who conducted the engine testing.

REFERENCES

1. Penny, Noel: "Rover Case History of Small Gas Turbines." SAE Paper 634A, January 1963.
2. Castor, J. G. Davis, R. C. and Riddle, B. C.: "Automobile Gas Turbine Optimumization Study." Prepared for the Environmental Protection Agency by Ai Research Manu. Co. of Arizona, July 1972.
3. Sheridan, David C., Nordenson, Gary E. and Amman, Charles A.: "Variable Compressor Geometry in the Single-Shaft Automotive Turbine Engine." SAE Paper 740166, February 1974.
4. G. K. Serovy, et al., Experimental Performance in Annular Cascade of Variable Trailing-Edge Flap, Axial-Flow Compressor Inlet Guide Vanes. ASME 70-GT-106.
5. Jones, B. A., "Single Stage Experimental Evaluation of Variable Geometry Inlet Guide Vanes and Stator Blading." (Part VI, Final Report) NASA CR-54559, March 15, 1970.
6. Bilwakesh, K. R., "Evaluation of Range and Distortion Tolerance for High Mach Number Transonic Fan Stages, Volume I," NASA CR-72787, January 1971.
7. Lieblein, Seymour and Roudebush, William H., "Theoretical Loss Relations for Low-Speed Two-Dimensional-Cascade Flow. NACA TN 3662, March 1956.

Society of Automotive Engineers, Inc.
400 COMMONWEALTH DRIVE, WARRENDALE, PA. 15096

____ page booklet.

Printed in U.S.A.