Total pressure loss is one of the most important parameters in the design of a turbine. This parameter affects not only the turbine performance, but consequently the engine power balance and engine performance. Computational Fluid Dynamics (CFD) can be an effective tool in predicting turbine total pressure loss, and also for performing sensitivity studies to achieve an optimal design with respect to pressure loss. In the present study, the AEROVISC code was used to predict the total pressure loss in the Turbine Technology Team Gas Generator Oxidizer Turbine (GGOT).

The objectives in this study are two-fold. It is first necessary to determine an optimal methodology in predicting total pressure loss. The type of grid, grid density and distribution are parameters which may effect the loss prediction. Also, the effect of using a standard K-ε turbulence model with wall functions versus a two-layer turbulence model needs to be investigated. The use of grid embedding to resolve areas with high flow gradients needs to be explored. The second objective of the study is to apply the optimal methodology toward evaluating different tip leakage control concepts.

The approach taken in this study was as follows:

1) A nominal baseline case was run (baseline grid with standard wall functions)
   a) Grid parametrics were performed on grid density
   b) Grid embedding was applied to the rotor leading and trailing edges, and in the tip region.
   c) Evaluation of a two-layer turbulence model (in progress)

Each of the above cases were assessed in terms of total pressure loss in comparison with the baseline case, and in terms of the difference in secondary flow resolution in comparison with the baseline case.

2) The optimal methodology from Step 1 is applied towards evaluating different tip leakage control concepts which will include
   a) Hollow rotor
   b) Hollow rotor with partitions (labyrinth seal approach)
   c) Hollow rotor with partitions and suction-side rotor slots (to reduce fluid impingement angle)

As this work is still in progress, conclusions are not available at this time.
GGOT TOTAL PRESSURE LOSS
CONTROL CONCEPT EVALUATION

R. F. BLUMENTHAL
AEROJET PROPULSION DIVISION

APRIL 22, 1993
OXIDIZER TURBINE BASELINE DESIGN

Full Scale Turbine Flowpath
GGOT TOTAL PRESSURE LOSS
CONTROL CONCEPT EVALUATION

OBJECTIVE: EVALUATE TIP LEAKAGE CONTROL CONCEPTS
WHICH REDUCE TIP LEAKAGE AND TOTAL PRESSURE LOSS

APPROACH: 1.) PERFORM GRID DEPENDENCY STUDY

RUN NOMINAL BASELINE CASE WITH BASELINE GRID
USING AEROVISC CODE AND STANDARD LOG–LAW WALL FUNCTION

a.) PERFORM GRID PARAMETERICS ON GRID DENSITY
b.) EVALUATE MERITS OF GRID EMBEDDING
c.) EVALUATE TWO–LAYER TURBULENCE MODEL

2.) EVALUATE TIP TREATMENT CONCEPTS, INCORPORATING
OPTIMAL METHODOLOGY/PROCEDURE FROM STEP 1
GGOT TOTAL PRESSURE LOSS/
GRID DEPENDENCY STUDY

APPLIED BOUNDARY CONDITIONS

Propulsion Division

PERIODIC

TURBULENT WALL (COUNTER-ROTATING
AT -825.19 RAD/SEC W.R.T.
RELATIVE FRAME)

PT, TT AND FLOW
DIRECTION BASED
ON P&W EULER CALC

PS=F(R) BASED ON
P&W EULER CALC

TURBULENT WALL (STATIONARY W.R.T.
RELATIVE FRAME)
GGOT TOTAL PRESSURE LOSS/
GRID DEPENDENCY STUDY

GRID PARAMETRIC APPROACH AND RESULTS

- BASELINE GGOT ROTOR GRID (82 x 41 x 24 w/ 5 GRIDS IN TIP GAP RADIAL DIRECTION)

- GRID PARAMETERICS PERFORMED BY INCREASING GRID COUNT UNIFORMLY IN EACH
PARAMETRIC DIRECTION (AXIAL, CIRCUMFERENTIAL, RADIAL). THREE CASES IN EACH
DIRECTION WERE RUN, FOR A TOTAL OF TEN CASES (INCLUDING THE BASELINE).

- ALL CASES WERE RUN UNTIL A SIMILAR CONVERGENCE LEVEL WAS ACHIEVED
# GGOT TOTAL PRESSURE LOSS/GGRID DEPENDENCY STUDY

## GRID PARAMETRIC APPROACH AND RESULTS

<table>
<thead>
<tr>
<th>CASE</th>
<th>I-DIR</th>
<th>J-DIR</th>
<th>K-DIR</th>
<th>TIP GAP</th>
<th>TOTAL</th>
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GRID PARAMETRIC APPROACH AND RESULTS (PRELIMINARY)

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<th>PLOSS/ PLOSS BASE</th>
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<td>BASE</td>
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NOTE: ALL PRESSURES ARE BASED ON MASS-AVERAGED VALUES
EXIT STATIC PRESSURE USED FOR PRELIMINARY PARAMETERICS
BASED ON STATIC PRESSURE SPECIFIED AT ONE NODE IN EXIT PLANE
(PS=215.5 PSI AT CENTER OF EXIT PLANE)
GRID PARAMETRIC APPROACH AND RESULTS

<table>
<thead>
<tr>
<th>CASE</th>
<th>PT REL (INLET) [PSI]</th>
<th>PT REL (EXIT) [PSI]</th>
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NOTE: ALL PRESSURES ARE BASED ON MASS-AVERAGED VALUES
EXIT STATIC PRESSURE BASED ON RADIAL PRESSURE DISTRIBUTION
PROVIDED BY P&W FROM EULER CALC
BASELINE RESULTS
VELOCITIES IN MID-GAP REGION (K=22)
HIGH TIP FLOW VELOCITIES COUPLED WITH LARGE IMPINGEMENT ANGLE INFLUENCE MAINSTREAM FLOW AT SOME DISTANCE DOWNSTREAM OF ROTOR
BASELINE RESULTS

STREAKLINES AT TIP SHOW DEVELOPING PASSAGE VORTEX
(PARTICLES RELEASED IN MID-GAP REGION)
BASELINE RESULTS

VELOCITY CONTOURS SHOW EFFECT OF TIP LEAKAGE ON MAINSTREAM FLOW
CONSIDERABLE FLOW DECELERATION OCCURS
GGOT TOTAL PRESSURE LOSS/
GRID DEPENDENCY STUDY

GRID EMBEDDING AT TRAILING EDGE (22 x 43 x 70)
(EMBEDDED GRIDS EXTEND FROM HUB TO TIP ENDWALL)
GGOT TOTAL PRESSURE LOSS/
GRID DEPENDENCY STUDY

GRID EMBEDDING IN THE TIP GAP REGION (103 x 91 x 13)
(EMBEDDEDGRIDS EXTEND FROM ROTOR TIP TO ENDWALL)
GGOT TOTAL PRESSURE LOSS/GRID DEPENDENCY STUDY

BASELINE GRID STREAKLINES NEAR LEADING EDGE (K=2)
GRID LACKS RESOLUTION NEEDED TO RESOLVE SADDLEPOINT
GRID EMBEDDING AT LEADING EDGE IS USEFUL IN DEFINING IMPORTANT FLOW FEATURES SUCH AS THE SADDLEPOINT OF THE LIMITING STREAMLINES AT THE HUB.
GGOT TOTAL PRESSURE LOSS/GRID DEPENDENCY STUDY

GRID EMBEEDING IN TP GAP
RELATIVE TOTAL PRESSURE LOSS AT MIDGAP (K=22)
PT=PT_REL(IN AVE) - PT_REL(UPT_REL(IN AVE))
GGOT TOTAL PRESSURE LOSS/
GRID DEPENDENCY STUDY

TRAILING EDGE GRID EMBEDDING NEAR HUB PLANE (K<2)
EMBEDDING HELPS TO RESOLVE SUCTION SIDE RECIRC
## GGTOT TOTAL PRESSURE LOSS/
GRID DEPENDENCY STUDY

### GRID EMBEDDING RESULTS

<table>
<thead>
<tr>
<th>CASE</th>
<th>PT REL (INLET) [PSI]</th>
<th>PT REL (EXIT) [PSI]</th>
<th>DPT REL [PSI]</th>
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<th>PLOSS/ PLOSS BASE</th>
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**NOTE:** ALL PRESSURES ARE BASED ON MASS-AVERAGED VALUES
EXIT STATIC PRESSURE USED FOR PRELIMINARY PARAMETERICS
BASED ON STATIC PRESSURE SPECIFIED AT ONE NODE IN EXIT PLANE
(PS=215.5 PSI AT CENTER OF EXIT PLANE)
RESULTS PRESENTED THUS FAR ARE BASED ON THE STANDARD K–E TURBULENCE MODEL WHICH EMPLOYS WALL FUNCTIONS TO MODEL THE VISCOUS NEAR–WALL LAYER. THE ADVANTAGE OF THIS APPROACH IS THAT THE WALL FUNCTION ELIMINATES THE NECESSITY OF NUMERICALLY RESOLVING THE LARGE GRADIENTS IN THE THIN NEAR–WALL REGION, thus conserving computer resources. THE DISADVANTAGE IS THAT CERTAIN ASSUMPTIONS MUST BE MADE WHICH MAY NOT BE ACCURATE IN ALL FLOW SITUATIONS, ESPECIALLY WHERE THERE ARE SEPARATED FLOWS.


STATUS: MODEL IS CURRENTLY RUNNING. CONVERGENCE DIFFICULTIES HAVE BEEN ENCOUNTERED, PROBABLY RELATED TO HIGH ASPECT RATIOS (~ 25000 AT BLADE SURFACE AT MID–SPAN). SOLUTIONS BEING EXAMINED INCLUDE INCREASING NODE COUNT IN RADIAL DIRECTION, RUNNING CODE IN DOUBLE PRECISION.
Figure 39: $f_e$ versus $n^+$

Figure 40: $f_\mu$ versus $n^+$
Using baseline grid, 15 nodes were added between the wall and the first node away. Nodes are clustered such that 5 nodes are within yplus=5 (assuming yplus varies linearly away from wall).

112 x 71 x 24 (190848 nodes)

Leading edge (K=1)
IN ORDER TO QUANTIFY THE BENEFITS OF POSSIBLE TIP TREATMENTS, THE BASELINE GRID WAS RUN AT ZERO GAP AND AT A MAXIMUM GAP OF 0.030 IN. THE NODE COUNT IN THE TIP GAP FOR THE MAX CLEARANCE CASE WAS INCREASED FROM 5 TO 11 FOR A GRID DIMENSION OF 82 x 41 x 30.

<table>
<thead>
<tr>
<th>CASE</th>
<th>CLEARANCE [IN]</th>
<th>PLOSS</th>
<th>PLOSS/PLOSS NOM.</th>
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<td>MAX GAP</td>
<td>0.030</td>
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AS A RESULT OF THE GRID DEPENDENCY STUDY, THE AMOUNT OF VARIATION IN PRESSURE LOSS CALCULATED WAS +/- 4%. IN ORDER TO ADEQUATELY ASSESS DIFFERENT TIP TREATMENTS, THE FOLLOWING PROCEDURES ARE SUGGESTED:

1.) SIMILAR GRIDS FOR ASSESSING TIP TREATMENTS SHOULD BE USED, WHEN POSSIBLE.
2.) TIP TREATMENT CASES SHOULD BE FIRST EVALUATED AT THE MAXIMUM GAP (0.030 IN) IN ORDER TO MAXIMIZE DIFFERENCES BETWEEN DIFFERENT TREATMENTS. GOOD TIP TREATMENT CANDIDATES WILL THEN BE ASSESSED AT THE NOMINAL CLEARANCE.
GGOT TIP TREATMENT EVALUATION STUDY

GIVEN THE RELATIVELY LARGE SURFACE AREA AT THE BLADE TIP, A PROMISING METHOD FOR REDUCING TIP LEAKAGE MAY BE TO CREATE A POCKETED SURFACE ON THE ROTOR TIP; SIMILAR TO A LABYRINTH SEAL.

IN ORDER TO DETERMINE THE SENSITIVE PARAMETERS INVOLVED, IT IS USEFUL TO EXAMINE A LABYRINTH SEAL FLOW EQUATION. THE FOLLOWING IS A METHOD PROPOSED BY VERMES (1961) WHICH IS A MODIFICATION OF MARTIN'S FORMULA FOR LABYRINTHS:

\[ W = 5.76 \times K \times A \times P_0 \times \beta \times [R \times (1 - \alpha)]^{0.5} \]

- **W** = WEIGHT FLOW [LB/SEC]
- **K** = \(f(RE, L/C)\) - CLEARANCE FACTOR OF SINGLE ANNULAR ORIFICE
- **A** = ANNULAR ORIFICE FLOW AREA [IN^2]
- **P_0** = UPSTREAM TOTAL PRESSURE [PSI]
- **T_0** = UPSTREAM TOTAL TEMPERATURE [DEG R]
- **\alpha** = 8.52/[(P-L)/C+7.23] - RESIDUAL ENERGY FACTOR
- **P** = DISTANCE BETWEEN TEETH [IN]
- **L** = TOOTH TIP WIDTH [IN]
- **C** = CLEARANCE [IN]
- **\beta** = \((1-(P_0/P)^{0.5})/([N\cdotLN(P/N)]^{0.5})\) - GLAND FACTOR
- **P_0** = STATIC PRESSURE AT EXIT OF LAST TOOTH [PSI]
- **N** = NUMBER OF TEETH
- **R** = GAS CONSTANT FT/DEG R
GGOT TIP TREATMENT EVALUATION STUDY

Propulsion Division

LABYRINTH GEOMETRY DEFINITION
ASSUMING PRESSURES, TEMPERATURES, SEAL CLEARANCE AND TOTAL SEAL LENGTH ARE DEFINED, THE REMAINING DESIGN PARAMETERS ARE NUMBER OF TEETH AND TOOTH WIDTH. ASSUMING MINIMUM TOOTH WIDTH (DETERMINED BASED ON STRUCTURAL REQUIREMENTS), THE ONLY REMAINING PARAMETER WHICH MAY BE MODIFIED IS THE NUMBER OF TEETH.


AS AN EXAMPLE APPLIED TO THE GGOT, A TYPICAL STEAMLINE STARTING NEAR THE LEADING EDGE IS SELECTED FROM THE MAX CLEARANCE CASE. THE ASSUMED PARAMETERS ARE:

\[ L = 0.030 \text{ in} \quad C = 0.30 \text{ in} \quad P_O = 419.5 \text{ PSI} \quad P_N = 197.8 \quad T_O = 1261.2 \quad L_{TOT} = 0.927 \text{ in} \]

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<th>NTEETH</th>
<th>PITCH</th>
<th>ALPHA</th>
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<th>MDOT (NORM.)</th>
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\[ \text{OPTIMAL TOOTH NUMBER} \]
GGOT TIP TREATMENT EVALUATION STUDY

VALIDATION CASE FOR LABYRINTH SEAL BASED ON VERMES TEST DATA

FLUID: AIR
L=0.015 IN
E=0.25 IN
P=0.25 IN
C=0.030 IN
R=5 IN
THETA=14 DEG
NTEETH=10

PO=73.5 PSI
TO=530 DEG R
PN=14.7 PSI

MDOT TEST = 0.70 LB/SEC
MDOT CFD = 0.91 LB/SEC

SYMM. WALLS
CURRENT STATUS:

1.) RUNNING HOLLOW BLADE CASE (TWO-TOOTH LABYRINTH)
   - 104 x 62 x 30 (10 NODES IN TIP GAP RADIAL DIRECTION)
   - 0.030 IN WALL THICKNESS WITH 0.030 IN TIP CLEARANCE.
     HOLLOW PORTION OF BLADE EXTENDS FROM MIDSPAN TO TIP.
   - RESULTS WILL BE COMPARED WITH SOLID BLADE TO ASSESS
     BENEFITS IN TERMS OF LOSS REDUCTION/REDUCED LEAKAGE.

2.) CONSTRUCTING ROTOR GRID FOR BASELINE MULTI-TOOTH
    LABYRINTH TIP SEAL (USING GRID EMBEDDING)
   - PARAMETERICS WILL BE NECESSARY TO OPTIMIZE DESIGN

3.) INVESTIGATING OTHER TIP TREATMENTS WHICH MAY REDUCE
    RELATIVE TOTAL PRESSURE LOSSES
   - SUCTION SIDE TRAILING EDGE SLOT TO PROVIDE FLOW GUIDANCE
     (TO REDUCE IMPINGEMENT ANGLE OF TIP LEAKAGE FLOW ON
     MAINSTREAM FLOW)
GGOT TIP TREATMENT EVALUATION STUDY

PARTIALLY HOLLOW BLADE WITH 0.030 IN WALL THICKNESS
104 x 62 x 30 (10 NODES IN TIP GAP RADIAL DIRECTION)
GGOT TIP TREATMENT EVALUATION
STUDY

ALTERNATE TIP TREATMENT METHODS - TRAILING EDGE SUCTION-SIDE SLOTT

OBJECTIVE: PROVIDE FLOW GUIDANCE TO REDUCE TIP LEAKAGE IMPINGEMENT ANGLE

ISSUES: 1.) NEED TO MAXIMIZE SLOTT ANGLE TO PROVIDE MAXIMUM GUIDANCE.
2.) RESISTANCE PATH THOUGH SLOTT SHOULD BE LESS THAN OVER TOP TO INDUCE FLOW THROUGH SLOTT (FUNCTION OF FLOW AREA).
3.) SLOTT DEPTH SHOULD BE MINIMIZED TO LOCALIZE EFFECTS TO TIP REGION.