Enhancement/Upgrade of Engine Structures Technology Best Estimator (EST/BEST) Software System

Ashwin Shah
Sest, Inc., Middleburg Heights, Ohio

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Enhancement/Upgrade of Engine Structures Technology Best Estimator (EST/BEST) Software System

Ashwin Shah
Sest, Inc., Middleburg Heights, Ohio

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Foreword

This report represents a summary of the technical work performed during the entire contract period for the Order No. C-76751-J entitled “Enhancement/upgrade of the EST/BEST (Engine Structures Technology Benefits Estimator) Software System.” ALCCA module has been integrated with the EST/BEST software system and the documentation for the work performed has been completed. Also, the EST/BEST software system package has been prepared and delivered along with.

SUMMARY OF ACTIVITIES:

The following sections of the report describes the work performed during the contract period and the capabilities included in the EST/BEST software system. The developed EST/BEST software system includes the integrated NESSUS, IPACS, COBSTRAN and ALCCA computer codes required to perform the engine cycle mission and component structural analysis. Also, the interactive input generator for NESSUS, IPACS and COBSTRAN computer codes have been developed and integrated with the EST/BEST software system. The input generator allows the user to create input from scratch as well as edit existing input file interactively. Since, it has been integrated with the EST/BEST software system, it enables the user to modify EST/BEST generated files and perform the analysis to evaluate the benefits. Appendix A gives details of how to use the newly added features in the EST/BEST software system.

Highlights of the added capabilities and further testing of the EST/BEST software system are as follows:

(I) INTEGRATION OF THE NESSUS COMPUTER CODE WITH EST/BEST SOFTWARE SYSTEM:

The NESSUS computer code and the developed interactive input generator modules have been integrated with the EST/BEST software system. The existing capabilities in the in the integrated EST/BEST software system have been enhanced as well as improvements on the results have been made. The highlights of the capabilities are summarized below:

• User can generate the following input required to perform the probabilistic structural analysis using NESSUS:

  ♦ Nodal Coordinates
  ♦ Element connectivity
  ♦ Boundary conditions
  ♦ Mechanical loads such as point loads, nodal pressures, distributed pressure load, centrifugal forces
  ♦ Thermal loads. Each layer temperature can be interpolated by providing top and bottom surface temperatures and specifying the interpolation method.
  ♦ Analysis options: static, frequency with and without stress stiffening and buckling
Primitive random variables related to geometry, boundary conditions, mechanical and thermal loads, etc., their probability distributions and perturbations.

Probabilistic analysis methods: mean value first order analysis (MVFO) and advanced mean value first order analysis (AMVFO). The user can perform both non-iterative as well as iterative probabilistic methods. MVFO provides faster solution whereas the AMVFO can be used for structures with non-linear responses where convergence of probability needs iterations.

Output request definitions.

- The entire input can be prepared using default options and/or non-default options.
- The geometry can be generated using the integrated COBSTRAN computer code. User can generate the coordinates and connectivity for complicated structures like blades with a minimal input.
- User can edit the COSMO generated NESSUS file and enhance the input data for other NESSUS features.
- Input can be prepared in one or more sitting sessions (for larger problems).
- Each individual input set can be created through direct keyboard entry or by importing files containing the respective input set e.g. thermal loads can be read from the file also.
- Program checks for consistency of the input and eliminates possible general errors made by the user.
- Previously available options related to NESSUS have been kept intact.

Additional capabilities were demonstrated by performing the probabilistic analysis of the high-pressure compressor blade. Static, frequency (with and without stress stiffening) and buckling analyses were performed for the High Speed Civil Transport engine blade. The problem details of the results were submitted in the monthly progress reports and are attached in Appendix B.

Graphical User Interface (GUI) in the EST/BEST system was modified/updated to enable the use of additional NESSUS features. The typical updated GUI screens are given in the Appendix C.

(II) INTEGRATION OF THE IPACS COMPUTER CODE WITH EST/BEST SOFTWARE SYSTEM:

The IPCAS computer code (with FORTRAN 77 features) received from Mr. Chuck Putt was debugged and tested for static, frequency with and without stress stiffening, and buckling analysis capabilities. Several problems related to these analyses options were fixed and verified. The IPACS code is made available as stand alone as integrated computer code with EST/BEST.

The IPACS computer code and the developed interactive input generator modules have been integrated with the EST/BEST software system. The existing capabilities in the in the integrated EST/BEST software system have been enhanced as well as improvements on the results have been made. The highlights of the capabilities are summarized below:
• User can generate the following input required to perform the probabilistic structural analysis using IPACS:

  ♦ Nodal Coordinates
  ♦ Element connectivity
  ♦ Boundary conditions
  ♦ Mechanical loads such as point loads, nodal pressures, distributed pressure load, centrifugal forces
  ♦ Thermal loads. Each ply temperature can be interpolated by providing top and bottom surface temperatures and specifying the interpolation method.
  ♦ Analysis options: static, frequency with and without stress stiffening and buckling
  ♦ Composite properties uncertainty definitions of the constituents, fabrication and geometry variables. The mean values of the constituents are retrieved directly from the material property database based on the constituent keyword name. Thus, the user input is minimized.
  ♦ Ply group and arrangement definitions on the structure.
  ♦ Primitive random variables related geometry, boundary conditions, mechanical and thermal loads, etc., their probability distributions and perturbations. Thermal loads can be fully or partially correlated random variables.
  ♦ Perturbation magnitude definitions.
  ♦ Ply response table and structural response definitions for the desired output.
  ♦ Output request definitions.
• The entire input can be prepared using default options and/or non-default options.
• The geometry can be generated using the integrated COBSTRAN computer code. User can generate the coordinates and connectivity for complicated structures like blades with a minimal input.
• User can edit the COSMO generated IPACS file and enhance the input data for other IPACS features.
• Input can be prepared in one or more sitting sessions (for larger problems).
• Each individual input set can be created through direct keyboard entry or by importing files containing the respective input set e.g. thermal loads can be read from the file also.
• Program checks for consistency of the input, and eliminates possible general errors including those related to inter dependence of different input cards.
• Previously available options related to IPACS have been kept intact.

Additional capabilities were demonstrated by performing the probabilistic analysis of the COBSTRAN generated hollow blade. Static, frequency (with and without stress stiffening) and buckling analyses were performed for the hollow engine blade. The problem details of the results were submitted in the monthly progress reports and are attached in Appendix D.

Graphical User Interface (GUI) in the EST/BEST system was modified/updated to enable the use of additional IPACS features. The typical updated GUI screens are given in the Appendix C.
INTEGRATION OF THE COBSTRAN COMPUTER CODE WITH EST/BEST

Additional capability of generating mesh for complicated structures like hollow engine blade with and without spars was added and made operation in the COBSTRAN computer code. The input can be created or modify the existing input interactively. Also the mesh can be generated interactively and corresponding output files can be imported by NESSUS as IPACS computer codes. Such a capability minimizes the mesh data input in NESSUS and IPACS.

Inputs for the hollow blade with and without spars were generated using the integrated COBSTRAN computer code in the EST/BEST software system. Graphical User Interface was developed to integrate the COBSTRAN computer code and its interactive input generator module. The typical updated GUI screens are given in the Appendix C.

Added capabilities have been demonstrated by generating the input for a typical composite hollow blade with and without spars for an engine structure using the integrated COBSTRAN and the interactive input generator in the EST/BEST software system. The details of these capabilities were reported in the previous monthly reports.

Also, GUI programming to integrate ALCCA computer code in a modular fashion with the EST/BEST software system has been completed and analysis for a test problem has been done. The ALCCA module augments the existing FLOPS cost-analysis computation for the engine cycle missions and component/structures using new cost models. Further testing is in progress and is expected to be complete during the next reporting period.

INTEGRATION OF THE ALCCA COMPUTER CODE WITH EST/BEST

The ALCCA (Aircraft Life Cycle Cost Analysis) computer code to perform the cost analysis of composite structure was integrated with the EST/BEST software system. Graphical User Interface required to integrate the code was developed. A sample problem to perform the cost analysis was run and the typical cost analysis results are listed in Appendix E. The ALCCA computer code can be used as a substitute to the FLOPS (Flight Optimization Code) for the engine cycle analysis. However, the current effort of integration is limited to the standalone version of ALCCA analysis. ALCCA computer code has cost analysis based on newer and advanced models.

PROBABILISTIC FATIGUE LIFE ANALYSIS OF COMBUSTOR LINER:

Probabilistic fatigue life cycle analysis of the combustor liner was performed as required by the NASA project manager. The NESSUS capability for the harmonic loads was used to compute the probabilistic responses of a combustor liner subject to high temperatures. Material properties were input using the elasticity matrix coefficients. The probabilistic analysis input file was received from Dr. S. Pai of the NASA Glenn Research Center. Several NESSUS analyses runs were made for different degraded D-matrix coefficients due to the cyclic loads. Material degradation of these coefficients was performed using the multi-factor-interaction-model
Probabilistic cyclic stresses and respective sensitivity factors were computed using NESSUS computer code.

Also, the material strength cumulative distribution function using the Weibull distribution was computed for different cyclic load cycles. The strength degradation was achieved using MFIM. Degradation due to both the temperature as well as cyclic load effects was accounted in the computation process. CDF of strength under different load cycles was computed. The life cycle curves at different probability levels generated using the results of probabilistic strength and stress. Also, the probability of failure as well as survival probability curves for different load cycles were developed. The details of the analysis were reported in the March 1997 monthly progress report and are attached in the Appendix F.
A.1 Interactive Input General Information

The structure of the IPACS input file reflects the modularity of each module. The structured format helps the user locate specific input data and manually enter or edit it. The IPACS input file can have any user-specified filename, but must have a .DAT extension. The input file may consist of up to six input data blocks; the data blocks must be separated by delimiters beginning with the $ character. If multiple sections are desired, they must be arranged in the following order:

$COB
- Automatic Mesh Generation Input -
  •
  •
  •

$PIC
- Material Property Uncertainty Input -
  •
  •
  •

$NES
- Finite Element Input -
  •
  •
  •

$RAN
- Structure Level Random Variable Input -
  •
  •
  •

$FPI
- Probabilistic Output Request Input -
  •
  •
  •

$EXE2
- Execution Control Input
  •
  •
  •

The delimiters may be abbreviated to the first four characters (i.e. $COB, $PIC, $NES, $FPI).
The structure of the NESSUS input file is same as that is described in the NESSUS manual.

During interactive processing of NESSUS input blocks, scratch files may also be created with the following extensions and formatting:

**IPACS/NESSUS Body Force Block**

*input filename*.BODY

Card 1: *BODY, IBODY(I)

Card 2 (IBODY=1): X-COMP(F), Y-COMP(F), Z-COMP(F)

Card 2 (IBODY=2): X1(F), Y1(F), Z1(F)

Card 3 (IBODY=2): X2(F), Y2(F), Z2(F)

**IPACS/NESSUS Boundary Conditions Block**

*input filename*.BOUND

Cards 1 thru N: NODE #(I), DOF #(I), DISP(F)

**NESSUS Material Properties Block**

*input filename*.prop

Cards 1 thru N: NODE #1, NODE(J), (PROP(I), I=1,5)

**NESSUS Layer Temperature Block**

*input filename*.temp

Cards 1 thru N: NODE #1, NODE(J), (TEMP(I), I=1,5)

**IPACS/NESSUS Element Connectivity Block**

*input filename*.CONN

Cards 1 thru N: ELEM #(I), INODE(I), JNODE(I), KNODE(I), NODE(I)

**IPACS/NESSUS Nodal Coordinates Block**

*input filename*.COORD

Cards 1 thru N: NODE #(I), X(F), Y(F), Z(F), TH(F)

**IPACS/NESSUS Random Variable Coordinates Block**

*input filename*.CRDxxx

Card 1: MEAN(F), STD DEV(F), DIST TYPE(I)

Cards 2 thru N: NODE #1, X-SDF(F), Y-SDF(F), Z-SDF(F), TH-SDF(F)

**IPACS/NESSUS Distributed Loads Block**

*input filename*.DIST

Cards 1 thru N: BEG ELEM(I), END ELEM(I), ICODE(I), TRAC(F), PRESS(F), BODY FORCE(F)

**IPACS/NESSUS Random Variable Distributed Loads Block**

*input filename*.DSTxxx

Card 1: MEAN(F), STD DEV(F), DIST TYPE(I)

Cards 2 thru N: BEG ELEM(I), END ELEM(I), ICODE(I), TRAC SDF(F), PRESS SDF(F), BODY FORCE SDF(F)

**IPACS/NESSUS Duplicate Nodes Block**

*input filename*.DUPL

Cards 1 thru N: MASTER NODE(I), SLAVE NODE(I)
IPACS/NESSUS Nodal Forces Block

*input filename.FORCE*    Cards 1 thru N:  NODE #(I), DOF #(I), FORCE(F)

IPACS/NESSUS Random Variable Forces Block

*input filename.FRCxxx*   Card 1: MEAN(F), STD DEV(F), DIST TYPE(I)
                          Cards 2 thru N:  NODE #(I), DOF #(I), FORCE SDF(F)

IPACS Material Orientation Block

*input filename.orie*    Cards 1 thru N:  BEG NODE(I), END NODE(I), X-COMP(F), Y-COMP(F), Z-COMP(F)

where xxx is a three-digit number identifying the random variable and where (I) indicates integer and (F) indicates floating point numbers.

The IPACS/NESSUS scratch files are useful in recovering data following a program abort or a system failure. To recover data, use the "Input Existing File" options found on many of the menus, after reentering the input module using a filename different than the one used in the previous run. The quantities found in each of these files are written in free format consistent with the IPACS/NESSUS convention. This feature also allows users to import their own mesh, boundary conditions, and loads from outside the input module. To import this data, use the scratch file naming convention described above and simply have the data read into the program.
A.2 Detailed Description of the Interactive Input Module

As described in section 3.1, the IPACS/NESSUS input file consists of five separate sections including automatic mesh generation module, a module to compute probabilistic composite material properties, probabilistic finite element analysis module, and probability algorithm module.

The IPACS code contains an interactive input module that allows the user to interactively create or edit an IPACS input file and submit it for processing. Interactive module enables an inexperienced user to prepare the input in a user-friendly manner in a short time without making common mistakes. This module allows creating or editing the input file with little or no knowledge of the file's structure and format, and thus allows an inexperienced user to run the code and come up to speed more quickly.

The interactive input module is designed for ease of use. An input session need not be completed in one sitting: once an IPACS input file has been created it can be saved and returned to later for further editing, or in order to enter the execution mode and run the code. (For example, the user can enter or change the finite element mesh inputs, save the entries or edits, exit the IPACS program, and return later to add or edit the material specifications.)

An input session is begun at the main menu, which offers six options that allow the user quick access to input functions (refer to Figure 3.2.1 of the IPACS manual). The six input options may be selected and run in any order. The options access a series of menus in which the user is prompted for information to enter or change.

A.3 Batch Input

IPACS input can be prepared manually or by using any other preprocessor and processing it in a batch mode. The procedure to prepare the input is described in the following section.

As described in section A.1, the input file is divided into several different blocks. The block pertaining to the automatic mesh generation data should not be used in the batch mode. Each of the material property uncertainty input and finite element input data blocks are divided into parameter and model data groups. The parameter group of a data block defines the size of the problem, whereas the model group of the data block contains the actual model data. In both the data blocks, the model group always follows the parameter group. Also, a ‘END’ card marks end of the parameter group in a data block. The $PIC input data block contains the data related to the material properties and the lay-up configuration of composites in the structure. The $NES input data block contains the actual finite element data. Detailed input information on each block is discussed below:

A.3.1 Material Property Uncertainty Input Data Block:

The material property uncertainty input data block begins with a 'SPIC' card. The composite lay-up configuration and material property uncertainties are defined in this block.
Normally, the $PIC data block ends with the beginning of the $NES data block (i.e., with a 'NESSUS' card). Different key words (a key word always begins with an '*'; asterisk) used in the material property uncertainty data block are discussed below:

A.3.1.1 Material Property Uncertainty Parameter Input Data Group:

CFEM
The above card is used to flag ifemx (MV) analysis

$PICn
where n = 0 is used if material properties PDF computation is desired
= 1 is used material properties PDF computation is to be bypassed

*PROSOL
The keyword PROSOL is used to define the probabilistic structural analysis solution method. The general format is

*PROSOL
  NSOL
  NMCS

where NSOL is the probabilistic solution method. Different available probabilistic solution methods and their NSOL values are given below:

NSOL = 21 PV Based method using fast probability integrator
= 22 Monte Carlo simulation technique for material property related uncertainties

NMCS = No. of samples for Monte-Carlo simulation (required for NSOL = 22)

*INDZON
The keyword INDZON is used to define the total number of statistically independent zones in the structure. The general input format is

*INDZON
  NDZON

where NDZON is the total number of independent zones in a composite structure.

*PLYGRP
The keyword PLYGRP is used to specify the total number of ply groups in each independent zone. The general input format is

*PLYGRP
  INDI(1)  NLGRP(1)
  INDI(2)  NLGRP(2)
  INDI(3)  NLGRP(3)
  .
  .
  .
  INDI(n)  NLGRP(n)
Where INDI is the independent zone no. NLGRP is the total number of ply groups in an independent zone.

There will be NDZON number of lines under this keyboard.

Note: *INDZON key word card must precede *PLYGRP key word card.

*NODGRP

The above keyword is used to specify the total number of node groups. A node group used to identify the common independent zone and the common layer group for all the nodes in a group. The general format is:

*NODGRP
  NGRP
where NGRP is the total number of node groups.

*PLIES

The keyword PLIES is used to specify the maximum number of plies that exists in an independent zone. The general input format is:

*PLIES
  INDI(1)    NMAXPL(1)
  INDI(2)    NMAXPL(2)
  INDI(3)    NMAXPL(3)
  .          .
  .          .
  .          .
  INDI(n)    NMAXPL(n)

where INDI is the independent zone No., and NMAXPL is the maximum number of plies in an independent zone. The maximum number of plies for all the independent zones must be defined.

Note: *INDZON key word card must precede *PLIES key word card.

*MATSYS

The keyword MATSYS is used to specify the total number of material systems in a structure. The general input format is:

*MATSYS
  NMAT
where NMAT is the total number of material systems in a structure.

*ORISYS

The keyword ORISYS is used to specify the total number of orientation systems in a structure. The general input format is:

*ORISYS
  NORI
where NORI is the maximum number of orientation systems in a structure.

*THKSYS
The keyword THKSYS is used to specify the total number of thickness systems in a structure. The general input format is:

*THKSYS
NTHK
where NTHK is the total number of thickness systems in a structure.

*RNDGRP
This key word is used to specify the maximum number of random field groups related to material properties for each independent zone in a structure.

The general input format is:

*RNDGRP
INDI(1)  NRFT(1)
INDI(2)  NRFT(2)
INDI(3)  NRFT(3)
INDI(n)  NRFT(n)

where INDI is the independent zone number NRFT is the total number of random field groups (*CORTAB) related to the constituent material properties in an independent zone.

The number of random field groups related to the constituent material properties for all the independent zones must be defined.

Note: *INDZON key word card must precede *RNDGRP card.

*RANTEM
This key word is used to specify the maximum number of random variables related thermal loads and corresponding number of perturbation sets.

The general input format is:

*RANTEM
NRTEM  NTPER

where NRTEM is the number of temperature related random variables and NPER is the total number of perturbations related to the temperature related random variables.

The number of random variables related to the temperatures for all the independent zones must be defined.

*END
This key word card is always required to terminate the parameter data block input. It must always be put at the very end of parameter data input block. The general input format is

*END

A.3.1.2 Material Property Uncertainty Model Input Data Group:

*NODGRP
The keyword NODGRP is used to specify the node numbers that belong to a specific ply group of a specific independent zone. The general input format is shown below:

*NODGRP
IG
NODB(IG) NODE(IG) INDZ(IG) ILAY(IG)
where
IG is the node group number
NODB(IG) is the beginning node number of a series of nodes in group IG,
NODE(IG) is the end node number of a series of nodes in group IG,
ILAY(IG) is the ply group number to which NODB(IG) through NODE(IG) belongs
INDZ(IG) is the independent zone number to which NODB(IG) through NODE(IG) belongs

Remember that the node groups for all the ply groups and all the independent zones must be specified.

*RESTAB

The keyword RESTAB is used to specify the plies and their responses for which the probabilistic simulation is desired. The response table for all the plies within an independent zone must be specified. The code used to specify the computational request is 0(zero) or 1(one). 0 means the probabilistic ply response computation is not desired and 1 means the probabilistic ply response computation is desired. The general input format is:

*RESTAB
IZ
NPB, NPE
IEX(1) IEXE(2) … (EX(23)
where
IZ is the independent zone number
NPB is the beginning ply number of independent zone IZ
NPE is the end ply number of independent zone IZ
IEX(I) is the code to request i\textsuperscript{th} probabilistic ply response

Following is the list of ply responses for which the probabilistic analysis can be performed.
1 Longitudinal strain
2 Transverse strain
3 Shear strain
4 Longitudinal stress
5 Transverse stress
6 Shear stress
7 Longitudinal tensile strength
8 Longitudinal compressive strength
9 Transverse tensile strength
10 Transverse compressive strength
11 Shear strength
12 Modified distortion energy failure criterion
13 Hoffman’s failure criterion
14 Interply delamination failure criterion

15 Fiber crushing criterion (compressive strength)
16 Delamination criterion (compressive strength)
17 Fiber micro buckling criterion (compressive strength)

18 Failure in longitudinal direction
19 Failure in transverse direction
20 Failure in Shear strength

21 Out of plane Shear 13
22 Out of plane Shear 23
23 Sigma zz

*PLYTAB
The keyword PLYTAB is used to specify the ply configuration of a laminate in a ply
group of any independent zone. The ply configuration of a laminate is specified by the existence
of a ply. The code used to specify the existence is 0(zero) or 1(one). 0 means the ply does not
exists and 1 means the ply exists. The general input format is:

*PLYTAB
IZ, LG,
NPL(1,IZ,LG), NPL(2,IZ,LG), ... NPL(NMAXPL(IZ),IZ,LG)
where
IZ is the independent zone number
LG is the ply group number of independent zone IZ
NMAXPL(IZ) is the maximum number of plies in an independent zone IZ
NPL is the ply existence code, either 0 or 1. Code zero indicates that
the ply does not exist and 1 indicates that the ply exists

*MATSYS
The keyword MATSYS is used to specify the uncertainties of a specific material. The
general input format is:
*MATSYS
I
'KEY(I)KEYS(I)' FVRM(I) VVRM(I) FRS(I) FVRMS(I) VVRMS(I)
C(1,I) C(2,I) C(3,I) ... C(29,I)
CF(I), CVV(I), CRS(I), CFS(I), CVVS(I)
CS(1,I)CS(2,I)CS(3,I) ... CS(29,I)
IM(1,I)IM(2,I)IM(3,I) ... IM(29,I)
IF(I), IV(I), IFR(I), IFS(I), IVS(I)
IMS(1,I) IMS(2,I) IMS(3,I) ... IMS(29,I)
where I is the material system number KEY(I) and KEYS(I) are the acronyms defining the I th primary and secondary composite material system. The acronym must be specified in quotes ('). The acronym is used to pull the mean values of composite material properties from the data bank. Refer to Table 3.4.1.1 and Table 3.4.1.2 of the IPACS manual for the description of composite material acronyms. FVRM(I), VVRM(I), FRS(I), FVRMS(I), and VVRMS(I) are mean values of the primary system fiber volume ratio, the primary system void volume ratio, fraction of secondary system, the secondary system fiber volume ratio and the secondary system void volume ratio respectively of the I th material system. C(n,I) is the coefficient of variation for the n th primary material property random field of the I th material system. The list of the random field numbers is given in section 3.5 of IPACS manual. CF(I), CVV(I), CFRS(I), CFS(I), CVVS(I) are the coefficient of variation for the primary system fiber volume ratio, the primary system void volume ratio, fraction of secondary system, the secondary system fiber volume ratio and the secondary system void volume ratio respectively of the I th material system. IM(n,I) is the distribution type for the n-th material property random field number of I th primary material system. IF(I), IV(I), IFR(I), IFS(I), IVS(I) are the distribution types for the primary system fiber volume ratio, the primary system void volume ratio, fraction of secondary system, the secondary system fiber volume ratio and the secondary system void volume ratio respectively of the I th material system. IMS(n,I) is the distribution types for the n th secondary system material property number. No more than ten integer numbers and eight real numbers in a given line can be specified. If there are more numbers for a particular data type, then their input should continue in the subsequent lines.

*ORISYS

The keyword ORISYS is used to specify uncertainties of the ply orientations. The general input format is:

*ORISYS

  OM(1) OM(2) ... OM(NORI)
  OC(1) OC(2) ... OC(NORI)
  IO(1) IO(2) ... IO(NORI)

where OM(i), OC(i) and IO(i) are the mean, a constant to specify standard deviation (standard deviation = 90 x constant), and the distribution type respectively of the i th orientation angle system. NORI is the total number of orientation systems.

*THKSYS

The keyword THKSYS is used to specify uncertainties of the ply thickness. The general input format is:

*THKSYS

  TM(1) TM(2) ... TM(NTHK)
  TC(1) TC(2) ... TC(NTHK)
  IT(1) IT(2) ... IT(NTHK)

where TM(i), TC(i) and IT(i) are the mean, the coefficient of variation and distribution type respectively of the i th thickness system. NORI is the total number of orientation systems. NTHK is the total number of thickness systems.
*MATTAB
The keyword MATTAB is used to specify the material of each ply of a laminate in an independent zone. The material property uncertainty specification of a ply in an independent zone corresponds to a material system id. All the plies of an independent zone must have a material system id defined, and the material property uncertainty for that id must also be defined in

*MATSYS card. The general input format is:

*MATTAB
IZ
NMT(IZ,1) NMT(IZ,2) NMT(IZ,3) ... NMT(IZ,NMAXPL(IZ))
where IZ is the independent zone number. NMT(IZ,n) is the material system number of the n^{th} ply of independent zone IZ, and NMAXPL(IZ) is the maximum number of plies in independent zone IZ.

*ORITAB
The keyword ORITAB is used to specify the uncertainties of each ply orientation of a laminate in an independent zone. The orientation uncertainty specification of a ply in an independent zone corresponds to an orientation system id. All the plies of an independent zone must have an orientation system id defined, and the orientation uncertainty for that id must also be defined in

*ORISYS card. The general input format is:

*ORITAB
IZ
NOT(IZ,1) NOT(IZ,2) NOT(IZ,3) ... NOT(IZ,NMAXPL(IZ))
where IZ is the independent zone number, NOT(IZ,n) is the orientation system number of the n^{th} ply of independent zone IZ, and NMAXPL(IZ) is the maximum number of plies in independent zone IZ.

*THKTAB
The keyword THKTAB is used to specify the uncertainties of each ply thickness of a laminate in an independent zone. The thickness uncertainty specification of a ply in an independent zone corresponds to a thickness system id. All the plies of an independent zone must have a thickness system id defined, and the thickness uncertainty for that id must also be defined in

*THKSYS card. The general input format is

*THKTAB
IZ
NTT(IZ,1) NTT(IZ,2) NTT(IZ,3) ... NTT(IZ,NMAXPL(IZ))
where IZ is the independent zone number and NTT(IZ,n) is the thickness system number of n^{th} ply of independent zone IZ, and NMAXPL(IZ) is the maximum number of plies in independent zone IZ.
**CORTAB**
This key word is used only in case of a primitive variable based method to specify the correlation of a particular random field between different plies (correlation table) of a composite material. Refer to Appendix A for the definition of a correlation table. The general input format for the primitive variable based method is:

* CORTAB
  IZ
  NRFi  NRFj
  ICOR(1) ... ICOR (NMAXPL(IZ))

Where IZ is the independent zone number
NRFi is the beginning material related random field number.
NRFj is the end material related random field number (Legal list of material related random field numbers are given in Appendix A, Section A.3).
ICOR(i) is the correlation id number for the i-th ply, 0<= ICOR(i) <=NMAXPL(IZ)
NMAXPL(IZ) is the maximum number of plies in independent zone, IZ.
The cards (NRFi NRFj) and (ICOR(1), ... ,ICOR(NMAXPL(IZ))) can be repeated for additional random fields in independent zone, IZ. For additional independent zones the data should be specified in the same order discussed above.

Remember that the correlation table for all the material related random fields of all the independent zones should be specified. The random field automatically becomes deterministic if its correlation table is not defined.

**MEANTM**
This key word is used to specify mean ply temperatures at different nodes. The temperature groups and the number of node groups must be exactly same. The correlated temperatures at different nodes can be specified using the *RELPER card. The standard deviations for the temperatures are specified in the *STDVTM card. The first ply is the bottom ply based on the local z-definition. The general input format for the definition of the mean ply temperatures is:

* MEANTM
  NODi  NODj
  PT1  PT2  ...  PTn

NODi is the beginning ply number.
NRFj is the last node number in a group.
PTi is the mean i-th ply temperature.
The cards (NODi NODj) and (PT1, ... ,PTn) can be repeated for additional nodes.

**STDVTM**
This key word is used to specify standard deviation of the ply temperatures at different nodes. The temperature groups and the number of node groups must be exactly same. The first ply is the bottom ply based on the local z-definition. The general input format for the definition of the ply temperature standard deviation is:
*STDVTM
NODi  NODj
PSTD1  PSTD2  …  PSTDn

NODi  is the beginning ply number.
NRFj  is the last node number in a group.
PSTDi  is the $i^{th}$ ply temperature standard deviation
The cards (NODi  NODj) and (PSTD1, ... ,PSTDn) can be repeated for additional nodes.

*RELPER

This key word is used to specify the autocorrelation matrix for random temperature variables. Basically, it represents the eigen-vectors of the correlation matrix. The general input format for the definition of the ply temperature standard deviation is:

*RELPER
NR
NODi  NODj
EG1  EG2  …  EGn

NODi  is the beginning ply number.
NRFj  is the last ply number.
EGi  is the $i^{th}$ ply autocorrelation coefficient
The cards (NODi  NODj) and (EG1, ... ,EGn) can be repeated for additional nodes.

*IRVPER

This key word is used to specify the perturbation of particular temperature random variables. Any random variable can be perturbed for any number of times. It also signifies in what order the variables shall be perturbed. Input entry in this card must be used in conjunction with the *ABSPER card which specifies the corresponding perturbation magnitude. Basically, it represents the eigen-vectors of the correlation matrix. The general input format for the definition of the temperature random variables perturbation definition is:

*IRVPER
NP(1)  NP(2) … NP(n)

where NP(i) represents the $i^{th}$ perturbation of random variable NP(i).
The cards (NPi  NPn) can be repeated for additional variable perturbations.
**ABSPER**

This key word is used in conjunction with the *IRVPER input card. It is used to specify the magnitude of the perturbation for the corresponding random variable in the *IRVPER card. The general input format for the definition of the perturbation magnitude is:

```
*ABSPER
PV(1) PV(2) ... PV(n)
```

where PV(i) represents the magnitude of the i\(^{th}\) perturbation of random variable NP(i) specified in *IRVPER card. The cards \((PV_i \ PV_n)\) can be repeated for additional variable perturbations.

**REFTEM**

This key word is used to specify the reference temperature of the material. The general input format for the definition of the reference temperature is:

```
*REFTEM
IZ
REFTM
```

where IZ represents the independent zone and the REFTEM the reference temperature in °F units. The cards IZ and REFTEM can be repeated for additional independent zones.

**A.3.2 Input for Probabilistic Output Request:**

This section of input always begins with $FPI card. The response locations on the structure and the type of probabilistic analysis are defined in this section of input. The input details are given in the following card:

```
*STRU
ISTAT NTYPE NODN IDUMP IDUMP NCOMP
```

where

- ISTAT = 1 for the Static Analysis
  = 2 for the Buckling Analysis
  = 3 for the Frequency Analysis
- NTYPE = 1 for Displacement Response
  = 2 for Ply Strain/Stress Response
- NODN Node Number where probabilistic output is requested
- IDUMP Reserved for future use
- NCOMP displacement or stress/strain component in static analysis mode number in case of buckling or frequency analysis
A.3.3 IPACS Execution Control Input:

The input to this section always begins with $EXE2$ card. The IPACS execution control is defined in this section. The input to this section is as follows:

\[
\text{IX1 IX2 IX3 IX4 IX5}
\]

where the variables IX1, IX2, IX3, IX4 and IX5 could be either 0 (zero) or 1. 0 means suppress the execution of the analysis type discussed below. 1 means perform the analysis.

- $\text{IX1} = 1$ Compute the perturbed material properties at every scale.
- $\text{IX2} = 1$ Prepare the input file for the probabilistic finite element analysis.
- $\text{IX3} = 1$ Perform the probabilistic finite element analysis.
- $\text{IX4} = 1$ Extract desired structural responses as indicated in $\text{FPI}$ section.
- $\text{IX5} = 1$ Compute the CDF of desired structural responses

A.3.4 Output

The user generally controls IPACS output. However, by default IPACS provides minimum necessary output required for the probabilistic assessment of composite structure. The minimum output consists of the following: (i) an echo of the input, (ii) CDF of the material properties and the desired structural response, (iii) the sensitivity factors of the primitive variables for the material properties and the desired structural response. The important output files are xxx21.fpimov, xxx21.nesout and xxx21.rantab. The names of these files and their respective contents are listed in Table A.3.4.1, on the next page.

Several other output files are created at intermediate computation stage or at the end of the computations. Some of these files provide an interface between different modules or serve as a database system. These files contain information for the user to study the overall problem behavior in greater detail.
Table A.3.4.1  List of Output Files

jn -  jobname
IZ -  Independent Zone No.
LG -  Ply Group No.
IPM -  Method No.
$$ -  A unique job number assigned by the computer

<table>
<thead>
<tr>
<th>File Name</th>
<th>File Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>jn.msp-IZ-LG</td>
<td>Mean value and standard deviations for ply material properties.</td>
</tr>
<tr>
<td>jn.cpp-IZ-LG</td>
<td>CDF of ply material properties.</td>
</tr>
<tr>
<td>jn.cpl-IZ-LG</td>
<td>CDF of laminate material properties.</td>
</tr>
<tr>
<td>jn-IZ-LG-IPM-IC.PIC</td>
<td>If IC = 0 Mean Values of material properties. Perturbations of A, C, and D matrices terms for primitive variable based method</td>
</tr>
<tr>
<td>jn-IZ-IPM.dat</td>
<td>Data required for finite element analysis. The file contains the data supplied by the user and that generated by the program</td>
</tr>
<tr>
<td>jn-IZ-IPM.pdb</td>
<td>Perturbation database.</td>
</tr>
<tr>
<td>jn-IZ-IPM.datu</td>
<td>Perturbation data for each desired response.</td>
</tr>
<tr>
<td>jn-IZ-IPM.dist</td>
<td>Statistics of Primitive Variables for each independent zone.</td>
</tr>
<tr>
<td>jn-IPM.datu</td>
<td>FPI input file.</td>
</tr>
<tr>
<td>jn-IPM.dist</td>
<td>Statistics of primitive variables required for the probabilistic analysis of structural response.</td>
</tr>
<tr>
<td>jn-IPM.fpinp</td>
<td>Input file prepared by program to perform fast probability integration.</td>
</tr>
<tr>
<td>jn-IPM.fpimov</td>
<td>Sensitivity factors of primitive variables at cumulative probability levels of 0.001 and 0.999.</td>
</tr>
<tr>
<td>jn-IPM.fpibin</td>
<td>FPI logfile</td>
</tr>
<tr>
<td>jn-IPM.nesout</td>
<td>Discretized CDF of a structural response.</td>
</tr>
<tr>
<td>jn-IZ-IPM.out</td>
<td>Echo of FEM input and Results of Unperturbed Solution.</td>
</tr>
<tr>
<td>jn-IBM.FPIMOV</td>
<td>Sensitivity factors for independent random variables at probability levels 0.001 and 0.999.</td>
</tr>
</tbody>
</table>
SAMPLE INPUT FILE:

CFEM
$PIC1
*INDZON
1
*NODGRP
1
*PROSOL
21
*PLYGRP
1 1
*PLIES
1 8
*RNDGRP
1 2
*MATSYS
1
*ORISYS
4
*THKSYS
1
*RANTEM
1 4
*END
*NODGRP
1
1 9 1 1
*RESTAB
1 8
 c o-skip fpi 1-with fpi
0 0 0 1 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0
0 0 0
*PLYTAB
1 1
1 1 1 1 1 1 1 1
*MATSYS
1
'AS--EPOXAS--EPOX' 0.60 0.02 0.000001 0.60 0.02
0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
2 2 2 2 2 2 2 2 2 2
2 2 2 2 2 1 1 1 2 2
2 2 2 2 2 1 1 1 2 2
2 2 2 2 2 1 1 1 2 2
2 2 2 2 2 1 1 1 2 2
*MATTAB
1
1 1 1 1 1 1 1 1
*ORISYS
-45.0 0.0 45.0 90.0
0.02 0.02 0.02 0.02
2 2 2 2
*ORITAB
1
3 1 2 4 4 2 1 3
```

*THKSYS
  0.020
  0.050
  2

*THKTAB
  1
  1 1 1 1 1 1 1 1

*CORTAB
  1
  1
  1 1 1 1 1 1 1
  33 33
  1 1 1 1 1 1

*MEANTM
  1
  9
  200.0 200.0 200.0 200.0 200.0 200.0 200.0 200.0

*STDVM
  1
  9
  10.0 10.0 10.0 10.0 10.0 10.0 10.0 10.0

*RELPER
  1
  1
  1.0 1.0 1.0 1.0 1.0 1.0 1.0

*IRVPER
  1 1 1 1

*ABSPER
  -2.0 -1.0 1.0 2.0

*END

$NES

*fem

*disp

*forc 1

*elem 4

75

*composite

*temp

*pert

*nodes 9

*bound 18

*cons 0

*prin

*end

*inc

0

*iter

100 0.0001 0.0001 0.0001 0.0001

*coor

1 0.000 0.000 0.000 1.0
2 1.000 0.000 0.000 1.0
3 2.000 0.000 0.000 1.0
4 0.000 1.000 0.000 1.0
5 1.000 1.000 0.000 1.0
6 2.000 1.000 0.000 1.0
7 0.000 2.000 0.000 1.0
8 1.000 2.000 0.000 1.0
9 2.000 2.000 0.000 1.0

*elem 75

1 1 2 5 4
2 2 3 6 5
3 4 5 8 7
4 5 6 9 8

*bound

1 1 0
4 1 0
7 1 0
1 2 0
4 2 0
```
7 2 0
1 3 0
4 3 0
7 3 0
1 4 0
4 4 0
7 4 0
1 5 0
4 5 0
7 5 0
1 6 0
4 6 0
7 6 0
*FORC
  5 3 1000.0
*ORIEN
  1 9 1.00 0.00 0.00
  1 9 0.00 0.00 1.00
C*LAMI
INCLUDE
*PRINTOPTION
REACTION
STRESS
STRAIN
TOTALDISPLACEMENT
*END
$RAN
*DEFI 1
  1000.0 100.0 2
FORCE
  5 3 1.0
$FPI
*STRU
  1 1 5 0 0 3
$EXE2
  1 1 1 1 1
APPENDIX B:

The probabilistic stress, frequency and buckling analysis for a typical engine structure was created and the analysis was performed. The probabilistic analysis of an engine fan, high-pressure compressor blades was performed using the integrated EST/BEST software system. The uncertainties assumed for the blade are listed in the Table I. Figure 1 shows the cumulative distribution (CDF) of the total displacement at the tip of the blade. Figure 2a and Figure 2b shows the sensitivity of the total displacement to the primitive variables. The sensitivity of the displacement is controlled by the length, modulus, thickness, temperature and coefficient of thermal expansion at probability level of 0.001 whereas modulus controls at the probability of 0.999. Figure 3 shows the CDF of the first natural frequency and figure 4 shows its sensitivity to the primitive variables. The scatter of the frequency range between 900 to 1280 cps. The natural frequency of the high-pressure compressor (HPC) blade is found to be sensitive to the modulus, thickness and mass density at probability level of 0.001 whereas the order of sensitivity changes to mass density, modulus and thickness at probability level of 0.999. Figure 5 and figure 6 shows the CDF and sensitivity of the critical buckling load for the HPC blade stage 4. The modulus and the thickness dominate the critical buckling load at all probability levels. Thus, the critical load is thus controlled by the stiffness.

Table I. Primitive variable uncertainties used for the engine blade

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scatter (%)</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>10.0</td>
<td>Normal</td>
</tr>
<tr>
<td>Length</td>
<td>4.0</td>
<td>Log Normal</td>
</tr>
<tr>
<td>Thickness</td>
<td>2.5</td>
<td>Log Normal</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>7.0</td>
<td>Weibull</td>
</tr>
<tr>
<td>Coefficient of thermal Expansion</td>
<td>7.0</td>
<td>Normal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High pressure compressor Stage 2 (Frequency analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
</tr>
<tr>
<td>Mass density</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High pressure compressor Stage 4 (Buckling analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
</tr>
</tbody>
</table>
Figure 1.—Cumulative distribution function of the total displacement at the tip of the blade stage 1.

Figure 2.—Sensitivity of total displacement at the tip of the fan blade stage 1 to the primitive random variable for (a) 0.001 probability and (b) 0.999 probability.
Figure 3.—Cumulative distribution function of the first natural frequency—high pressure compressor blade stage 2.

Figure 4.—Sensitivity of first natural frequency to the primitive variables—high pressure compressor blade stage 4.
Figure 5.—Cumulative distribution function of the critical buckling load—high pressure compressor blade stage 4.

Figure 6.—Sensitivity of the critical buckling load to the primitive variables—high pressure compressor blade stage 4.
APPENDIX C: EST/BEST GRAPHICAL USER INTERFACE SCREENS

![EST/BEST Graphical User Interface Screen]

Multi-faceted Engine Structures Optimization

<table>
<thead>
<tr>
<th>Component</th>
<th>Stage</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAN</td>
<td>1</td>
<td>blade</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>blade</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>blade</td>
</tr>
<tr>
<td>HPC</td>
<td>1</td>
<td>blade</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>blade</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>blade</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>blade</td>
</tr>
<tr>
<td>HPT</td>
<td>1</td>
<td>blade</td>
</tr>
<tr>
<td>LPT</td>
<td>1</td>
<td>blade</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>blade</td>
</tr>
</tbody>
</table>

![NESSUS Graphical User Interface Screen]

Probabilistic assessment of metal structures

Component: FAN  Stage: 1  Structure: blade

- Take input from EST/BEST
  - Set Options
  - Edit/Create input
- Take input from file
  - Edit/Create input

Run  Close  Help
The image shows a user interface for selecting blade options in a simulation software. The interface includes sections for mesh options, material options, and analysis options.

- **Mesh Options**:
  - Airfoil: NACA-65D
  - Element: shell
  - Chordwise: 4
  - Spanwise: 10

- **Material Options**:
  - Metal: TAIAl
  - Composite:
    - Type: PMC
    - Fiber volume ratio:
    - Fibers: AS-3
    - Void volume ratio:
    - Matrix: EPOX
    - Interface thickness:
    - Ply Orientation Thickness 1:

- **Analysis Options**:
  - Blade impact damage data:
    - Velocity (knots):
    - Object density:
    - Object radius:

- **Structural analysis module**:
  - CSTEM
  - IPACS

- **Airfoil Details**:
  - Airfoil name: NC65A010
  - Number of coordinates in upper airfoil: 26
    - X UPPER, Y UPPER:
      - 1: 0.0, 0.00765
      - 2: 0.00578, 0.00828
      - 3: 0.0125, 0.00813
      - 4: 0.0125, 0.00828
      - 5: 0.05, 0.01263
      - 6: 0.0575, 0.00826
      - 7: 0.1, 0.00804
      - 8: 0.15, 0.00868
      - 9: 0.2, 0.04127

  - Number of coordinates in lower airfoil: 26
    - X LOWER, Y LOWER:
      - 1: 0.0, 0.005
      - 2: 0.0075, -0.00828
      - 3: 0.0125, -0.01183
      - 4: 0.0125, -0.00828
      - 5: 0.05, -0.01263
      - 6: 0.0575, -0.00826
      - 7: 0.1, -0.00804
      - 8: 0.15, -0.00868
      - 9: 0.2, -0.04127

The interface includes buttons for plotting blade cross sections, adding or deleting plies, and options for setting, editing, or creating inputs for various modules.
### HPC Stage 1 Blade NESSUS Options

**Response function:**
- Total displacement
- Total stress
- Total strain
- Natural frequency

**Scatter variables:**
- Load:
  - Omega
  - Pressure
  - Temperature

- Geometry:
  - Length
  - Thickness

- Material:
  - Elastic modulus
  - Density
  - Poisson’s ratio

**FPI Options:**
- CDF
- Z-Levels
- P-Levels

**Range of Perturbation (%)**

**Order of Perturbations**

**Distribution Type**
- Normal

---

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APPENDIX D: IPACS/COBSTRAN DEMONSTRATION PROBLEMS

The epoxy-graphite laminate with configuration (0/45/-45/90)\textsubscript{2} was used for the blade. The uncertainties in the constituents such as fiber, matrix, and fabrication variables were considered at the material level. Pressure loads were considered in the assessment process. Initially uncertainties in all the material variables were included in the analysis. However, the significant variables have been listed here for the sake of brevity. All the uncertainties considered for the probabilistic analysis of a blade are listed in the Table I. Figure 2a through 4a respectively show the cumulative distribution function (CDF) of the longitudinal, transverse and shear stresses at the root of blade for a 0\textdegree ply. Correspondingly, the Figures 2b through 4b show their respective sensitivities to the primitive variables. It is seen that the longitudinal, transverse and shear stresses in the 0\textdegree ply at the root are mainly sensitive to the ply thickness indicating the stiffness control. However the transverse and the shear stresses are sensitive to the additional primitive variables such as fiber modulus, matrix modulus and fiber volume ratio. Similarly Figures 5a through 7a show the CDF of longitudinal, transverse and shear stresses for a 45\textdegree ply and Figures 8a through 10a for the 90\textdegree ply. Respective sensitivities are shown in Figures 5b through 10b. Trends similar to the 0\textdegree ply are also observed for the 45\textdegree and 90\textdegree plies except the fact that matrix modulus and shear modulus participation becomes obvious. The shear stress in the 90\textdegree ply shows stress reversal since it is controlled by the ply mis-alignment. Nonetheless, the stiffness controls stresses in all the plies. Therefore, the uncertainties in the thickness as well as ply mis-alignment must be controlled to reduce scatter in the stresses. Uncertainties in the displacements, ply strains, strengths can also be simulated in an exactly identical manner.

Figure 11a show the cumulative distribution function of the first natural frequency of the hollow blade and the Figure 11b show its sensitivity to the primitive variables. The scatter in the frequency is 1000 cps to 1350 cps. The Fiber modulus, fiber density, matrix density, fiber volume ratio and the ply thickness are the most significant variables to the scatter in the frequency. The variable sensitivity shows that the stiffness controls at the low probability level, whereas the mass dominates at the higher probability level.

A distributed point load at the tip of the blade in its axial direction was applied to evaluate the probabilistic buckling analysis. Figure 12a shows that first critical buckling load scatter range is 5 Lbs. to 18 Lbs. (compressive). The critical load magnitude is quite small since it is controlled by the stiffness as evidenced by sensitivities shown in Figure 12b. At low probability level the most significant variables are fiber modulus 11, ply thickness and the fiber volume ratio (FVR) whereas the ply thickness, FVR and fiber modulus 11 are sensitive at the high probability level. Permissible scatter in these variables should be reduced to minimize the scatter in the buckling load.
Table I. Primitive variable uncertainties used for the composite engine blade

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scatter (%)</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Graphite Fiber (AS--):</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus 11</td>
<td>7.0</td>
<td>Weibull</td>
</tr>
<tr>
<td>Modulus 22</td>
<td>7.0</td>
<td>Weibull</td>
</tr>
<tr>
<td>Modulus 12</td>
<td>8.0</td>
<td>Log Normal</td>
</tr>
<tr>
<td>Density</td>
<td>5.0</td>
<td>Normal</td>
</tr>
<tr>
<td><strong>Epoxy matrix (EPOX)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus</td>
<td>4.0</td>
<td>Weibull</td>
</tr>
<tr>
<td>Density</td>
<td>5.0</td>
<td>Log-Normal</td>
</tr>
<tr>
<td><strong>Fabrication variables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber volume ratio</td>
<td>5.0</td>
<td>Normal</td>
</tr>
<tr>
<td>Thickness</td>
<td>6.0</td>
<td>Log-Normal</td>
</tr>
<tr>
<td>Ply mis-alignment</td>
<td>2.0 Degrees</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Figure 1.—(a) Finite element model of the hollow engine blade. (b) Finite element model of the hollow engine blade with spars.
Figure 2.—(a) Cumulative distribution function of the longitudinal stress at root in a 0 degree ply. (b) Sensitivity of longitudinal stress in 0 degree ply at root to the primitive variables.

Figure 3.—(a) Cumulative distribution function of the transverse stress at root in a 0 degree ply. (b) Sensitivity of transverse stress in 0 degree ply at root to the primitive variables.
Figure 4.—(a) Cumulative distribution function of the shear stress at root in a 0 degree ply. (b) Sensitivity of shear stress in 0 degree ply at root to the primitive variables.

Figure 5.—(a) Cumulative distribution function of the longitudinal stress at root in a 45 degree ply. (b) Sensitivity of longitudinal stress in 45 degree ply at root to the primitive variables.
Figure 6(a).—Cumulative distribution function of the transverse stress at root in a 45 degree ply. (b). Sensitivity of transverse stress in 45 degree ply at root to the primitive variables.

Figure 7.—(a) Cumulative distribution function of the shear stress at root in a 45 degree ply. (b) Sensitivity of shear stress in 45 degree ply at root to the primitive variables.
Figure 8.—(a) Cumulative distribution function of the longitudinal stress at root in a 90 degree ply. (b) Sensitivity of longitudinal stress in a 90 degree ply at root to the primitive variables.

Figure 9.—(a) Cumulative distribution function of the transverse stress at root in a 90 degree ply. (b) Sensitivity of transverse stress in a 90 degree ply at root to the primitive variables.
Figure 10.—(a) Cumulative distribution function of the shear stress at root in a 90 degree ply. (b) Sensitivity of shear stress in a 90 degree ply at root to the primitive variables.

Figure 11.—(a) Cumulative distribution function of the first natural frequency. (b) Sensitivity of the first natural frequency to the primitive variables.
Figure 12.—(a) Cumulative distribution function of the critical buckling load. (b) Sensitivity of the critical buckling to the primitive variables.
**APPENDIX E: ALCCA SAMPLE OUTPUT**

******************************************************************************
** ALCCA **
** Aircraft Life Cycle Cost Analysis **
** IBM RS/6000 FLOPS Module Version **
** Aerospace Systems Design Laboratory **
** Georgia Tech, Atlanta GA 30332 **
******************************************************************************

------------- UNIT PRODUCTION COSTS -- 1992. DOLLARS ----------------

Breakdown of Manufacturing Cost  Inflated from 1970 base dollars at 8.00% rate
AMPR Weight/Takeoff Gross Weight (lbs)  200132./ 735187.
Monthly Production Rate  (ac/month)  7.00

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Manufacturing - First Unit Cost (FUC) ( 382.065) Spares not included
Airframe ( 257.747)
Avionics & Instrumentation ( 28.682)


NASACR—2003-212126  47
***** Millions of U.S. dollars *****

RESEARCH, DEVELOPMENT, TEST, AND EVALUATION 22399.066

AIRFRAME DEVELOPMENT  (Eng. labor $65./hr)  5932.594
   CONCEPT FORMULATION  (150. man-yrs)  15.210
   CONTRACT DEFINITION  (500. man-yrs)  67.600
AIRFRAME ENGINEERING  (43268. man-yrs)  5849.784
SUBSYSTEMS DEVELOPMENT  1396.944
   AVIONICS DEVELOPMENT  (1.00x Factor)  1142.428
   PROPULSION DEVELOPMENT  (53.% Spares)  5098.428
DEVELOPMENT SUPPORT  4066.667
   GROUND TEST VEHICLES  (1. aircraft)  257.747
   GROUND TEST SPARES  (10.0% of GTV)  25.775
   FLIGHT TEST SPARES  (20.0% of FTV)  76.413
   TOOLING EQUIPMENT  (Tooling labor $55./hr)  3162.146
   FLIGHT TEST OPERATIONS  (1. aircraft)  193.005
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   MISCELLANEOUS EQUIPMENT  4394.380
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FEE  4762.006

AIRCRAFT PRODUCTION  165535.984
OPERATIONAL VEHICLES  (504. aircraft)  80723.586
   SPARES - Airframe  (6.0% of Afrm)  7388.542
   - Engines  (23.0% of Engs)  8955.563
SUSTAINING ENGINEERING  16071.595
   SUSTAINING TOOLING  4934.380
GROUND SUPPORT EQUIPMENT  11460.934
   TECHNICAL DATA  16479.281
   MISCELLANEOUS EQUIPMENT  32.945
TRAINING EQUIPMENT  1872.736
   INITIAL TRAINING  1551.036
   INITIAL TRANSPORTATION  1274.070
FEE  35192.691

TOTAL COST  187935.047
AVERAGE UNIT AIRPLANE COST (including spares)  732.887
AVERAGE UNIT AIRPLANE COST (excluding spares)  331.702

Aircraft Cost Versus Quantity

Learning Curve Percentages

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Production Line Learning Curve Breaking Point  200.

Propulsion based on production of 2500 engines

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**Totals**

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**Totals**

### MANUFACTURERS ANNUAL CASHFLOW -- 1992. DOLLARS ---

**Production Size** = 504.
**Average Aircraft Price** = $335.6 M

### MANUFACTURERS CUMULATIVE CASHFLOW -- 1992. DOLLARS ---

**Production Size** = 504.
**Average Aircraft Price** = $410.2 M

### MANUFACTURERS ANNUAL CASHFLOW -- 1992. DOLLARS ---

**Production Size** = 504.
**Average Aircraft Price** = $410.2 M

**Year**

**Annual Deliveries**

**Cumulative Deliveries**

**Costs**

**RDT&E Manufacturing**

**Sustaining**

**Net Income**

**Annual Cashflow**

### MANUFACTURERS CUMULATIVE CASHFLOW -- 1992. DOLLARS ---

**Production Size** = 504.
**Average Aircraft Price** = $410.2 M

**Year**

**Annual Deliveries**

**Cumulative Deliveries**

**Costs**

**RDT&E Manufacturing**

**Sustaining**

**Net Income**

**Annual Cashflow**
### MANUFACTURERS CUMULATIVE CASHFLOW — 1992. DOLLARS

**Production Size**: 504.
**Average Aircraft Price**: $447.5 M

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**Totals**: 504.0 17637.1 80723.6 49619.7 244316.3 96336.0

### MANUFACTURERS ANNUAL CASHFLOW — 1992. DOLLARS

**Production Size**: 504.
**Average Aircraft Price**: $447.5 M

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**Totals**: 504.0 17637.1 80723.6 49619.7 244316.3 96336.0

### MANUFACTURERS CUMULATIVE CASHFLOW — 1992. DOLLARS

**Production Size**: 504.
**Average Aircraft Price**: $484.8 M

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**Totals**: 504.0 17637.1 80723.6 49619.7 244316.3 96336.0
### MANUFACTURERS ANNUAL CASHFLOW — 1992. DOLLARS ————

**Production Size:** 504  
**Average Aircraft Price:** $484.8 M

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**Totals:** 504.0  
**Cumulative Cashflow:** 17637.1  
**Total Annual Cashflow:** 80723.6  
**Total Income:** 49619.7  
**Total Net Cashflow:** 39954.8

### MANUFACTURERS CUMULATIVE CASHFLOW — 1992. DOLLARS ————

**Production Size:** 504  
**Average Aircraft Price:** $372.9 M

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual Deliveries</th>
<th>Cumulative Deliveries</th>
<th>Cost</th>
<th>RDT&amp;E</th>
<th>Manufacturing</th>
<th>Sustaining</th>
<th>Net Cashflow</th>
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<tbody>
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<td>504.0</td>
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-------- MANUFACTURERS ANNUAL CASHFLOW — 1992. DOLLARS ————

**Production Size:** 504  
**Average Aircraft Price:** $372.9 M

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**Total Income:** 49619.7  
**Total Net Cashflow:** 39954.8
### MANUFACTURERS RETURN ON INVESTMENT -- 1992. DOLLARS ###

**Production Size = 400.**

**Monthly Rate:**
- $1.6$ 
- $3.2$ 
- $4.4$ 
- $4.8$ 
- $5.2$ 
- $5.6$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$

<table>
<thead>
<tr>
<th>Aircraft Price (Mill. $)</th>
<th>ROI Manufacturing (%)</th>
<th>Profit (Mill. $)</th>
<th>Breakeven Unit #</th>
</tr>
</thead>
<tbody>
<tr>
<td>411.404</td>
<td>1.40</td>
<td>2590.609</td>
<td>390.</td>
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<tr>
<td>462.829</td>
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<td>514.254</td>
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<td>668.531</td>
<td>50.40</td>
<td>105441.375</td>
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</table>

**Production Size = 800.**

**Monthly Rate:**
- $3.2$ 
- $6.3$ 
- $7.9$ 
- $8.7$ 
- $9.5$ 
- $9.5$ 
- $10.3$ 
- $11.1$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$

<table>
<thead>
<tr>
<th>Aircraft Price (Mill. $)</th>
<th>ROI Manufacturing (%)</th>
<th>Profit (Mill. $)</th>
<th>Breakeven Unit #</th>
</tr>
</thead>
<tbody>
<tr>
<td>292.467</td>
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<td>3685.859</td>
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<td>402.142</td>
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<tr>
<td>438.701</td>
<td>53.30</td>
<td>149918.937</td>
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</table>

**Production Size = 504.**

**Monthly Rate:**
- $2.0$ 
- $4.0$ 
- $5.0$ 
- $5.5$ 
- $6.0$ 
- $6.0$ 
- $6.5$ 
- $7.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$ 
- $0.0$

<table>
<thead>
<tr>
<th>Aircraft Price (Mill. $)</th>
<th>ROI Manufacturing (%)</th>
<th>Profit (Mill. $)</th>
<th>Breakeven Unit #</th>
</tr>
</thead>
<tbody>
<tr>
<td>298.309</td>
<td>1.30</td>
<td>2367.922</td>
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<tr>
<td>335.598</td>
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<tr>
<td>447.464</td>
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</table>

Return on Investment = 12.%

Aircraft Price = 340.313

### DOC, IOC, & TOC -- 504. UNITS -- 1992. DOLLARS ###

- **Airframe Cost** (millions $) 232.218
- **Engine Cost** (per engine) 17.627
- **Spares Cost** (airframe and engine) 41.185

Annual Utiliz., Sup. Cruise Mach # and Alt. 4000.0 hrs at M = 2.40 and 57840. ft

- **Stage Length** (sm) 668. 1102. 756. 1161.
- **Stage Length** (nmi) 5754. 3200. 5000. 3000.
- **Trips per year** 668. 1102. 756. 1161.
- **Block Speed** (mph) 1105. 1015. 1087. 1002.
- **Time** (hr) 5.991 3.630 5.294 3.445
- **Ground Time Idle/Maneuver** (hr) 1.500/0.180
- **Flight Time** (hr) 5.811 3.450 5.114 3.265
- **Climb + Descent Time** (hr) 0.857
- **Block Fuel** (lb) 379098. 213591. 330295. 200595.
- **Block Fuel** (gal/hr) 9374. 8718. 9243. 8627.

Direct Operating Costs $/Trip

Flying Operations Costs: 3. person crew
- **Flight Crew** ($828./Blk hr) 4961. 3397. 4499. 3274.
- **Fuel and Oil** ($0.65/gal) 37242. 20983. 32448. 19707.
- **Total** 42203. 24380. 36947. 22981.

Direct Maintenance Costs: Labor rate $19.50/hr
- **Airframe Labor** (1.00 Complexity) 1620. 1110. 1469. 1070.
- **Burden** (200% of Labor) 3240. 2220. 2999. 2141.
- **Material** 2805. 1958. 2555. 1892.
<table>
<thead>
<tr>
<th>Description</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
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<tbody>
<tr>
<td>Engine Labor Total (1.00 Complexity)</td>
<td>156</td>
<td>93</td>
<td>138</td>
<td>88</td>
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<td>Line Maint. Labor Cost</td>
<td>37</td>
<td>22</td>
<td>33</td>
<td>21</td>
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<tr>
<td>(Man hrs per Installation)</td>
<td>71.9</td>
<td>71.9</td>
<td>71.9</td>
<td>71.9</td>
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<tr>
<td>Shop Maint. Labor Cost</td>
<td>56</td>
<td>33</td>
<td>49</td>
<td>31</td>
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<td>Basic Eng. Maint. Labor Cost</td>
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<td>49</td>
<td>73</td>
<td>46</td>
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<tr>
<td>(Man hrs for QEC build-up)</td>
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<td>791.4</td>
<td>791.4</td>
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<td>Outside Service Labor (0.0 % Labor)</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Burden (200.0 % of Labor)</td>
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<td>186</td>
<td>275</td>
<td>176</td>
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<td>Engine Material Cost</td>
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<td>2717</td>
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<td>2571</td>
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<td>Line Maint. Material Cost</td>
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<td>66</td>
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<td>Shop Maint. Material Cost</td>
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<td>80</td>
<td>119</td>
<td>76</td>
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<tr>
<td>Basic Eng. Maint. Material Cost</td>
<td>4368</td>
<td>2593</td>
<td>3844</td>
<td>2454</td>
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<tr>
<td>Outside Service Material Cost</td>
<td>0</td>
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<tr>
<td>Total</td>
<td>12709</td>
<td>8284</td>
<td>11402</td>
<td>7938</td>
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</table>

**Investment Costs:** averaged
- Depreciation (20.0 years, 10.0 % residual) 22937. 13896. 20268. 13188.
- Financing (100.0 % @ 8.00 % interest) 26430. 16012. 23354. 15196.
- Hull Insurance (.35 % aircraft cost) 1784. 1081. 1576. 1026.
- Total 51151. 30988. 45198. 29409.

**Total Direct Operating Cost**
- $/Trip-DOC 106062. 63652. 93548. 60328.
- $/Flight hr 18252. 18453. 18293. 18480.
- $/Block hr 17703. 17537. 17671. 17514.
- $/Aircraft Mile 16.02 17.29 16.36 17.42
- $/ASM 0.05486 0.059197 0.055679 0.059845

**DOC per Aircraft Trip Equation** = $ 10515.77 + $ 14.43/sm

**DOC per available seat trip** = $ 36.01 + $ 0.0494/sm

**OliverDOC = 0.059197**

**Indirect Operating Costs $/Trip**
- Coach Passengers/Flight Attendents 38.0
- First Class Passengers/Flight Attendents 11.0
- Passenger Trip Distance (sm) 6621. 3682. 5754. 3452.
- Departures/Trip 1.000 1.000 1.000 1.000
- Coach Load Factor 0.650
- First Class Load Factor 0.650
- Maintenance - System (0.5000) 888. 602. 804. 579.
- Aircraft Servicing - Aircraft Cont (215.00) 1288. 780. 1138. 741.
- Passenger Service - Cabin Crew (63.55) 2926. 1772. 2585. 1682.
- Passenger Service - Food and Bev (2.0000) 2274. 1378. 2010. 1308.
- Traffic Servicing - Passenger Hand (11.00) 2088. 2088. 2088. 2088.
- Traffic Servicing - Bag and Cargo (80.00) 1028. 1028. 1028. 1028.
- Passenger Service - Comm/Publ/Res (0.0214) 26895. 14957. 23370. 14022.
- Cargo Service - Comm/Publ/Resrv (0.0120) 0. 0. 0. 0.
- General and Administrative (0.0703) 10353. 6332. 9166. 6017.
- Total Indirect Operating Expense 51562. 32760. 46012. 31287.

**Total Indirect Operating Costs**
- $/Trip-IOC 51562. 32760. 46012. 31287.
- $/Flight hour 8873. 9497. 9897. 9584.
- $/Block hour 8606. 9026. 8691. 9083.
- $/Aircraft Mile 7.79 8.90 8.00 9.06
- $/ASM 0.026668 0.030467 0.027386 0.031037

**IOC per Aircraft Trip Equation** = $ 9202.12 + $ 6.40/sm

**IOC per available seat trip** = $ 31.51 + $ 0.0219/sm

**Total Operating Costs**
- $/Trip-TOC 157624. 96412. 139559. 91615.
- $/Flight Hour 27125. 27950. 27290. 28063.
- $/Block hour 8606. 9026. 8691. 9083.
- $/Aircraft mile 25.61 26.18 24.26 26.54
- $/Available Seat Mile 0.081524 0.089663 0.083066 0.090882

**TOC per Aircraft Trip Equation** = $ 19717.89 + $ 20.83/sm

**TOC per available seat trip** = $ 67.53 + $ 0.0713/sm
Breakeven Required Yield  ($/RPM)  .125422 .137944 .127793 .139819  
at Load Factors of .650 and .650

Base ticket price for 6621.sm distance = $ 1854.01  
Based on Average Yield $/ASM of .140000 and .140000

OliverIOC = .030467  
OliverTOC = .089663

------------- AIRLINE RETURN ON INVESTMENT -- 1992. DOLLARS -------------

Trips/Year = 1102.  
Trip Distance = 3682.(sm) = 3200.(nmi)

Average Yields:  First Class .130000  Coach Class .130000 $/RPM

<table>
<thead>
<tr>
<th>Price (Mill. $)</th>
<th>ROI (%)</th>
<th>Total Operating</th>
<th>Direct Operating ($/ASM)</th>
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<tr>
<td>340.313</td>
<td>5.600</td>
<td>.089663</td>
<td>.059197</td>
</tr>
<tr>
<td>374.344</td>
<td>9.100</td>
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<td>.059197</td>
</tr>
<tr>
<td>408.375</td>
<td>12.100</td>
<td>.089663</td>
<td>.059197</td>
</tr>
<tr>
<td>442.406</td>
<td>14.400</td>
<td>.089663</td>
<td>.059197</td>
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<tr>
<td>476.438</td>
<td>16.400</td>
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Average Yields:  First Class .140000  Coach Class .140000 $/RPM

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Average Yields:  First Class .150000  Coach Class .150000 $/RPM

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<tr>
<td>340.313</td>
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<td>.059197</td>
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<tr>
<td>374.344</td>
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<tr>
<td>476.438</td>
<td>27.400</td>
<td>.089663</td>
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Average Yields:  First Class .160000  Coach Class .160000 $/RPM

<table>
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<tr>
<th>Price (Mill. $)</th>
<th>ROI (%)</th>
<th>Total Operating</th>
<th>Direct Operating ($/ASM)</th>
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<td>340.313</td>
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<tr>
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<tr>
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<tr>
<td>476.438</td>
<td>31.400</td>
<td>.089663</td>
<td>.059197</td>
</tr>
</tbody>
</table>

Manuf. Return on Investment = 12. %  
Airline Return on Investment = 12. %  
Aircraft Price Mil $ = 340.313  
Average Yield/RPM = .149500  
Production Quantity = 504.

------------ RETURN ON INVESTMENT, OPERATIONS -- 1992. DOLLARS ------------

Stage Length (nmi) = 3200.  
Utilization = 1102.08 trips/yr  
Initial Aircraft Price = 340.313  
Tax Rate = 34.00 %  
Initial Investment = .140000  
Interest Rate = 8.00 %  
Average Yield: Coach = .140000  
First Class = .140000 $/RPM

Operating Cost 115.833 115.238 114.595 113.901 113.152
Interest 27.225 26.630 25.988 25.294 24.544
Depreciation 15.314 15.314 15.314 15.314 15.314
Income Tax 0.000 0.000 0.000 0.000 0.000
Net Earnings -7.995 -7.400 -6.758 -6.064 -5.314
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<th>2007</th>
<th>2008</th>
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<th>2010</th>
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<tr>
<td>Discount Factor</td>
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<td>15.314</td>
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<tr>
<td>Earnings Before Tax</td>
<td>-4.505</td>
<td>-3.631</td>
<td>-2.687</td>
<td>-1.667</td>
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<tr>
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<td>0.000</td>
<td>0.000</td>
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<tr>
<td>Net Earnings</td>
<td>-4.505</td>
<td>-3.631</td>
<td>-2.687</td>
<td>-1.667</td>
<td>-0.566</td>
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<tr>
<td>Net Cash Flow</td>
<td>34.544</td>
<td>34.544</td>
<td>34.544</td>
<td>34.544</td>
<td>34.544</td>
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<tr>
<td>Discount Factor</td>
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<td>0.502</td>
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<td>17.322</td>
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<td>15.314</td>
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<tr>
<td>Earnings Before Tax</td>
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<td>1.120</td>
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<td>Net Earnings</td>
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<td>Net Cash Flow</td>
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<td>2019-20</td>
<td>2020-20</td>
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<td>Operating Cost</td>
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<td>97.792</td>
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<td>Depreciation</td>
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<td>15.314</td>
<td>15.314</td>
<td>15.314</td>
<td>15.314</td>
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<td>6.630</td>
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<td>0.212</td>
<td>0.194</td>
<td>0.178</td>
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Total

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<th>Annual Revenue</th>
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<td>Depreciation</td>
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<td>Principle</td>
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<td>Earnings Before Tax</td>
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<td>Income Tax</td>
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<td>Net Earnings</td>
<td>27.528</td>
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<tr>
<td>Net Cash Flow</td>
<td>346.416</td>
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Discounted Rate of Return on Investment  9.1 %
APPENDIX F: PROBABILISTIC LIFE CYCLE ANALYSIS OF COMBUSTOR

The NESSUS capability for the harmonic loads was used to compute the probabilistic responses of a combustor liner subject to high temperatures. Material properties were input using the elasticity matrix coefficients. Several NESSUS analyses runs were made for different degraded D-matrix coefficients due to the cyclic loads. Material degradation of these coefficients was performed using the multi-factor-interaction-model (MFIM). Probabilistic cyclic stresses and respective sensitivity factors were computed using NESSUS computer code. Hoop stress cumulative distribution function (CDF) for different load cycles at a critical node are plotted in Figure 1 and its sensitivity to the respective primitive random variables are shown in Figure 2. The temperature gradient at the location under study has been found most sensitive to the hoop stress.

Also, the material strength cumulative distribution function using the Weibull distribution was computed for different cyclic load cycles. The strength degradation was achieved using MFIM. Degradation due to both the temperature as well as cyclic load effects was accounted in the computation process. Figure 3 shows the CDF of strength under different load cycles. Using the results of probabilistic strength and stress, the life cycle curves at different probability levels generated as shown in Figure 4. Also, the probability of failure as well as survival probability curves for different load cycles were developed as shown in figures 5 and 6 respectively.

![Figure 1.—CDF of hoop stress at a critical location for different load cycles.](image-url)
Figure 2.—Sensitivity of random variables to the hoop stress at different load cycles at 0.01 probability.

Figure 3.—CDF of Hoop strength for different load cycles.
Figure 4.—Strength vs stress at different load cycles.

Figure 5.—Probability of failure.

Figure 6.—Survival probability.
**Enhancement/Upgrade of Engine Structures Technology Best Estimator (EST/BEST) Software System**

**Sest, Inc.**
18000 Jefferson Park Road
Middleburgh Heights, Ohio 44130

**National Aeronautics and Space Administration**
Washington, DC 20546–0001

**Computer codes; Structural analysis; Aerodynamic analysis; Probabilistic evaluations; Damage tolerance; Systems evaluations**

This report describes the work performed during the contract period and the capabilities included in the EST/BEST software system. The developed EST/BEST software system includes the integrated NESSUS, IPACS, COBSTRAN, and ALCCA computer codes required to perform the engine cycle mission and component structural analysis. Also, the interactive input generator for NESSUS, IPACS, and COBSTRAN computer codes have been developed and integrated with the EST/BEST software system. The input generator allows the user to create input from scratch as well as edit existing input files interactively. Since it has been integrated with the EST/BEST software system, it enables the user to modify EST/BEST generated files and perform the analysis to evaluate the benefits. Appendix A gives details of how to use the newly added features in the EST/BEST software system.

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Washington, DC 20546–0001