THE USE OF DESIGN OF EXPERIMENTS WITHIN THE MECHANICAL DESIGN PROCESS IN EVALUATING COMPOSITE MATERIAL SYSTEMS FOR A HSCT EXHAUST SYSTEM

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Abstract

Many advances in technology will be required to make the High Speed Civil Transport (HSCT) economically viable. A key area that has been identified by NASA and Industry as an enabling technology for the HSCT is the development of a high strength, high temperature, long exposure material system that can be made economically and to the size required for this type of system. During this process advanced materials were considered that included metal matrix composites (MMC's), intermetallic matrix composites (IMC's), and ceramic matrix composites (CMC's). This paper describes a process that integrates the mechanical design process with the material development process.

In developing this type of technology there are many approaches that can be taken to determine the required material properties for the HSCT. The approach taken here to help guide the development of these advanced materials is the use of Design of Experiments (DoE) technique within the mechanical design process.

Introduction

In the past metallurgists and mechanical designers have not always been in sync when it has come to material development. Normally the metallurgists predicted material properties for a particular material system and the mechanical designers used the property information to design hardware. As the designs evolved the material properties are updated and the mechanical designers re–evaluate the material system by redesigning the part to meet the new properties. At the same time material developers are lead astray by what the mechanical designers think they require to make the design viable. Each time one discipline is one step behind the other. This creates a waste of effort, evaluating material system that never really have the potential to become reality. In the current environment of today, companies can neither afford the wasted time or effort that is exerted on materials that have no payoff.

Because of the uncertainty involved in the material development of these systems and what the actual material properties will be, a Design of Experiments (DoE) approach was taken to evaluate the material systems. This DoE approach evaluates a material property design space rather than looking at several specific material systems. The benefits of doing this are two fold; 1) it allows the development of sensitivities relative to particular material properties so that trades can be made and 2) a design tool can be developed using these sensitivities so that in the future, as real material properties become available, they can be evaluated quickly.

The DoE technique has been around for many years and has been used by the Japanese since the early 1950's. They have used this technique in quality control and for understanding processes used in manufacturing and design cycles. DoE is a statistical approach useful for evaluating complex systems by determining what the important factors (independent variables) are and running a controlled experiment that looks at the effects on the system (the dependent variables) when these factors are changed. The changes in the factors are determined by what limits they may have within their environment and are defined as levels. For example an experiment with two levels would have two values (an upper and a lower limit), while one with three levels might have an upper, a lower, and a median value. A two level experiment provides a linear (planer) result, nonlinear results can be accounted for by increasing the number of levels in the experiment. Nonlinearity can also be handled by running selected points (i.e. a center point) in the experiment of a two level experiment as will be discussed later.

During the development of the DoE, several components from a potential HSCT exhaust system (see Figure 1) were chosen and mechanical designs were developed to take into account varying levels of manufacturing complexity. These configurations where then used to develop finite element models for the analysis used in the experiment. The finite element analysis utilized composite elements that would allow the ply lay up to be optimized depending on the loading condition of the component. As each material system in the DoE was analyzed, the lay ups were tailored by the number of plys and ply angle to achieve the optimum failure criteria for that system. This iterative process, once complete, would yield a volume (weight) for each component analyzed. Once the DoE data was compiled, a statistical analysis was performed to develop predictive models of weight versus material properties.

With this integrated approach the concerns of the mechanical designer, material developer, and the manufacturing engineer can be addressed at the same time and early in the design cycle. The total process involves several well defined steps as outlined in Figure 2. During each of these steps, a small multi–disciplined team of engineers made decisions that shaped the final DoE experiment, as well as the design tool, so the process would yield the desired results. This approach was selected for this program because it was known before hand that the material systems being evaluated were state–of–the–art and that the properties of each of these systems would evolve over time. By using this approach a system could be set up such that, as new information about the material systems was gathered the materials could be evaluated quickly and information fed back to the material developers as

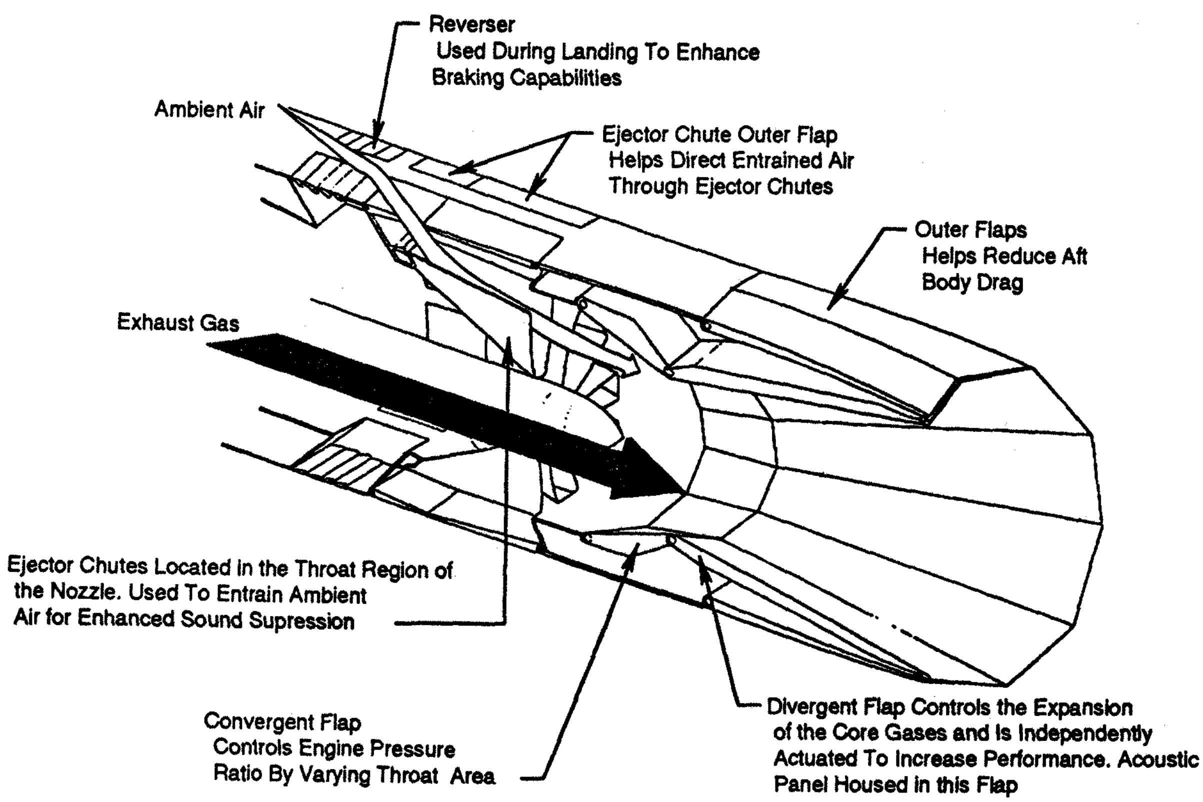


Figure 1 – Potential HSCT Exhaust System.

to what benefits may be derived from these material systems. With the high–payoff properties and effects of manufacturing identified, the likelihood of making a viable HSCT becomes more of a reality.

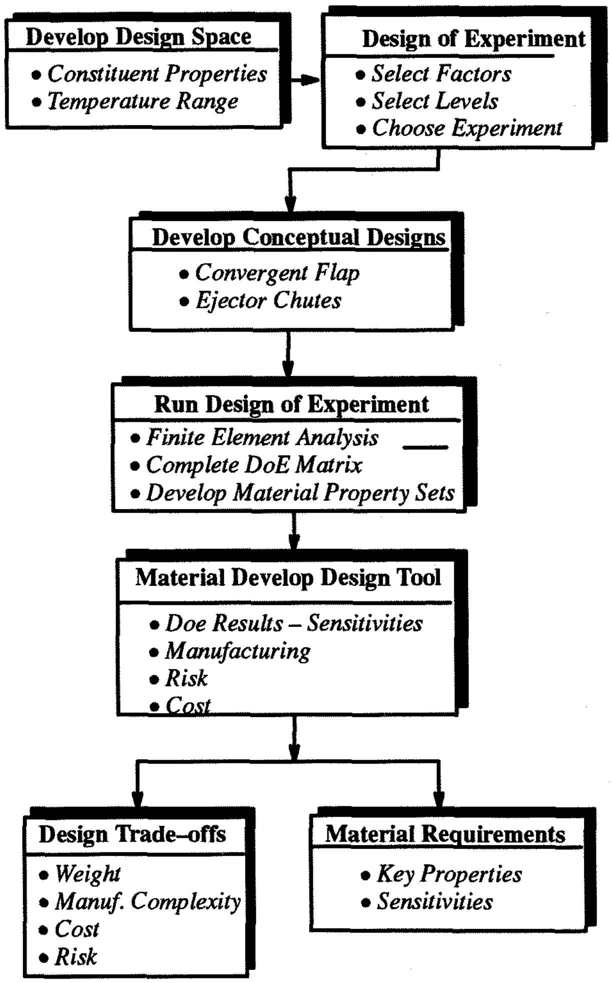


Figure 2 – DoE Process

List of Symbols

Symbols without Subscripts

A, B, C, D, E, F, G, H – DoE factors: see Table 1
FC – failure criteria: stress/strength

Symbols with Subscripts

S – material strength
E – Young's Modulus
α – coefficient of thermal expansion
μ – longitudinal Poissons ratio
K – longitudinal thermal conductivity
m – negative slope of strength verse temperature
b – strength at 2000°F
c – strong bond/weak bond variable defines relationship between S_{2c} and S_{2t}.
FC – failure criteria: stress/strength

Subscripts

$_1$ – longitudinal direction
$_2$ – transverse direction
$_3$ – out of plane direction

$_t$ – tensile
$_c$ – compressive

$_{\Delta T}$ – due to temperature
$_{\Delta P}$ – due to pressure

Design of Experiments

Development of the Experiment

Selection of Factors and Levels

The development of the experiment is the most consuming portion of the task and care must be taken in selecting the right factors and levels so that the experiment will yield the desired outcome for future use. The selection of factors and their levels will drive the size (number of runs) of the experiment that will be required to understand the effects of the factors on the system. In this program several different material systems were evaluated, all of which were composite systems utilizing either a metal, an intermetallic, or a ceramic as the matrix and either a monofilament or TOW fiber (a yarn like structure made of many very small diameter monofilament fibers). Since there was a broad range of composite constituents, much work was needed to ensure that the levels and factors chosen for the experiment would represent the range of properties that might be developed from them.

In setting up the experiment the first thing that needed to be defined was the factors (the independent variables in the experiment), some of which would have an impact on the dependent variable (in our case the component weight). For this experiment, finite element analysis was used as the evaluation tool. A list of properties required by the finite element code was the starting block for determining the factors which would be used in the experiment. These properties included:

longitudinal and transverse tensile strengths (S_{1t} and S_{2t} respectively)

longitudinal and transverse compression strengths (S_{1c} and S_{2c} respectively)

interlaminar shear strength (S_{12})

longitudinal, transverse and out of plane modulus (E_1, E_2 and E_3 respectively)

longitudinal, transverse and out of plane thermal growth (α_1, α_2, and α_3 respectively)

longitudinal, transverse and out of plane Poisson's ratio (μ_1, μ_2 and μ_3 respectively)

longitudinal, transverse and out of plane thermal conductivity (K_1, K_2 and K_3).

Density was not required for the finite element stress analysis but was used later to calculate the weight of the component after it's volume (for a particular material system) was determined.

If all of the properties listed above were used as factors (independent variables) in the experiment, the experiment would require hundreds of runs in order to extract any useful information. In order to keep the size of this experiment manageable, an effort was made to select only the most important material properties as factors. Properties from all of the composite constituents under consideration for this program were used to develop ply properties. The ply properties were then cross plotted in order to determine which properties were independent of the rest. An example of one of these plots is shown in Figure 3. From the plotted data several representative equations were developed that defined all of the material properties as a function of seven independent properties: S_{1t}, S_{2c}, E_1, K_1, α_1, α_2 and c (a variable which indicates strong bond or weak bond between the fiber and the matrix).

As the experiment set–up evolved it became clear that temperature variation in the properties would

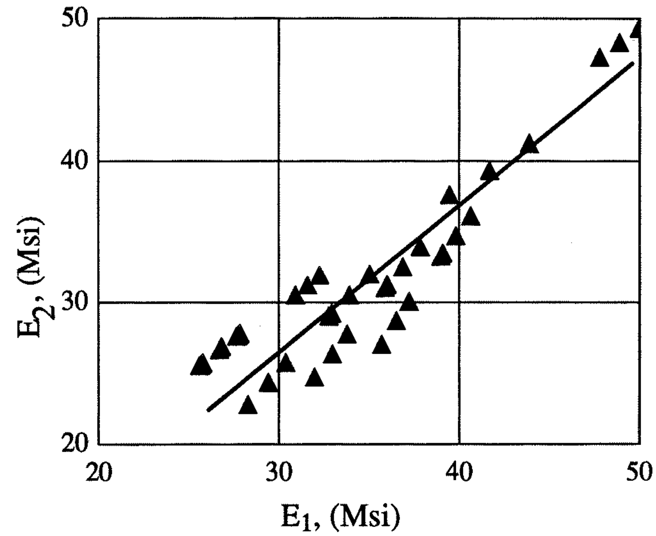


Figure 3 – Material Property Range.

also have to be accounted for. To handle this, several factors were further refined in terms of a slope and an intercept (i.e. y = m*x+b). For example S_{1t} versus temperature is shown in Figure 4. Plots like this were used to set the upper and lower limits in the experiment. As can be seen in this figure, the two limits set for this property capture all the material systems temperature variation being evaluated. For this experiment, it was felt that the number of factors could be limited to 8 without discarding any obviously important factors, thus the size of the experiment could be kept at a reasonable level. The

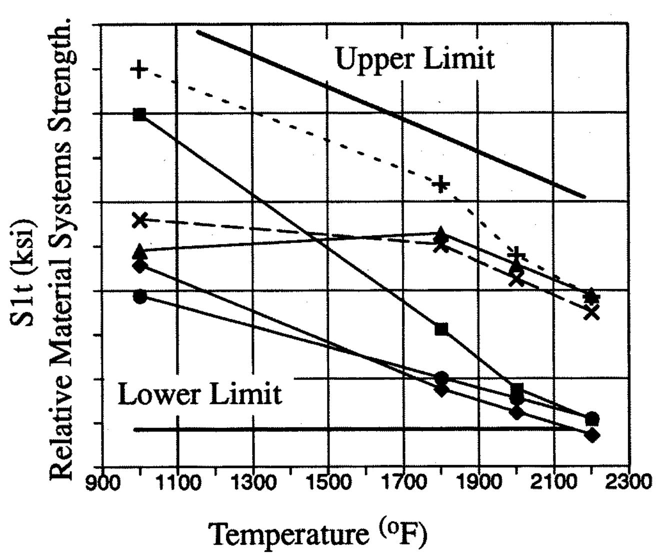


Figure 4 – Material Prop. vs Temperature

DoE Factor	Material Variable	Units	Description
A	b_2	ksi	2–2 compressive strength at 2000°F
B	m_2	ksi/°F	Negative slope of 2–2 compressive strength vs temperature
C	c	—	Multiplier relating 2–2 tensile to 2–2 compressive strength
D	$\Delta\alpha$	υin/in/°F	Difference between the 2–2 and 1–1 thermal expansions
E	E_1	Mpsi	Elastic modulus in the 1–1 direction
F	α_1	υin/in/°F	Coefficient of thermal expansion in the 1–1 direction
G	b_1	ksi	1–1 tensile strength at 2000°F
H	m_1	ksi/°F	Negative slope of 1–1 tensile strength vs temperature

Table 1 – DoE Factors and Material Variables

final DoE factors which were selected are shown in Table 1.

The second step in setting up the experiment is deciding on the number of levels. If there is a concern over the size of the experiment as there was here it is suggested that the number of levels be limited to an upper and a lower bound. Using the results of the two level experiment, additional runs at different points can be added in order to clarify selected areas of the material design space.

Once the number of factors and levels have been determined an experimental arrangement must be selected that will yield the best results in the time or money constraints of the program. Experimental arrangements are well documented in text such as Designing For Quality [1] and "Handbook of Designs: Experimental Design and Graphical Analysis Tools for Experimenters"[2]. These experiments allow the investigator to draw out the most information with the least effort depending on the number of factors and levels. It is also important to note here that the type of experiment chosen will also define the level of interaction and confounding that will be inherent in the analysis. An interaction between factors occurs when their product causes a change in the systems response. The fewer and the higher the order of the interactions, the easier the results will be to interpret.

For this case once the factors and levels had been defined, a DoE 2^{8-4} experiment with a level IV resolution was chosen (experiment layout is shown in Figure 5). This provides single factor sensitivities which are confounded with three–way and higher interactions. (When factors are confounded with other factors, or other factor interactions, the effect of the confounded factors is actually due to the their combination, thus, their effects can not be estimated independent of each other.) Statistically significant three–way interactions, however, are very rare; therefore, the single factor effects will dominate the confounded three way interaction effects. Hence, the effects of the confounding three way interactions were assumed to be zero. Also, in this experiment each two factor interaction will be confounded with three other two factor interactions. Thus, in the event of a statistically significant two factor interaction, judgment must be used in picking which of the confounded interactions was primarily responsible for producing the observed effect.

Concept Development

During the development of the DoE the team also developed mechanical designs of two components from one of the exhaust systems under consideration for the HSCT, (Figure 1). This allowed the team to focus on the material requirements as opposed to the overall exhaust system design. Several key components were selected utilizing the Quality Function Deployment (QFD) method, in order to evaluate them in more depth. From this analysis four subcomponents where selected. They were

Design: 2^{8-4}_{IV}
Factors: 8
Runs: 16

Std. Order	Random Order	A	B	C	D	AB	AC	AD	BC	BD	CD	E	F	G	H	ABCD	Response(s)
1		–	–	–	–	+	+	+	+	+	+	–	–	–	–	+	
2		+	–	–	–	–	–	–	+	+	+	+	+	+	–	–	
3		–	+	–	–	–	+	+	–	–	+	+	+	–	+	–	
4		+	+	–	–	+	–	–	–	–	+	–	–	+	+	+	
5		–	–	+	–	+	–	+	–	+	–	+	–	+	+	–	
6		+	–	+	–	–	+	–	–	+	–	–	+	–	+	+	
7		–	+	+	–	–	–	+	+	–	–	–	+	+	–	+	
8		+	+	+	–	+	+	–	+	–	–	+	–	–	–	–	
9		–	–	–	+	+	+	–	+	–	–	–	+	+	+	–	
10		+	–	–	+	–	–	+	+	–	–	+	–	–	+	+	
11		–	+	–	+	–	+	–	–	+	–	+	–	+	–	+	
12		+	+	–	+	+	–	+	–	+	–	–	+	–	–	–	
13		–	–	+	+	+	–	–	–	–	+	+	+	–	–	+	
14		+	–	+	+	–	+	+	–	–	+	–	–	+	–	–	
15		–	+	+	+	–	–	–	+	+	+	–	–	–	+	–	
16		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
Σ(+)																	
Σ(–)																	
Σ(+)+Σ(–)																	
Σ(+)–Σ(–)																	
[Σ(+)–Σ(–)] ÷ 8																	
Contrasts		$\mathcal{L}_1$	$\mathcal{L}_2$	$\mathcal{L}_3$	$\mathcal{L}_4$	$\mathcal{L}_4$	$\mathcal{L}_6$	$\mathcal{L}_7$	$\mathcal{L}_8$	$\mathcal{L}_9$	$\mathcal{L}_{10}$	$\mathcal{L}_{11}$	$\mathcal{L}_{12}$	$\mathcal{L}_{13}$	$\mathcal{L}_{14}$	$\mathcal{L}_{15}$	

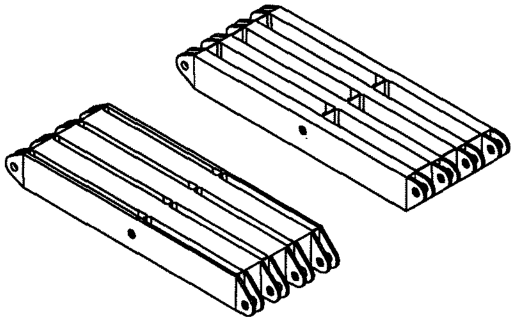
Figure 5 – Proposed DoE Arrangement

the ejector chutes, the convergent flap, the divergent flap, and the acoustic liner. It was decided that the DoE approach would focus on the ejector chute and the convergent flap.

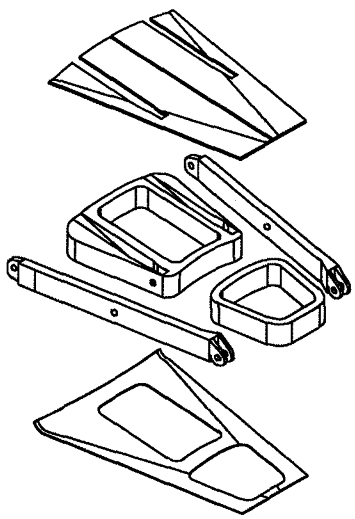
These were chosen because it was felt that they represented the extremes of manufacturing in the exhaust system. The convergent flap would represent all of the assemblies, such as the divergent flap and outer flap and the chutes would represent simpler sheet metal type constructions. The team used brain storming sessions to try and develop different levels of manufacturing techniques that could be used to manufacture the components. During these sessions fabrication techniques were considered that were compatible with the materials systems being investigated. Out of these sessions came three concepts for each of the components as shown in Figures 6 and 7.

Running the Experiment

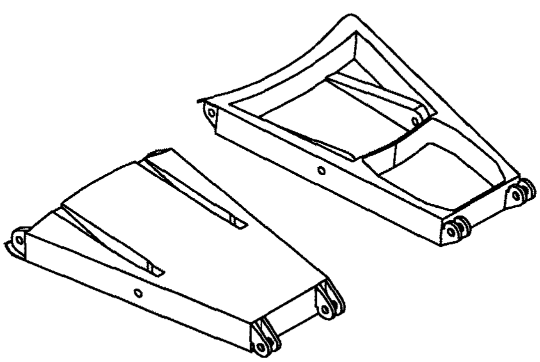
As described earlier, the experiment was developed to have 8 factors (independent variables) at two levels. It was decided by the team that a fractional factorial would be run such that only 16 runs would be required for each level of manufacturing complexity of each component. An additional point at the mean level of each factor (in the middle of the design space – in DoE terms called a centerpoint) would be run. By comparing the linear results of



Multi–Rib Convergent Flap
Low

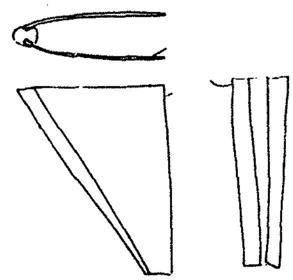


Modular Box Convergent Flap
Medium

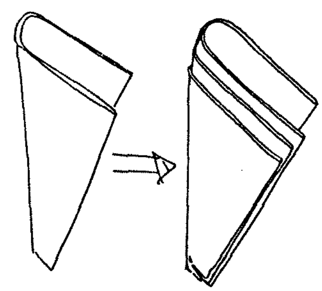


Integrated Frame Conv. Flap
High

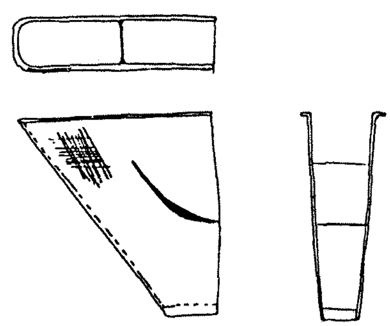
Figure 6 – Manufacturing Complexity Levels for A Convergent Flap.



Single Sheet w/Leading Edge Cone
Low



Single Ply Stacked Lay Up
Medium



Cast Whisker/TOW
w/Monofilament Lay Up
High

Figure 7 – Manufacturing Complexity Levels for A Ejector Chute.

the two level portion of the DoE (the first 16 runs) with the centerpoint, non–linearity (curvature) can be detected. If significant curvature of the response surface is detected, more runs at different points can be added in order to accurately model the curvature.

As the finite element (FE) models for the three manufacturing levels of the ejector chute were being developed, it became clear that the chute analysis of the medium complexity (stacked laminate construction) and high complexity (integrally cast fiber) would be nearly identical. Likewise, the convergent flaps of medium complexity (modular box construction) and high complexity (integrated frame construction) had very similar geometry, thus only one DoE was performed for these configurations. Thus the number of FE models was reduced from the original six (three complexity levels for both the flap and the chutes) to four.

ANSYS was used as the analytical tool and each model utilized composite elements (STIF 99) that would allow up to 99 plys in any orientation. The number of elements was adequate enough to capture the overall stress levels in the parts and to highlight areas that might be of concern. The FE models were not, however, developed to resolve stress concentration effects in the components.

Initially, a steady state heat transfer run was made for each FE model. Heat transfer coefficients were calculated and applied to the models, permitting the computation of the temperatures within each model. Next, the finite element stress analysis (which computed stresses due to both thermal gradients and pressure loads) of each component model was run for all 16 material combinations defined by the basic DoE. A 17th run was also performed at the center point of the experiment as mentioned earlier.

As the finite element stress analysis was run on each of the material sets, the composite layup (fiber orientation in each ply) required optimization in order to minimize the stresses in the part. This was an iterative process that was concluded when the failure criteria (actual stress divided by the allowable stress) was minimized, after which ply layers could be removed until a failure limit was reached, thus minimizing the part volume and weight. During this time there were several areas around lugs and attachment points (in the convergent flap models) that were not optimized because of the time that would have been involved in doing this. It was assumed that for the level of results that were being sought, optimizing localized attachment points would not benefit the program at this time and these areas would be addressed in a latter portion of the program. In addition, there were unavoidable edges on the convergent flap models where 0° plys would meet 90° plys. For instance, the ribs, face plates, and bulkheads on the multi–rib convergent flap were constructed perpendicular to each other and high thermal stresses, due to mismatch in the longitudinal and transverse coefficient of thermal expansion (α_1 and α_2), would occur where these components intersected. When the finite element models were optimized, these local high stress regions were not used in sizing the component.

As each run was performed, the primary failure modes and the optimized part volume were recorded. A sample of this data is shown in Table 2. Some material sets were not viable, that is the failure criteria could not be reduced to less than 1.0 (generally due to high thermal stresses). For these systems, the part volume was scaled, based on the lowest achievable failure criteria (this always resulted in a high volume part).

Results

The following sections describe the DoE results and the weight equations (derived from the regression analysis of the DoE data) for each of the nozzle components. After completing the basic sixteen run DoEs for both of the ejector chute and both of the convergent flap models, comparisons with the centerpoints showed that there were significant curvatures in all of the the response surfaces (part volumes); thus, additional points were added to the DoE set ups for each FE model.

Ejector Chutes

For the low complexity ejector chute (monolithic leading edge with single–sheet sidewall construction) points for factors B and C (material variables m_2 and c) were added (the first 16 runs indicated these were the most significant variables and would thus be most likely to produce significant non–linear effects); for the medium complexity

DoE Mat #	$FC_{\Delta T}$	$FC_{\Delta T+\Delta P}$	ΔFC* ($FC_{\Delta T+\Delta P}-FC_{\Delta T}$)	Volume	ΔT Failure Modes	$\Delta T+\Delta P$ Failure Modes
1	6.86	11.32	7.92	300.00**	SY	SY
2	5.48	10.71	7.71	280.00**	SY	SY
3	2.37	2.37	1.25	160.00**	SXY	SX,SY,SXY
4	0.53	1.63	1.46	80.70	SXY	SY
5	0.56	1.16	0.80	66.80	SXY	SX,SY
6	1.21	1.04	0.49	61.30	SY	SY
7	0.99	1.95	1.30	116.80	SY	SY
8	1.40	2.04	1.32	130.70	SY	SY
9	2.07	3.60	2.95	180.00**	SY,SXY	SY
10	2.46	3.80	2.60	240.00**	SXY	SY
11	1.38	4.82	4.07	240.00**	SY	SY
12	6.12	7.10	2.98	260.00**	SY	SY
13	3.29	3.10	1.50	180.00**	SY	SY
14	0.58	2.36	2.01	97.40	SY	SY
15	0.52	0.74	0.45	50.20	SX,SY	SX,SY
16	0.53	0.67	0.63	50.20	SXY	SY

* Failure modes at the same location ** Calculated Volumes

Table 2 – Sample Data From DoE.

chute(stacked laminate construction) points were added for factors A, B, C and E (variables b_2, m_2, c, and E_1). After the additional DoE runs were completed, a regression analysis was performed in order to express the chute volumes in terms of the DoE factors. The resulting low complexity ejector chute volume was:

$$VOL_1 = 137.304 - 8.18754*A - 36.2395*B - 43.414*C + 8.79596*A*B + 5.86282*A*C - 6.07384*C*G + 19.9218*B*C - 4.51654*C*H + 8.97132*E - 5.56690*H - 12.6116*B^2$$

where VOL_1 is in in^3. This produced a 96.5% adjusted R–squared regression value, indicating a good curve fit. When this equation is used to back calculate the chute volumes in the DoE runs, all but one point are fit with less than 15% error.

The coefficients of each factor indicate the relative significance of the factor. Thus, it is obvious that factors B and C, which are used to define the composites transverse strength, are the most important single factor terms. The negative sign on the coefficients of factors B and C indicate a high value of B or C would result in a lower volume and thus a lighter part. As mentioned previously, each of the interaction effects (A*B, A*C, C*G, B*C and C*H) were confounded with three other two factor interactions, so judgement had to be used in picking the interactions shown in the equation. Generally, factors which show a strong single factor effect on the system are more likely to be important in interaction terms. For instance, the two factor interaction B*C is confounded with interactions A*E, D*H, and F*G; since both factors B and C had large single factor effects their interaction was chosen as the important factor and the other interactions neglected. The B^2 term indicates curvature of the volume equation due to this factor.

The low complexity ejector chute volume, written in terms of the composite material variables, becomes:

$$VOL_1 = 381.9 - 4.498*b_2 - 1962.8*m_2 - 241.7*c + .94435*E_1 + .25308*b_1 + 73.75*m_2 + 33.508*b_2*m_2 + 2.3451*b_2*c - .37962*b_1*c + 1707.6*m_2*c - 288.29*m_1*c - 10295*m_2^2$$

The units on the material property variables are shown in Table 1. It should be stressed that these regression equations only apply to the range of variable values analyzed in the DoE. Extrapolation of the equations outside of the design space can result large errors because the design space is non–linear and should be done with great care.

The regression analysis of the medium complexity chute volume, in terms of DoE factors provided:

$$VOL_2 = 94.1945 - 9.48319*A - 37.639*B - 51.5735*C + 5.47847*D + 5.20877*A*B + 6.74773*A*C - 6.61797*C*G + 23.6163*B*C - 5.94297*C*H - 8.47864*B*H + 12.1501*E - 2.11441*F - 3.87508*G - 4.5508*H + 13.6718*B^2 + 27.4514*C^2$$

where VOL_2 is in in^3. This curve fit produced an adjusted R–squared value of 99.3%, indicating an excellent fit. Using this equation, the curve fit errors of the DoE points were all under 10%. As in the low complexity equation, factors B and C are clearly the dominant single factor effects and their interaction effect (B*C) is also important. Additionally, significant curvature exists due to these factors.

Substituting the material variables for the DOE factors results in:

$$VOL_2 = 511.1 - 4.1548*b_2 - 3956.1*m_2 - 615.5*c + 1.826*\Delta\alpha + 1.279*E_1 - .50283*\alpha + 19502*b_1 + 439.56*m_1 + 19.843*b_2*m_2 + 2.6991*b_2*c - .41362*b_1*c + 2024.3*m_2*c - 379.34*m_1*c - 5154.2*m_1*m_2 + 11161*m_2^2 + 247.06*c^2$$

In both of the DoE's the primary failure mode was a transverse tensile or compressive failure of an outer ply in the chute wall. This failure mode is due to the fact that the chute sidewalls are pressure loaded putting them in biaxial bending; thus, the outer plys carry most of the load. Because the biaxial bending components are nearly equal, it is impossible to orient the outer ply so that there is not a large stress component transverse to the fiber direction. Consequently, both DoE's showed that the chute volume is most sensitive to factors B and C which correspond to variables m2 (negative slope of the transverse tensile strength) and c (weak bond/strong bond factor) and are used to define the transverse tensile and compressive material strengths. These transverse strengths are matrix driven and in the case of a weak bonded composite (low C value) the transverse tensile strength is typically much lower than the monolithic strength. This indicates a monolithic chute with high strength at the temperature of the design point and also "enough" strength at the low–load/high–temperature conditions will result in the lightest and probably the most cost effective ejector chute.

Multi–Rib Convergent Flap (Low Complexity)

For the multi–rib convergent flap additional DoE runs were made in order to determine the curvature associated with factors G, H and C (variables b_1, m_1 and c). As in the ejector chute DoE, these factors were chosen since they produced the most significant effects in the basic 16 run experiment. The regression analysis of the convergent flaps was not as straight forward as that of the ejector chutes. None of the DoE factors were so clearly dominant as in the ejector chutes. The regression analysis based on the DoE factors did not provide the desired accuracy; however, the regression analysis of the inverse volume, based on the composite material variables, did produce fairly good results: an adjusted R–squared regression value of 87.6%. The resulting low complexity convergent flap volume equation, based on the composite material variables, is:

$$VOL_1 = 1 / [-.00213 + .0483*m_2 + .00285*c - .00109*b_2*m_2 + .000142*b_2*c + .00003*E_1 - .000058*\alpha + .000035*b_1 + .0132*m_1 - .00373*c^2 - .0000001*b_1^2]$$

where VOL_1 is in in^3 and the units for the material property variables are shown in Table 1. When this equation is used to back calculate the DoE volumes, all but one of the points fit within ±16% error.

It is important to note that the viable convergent flap material sets had low values of $\Delta\alpha$ (defined as $\alpha_2 - \alpha_1$). Because the localized high thermal stresses (driven by $\Delta\alpha$) at the intersections of ribs, face plates, and bulkheads were ignored during the part optimization, $\Delta\alpha$ was not included in the regression analysis. The optimum ply orientation for the convergent flap was generally unidirectional.

In the multi–rib convergent flap DoE, there were two primary mechanical failure modes. The flap ribs encountered large tensile and compressive stresses in the longitudinal direction due to the pressure and seal loading and the poor mechanical advantage of the actuator links. The sides of the ribs which form the acoustic treatment cavities were also pressure loaded creating smaller transverse tensile and compressive stresses. Consequently, the DoE shows that the most important material factors driving flap weight (volume) for the multi–rib concept were the variables m_1 (slope of longitudinal tensile strength) and m_2 (slope of transverse compressive strength).

Interaction terms were also important factors driving flap weight. These interaction terms included b_2*m_2 and b_2*c. Confounding occurs between the interactions b_2*m_2, b_1*m_1, $c*E_1$ and $\Delta\alpha*\alpha$. Because m_2 and m_1 both have strong single factor effects, either b_2*m_2 or b_1*m_1 or both could be important. Clearly longitudinal tensile and compressive strength is important for the convergent flap ribs and face plates along with some degree of transverse strength. Since the ribs and face plates are subject to a biaxial bending state, the outer plys carry most of the load. Although cross–plying proved ineffective for the flap ribs and face plates, the lugs of the convergent flap would have to be cross–plyed or at least have fibers wrapped around the lug radius. The need for cross–ply capability in the lugs is due to the varying stress directions encountered as the flap rotates to provide the various throat areas required throughout the flight regime.

Modular Box / Integrated Frame Convergent Flap (Medium and High Complexity)

For the medium and high complexity convergent flap additional DoE runs were made in order to determine the curvature associated with factors H, A and B (material variables m_1, m_2 and b_2). As with the low complexity flap, the modular box / integrated frame concept showed the best regression results for the inverse volume as a function of the material variables:

$$VOL_2 = 1 / [-.00827 + .000521*b_2 + .118*m_2 - .00163*b_2*m_2 + .000026*b_2*c + .213*m_2*m_1 - .502*m_2^2 - .000007*b_2^2]$$

where VOL_2 is in in^3 and the units for the material property variables are shown in Table 1. This equation fits the DoE points with a ±20% error.

Similar to the multi–Rib convergent flap, the modular box and integrated frame concepts experience the same high thermal stresses when mismatches occur between the longitudinal and transverse coefficients of thermal expansion; therefore, the $\Delta\alpha$ factor was dropped from the DoE matrix. Again, it should be noted that $\Delta\alpha$ is a very important factor in composite design and the viable concepts generally had a low value of $\Delta\alpha$. For these two flap concepts, the key material property factors which influenced weight (volume) were b_2 and m_2 (slope and intercept for transverse compressive strength). The b_1*c and m_2*m_1 interactions also appeared to be important in influencing flap weight. Bi–axially loaded components (face sheets) made up a large percentage of the overall flap weight which would explain why transverse properties play a more important role than they did in the Multi–Rib convergent flap. Additionally, as in the low complexity flap, cross–plying proved ineffective due to biaxial bending states in the majority of flap components. However, the lugs of the convergent flap would have to be cross–plyed or at least have fibers wrapped around the lug radius, for reasons stated earlier.

Material Evaluation Tool

The Design of Experiments approach taken to evaluate materials was combined in a computer program that assess materials based on weight, cost, probability of success (risk), and manufacturing complexity. This program is outlined in the flow chart shown in Figure 8. The weight and manufacturing complexity portion of the program were developed by incorporating the DoE results from each of the experiments performed on the two components. The cost portion of the program uses data that was developed during process downselect. Finally, the probability of success of the material is developed utilizing a Monte Carlo simulation technique to determine probable weight. This program, as currently developed, takes fiber and matrix

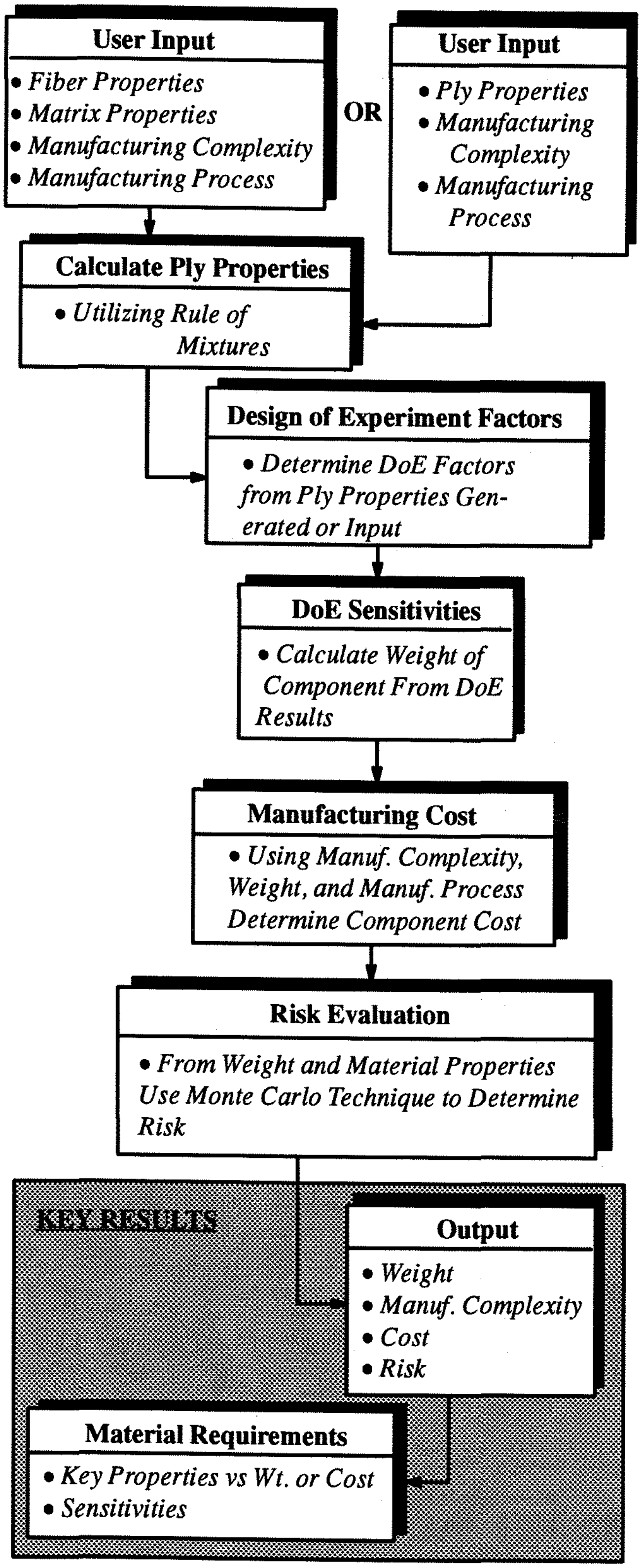
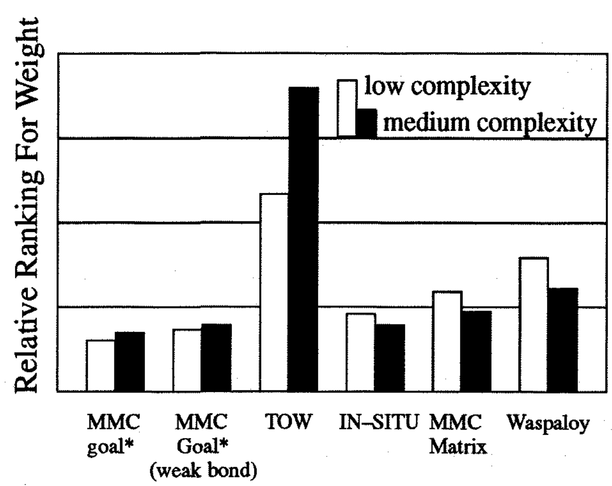


Figure 8 – Evaluation Tool Flow Chart

properties input by the user and uses rule of mixture equations to develop composite ply properties for the particular material system. The program then takes these properties and determines the resulting DoE factors and then uses these factors in the regression equations to determine weights.

One of the inputs to the program is manufacturing complexity which effects the weight equations and the cost calculated. There are three levels of manufacturing complexity for each of the components, low, medium, and high. When calculating cost of components, processes that have been selected in the process downselect are then associated with each level of manufacturing complexity. The cost is calculated for material and labor. The labor cost at this time are preliminary until more accurate assessments can be made of times required for each process. The material cost is calculated taking the weight of the component and determining the fiber and matrix fraction by weight and using cost developed in the process downselect.

This design tool was developed and used to evaluate all types of material systems. A sample of the different material systems evaluated versus weight on the convergent flap is shown in Figure 9. Also, a similar set of data can be generated for cost of the component based on manufacturing complexity and material. Sensitivities, as shown in Figure 10, were also developed to identify key properties in



* Material properties out of DoE range

Figure 9 – Predicted Convergent Flap Weights – Based on Strength

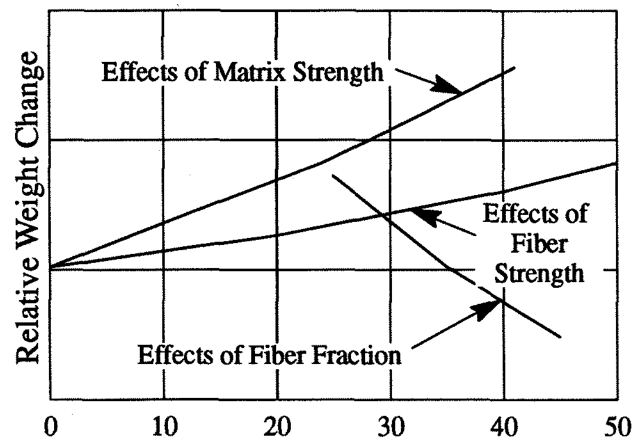


Figure 10 – Property Variation for Low Complexity Convergent Flap.

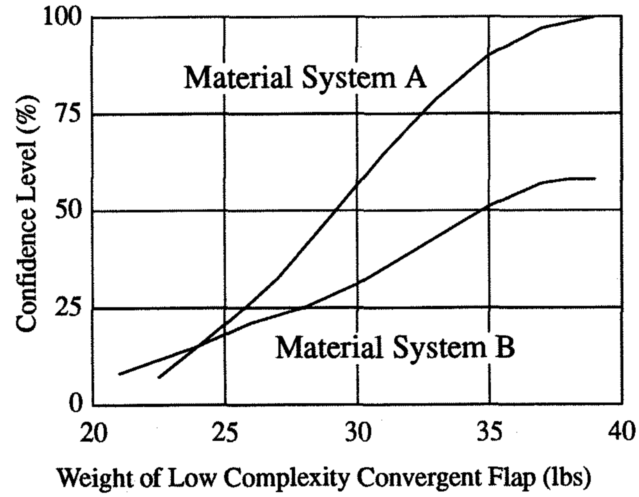


Figure 11 – Distribution of Convergent Flap Weight.

the material systems evaluated. This helps focus the efforts on the properties that are most influential in the design.

The final feature of this tool is to determine the probability of success for a material system. To do this additional property data for the fiber and matrix was required. This additional data is the most and least likely value for each of the properties. A Monte Carlo analysis is then performed and a plot of component weight versus probability of making a specific weight is constructed. A sample of this plot is shown in Figure 11. This will allow the user to determine if the weight goal of the component is obtainable within some confidence level for a particular material system.

By coupling these techniques, a realistic approach to fabrication and cost can be integrated into the development of material systems. The coupling of DoE and mechanical design will also allow the material developers to focus on what properties have the greatest payoff from an overall system perspective thus making the potential for a viable HSCT more realistic.

Conclusions

This paper has presented an approach to evaluating material systems that was centered around a technique called Design of Experiments. Although this was a major portion of the approach, methods to include the mechanical design and manufacturing process into the material evaluation were also developed. This approach uses proven techniques in statistical experimentation to couple the mechanical design process with the material development process.

As an outcome to this approach a design tool was developed, as shown here, that will account for global manufacturing techniques, material cost, and processing capabilities to evaluate material systems. The benefits from this approach come from the ability to evaluate material systems as new ones are developed, (provided they are within the limits of the experiment). This means that as real material property data is gathered this design tool can be used to evaluate the system and give immediate feed back to the material developers. The approach takes quite a bit of up front work and patience but in the long run will show payoffs by developing the best material system for the appropriate application.

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