Potential Effects of Using Guaranteed Premium in Lieu of Minimum Guaranteed Mechanical Properties of Materials

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POTENTIAL EFFECTS OF USING GUARANTEED PREMIUM IN LIEU OF MINIMUM GUARANTEED MECHANICAL PROPERTIES OF MATERIALS

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ABSTRACT

The use of premium mechanical properties for materials, in lieu of minimum guaranteed properties, will result in substantial weight and overall Shuttle program cost savings. To obtain materials with premium mechanical properties (properties that exceed present minimum guaranteed values) will require negotiation with the material suppliers; the prime objective is to obtain the highest supplier guaranteed mechanical properties at an acceptable additional raw material cost. To illustrate the potential benefits of typical properties a study involving a Space Shuttle orbiter wing resulted in a total program cost reduction of $39.3 million, and a weight saving of 1414 lbs. Suggested means of quality control, inspection and controlled in plant use of premium materials are covered.

INTRODUCTION

For the Space Shuttle every feasible avenue for overall weight and program cost saving is being pursued. However, most weight savings methods are associated with increased costs and risks. One of the more promising weight saving approaches considered is use of guaranteed premium mechanical properties in lieu of minimum guaranteed properties. The higher mechanical properties would be obtained for a reasonable material cost increase and no increased risk.

To properly assess the merits of increased performance of aircraft, missiles and spacecraft obtained from a decrease in vehicle weight necessitates a dollar value be assigned to each pound of weight saved. For typical aircraft and spacecraft values range from $40 to $500/lb. Payload sensitivity of the Space Shuttle has raised the value of a pound saved to approximately $28,000 for the straight wing orbiter (Figure 1). For the booster, the value is somewhat less, namely $6200 per pound. These values presume early incorporation of the weight saving ideas such that they influence sizing of vehicles. The merits and problems associated with use of premium mechanical properties will be discussed in the subsequent paragraphs.

USE OF PREMIUM PROPERTIES

Premium mechanical properties as used in this paper are defined as those properties that exceed minimum guaranteed values obtained from MIL-HDBK-5A, MIL specifications or properties previously guaranteed by material suppliers. To justify the use of materials with premium mechanical properties, four major questions need to be answered.

a. How can premium properties be obtained?
b. How can we be sure that properties specified are received?
c. How can material usage be controlled to ensure use of premium stock?
d. What benefits are obtained from using premium mechanical properties?

OBTAINING PREMIUM PROPERTIES

Material chemistry tolerances and process variations within lot sizes as well as between mill runs result in mechanical property variations consistent with a normal frequency distribution. The "A" and "B" values prescribed in MIL-HDBK-5A are computed using test data and standard statistical equations. To obtain premium property material, selective purchases would be made of only those sheets, plates, etc. whose properties exceed preselected premium values. This procedure of course, will require negotiation with material suppliers. The objective in all negotiations with suppliers is to obtain highest guaranteed properties at an acceptable additional cost in raw material.

FIGURE 1

LOW CROSS RANGE STRAIGHT WING ORBITER
Payload sensitivity indicates a pound saved on the orbiter results in a pound increase in payload, while a pound saved on the booster results in about one fifth of a pound increase in payload. Therefore, it is cost effective to pay a higher premium price to obtain higher mechanical properties for orbiter than for booster applications.

Mechanical properties frequency distributions such as shown in Figures 2, 3, 4, and 5 for Rene' 41 and 6, 7, 8 and 9 for L-605 would be beneficial in negotiating premium properties with material suppliers. Data in these figures were obtained from Reference (a). It should be noted that for Rene' 41, relative to minimums, a 40 percent variation in tensile ultimate and yield strengths exist and over 100 percent variation in elongation. Similarly, for L-605 (Haynes 25) a variation in ultimate strength of 34 percent of the minimum for t = .008 in sheet and 17 percent of the minimum for t = .016 in sheet exists. Yield strength and elongation variations were 34 and 40 percent, respectively, and appear to be insensitive to sheet thickness. Such variations indicate that the improvement in mechanical properties in lieu of minimum guarantee, will vary for each material.

It is important to note that the full benefit of the premium properties, as well as any other weight saving scheme, can only be obtained if employed during the vehicle sizing studies. Subsequent adoption of premium properties would result in weight savings but the value derived as a result of vehicle size reduction would be lost.

For a preliminary assessment of benefits that may result from use of premium mechanical properties, typical (the statistical mean of a lot sample with a normal distribution) mechanical properties may be selected as the level of premium properties to be used for vehicle sizing studies. Typical properties may either be obtained from vendor data or derived from MIL-HDBK-5A through statistical analysis procedures. Actual typical mechanical properties for many of the Space Shuttle candidate materials were computed from the "A" and "B" values of MIL-HDBK-5A and from the normal distribution equations of statistics and presented in Table A1 of Appendix A. The relative increase in mechanical properties for these materials is from 4 to 26 percent. Based on these data it is judged that a factor of 1.07 times "A" will be reasonable as an interim for all materials if typical values are not obtainable from supplier data.

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**Table 1**

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Test Condition</th>
<th>Thickness</th>
<th>Tests</th>
<th>YIELD STRENGTH</th>
<th>ELONGATION</th>
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<tbody>
<tr>
<td>Orbiter</td>
<td>Rene' 41</td>
<td>Aged 16 hours at 1400°F Air Cooled</td>
<td>0.008&quot; to 0.010&quot;</td>
<td>113 tests</td>
<td>60 80 100 120 140 160</td>
<td>0.01 0.1 1.5 20 40 60 80 95 99 99.9 99.99</td>
</tr>
<tr>
<td>Booster</td>
<td>L-605</td>
<td>Aged 16 hours at 1400°F Air Cooled</td>
<td>0.008&quot; to 0.010&quot;</td>
<td>137 tests</td>
<td>60 80 100 120 140 160</td>
<td>0.01 0.1 1.5 20 40 60 80 95 99 99.9 99.99</td>
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**Table 2**

<table>
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<tr>
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<th>Test Condition</th>
<th>Thickness</th>
<th>Tests</th>
<th>YIELD STRENGTH</th>
<th>ELONGATION</th>
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<tbody>
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<td>0.021&quot; to 0.025&quot;</td>
<td>50 tests</td>
<td>60 80 100 120 140 160</td>
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<td>L-605</td>
<td>Aged 16 hours at 1400°F Air Cooled</td>
<td>0.021&quot; to 0.025&quot;</td>
<td>50 tests</td>
<td>60 80 100 120 140 160</td>
<td>0.01 0.1 1.5 20 40 60 80 95 99 99.9 99.99</td>
</tr>
</tbody>
</table>
QUALITY CONTROL AND INSPECTION

A brief description of typical quality control and inspection procedures for premium material is provided.

1. Acquisition of "premium" material is generally achieved by tightened Purchase Order requirements (selective closer tolerances) and screening of the standard product at source to select those portions of the lot, or batch, falling within the established premium limits.

2. It is most common to require the supplier to certify that the material conforms to applicable specification physical, mechanical, and chemical properties requirements. This is typically accomplished by providing a quantitative report of laboratory analyses performed on each ingot and lot of material. If it is critical to know actual properties of the finished product, certification of each gage of sheet or plate accountable to each lot must be accomplished, after processing, at extra cost.

CONTROL OF MATERIAL USAGE IN PRODUCTION

In order to ensure that only premium materials when specified are dispensed and used on the Space Shuttle vehicles, the following in-plant procedures would be initiated:

- All raw premium material would be color-coded
- All material requisitioned or dispensed from the in-plant storage areas would be validated by the Inspection Department as being coded and the proper material
- Raw material would be procured in quantities sufficient to minimize possibility of later material substitutions, which might result in error
- All coded material would be stored in a separated and controlled area to ensure separation of coded and uncoded materials
- Special handling procedures and marking of shop travelers or work orders would be initiated further to ensure matching of properly validated material and work orders.

BENEFITS FROM USE OF PREMIUM PROPERTIES

Benefits obtained from use of premium properties will depend upon critical design condition and critical strength parameter used to size each component. For components sized by stiffness or manufacturing handling requirements (minimum gage) premium mechanical strength properties will offer little if any benefit. For sections involving tension,
such as pressure vessels, the weight decrease will be directly proportional to the tensile strength. For components that are critical from loads that cause crippling (local buckling), such as long- rons, stiffeners, beams, etc., the weight decrease will be proportional to the $0.6^\text{th}$ power of the compressive yield strength ratio.

In some structures weight reductions resulting from use of premium properties are small. One such structure is the thermal protection system single faced corrugated titanium sandwich panel. These panels are exposed to such low pressure loads that the gage thicknesses are based on minimum manufacturing handling limitations. The geometry of the single faced corrugated thermal protection panels is such that considerable increase in moment carrying capability for a small weight increase is obtained by increasing the corrugation height and changing the section geometry. For example, a 10 percent increase in yield strength may only result in a 2 percent weight saving.

Sizable weight savings are possible thru use of typical mechanical properties on some major components. The wing of a low cross-range, fixed straight wing orbiter was selected for comparing structural weights resulting from use of typical and minimum guaranteed mechanical properties and the effect on total program cost.

The wing was separated into two major sections (exposed and wing carry through) and three subsections (skin, spar webs, and ribs).

Critical stress parameters used to evaluate design load conditions are:

a. tension critical: $F_{tu}$  
b. bending critical (local crippling): $F_{cc}$  
c. compression (pressure) critical (local crippling): $F_{cc}$  
d. shear critical: $F_{sc}$

Program cost comparison included the negligible effects of increased material cost, and is based on the following data:

a. 1 lb of weight saved in the orbiter dry weight equals 1 lb of payload, worth $28,000.

b. 1 lb of raw material stock costs $4/lb for 6Al-6V-2Sn titanium.

c. 7 lbs of raw material are required to deliver 1 lb of hardware.

d. Material supplier estimates that raw material costs less than 50 percent more to obtain guaranteed typical mechanical properties.

The Wing Weight comparison study was based on "A" values from MIL-HDBK-5A as minimum guaranteed properties and corresponding typical properties from TMCA. The ratio of minimum to typical properties for this material is approximately 0.9. The use of typical mechanical properties, in lieu of minimum guaranteed properties, resulted in a potential weight saving of 928 lbs out of 9043 lbs of total exposed wing and carry through structure. Superimposing a 1.525 nonoptimum factor would result in a total weight saving of 1414 lb. The 1414 lb weight saving could result in an overall program cost reduction of $39.3 million for 445 flights (NASA baseline Traffic Model). Key factors, and data used in the study, are summarized in Tables 1 and 2.

### TABLE I

**SHUTTLE ORBITER WING WEIGHT COMPARISON**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>WEIGHT EFFECTED</th>
<th>CRITICAL DESIGN LOADING</th>
<th>CRITICAL STRENGTH PARAMETER</th>
<th>$F_{cc}$*$^{6.5-4}$</th>
<th>$F_{tu}$</th>
<th>$W_{typ}$</th>
<th>$W_{M}$</th>
<th>$W_{typ}$/$W_{M}$ RATIO</th>
<th>$W_{typ}$/$W_{M}$</th>
<th>$W_{typ}$/$W_{M}$</th>
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</thead>
<tbody>
<tr>
<td>Out'B'd Skins</td>
<td>100 Bending (Crippling)</td>
<td>$F_{cc}$*</td>
<td>.89</td>
<td>4586</td>
<td>4050</td>
<td>536</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Spar Webs</td>
<td>100 Shear (Buckling)</td>
<td>$F_{cc}$*</td>
<td>.94</td>
<td>1162</td>
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<td>50 Shear (Buckling)</td>
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<td>259</td>
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<td>276</td>
<td>246</td>
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**CARRY-THRU**

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<th>ITEM</th>
<th>WEIGHT EFFECTED</th>
<th>CRITICAL DESIGN LOADING</th>
<th>CRITICAL STRENGTH PARAMETER</th>
<th>$F_{cc}$*</th>
<th>$F_{tu}$</th>
<th>$W_{typ}$</th>
<th>$W_{M}$</th>
<th>$W_{typ}$/$W_{M}$ RATIO</th>
<th>$W_{typ}$/$W_{M}$</th>
<th>$W_{typ}$/$W_{M}$</th>
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<td>Skins</td>
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<td>$F_{cc}$*</td>
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<td>Spar Webs</td>
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<td>Ribs</td>
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<tr>
<td>Ribs</td>
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<td>$F_{cc}$*</td>
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**GRAND TOTALS**

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<th>$W_{typ}$</th>
<th>$W_{M}$</th>
<th>$W_{typ}$/$W_{M}$</th>
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</thead>
<tbody>
<tr>
<td>536</td>
<td>8115</td>
<td>928</td>
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* Weight based on typical prop., $W_{M}$ Weight based on minimum guarantee.

$^*$ Strength allowable Ratio of Min. Guar/Typical Critical Strength parameter.

* The weight ratio is inversely proportional to the strength ratio.

** These data include 1.525 nonoptimum weight factor (average).
A similar study was conducted on the integral main cryogenic propellant tanks of a straight wing orbiter. A weight savings of 680 lb out of 9812 lb was realized. This resulted in a cost saving of $19 million dollars.

**CONCLUSION**

Studies conducted to date indicate that a significant weight and total program cost saving would result from using materials with premium mechanical properties in lieu of minimum guaranteed mechanical properties at moderate material cost increases and no increased risk. The decrease in weight associated with use of premium properties will vary from component to component depending upon the critical design load and strength parameters of the component. However, in order to take advantage of using premium property material the need exists to establish uniform guide lines and procedures for:

1. specifying premium grade material,
2. establishing potential cost of premium property material,
3. establishing procedures to certify the premium properties,
4. set up means of identification of the material stock.

To obtain maximum benefit from use of premium mechanical property materials, the commitment must be made before the shuttle is sized. Before actual supplies premium guaranteed properties can be negotiated, use of 1.07 times the "A" values of MIL-HDBK-5A for interim mechanical properties is reasonable.

However, the material suppliers should begin preparing positive means of identifying premium material stock, establishing procedures to certify premium properties, and establishing potential cost of premium property materials.

**APPENDIX A**

Typical material mechanical properties can be obtained from MIL-HDBK-5A by use of standard statistical analysis procedures. The "A" values denote the stress level above which at least 99 percent of the population of values is expected to fall with a confidence of 95 percent. The "B" values denote the stress level above which at least 90 percent of the population of values is expected to fall, with a confidence of 95 percent. The data used to establish "A" and "B" values are based on a minimum of 100 individual measurements from at least 10 production heats or lots from each of the major producers of the materials.

**Normal Distribution**

Assuming a normal distribution, typical mechanical properties of a material can be calculated from MIL-HDBK-5A "A" and "B" values by use of the standard statistical equation,

\[ X_N = \bar{X} - K \cdot \sigma_u \]

where

\[ \sigma_u = \sigma \cdot \sqrt{\frac{n}{n-1}} = \sqrt{\frac{\sum X^2 - (\sum X)^2}{n-1}} \]
\[
\sigma_u = \text{unbiased standard deviation} \vspace{1em} \\
\sigma = \sqrt{\frac{\sum (X - \bar{X})^2}{n}} \text{ Standard deviation} \vspace{1em} \\
\bar{X} = \text{the arithmetic mean of the sample} \vspace{1em} \\
K_{PY} = \text{composite factor of probability and confidence for one-sided tolerances limit} \vspace{1em} \\
n = \text{sample size} \vspace{1em} \\
p = \text{probability} \vspace{1em} \\
\gamma = \text{confidence} \vspace{1em} \\
\]

Probability and confidence limits for MIL-HDBK-5A are as follows:

"A" values: \( P = 99 \) \( \gamma = 95 \)

"B" values: \( P = 90 \) \( \gamma = 95 \)

From equation (1), equations establishing the relationship between typical and "A" or "B" values can be written.

For "A" values:

\[ X_{NA} = \bar{X} - K_{PYA} \sigma_u \vspace{1em} \\
(2) \]

For "B" values:

\[ X_{NB} = \bar{X} - K_{PYB} \sigma_u \vspace{1em} \\
(3) \]

where the subscripts (A) and (B) refer to "A" or "B" values of MIL-HDBK-5A.

Since these equations are for "A" and "B" values of the same normal distribution:

\[ X_A = X_B = \bar{X} \vspace{1em} \\
(4) \]

\[ \sigma_{uA} = \sigma_{uB} = \sigma_u \vspace{1em} \\
(5) \]

By substituting these data into equations (2) and (3), the following equations can be obtained

\[ X_{NA} = X_{NB} = \bar{X} - K_{PYA} \sigma_u \vspace{1em} \\
(6) \]

\[ X_{NB} = X_{NA} = \bar{X} - K_{PYB} \sigma_u \vspace{1em} \\
(7) \]

From equations (6) and (7), \( \bar{X} \) is obtained:

\[ \bar{X} = X_{NA} + K_{PYA} \sigma_u = X_{NB} + K_{PYB} \sigma_u \vspace{1em} \\
(8) \]

Solving for \( \sigma_u \):

\[ \sigma_u = \frac{X_{NB} - X_{NA}}{K_{PYA} - K_{PYB}} \vspace{1em} \\
(9) \]

Substituting \( \sigma_u \) into equations (6) and (7) we note that:

\[ \vspace{1em} \\
(10) X_{NA} = \bar{X} - \left( \frac{K_{PYA}}{K_{PYA} - K_{PYB}} \right) (X_{NB} - X_{NA}) \vspace{1em} \\
\]

Solving for \( \bar{X} \) we arrive at the general equation for obtaining typical mechanical properties:

\[ \bar{X} = X_{NA} \left( 1 + \left( \frac{K_{PYA}}{K_{PYA} - K_{PYB}} \right) \frac{X_{NB} - X_{NA}}{X_{NB} - X_{NA}} \right) \vspace{1em} \\
(11) \]

equation (11) can also be written as follows:

\[ \bar{X} = X_{NB} \left( 1 + \left( \frac{K_{PYB}}{K_{PYB} - K_{PYA}} \right) \frac{X_{NB} - X_{NA}}{X_{NB} - X_{NA}} \right) \vspace{1em} \\
(12) \]

Based on \( n = 100 \) samples, for "A" values where,

\( P = 99\% \text{ probability} \) \( \gamma = 95\% \text{ confidence} \)

Using tables for one-sided tolerance limit curves found in Reference (b), Page 6.4.1

\[ K_{PYA} = 2.684 \vspace{1em} \\
(13) \]

Similarly, based on \( n = 100 \) samples, for "B" values where,

\( P = 90\% \text{ probability} \) \( \gamma = 95\% \text{ confidence} \)

Using tables for one-sided tolerance limit curves found in Reference (b), Page 6.4.1

\[ K_{PYB} = 1.527 \vspace{1em} \\
(14) \]

Substituting \( K_{PYA} \) and \( K_{PYB} \) into equations (11) and (12) the equations for \( \bar{X} \) become:

\[ \bar{X} = X_{NA} \left[ 1 + \left( \frac{2.684}{2.684 - 1.527} \right) \frac{X_{NB} - X_{NA}}{X_{NB} - X_{NA}} \right] \vspace{1em} \\
(15) \]

\[ \bar{X} = X_{NB} \left[ 1 + \left( \frac{2.684}{2.684 - 1.527} \right) \frac{X_{NB} - X_{NA}}{X_{NB} - X_{NA}} \right] \vspace{1em} \\
(16) \]

To calculate the typical values of tensile ultimate \( (F_{tu}) \) and tensile yield \( (F_{ty}) \) of any material, let \( X_{NA} \) be \( F_{tuA} \) or \( F_{tyA} \) and let \( X_{NB} \) be \( F_{tuB} \) or \( F_{tyB} \) in equation (15) or (16).
<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>t</th>
<th>MECH. PROP.</th>
<th>$X_B$</th>
<th>$X_A$</th>
<th>$\bar{x}$</th>
<th>$\bar{X}$</th>
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<tr>
<td>2219-T87</td>
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<td>63</td>
<td>64</td>
<td>65.3</td>
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<td>2 - 3 in.</td>
<td>$F_{ty}$</td>
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<td>52</td>
<td>53.3</td>
<td>1.045</td>
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<td>$F_{tu}$</td>
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<td>L-605</td>
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<td>139</td>
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<td></td>
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</tbody>
</table>

\[ * \overline{x} = x_N \left[ 1 + 2.32 \left( \frac{x_B - x_N}{x_N} \right) \right] \]

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