Adaptive Blade Concept Assessment:
Curved Planform Induced Twist Investigation

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Abstract

Improving wind turbine blades via bend-twist coupling confronts two difficult challenges. The first is that off-axis fiber for the major structure is difficult to fabricate. Suitable fabrics with the primary fiber ~20 degrees off-axis are not commonplace and may present dimensional stability problems when handled, due to a tendency to shear when tensioned along their long dimension. These are ultimately cost issues. The second category of challenges is in the area of possible fatigue limits due to ending or curving angled fibers. Spar caps with angled fibers must either end those fibers at the edge or have them carry around a web type structure. Either approach implies additional stresses in the resin system binding the fibers and may lead to lowered fatigue allowables for design.

The vision driving this work was to look at the possibility of using novel planform and structural combinations to provide response similar to classical bend twist coupling, but without the use of off-axis lay-up in the structure. Sweep distributed along the span is used to create a moment that induces twist, and airfoil thickness reduction via carbon fiber spar caps is used to increase twist response to the induced moment. If a suitable magnitude of twist response can be shown using this approach, then the blade structure might be fabricated much as it is now, without off-axis spar cap fiber, and the benefits of bend twist coupling could still be obtained.
Acknowledgements

Sandia Technical Monitors:  Tom Ashwill and Paul Veers
Background
Considerable work has been done by Sandia National Laboratories and others (Ref. 1,2,3) on the possible use of twist-coupled blades to enhance wind turbine cost efficiency and performance. This work has shown considerable promise and led to the desire to consider in more depth how such blades might be built and what their properties might be.

Motivation
Improving wind turbine blades via bend-twist coupling confronts two difficult challenges. The first is that off-axis fiber for the major structure is difficult to fabricate. Suitable fabrics with the primary fiber ~20 degrees off axis are not commonplace and may present dimensional stability problems when handled, due to a tendency to shear when tensioned along their long dimension. These are ultimately cost issues. The second category of challenges is in the area of possible fatigue limits due to ending or curving angled fibers. Spar caps with angled fibers must either end those fibers at the edge or have them carry around a web type structure. Either approach implies additional stresses in the resin system binding the fibers and may lead to lowered fatigue allowables for design.

The vision driving the work reported herein was to investigate a way to move beyond both of those challenges. The major thrust is to look at the possibility of using novel planform and structural combinations to provide response similar to classical bend twist coupling, but without the use of off-axis layup in the structure. Sweep distributed along the span is used to create a moment that induces twist, and airfoil thickness reduction via carbon fiber spar caps is used to increase twist response to the induced moment. If a suitable magnitude of twist response can be shown using this approach, then the blade structure might be fabricated much as it is now, without off-axis spar cap fiber, and the benefits of bend-twist coupling could still be obtained.
Baseline Blade

To provide results linked to other research work and current commercial turbine sizes, a 30m (98.4 ft) blade derived from a separate Sandia blade-scaling study (Ref. 4) was chosen as the baseline. This is a single shear web generic interior blade with fiberglass spar caps and skins, and balsa core for the aft panels and shear web. The basic parameters for this blade are summarized in the following table. The baseline for this work is the thinnest of the three blade variations shown.

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<th>Blade Station (m)</th>
<th>Blade Length (m)</th>
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<th>Rotor Radius (m)</th>
<th>Rotor Speed (rpm)</th>
<th>Wind Speed (m/s)</th>
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The baseline blade shown above was only the starting point for the present work. In order to enhance twist response, the outboard blade thickness was reduced, as will be discussed in the following. The length, planform, and airfoil selections remained unchanged, except that the airfoil t/c was reduced as required.
Study Approach

This study initially assumed a circular arc sweep curve whose center depth could be specified. An inverse triangle thrust distribution with zero thrust at the blade root and maximum thrust at the tip was assumed as representative of a typical operating thrust distribution near rated power. A single blade thrust of 5670 kg (12,500 lbs) was used to represent the condition of about 1MW steady power production of a three bladed turbine. For a straight blade, these loads would lie near the blade axis at all spanwise stations, but for a blade with edgewise curve, the outer blade thrust will be offset from the axis of the inner blade segments. Based on the chosen depth of the bend curve and the assumed spanwise loading distribution, it is possible to calculate the torsional moment distribution along the blade from the offset distances implied by the bend curve.

In order to compute the twist response of the baseline blade, section analysis calculations were performed at 15%, 25%, 45%, 65%, and 85% r/R. Interpolation or extrapolation as appropriate was used to give GJ values at the center of each 10% of span blade segment, based on these five evaluation stations. From this, an initial computation of blade twist was made, which indicated about 0.8° of tip twist for 0.305 m (12 in) of bend depth. This result made it clear that steps to increase the twist response of the blade were appropriate, if the amount of twist indicated in the Sandia studies was to be achieved.

Increasing the depth of the sweep curve can increase the amount of twist. However, it was a goal of this study to investigate practical ways to enhance twist response. One way to do this is by reducing the thickness of the airfoils, but that will also decrease the strength and bending stiffness, unless the amount of material in the spar caps is increased to compensate. The first step to increase the twist response of the fiberglass baseline blade was to reduce its thickness at the 45%, 65%, and 85% stations. This was done by scaling the airfoil thickness, subject to the constraints that the flatwise-bending stiffness must be held constant and that maximum spar cap thickness could not exceed 10% of airfoil thickness. An iterative process was required to find the minimum thickness that would satisfy these constraints. The 15% and 25% stations were not altered because it was judged that this would have too much impact on blade weight, which is a cost issue, and because this part of the blade is designed to match a root pitch bearing of given size. As it turned out, the spar caps at 45% and 65% were already rather near the 10% spar cap limit, so only a modest increase in tip twist to about 0.9° was possible for the thinned variant of the all fiberglass baseline blade, with 0.305 m (12 in) bend depth.

After examining the distribution of induced twist along the blade and the estimates of the resulting blade shell shear stresses, it was clear that the circular arc bend curve was producing a lot of twisting moment on the inboard part of the blade (that was too stiff torsionally to respond very much), while the torsionally softer outer part of the blade was not experiencing enough moment to twist as much as it might. This suggested that a different bend curve might produce substantially better results. While a rigorous optimization was judged to be outside the scope of this study, implementing a power law bend curve was chosen as a way to give an initial feel for what might be possible. This meant leaving behind the mathematical simplification a constant arc provided, but tip twist increased substantially to about 1.2° for 0.305 m (12 in) of bend, with a bend curve exponent of 4. This is nearly 4° tip twist for a 1 m (39.4 in) bend depth on a 30 m (98.4 ft) blade, enough to be useful.
Carbon Fiber Spar Cap Investigation

Substituting carbon fiber for the spar cap material in the outer blade was another strong candidate to increase twist response. Because this material is much stiffer than the fiberglass baseline material, it would retain bending stiffness with much thinner airfoil sections. For this study, a longitudinal modulus of 110.0E+3 MPa (16.0E+6 psi) was chosen for the carbon spar cap material, in contrast to the 37.0E+3 MPa (5.4E+6 psi) assumed for the fiberglass. This is not the most aggressive value one might assume and leaves room for some DB (double bias) material within the laminate to add toughness. Even so, it provides nearly a factor of 3 increase in the spar cap modulus, along with a small decrease in density.

It is worth noting that thinner airfoils in the outer blade are desirable for aerodynamic efficiency as well as twist enhancement, so there would be a dual motive to pursue a carbon hybrid blade with thinner outboard airfoils. But since carbon currently costs significantly more than fiberglass, there is a substantial question how much of the blade would justify using carbon spar caps. Since the relative costs may change substantially over time, it was decided to calculate three different spanwise extents of carbon spar caps. In the first case only the outer 85% station was converted to carbon, in the next the 65% station was converted as well, and in the last 45% was also converted to carbon. Because the intermediate stations are interpolated, the net effect is the same as using carbon from 75%, 55%, and 35% r/R out to the blade tip. This is how the results are designated herein. The 35%-> carbon blade shows an increase from about 4° tip twist for a 1 m (39.4 in) bend depth (with a bend curve exponent of 4), to over 7° with the same bend depth and exponent. The plot below shows the planform shape that results for a 1 m (39.4 in) bend depth with a sweep exponent of 4. The data blocks summarize the key results for the all-fiberglass blade and the three different lengths of carbon spar cap hybrid.

### Data Blocks

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<th>Weighted Twist (deg)</th>
<th>Tip Twist (deg)</th>
<th>Max Shear (psi)</th>
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Notes: X axis is approximate blade pitch axis
Bend depth is the maximum offset of the leading edge relative to a straight line from the leading edge at the root to the leading edge at the tip
The tip is shown aft of the blade tip by this same amount
* Segment twists weighted by fraction of disk area affected
Additional Blade Property Comparisons
The tables and graphs below show the twist data, the blade shell weight (no root fitting weight was added), and carbon spar cap weights implied by the underlying blade section analysis. The figure below shows the airfoil structure (for both glass and carbon spar caps) at station 65% r/R.

<table>
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<th>Blade Type</th>
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<td>Carbon 35%-&gt;</td>
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**Twist vs Blade Type**

**Blade Weight vs Type**

**Carbon Weight vs Spanwise Extent**
Glass vs Carbon Spar Cap
Construction Comparison

at Station 65% r/R

19.9% t/c with Glass Spar Caps

Nose Panels:
DB Glass Skins .036" Thick
Spar Cap Skins .022" Thick

Tail Panels:
Balsa Core 1% of Chord Thick
DB Glass Skins .036" Thick

14.1% t/c with Carbon Spar Caps

Spar Caps:
Center is 10% of Foil Thickness
Tapers to 1/2 Thickness at Edges
Extend from 15% to 45% Chord

Shear Webs:
Balsa Core 3% of Foil Thickness
DB Glass Skins .060" Thick
Centered at 30% of Chord
Further Discussion

Blade Structural Detailing

In order to enhance the twist response from a given level of sweep-induced, torsional moments, it is desirable that the sectional GJ product be no larger than necessary. Carbon fiber spar caps increased the twist response precisely because they made the torque tube smaller and less stiff. What may be less obvious are the other measures that were included in the design for the same purpose.

The tail panel construction is near the minimum considered reasonable for a 1MW blade; the DB glass skins are only 0.914 mm (0.036 in.) thick on either side of a balsa core. While a 0/90 fabric would be more flexible than a DB, it is not as suited to carrying the long-term torsional fatigue as DB, and also suffers crack initiation due to flatwise bending at much lower strains. However, it is possible that somewhat thinner skins, particularly on the inside of the panel, could be acceptable, if more twist response was needed. The twist-induced shear stresses are not a limitation; it is strictly the panel strength for handling and enduring maximum winds that is an issue. Note that thicker core could be used to compensate for thinner skins as long as they remain acceptable for handling. The balsa core has very low (rolling) shear stiffness in the direction that resists twist, so this is a promising path that could be further explored. The gains from fine-tuning this aspect of the design might be 10% or greater, significant though not dramatic.

An aspect of the design that is quite important and might be easily overlooked is that it has only a single shear web. This makes the structural spar composed of spar caps and shear web an “I” beam, with low resistance to torsion. As long as the tail panels are compliant, the overall torque tube will be relatively soft, in spite of the fact that the spar caps are quite stiff in shear. If double shear webs at the forward and aft edges of the spar caps had been used instead, they would cause the spar caps to become part of a tube whose torsional stiffness could be quite high if the shear webs were of robust construction. Double shear webs are quite common in large wind turbine blades, because they reduce panel free span and the tendency for panel buckling and create good resistance to torsional instability. However, if blade twist response is to be enhanced, then the single shear web concept, which has been quite successful in smaller blades, may need to be carried to much larger sizes due to its lower resulting torsional stiffness.

The purpose of these comments is to record the impact of these aspects of the design. Optimization must await further work that can consider these and other ways of obtaining necessary strength, while eliminating undesirable torsional stiffness.
**Weighted Twist and Optimum Sweep Exponent**

The first look at twist coupling considered tip twist as a comparative measure of design variations. However, it quickly became apparent that one might induce a lot of twist in the torsionally soft outer extremity of the blade and have rather limited effect overall. Certainly a degree of twist in the innermost 10% of the blade will have a lot more effect than a degree of twist in the outermost 10%, because the former case affects essentially the whole span of the blade. This leads to the concept of weighted twist, wherein the twist in a blade segment is weighted by the fraction of the total disk area it affects, in creating a net summation for assessment of induced twist effect.

Using weighted twist as the measure of twist effect, it was found that the glass spar cap blade had its optimum response with a sweep exponent near 4, whereas on the basis of tip twist, the maximum occurred near 7. A similar result was found for the carbon spar cap blade designs, although in that case the optimum exponent was higher, near 4.8 for the design using carbon from 35% outboard. To unify the results for presentation, a sweep exponent of 4 was chosen as a round number value that gave near optimal weighted twist for all the design variants.

**Inverse Triangle Loading Assumption Limitations**

To create a torque distribution along the blade due to the specified sweep profile, an inverse triangular loading distribution with zero loading at the blade root and maximum loading at the tip was used. This is a usual approximation to the loading near rated power, which is what the twist calculations are meant to represent. For modest amounts of induced twist, this remains a reasonable approximation. However, for a tip twist of 7°, about 2/3 of the section lift would be gone, and this approximation is clearly no longer accurate. It would not be unduly difficult to iterate the loading to reflect the induced twist, but that destroys the easily understood load distribution and replaces it with one that is different for each set of blade properties. To keep the results of this study on a basis where comparisons could be easily made and understood, it was decided to retain the same loading distribution for all twist calculations. Follow on work can investigate the effect of altered angles of attack on steady state twist, or likely of more value, the blade torsional properties presented herein could be incorporated into a more comprehensive evaluation of load and power response. For the present, the reader should be aware that the loading assumption does not reflect the effects of induced twist, primarily so that case-to-case comparisons can be made easily without correcting for different implied loading conditions.
**Trailing Edge Centrifugal Tension**

The aft sweep of the blade will clearly create added tension in the trailing edge of the blade due to centrifugal forces. This will be at its worst in the outer part of the blade where sweep angles are largest, centrifugal acceleration is highest, and blade chord is shortest. At an assumed 20 rpm, the tip region of the blade will see about 14 gs of acceleration. The outer 10% of the fiberglass blade (which is heaviest) will weigh about 44 kg (97 lb) based on the blade section analysis. This gives a centrifugal force of 620 kg (1360 lb). If this force is assumed to act at 95% radius, its offset to the next blade segment centered at 85% is about 0.6 m (24 in) for a 1 m (39.4 in) bend depth, resulting in an edgewise moment of 3700 N-m (32,600 in-lb). From the 85% section analysis results, we find the edgewise moment capability at 3,750 µs is 4.1E+4 N-m (3.675E+5 in-lb). So the implied trailing edge strain from centrifugal force acting on the sweep is 3,750 * (3.26E4/3.675E5) = 330 µs. This calculation is a bit conservative, because the center of mass of the outermost blade segment will be inboard of 95% radius. Even so, the computed trailing edge strain is small. It is concluded that trailing edge stress is not a design limit for any reasonable degree of blade sweep, even with the lightly built tail panels assumed in the present work.

**Curved Spar Cap Manufacturing Implications**

A fundamental driver in investigating a sweep-twist blade option is to remove the need for off-axis carbon fiber in the spar caps, but this advantage does not come completely free of tradeoffs. Wide layers of fabric, while easily bent out of their plane, will resist the sort of in-plane bending that a swept spar cap implies. If some special provision to account for this is not made, the fiber on the inside of the curve will become wavy or kinked due to its excess length compared to the fiber on the outside of the curve. One solution would be to use a type of fabric with minimal in-plane shear resistance, so that the fibers could shear rather than wrinkle. Another approach is to compose the spar caps of narrow tapes or fiber bundles, which accomplish much the same thing. In large volume, one could imagine fabric or 3D weave custom formed with the required curve. This manufacturing implication does not appear to constitute a fundamental barrier to this kind of blade design, but the economics of this unconventional feature must be demonstrated.

**Low Cost Bend-Twist Hybridization**

In principle, there is nothing to stop structural bend-twist coupling from being used with sweep-twist coupling as described herein, except cost. Both methods have additional manufacturing costs associated with them, so the cost penalty of combining them would appear prohibitive, if either alone can do the job. However, there is one way a modest degree of bend-twist coupling could be combined with sweep-twist at modest added cost. This is via the use of a hybrid glass-carbon DB cloth for the blade shell skins. The aft panels are lightly built and quite compliant, and the single web “I” beam spar has low torsional resistance, so having one of the two 45° plies made of carbon would have highly leveraged effect in producing classic bend-twist response. It is beyond the scope of this work to do more than simply note that this possibility exists and may be worthy of follow-up, if dynamic analysis leads to the conclusion that combined sweep and bend twist coupling may have special benefits that warrant the additional complexities.
Conclusions
This initial study of blade planform curvature as a method to induce twist response indicates that a 1 m (39.4 in) bend depth on a 30m (98.4 ft) blade can produce substantial twist. With a bend exponent of 4, which produces more rapid edgewise bend in the outer blade, the all-fiberglass blade provided about 4 degrees of tip twist, whereas the same planform with carbon spar caps to reduce torsional stiffness (via lessened airfoil thickness) produced more than 7 degrees of tip twist. This assumes that blade thrust has an inverse triangle load distribution with zero thrust at the root and maximum thrust at the tip, with the total thrust being approximately that for 1MW steady state power production on a three-bladed wind turbine. Since a 10-degree angle of attack reduction would bring a typical wind turbine blade design to near zero lift, the potential to shed a large load from the outer rotor exists. This can reduce bending moments and power peaks, and thereby reduce fatigue. Alternatively, a larger and more energy productive rotor may be possible, which is a powerful path to lowered cost of energy. This is the lure of adaptive twist blades, and the magnitude of the twist response appears to make curved planform blades solid contenders in this category.

To maximize twist response, the blades must be built with relatively lower torsional stiffness. This favors a single shear web design, with tail panels that avoid excess structure to encourage enhanced twist response. The dynamic stability boundaries need further study to assure that significant operational limitations do not accrue to this reduced torsional stiffness. This must account for the phasing of the twist response, which appears to occur sooner than with classic bend-twist coupling, and may thereby stabilize certain dynamic motions. Further evaluation of the potential of this class of blades must also address the manufacturing implications of making spar caps that curve substantially in their own plane.
References


Appendix A – Key Section Analysis Results

The purpose of the 10 following pages is simply to document the section analysis results for the both the fiberglass and carbon spar cap constructions. These are the values that resulted once the airfoil t/c was converged to the value that equaled the baseline flatwise stiffness, with spar caps whose center thickness was 10% of the overall airfoil thickness. The units are pounds and inches, and the limiting strengths shown are those for a critical fiber strain of 3,750 µs. Note that the procedure of thinning the airfoils at equal flatwise stiffness results in flatwise strength that exceeds the baseline values. Stations 15% and 25% were not modified from the baseline; thickness convergence was performed only at stations 45%, 65%, and 85%.
## 85% Station – Fiberglass Spar Caps @ 15.95% t/c

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**REPORT FOR STATION 85% 15.95%max WITH FOIL Sta85% 15.95%**

Accuracy factor: 0.20  Cut plane angle: 5.16  Me Axis Rotation Ang: 0.00

### WEIGHT PER FOOT

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**GJ PRODUCT IS 1.542e+8**

---
85% Station - Carbon Spar Caps @ 11.49% t/c

REPORT FOR STATION 85% 11.49%carb WITH FOIL Sta85% 11.49%

Accuracy factor:0.20  Cut plane angle: 4.43  Me Axis Rotation Ang: 0.00

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<th>EDGWISE MOMENT</th>
<th>FWD EDGE</th>
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<th>FWD EDGES CRITICAL DISTANCE</th>
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<th>AFT EDGES CRITICAL DISTANCE</th>
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| LAYER SUMMARY DATA |

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| TORSIONAL CELL DATA |

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GJ PRODUCT IS 7.527e+7

**********************************************************************
65% Station - Fiberglass Spar Caps @ 19.90% t/c

REPORT FOR STATION 65% 19.90%max WITH FOIL Sta65% 19.90%

Accuracy factor: 0.20  Cut plane angle: 4.57  Me Axis Rotation Ang: 0.00

<table>
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<tr>
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<th>FLATWISE EI</th>
<th>EDGEWISE EI</th>
<th>UPPER SURF FLATWISE</th>
<th>FWD EDGE</th>
<th>CHORDWISE CG</th>
<th>FLATWISE SHEAR</th>
<th>EDGEWISE SHEAR</th>
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| 21.85          | 17.97      | 0.219       | 5.726               | 18.80   |

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GJ PRODUCT IS 7.900e+8
### 65% Station - Carbon Spar Caps @ 14.10% t/c

REPORT FOR STATION 65% 14.10%carb WITH FOIL Sta65% 14.10%

Accuracy factor: 0.20  Cut plane angle: 3.24  Me Axis Rotation Ang: 0.00

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<th>FWD EDGE EDGewise MOMENT</th>
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<th>AFT EDGE CRITICAL</th>
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GJ PRODUCT IS 3.987e+8
**REPORT FOR STATION 45% 21.91%max WITH FOIL Sta45% 21.91%**

Accuracy factor: 0.20  Cut plane angle: 8.75°  Me Axis Rotation Ang: 0.00

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<th>FWD EDGE EDGEWISE MOMENT</th>
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**CHORDWISE**

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<th>FWD EDGE CRITICAL DISTANCE</th>
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**FLATWISE**

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**ROTATIONAL**

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GJ PRODUCT IS 2.465e+9
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REPORT FOR STATION 45% 15.43% carb WITH FOIL Sta45% 15.43%

Accuracy factor: 0.20  Cut plane angle: 6.17  Me Axis Rotation Ang: 0.00

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GJ PRODUCT IS 1.245e+9
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GJ Product Is 8.605e9
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GJ PRODUCT IS 2.731e+10