BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division
Magnet Note

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Topic: AGS Snake Magnet

Title: Engineering of the AGS Snake Coil Assembly

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Engineering of the AGS Snake Coil Assembly

SUMMARY

A 30% Snake superconducting magnet is proposed to maintain polarization in the AGS proton beam. The required helical coils for this magnet push the limits of the technology developed for the RHIC Snake coils. First, fields must be provided with differing pitch along the length of the magnet. To accomplish this, a new 3-D CAD system ("Pro/Engineer" from PTC), which uses parametric techniques to enable fast iterations, has been employed. Revised magnetic field calculations are then based on the output of the mechanical model. Changes are made in turn to the model on the basis of those field calculations. Using this technique, nine such iterations have been made faster than it took to complete a single design on the RHIC program. Upon completion of the model, to ensure that accuracy is maintained, the solid model is imported directly into the CNC machine programming software, rather than by the use of IGES or other graphics translating software. Next, due to the large coil size and magnetic field, there was concern whether the structure could contain the coil forces. A finite element analysis was performed, using the 3-D model, to ensure that the stresses and deflections were acceptable. Finally, a method was developed using ultrasonic energy to improve conductor placement during coil winding, in an effort to minimize electrical shorts due to conductor misplacement, a problem that occurred in the RHIC helical coil program. Each of these activities represents a significant improvement in technology over that which was used previously for the RHIC snake coils.

Development Of A Process For Producing AGS Snake Magnet Helical Coil Models Using Pro/Engineer

Previously, helical coil grooves or blocks were created through a time-consuming process using EDS I-DEAS software. After defining the helical path of each groove, numerous cross-sections of the groove were constructed at intervals along the paths. All cross-sections were required to be manually oriented normal to their helical path during construction. Surfaces were then lofted through these cross-sections and used to perform the cuts necessary to produce the grooves in the basic cylindrical part. This process made changes quite difficult. Where variable pitch helixes were required separate helixes were constructed and joined to form the completed paths.

With the adoption of Pro/Engineer as our standard modeling tool the process of creating variable pitch helical grooves changed dramatically. PTC's Advanced Surfacing module was added to the Pro/Engineer Foundation module providing the increased functionality needed to produce the complex helical cuts in a more efficient manner. Since Pro/Engineer can easily construct variable pitch helixes (see Figure 1) the process of creating the helical paths was greatly simplified. The paths produced in this manner were parametric, meaning they could easily be changed without the need to reconstruct them as the design evolved.

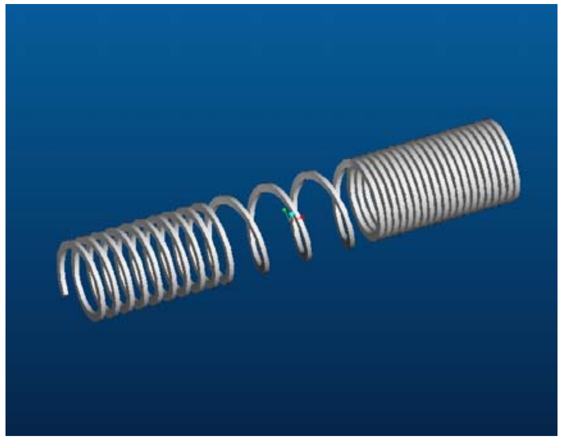

Figure 1.

After some brief experimentation with the functionality of the Advanced Surfacing module a technique was developed to construct the variable pitch cuts in the basic cylindrical part. Helical surfaces were constructed normal to a basic cylindrical surface (see Figure 2) and then intersected with that cylindrical surface to produce the curves that define the helical portions of the grooves' paths. Various construction techniques were used to develop the paths of the coil ends as required by the physicists' evolving definitions of these portions of the coil. The end curves along with the helical curves define the basic paths of the grooves (see Figure 3). These basic curves were then projected onto a second, larger cylindrical surface to produce the remaining curves required to define the orientation of the variable cross-section sweeps (see Figure 4). The completed cuts were then produced using the Pro/Engineer variable section sweep cut functionality (see figure 5).

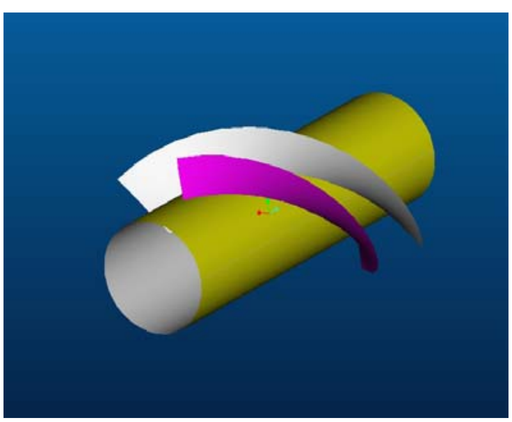

Figure 2.

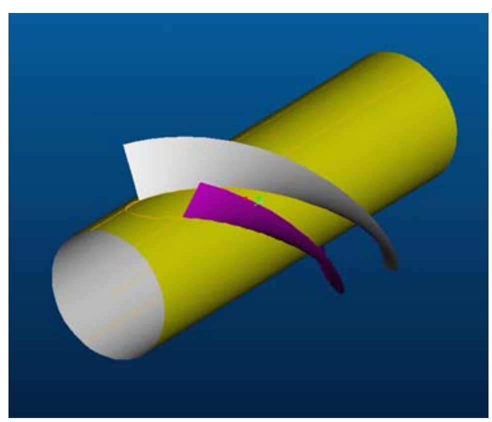

Figure 3.

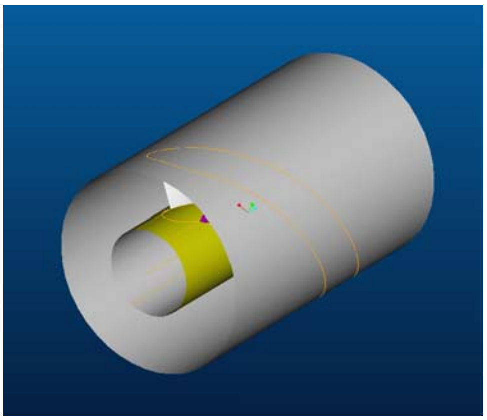

Figure 4.

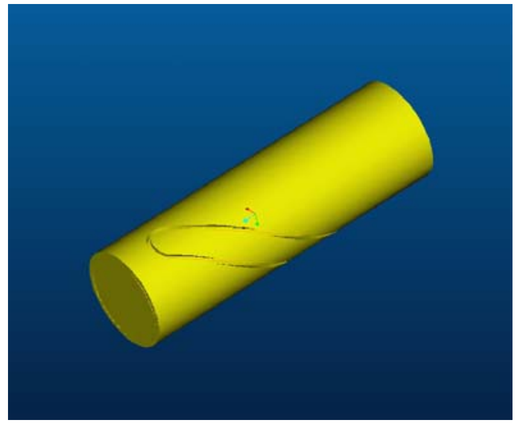

Figure 5.

In the construction of the actual coil models all remaining grooves were defined and created in this manner. A typical, completed coil produced using this process is shown in Figure 6.

Since most of the geometry created using this process is parametric, design changes that would normally require extensive geometry modifications could frequently be accomplished by changing a single parameter, resulting in all subsequent geometry being automatically updated. In an evolving, iterative design such as this, changes are the norm so considerable time has been saved as a result of these capabilities.

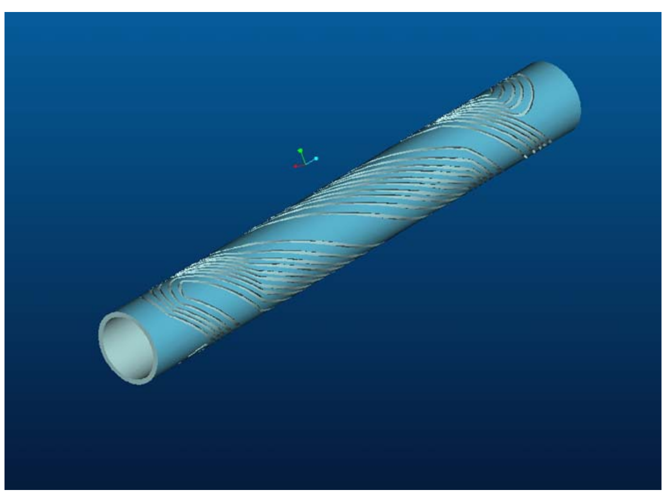

Figure 6.

Once the final design had been established and verified through analysis of the resulting magnetic field, the models of the two coil support tubes were sent electronically to the machine tool, using NC programming software and post processors developed by both PTC and MasterCam. In this way, tool paths were developed directly from the engineering surfaces, and not as interpreted by IGES or other graphics translation software. Parts were subsequently machined using a 4-axis CNC machine tool and inspected to be within 0.25 mm of desired surface position along all locations of the helices. The inner coil support tube in the machine tool is shown below in figure 7.

Figure 7. Machined inner coil support tube

AGS Snake - Support Tube Analysis

A three-dimensional finite element structural analysis was done on the inner and outer support tubes for the AGS snake magnet to determine the stress and deflections in each tube under the azimuthal coil forces. A 30 inch long piece from the center section of the tube, where the helical pitch is the smallest, was used for each analysis. The calculated azimuthal pressures exerted by each coil block were scaled based on the percentage of the groove depth occupied by the coil windings. The resulting pressure for each block as indicated in Table II was applied to the full sidewall of the groove. Both ends of the tube were completely constrained and the outside diameter of the tube was constrained in the radial direction. Material was assumed to be aluminum with a Young's modulus of 10e6 psi. Results shown in figures 8 through 11 indicate a peak stress of 34000 psi for the inner tube and 13000 psi for the outer tube with maximum deflections of .0020 inches and .0016 inches respectively.

Support Tube Dimensions

–Inner 7.70 ID, 9.04 OD
–Outer 9.76 ID, 11.10 OD
–0.67 Wall Thickness
–0.512 Deep Slots
–30 Inches Long

Table I. Tube Dimensions

Block Number	Coil Azimuthal Pressure (psi)	Coil Block Height	Load Applied to Slot Wall (psi)
Inner			
1	350	0.422	288
2	900	0.422	742
3	1650	0.422	1360
4	2239	0.422	1845
5 pole	2777	0.239	1296
Outer			
1	331	0.422	273
2	607	0.422	500
3	1176	0.422	969
4	1404	0.422	1157
5 pole	1324	0.422	1091
Slot depth = 0.512 in all cases			

Table II. Lorentz Force Loads

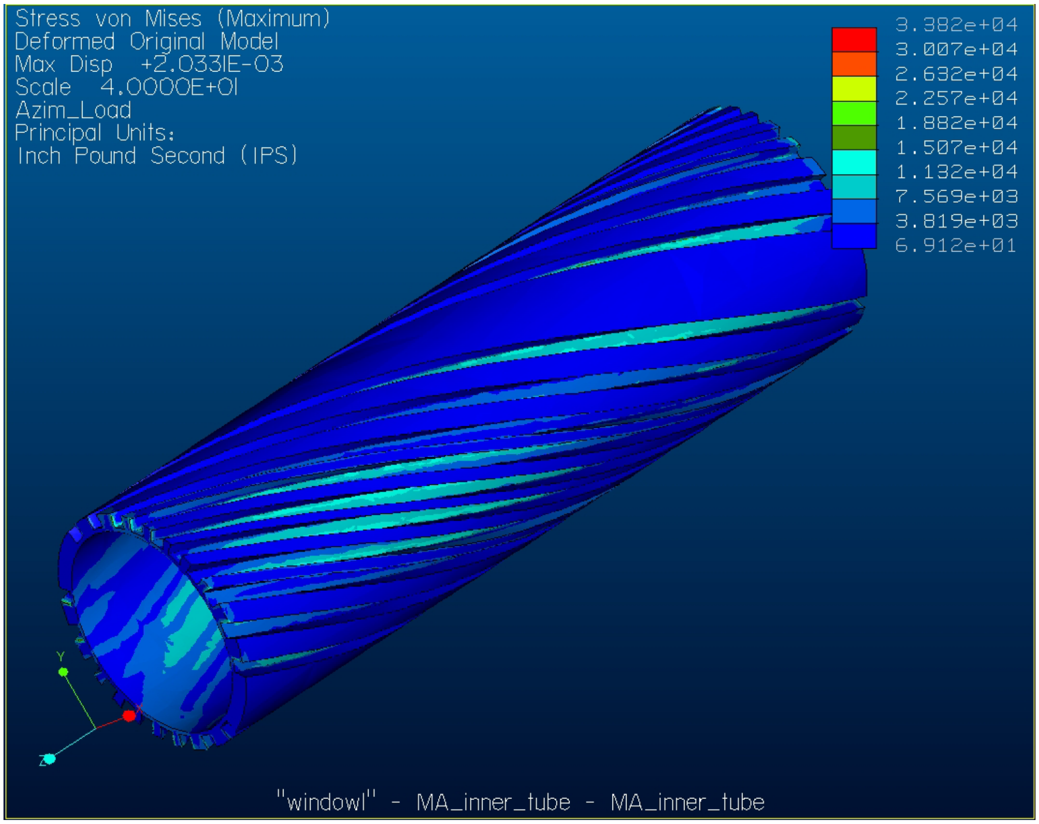

Figure 8. Inner Tube Stress

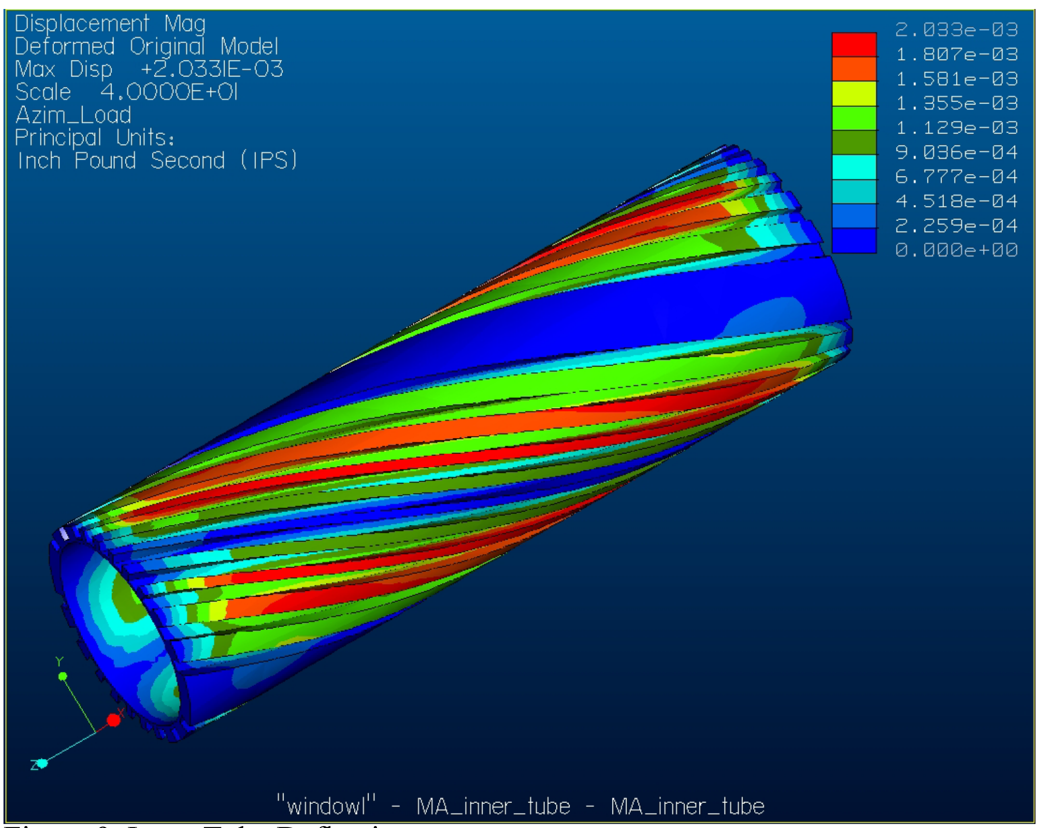

Figure 9. Inner Tube Deflection

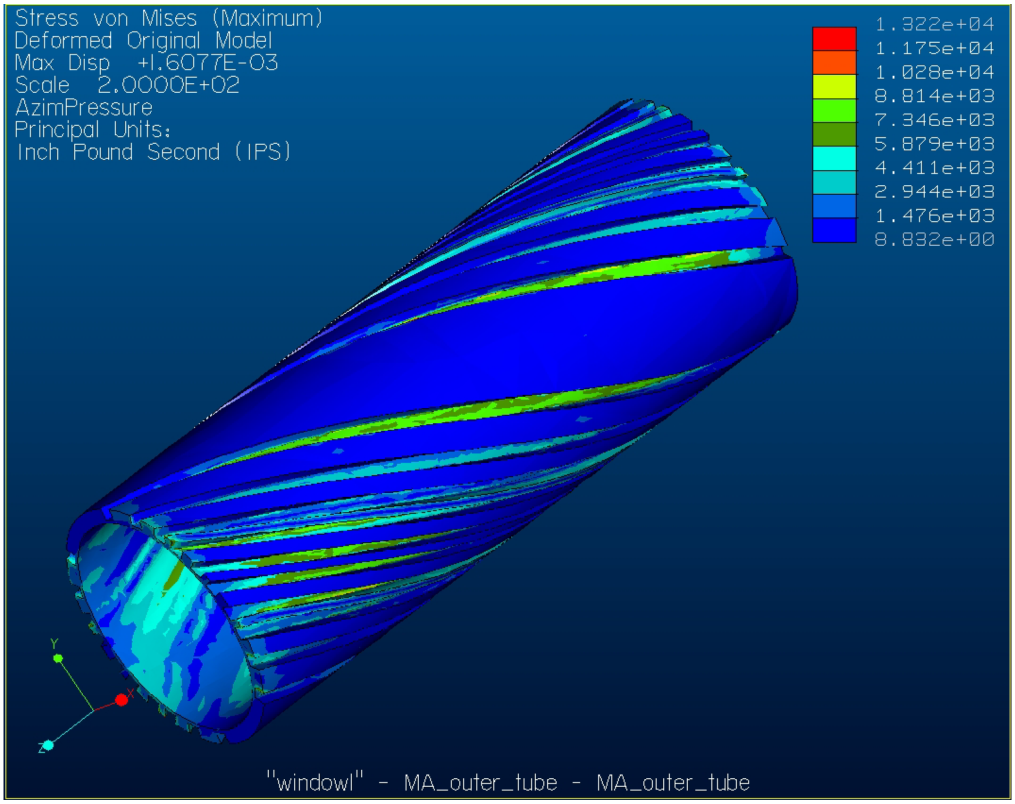

Figure 10. Outer Tube Stress

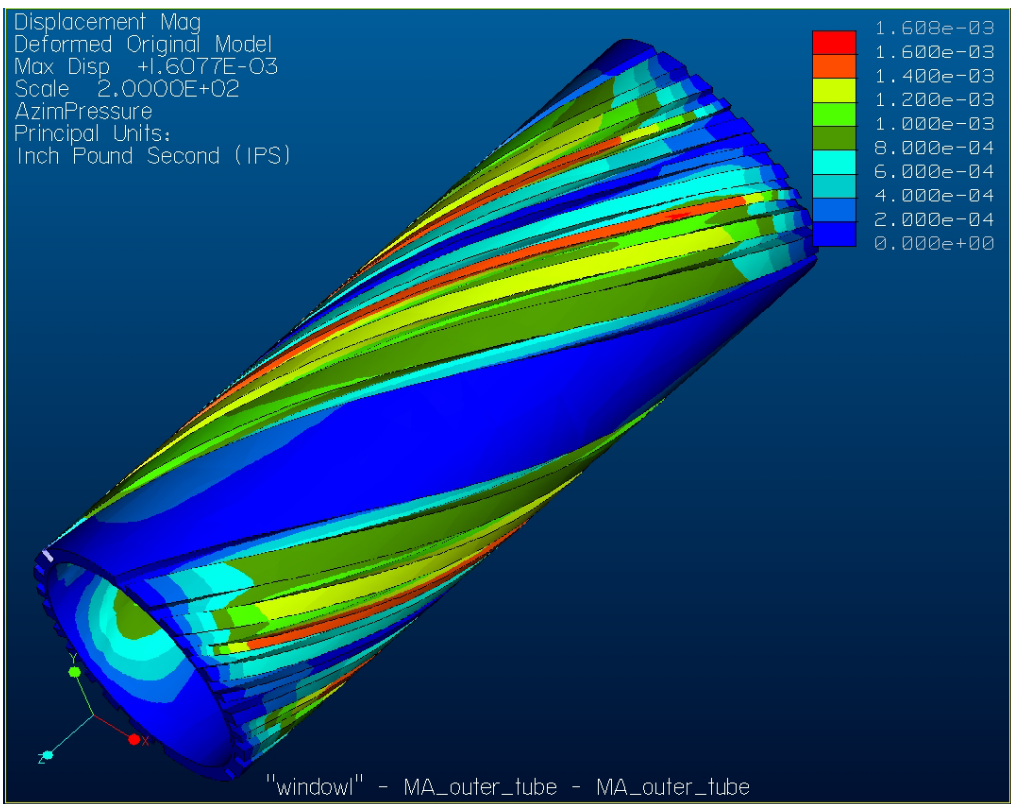

Figure 11. Outer Tube Deflection

Development of a Method to use Ultrasonic Energy to Improve Conductor Placement During Coil Winding.

As was done previously for RHIC helical coils, AGS Snake coils are arranged in blocks of windings within the machined tube grooves. These winding blocks are arrays of round cable, twelve rows wide and nine layers high as shown in Figure 12. Between each vertical layer is installed a b-stage epoxy impregnated fiberglass substrate. After winding, the cables are compressed into the substrate during an elevated temperature and pressure cure cycle. The cure cycle seats the conductors into the substrate while the epoxy flows to eliminate voids, thereby providing a suitable support for the conductors against the magnetic field forces.

Inherent in the helical winding pattern and the inward shift in radial position described above is a surplus of wire placed into the grooves during winding. This wire surplus is simply the change in diametric position of the cable multiplied by the angle of revolution of the helix in radians. It was found during production of the RHIC helical coils that this excess conductor led to electrical shorts in several instances due to the resulting incorrect positioning of conductor, as is seen in Figure 13. In the AGS Snake application, therefore, as the helix rotation required is twice that of the RHIC coils, this problem would become more severe. As can be seen in Figure xx, the tests conducted using established winding methods resulted in a change in position during curing of the ninth conductor layer of 2.4 mm. This would then result in 30.6 mm of extra conductor in that layer of the coil block. Therefore, a method was developed using a 500-watt hand-held ultrasonic welder to seat each layer of conductors into the substrate below during the winding process. This process was used after each of the nine layers of conductors was placed into the grooves. Measurements of the height of conductor layers in the block were made before and after each layer was wound and ultrasonically seated. Tests conducted using this method of cable placement, the results of which are also shown in Table III and Figure 14, indicate that each conductor layer was successfully seated 0.15 mm into the substrate, for a cumulative effect of 1.35 mm improvement over previous methods. Electrical hypot testing at 2KV potential was performed afterwards, between adjacent wires and between all wires and the grounded groove, to verify that the insulation was not damaged by the ultrasonic welding process.

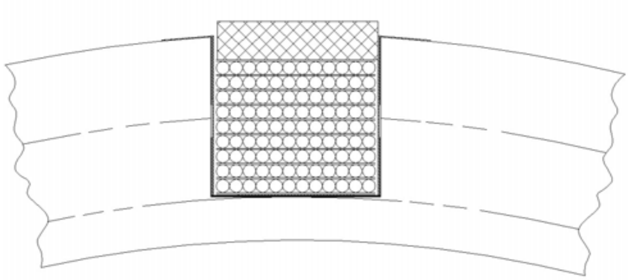

Figure 12. Coil Block cross-section

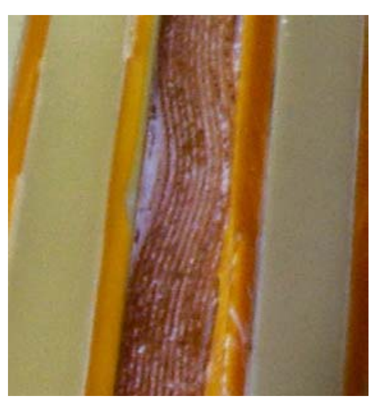

Figure 13. Cable positioning error

Vertical Dimension Over Conductor at Layer (in.)					
Layer	Nominal height	Height before ultrasonic	Height after ultrasonic	Fully seated height	Ultrasonic Depth
1	0.06	0.06	0.054	0.052	0.006
2	0.117	0.109	0.103	0.098	0.006
3	0.174	0.161	0.154	0.144	0.007
4	0.231	0.212	0.206	0.19	0.006
5	0.288	0.266	0.258	0.236	0.008
6	0.345	0.315	0.308	0.282	0.007
7	0.402	0.365	0.359	0.328	0.006
8	0.459	0.416	0.41	0.374	0.006
9	0.516	0.468	0.463	0.42	0.005

Table III. Ultrasonic Cable Seating Data

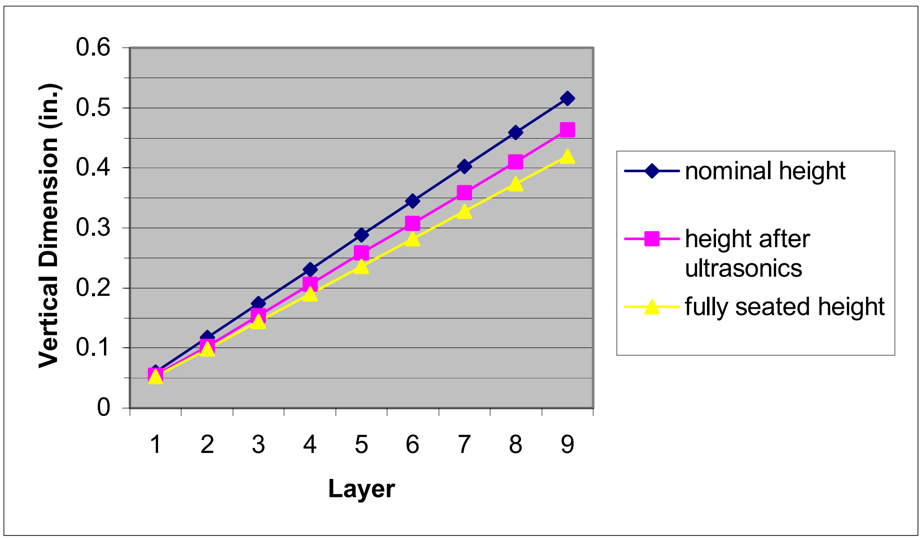

Figure 14. Comparison of Cable Seating Depths