A FIGURE OF MERIT FOR CABLE COMPACTION VS. DEGRADATION
And Its Application to the SSC Dipoles

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Introduction.

Increasing the compaction of the cable at its thin edge allows more turns to be crammed into each layer, which increases the load-line slope and hence the critical operating field. But increasing the compaction also increases the degradation, which decreases the critical operating field. This raises the question: "Is there a parameter--a 'figure of merit'--that expresses the combined effect, one that depends only on the cable parameters and is independent of the coil configuration?" The answer is: "Yes, to first order", and I show how it varies with compaction for several kinds of cable.

It is known that for a given overall packing factor $\overline{PF}$ (See Appendix I), increasing the keystone angle increases the degradation. And it is known that for a given keystone angle, increasing the overall packing factor also increases the degradation [1]. If one postulates that degradation is related to the distortion of the strands that occurs during cabling and compaction, and one examines a piece of cable or a cross-section photomicrograph, it doesn't take a whole lot of brains to figure out that the dominating factor affecting degradation is the degree of compaction of the thin edge rather than the independent effects of overall packing factor and keystone angle. (For very small keystone angles this notion might fall apart, but we are not concerned with such small angles.)

The Figure of Merit.

In an earlier report [2] I expressed the thin-edge compaction by what I called the "thin edge packing factor", PF_1 (see appendix I), suggested its use as a correlating parameter for the two effects, and showed that for a particular cable measured by Furukawa [1] it correlates the data rather well. (The graph showing the correlation is repeated here in Appendix II.)

In another report [3] I presented a first-order formula showing how the parameters that describe small changes in the load line and the B-vs-I characteristic of the the cable affect the critical operating field (See Appendix I for nomenclature):

$$\frac{\Delta B_o}{B_o} = \frac{R}{1+R}\left[\frac{B_o - B_1}{B_o}\left(\frac{\Delta K_1}{K_1} - \frac{\Delta K_2}{K_2}\right) + \frac{B_1}{B_0}\frac{\Delta B_1}{B_1} + \frac{1}{R}\frac{B_2}{B_0}\frac{\Delta B_2}{B_2}\right]$$

where $R \equiv K_2/K_1$. For magnets of interest to the SSC, $B_1 << B_0$, so $(B_0 - B_1)/B_0 \approx 1$, and for the present case $\Delta B_2 = 0$ leaving simply

$$\frac{\Delta B_o}{B_o} = \frac{R}{1+R}\left[\frac{\Delta K_1}{K_1} - \frac{\Delta K_2}{K_2}\right]$$

The relative change in load-line slope, $\Delta K_1/K_1$ is equal to the relative change in the number of turns $\Delta N/N$ which, to first order, is given by

$$\Delta K_1 / K_1 = \Delta N / N = (t_1 / t_1')(\Delta PF_1 / PF_1)$$

The relative change in the slope of the conductor characteristic K_2/K_2 is simply the degradation, Deg. So finally,

$$\frac{\Delta B_o}{B_o} = \frac{R}{1+R}\left[\frac{\Delta PF_1/PF_1}{t_1' / t_1} - \mathrm{Deg}\right]$$

and so the desired figure of merit is simply the term in brackets,

$$FM = \frac{\Delta PF_1/PF_1}{t_1' / t_1} - \mathrm{Deg}$$

independent of all the various parameters that affect R. The factor R/(1+R) tells the effect of a change in load-line slope on the operating field, so the FM is, in effect the equivalent change in load-line slope for a given change in PF_1 and Deg.

Application to the SSC Dipoles.

In Fig. 1 I show how the figure of merit varies with thin-edge packing factor for several cables. Since I am showing the effect of compaction rather than comparing cables, I have normalized the data to $FM_1 = 0$ for the current SSC dipole inner layer PF_1 of 0.957.

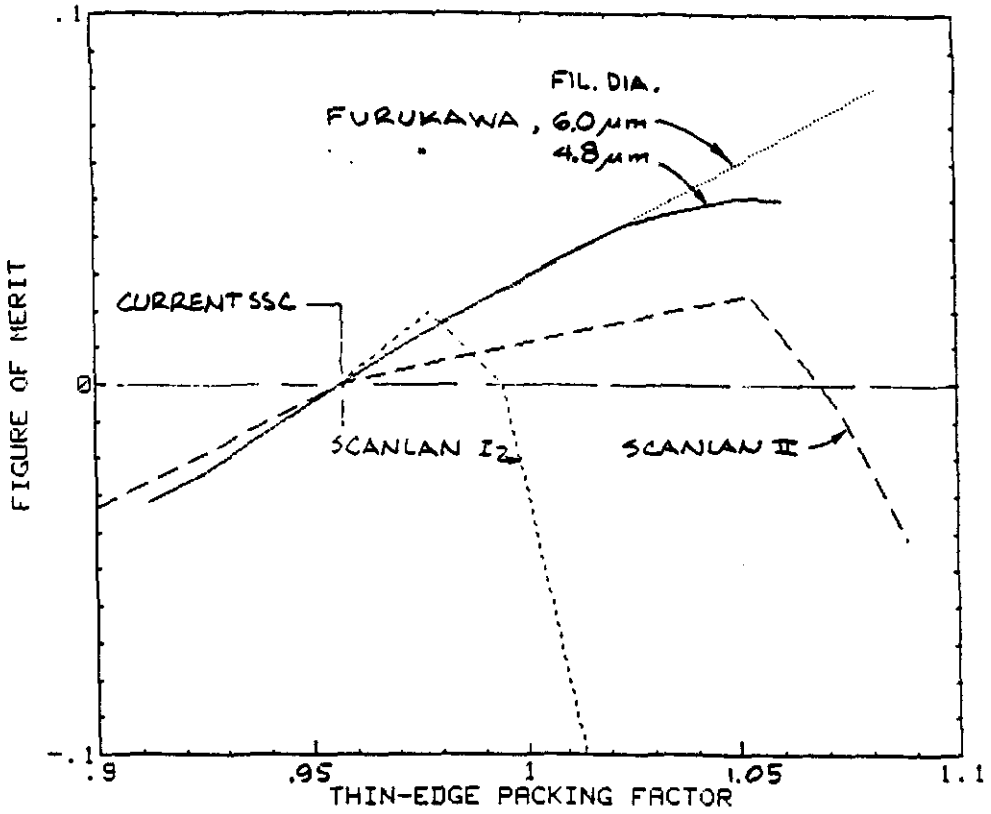


Figure 1. Effect of thin-edge packing factor on degradation for several sets of data. Data labeled "Furukawa..." are from Ref. 2 based on data presented in Ref. 1. Data labeled "Scanlan..." are from data presented recently by Ron Scanlan of LBL.

The curve labeled "Furukawa 4.8-micron" is from a smoothed curve fitted to the data in Appendix II. The curve labeled "Furukawa 6-micron" is based on data from Ref. 1 for a 3-deg keystone angle and three values of compaction. The curves labeled "Scanlan I" and "Scanlan II" are from data recently presented by Ron Scanlan which I won't attempt to describe further.

Impact on the 50-mm-Bore Dipole Design and Schedule.

The Furukawa material with the 4.6-micron filaments is made by the multiple-stacking process, and it is not at all surprising, according to Scanlan, that it degrades more than the 6-micron-filament material. If the Furukawa material data were the only data available, one might conclude that the figure of merit could be increased by 8% by compressing the cable to a PF_1 value of 1.08. For the SSC dioles, the factor R/(1+R) is 0.31 [3] and so the overall effect on critical operating field--or operating margin--is 0.31x8 = 2.5%. While that might seem like a small number, getting that by other means, such as increasing the

coil thickness or lowering the operating temperature, is extremely expensive, and so simply increasing PF_1 seems like the best bargain in town. Another way of looking at this is to say that increasing the compaction would allow a decrease in coil thickness -- with a corresponding decrease in the collar, yoke, and cryostat sizes -- for the same operating margin. But all of this depends on the credibility of the Furukawa data.

However, Scanlan's data shows only a potential increase in figure of merit of about 2%, and also indicates a great deal of uncertainty as to the greatest compaction one would dare to use.

So, if one is forced to chose a compaction based on the currently available data, one wouldn't dare go beyond the present compaction. Since big bucks are involved, however, it would seem wise to spend a few bucks now on getting more and better data.

A decision concerning an increase in PF_1 is not one that must be made immediately, and need not affect either work in process or the schedule. But if it is decided that an increase in PF_1 is to be considered at some later time, then some groundwork must be laid rather soon. That groundwork would be:

1. Design of several coils with various values of PF_1. (The current strand diameters and numbers of strands are maintained.) This is to determine whether such designs would fit within the present coil envelope, or to what extent, if any, the present design must be modified. Such modification, if required, would merely be to include additional insulation at the poles which could be reduced later to accept a higher-PF_1 coil.

2. Experimental work on the effect of compaction on degradation on a less relaxed schedule than is being pursued at present.

References.

1. Ikeda, Masaru, "Development of SSC Cable in Furukawa", unpublished (?)

2. Meuser, Robert B., "Rehashing of the Furukawa Cable Compaction Data", May 1989. SSC-N-640

3. Meuser, Robert B., "Effect of Perturbations of Magnet Parameters on the Operating Point", June 1989. SSC-N-643

Appendix I.

Overall Packing Factor

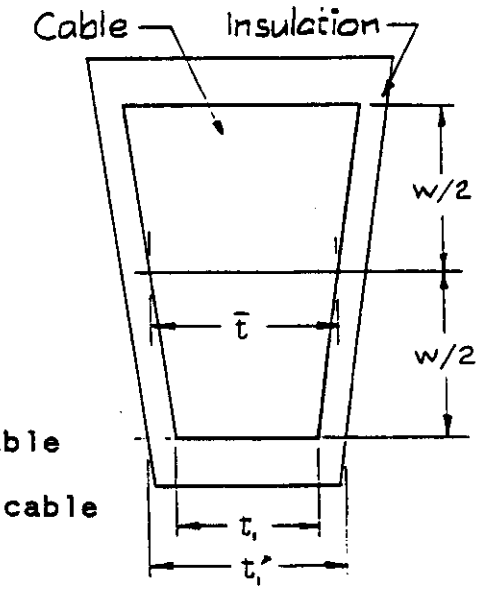
$$\overline{PF} = \frac{\pi d^2 n}{4 w \bar{t} \cos \theta}$$

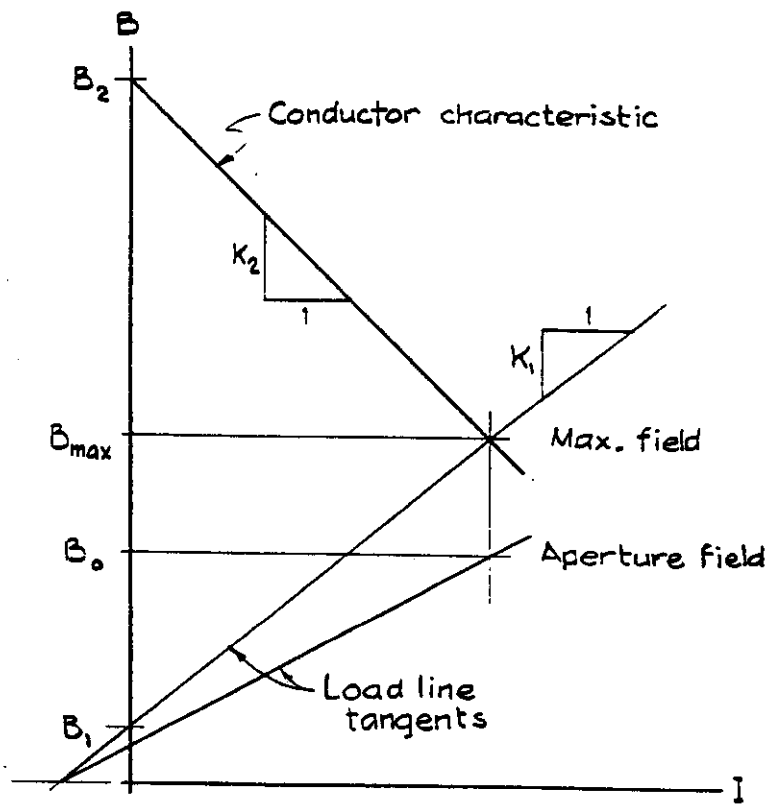
where $\cos \theta = \sqrt{1 - (n d / p)^2}$

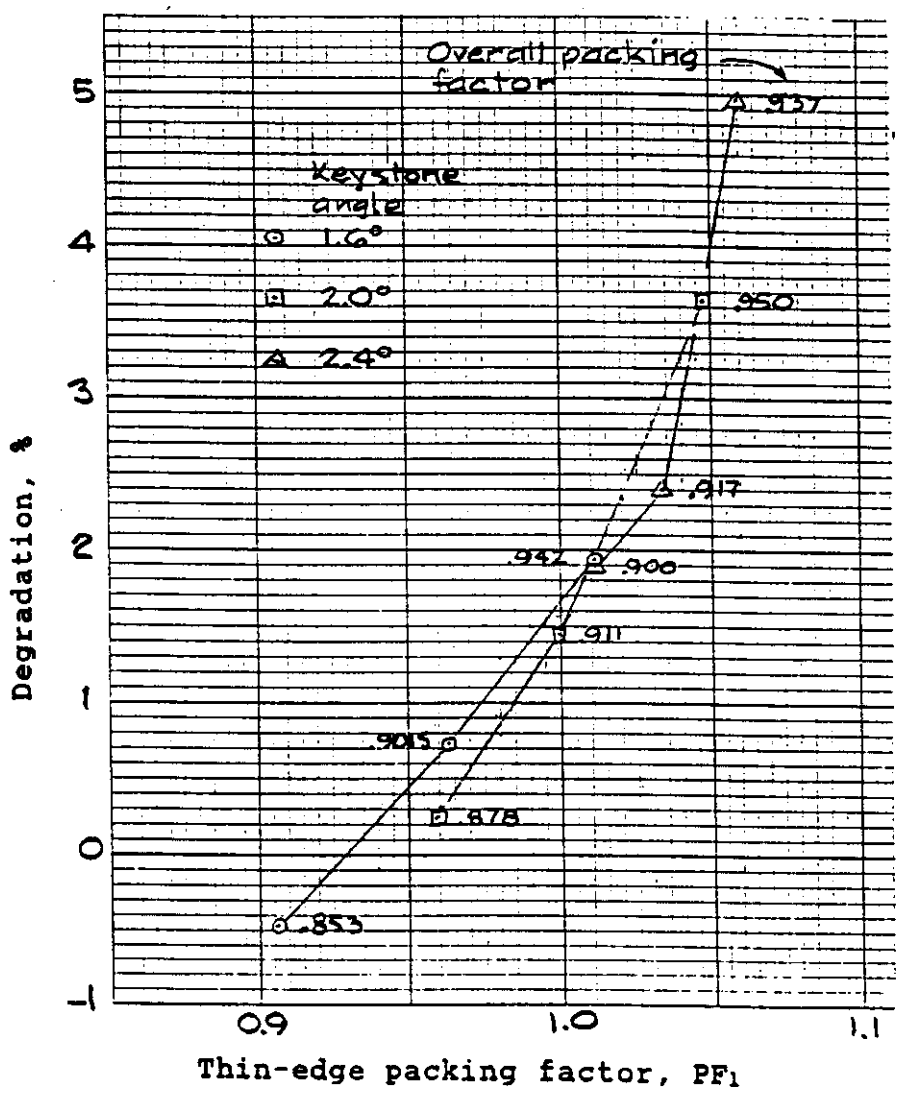
Thin-Edge Packing Factor

$$PF_1 = (\pi d)/(2 t_1)$$

where
- n = number of strands in cable
- d = strand diameter
- θ = lay angle of strand in cable
- p = cabling pitch width
- $\bar{t}$, t_1, t_1', w see sketch





Appendix II

Correlation of Degradation vs. PF_1 from Ref. 2.