Roller Gap Model Derivation

and the

Wetout Process Resin Yield Error

Analysis

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Executive Summary

This treatise on gap derivation and resin yield error analysis follows an organizational structure where assumptions, assertions and facts are stated to lay the foundation for the development of the mathematical model(s) and the error analysis thereof. The process to develop the models start with the final installed cured-in-place pipe of the correct dimensions and reverse engineers it to the starting point of the layflat liner felt-tube on the wetout train, particularly at the pinch roller, the resin metering point. The model is adapted to compute the volume of resin per unit length (i.e., lbs./ft) required to properly fill the voids in the felt, and compensate for cure shrinkage. The next section gets into the variance analysis (in rigorous mathematical terms, this is an error analysis, and the two words, variance and error are interchangeable in this treatise). The variance analysis section covers a brief example to bring the reader up to speed on the general concepts, then moves into the specific model at issue, the gap setting and the variance of resin yield with a variance of each parameter. The method of error analysis is based on taking the partial derivative of a function of several variables. We have in this instance 6 variables (parameters): the thickness “t”, Diameter “D”, stretch factor “s”, Gap “W”, resin density “r”, and void volume percentage “v”.

The parameter based roller gap dimension is a value (given the symbol of “T”) that can be directly calculated from the model’s formula. A common, but arbitrary industry standard is to set the gap at 2t +2mm, where “t” is the felt liner nominal wall thickness. The approach I have taken is a hybrid of the parametric based “T” and the arbitrary “2t+2mm” method where I derive the parametric based “T”, but in order to aid in comparisons between the two methods, I have invented a term “W”, such that “T =2t+W mm”. This holds onto the stubbornly ingrained “2t plus ….” terminology and yet allows us get to a value that correctly matches the wetout metering process to the goal of the final installed product through a designed and controlled method.

The result of the error analysis shows that the systematic error invoked by the persistent 2t+2mm standard rule-of thumb is the largest source of variance. It also shows that small random and other systematic errors in the gap dimension provide the greatest variance in the wetout resin yield. It shows that there is an offsetting effect of three systematic error that makes several of the assumptions valid. One interesting result of note is for the variance of resin yield with respect to felt density, is that it has $1/20^{th}$, or less, of the effect that typical gap roller setting variance has.

The strongest recommendation to come from this study, is that the we adopt parametric based gap recommendations and the gap roller equipment, adjustment methods and quality control be brought in line with the need to accurately control the wetout resin yield to ±2-3%

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Goals: One to determine the roller gap dimension “T” or “2t + W” that yields the final installed CIPP wall thickness with the proper amount of resin per the ASTM-F1216 sub-section 7.2, *Resin Impregnation.* Secondly through proper application of statistical error analysis (variance analysis), we determine the cause of problematic resin yield performance and control.

First Order Assumptions:

- ☐ Per ASTM F1216, 7.2, the resin quantity is calculated for the tube material at nominal thickness and diameter (a hollow cylinder).
- ☐ The polyester resin has a nominal 7% volumetric shrinkage upon curing, i.e., transitioning from the liquid to a solid. For vinyl ester resin, use 9% and for epoxy resin, use 3% nominal shrinkage rate.
- ☐ There is no stretch or shrinkage in the axial direction, either upon installation or upon cure. (There typically is minor (1-1.5%) stretch during inversion; it should be mechanically locked into the host pipe in the axial direction after installation and cure).
- ☐ The liner felt-tube in the layflat configuration, typical of the condition at the time it passes through between the roller system, is a cross-section that is an oval comprised of a regular rectangle capped by two hemispheres, see fig. 2 of sketch SK-G1.
- ☐ The resin is non-compressible in the liquid state.
- ☐ The final installed CIPP is uniformly circular with respect to a cross-section taken perpendicular to the longitudinal axis. The OD and the ID are described as concentric circles. See fig.1, of sketch SK-G1.
- ☐ The liner felt-tube in the layflat configuration has a thickness greater than or equal to the twice the design thickness “t” and it will hold its thickness at typical installation compression (pressure) regardless of resin content.
- ☐ The coating on the felt has negligible thickness.
- ☐ The gap between the rollers in the pinch roller system is fixed a predetermined value during operation, i.e., the rollers are true and round, and they rotate true around the axis.
- ☐ Assume that there is negligible shrinkage away from the host pipe ID (annulus) in the final installed CIPP

Assertions and Facts:

- ☐ The coating forming the ID of the installed CIPP is the coating forming the perimeter of the layflat felt-tube during wetout.

- The targeted volume per unit length of the cured CIPP depends on the volume of the hollow cylinder (ASTM F1216, 3.2.1) of thickness “t” the nominal felt thickness (targeted specified design thickness may equal a nominal felt thickness), times the unit length, in like units of measure.
- The proper volume of resin in the hollow right cylinder of unit length after cure is the volume as calculated above less the volume of the woven or non-woven (or a combination of both) material of the liner felt-tube at nominal thickness.
- The nominal volume of the felt fibers within the bulk felt is typically in the range of 13-14%.
- The nominal void volume within the bulk felt is typically in the range of 86-87%.
- The volume per unit length of the layflat felt-tube is the area of the cross section (taken perpendicular to the axial direction) times the unit length
- Because we assume the unit length is non-changing in both the cured CIPP and the layflat – the length component will ultimately divide out, so the cross-sectional areas of each lead directly to the volume and so they may be compared to ascertain the volume correlation.
- The ASTM F1216 standard in section 5.1, in essence says the liner felt-tube should be able to stretch and an allowance made for circumferential stretching during inversion. Therefore, the coating forming the perimeter “P” of the layflat felt-tube is less than, i.e. “undersized”, by some percentage (stretch factor “s”) of the circumference of the ID, C_{ID}, of the final installed CIPP;

$$P = s * C_{ID} \qquad \text{(eq.1)}$$

- The ID of the CIPP is directly related to the OD of the CIPP by the wall thickness “t”

$$ID = OD - 2t \qquad \text{(eq.2)}$$

- The cross-sectional area of the layflat liner felt-tube of thickness “T” and enclosed within perimeter “P” <u>must be</u> equal to the cross sectional area of the CIPP, <u>plus</u> some nominal area equal to the cure shrinkage. Cure shrinkage is compensated by resin excess “E” (see ASTM F1216, 7.2)
- The coating forms the limiting perimeter on the layflat liner felt-tube

<u>Calculations:</u>

NOTE: An EXCEL spreadsheet, <u>gaperroranalysis.xls</u>, that supports this treatise. It accepts the parameters and computes results for eq.’s 11,12,13,14,20-25,26 and 27. An example is located in Attachment 1.

CURED-IN-PLACE PIPE (CIPP):

The area A_1 is the cross-sectional area of the CIPP in fig. 1, SK-G1;

$$A_1 = \pi\,(OD/2)^2 - \pi\,(ID/2)^2 = \pi\,(OD/2)^2 - \pi\,((OD - 2t)/2)^2 \quad \text{(eq.3)}$$

The area A_1 is some percentage smaller than the uncured area A_0 due to the polymerization shrinkage "PS", so;

$$A_1 = PS * A_0 \qquad \text{or} \qquad A_0 = 1/PS * A_1$$

The circumference of the coating of the cured CIPP in fig. 1, is;

$$C_{ID} = \pi * ID \quad = \pi * (OD - 2t) \qquad \text{(eq.4)}$$

LAYFLAT LINER FELT-TUBE:

From fig. 2 of SK-G1, the perimeter "P" of the layflat, is two long sides of the rectangle and the combined circumference of the hemispherical end caps;

$$P = 2*L + 2*(\pi * T/2) = 2*L + (\pi * T) \quad \text{(eq.5)}$$

The cross sectional area "A_2" is then the sum of the regular rectangle and the area of the two hemispherical ends;

$$A_2 = (L * T) + \pi * (T/2)^2 \qquad \text{(eq.6)}$$

By virtue of the fact that the coating is the same before and after installation, and related in dimensions by the sizing and stretch, the perimeter is equal to the C_{ID} times a size factor "SF";

$$P = C_{ID} * SF = SF * (OD - 2*t) \qquad \text{this is (eq.1)}$$

We then set the two equations for "P" (eq.1 and eq.5) equal to each other and solve for "L" in terms of "OD", "T", and "t";

$$P = SF * \pi\,(OD - 2t) = 2L + \pi*T$$

$$L = ((SF * \pi * (OD - 2t)) - \pi * T)/2 \qquad \text{(eq.7)}$$

We next set the two areas, A_0 and A_2 equal to each other and substitute eq.7 into eq.8 for "L";

$$A_0 = A_2$$

$$1/PS * A_1 = A_2$$

$$1/PS = E$$

$$E * A_1 = A_2$$

$$E * [\pi * (OD/2)^2 - \pi * (OD - 2t)^2] = (L * T) + \pi * (T/2)^2$$

$$E*[\pi * (OD/2)^2 - \pi * (OD - 2t)^2] = [(SF * \pi * (OD-2t) - \pi * T)/2 * T] + \pi *(T/2)^2 \qquad \text{(eq.8a)}$$

We could solve for “T” at this point and get an exact solution, but, it may be more illustrative to redefine “T” in terms of the design or standard felt-tube wall thickness “t” and some additional width “W”, so;

$$T = 2t + W \qquad \text{(eq.9)}$$

We can substitute eq.9 into eq.8a and get the equation in terms of OD, “t”, “W”, SF and “E”;

$$E*[\pi(OD/2)^2 - \pi(OD - 2t)^2] = [(SF*\pi (OD-2t) - \pi *(2t+W))/2 * (2t+W)] + \pi *((2t+W)/2)^2 \qquad \text{(eq.10)}$$

Then we solve the left side of eq.8 exactly in terms of OD and “t” and then “force” “W” until the right side of eq.8 equals the left side, or plug in values of “W”, solve both sides and compare them to each other. We can compare in terms of percentage by dividing the right side by the left side.

$$A_0 = E*[\pi * (OD/2)^2 - \pi * (OD - 2t)^2] \qquad \text{(eq.11)}$$

$$A_2 = [((SF*\pi (OD-2t) - \pi *(2t+W))/2 * (2t+W)] + \pi *((2t+W)/2)^2 \qquad \text{(eq.12)}$$

These two equations are put into a spreadsheet and the following four independent parameters are used as data inputs;

E = ________, %; E is the excess resin called for in ASTM F1216, 7.2; Typical values range from 1.03 for epoxies and 1.07 for polyesters. Vinyl ester resins have nominal volumetric shrinkage in the order 9%, and a factor of 1.09 would be a nominal E value.

SF = _______, %; SF is the undersize cut percentage to compensate for stretch as called for in ASTM F1216, 5.1; Typical values range from 88% to 95% with the range of 91-93% being the most common values.

OD = ______, inches (converted to mm); OD is the CIPP outside diameter, which is the nominal host pipe inside diameter as called out in ASTM F1216, 7.2; per field verification.

t = _______, mm; t is the nominal thickness of the liner felt-tube, determined by the CIPP design in the Technical Specifications, 5.1, and called for in ASTM F1216, 7.2 and rounded up to the nearest nominal commercial felt thickness unit, typically based on 1.5-mm increments.

W = ______, mm ; W is the additional gap width used to generate the correct volume at the gap of the roller system in order to fill all the voids and compensate for cure shrinkage and resin migration, as called for in ASTM F1216, 7.2,(and perhaps the applicable sections of Contract Technical Specifications); This should be dependent on the values input into the equations above and based on the assumptions and assertions listed at the beginning. If an arbitrary value is used, then there may be resin volumes different than per specification, depending on the equipment performances.

The areas A_0 and A_2 above, satisfactorily illustrate the comparison of the final installed product to the gap setting dimension. By converting to a volume per unit length, i.e., cubic inches per lineal foot, then to gallons per foot and through the resin density, to pounds per foot we get the targeted resin yield. The volume of resin has to be adjusted by the volume of the felt fibers. Thus, two new variables have been created, the resin density, “r”, and the void volume, “v”. The void volume is the total volume less the nominal fiber volume.

r = ______, lbs/gal; r the resin density in lbs./gal (weight units per volume unit) that will allow us to convert the volume per unit length to weight per unit length, i.e., pounds per foot the usual units that yields are figured.

v = ______, %; v is the void content by volume that, according to ASTM-F1216, 7.2 *Resin Impregnation,* is supposed to be all filled with a sufficient volume of resin. The excess called for in that sub-section is taken into account in E, above.

$$V0 = (E*[\pi * (OD/2)^2 - \pi * (OD - 2t)^2])*12/645.46/231 \qquad (eq.13.1)$$

$$V2 = ((([(SF*\pi (OD-2t) - \pi *(2t+W))/2 * (2t+W)] + \pi *((2t+W)/2)^2)*12/645.46)/231) \qquad (eq.13.2)$$

$$Wt0 = ((E*[\pi * (OD/2)^2 - \pi * (OD - 2t)^2])*12/645.46/231)*r*v \qquad (eq.14.1)$$

$$Wt2= ((([(SF*\pi (OD-2t) - \pi*(2t+W))/2*(2t+W)] + \pi *((2t+W)/2)^2)*12/645.46)/231)*r*v \qquad (eq.14.2)$$

RESIN YIELD VARIANCE ANALYSIS:

The intent of this variance analysis is to look at all of the parameters that affect the resin yield of a wetout of a felt-tube liner for the CIPP process and through a process where we guess the practical limits of variance in those parameters, we can see the effect of the variance of each one on the outcome of the yield.

The variance of any parameter has its root in one of two, maybe three causes. The first is random errors (scatter, variance, …). An example of a random error is reading a low pressure on a high pressure gauge. The correct pressure may be 20 psi, but the gauge may not be accurate at the low end, the needle is several psi broad, the bounce in the needle is several psi, your angle to the needle may not be straight on, etc. Therefore you may read/guesstimate a pressure of 19 or 21 psi. You have a level of precision of 5%. Random errors can not be eliminated as they are a fact of nature, they can only be minimized. A system that has the minimum level of random errors is called high precision. The second are systematic errors. Say the above gauge is not zeroed, so that it reads 2-psi when no pressure is applied. Then your pressure reading is 21-23 psi when the actual pressure is 20 psi (5-10% ACCURACY). Another example of systematic error is mixing and dispensing catalyst solution from a bucket. When you mix and pour, there is a certain amount of catalyst solution that clings to the walls of the bucket, say a quarter of a pound. In a 15-pound batch, that's roughly a 1.5% systematic variance. We can sometime eliminate systematic errors, such as by replace a tape measure with a broken end, but others, as in the clingage on the walls of a bucket, are unavoidable, but we can work to minimize them, also. A system with minimized systematic errors has what we call, a high degree of accuracy.

The third type of error is the true mistake. Examples of these are adding/subtracting errors, grabbing the wrong shim block, using a broken scale, adding Trigonox twice, etc. Mistakes are not dealt with in this paper, as they are completely avoidable (IN THEORY), as opposed to random and systematic errors or variances that are facts of nature.

We can work to minimize random and systematic errors through better precision and accuracy where applicable within reason. We should use this exercise to see where the biggest return on better precision and accuracy will occur, who is in control at those points, and, what does it take to exercise control.

THE MODEL

A model is a formula that mathematically describes the behavior of typically, a physical thing or process. The model may be a true representation, a good approximation or a poor approximation, based on the assumptions and tolerances of the parameters, particularly within the limit of some scope. We develop the model in general, meaning no values for the parameters are used, but the functions and relationships are built with symbols we call variables. Then, we get a body of values for the variables typical for the case at hand, i.e., 8-inch diameter, 6-mm thickness, 92% undersizing, 87% void content, 9.1 lbs./gal, and W is chosen according to what effect on the resin yield we wish to achieve. The "W"'s we see for 8-inch liners ranges from 1-mm to 2-mm from the archaic arbitrary rule-of-thumb "2t plus 1" or "2t plus 2", to 3.1-mm from model based calculation for volume matching between the final installed product to the volume metering device we call the pinch roller. If the model is a true representation or a good first order approximation, then the numerical output of the model, I've labeled the output as Q in general, is accurate within the tolerances of the parameters that went into the model. The key to this portion is how does Q vary when each of the parameters vary? The answer is the essence of error analysis.

VARIANCE ANALYSIS METHOD

The change of Q, ΔQ, with a change in a parameter x, Δx, is found by taking the first derivative of Q with respect to x, symbolized by dQ/dx.

An simple example may provide a better illustration of the concept before moving to the general case, then moving on to the specific case for resin yield.

The volume of a cylinder is modeled by the equation:

$$V = \pi r^2 h \quad \text{(eq.15)}$$

The model has two parameters, radius “r” and height “h”. This is an exact representation. Now if we want to know volume changes if “r” or “h” changes, then we say the volume change is ΔV, the radius change is Δr and the height change is Δh. The model that describes the volume V plus the change in volume ΔV with respect to the two parameters, is:

$$V+\Delta V = \pi(r+\Delta r)^2 * (h+\Delta h) \quad \text{(eq.16)}$$

The change in volume V, ΔV, is then found by substituting $\pi r^2 h$ for V and subtracting from both sides.

$$\Delta V = \pi(r+\Delta r)^2 * (h+\Delta h) - \pi r^2 h \quad \text{(eq.17)}$$

In generalized and correct mathematical terminology, the volume V is a quantity Q that is a function of multiple variables (parameters), Q = f(r,h), or for the general case it would look like, Q = f(x,y,…) . When we talk about the rate of change of Q with respect to one of the variables (holding all other variables constant), it is called the partial derivative of Q with respect to, say x, and it is symbolically represented by $\partial Q/\partial x$. We can, and should, do partial derivatives for all the parameters in the function. The total change in Q, ΔQ resulting from the changes with respect to all of the variable is the sum of terms of the rate of change with respect to each variable times the error or variance of the variable, i.e.,:

$$\Delta Q = \partial Q/\partial x * \Delta x + \partial Q/\partial y * \Delta y + \ldots \quad \text{(eq.18)}$$

The fractional error (variance) is found by dividing eq.18 by the quantity Q:

$$\Delta Q/Q = 1/Q * \partial Q/\partial x * \Delta x + 1/Q * \partial Q/\partial y * \Delta y + \ldots \quad \text{(eq.19)}$$

It is useful to look at both the change in Q with respect to each parameter (variable) and the fractional (expressed in percentages) changes with respect each parameter by looking at each term in eq.18 and eq.19 separately as well as the total change and percentage change because we get a clear picture of where the aspect of our process is most highly influenced by variance, tolerances, and where we get the best return on out efforts to control our process.

SPECIAL TOPIC – WETOUT PARAMETERS AND RESIN YIELD

The function for determining resin yield based on the liner and resin parameters, and the gap dimensions, is eq.14. This is, in shorthand notation, $Q = f(W,s,t,D,r,v)$. I took equation 14 above and differentiated it with respect to each variable, as follows:

$$\partial Q/\partial W = \partial f(W,s,t,D,r,v)/\partial W = (\pi/2*D*r*s*v-\pi*r*t*v-\pi*r*s*t*v-\pi/2*r*v*W)*0.0000805 \qquad \text{(eq.20)}$$

$$\partial Q/\partial s = \partial f(W,s,t,D,r,v)/\partial s = (\pi*D*r*t*v-2\pi*r*t2*v+\pi/2*D*r*v*W-\pi*r*t*v*W)*0.0000805 \qquad \text{(eq.21)}$$

$$\partial Q/\partial D = \partial f(W,s,t,D,r,v)/\partial D = (\pi*r*s*t*v+\pi/2*r*s*v*W)*0.0000805 \qquad \text{(eq.22)}$$

$$\partial Q/\partial t = \partial f(W,s,t,D,r,v)/\partial t = (\pi*D*r*s*v-2\pi*r*t*v-4\pi*r*s*t*v-\pi*r*v*W-\pi*r*s*v*W)*0.0000805 \qquad \text{(eq.23)}$$

$$\partial Q/\partial r = \partial f(W,s,t,D,r,v)/\partial r = (\pi*D*s*t*v-2\pi*t^2*v-2\pi*s*t^2*v+\pi/2*D*s*v*W-2\pi*t*v*W-\pi*s*t*v*W-\pi/2*v*W2+\pi*v*(1*T+0.5*W)^2)*0.0000805 \qquad \text{(eq.24)}$$

$$\partial Q/\partial v = \partial f(W,s,t,D,r,v)/\partial v = (\pi*D*s*t*r-2\pi*t^2*v-2\pi*s*t^2*r+\pi/2*D*s*v*W-2\pi*t*r*W-\pi*s*t*r*W-\pi/2*r*W2+\pi*r*(1*T+0.5*W)^2)*0.0000805 \qquad \text{(eq.25)}$$

The number 0.0000805 above attached to the end of each equation is the constant of conversion for changing the cross-sectional area A_2 in mm^2 to in^2, then by 12 inches per foot to volume in in^3 per foot, then into gallon per foot. The main body of the equation has the void content and the resin density, so the final units of the equations 20-25 are lbs. per foot, per unit of the parameter.

The variance is found by the following typical equation:

$$\text{Variance} = \partial Q/\partial W * \Delta W \qquad \text{(eq.26)}$$

and repeated similarly for the other five parameters.

The percentage variance is found by eq.26 by Q:

$$\text{Percentage Variance} = (\partial Q/\partial W * \Delta W)/Q \qquad \text{(eq.27)}$$

And likewise repeated similarly for the other parameters.

PARAMETER W, OF 2t +W, mm

We'll start with eq.20, for the change of resin yield with a change in the dimension W, the roller gap width added to the twice the thickness (2t) portion of the gap. When the rate of change, for our case it is the change in pounds of resin per foot, per mm, is found at some point, say for the proper gap "W" = 3.1 mm, and we then multiply that by say -ΔW = -1.1mm, a reasonable expectation for the change in W if one sets the roller gap at 2t+2mm, we then get the change of resin weight for that parameter variance. In this case, it (the resin yield variance) is found to be about -0.176 lbs./ft/mm. I picked W=3.1 for this example because the model output shows that, 2t+3.1mm to be the proper match between the final installed pipe and the wetout liner passing through the pinch roller gap. The percentage variance at 2t+2mm is -7%, or 7% lean. If the gap is set to 2t+1mm, then the resin yield variance and percentage variance is -0.336 lbs./ft and -13.3% respectfully. If we can set the gap to ±0.5mm as our tolerance, we plug that into equations 26 and 27, we find that the resin yield variance due to our limited precision, is ±0.08lbs.ft variance or ±3.2% percentage. If, as we find on some pinch rollers, that the rollers are not true and they wobble (not very accurate) by an average of ±1.5 mm, then that contributes ±2.4 lbs./ft (±9.5%) variance. If we consider that the thickness of the PU coating is roughly 0.36mm, that systematically decreases the W by 0.72 mm for a variance of -0.115 lbs./ft (-4.6%)

PARAMETER s, STRETCH OR UNDERSIZING FACTOR

We look at this for two main reasons. First, the arbitrary and archaic 2t+2mm gap does not take into account the effect of the stretch factor as it changes the perimeter that encloses the volume that gets metered through the pinch roller. The second is the fact that the various liner felt-tube manufacturers have their own percentage undersizing they use to make their liners. If the correct gap setting that is recommended by one manufacturer is used for the wetout of another manufacturer's liner product with a different undersize (stretch factor), it will make a difference. (The manufacturer's cut size tolerance is looked at in the diameter parameter below) I picked a nominal s = 92% (0.92) as the average between the common three undersize values. Then applying variance = $\partial Q/\partial s * \Delta s$, with $\Delta s = 0.01$, we get 0.029lbs/ft (1.1%) variance. Should the wetout always use the correct gap setting for the nominal stretch factor, then there is no variance, so $\Delta s = 0$ and there is no contribution to the overall variance.

PARAMETER D, DIAMETER

We look at this, because it has two important, but widely differing causes for the effects on the resin yield variance. The first is the liner manufacturer's manufacturing tolerance. It is listed as wide as a ¼ inch flat cut width, that translates to 2mm ± in diameter change, to as small a 1/16 inch flat cut and that is 0.5mm diameter variance. We find for the greater of the listed manufacturer's tolerances, the variance is 0.028 lbs./ft (1.1%). The second is the swelling of the polyurethane coating with absorption of styrene when in contact with the resin. I have produced lab testing results that PU can swell 3% in 6 hours. That translates into a systematic 6mm increase in diameter, for a variance of +0.083 lbs./ft (+3.3%). I think the most significant effect of the styrene swelling of the PU coated layer and the increase in diameter is, that it roughly offsets the systematic variance of the PU thickness, decreasing the yield.

PARAMETER t, THE THICKNESS

“t” we take as a constant, with all of the change taking place in the gap setting is with the W parameter above.

PARAMETER r, RESIN DENSITY

We look at this with two main aspects in mind. The first is the lot to lot density tolerance in resin density as supplied from the manufacturer. The typical range is ±0.1 lbs./gal. The second is the increase in density from that listed in the resin standard properties at 25°C (77°F) and the temperature of the resin at wetout. I don’t know the increase in density of resin, say going from 77°F to say 55°F, but 0.1 lbs./gal would be a good estimate. At 0.1 lbs./gal, the variance is 0.028 lbs./ft (1.1%).

PARAMETER v, VOID VOLUME

We look at this because it has been a common impression that the density of the felt plays a big role in the large variance in resin yield seen in the wetout process. One felt manufacturer has stated that their manufacturing tolerance is ±1% of the felt content. If the felt content is nominally 14% (0.14) by volume, then the variance is 0.14 * 0.01, and that is 0.0014. With that run through the equation for resin yield as a function of void volume, that returns a yield variance of 0.004 lbs./ft (0.2%). If it were tens times the stated tolerance, at $\Delta v = 0.014$, then the variance would be 0.041 lbs./ft (1.6%). This in my opinion, clearly removes felt density as a significant portion of the total resin yield variance.

SUMMARY

Through the process of constructing a mathematical model that goes by reverse engineering from the targeted final installed CIPP product, back through to the gap setting, the geometry of the liner product, and taking into account resin and felt properties, we are able to conduct an error (variance) analysis on the effect of variance, tolerances and such, in each of the parameters, on the resin yield.

We find that far and away, the roller gap setting and the variance thereof is the largest source of or cause of variance in the resin yield. We find that the simplifying assumption that the PU coating has negligible thickness is valid, because it is largely offset by the swelling of the PU coating prior to passing through the pinch roller, and the density of cool resin.

The roller gap setting situation currently has a twofold problem in achieving resolution. One is the stubbornly persistent arbitrary and archaic, one-size-fits-all rule-of-thumb practice for setting the roller gap dimensions at 2t+2mm. It finds wide acceptance in part because it is easy to remember, it has been around from the earliest days of the CIPP business, and it continues to find its way into various technical references, placed there by people who accept it without critical review, usually from someone who has appearance of credibility.

The second source of problems stems from the equipment used as the pinch roller, power conveying system. Here, the author believes we can identify two major deficiencies that would require different solutions. One, is equipment that is poorly designed and fabricated with wide tolerances and slop in construction and linkages. Another is the dual use of the pinch roller/conveyor as the sole source of motive power used to pull the resin slug and liner off of the pallet stack, along roller beds and into through the gap. The roller gap technically should be a metering device, not a motive drive unit. In order to get enough drag at the point of contact between the roller and the liner, there has to be a certain amount of friction, area of contact and normal force. Because the roller exhibits such a small surface to the liner, then the normal force needed to get the drag is generated through the action of the roller compressing the felt to a degree that it, the compressive behavior of the felt, has enough resistance to generate the drag. The proper gap does not compress the felt to the extent needed to generate the drag, and in the absence of other or enough other powered conveyance, the wetout operator will typically lower the gap to get the drag. The rollers (and sometimes in combination with a powered conveyor belt) do not act as an adequate conveyance motive with the proper gap setting dimension to correctly meter the resin into the felt, and the proper conveyance gap setting does not properly meter the resin to the volume required to achieve installed thickness, resin saturation and sometimes, physical properties.

RECOMMENDATIONS

Gap roller machines need to be fabricated (retrofitted if necessary) to an accuracy of ±0.5 mm accuracy in trueness and repeatability. Gaps should be checked with modeling clay and calipers accurate to 0.1 mm.

Wetout trains need to be constructed (retrofitted if necessary) with proper power conveyances so that the pinch roller can serve predominately as a metering device.

Stop all use of the one-size-fits-all arbitrary 2t+2mm gap (or any other arbitrary method) setting practice.

Adopt gap setting recommendations based on methods outlined in this treatise or similar methods that take into account all parameters and are derived, based on, or directly correlated to, the targeted final installed CIPP product.

Attachment 1:

Roller System Gap vrs System Variables Comparator

Host Pipe Diameter, D =	8	in.	= 203.2 mm	
Thickness, t=	6	mm	t = felt-tube wall thickness	
π =	3.14		PU Perim. = 21.8 in.	
s =	92%		s = stretch factor, or undersizing	
W =	3	mm	W = width over the 2t nominal thickness	
E =	1.07		E = excess resin for cure shrinkage	
gap =	15	mm		

E*p*(t*OD-4*t) = (p*((2t+W)/2)2 + [(p*(OD-2t)*(SF)-p(2t+W))/2]*(2t+W)

Area A_0 = area of the hollow cylinder, fig.1 of sketch SK-G1, before cure shrinkage and area A_2 = cross-sectional area of the layflat felt-tube, see fig.2 of sketch SK-G1.

Area A_0			Area A_2	
3977.3	mm^2	=	3967.9	mm^2
6.16	$in.^2$	=	6.15	$in.^2$

Ratio of A_2/A_0 = 99.7%

	Vol. 0		Vol. 2	
	39.8	l/m	39.7	l/m
0.320253	74.0	$in.^3/ft$	73.8	$in.^3/ft$

Ratio ofV_2/V_0 = 100%

Resin Density, r = 9.12 lbs/gal
Felt fiber content = 13%
Void Content, v = 87%

Resin Yield, Wt_0,Theoretical	Resin Yield, Wt_2, Actual
2.54 lbs./ft	2.53 lbs./ft

Parameters of the Model	dQ	units	Δx	dQ*Δx,lbs.	1/Q*dQ*Δx
Gap "W" Additional Width Factor	0.161	lbs/ft/mm	-0.5	-0.081	-3.2%
Stretch Factor = Liner sizing	2.877	lbs/ft/100%	0.01	0.029	1.1%
Diameter	0.014	lbs/ft/mm	1	0.014	0.5%
Nominal Wall Thickness	0.295		Constant (Change occurs in "W", above)		
Resin Density	0.278	lbs/ft/lb	0.1	0.028	1.1%
Void Volume	2.913	lbs/ft/100%	0.0014	0.004	0.2%
			Cumulative	**-0.006**	**-0.2%**