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Structural failure of composite pipes – a trilogy

Part 2 – Weep failure

Presented at the 2009 ACMA conference in Las Vegas
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Abstract – The long-term structural failure of composite pipes is addressed from the perspectives of burst and weep. The long-term burst is controlled by the glass fibers – not by the resin - and typically occurs in pipes operating at low strains. The weep failure is controlled by the glass-resin interphase and typically occurs in pipes under high strains. These modes of failure are independent and do not interact. There is still a third mode of long-term structural failure, known as strain-corrosion rupture, which occurs when the pipe is subjected to bending strains while immersed in corrosive environments. The strain-corrosion failure can be fully explained as a combination of the weep and rupture modes. The structural design of composite pipes for long-term durability in corrosive or non-corrosive environments must meet both rupture and weep criteria.

We have developed a series of three papers to address each of these modes of failure. The first paper recognizes that the long-term burst is caused by strain corrosion of the glass fibers in water under tensile strains. The second paper deals with the weep mode of failure and introduces the concept of threshold strain in place of the traditional HDB generated by the ASTM D 2992 protocol. And finally the third paper explains and quantifies the elusive phenomenon of strain corrosion rupture. The commercial standards for composite pipes, like AWWA C950, API 15HR and ISO 14692, focus on the weep and the strain-corrosion modes of failure. The long-term burst failure is ignored in all pipe codes.

Introduction – This is the second paper in a trilogy. It opens with a discussion of the classical weep regression line obtained from pressure testing water filled pipes. Next it identifies the glass-resin interphase as the controlling factor for weep failure and introduces the concept of threshold strain. The threshold strain and its measurement are the focus of this paper. The concept of threshold strain introduces two innovations in the composite pipes industry. First, it indicates that the weep resistance of composite pipes may be higher than implied by the classical HDB. And second, it relieves the pipe manufacturers of the burden to do the expensive and time consuming ASTM D 2992 test.

The weep failure results from the passage of water through pathways formed by the coalescence of cracks that form in the glass-resin interphase. The long-term burst failure results from the slow deterioration of the glass fibers tensioned in contact with water. If the tensile strain is small, the pipe will fail by burst instead of by weep. This statement may sound preposterous, but we hope to make it clear as we go.

This paper will focus on the strain that controls weep design, known as HDB, or Hydrostatic Design Basis. The test protocol currently used to estimate the HDB is described in ASTM D 2992. It consists essentially in pressure testing a minimum of 18 water filled pipes under different sustained high strains. The pipes under higher strains fail first. The hoop strains and times to weep are annotated to derive a regression line that is used to predict the long-term failure strain. The extrapolated long-term strain is known as Hydrostatic Design Basis, or HDB. This paper will show that the regression line established this way should be used to make long-term predictions. This paper builds a strong case against the HDB measured by the ASTM D 2992 test protocol and its use in the design of composite pipes.

The glass-resin interphase debonds when placed under shear or tensile loads. The debonds arising from shear loads reduce the stiffness and the light transmission properties of the laminate but do not open cracks. Only the tensile loads are able to open cracks. The weep failure involves the passage of fluids through cracks that develop and open under tensile strains. The length, opening and number of cracks depend on the magnitude of the tensile strain. As the tensile strain increases, so do the number, length and opening of the cracks. Eventually the tensile strain reaches a critical value that causes the cracks to coalesce and form a pathway for the passage of fluids. The critical tensile strain is known as threshold strain. When strained below the threshold, the pipes never weep. And above the threshold they certainly weep. The time to weep depends on the wall thickness of the pipe and on the pathway that is formed along the glass-resin interphase. If the cracks are many and their opening and length are large, the time to weep is short. Thin walled pipes also have short times to weep.

The concept of threshold strain is in sharp contrast to the current practice of extrapolating weep regression lines to predict the long-term HDB. The extrapolation process is based on the false assumption that the cracks will coalesce regardless of their number and size. This assumption is simply untenable. This paper will show that (a) the weep line changes slope and becomes horizontal at the threshold strain and (b) no weeping occurs at strains below the threshold.

The HDB concept can be expanded to include cyclic loads as well, implying the existence of a static as well as of a cyclic HDB. This paper will deal with both the static and cyclic cases at room temperature and at elevated temperature.

The ASTM D 2992 test method – The current test method to develop the weep regression line of composite pipes is described in the ASTM D 2992 protocol. The method consists in subjecting several water filled pipes to different pressure levels (cyclic or static) and annotating the times to weep. To accelerate the testing, the specimens are subjected to very high strains, higher than the threshold strain and certainly much higher than those found in use. The data points (hoop strains and times to weep) are plotted on log x log space to produce a regression line which is extrapolated to yield the HDB. Equation (1) shows the weep regression line on log x log space. The Greek letter "Є" denotes the hoop elongation that weeps the pipe in the time "t". The intercept A is related to the short-term elongation at weep of the pipe and the slope G is related to the wall thickness and the density and size of the cracks that form the pathway for the passage of the water. The parameters A and G depend on the temperature and the toughness of the interphase resin.

$$\log \varepsilon = A - G \log t \qquad (1)$$

In equation (1) the tensile static elongation "Є" determine the number and size of the cracks that form in the pipe wall. And "t" is the time that the water takes to travel the pathway that is formed by the cracks. The cracks that form in static loadings are stationary and do not grow with time. The weep time "t" in equation (1) is not related to any deterioration of the pipe, but to how wide and how long the stationary cracks are that form the pathway. The time "t" is the travel time for the water to traverse the cracked wall. This is a very important concept.

The weep regression line (1) is related to the glass-resin interphase, the thickness and layup of the pipe wall. Figure 1 shows typical longitudinal cross-sections of commercial pipe walls used in sanitation and oil applications. What follows is a description of the plies that are used to make such pipes.

Liner: Both sanitation and oil pipes have an inner resin rich layer which, if not broken or otherwise punctured, assures full water tightness. The liner of sanitation pipes is made by saturating a special lightweight veil with polyester or vinyl ester resins. As a rule, the liners of oil pipes do not have a veil.

Weep barrier: All sanitation pipes have a layer of chopped glass, also saturated with polyester or vinyl ester resins, placed immediately on top of the liner. This layer of chopped glass fibers serves two functions. First, it works as a corrosion barrier in pipes used to convey chemical products. And second, it helps to maintain the water tightness. The chopped glass layer is known as “corrosion barrier” or “weep barrier” according to the application.

Structural layer: The structural layer of both sanitation and oil pipes is made of several plies of high modulus unidirectional, continuous glass fibers. The unidirectional fibers (referred to as UD fibers) in the structural layer provide the high modulus and strength required to handle the pressure and other loads on the pipe.

Core: The sanitation pipes for underground use may have a core of sand-filled resin which builds up the wall thickness to provide ring stiffness. The core plies crack easily and are not good as weep barriers.

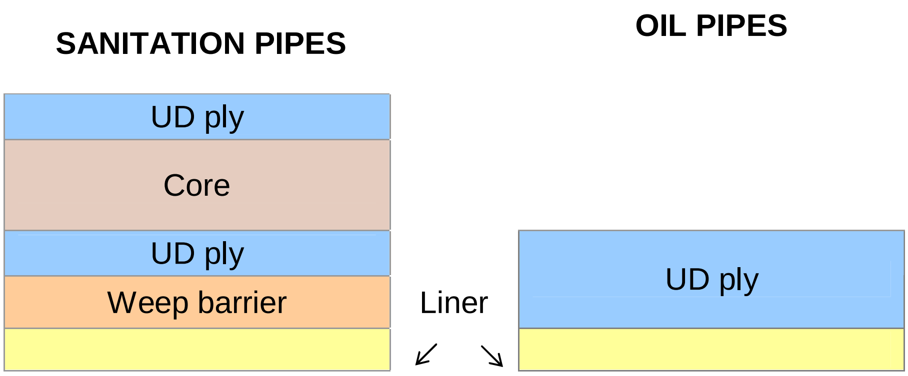

Figure 1
Typical wall construction of commercial sanitation and oil pipes.

Figure 2 shows typical weep regression lines for sanitation and oil pipes. The line with the flatter slope is typical of epoxy oil pipes that do not have a weep barrier of chopped glass. The line with the steeper slope is typical of polyester sanitation pipes used to convey water, sewage and chemical effluents. All sanitation pipes have a weep barrier of chopped glass.

We proceed to explain the relationship between the weep lines and the pipe construction. The first thing to have in mind is that the liner must break before the pipe weeps. This statement is obvious and seems to indicate that pipes with highly resilient liners are protected against weep. This is not so. The cracking of the liner is controlled not by the liner itself, but by the substrate ply that is attached to it. In oil pipes a UD ply is laid directly on top of the liner. Therefore, for oil pipes the cracking of the liner is controlled by the UD ply. In sanitation pipes, the weep barrier of chopped glass has the control. These unusual remarks about crack initiation can be easily explained by the theory of fracture mechanics.

Suppose a pipe with a very resilient liner. Under increasing pressure the pipe stretches and grows cracks in the UD or chopped ply. Under low strains the borders of the cracks are temporarily arrested on reaching the resilient liner and grow into the laminate. This growth is stopped when the crack borders encounters the very tough glass fibers. When that happens, the crack has no option but to grow into the liner, regardless of its resiliency. And the liner, as we know, has no fibers to arrest the crack growth. That is the reason why the cracking of the liner is controlled not by the liner itself, but by its substrate.

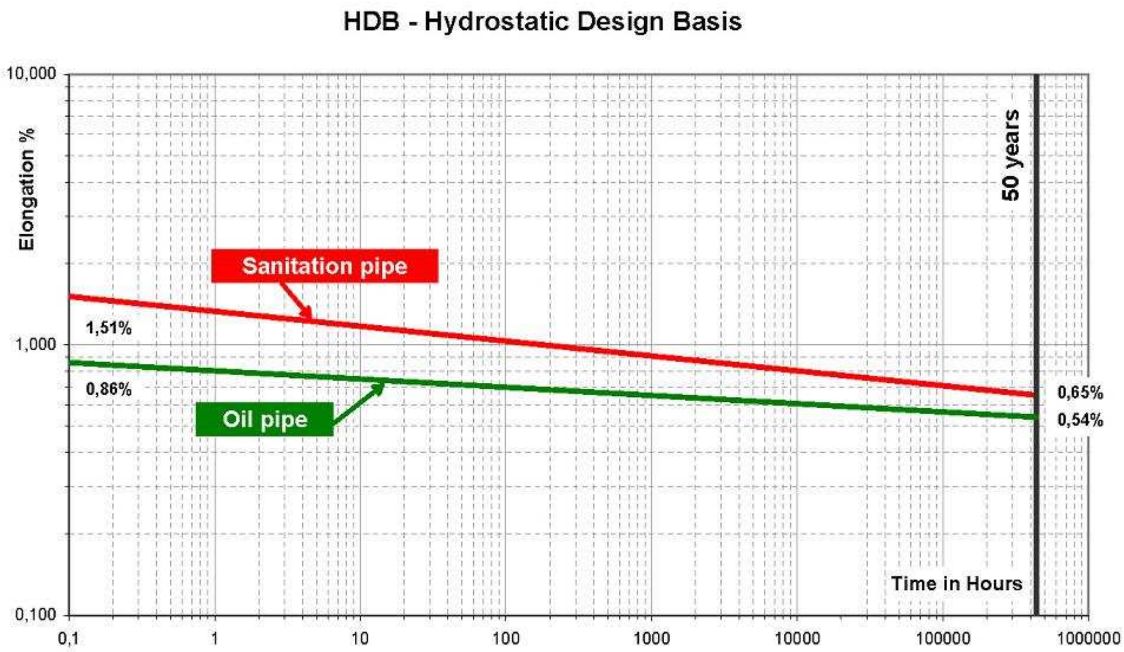

Figure 2
Typical weep regression lines for sanitation and oil pipes. Notice the flatter line of oil pipes.

This simple argument explains why the rupture of the liner is controlled by the substrate ply. For oil pipes the cracking of the liner is controlled by the innermost UD ply. And for sanitation pipes the chopped glass ply is critical. The events just discussed have been observed and reported by many authors. For a quick review the reader is directed to references 3 and 8. The elongations at break of liners embedded in laminates are sometimes called "in-situ" elongations to differentiate them from those measured on isolated plies.

Note: The "in-situ" elongation of the liner is determined by the interphase in the substrate ply. The reader will have to make an effort and remember that it is the interphase in the substrate, and not the resin in the liner, that controls the weep process. Few people realize this.

We close this section with a few remarks regarding the parameters A and G in the regression equation (1). The slope G reflects the time taken by the water to traverse the pathway in the pipe wall. It does not reflect crack growth or any deterioration of the pipe. Cracks do not grow under static loads. When the static load is increased to a higher level the crack widens and increases in length, but ceases to grow once the load stabilizes. And they remain stable as long as the load does not change. The higher the static load, the wider and longer are the (stationary) cracks and the shorter is the time for the water to travel through the pipe wall. The slope G of the weep line is related to the travel time taken by the water to traverse the pathway of stationary cracks. It is not related to crack growth, because cracks do not grow under static loads.

The length of the cracks depends on the toughness of the interphase resin. Other things being equal, the crack length increases with the temperature and the resiliency of the resin. Longer crack lengths means shorter weep times and steeper regression lines. Figure 3 shows the slope of weep lines increasing from G = 0.03 at 25C to G = 0.07 at 65C. The same thing would be observed if the resiliency of the resin were increased. The slope of the regression line increases with the temperature as well as with the resiliency of the interphase. However, the threshold strain increases with the temperature and the resin toughness. Taken to its logical conclusion, this argument implies that higher temperatures (a) increases the gradient and (b) at the same time improves the pipe performance. The reader should take a moment and try to understand this paradox.

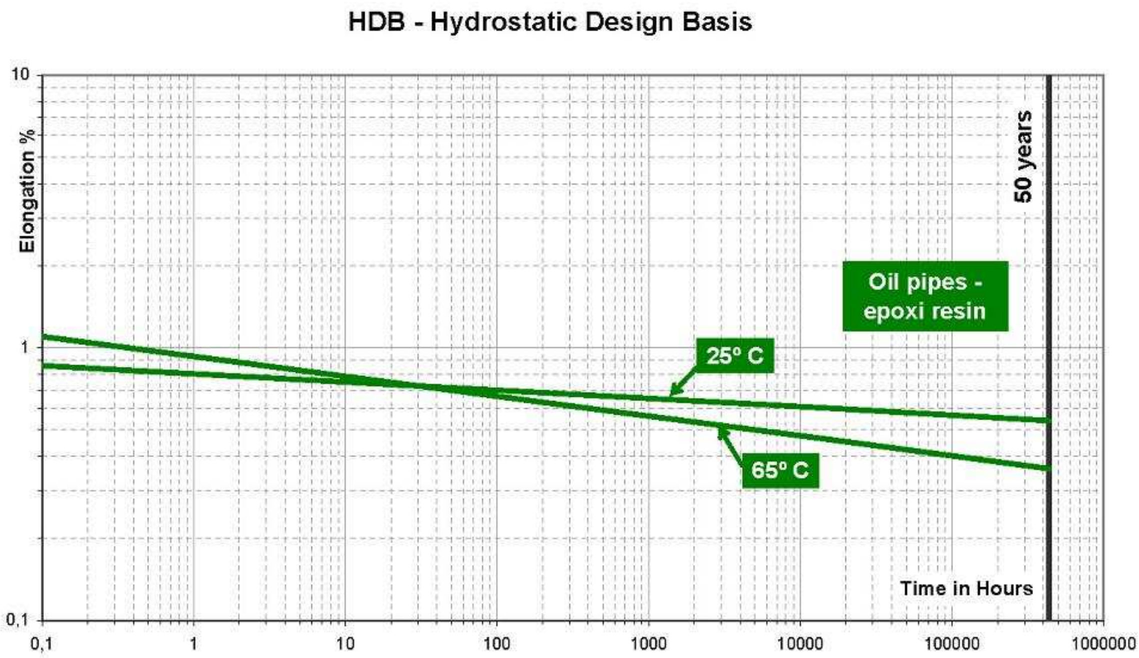

Figure 3
The slope of the regression line increases with the temperature and the resiliency of the resin. This is a scary situation for the oil pipe manufactures. However, given that the threshold strain increases with the temperature, the pipe performance may actually improve.

Table 1 shows some typical values for the intercept A and the slope G of commercial pipes at several temperatures. The intercept A has been adjusted to give the elongation in % when the time is expressed in hours. Note the large dependence of G on the operating temperature. The HDB values in table 1 were extrapolated by equation (1) to 50 years (438 000 hours).

$\log \varepsilon = A - G \log t$	A	G	HDB (50 years)
Sanitation pipe @ 25 C	0.124	0.055	0.65%
Oil pipe @ 25º C	-0.096	0.030	0.54%
Oil pipe @ 65º C	-0.032	0.073	0.36%
Oil pipe @ 82 C	0.087	0.102	0.32%

Table 1
Temperature dependence of the weep parameters and 50 years HDB for typical oil and sanitation pipes.

So far we have discussed the old ideas behind the classical weep regression lines and the HDB. The next section will introduce a new approach to this subject.

The new approach – We start this section with arguments that indicate the inadequacy of the classical approach to measure the HDB. Specifically, this section will show that the ASTM D 2992 protocol is good only to predict short-term (3 to 5 years) weep failures. Let us see the reason for that.

The high strains required by the ASTM D 2992 test protocol create many interphase cracks. Large strains produce large cracks, but the size of the cracks remains the same as long as the strain is not changed. The number of cracks also increases with the strain level. Higher strains activate smaller cracks (see any book on fracture mechanics) and increase the crack density. The combination of high crack density with large cracks explains the shorter times to weep at higher strains. Lower strains produce less and smaller cracks that increases the travel time. If the strain is low enough, below a certain threshold, the cracks may be too small and the crack density too low to coalesce and form the pathway for the passage of water. Under these conditions the pipe will not weep. Every resin has a limiting strain which marks the onset of coalescence. We refer to this onset strain as the threshold strain. The threshold strain is indicated by a loss of proportionality in the stress-strain diagram, by the emission of acoustic signals, and by a whitening of the laminate.

The threshold strain separates weep from no-weep. The regression line developed by the traditional ASTM D 2992 test method is good to predict the weep time (actually travel time) above the threshold strain. Below the threshold strain, the regression line is not applicable and the pipes run out indefinitely without weeping. The existence of a threshold strain is obvious and has been suggested without proof by many authors. The lack of proof can be justified by the short duration of the ASTM D 2992 test protocol, which stops at 10 000 hours, just short of capturing the threshold strain. Had the ASTM D 2992 test been extended a little longer, say to 30 000 hours instead of 10 000 hours, the threshold would have become apparent.

Many authors have suggested that the weep regression line should turn horizontal in the long-term, but no test results have been offered to support that claim. The first author to reject the ASTM protocol was Frank Pickering (reference 6, 1983) who proposed that it be replaced by a parameter that he referred to as PEL, or Proportional Elastic Limit, determined by the strain at which the pipe “stress-strain” response ceases to be linear. That is the same idea advocated in the present paper, except that we propose the threshold strain be measured on plies, not on pipes. The threshold strain is a ply property, not a laminate property. We have more to say about this in the following paragraph. For now, it suffices to say that the data generated by short-term tests are questionable to predict long term weep.

The threshold strain can be measured by the loss of linearity in pressure-strain diagrams, by light transmission or by acoustic emission. One problem with these procedures is the difficulty to separate the response coming from different plies. Also shear cracks should be avoided in the test protocol, since shear cracks cause loss of linearity, loss of translucency and acoustic signals without opening the cracks to cause weep.

As explained earlier, we are interested in the response of the ply that serves as substrate for the liner. To make sure the measured signals come from this critical ply, the test specimens should be made exclusively with that type of ply. And the test protocol should be designed to eliminate the shear strains. The test specimens made exclusively with the critical ply eliminates the spurious response from other plies. This argument holds for both sanitation and oil pipes. For example, the threshold strain for sanitation pipes should be measured on pipes made exclusively of chopped glass. And that of oil pipes measured on specimens made exclusively of UD plies wound with angles 90 degrees or 0 degrees to eliminate the shear strains.

Figure 4 shows the threshold strain superimposed on the classical weep line of sanitation pipes. The first thing to notice is that the classical ASTM line holds for strains above the threshold line. This is in line with what we have said earlier, that the classical line is valid to make short-term predictions. However, figure 4 also shows that for strains below the threshold value, the regression line flattens out and merges with the threshold strain. The classical ASTM line is obviously not valid to make long-term predictions.

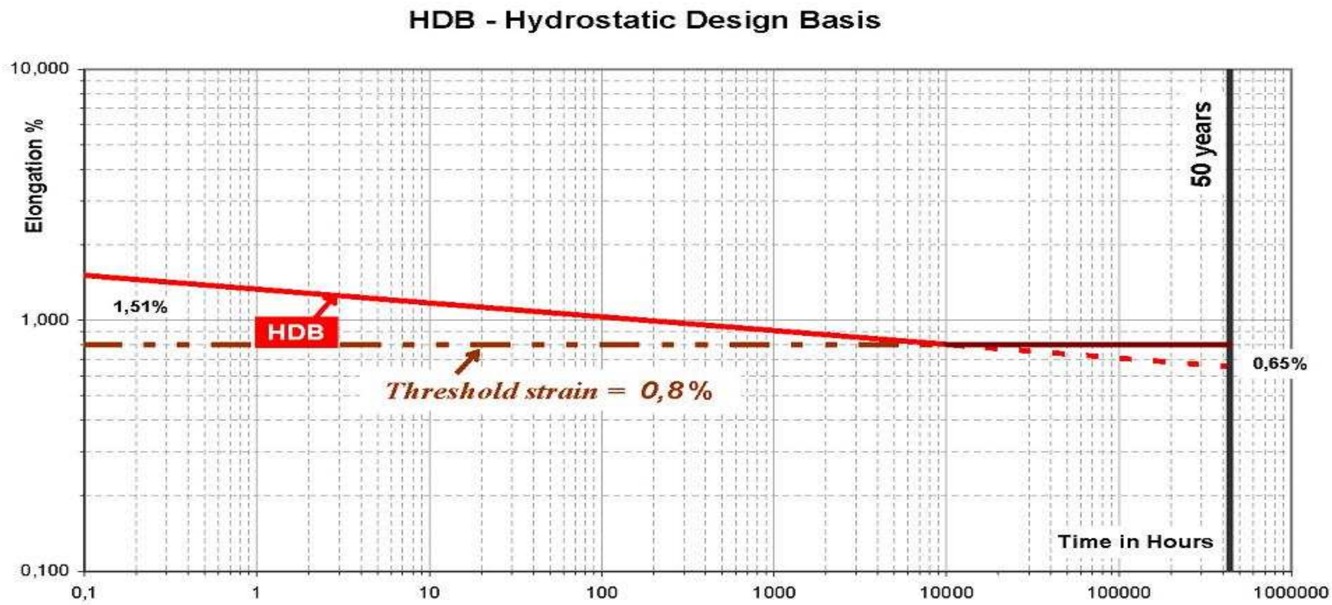

Figure 4

Weep regression line of sanitation pipes with the inclusion of the threshold line. The threshold strain is assumed at 0.8%, which is reasonable for a matrix resin with elongation of 3.0%.

The point of transition, where the classical line merges with the threshold strain, is controlled by the resin-glass interphase. Both the short-term regression line and the long-term threshold strain are dominated by the interphase.

Suggested values for the threshold strain – The threshold strain depends on the toughness of the resin-glass interphase and has not been measured yet. The few reports available on this topic were written not to measure the threshold strain, but to explain the cracking of gelcoats backed by chopped glass laminas. Such reports are of limited value to estimate the threshold strain, but are the only information available at this time.

Reference 1 reports threshold strains of 2.0% and 1.0% respectively for flat chopped glass laminates (not pipes) made of vinyl ester and polyester resins. These results, however, are not reliable as they were obtained by testing gelcoated specimens submitted to three point bending. Better results would have been obtained by testing non-gelcoated laminates in tension. Table 2 shows the threshold strains measured by acoustic emission as reported by Norwood and Millman (ref 3) on two sets of flat laminates (not pipes) made of chopped glass and woven roving.

Elongation at break of the resin	Threshold strain measured by acoustic emission on isolated lamina	
	Chopped glass lamina	Woven roving lamina
2.5%	0.4%	0.3%
3.8%	0.8%	0.6%

Table 2
Threshold strains reported by Norwood and Millman from tensile tests performed on isolated plies of chopped glass and woven roving.

We recall that the weep barrier of sanitation pipes is made of chopped glass saturated with polyester resins having a minimum elongation of 3.0%. From table 2 such pipes would have a threshold strain in the neighborhood of 0.8%. We suggest the value 0.8% as the threshold strain for sanitation pipes made of polyester resins with 3.0% elongation. Work done at the University of Liverpool (ref. 11) indicates a threshold strain of 0,4% for ± 55 degrees oil pipes.

The temperature paradox – The influence of the temperature on the weep line has never been systematically studied. Data developed by a leading oil pipe manufacturer indicate a strong increase of the slope G with temperature, as shown in table 1. Similar results are expected for sanitation pipes, but there is no study available to quantify that. The steeper slopes indicate that the cracks in the interphase are larger at higher temperatures. This is valid for the short-term. The influence, if any, of the temperature on the threshold strain is yet to be determined.

Higher temperatures increase the size of the cracks and therefore increase the slope of the weep line. However, there is no overriding reason why higher temperature should lower the threshold strain. It is more likely (but still unproven) that the plasticization of the resin at high temperature would increase, not decrease, the threshold strain. Figure 5 shows how the weep lines of oil pipes would look like at 25 C and 65 C under the assumption that the threshold strain is unaffected by the temperature. The figure indicates that the temperature is an important design factor for the short-term, which is dominated by the classical weep line. For the long-term, however, the temperature appears to be irrelevant. This is an unexpected conclusion that, if true, would have an enormous impact on the composites pipe industry.

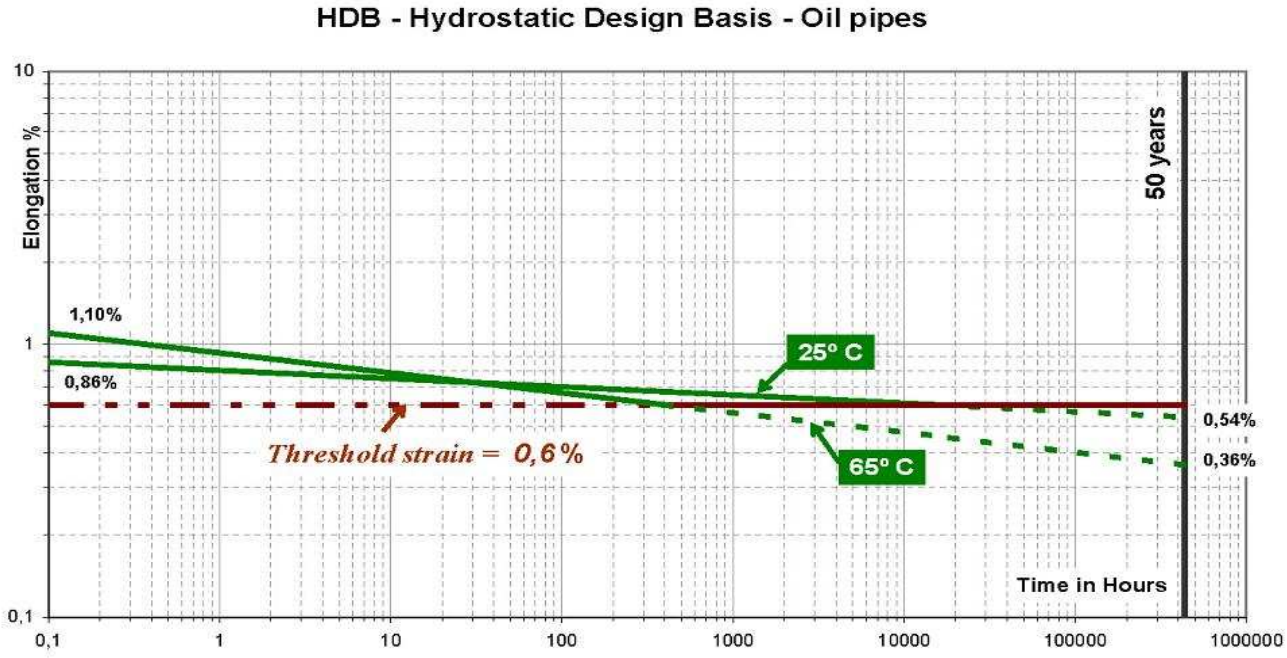

Figure 5
The gradient of the regression lines increases with the temperature. However, the threshold strain may not change, or may increase with the temperature. As a result the pipes would perform better at higher temperatures. This paradox may have a significant impact on composite oil pipes

Cyclic loading – Cyclic loads grow cracks, while static ones do not. From this we conclude that there is no threshold strain for cyclic loads. Given enough time (or better, enough cycles) the cyclic loads will grow cracks that will always weep the pipe no matter how small the cyclic strain. The number of cycles to weep is given by an equation similar to the static regression equation (1).

$$\log \Delta\varepsilon = A - G \log N \qquad (1A)$$

Equation (1A) is cycle, not time, dependent. It gives the number of cycles that would weep the pipe under cyclic loads. Equation (1A) is valid for pipes with cracks that have already coalesced and formed the required pathway. The cracks developed by low cyclic strains are too small, and may require many cycles before they grow to coalesce and allow the application of equation (1A).

The total time to weep is estimated by adding two distinct times

$$\begin{bmatrix} total & time \\ to & weep \end{bmatrix} = \begin{bmatrix} crack & time \end{bmatrix} + \begin{bmatrix} travel & time \end{bmatrix} \qquad (2)$$

Where “crack time” is the number of cycles (expressed in time) to grow the cracks to the point where they reach the threshold value of the critical ply. The critical ply is the ply that controls the weeping process. For oil pipes it is the ± 55 UD ply. For sanitation pipes it is the weep barrier of chopped glass. Once the critical ply is cracked, the weeping process starts and the “travel time” is computed from equation (1A). The problem that we now have is how to calculate the crack time, a topic which is beyond the scope of this paper. The interested reader may find details in the unified equation (ref. 10).

Equation (2) indicates that the time to weep is determined in two steps. The first is the time to cyclic crack the critical ply. And the second is the time for the fluid to travel through the cracked wall. We repeat that the concept of threshold strain is valid only for static loading. There is no threshold strain for cyclic loading.

Rupture versus weep – The preceding discussions have shown that the weep failure is controlled by the interphase and has nothing to do with the composition of the glass fibers. The glass fibers control the rupture/burst failure, not the weep failure. This section will compare the weep line of sanitation pipes with the rupture lines of UD plies made of E glass and of boron-free glass. To facilitate the mathematics the analysis is performed on “hoop-chop” sanitation pipes, that is, pipes with the UD plies in the hoop direction. This simplification is not necessary and will not cause loss of generality. The UD plies of hoop-chop pipes are placed in the hoop direction and do not require rotation of the global strains.

In figure 6, if the strain is below the threshold value, the pipes never weep. However, from figure 6 we see that under low strains both pipes will burst, even if they do not weep. Under high strains – above the threshold value – the pipes may weep before they burst. Figure 6 also shows the dramatic impact of the glass composition on the long-term rupture strains. The boron-free glass extrapolates to a rupture strain of 0.92% at 50 years, versus 0.41% for the standard E glass. The weep line is controlled by the interphase and is the same for both types of glasses.

The reader is advised that the graphs in figure 6 are applicable to hoop-chop pipes used in sanitation. They do not apply to oil pipes or to sanitation pipes other than hoop-chop. If the applied strain is too high and the test time is too short, as in ASTM D 1599, the pipe may burst (rupture) before the water has time to weep.

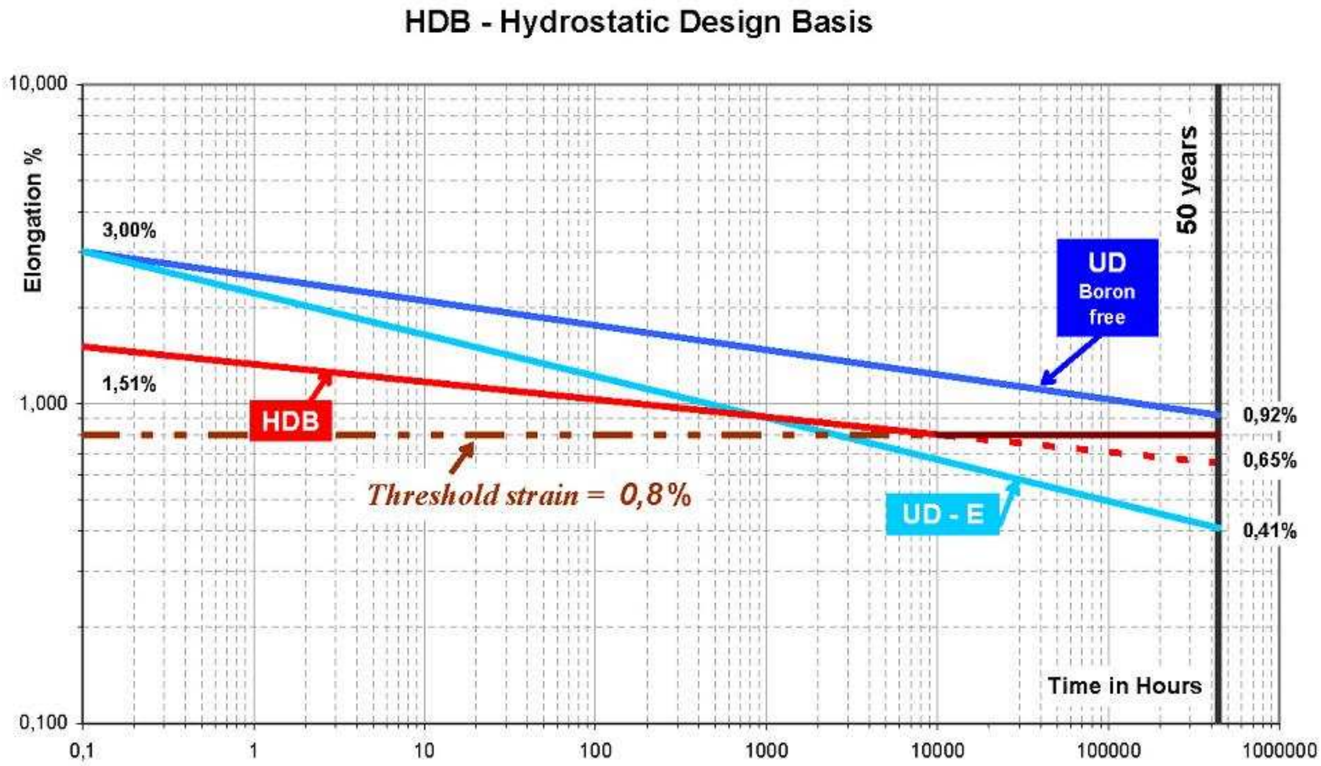

Figure 6
Weep and rupture lines for "hoop-chop" sanitation pipes. Rupture data from Mark Greenwood. Weep data from Amiantit. The threshold line is my suggestion.

Conclusions – There are two approaches to account for the weep failure of composite pipes. These approaches agree on the short-term and conflict on the long-term.

The classical approach proposes that the few small cracks that develop under low static strains coalesce to form pathways for the passage of water. The regression lines derived by this approach have no technical support and are not valid.

The new approach, introduced in this paper, proposes that all pipes have a threshold strain below which weeping never occurs.

A conclusive experiment to discriminate between these two proposals would require tests performed on water filled pressurized pipes at low strains over long times. Such tests have never been performed. The best approximation to these long-term pressure tests was published early in 2009, by Hogni Johnson, who reported the results of 30 years of tests on deflected pipes under strain-corrosion. See reference 4. Figure 7 shows the flattened strain-corrosion line published by Hogni in exactly the same fashion as proposed in this paper. This is the best evidence available at this time to prove the reality of the threshold strain concept.

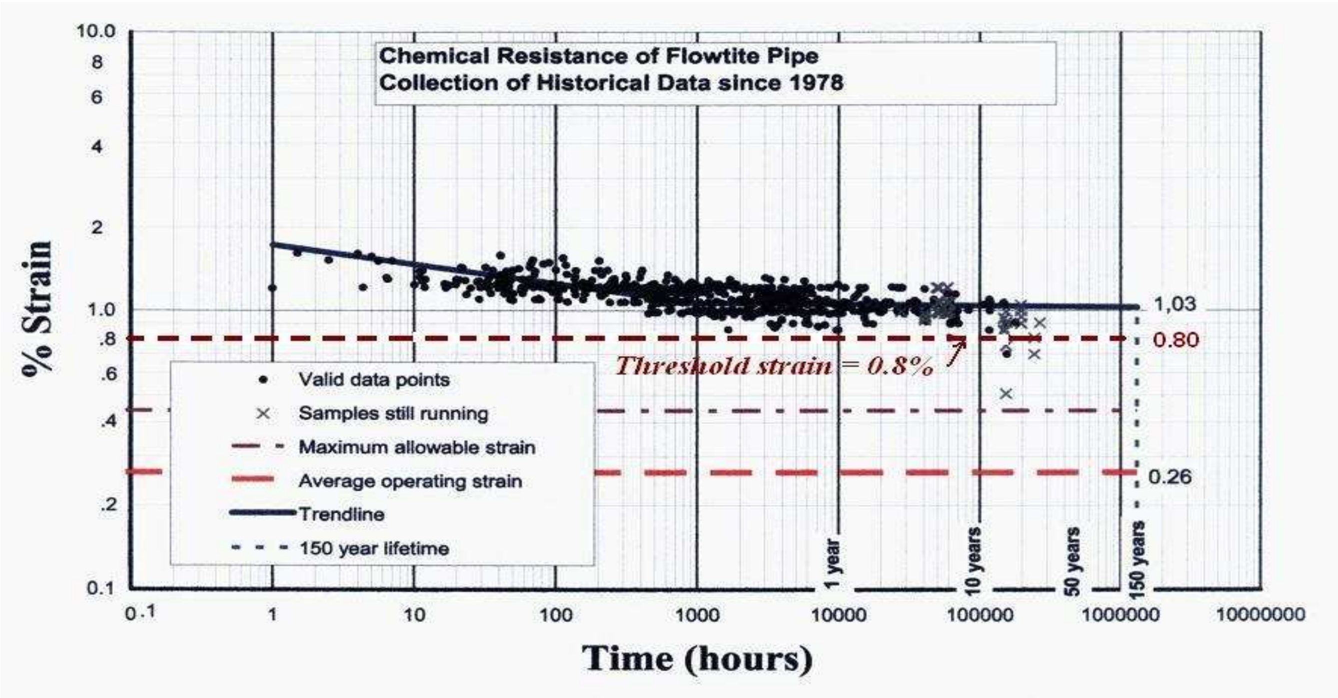

Figure 7
The long-term strain-corrosion tests of composite pipes in acidic media shows a flattened regression line. The threshold strain of 0.8% has been superimposed on the graph. (Courtesy Amiantit)

It may be argued that strain-corrosion tests performed on deflected pipes are not valid to vindicate a hypothesis for weep failure of pressurized pipes. A rebuttal of this argument will be presented in connection with the discussion of strain corrosion rupture, in the third paper of this trilogy. The third paper will show that the phenomenon of strain corrosion rupture is a special case of the weep failure that we have just discussed. Therefore, the Hogni's results in figure 7 are valid as proof of weep failure.

Biography: Antonio Carvalho is an engineer with 40 years dedicated to composites. Past experience includes 30 years with Owens Corning and 9 years as a full time consultant for Reichhold. His current responsibility includes technical support and market development for Reichhold`s DION resins in Brazil and Latin America. For direct communication please contact Antonio.carvalho@reichhold.com

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Appendix A – Further comments on the weep lines

This appendix explains the differences between the weep regression lines of oil and sanitation pipes. From figure 2 the points requiring explanation are: (a) the different slopes between the two lines and (b) the position of the sanitation pipe line above that for oil pipes.

We begin with the relative position of the lines. The random chopped fibers in the weep barrier of sanitation pipes prevent the formation of large and long cracks. The weep barrier of sanitation pipes requires a large number of small cracks to form the pathways for the passage of water. And a large number of cracks require high strains. In contrast, the UD laminas in oil pipes require lower strains to develop long cracks along the fibers. The strain level required to weep ± 55 degrees UD plies is less than that required to weep plies of chopped fibers. That explains why the weep line of sanitation pipes plots above that of ± 55 degrees oil pipes. The regression line of oil pipes could be substantially improved by introducing a thin ply of chopped glass under the first UD lamina.

Next we address the difference in slopes. We begin by recalling that cracks do not grow under static loads and the time to weep is in fact the travel time for the water to traverse the stationary pathways in the cracked pipe. For the same hoop strain, the travel time for the water is longer in UD plies. This is explained in figure A1. The points where the water can pass from an inner UD ply to the next outer ply are those at the intersection, or crossing, of the cracks. The water must travel long distances, meaning long travel times, to reach the crossing points and change plies. By contrast, the pathways in the chopped glass plies are direct and shorter. The long pathway and long travel time in oil pipes stretch out the regression line and explain its flat slope.

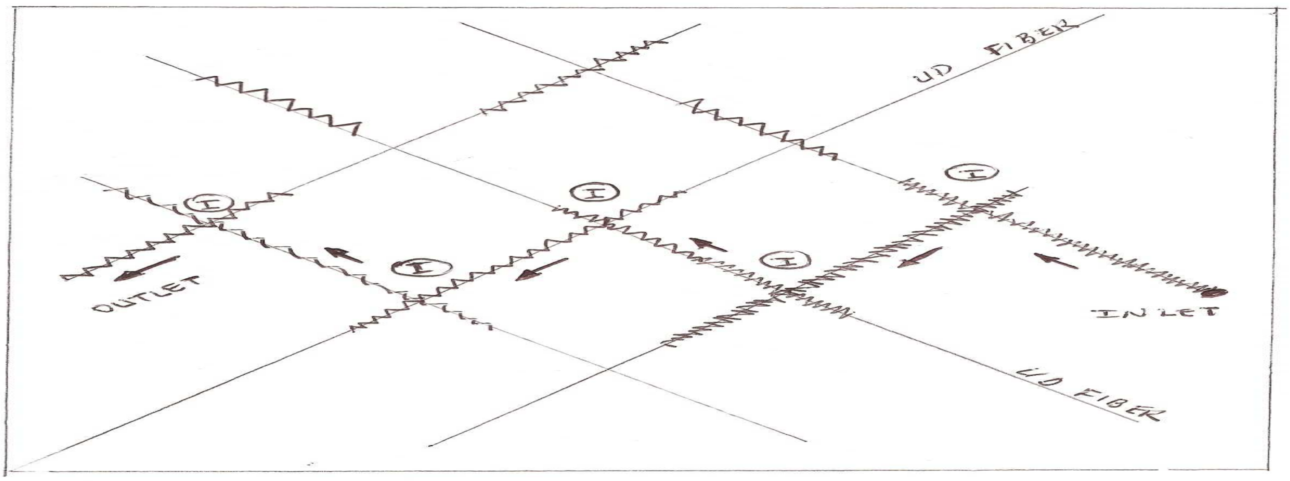

Figure A1

The crack pattern of UD plies explains the flat weep lines of oil pipes. The pathway followed by the water is shown by the arrows. The water moves to the next ply at the intersection points "I". The flat slope is explained by this long, tortuous pathway.

Appendix B. The interphase

The UD plies of oil pipes have a large number of closely spaced individual fibers. By contrast, the chopped strand plies of the weep barrier in sanitation pipes have a large collection of widely spaced strands. The filaments in the chopped strands, however, are bundled in close proximity like those in the UD plies. The filaments within a strand in the weep barrier show strong interaction. But those outside the strands do not interact. This minor feature helps the understanding of the threshold strain.

When the resin matrix impregnates the fibers it dissolves the sizing and forms a new resin that we call "interphase resin". The interphase resin is a blend formed by the glass sizing and the resin matrix. This blend is a distinct resin with properties that differ from those of the original resin matrix. The interphase resin fills the space within the glass strands and we can say that, as far as the glass filaments are concerned, they are in fact surrounded by the interphase resin, not by the resin matrix. All phenomena involving the immediate glass-resin vicinity, such as fiber blooming, debonding, etc, are controlled by the interphase resin, not by the matrix resin.

The filaments in the UD plies are located in very close proximity, like those in the strands of the weep barrier. In fact, the glass manufactures refer to the type of reinforcement they sell to make UD plies as a "single strand" roving. The threshold strain and the weeping behavior of oil pipes are controlled by the interphase resin.

The idea of an interphase layer surrounding the glass fibers (filaments) is not new (ref 9). In spite of its obvious merit to explain the behavior of UD plies, however, this idea has never been pursued by researchers. The interphase resin has never been characterized. It is hoped that the concept of threshold strain introduced in this paper, and its dependence on the interphase, would revive the interest in this topic. The glass fiber manufacturers should benefit greatly from this concept.

Appendix C – Is there a weep threshold strain?

This appendix addresses an interesting objection regarding the validity of the weep threshold strain. The argument against the existence of such threshold strain can be divided in four parts:

1 – All plies have a large number of pre-existing "flaws" that serve as starting points for cracks.
True.

2 – Under increasing tensile strains these pre-existing cracks grow and eventually weep the pipe.
Not true. According to fracture mechanics, only those few cracks above a certain critical length would grow, and their growth is arrested by the glass fibers.

3 – The pre-existing flaws will therefore weep the pipe regardless of the applied strain.
Not true. The applied strain must be high enough to activate the large number of cracks that is required to coalesce and form the pathway for the water.

4 – Therefore, there is no threshold strain.
Not true. There must be a threshold strain below which the arrested cracks are too few and too small to coalesce.

Homogeneous materials, like metals or neat polymeric matrices, do not arrest crack growth and do not have threshold strains. This situation does not occur in composites, because the fibers would arrest the crack growth. Composites weep not because they develop large cracks, but because a large number of small cracks coalesce to allow the passage of water. For this coalescence to take place, the number of small cracks must be very large, far larger than those from pre-existing “flaws”.

To develop the required large number of cracks, the pipe must be placed under high tensile strains. That is the justification for the existence of a threshold for static strain. Cyclic strains are different since, unlike tensile strains, they cause cracks to grow.