Validation of the Traditional USDA Forest Products Laboratory Tie Life Curve Using Recent Data from US Class 1 Railroads

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The Railway Tie Association (RTA)

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1. Introduction

This report presents the results of a RTA sponsored project to utilize current tie condition data to validate and/or calibrate the traditional USDA Forest Products Laboratory Tie Life Curve, originally developed in the 1950's [1]. The Forest Products Laboratory Tie Life Curve provides railway engineers with a statistical distribution of cross-tie failures, with respect to the average life of a tie. This curve is shown in Figure 1 below.

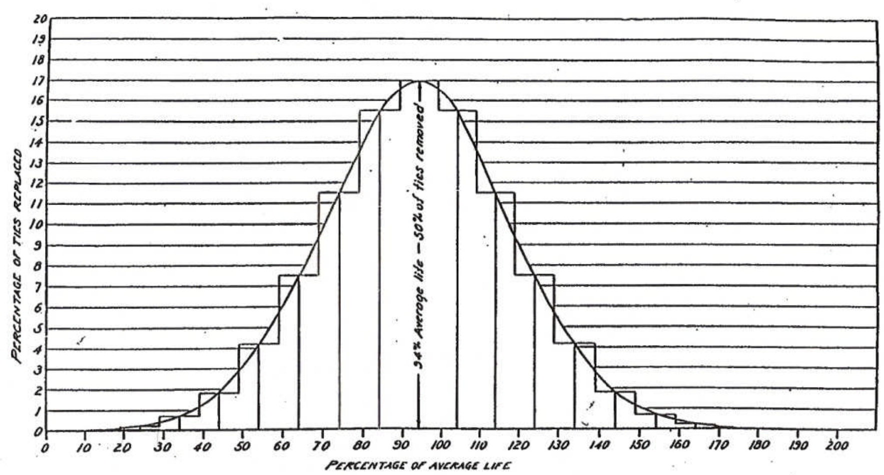

Figure 1: Frequency curve showing successive percentage tie replacements for 10% intervals of average life. Symmetrical form – Origin taken at 94%.

It can be seen from this curve that, according to historical research, the distribution of tie failures around the average life, which is a function of climate, traffic, track, and operating conditions, is in the form of a skewed "normal" distribution. As such, approximately 50% of the ties in newly constructed track will have been replaced by the time the track has reached 94% "average life" with the remaining 50% replaced at lives greater than 94% of average life. Thus, wood cross-tie failure occurs over time with a significant number of ties failing earlier than average and likewise a significant number of ties having a life greater than average for the given track conditions. This behavior has been well established and validated (and revalidated a number of times) [1].

The focus of this activity was to use a broad population of recent in-track tie condition data to see if this behavior still holds today. The data that was utilized was tie condition data, as collected by the *TieInspect* condition monitoring and recording system for a Class 1 railroad. The data consisted of tie conditions divided into four classes: Good, Marginal, Bad, and Failed, the condition of which is recorded for every tie in the inspected mile. Over 2,500 miles of data was utilized in this analysis. In addition to the *TieInspect* data, data from the railroad regarding traffic and track conditions, as well as current tie lives was utilized.

This data was analyzed to emulate tie failure with respect to that of the Forest Products Curve (Figure 1). With the aggregate tie data being in the early stages of failure, it was necessary to project forward to develop a revised Forest Products Curve.

2. Data Utilized

***TieInspect* Data**

Tie condition data as recorded by the *TieInspect* system was collected for the analysis from a Class 1 railroad. The *TieInspect* data contains individual tie condition data as rated by the tie inspector for four conditions: Good, Marginal, Bad, and Failed (as well as identifying bad joint ties). Additional *TieInspect* information includes, tie material, tie type, and curvature. The tie inspector walks the track and keys in the tie condition based on his visual inspection. The matrix of tie conditions is defined in Figure 2 below [2]:

Terms

Break – Damage from load or impact cross wise to the grain of the wood
Split – Damage from load or impact parallel with the grain of the wood
Deteriorated – Crushed or breakdown in grain structure
Plate Cut – Damage from load and plate movement on tie
Wheel Cut – Any cut like damage from equipment moving across the grain of the wood
Rot or Hollow – Void in tie area may be due to weather or insects

1-4 Rating System

	TIE CLASS			
CONDITION	**1 FRA Defective BLACK**	**2 BNSF Defective RED**	**3 Moderate YELLOW**	**4 Good GREEN**
Broken	Broken through - separated	Broken through – Not separated	Not broken through	No Breaks
Split or Otherwise Impaired	To the extent the crossties will allow ballast to work through, or will not hold spikes or rail fasteners	Will not hold spikes or rail fasteners. *Loose spikes in curves greater than 2 degrees.*	Tie holds spikes, some splits deep enough to allow water into tie. *Tie can be plugged and respiked if in tangent or curves 2 degrees and less.*	Slight weather splits but integrity not compromised
Deteriorated	So that the tie plate or base of rail can move laterally more than ½ inch relative to the crosstie	So that the tie plate or base of rail can move laterally more than ¼ inch but less than ½ inch relative to the crosstie	Less than ¼ inch of lateral plate or rail movement	No plate movement or cut and no sign of deterioration
Plate Cut	More than 40% of the ties' thickness	More than 1 inch but less than 40% of the ties' thickness	Greater than ¼ inch, up to 1 inch in depth	¼ inch plate cut or less.
Wheel Cut		More than 2 inches deep within 12 inches of the base of the load-bearing area, not broken through the tie.	½ inch to 2 inches deep not broken through the tie	½ inch or less with no structural damage to tie
Rotted or Hollow		Substantial amount of wood decayed or missing. Hollow under plate area.	Some rot over tie and on ends. Not hollow under plate area.	None
Expected Remaining Life			Less than 20 years	20 years or greater

Figure 2: BNSF Tie Condition Rating System [2]

While there were almost 39,000 miles of track inspected in the past six years, the data was reduced to approximately 11,000 miles of track that had at least two inspections more than one year apart. This data was then further filtered to remove any miles of track that had obvious tie work performed (e.g. Good ties increased significantly), and to eliminate sidings and any outlier data. This resulted in over 2,500 miles of track with tie condition data to be utilized for analysis purposes.

As an initial step, some statistical analyses were performed on the data. For the 2,500 miles of usable data, tie counts and percentages (by condition) were analyzed for each of the two inspections. The results are presented in Table 1 below. Note the increase in Bad and Failed ties with an increase in time (and traffic) from Inspection 1 to Inspection 2. This is expected as only miles that have not had significant tie work were chosen for analysis.

Table 1: Summary of Ties Used in Analyses

	Inspection 1		**Inspection 2**[1]	
Good	3,383,326	42%	2,513,520	31%
Marginal	2,907,784	36%	2,881,502	36%
Bad	1,693,076	21%	2,495,017	31%
Failed	86,697	1%	174,159	2%
Total	8,070,883		8,064,198	

In addition, it should be noted that the average expected life for the ties in a mile of track ranged from 14 to 68 years, with an average of 42 years. Note that tie lives were determined based on established tie life equations, which take into account the effects of tonnage, curvature, and climate, and were calibrated to match and satisfy the experiences of the Class 1 railroad.

In this analysis, it is the Bad and Failed ties that are taken as replacement ties when developing the revised Forest Products Curve. For Inspection 1, this shows that 22% are considered replacement ties, while for Inspection 2 that figure rises to 33%. Note, however, that of those replacement ties, the failed ties comprise only 5% and 6.5%, respectively for Inspections 1 and 2.

[1] Note that the tie totals are not exact as tie counts for each mile are not always equal

3. Results of Data Analysis

The 2,500 miles of data was analyzed utilizing the tie condition counts for Good, Marginal, Bad, and Failed ties. This data was evaluated using several engineering and statistical techniques. For the purposes of this report, the most successful technique will be discussed.

Considering the traditional Forest Products Curve, the primary data required is the number of ties that have been replaced and the age at replacement (which is used to calculate percentage of average life). The available data includes the individual tie condition counts for each mile, as well as an expected average life for ties in that mile. These miles had a range of ties in the Bad and Failed categories, and were in a varying stage of the average tie life. However the absolute installation date was not known, and so the actual tie age cannot be determined. As a proxy, the average age of the ties in track was taken as follows:

$$PctAvgLife = 1 - \frac{GoodTies}{TotalTies}$$

In addition, the number of ties to be replaced was determined as follows:

$$PctTies\,\mathrm{Re}\,placed = \frac{BadTies + FailedTies}{TotalTies}$$

These equations were applied to the total 2,500 miles to provide a distribution of the quantity of ties replaced versus the percent of average life at the time of inspection. This was performed for the tie counts for the two consecutive inspections, resulting in 5,000 points of data as shown in Figure 3 below.

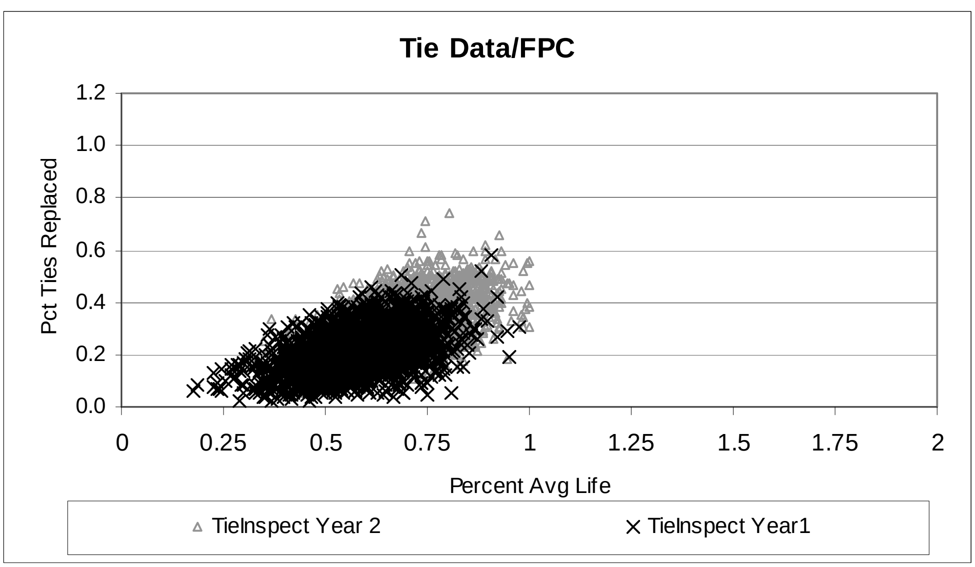

Figure 3: TieInspect Failure Data

It can be seen from this figure that the distribution of replaced ties is scattered between 10% and 50%+, for a range of percentage of average tie lives of 20% to 90%. It is interesting to note that the data for the same miles shifts up (more ties failed) and to the left (further into the average life) for the second inspection, as is expected.

Considering that this is a cumulative distribution of replaced (failed) ties, the corresponding cumulative failure distribution for the original Forest Products Curve is overlaid in Figure 4 below.

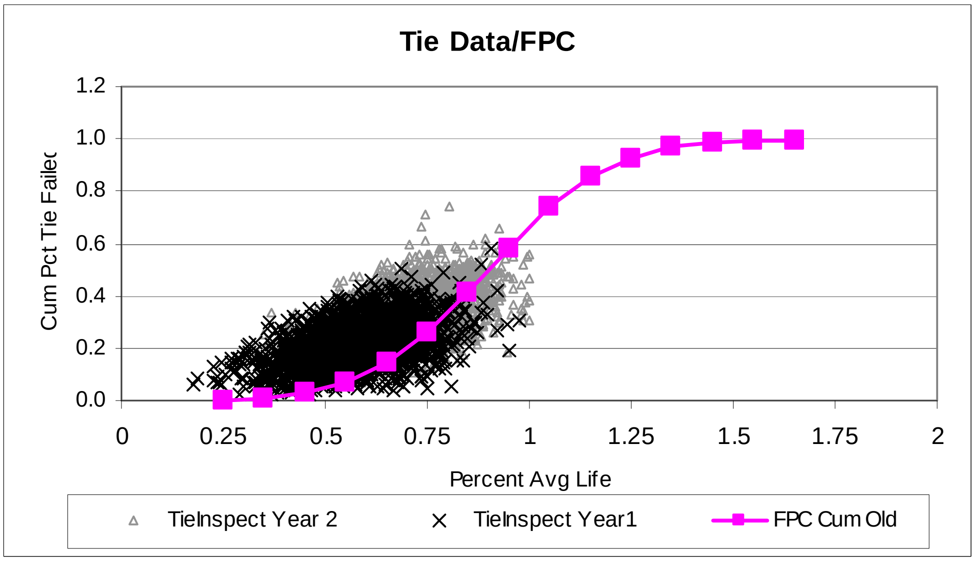

Figure 4: Cumulative failure data vs. Forest Product Curve

This figure shows that the recently measured data lies up and to the left of the traditional Forest Products Curve. Utilizing this data, a revised curve was fit and is overlaid in Figure 5 below.

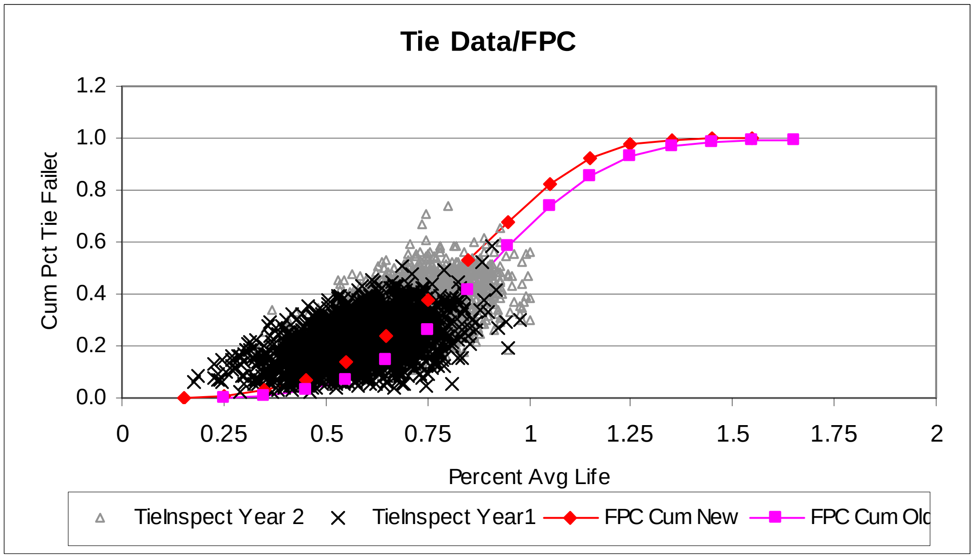

Figure 5: Comparative Cumulative Failure Data

This revised cumulative distribution is indicative of the failure behavior of ties under today's track and traffic conditions. In order to compare this to the traditional Forest Products Curve of Figure 1, the cumulative distribution was converted using 10% intervals (since that is what the Forest Product Curve uses) and the result is presented in the figure below.

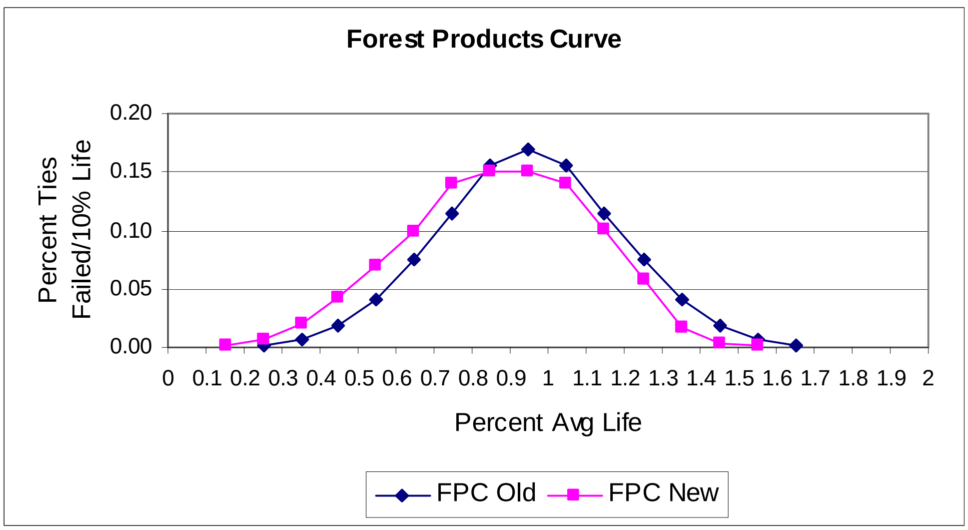

Figure 6: Comparison of Traditional Forest Product Curve to Curve Generated with New Data

It can be seen from this figure that the revised Forest Products Curve is shifted to the left, is slightly wider, and reaches a maximum at a lesser value than the traditional curve. Specifically, the ties are replaced around a distribution of the percentage of average tie life of 15% to 155% as opposed to 25% to 165%. In addition, 50% of the ties are replaced by the time the average tie life is 85%, as opposed to the 94% value from the traditional curve. Furthermore, the revised curve exhibits a maximum replaced value of 15% as opposed to the traditional maximum of 17%, for the 10% interval utilized.

While the changes are not drastic they are very interesting. The analysis shows that ties are replaced in a similar skewed normal distribution as previously determined; however, the replacement seems to occur at an earlier life interval, indicating that railways are replacing ties sooner and at a condition that may be slightly better than historical replacements. This is consistent with recent railroad practices of taking ties out earlier than traditional or FRA failure levels, as illustrated in Figure 2 which shows Bad ties, which are defined as needing replacement, are not as severely degraded as FRA bad ties.

In view of the recent trend towards heavier axle loads and corresponding heavier lateral loads, the shift of the curve to the left appears to be consistent with railroad industry recognition that ties must be in better condition and should not be left in track past the point where they can carry these higher vertical and lateral loads. It is also consistent with the increased rate of tie degradation associated with these heavier loads. Thus, this shift of the curve to the left is consistent with tightened tie replacement standards to reduce risk of failure as well as increased levels of loading associated with heavier axle loads. This is also consistent with the historically increasing level of traffic density, as shown in Figure 7 below. This figure shows a dramatic increase in traffic levels over the past fifty years. Concurrent with this traffic increase has been an increase in axle loads increasing from 27 tons in the 1960s to the current 36 to axle load level. Both these trends contribute to the need to take ties out earlier to avoid the risk of failure under traffic and derailment.

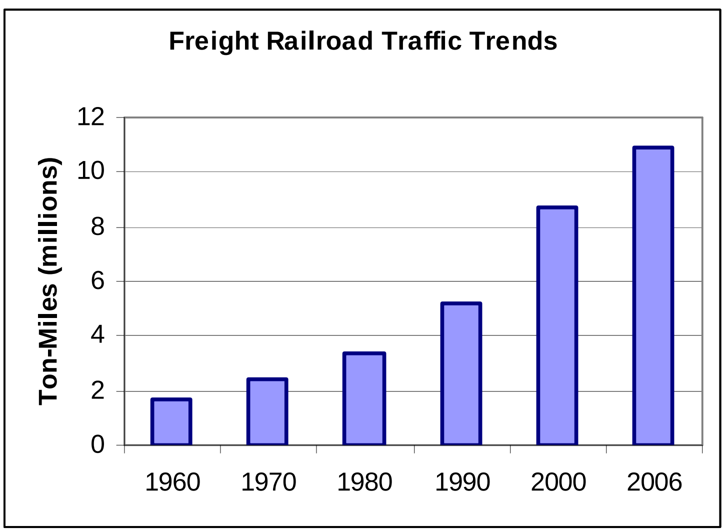

Figure 7. Freight Railroad Traffic Trends [3].

In addition, railroads are facing significant decreases in track access time for maintenance purposes. Thus, ties may be replaced earlier in the life cycle, while track access is available, in order to optimize maintenance time and cycles.

While the data appears to support the traditional Forest Products Curve, with a slight shift to the left, it is important to understand the utilization of this data [4]. For maintenance planning purposes, it is useful to understand that ties do not fail uniformly; rather they fail according to the distribution presented in Figure 6 above. In order to illustrate the usage of the Forest Product Curve an example is presented here.

Table 2: Forest Product Curve Distributions

Pct Avg Life	FPC Old Ties failed	FPC Old Cumulative ties failed	FPC New Ties failed	FPC New Cumulative ties failed
0.15			0.001	0.001
0.25	0.00	0.00	0.01	0.01
0.35	0.01	0.01	0.03	0.02
0.45	0.02	0.03	0.07	0.04
0.55	0.04	0.07	0.14	0.07
0.65	0.08	0.14	0.24	0.10
0.75	0.12	0.26	0.38	0.14
0.85	0.16	0.41	0.53	0.15
0.95	0.17	0.58	0.68	0.15
1.05	0.16	0.74	0.82	0.14
1.15	0.12	0.85	0.92	0.10
1.25	0.08	0.93	0.98	0.06
1.35	0.04	0.97	1.00	0.02
1.45	0.02	0.99	1.00	0.00
1.55	0.01	1.00	1.00	0.00
1.65	0.00	1.00		

Table 2 above provides the percentage of average life and percentage of ties failed, as well as cumulative percentage for both the traditional and revised Forest Products Curves. As an example, consider a mile of track with 3,250 ties and an average tie life of 32 years. Utilizing Table 2 above, the years that ties will fail, along with number of ties failed per year (as well as cumulative ties) can be determined by multiplying the first column by the average life and the remaining four columns by the number of ties per mile to give Table 3 below.

Table 3 can then be used to evaluate the expected number of tie failures in a given year or cumulative failures over time. Note the increase in ties in the early years and decrease in latter years for the revised Forest Products Curve. This again illustrates the earlier removal of ties under today's conditions of heavier axle loads and higher tonnage levels. In addition, tables of this type can be added together for varying installation dates, average lives, etc. to accommodate complete tie programs [3].

Table 3: Example Case

	FPC Old		FPC New		FPC New - FPC Old	
Years From Installation	Ties/Year	Cum Ties	Ties/Year	Cum Ties	Ties/Year	Cum Ties
5	0	0	3	3	3	3
8	3	3	23	26	20	23
11	23	26	65	91	42	65
14	62	88	137	228	75	140
18	133	221	228	455	94	234
21	244	465	325	780	81	315
24	374	839	455	1235	81	397
27	504	1342	488	1723	-16	380
30	553	1895	488	2210	-65	315
34	504	2399	455	2665	-49	267
37	374	2772	325	2990	-49	218
40	244	3016	189	3179	-55	163
43	133	3149	55	3234	-78	85
46	62	3211	13	3247	-49	36
50	29	3240	3	3250	-26	10
53	10	3250	0	3250	-10	0

4. **Summary and Conclusions**

The focus of this study was to validate and/or calibrate the USDA Forest Products Laboratory Tie Life Curve utilizing recent tie condition data from a Class 1 railway. The data utilized was the tie condition data (Good, Marginal, Bad, Failed) collected using the *TieInspect* system of collecting tie condition data.

Over 2,500 miles of tie condition data was utilized each containing two consecutive tie inspections (for over 5,000 data points). This data provided a statistically significant range of data points allowing for the calculation of percentage of average tie life and percentage of ties replaced. This data was then analyzed statistically to generate a revised Forest Products Curve.

The results of this analysis showed that the distribution of tie failures still follows a skewed normal distribution similar to the original Forest Products curve. However, the replacement seems to occur at an earlier life interval (i.e. the curve is shifted to the left). This suggests that railways are replacing ties sooner and at a condition that may be slightly better than historical replacements conditions. This is consistent with recent railroad practices of taking ties out earlier than traditional or FRA failure levels. In view of the recent trend towards heavier axle loads and corresponding heavier lateral loads, the shift of the curve to the left appears to be consistent with railroad industry recognition that ties must be in better condition and should not be left in track past the point where they can carry these higher vertical and lateral loads. It is also consistent with the increased rate of tie degradation associated with these heavier loads. Thus, this shift of the curve to the left is consistent with tightened ties replacement standards to reduce risk of failure as well as increased levels of loading associated with heavier axle loads

Thus, while the shape of the original Forest Products Curve is once again confirmed, it appears that the philosophy on tie replacements appears to have been "tightened" with ties coming out earlier, as manifested by the shift of the skewed normal distribution to the left. This shift results in 50% of tie replacements occurring at 85% of the average life, as opposed to the traditional 94% of average life (from the previous Forest Products Curve).

Finally, it should be noted that limitations of data utilized for this analysis resulted in only the first half of the curve being validated with actual data. An extrapolation was performed for the second half of the data, consistent with the traditional Forest Products Curve to generate the full curve. While this is a realistic assumption, it is not a full validation of the entire curve. In order to further validate (and calibrate) the Forest Products Curve, a controlled test would need to be performed, where by tie replacements are monitored over time knowing the exact installation date, and all tie life controlling factors.

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