SURFACE VEHICLE INFORMATION REPORT

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Cumulative Damage Analysis for Hydraulic Hose Assemblies

RATIONALE

The technical report covers technology, products, or processes which are mature and not likely to change in the foreseeable future.

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Foreword

WARNING—Hydraulic hose assemblies have a finite life and the exposure to surge pressures above the maximum working pressure will substantially reduce their service life. This analysis is intended to show the loss of hose working life due to elevated hydraulic pressures. Use of this SAE Information report is intended for those individuals that can produce a recorded history of pressure peaks and the frequency of the peaks. Under no circumstances should cumulative damage analysis be used unless recorded pressure history can be verified before implementing the design. Without proper documentation of the system pressure history, the application of any hose assembly above the rated working pressure is not recommended by hose manufacturers and will substantially decrease the working life of the hose. The user/installing company is accountable for the analysis and application of results.

1. Scope—This SAE Information Report is intended to provide the hydraulic system analyst with a procedure which will assist in the selection and use of high-pressure wire reinforced hydraulic hose assemblies. Many construction, agricultural, industrial, or commercial equipment systems utilize hydraulic hose assemblies that are subjected to irregular cyclic pressure variations (cannot be approximated by a constant amplitude pressure cycle). This document relates damage done by pressure cycles with the pressure-life performance curve for the hose assembly being evaluated, using a linear damage rule to predict fatigue life similar to that used for predicting metal fatigue life. More detailed information on the subject may be found in SAE Paper No. 880713. The accuracy of cumulative damage calculations is directly related to proper measurement of the service pressure history and pressure-life performance for the hose assembly being evaluated. Final selection of a hose assembly must also consider installation and maintenance as noted in SAE J1273.

1.1 Background—In the current SAE J517 for hydraulic hose, each style and size hose is assigned a maximum operating pressure rating to assure the user reasonable service life in a wide variety of applications. (See Appendix A for further explanation of nomenclature used in this document.) This rating is based on assessment of many factors, including repeated pressure cycling under controlled laboratory conditions at a pressure equal to or greater than the assigned maximum operating pressure. This standard test procedure, as detailed in SAE J343 minimizes variables so as to provide a baseline for performance capability. SAE J517 takes note that actual pressure cycling in a hydraulic system will seldom duplicate those test parameters precisely. It provides basic hose construction details; SAE J343 establishes standard test procedures—which may be utilized to develop data at pressures other than the established test value for any hose assembly. SAE J1273 provides a guide for selection, installation, and maintenance for hose and hose assemblies.

Many hydraulic systems will be subjected to variable amplitude pressure cycles, and in some of these the highest surge peaks will occur only a few times. Strict interpretation of SAE J517 indicates the use of hose assemblies with a maximum operating pressure equal to or greater than the highest peak—even if that peak should occur only once in the life of the system. If this were done, the hose would have more reinforcement, larger outside diameter, less flexibility, and higher cost than might be needed. It should not be necessary to use a hose that has over a million cycle capability at a pressure which is likely to occur only a few times in the application. What is needed, then, is a design verification procedure that assures adequate fatigue life for applications with variable amplitude pressure usage where the highest surge peaks are between 100 and 200% of rated pressure.

1.1.1 Cumulative damage of hydraulic hose is in many ways comparable to cumulative damage of metal components. The design verification of metal components is done in two ways depending on whether loading is of constant amplitude or variable amplitude:

a. Size the part cross section so the constant amplitude (maximum) load will not produce a stress at the highest stressed area in excess of the material "endurance limit stress." This is a stress that will not cause failure in a million cycles of loading.
b. Do a cumulative damage analysis on the variable amplitude load or strain history to predict fatigue life as is normally done to evaluate prototype machines in the ground vehicle industry.

1.1.2 In a similar manner, hydraulic hose design verification should be done in two ways:

a. Select a hose assembly so the constant amplitude (maximum) pressure during service is less than the SAE J517 rated pressure.
b. Do a cumulative damage analysis with the variable amplitude pressure history to determine if the fatigue life will meet the design life of the product. The block diagram in Figure 1 illustrates how both the pressure history and the P-N curve information are the essential inputs for this procedure.

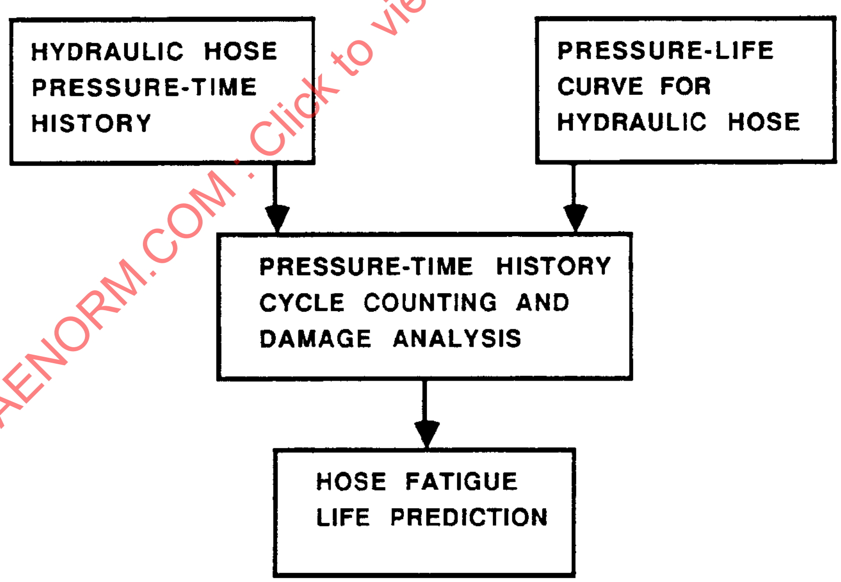

FIGURE 1—BLOCK DIAGRAM FOR HOSE FATIGUE ANALYSIS

For both metal parts and hydraulic hose assemblies, the first method is appropriate when the load (pressure) is known to be a large number of cyclic applications of nearly constant amplitude. However, if the load (pressure) involves infrequent cycling or includes only a few large peaks, then the first method may lead to designs that are heavy, bulky, inflexible, and more costly than need be. For variable amplitude loads or pressure applications, it is logical to do a cumulative damage analysis to judge the adequacy of the design.

Other factors, such as internal temperature, ambient temperature, and ozone exposure, for all intents and purposes, have not been considered in this cumulative damage analysis procedure. Long-term exposure to extreme limits or high levels of these elements could affect the overall hose assembly life.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest version of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J343—Tests and Procedures for SAE 100R Series Hydraulic Hose and Hose Assemblies
SAE J517—Hydraulic Hose
SAE J1273—Selection, Installation, and Maintenance of Hose and Hose Assemblies
SAE 880713—SAE Test Program on Cumulative Damage for Hydraulic Hose Assemblies

3. Use of P-N Curves in Design—A cumulative damage analysis is needed for a hydraulic system subjected to variable amplitude pressure cycles if system pressures in excess of rated pressure are to be in the design consideration. An approach for this analysis is to use the Reference P-N curve as defined in the previously mentioned reference paper and shown in Figure 2. Verification that the actual hose assemblies have a P-N curve in excess of the Reference P-N curve is essential. The equation for the Reference P-N curve in Figure 2 is:

$$P_a = P_b(N)^s \tag{Eq. 1}$$

where:

P_a = Zero-to-Max amplitude of pressure cycle
N = Cycles to failure at pressure amplitude P_a
P_b = Burst pressure (one cycle life)
s = Slope of curve on log-log plot

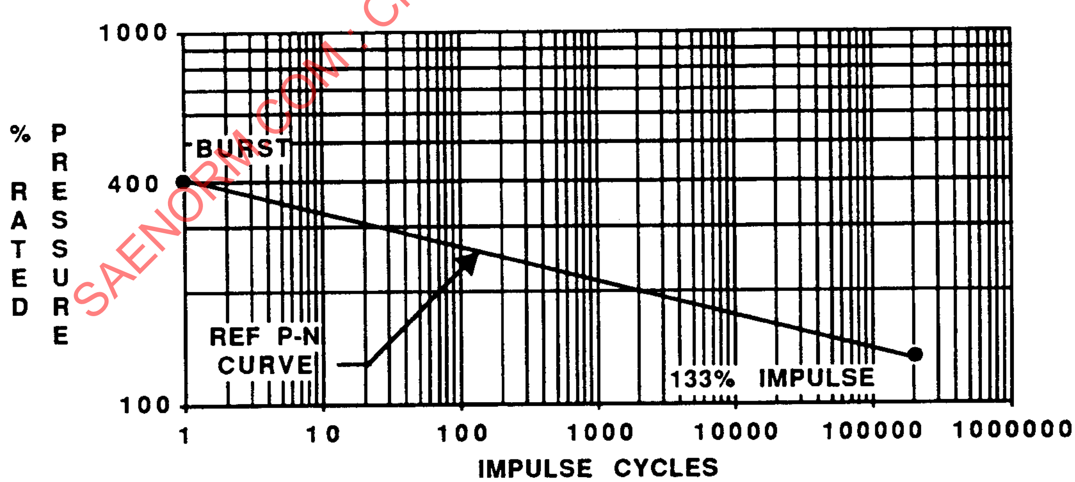

FIGURE 2—HYDRAULIC HOSE PRESSURE-LIFE PERFORMANCE CURVE (SECTION 3)

WARNING—This figure is here to show the concept of Equation 1. This should be used for conceptual purposes only. The user is responsible for the actual graph. The user's graph needs to be based on actual history of tested data.

By using two known points on this line:

- •1 cycle at 400% (Burst Point)
- •200 000 cycles at 133% (Impulse Point)

the values of P_b and s can be found:

$$P_b = 400 \text{ and } s = -0.0902 \tag{Eq. 2}$$

and

$$P_a = 400(N)^{-0.0902} \tag{Eq. 3}$$

Rearranged to a more useful form to solve for N cycles at any pressure P_a this becomes:

$$N = \left[\frac{400}{P_a}\right]^{11.086} \tag{Eq. 4}$$

If a different impulse point (for example 500 000 cycles at 133%) were used, this would result in a different slope for the P-N curve. The Hydraulic Design Analyst has the option of using other Reference P-N curves in the analysis as long as there are data to demonstrate the actual P-N curve is in excess of the Reference P-N curve. In addition, the analyst can increase statistical confidence by requiring a low percentage failure P-N curve (for example, a B_{10} Curve) for test data for the hose assembly being considered to be in excess of the Reference P-N curve used in the analysis. (This is explained in greater detail in SAE Paper No. 880713.)

In order to use this prediction procedure, a sample pressure history has to be available. The cycle counting procedure for a pressure history is explained in more detail in the next section. The fundamental theory for damage accumulation uses zero-to-max pressure cycles since the P-N curve is determined from zero-to-max test pressure cycles. This is slightly different than for stress-life or strain-life curves for metal where there are fully reversed loads (zero mean stress). It is appropriate to resolve pressure cycles to zero-to-max cycles (mean pressure equals one-half of the maximum) since any possible negative pressure must be very small compared to the “high pressures” generally used in wire reinforced hydraulic hose assemblies. The damage is accumulated in a linear manner as is done for metal fatigue (see Equation 5):

$$D = \sum_{i=1}^{j} \frac{n_i}{N_i} \tag{Eq. 5}$$

where:

D = Damage done ($D = 1$ assumes failure)
n_i = Number of cycles in the history at amplitude i
N_i = Number of cycles to cause failure at amplitude i
j = Number of different amplitudes in the history

This equation and the P-N curve illustrates that when subjected to repeated constant amplitude pressure cycles above a given level, a hose assembly will eventually fail. The higher this constant amplitude pressure, the shorter the life. If the pressure is large enough, then failure can occur in one cycle. This is a burst test and is represented by the one cycle pressure value at the left end of the P-N curve and is analogous to the ultimate strength of metal parts. Damage due to a variable amplitude pressure history (which has been resolved to zero-to-max cycles) is then simply the sum of the n_i/N_i for all the different amplitudes in the history. When this summation equals one, failure is predicted.

If a typical pressure history of a given length of time (t) (time factor is machine operation time, not calendar time) is analyzed, Equation 4 will give a decimal fraction for the damage done. Then the fatigue life prediction is as in Equation 5:

$$\text{Life}(L) = t(1/D) \qquad \text{(Eq. 6)}$$

For example, if D = 0.01, one one-hundredth of damage has been done in t units of time and the total expected life would be one hundred times t units of time for the total life.

The procedure will work with either constant or variable amplitude pressure histories. Figure 1 illustrates how the P-N curve and the pressure history are the two necessary inputs for the procedure. If the user of the procedure has test data to demonstrate that the actual P-N curve is in excess of the reference P-N curve, then life predictions will be conservative for the sample pressure history that is used in the analysis.

4. ***Pressure History Cycle Counting*****—**Typical hydraulic hose pressure histories are variable amplitude and are almost totally positive pressure. Depending on the hydraulic component that the hose may be connected to, it is sometimes possible to have a partial vacuum in a hose. In the worst possible case, this could never be more than one atmosphere, which is small compared to the maximum that "high pressure" hoses normally experience, but should be avoided in system design as the impact on useful life is far greater than a numerical relationship would suggest. For cycle counting, pressure cycle histories will be considered to be all positive pressures. As indicated in the previous section, the cycle counting procedure needs to be designed to resolve the pressure history into zero-to-maximum pressure cycles since this is the type of pressure cycle used to determine the P-N curves.

A cycle counting procedure is discussed in detail in SAE Paper No. 880713 and suggests the following three steps:

a. Tabulate the pressure peaks from the history and assume each is followed by a minimum pressure value of zero.
b. A pressure peak is defined as a maximum value that is preceded and followed by pressure minimums of a specified lower magnitude (threshold). A pressure maximum that does not meet this requirement is not counted.
c. Threshold must be selected based on engineering judgment of the analyst.

As a result of the previous steps, all cycles that are counted will be zero-to-max cycles and can be used directly in the damage Equation 5. The threshold value needs to be at least 35 to 50% of the hose rated pressure to avoid counting cycles that are small pressure undulations and not pressure cycles that cause significant fatigue damage. Engineering judgment must be used to select the threshold to make an appropriate cycle count. This cycle counting procedure assumes the pressure minimums following significant maximums are zero. This was done to keep the procedure simple, practical, and conservative but not ultraconservative when only a few large pressure cycles are in the history. If, however, the service history does have a large number of cycles at the largest value, this evaluation procedure will still give the appropriate cycle count and life prediction. It will work with constant amplitude histories just as well as with variable amplitude histories.

An important part of the cycle counting is the ability to determine when a maximum should be kept as a peak. Figure 3 shows the four possible cases that can occur. Only case one is considered a valid peak and kept for the cycle counting. From Figure 3:

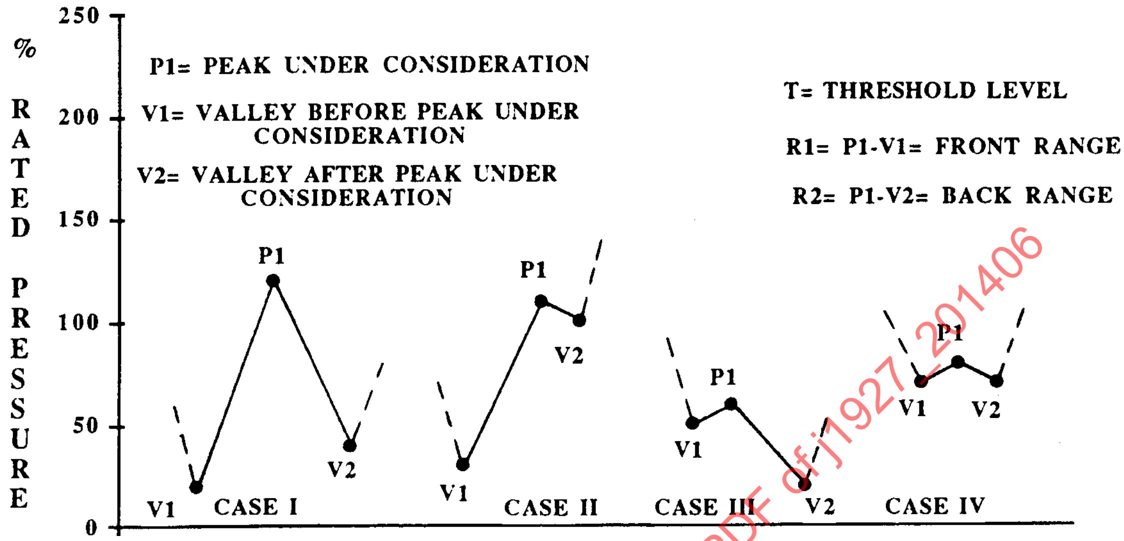

FIGURE 3—PEAK-VALLEY COMBINATIONS (SECTION 4)

a. Case I
   R1 > T and R2 > T

   Count P_1

b. Case II
   R1 > T and R2 $\leq$ T

   Discard P1 and V2
   Keep V1 as Valley
   Consider next Peak and Valley

c. Case III
   R1 $\leq$ T and R2 > T

   Discard P1 and V1
   Keep V2 as Valley
   Consider next Peak and Valley

d. Case IV
   R1 $\leq$ T and R2 $\leq$ T

   Discard P1 and highest Valley
   Keep lower Valley
   Consider next Peak and Valley

5. Summary of Procedure to Predict Hose Assembly Life

5.1 The analyst must have data to demonstrate that the actual P-N curve for the hose assembly under consideration falls above and to the right of the Reference P-N curve.

$$P_a = P_b(N)^s \quad \text{(Eq. 7)}$$

For a burst of 400% of rated pressure and a 200 000 cycle life at 133% of rated pressure this is:

$$P_a = 400(N)^{-0.0902} \text{ rearranged } N = \left[\frac{400}{P_a}\right]^{11.086} \quad \text{(Eq. 8)}$$

5.2 Establish a sample pressure history for the system for a known time.

5.3 Determine valid "peaks" and count the number of occurrences (n_i) for each peak value (amplitude) in the sample pressure history.

5.4 For each peak value, calculate cycles to failure (N_i) from the Reference P-N curve (step 5.1).

5.5 For each peak value, calculate the ratio of counted cycles (n_i) and the projected number to failure (N_i) to determine the fraction of damage for each peak value.

5.6 Total all fractions of damage from (step 5.5) for total damage (D) due to the sample pressure history.

5.7 Project the fatigue life (L) as the ratio of system operation time (t) for the sample pressure history divided by the total of all damage incurred during that time.

$$L = t(1/D) \quad \text{(Eq. 9)}$$

6. Sample Problem for Cumulative Damage—This simple example is used to illustrate the complete cumulative damage procedure. It shows how to cycle count a sample pressure history, Figure 4, and then calculate the damage done and predict the life of the hose for the sample pressure history. The example is done "by hand" since it is only a few peaks and valleys. "Real" histories would be much longer and would logically be done with a computer program that has been programmed to consider the various special cases of cycle counting and choice of threshold.

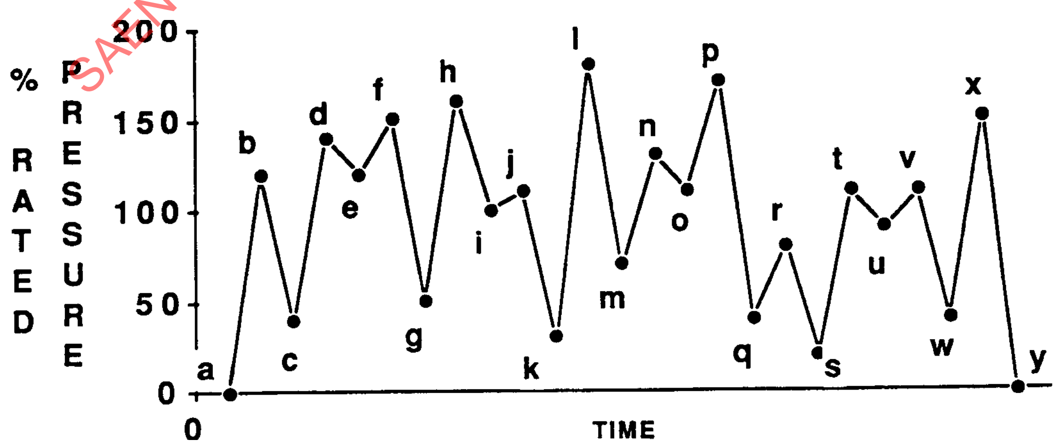

FIGURE 4—PRESSURE-TIME HISTORY (SECTION 6)

Tabulate original maximum-minimum sequence as potential peaks and valleys:

V-P-V-P-V-.....P-V

Note history is assumed to start and end with a valley of zero. See Figure 5.

a	b	c	d	e	f	g	h	i	j	k	l
0	120	40	140	120	150	50	160	100	110	30	180

m	n	o	p	q	r	s	t	u	v	w	x	y
70	130	110	170	40	80	20	110	90	110	40	150	0

FIGURE 5—VALLEY-PEAK HISTORY

Follow procedure in the previous section and Figure 3 to determine which potential peaks will be counted.

For this example assume threshold is 35%.

Counted peaks which result are shown in Figure 6:

b	**f**	**h**	**l**	**p**	**r**	**t**	**x**
120	150	160	180	170	80	110	150

FIGURE 6—COUNTED PEAKS

Then for a hose assembly that has a P-N curve in excess of Reference P-N curve, use Equation 4 to calculate N_i for each P_a. Table 1 shows the tabulated results for the sample pressure history.

TABLE 1—TABULATED DATA

Pressure as a % of Rated Pressure P_n	**Calculated Cycles to Cause Failure at Pressure i N_i**	**Counted Cycles in History at Pressure i n_i**	**Degree of Damage Effected by n_i n_i/N_i**
80	56×10^6	1	0.178×10^{-7}
110	16.4×10^5	1	6.09×10^{-7}
120	62.6×10^4	1	16.0×10^{-7}
150	52.8×10^3	2	3.79×10^{-5}
160	25.8×10^3	1	3.87×10^{-5}
170	13.2×10^3	1	7.59×10^{-5}
180	6.99×10^3	1	14.3×10^{-5}

Using Equation 5:

$$\sum \frac{n_i}{N_I} = 29.8 \times 10^{-5} \tag{Eq. 10}$$

Assume pressure history is for 0.5 h. Then from Equation 6:

$$\text{Life}(L) = \frac{0.5}{29.8 \times 10^{-5}} = 1679 \text{ h} \tag{Eq. 11}$$