

RESULTS AND EXPERIENCES OBTAINED BY STUDSVIK FROM LONG-TERM PRESSURE TESTS ON PLASTIC PIPES FOR VALIDATION OF MINER'S RULE

Leijström H, Ifwarson M
Studsvik Polymer AB
S-611 82 Nyköping, Sweden
E-mail: polymer@studsvik.se
Internet: www.studsvik.se/polymer

This paper presents experimental evidences and experiences obtained from the use of the so-called Miner's rule for determination of lifetime expectancies of plastic pipes subjected to varying testing conditions, i.e. altering temperatures and pressures. Results obtained from some unique long-term pressure tests of PE, PP, PB and PEX (Stage III) performed at constant temperatures are presented as well as results obtained from cycling tests for validation of Miner's rule. The latter results show that Miner's rule is overestimating the lifetime in many cases for the investigated materials. In one case was just 57% of the lifetime observed compared to the one predicted with Miner's rule. This indicates that much too optimistic results may be predicted with Miner's rule if no care is taken in validating this method before usage. However, more work is needed in order to definitely confirm this conclusion. The paper also gives a background and an introduction to Miner's rule according to ISO/DIS 13760 and the Standard Extrapolation Method (SEM) according to ISO/TR 9080. Where the SEM is used to support the Miner's rule calculations of the lifetime at altering service conditions.

BACKGROUND

The lifetime of plastic pipes used for distribution of hot- and cold water, industrial chemicals and gas has been investigated at Studsvik since 1973 (1-21). Today, there are some pipe samples which are still under pressure test after more than 23 years. These long-term tests have resulted in unique creep rupture curves (or lifetime curves) for pipe materials made of polyethylene (PE), cross-linked polyethylene (PEX), polybutene (PB) and polypropylene (PP). The experiences at Studsvik from these long-term tests have shown that the creep rupture curves, generated at elevated temperatures, generally may be divided into three different parts, referred to as Stages I, II and III in Figure 1.

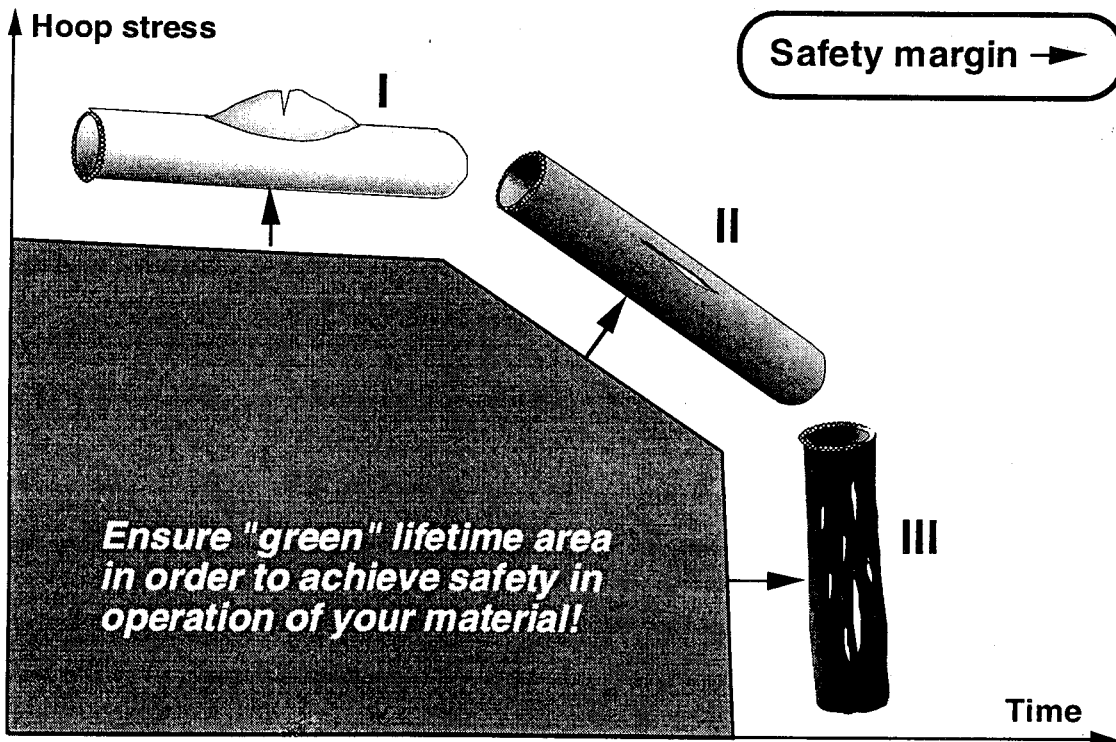


Figure 1. Schematic creep rupture curve for plastic pipes exposed to elevated temperatures.

Figure 1 illustrates the dominant type of failure modes which may occur for plastic pipes subjected to elevated temperatures for a long period of time. The figure also includes a "green" area where a plastic material always shall be used in operation. At high hoop stresses (Stage I), ductile failures are obtained when large defects are absent in the material. At lower stresses (Stages II and III), there is a competition between mechanical phenomena (slow crack growth) and chemical degradation (thermal oxidation) which gives brittle failures in a macroscopic sense. For Stage III, the curve is almost vertical which clearly demonstrates the extreme brittleness of the material. At this time limit, the very lifetime has been reached for a pipe material which is used for distribution of hot-water.

INTRODUCTION

To ensure safe operation in 50 years, or longer, for a given material there is a need for standardised methods which enable accurate lifetime estimations within a reasonable period of time. To meet this demand, accelerated testing procedures and methods like the Standard Extrapolation Method (SEM) according to ISO/TR 9080 is needed. The SEM includes an extensive amount of pressure testing at several temperatures, for generation of creep rupture curves, followed by multiple linear regression analysis in order to fit the data. By having a proper fit to the data, the SEM is subsequently used for determination of the long-term hydrostatic strength (LTHS) and for obtaining the classification, i.e. MRS (Minimum Required Strength) at 20°C and 50 years for material designation (e.g. PE100).

Two models are included in the SEM according to ISO/TR 9080 (20) for determination of the time to failure (t_f), referred to as Models Q and R. The equation of Model Q contains of three unknown regression coefficients A, B and C and two independent variables, temperature (T_i) and stress (σ_i):

Model Q according to ISO/TR 9080

$$\log(t_{fi}) = -A - (B/T_i) \log(\sigma_i) + C/T_i \quad \text{Equation I}$$

Provided it has been possible to establish a proper fit to a given set of test data, Equation I can be used for calculations of the expected failure time at any fixed combination of temperature and hoop stress (within the experimental temperature range and extrapolation time limits). However, in real operation it is more likely to have alterations in temperature and pressure (hoop stress) rather than constant service conditions. Assuming that each damage (caused by a constant service condition) is proportional to the duration of the attack ("proportionality rule") and the damages from different service conditions "i" may be cumulatively added ("additivity rule") Miner's rule appears as (21):

Miner's rule according to ISO/DIS 13760

$$1 / t_f = \sum_{i=1}^{i=n} [(t_i / t_{tot}) / t_{fi}(T_i, \sigma_i)] \quad \text{Equation II}$$

The following definitions are used for the purpose of this paper (safety factors not included):

t_f	Lifetime at various conditions
$t_{fi}(T_i, \sigma_i)$	Failure time for condition "i"
n	Number of service conditions
t_i	Exposure time at condition "i"
t_{tot}	Total exposure time

Combination of Equations I-II provides the tool for the determination of the expected lifetime of plastic materials subjected to varying service conditions, i.e. alterations in temperature and stress.

RESULTS AND DISCUSSION

Figures 2-3 below show the fit of Model Q according to ISO/TR 9080 (see Equation I) to Stage III pressure test data generated by Studsvik for the pipe materials MDPE-1, PP-1, PB-1 and PEX-7:

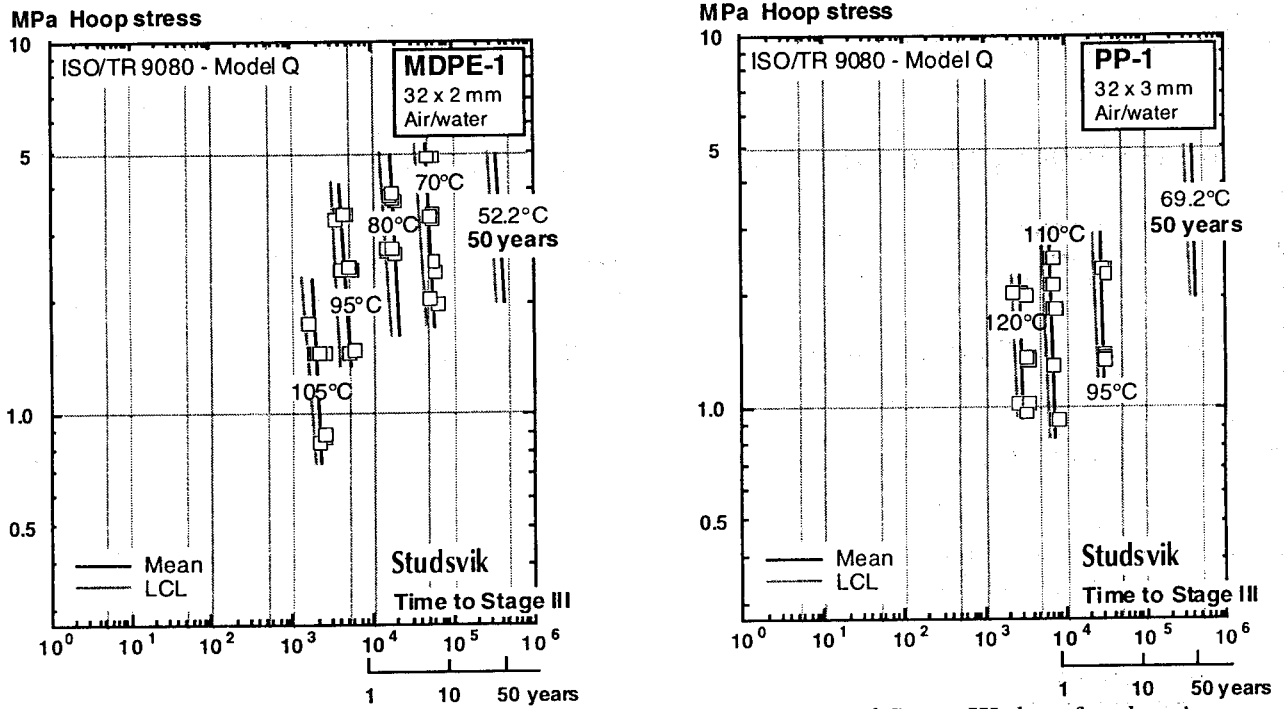


Figure 2. SEM-evaluation performed on experimentally determined Stage III data for the pipe grades MDPE-1 and PP-1 in order to fit the testing data with Model Q according to ISO/TR 9080.

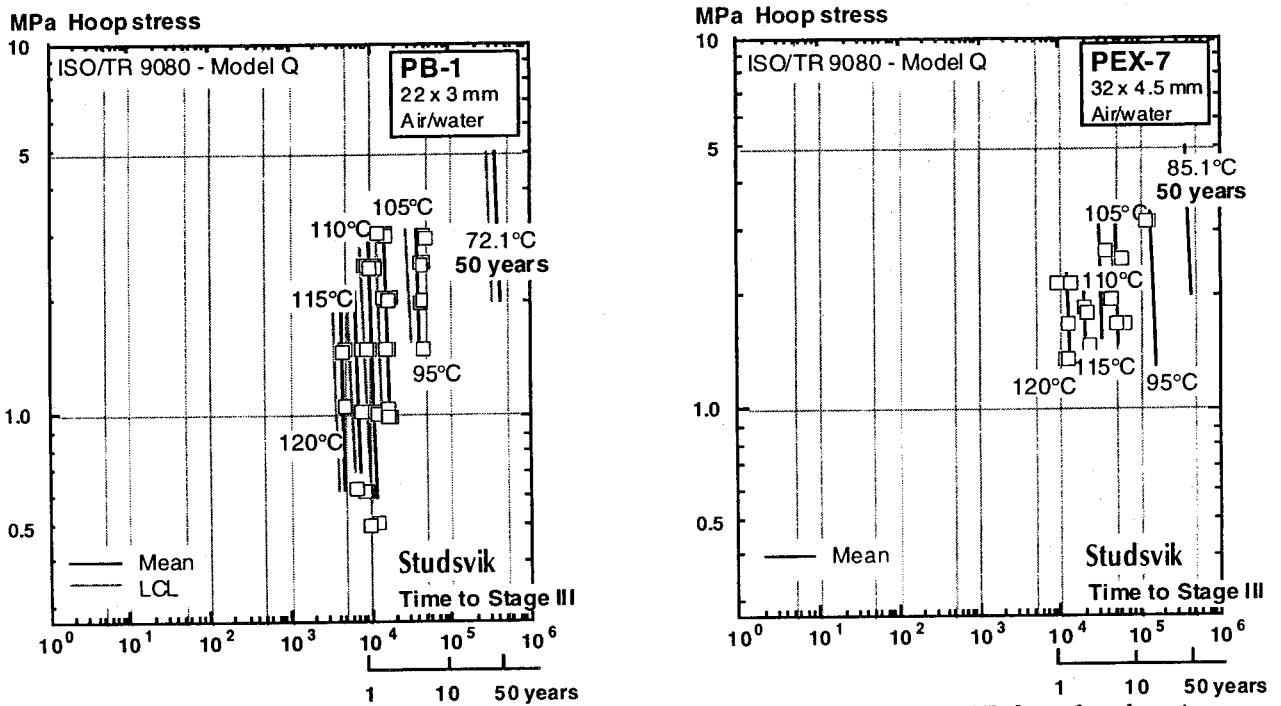


Figure 3. SEM-evaluation performed on experimentally determined Stage III data for the pipe grades PB-1 and PEX-7 in order to fit the testing data with Model Q according to ISO/TR 9080.

Figures 2-3 clearly demonstrate that it is possible to obtain a satisfactory fit to all Stage III data. However, it was not possible to determine LCL curves for PEX-7 due to a lack of experimental data (more failure points are needed). Figures 2-3 also include extrapolated curves to the service temperatures which are expected to give a lifetime of 50 years for $\sigma_{\text{mean}} = 3 \text{ MPa}$. Do observe that these service temperatures only are valid for the investigated pipe materials and pipe dimensions.

Since the fit of Model Q (Equation I) to the Stage III failure points shown in Figures 2-3 is regarded acceptable it may now be possible to apply Miner's rule (Equation II) for calculation of the expected lifetime for a pressure test performed by using varying testing conditions shown in Figure 4:

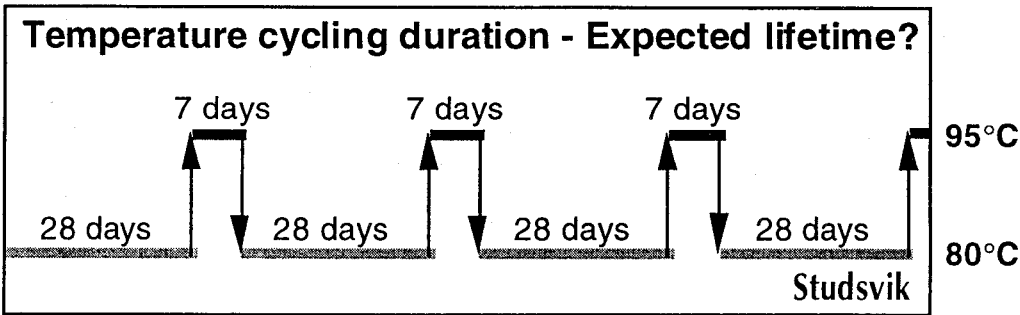


Figure 4. Illustration of a temperature cycling test between 80 and 95°C.

Figure 5 provides an example of Miner's rule calculations for the MDPE-1 material exposed for the temperature cycling duration presented in Figure 4 at a constant hoop stress of $\sigma = 2.5 \text{ MPa}$:

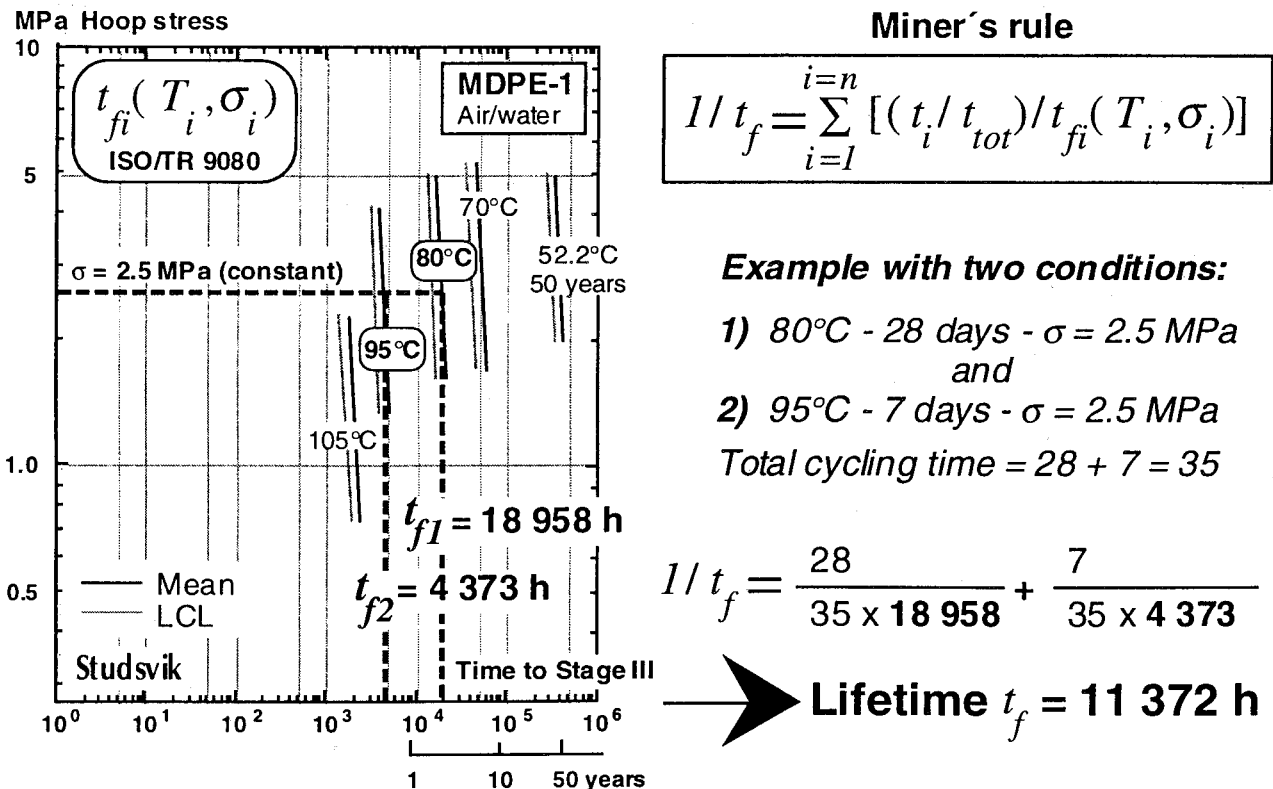


Figure 5. Miner's rule calculations (example) performed for determination of the expected lifetime for MDPE-1 pipes exposed to temperature cycling between 80 and 95°C at a constant hoop stress.

The answer to the question in Figure 4 regarding the lifetime of MDPE-1 for a temperature cycling test performed between 80 and 95°C at 2.5 MPa is thus 11 372 h (1.3 years), provided that Miner's rule holds. Figure 6 on next page shows the results obtained from this temperature cycling test:

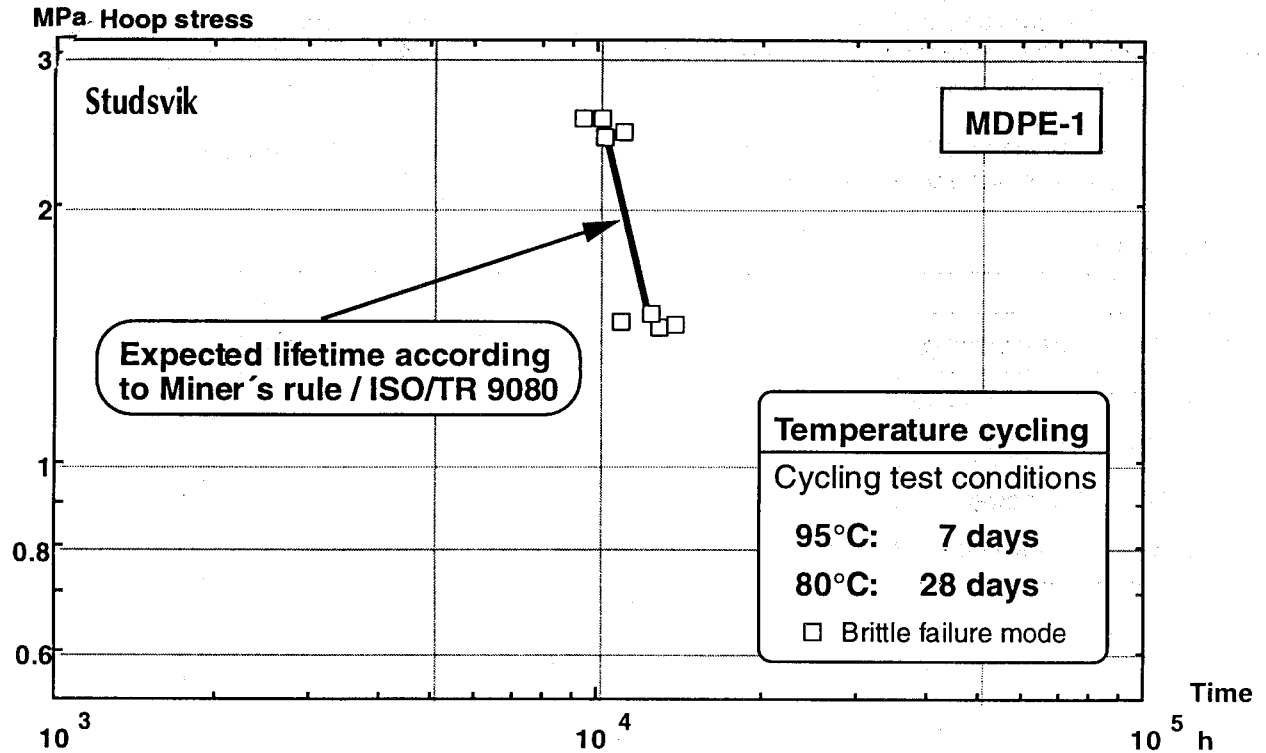


Figure 6. Validation of Miner's rule for MDPE-1 by performing temperature cycling tests between 95°C (7 days) and 80°C (28 days) for generation of brittle Stage III failures.

Figure 6 clearly demonstrates that Miner's rule is valid for this specific pipe material (MDPE-1) and the testing condition used. Hence, all four temperature cycling tests performed at 2.5 MPa failed close to the expected lifetime (11 372 h) as well as four additional tests cycling tests at 1.5 MPa.

Figure 7 shows the results obtained from temperature cycling tests on MDPE-1 performed at two constant hoop stresses (1.5 and 0.9 MPa) and temperatures altering between 90/105°C:

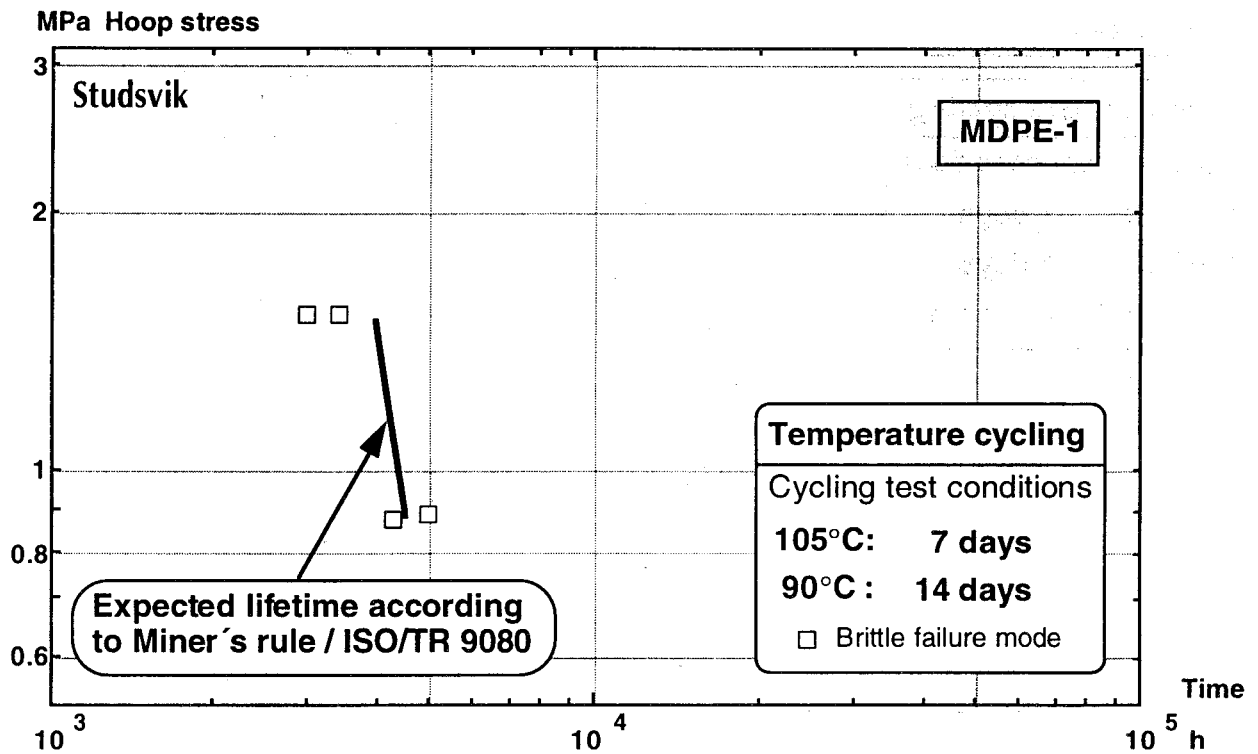


Figure 7. Validation of Miner's rule for MDPE-1 by performing temperature cycling tests between 105°C (7 days) and 90°C (14 days) for generation of brittle Stage III failures.

Figure 7 shows that the test results obtained are in agreement with Miner's rule at the lowest hoop stress. However, at the highest stress level is the failure time observed just 80% of the expected lifetime. Most likely due to that the testing temperature 105°C is rather close to the melting point.

Figures 8-9 presents the results obtained from temperature cycling tests on PB-1 performed at two constant hoop stresses and temperatures altering between 95/110°C and 90/105°C:

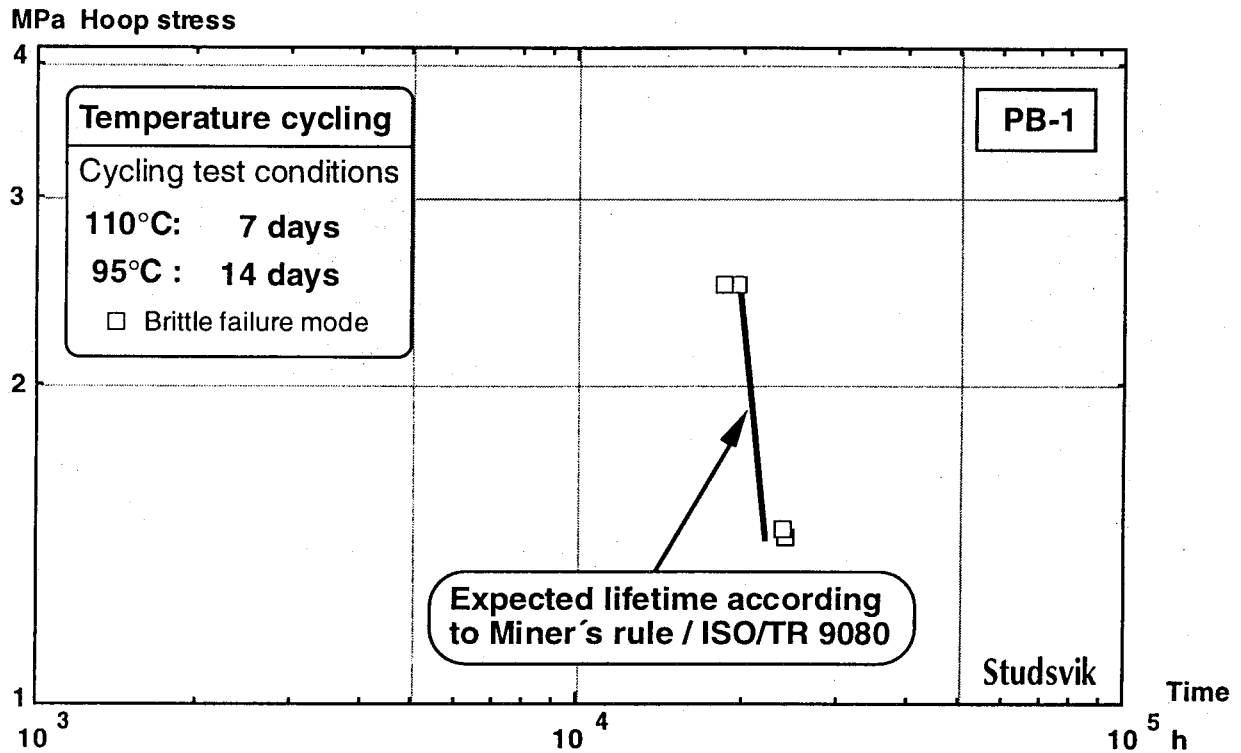


Figure 8. Validation of Miner's rule for PB-1 by performing temperature cycling tests between 95°C (14 days) and 110°C (7 days) for generation of brittle Stage III failures.

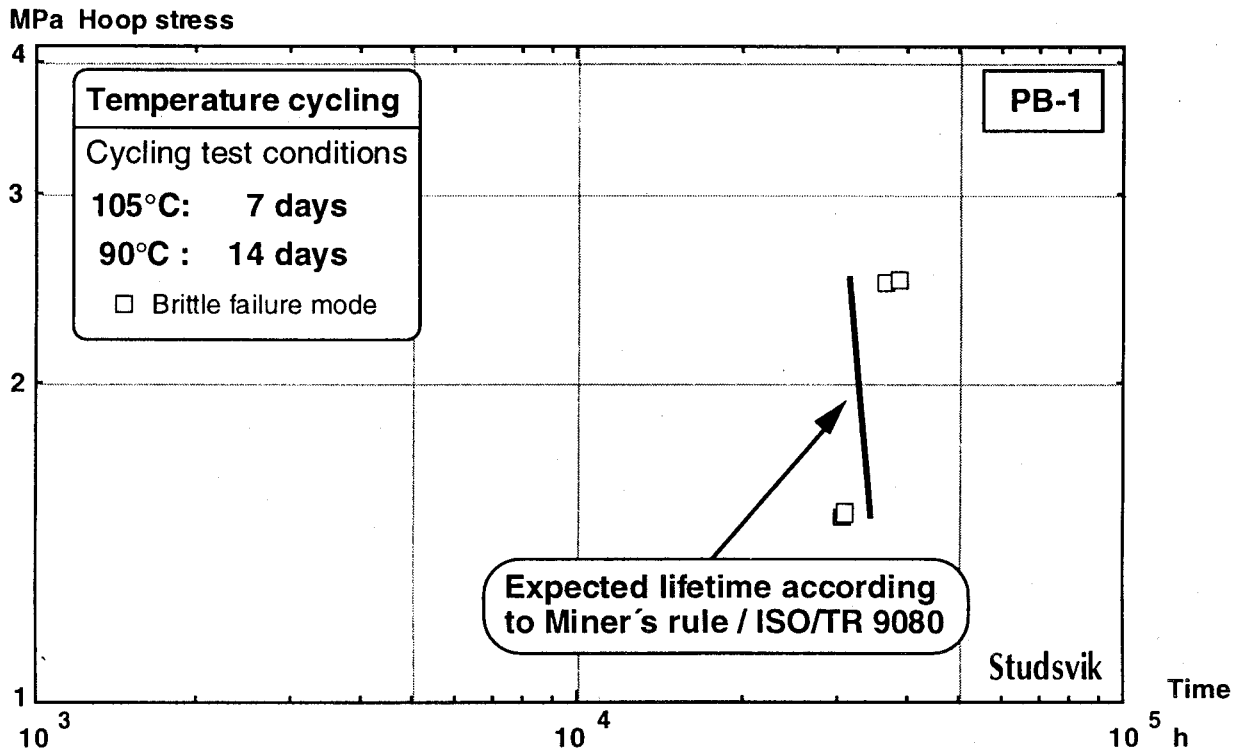


Figure 9. Validation of Miner's rule for PB-1 by performing temperature cycling tests between 90°C (14 days) and 105°C (7 days) for generation of brittle Stage III failures.

Figures 8-9 clearly demonstrate that Miner's rule is valid for this specific pipe material (PB-1) and the testing condition used since both temperature cycling tests performed show failure times which are close to the expected lifetime curve.

Figures 10-12 finally presents the results obtained from temperature cycling tests performed on PEX-7 and PEX-21 at temperatures altering between 95/110°C and 90/105°C.

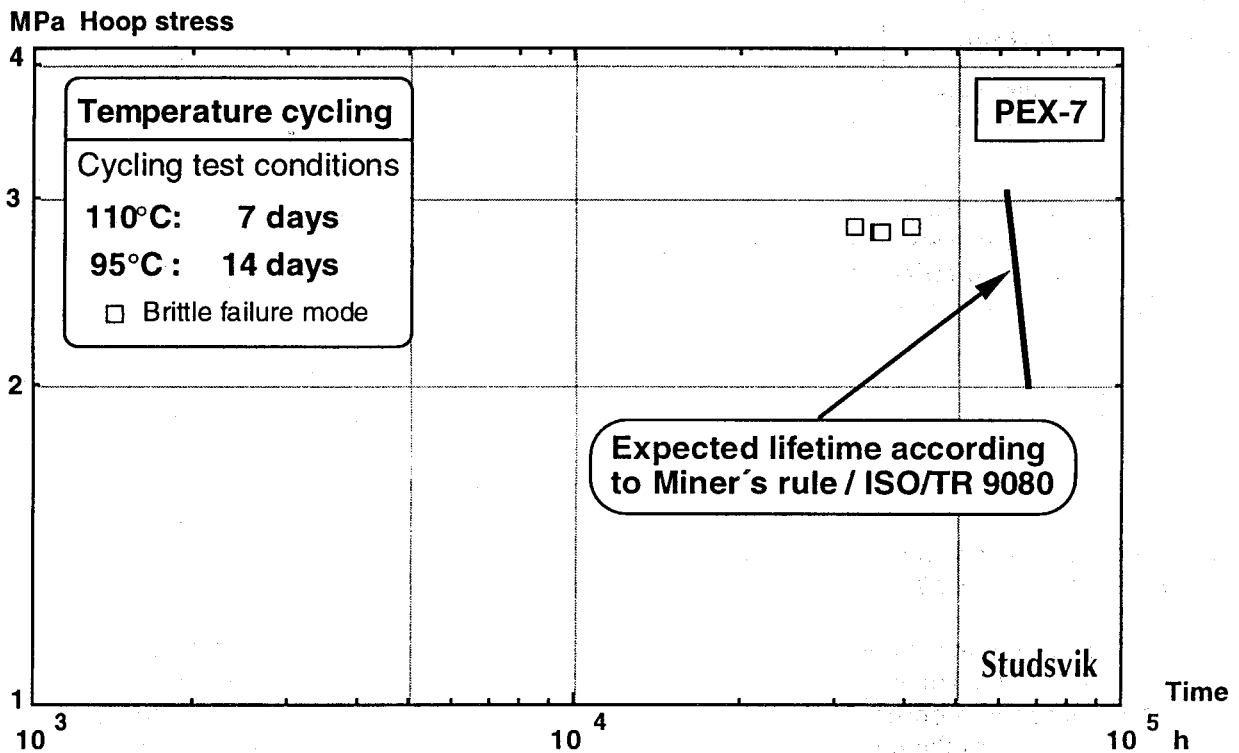


Figure 10. Validation of Miner's rule for PEX-7 by performing temperature cycling tests between 95°C (14 days) and 110°C (7 days) for generation of brittle Stage III failures.

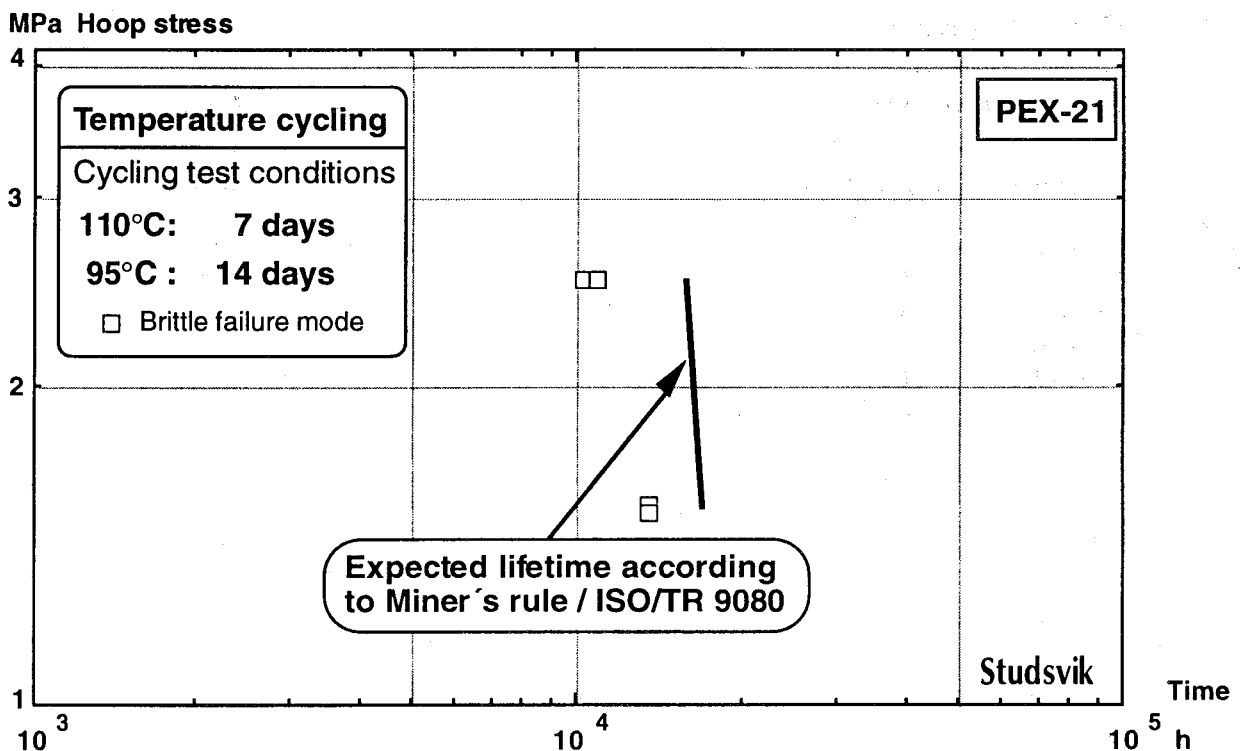


Figure 11. Validation of Miner's rule for PEX-21 by performing temperature cycling tests between 95°C (14 days) and 110°C (7 days) for generation of brittle Stage III failures.

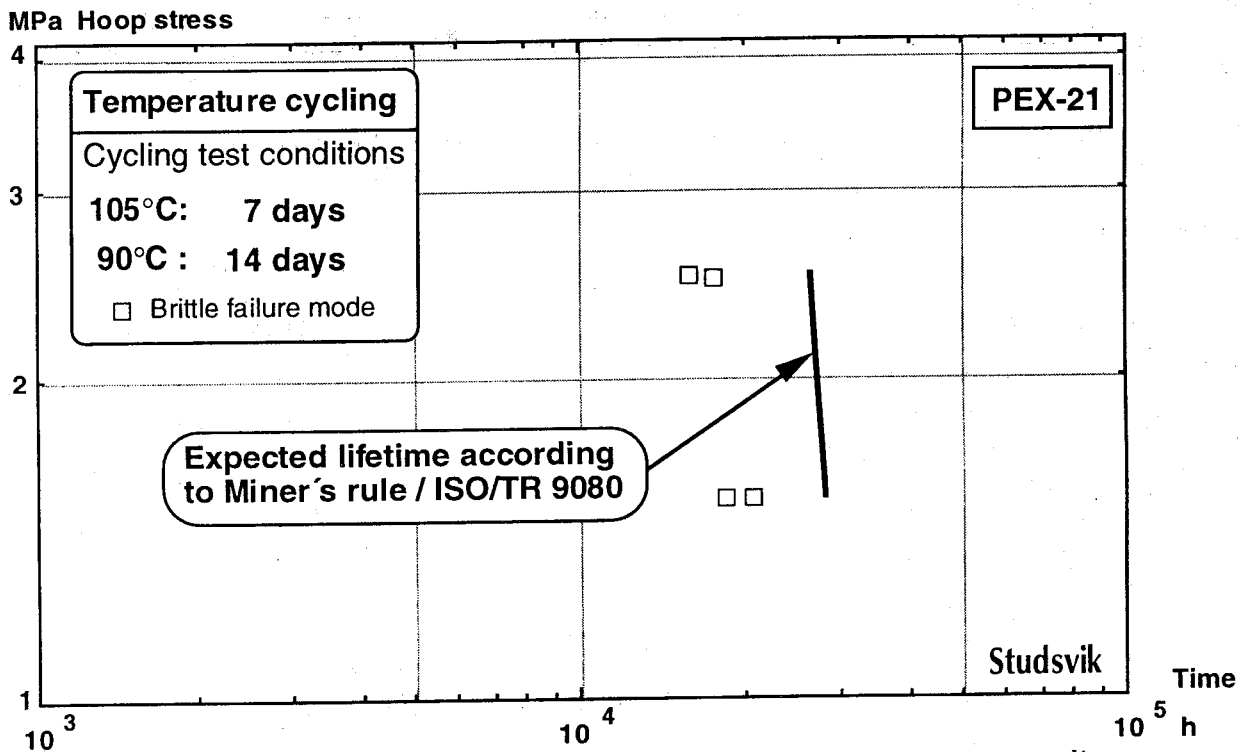


Figure 12. Validation of Miner's rule for PEX-21 by performing temperature cycling tests between 90°C (14 days) and 105°C (7 days) for generation of brittle Stage III failures.

Figures 10-12 show that the test results obtained for PEX-7 as well as for another PEX (PEX-21) are not in agreement with Miner's rule since all failure times are shorter than the expected lifetimes. However, the failure times observed for these PEX materials are still very long. This is shown in Table I which summarises the results obtained from some Miner's rule experiments performed at Studsvik as well as information about the expected lifetime for PP-1 subjected to corresponding temperature cycling tests (unfortunately, no data is currently available at Studsvik for PP):

Table I. Comparison between lifetimes according to Miner's rule and observed failure times

Material	Cycling test	Stress	Miner's rule	Observed time*	Relative time
MDPE-1	105/90°C	1.5 MPa	3 976 h	3 175 ± 319 h (2)	80%
MDPE-1	105/90°C	0.9 MPa	4 633 h	4 600 ± 509 h (2)	99%
MDPE-1	95/80°C	2.5 MPa	11 372 h	10 098 ± 704 h (4)	89%
MDPE-1	95/80°C	1.5 MPa	12 929 h	12 380 ± 1 156 h (4)	96%
PP-1	110/95°C	2.5 MPa	13 179 h	no tests performed	-
PP-1	105/90°C	2.5 MPa	21 226 h	no tests performed	-
PP-1	105/90°C	1.5 MPa	22 706 h	no tests performed	-
PP-1	95/80°C	2.5 MPa	73 470 h	no tests performed	-
PB-1	110/95°C	2.5 MPa	19 683 h	18 670 ± 750 h (2)	95%
PB-1	110/95°C	1.5 MPa	21 340 h	23 425 ± 106 h (2)	110%
PB-1	105/90°C	2.5 MPa	31 324 h	36 845 ± 1 308 h (2)	118%
PB-1	105/90°C	1.5 MPa	33 992 h	30 046 ± 303 h (2)	88%
PEX-7	110/95°C	2.8 MPa	62 919 h	35 723 ± 3 560 h (4)	57%
PEX-7	110/95°C	2.5 MPa	64 250 h	no tests performed	-
PEX-7	105/90°C	1.5 MPa	117 184 h	no tests performed	-
PEX-21	110/95°C	2.5 MPa	15 979 h	10 545 ± 488 h (2)	66%
PEX-21	110/95°C	1.5 MPa	17 051 h	13 308 ± 0 h (2)	78%
PEX-21	105/90°C	2.5 MPa	26 358 h	16 420 ± 1 131 h (2)	62%
PEX-21	105/90°C	1.5 MPa	28 149 h	19 170 ± 1 513 h (2)	68%

* Values within parentheses show the number of observations (number of pressure tested pipe samples)

Table I shows that temperature cycling tests performed on MDPE-1 resulted in brittle failures after 80 to 99% of the expected lifetime according to Miner's rule, PB-1 failed after 88-118%, PEX-7 after just 57% and PEX-21 failed after 62-78%.

Considering the results obtained, it is our recommendation that Miner's rule always is validated for every new material (based on experimental tests) before usage to enable a derating of the calculated lifetimes if it is necessary. Alternatively, a time safety factor should be used of say 0.5 for derating the lifetimes calculated according to Miner's rule. Do observe that the use of a stress safety factor (typically 1.5 at the operational temperature T_{oper}) is not sufficient to correct for the non-agreement between reality and Miner's rule since the lifetime curve for Stage III is almost vertical and thus the same lifetime is obtained regardless of the hoop stress.

CONCLUSIONS

- Creep rupture curves obtained from hydrostatic pressure tests performed on plastic pipes at elevated test temperatures may be divided into three stages referred to as Stages I, II and III.
- It is possible to use the Standard Extrapolation Method (SEM) according to ISO/TR 9080 for obtaining a proper fit (Model Q) to long-term Stage III test data generated at Studsvik for pipe materials made of MDPE-1, PP-1, PB-1 and PEX-7.
- In order to perform accurate lifetime estimations in operation (at varying service conditions) the SEM according to ISO/TR 9080 should be used to support the Miner's rule calculations.
- The failure times observed from temperature cycling tests performed on MDPE-1 show good agreement with the expected lifetimes according to Miner's rule. Hence, the observed failure times were always at least 80% of the expected lifetimes according to Miner's rule.
- The failure times observed from temperature cycling tests performed on PB-1 show very good agreement with the expected lifetimes according to Miner's rule and the observed failure times were always at least 88% of the expected lifetimes (Miner's rule).
- Temperature cycling tests performed on PEX-21 show that shorter failure times are observed for this specific material compared to the expected lifetimes according to Miner's rule. The observed failure times were thus 62% of the expected lifetimes (Miner's rule) in the worst case.
- Temperature cycling tests performed on PEX-7 show much shorter failure times compared to the expected lifetime according to Miner's rule. The observed failure times were just 57% compared to Miner's rule! However, the failure times for PEX-7 are still much longer than the failure times for PB-1 and PEX-21 if the same test conditions are considered (cycling between 110 and 95°C).
- Based on temperature cycling tests (Stage III), it is recommended that Miner's rule is validated for each new material before usage to avoid much too optimistic lifetime calculations. Another conservative approach is to use 50% of the expected lifetime according to Miner's rule in order to achieve safety in operation.

SYMBOLS AND NOMENCLATURE

Hoop stresses (LCL, LTHS and Mean)

σ_{LCL} is a quantity with the dimension of stress which represents the 97.5% lower confidence limit of the long-term hydrostatic strength. Where the 97.5% lower confidence limit is equivalent to the lower confidence limit of the 95% confidence interval. σ_{Mean} is the average strength and represents a stress calculated from the equation(s) obtained from the multiple linear regression analysis. σ_{LTHS} is a function of the ratio: $\sigma_{LCL}/\sigma_{Mean}$. If $\sigma_{LCL}/\sigma_{Mean} > 0.85$ then $\sigma_{LTHS} = \sigma_{Mean}$, otherwise $= \sigma_{LCL}/0.85$.

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