ROLE OF THE MEASUREMENT UNCERTAINTY IN CONE PENETRATION TEST RESULTS OF LUBRICATING GREASE

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Abstract:
The guard banding approach is tested to meet the NLGI grade of lubricating grease specifications. Different guard band formulae were tried to compare the customer and manufacturer risks during production release testing. The results show that the called risk management approach for guard banding offers the best results for the trade-off between the producer risk without compromising the targeted level of consumer risk for the particular case of symmetrical but high-preferred specifications limits.

Keywords: cone penetration test, guard band, manufacturer's risk, customer's risk

1. INTRODUCTION

The most frequent measurement of lubricating grease consistency is the cone penetration test (CPT) [1][2]. CPT could be understood as a hardness measurement of the grease. The National Lubricating Grease Institute (NLGI) defined a classification of lubricating greases as regards its consistency (Table 1), measured through the depth to which a standard metal cone penetrates the grease sample at 25 ºC. The CPT is reported in tenths of a millimetre (hereafter CPT units), and the metal cone has standardized dimensional characteristics, mass and shape [2].

Table 1: Lubricating grease consistency NLGI grades [1].

NLGI grade	Penetration range / CPT units	Food similar consistency
6	85 – 115	Cheddar cheese
5	130 – 160	Fudge
4	175 – 205	Frozen yoghurt
3	220 – 250	Butter
2	265 – 295	Peanut butter
1	310 – 340	Tomato paste
0	355 – 385	Mustard
00	400 – 430	Yoghurt
000	445 – 475	Ketchup

Also, before testing the consistency of the grease, the sample receipts 'work' in a particular device to avoid the presence of air bubbles and lumps of undispersed material during the manufacturing process [3].

On the other hand, when assessing a product's conformity regarding the specification limits (SL), the ideal situation is to accept all parts whose true value (TV) lies within SL and reject all the elements that have their TV outside SL. However, it is not possible to satisfy both conditions. The best estimate of a TV has an associated measurement uncertainty; hence, false-accepted (accepted parts whose TV lies outside of SL) and false-rejected (rejected parts whose TV lies inside of SL) will be present [4].

Several strategies have been reported regarding the test acceptance limits [4][5][6][7], which originate from the guard band approach (see Fig.1). These strategies seek to minimize the false-accepted risk (consumer's risk), to make equal the consumer's risk with the false-rejected risk (manufacturer's risk) or minimize the total risk.

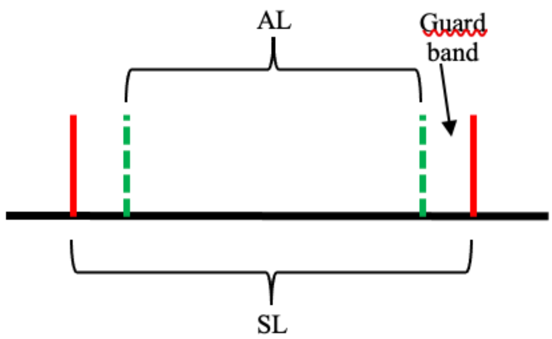

Figure 1: Relation between specifications and acceptance limits with a guard band.

This work shows the results of testing several strategies for the definition of *AL* to the results of CPT on lubricating grease NLGI grade 2. The inputs for the analysis include the results of penetrometer calibration and a gage repeatability and reproducibility (GR&R) analysis [9]. Those data allowed estimating the measurement uncertainty associated with the CPT.

2. METHODOLOGY

Two cases were analysed depending on the knowledge of the prior information on the lubricating grease manufacturing process. The first case assumes no previous data is available on the CPT results. Only the probability of non-conformity was computed in this case.

The second case considers the use of previous knowledge in the form of the standard deviation of the CPT results. This second case allows computing the risk for both the consumer and the manufacturer. For this case, results were obtained using CASoft software, jointly developed by LNE, NPL and RISE [8]. CASoft was developed in Matlab® and uses the Monte Carlo method to evaluate the complex integrals described in [4].

2.1. Measurement uncertainty for the CPT

CPT measurement uncertainty was computed through a GR&R analysis, and the calibration of the penetrometer regards its mass and dimensional characteristics.

GR&R analysis

The design and analysis of the GR&R were made following the guidelines in [9]. Two laboratory technicians measure twice seventeen samples of lubricating grease each. Samples were supplied to the technicians in a random order to avoid memorisation of the results.

In [9], it is indicated that the results to review are the repeatability percentage, that is, how much the same technician gives the same results on both tests of the same sample, and the reproducibility percentage, how much different technicians provide the same result of the same sample. Another evaluation result is the part-to-part variation, which must be high if the measurement systems contribute with a low proportion to the total variation (part-to-part + measurement system variations). Finally, the called *number of distinct categories* indicates the measurement system's discrimination power among the product's variability. This parameter must be greater than five [9].

The ASTM standard [2] indicates that the value for repeatability is 7 CPT units, and for reproducibility is 23 CPT units for worked samples method. However, these are not reference values; they are maximum limit values that are statistically defined at the 95 % probability level [10].

Uncertainty contributors

The main contributor in a CPT measurement is always determined by the skill of the operator [1]. The contributors to the uncertainty budget considered here were the results of GR&R and the results from the calibration certificate of the penetrometer.

The standard uncertainty of the CPT measurements will be considered unchanged throughout this work once the maximum values of the GR&R are considered.

2.2. Probability of conformity

The equations for the calculation of the probability of conformity are available in [4], from which the probability of non-conformity could be calculated as:

$$1 - p_c = 1 - \Phi\left(\frac{T_U - y}{u}\right) + \Phi\left(\frac{T_L - y}{u}\right). \quad (1)$$

Where T_U is the upper tolerance limit, T_L is the lower tolerance limit, and $\Phi(y)$ is the standard normal distribution function. Also, y and u will be the CPT measurements' mean and uncertainty. They will be defined next.

When no previous data are available, $y = y_m$, with y_m as the mean of the CPT measurement results, and $u = u_m$, with u_m as the corresponding measurement uncertainty.

When the prior information of the CPT measurement follows a normal PDF with mean y_0 and standard uncertainty u_0, according to [4], y and u are given by:

$$y = \frac{\frac{y_m}{u_m^2} + \frac{y_0}{u_0^2}}{\frac{1}{u_m^2} + \frac{1}{u_0^2}}, \text{and } u = \sqrt{\frac{1}{\frac{1}{u_m^2} + \frac{1}{u_0^2}}}. \quad (2)$$

For both cases, $y_m \in [LSL, USL]$, with LSL = 265 CPT units is the lower specification limit for the lubricating grease NLGI grade 2. Whereas USL = 295 CPT units is the upper specification limit for the lubricating grease NLGI grade 2.

2.3. Acceptance intervals and consumer's and manufacturer's risks

The equations for the risks of consumers and producers are published in [4]. They will not be reproduced here for the sake of space. Those equations will be solved inside the CASoft package [8].

In all cases, the acceptance limits will vary according to the cases defined in Section 2, following that $[A_L, A_U] \subseteq [LSL, USL]$, but changed by the guard band strategy equation used.

2.4. Guard banding strategies

Four guard banding strategies were studied. The four strategies correspond to the following equations.

Root Sum Square 1 (RSS-1)

This guard band strategy is applied when the producer states coverage probability for their SL. The equation for this guard band is [6]:

$$AL = \left(1 - \frac{1}{TUR^2}\right) SL. \quad (3)$$

Where TUR is the Test Uncertainty Ratio.

Root Sum Square 2 (RSS-2)

This is another equation to use when the manufacturer states confidence level to SL.

$$AL = SL\sqrt{1 - \frac{1}{TUR^2}} \, . \quad (4)$$

NCSL RP-10

The recommended practice [11] includes the following equation:

$$AL = \left(1.25 - \frac{1}{TUR}\right) SL \, . \quad (5)$$

ANSI Z540.3

This other standard [12] requires that a process assures a false-accept risk (consumer's risk) lower or equal to 2 %. This can be achieved by setting the AL according to the following equation [6]:

$$AL = SL - U\left[1.04 - e^{[0.38\ln(TUR) - 0.54]}\right] . \quad (6)$$

Where U is the expanded uncertainty (k = 2).

3. RESULTS AND DISCUSSION

The probabilities of non-conformity and risks have been evaluated when the different guard banding strategies are shown in Section 2.4.

3.1. Measurement uncertainties results

Table 2 shows valuable results from the GR&R analysis. The measurement system is satisfactory, and the most significant contribution variation comes from the samples (parts) used in the study.

Table 2: Sources of variation results from the GR&R.

Source	Contribution	Verdict
Repeatability	0.00 %	Very good
Reproducibility	0.57 %	Very good
Total GR&R	0.57 %	Very good
Part-to-Part	99.43 %	Very good
Number of distinct categories	18	Very good

It is important to note that the laboratory technicians who participated in the GR&R analysis and the measurement process for this work have more than 15 years of experience, making CPT every working day all working shifts long.

On the other hand, the calibration of the penetrometer gives a standard uncertainty equal to 0.32 CPT units, whereas the standard deviation of the GR&R analysis gives 1.38 CPT units. As repeatability variation includes the calibration uncertainty, the combined standard uncertainty remains as 1.38 CPT units, which results in 2.8 CPT units expanded measurement uncertainty, with k = 2.

3.2. Non-conformity without prior information

Regarding the probability of non-conforming of a lubricating grease NLGI grade 2, Figure 2 shows the results for the range TUR = [4, 12] when no guard band approach is used.

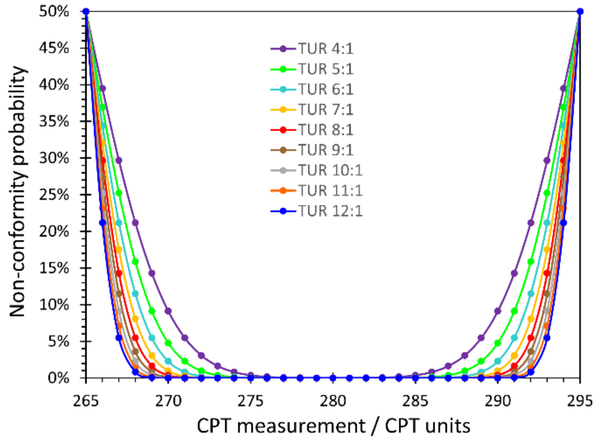

Figure 2: Non-conformity probability for different TUR values. No guard band strategy.

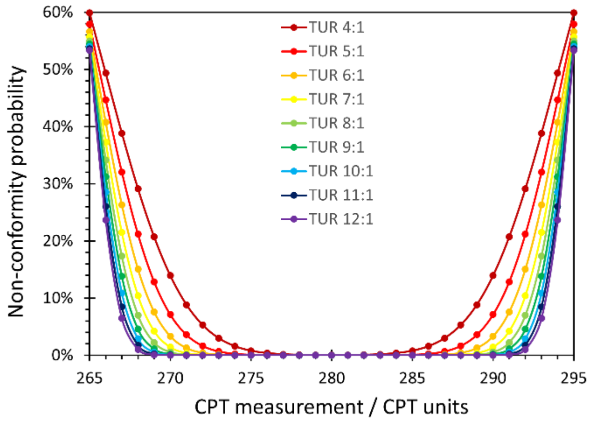

Figure 3: Non-conformity probability for different TUR values. RSS-1 guard band strategy.

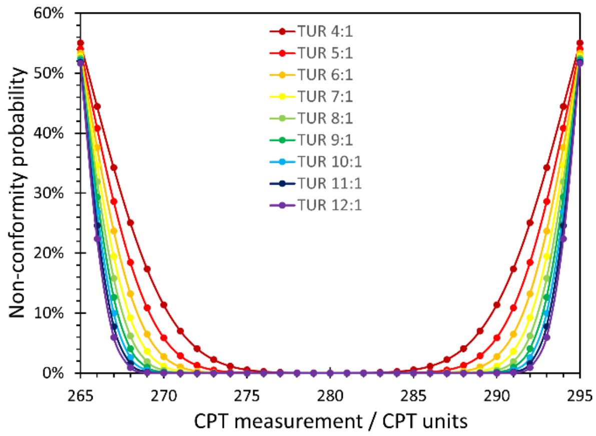

Figure 4: Non-conformity probability for different TUR values. RSS-2 guard band strategy.

For both RSS strategies, the outputs are pretty much the same. Barely the AL are lower, from a couple of tenths of a millimetre to less than 0.3 CPT units. So, these guard banding strategies are like no guard banding.

As in the rest, the expectation is the same in these figures: the probability of non-conformity increases when the CPT measurement is close to the *SL*.

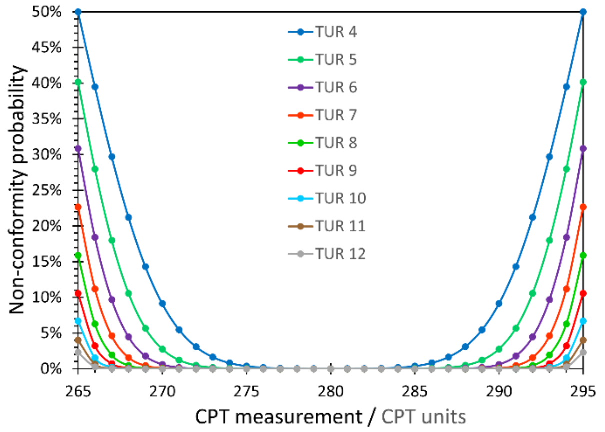

Figure 5: Non-conformity probability for different TUR values. NCSL RP-10 guard band strategy.

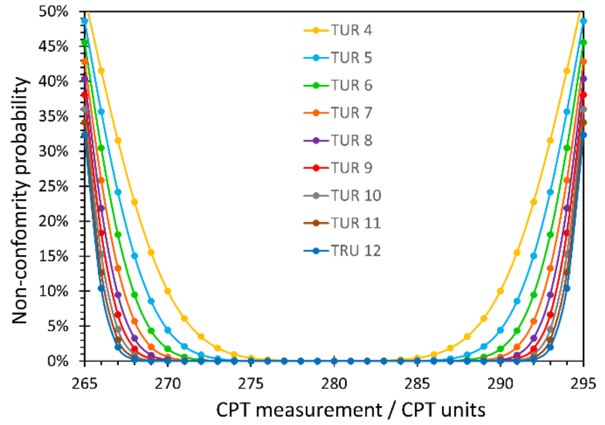

Figure 6: Non-conformity probability for different TUR values. Managed risk strategy.

Even when for NCSL RP-10, the response for *TUR* 4:1 is the same as without any guard band. For higher *TUR* values, the *AL* expands to even 35. This diminishes the producer's risk but increases the consumer's risk.

For the Managed risk approach, for *TUR* 4:1, *AL* is barely slight than for no guard band, and it keeps this way practically for all *TUR* values, in such a way that when *TUR* = 12 *AL*, it has barely increased 1.15 tenths of a millimetre.

3.3. Global risks

The results of risks for the manufacturer and the consumer computed with CASoft are shown in Figures 7 to 10. Only a worst-case scenario graph for every used guard band strategy will be shown.

Note that as with the no conformity graphs, the results are symmetrical, which implies that the sum of risk for the manufacturer and the consumer (the global risk) is the same. Of course, the cloud of simulation points will be on the opposite side of *SL*.

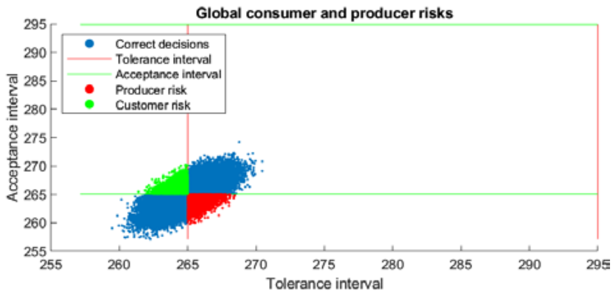

Figure 7: Global risk for RSS-1 guard band strategy. *TUR* 12:1, CPT = 265 CPT units.

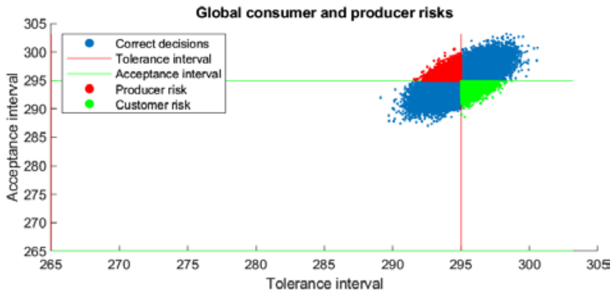

Figure 8: Global risk for RSS-2 guard band strategy. *TUR* 12:1, CPT = 295 CPT units.

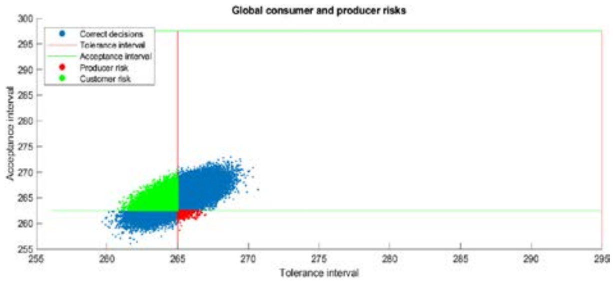

Figure 9: Global risk for NCSL RP-10 guard band strategy. *TUR* 12:1, CPT = 265 CPT units.

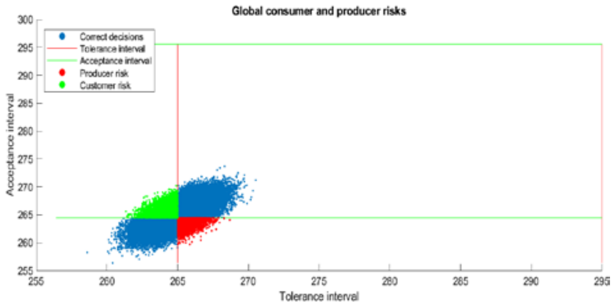

Figure 10: Global risk for Managed Risk guard band strategy. *TUR* 12:1, CPT = 265 CPT units.

Table 3 summarises the maximum risks computed for every strategy studied in its worst-case scenario. The greater value for the global risk belongs to the NCSL RP-10 strategy, which, even when it has a very good false-rejected, also has a high false-accepted risk. The RSS strategies offer almost the same global risk, with a light advantage for the consumer.

Table 3: Global risks for the guard band strategies.

Guard band	Consumer's risk	Producer's risk
RSS-1	0.1241	0.1461
RSS-2	0.1294	0.1404
NCSL RP-10	0.4134	0.0062
Managed risk	0.2007	0.0816

4. SUMMARY

Several strategies for guard banding choice had been available for a while. If the metrological conditions are considered, all of them could be useful. The trade-off between the risk for the consumer and the risk for the manufacturer must be considered. Regarding this work, the next step will be to consider the economic issue. Since bigger values of CPT favour the manufacturer's economy when putting at risk the consistency that the consumer is taken for granted.

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