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Enrico Lucon[1]

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[1] National Institute of Standards and Technology (NIST), 325 Broadway, Boulder, CO 80305, USA (Corresponding author), e-mail: enrico.lucon@nist.gov, https://orcid.org/0000-0002-3021-4785

ABSTRACT

ASTM E1921, *Standard Test Method for Determination of Reference Temperature, T_O, for Ferritic Steels in the Transition Range*, standardizes the Master Curve procedure for determining the reference temperature, T_O, of ferritic steels in the ductile-to-brittle transition range. In order for toughness test results to be included in the analyses, the corresponding test temperatures, T, must currently lie within the valid range defined as $T_O - 50°C \leq T \leq T_O + 50°C$. This study investigated the possibility of extending the valid test temperature range in a future revision of ASTM E1921 by assessing the consequences on the values of homogeneous (T_O) and inhomogeneous (T_{OIN}, T_m) reference temperatures calculated on 10 large "historical" data sets, already examined by the author in previous papers. The effect of expanding the valid temperature range on the macroscopical nature (homogeneous or inhomogeneous) of each data set was also considered by using the screening criterion presently proposed by ASTM E1921-22a. The results obtained appear to warrant a possible revision of the standard in this direction.

Keywords

ASTM E1921, homogeneous data sets, inhomogeneous data sets, Master Curve, reference temperature, valid test temperature range

Nomenclature

B = sample size uncertainty factor (°C)

$\Delta T_0 = T_0 - T_0^*$ (°C)

$\Delta T_{0I} = T_{0IN} - T_{0IN}^*$ (°C)

$\Delta T_m = T_m - T_m^*$ (°C)

K_{Jc} = value of stress intensity factor at cleavage used in Master Curve analyses (MPa$\sqrt{m}$)
K_{Ic} = critical value of stress intensity factor under linear-elastic conditions (MPa$\sqrt{m}$)
$K_{Jc,med}$ = median value of stress intensity factor for a fracture toughness data set (MPa$\sqrt{m}$)
K_{Jc} = value of stress intensity factor at cleavage used in Master Curve analyses (MPa$\sqrt{m}$)
$MLNH$ = measure of the likelihood that the data set is inhomogeneous according to the bimodal or multimodal method
N = number of fracture toughness tests performed within the $T_0 \pm 50$°C temperature range
N^* = N for a subset consisting of tests performed outside the original $T_0 \pm 50$°C temperature range
N_{tests} = number of fracture toughness tests performed
r = number of uncensored data points in a fracture toughness data set
SCI = Screening Criterion Index
$SCI_{E1921\text{-}22a}$ = Screening Criterion Index calculated for a rigorous E1921-22a analysis
σ_{Tm} = standard deviation of the multimodal reference temperature, T_m (°C)
T = temperature of a fracture toughness test (°C)
T_{28J} = temperature corresponding to a Charpy energy absorption of 28 J (°C)
T_0 = Master Curve reference temperature, corresponding to a median 1TC(T) toughness of 100 MPa$\sqrt{m}$ (°C)
T_0^* = Master Curve reference temperature corresponding to a modified valid test temperature range (°C)
T_{0IN} = alternative reference temperature for a macroscopically inhomogeneous data set, obtained by the simplified method (°C)
T_{0IN}^* = alternative reference temperature for a macroscopically inhomogeneous data set, obtained by the simplified method, corresponding to a modified valid test temperature range (°C)
T_{0scrn} = temperature value calculated within the homogeneity screening procedure of ASTM E1921 (°C)
T_m = alternative reference temperature for a macroscopically inhomogeneous data set, obtained by the multimodal method, corresponding to a modified valid test temperature range (°C)
T_m^* = alternative reference temperature for a macroscopically inhomogeneous data set, obtained by the multimodal method (°C)

Introduction

The Master Curve (MC) methodology was developed in the 1980s[1] to statistically analyze fracture toughness test results obtained in the ductile-to-brittle transition regime, where varying amounts of stable and unstable crack propagation can occur. The main outcome is the reference temperature T_0, which characterizes the fracture toughness of ferritic steels experiencing elastic or elastic-plastic instabilities due to cleavage cracking.

The weakest-link theory,[2] applied to a three-parameter Weibull distribution of fracture toughness values, K_{Jc}, is used to characterize the statistical effects of specimen size on fracture toughness in the transition regime, while enforcing a limit on K_{Jc} values to ensure high constraint along the crack front when fracture occurs.

Once T_0 is established, the median fracture toughness of the material for a standard specimen of 1-in. (25.4-mm) thickness is described by a fixed-shaped curve (MC), such that at T_0, the median fracture toughness $K_{Jc,med}$ is equal to 100 MPa$\sqrt{m}$. From a structural integrity and safety perspective, tolerance bounds can be established corresponding to low fracture probabilities, such as 5 % or 2 %. The standard deviation of the data distribution is a function of the Weibull slope and $K_{Jc,med}$.

The MC procedure was first standardized by ASTM in 1997 and has undergone multiple revisions up to the current version, ASTM E1921-22a, *Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range*.[3]

The first published version of the standard, E1921-97, recommended the test temperature, T, be as close as possible to T_0, and provided an empirical method for establishing a starting value for T, based on the temperature corresponding to a Charpy absorbed energy of 28 J:

$$T = T_{28J} + C \tag{1}$$

where C is a constant (in °C), which depends on the specimen thickness. In this early version, only a single-temperature option was available for the determination of T_0, and if different test temperatures were sampled and different T_0 values obtained, the reference temperature had to be calculated by averaging those individual values. In this 1997 version, no requirements on a specific validity range for test temperatures were provided.

However, already in the following version of the standard (ASTM E1921-02), a multitemperature option was made available, although for many years, the single-temperature approach remained the recommended option. The 2002 edition was also the first one to prescribe a valid range for the test temperature, $T_0 \pm 50°C$, outside which test results cannot be used in MC calculations. Within this range, data obtained in the range $T_0 - 50°C \leq T \leq T_0 - 14°C$ were deemed to provide a reduced accuracy contribution to the determination of T_0 and were therefore associated to a lower weight for the validation of the reference temperature.

Although the multitemperature approach became the reference option in 2013, with the single-temperature option labeled as a "special case" from then on, the $T_0 \pm 50°C$ valid temperature range has remained unchanged until the current version of the standard.[3] The implications of this prescribed range are as follows:

- For specimens tested more than 50°C below the reference temperature, the lower-shelf toughness of the steel is approached, and the uncertainty in T_0 determination increases to unacceptable levels. When lower-shelf conditions exist, the weakest-link theory and the Weibull distribution of fracture toughness values do not apply.[*]
- When tests are performed above $T_0 + 50°C$, the likelihood of cleavage becomes small, and upper shelf toughness conditions may be approached.

Based on personal communications between the author and some of the leading actors in standardizing the MC approach, the exact origin of the $T_0 \pm 50°C$ range is somewhat uncertain and appears to be based not on specific research but rather on engineering common sense. It was first mentioned in an Oak Ridge National Laboratory report that provided the technical basis for ASTM E1921.[4] The valid test temperature range was established to ensure that measurements are taken as close as possible to T_0 to account for the fact that some material properties might not explicitly follow the MC shape. This is especially crucial below T_0, where even small changes in toughness can have a large effect on the calculated T_0.

At the lower limit of the range, T_0 – 50°C, the median toughness of a generic ferritic steel, based on the MC equation, is 57.1 MPa$\sqrt{m}$. This toughness level is close to typical lower-shelf linear-elastic fracture toughness, K_{Ic}, values for numerous steels.[5] At the upper limit of the range, $T_0 + 50°C$, however, the median toughness is 211.0 MPa$\sqrt{m}$, which is less than typical values obtained from high-toughness steel

[*]Ideally, the fracture surfaces of specimens tested below T_0 – 50°C should be examined to confirm that failure was caused by a single cleavage initiation site, as required by the weakest-link theory, rather than by widespread brittle fracture. However, for most of the investigated data sets (particularly the older ones), the tested specimens are unavailable, and therefore, the conclusions obtained in this study are based on purely analytical considerations.

specimens failing by cleavage. At first sight, therefore, the upper limit appears technically less justified than the lower limit and might have been established on the basis of pure "symmetry" considerations with respect to the lower limit.

The purpose of this investigation is to assess whether an extension of the valid temperature range is technically justifiable, based on MC analyses of several large "historical" data sets. The consequences of using data below and above the current temperature limits were examined in terms of T_0 variation with respect to the reference temperatures determined in strict accordance with the current standard, ASTM E1921-22a.[3] For data sets that were screened macroscopically inhomogeneous, analyses were extended to alternative definitions of T_0, namely T_{0IN} (simplified method) and T_m (multimodal approach).

A possible extension of the test temperature range would bring benefits for many experimental programs. Specifically, it would facilitate testing small-size specimens, such as miniature compact tension specimen (MC(T), typical thickness = 4 mm) or Charpy-type miniaturized bend samples. Because excessive ductile crack growth tends to develop on very small specimens as test temperature is increased, it is often difficult to fully satisfy the current lower limit, $T_0 - 50°C$. Additionally, data sets generated before the MC method was standardized often contain significant amount of test data obtained above $T_0 + 50°C$, and therefore, an extension of the upper limit would facilitate their analysis.

Data Sets Considered and Analyses Performed

Ten large, publicly available data sets, including between 55 and 734 fracture toughness test results and corresponding to eight different ferritic steels (base metals and welds) and specimens of various type and size, were analyzed in this study (**Table 1**). Details of each data set are provided in the references listed in the last column of the table. The complete data sets can be obtained by contacting the author.

In **Table 1**, the number of test results included in each data set is indicated by N_{tests}, and N corresponds to the number of data points within the range $T_0 - 50°C \le T \le T_0 + 50°C$. r is the number of uncensored data, *i.e.*, below the maximum K_{Jc} capacity and with less than the maximum allowed ductile crack extension preceding cleavage.

The numbers of data points corresponding to tests performed below and above the current limits of the E1921 valid test temperature range, $T_0 \pm 50°C$, are listed in **Table 2** for each of the large data sets, split into 5°C intervals below T_0 – 50°C and into 10°C intervals above $T_0 + 50°C$. It is clear that many more test results are available above the upper limit than below the lower limit of the valid test temperature range.

TABLE 1
Large historical fracture toughness data sets considered in this study

Data Set	N_{tests}	N	r	Specimens Tested	References
72W unirradiated	77	44	44	1TC(T) to 8TC(T)	8
72W irradiated	56	16	16	1TC(T), 2TC(T), 4TC(T)	8
73W unirradiated	80	55	54	1TC(T) to 8TC(T)	8
73W irradiated	55	19	19	1TC(T), 2TC(T), 4TC(T)	8
Ingham et al.	216	52	36	PCCv, 1TSE(B) to 9TSE(B)	9
EURO	734	278	265	0.5TC(T), 1TC(T), 2TC(T), 4TC(T)	10
JSPS Round-Robin	116	85	85	1TC(T)	11
Midland 1 Weld irradiated	111	63	40	PCCv, MC(T), 0.5TC(T), 1TC(T)	12–15
Plate 13A(C(T) specimens)	124	64	64	0.5TC(T), 1TC(T), 2TC(T), 4TC(T)	16
Plate 13A(SE(B) specimens)	216	52	36	PCCv, 1TSE(B) to 9TSE(B)	

Note: C(T) = compact tension specimen; JSPS = Japanese Society for the Promotion of Science; NTC(T) = compact tension specimen with thickness of N in. (= N × 25.4 mm); NTSE(B) = single-edge bend specimen with thickness of N in. (= N × 25.4 mm); PCCv = fatigue precracked Charpy-type specimen; SE(B) = single-edge bend specimen.

TABLE 2

Specimens tested below and above the current E1921 valid test temperature range for the 10 large datasets

	Below T_0 – 50°C						Above T_0 + 50°C					
Data Set	N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	N_9	N_{10}	N_{11}	N_{12}
72W unirradiated	3	0	0	0	0	0	11	11	11	7	0	1
72W irradiated	1	0	0	0	0	0	7	16	11	4	0	1
73W unirradiated	4	0	0	0	0	0	10	9	0	1	1	1
73W irradiated	1	0	0	0	0	5	15	6	8	0	1	0
Ingham et. al	0	0	0	0	0	0	40	9	20	18	32	48
EURO	0	0	103	0	0	0	0	126	5	117	0	0
JSPS Round-Robin	0	0	0	0	0	0	50	0	0	0	0	0
Midland 1 Weld irradiated	0	0	0	0	0	0	5	0	0	8	7	7
Plate 13A(C(T) specimens)	0	47	0	0	0	0	0	8	0	0	0	5
Plate 13A(SE(B) specimens)	0	0	0	0	0	0	40	0	20	17	33	45

Note: N_1 = number of specimens tested below T_0 – 75°C; N_2 = number of specimens tested between T_0 – 75°C and T_0 – 70°C; N_3 = number of specimens tested between T_0 – 70°C and T_0 – 65°C; N_4 = number of specimens tested between T_0 – 65°C and T_0 – 60°C; N_5 = number of specimens tested between T_0 – 60°C and T_0 – 55°C; N_6 = number of specimens tested between T_0 – 55°C and T_0 – 50°C; N_7 = number of specimens tested between T_0 + 50°C and T_0 + 65°C; N_8 = number of specimens tested between T_0 + 60°C and T_0 + 70°C; N_9 = number of specimens tested between T_0 + 70°C and T_0 + 80°C; N_{10} = number of specimens tested between T_0 + 80°C and T_0 + 90°C; N_{11} = number of specimens tested between T_0 + 90°C and T_0 + 100°C; N_{12} = number of specimens tested above T_0 + 100°C.

Many of the data sets listed in **Table 1** were generated before the MC methodology was even formulated. Specifically, these data sets were obtained with no particular effort to target a temperature range close to the middle of the transition region. It is not surprising, therefore, that N is often significantly lower than N_{tests}. This makes them ideal candidates for assessing the effect of including data above and below the current temperature limits. Namely, for the 10 data sets combined, N_{tests} = 1996 and N = 977 (48.9 %). The overall number of uncensored data, r, is 851, or 87.1 % of N.

On each of the data sets listed in **Table 1**, the following MC analyses were performed:

- Standard MC analysis under the assumption of macroscopically homogeneous material (T_0).
- Application of the E1921 screening criterion to establish homogeneity or inhomogeneity ($T_{0,scrn}$).
- For potentially inhomogeneous data sets, calculation of the modified reference temperature, T_{0IN}, according to the simplified method.
- For potentially inhomogeneous data sets, calculation of the multimodal reference temperature,* T_m, and its associated standard deviation, σ_{Tm}.

The analyses listed here were performed on each data set using the following valid temperature ranges for data selection:

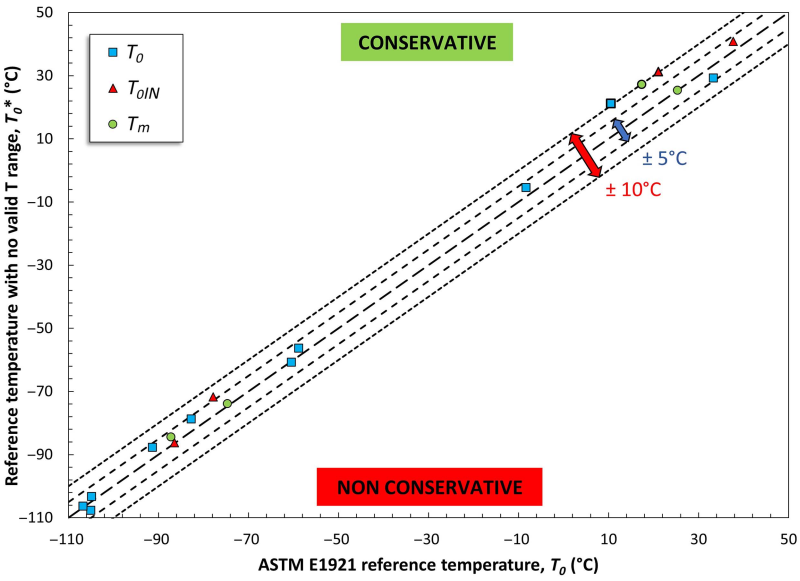
- Current ASTM E1921-22a range, T_0 – 50°C ≤ T ≤ T_0 + 50°C.
- No test temperature limits.
- Current lower limit (50°C ≤ T – T_0) and increased upper limit (T – T_0 ≤ 60°C, 70°C, 80°C, 90°C, and 100°C).
- Decreased lower limit (T – T_0 ≥ 55°C, 60°C, 65°C, 70°C, and 75°C) and current upper limit (T – T_0 ≤ 50°C).
- Valid temperature range symmetrically expanded (T_0 ± 55°C, T_0 ± 60°C, T_0 ± 65°C, T_0 ± 70°C, T_0 ± 75°C).

Analyses were performed using the open code T0TEM (T0 Test Evaluation Module – Ver. 1.5), developed by NASA[6] and explicitly mentioned in the current version of ASTM E1921.

*This investigation only focused on the multimodal procedure and did not consider the other approach for macroscopically inhomogeneous materials described in ASTM E1921-22a, the bimodal procedure.

FIG. 1

Comparison between homogeneous reference temperatures calculated according to ASTM E1921-22a and after removing the valid test temperature range.



Removal of Temperature Limits

If the valid temperature range is completely removed from the analysis, so that all data points are used for the determination of T_0, the outcome illustrated in **figure 1** is obtained, comparing "rigorous" reference temperatures from homogeneous (T_0) and inhomogeneous (T_{0IN}, T_m) analyses calculated in accordance with ASTM E1921-22a, with the corresponding values calculated after removing the temperature limits (T_0*, T_{0IN}*, T_m*).[*]

In case of homogeneous analyses (T_0 and T_0*), calculated values for nine out of ten data sets lie within ±5°C, which can be considered a range of practical equivalence between modified and reference values.[†] Most T_0* values (7 out of 10) are higher than T_0 and therefore conservative (higher reference temperature means lower toughness). The only difference larger than 5°C ($T_0^* - T_0 = 10.6$°C), again in a conservative direction, corresponds to 72W irradiated, which is one of the macroscopically inhomogeneous data sets.

In case of inhomogeneous analyses (T_{0IN} and T_{0IN}*, T_m and T_m*) on four data sets, all modified values of T_{0IN} and T_m are higher (and therefore conservative) than their E1921-22a counterparts.

The calculation results are summarized in **Table 3**.

Asymmetric Valid Temperature Ranges

INCREASED UPPER LIMIT (LOWER LIMIT UNCHANGED)

The effect of increasing the upper limit of the valid temperature range from $T_0 + 50$°C to $T_0 + 100$°C, in steps of 10°C, is illustrated by comparing rigorous and modified reference temperatures in **figure 2** (homogeneous analy-

*In this study, all reference temperatures calculated not in strict accordance with ASTM E1921-22a, after modifying or removing the limits of the valid temperature range, are identified by an asterisk (*).

†According to the Precision and Bias section of ASTM E1921-22a, the typical reproducibility of multitemperature T_0 values is of the order of 5.7°C.

TABLE 3

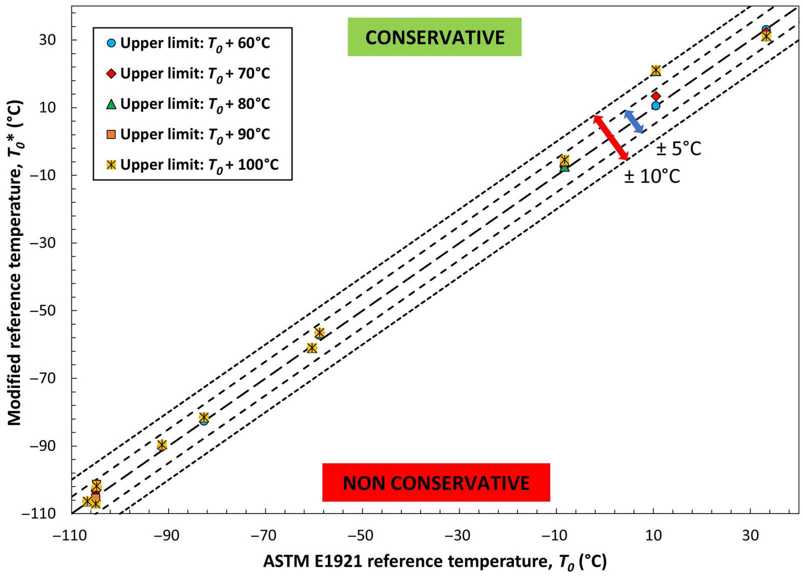
Homogeneous reference temperatures calculated according to ASTM E1921-22a and after removing temperature limits

Data Set	T_0, °C	T_0*, °C	$T_0* - T_0$ (°C)	T_{0IN}, °C	T_{0IN}*, °C	$T_{0IN}* - T_{0IN}$ (°C)	T_m, °C	T_m*, °C	$T_m* - T_m$ (°C)
72W unirradiated	−58.8	−56.3	2.5		−52.5			−55.3	
72W irradiated	10.6	21.2	10.6	21.0	31.3	10.2	17.4	27.3	9.9
73W unirradiated	−60.4	−60.8	−0.3						
73W irradiated	33.3	29.3	−4.0		38.6			31.0	
Ingham et. al	−105.0	−107.7	−2.7						
EURO	−91.3	−87.7	3.6	−86.5	−86.2	0.3	−87.2	−84.4	2.8
JSPS Round-Robin	−106.7	−106.3	0.4						
Midland 1 Weld irradiated	−8.3	−5.4	2.9	37.7	40.8	3.2	25.3	25.4	0.1
Plate 13A(C(T) specimens)	−82.7	−78.7	3.9	−77.8	−71.7	6.1	−74.7	−73.9	0.8
Plate 13A(SE(B) specimens)	−104.8	−103.3	1.6						

Note: Where no value is reported, the material screened homogeneous, and therefore T_{0IN} and T_m were not calculated.

FIG. 2

Comparison between homogeneous reference temperatures calculated according to ASTM E1921-22a and after increasing the upper limit of the valid test temperature range.



ses, T_0 and T_0*), **figure 3** (simplified inhomogeneous analyses, T_{0IN} and T_{0IN}*), and **figure 4** (multimodal inhomogeneous analyses, T_m and T_m*).

For the overwhelming majority of the analyses (9 out of 10 data sets) and for all reference temperatures (T_0, T_{0IN}, T_m), differences between rigorous and modified values are within ±5°C. The only exception is 72W irradiated, for which differences up to 11.2°C were obtained. In just 29 % of the cases, the effect of increasing the upper temperature limit is nonconservative (lower reference temperatures). This includes the largest recorded deviations for 72W irradiated.

Figure 5 shows the distribution of homogeneous reference temperature differences ($T_0* - T_0$), or residuals, for different values of the upper limit. A slight tendency of data scatter and mean values to increase with the upper limit can be observed. The two high outliers correspond to the 72W irradiated data set. The same trends are

FIG. 3

Comparison between inhomogeneous reference temperatures calculated according to the simplified method of ASTM E1921-22a and after increasing the upper limit of the valid test temperature range.

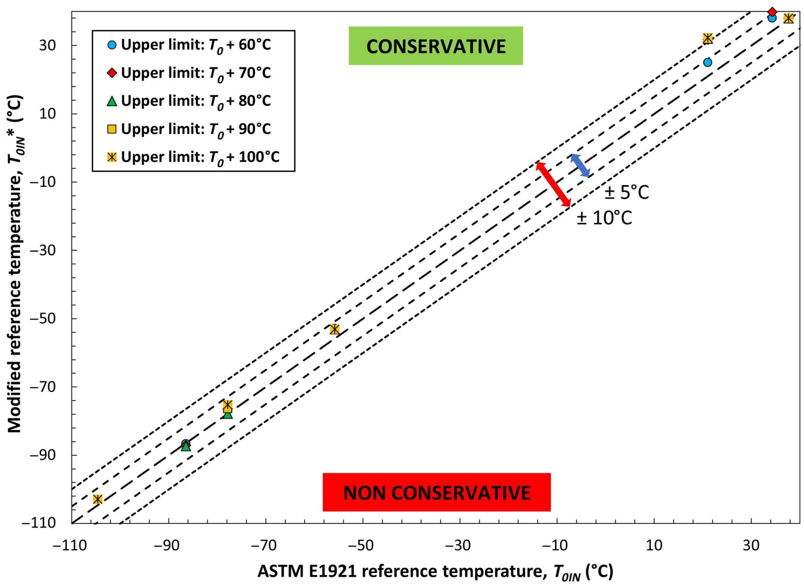
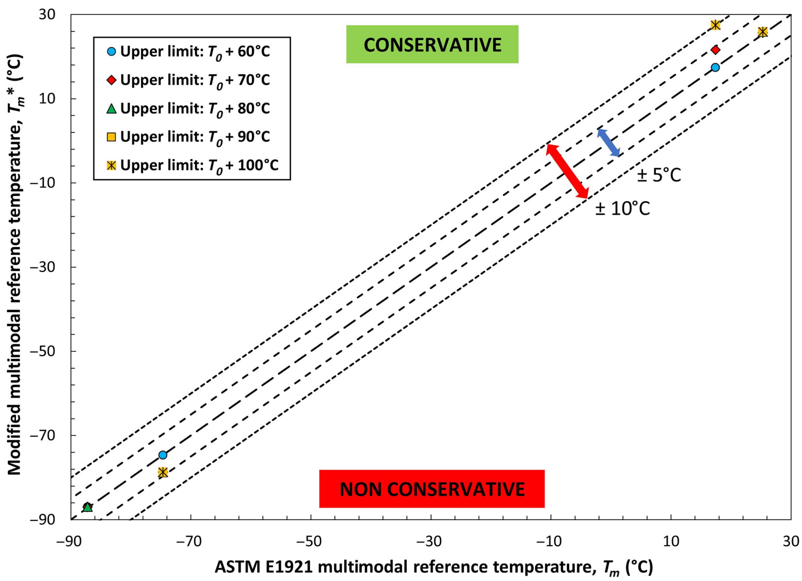


FIG. 4

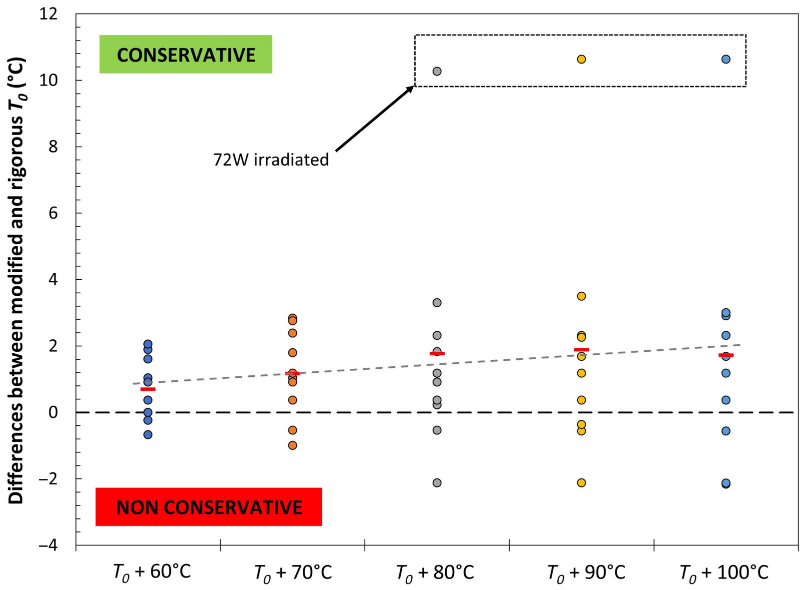
Comparison between inhomogeneous reference temperatures calculated according to the multimodal method of ASTM E1921-22a and after increasing the upper limit of the valid test temperature range.



observed for $T_{0IN}* - T_{0IN}$, whereas for $T_m* - T_m$, the mean and median values tend to decrease to more nonconservative values as the upper limit of the valid temperature range increases. The corresponding plots are not shown here for the sake of brevity.

A summary table with rigorous and modified reference temperature values, as well as relevant differences, is provided as Appendix A in the supplementary material.

FIG. 5

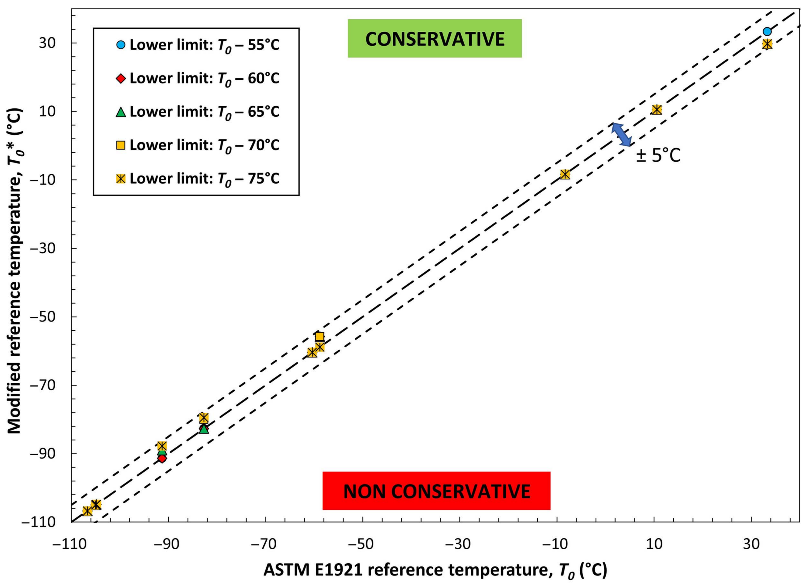


Residuals (differences between rigorous and modified homogeneous reference temperatures) obtained after increasing the upper limit of the valid test temperature range. Short red bars represent mean residuals.

DECREASED LOWER LIMIT (UPPER LIMIT UNCHANGED)

Values of rigorous and modified T_0, T_{0IN}, and T_m are compared for different lower limits of the valid temperature range from T_0 – 55°C to T_0 – 75°C (in steps of 5°C) in figures 6–8, respectively. For both T_0 and T_{0IN}, all observed differences are within ±5°C. In the case of T_m, the largest difference is 7.0°C (conservative). Only 25 % of all the modified reference temperatures, for both homogeneous and inhomogeneous analyses, are negative, i.e., nonconservative.

FIG. 6



Comparison between homogeneous reference temperatures calculated according to ASTM E1921-22a and after decreasing the lower limit of the valid test temperature range.

FIG. 7

Comparison between inhomogeneous reference temperatures calculated according to the simplified method of ASTM E1921-22a and after decreasing the lower limit of the valid test temperature range.

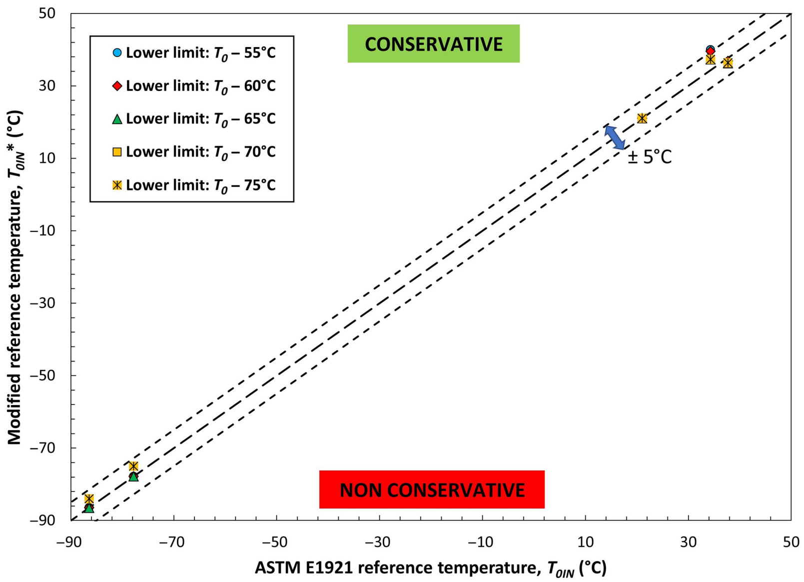
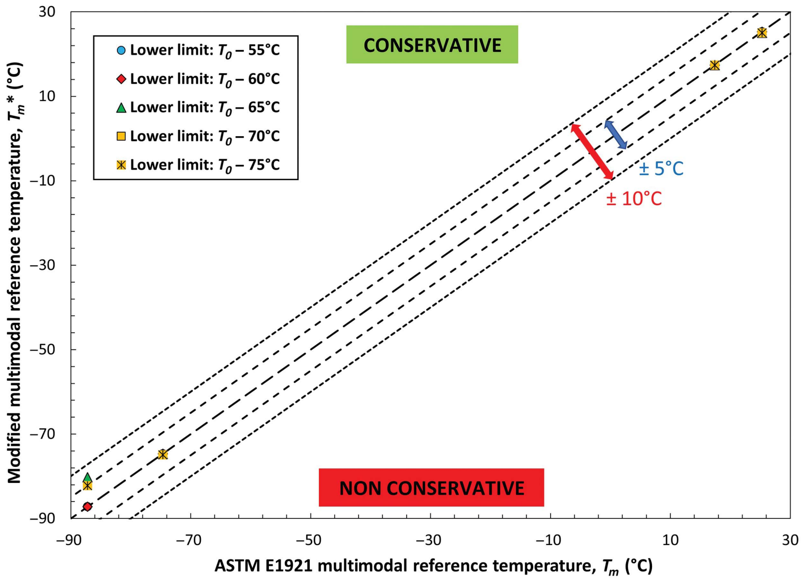


FIG. 8

Comparison between inhomogeneous reference temperatures calculated according to the multimodal method of ASTM E1921-22a and after decreasing the lower limit of the valid test temperature range.

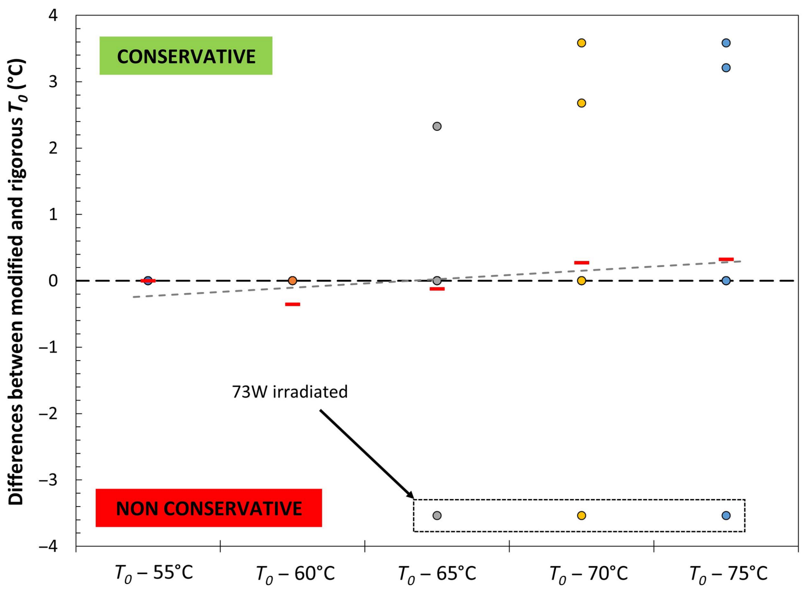


Very few data points are available when decreasing the lower limit of the temperature range (**fig. 9**). As the lower limit decreases, the mean $T_0* - T_0$ values (indicated in **figure 9** by short red bars) tend to slightly increase. Qualitatively similar trends with decreasing lower limits were also observed for $T_{0IN}* - T_{0IN}$ and $T_m* - T_m$. Again, plots are not shown for brevity.

Rigorous and modified reference temperature values, along with corresponding differences, are reported as Appendix B in the supplementary material.

FIG. 9

Differences between rigorous and modified homogeneous reference temperatures after decreasing the lower limit of the valid test temperature range.



Symmetric Valid Temperature Ranges

The consequences of evenly expanding the valid temperature range from $T_0 \pm 55°C$ to $T_0 \pm 75°C$, in steps of 5°C, are illustrated in **figure 10** (T_0* versus T_0), **figure 11** (T_{0IN}* versus T_{0IN}), and **figure 12** (T_m* versus T_m). Only 20°C of the reference temperatures calculated, homogeneous and inhomogeneous (both simplified and multimodal), are lower than their rigorous counterpart (nonconservative), and the largest differences, all conservative, are between 8°C and 11°C. These all correspond to the three widest ranges ($T_0 \pm 65°C$, $T_0 \pm 70°C$, and $T_0 \pm 75°C$).

FIG. 10

Comparison between homogeneous reference temperatures calculated according to ASTM E1921-22a and after symmetrically expanding the valid test temperature range.

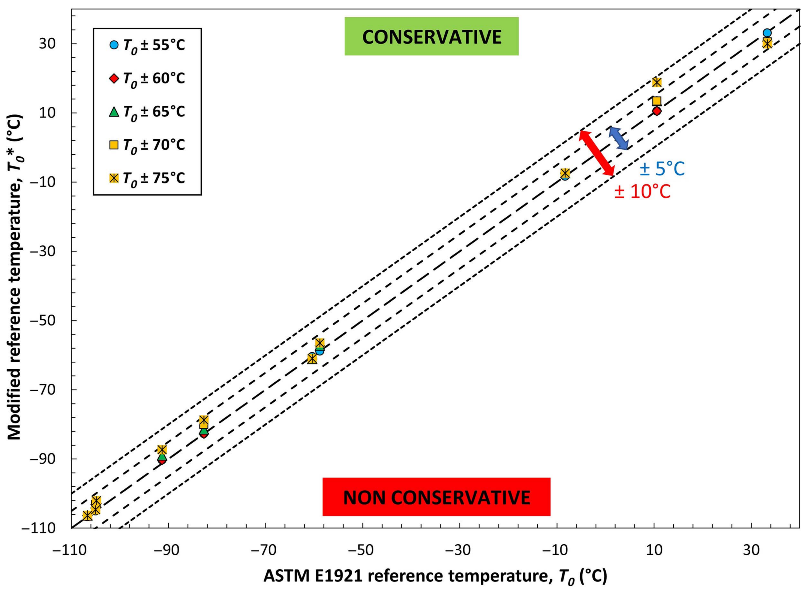


FIG. 11

Comparison between inhomogeneous reference temperatures calculated according to the simplified method of ASTM E1921-22a and after symmetrically expanding the valid test temperature range.

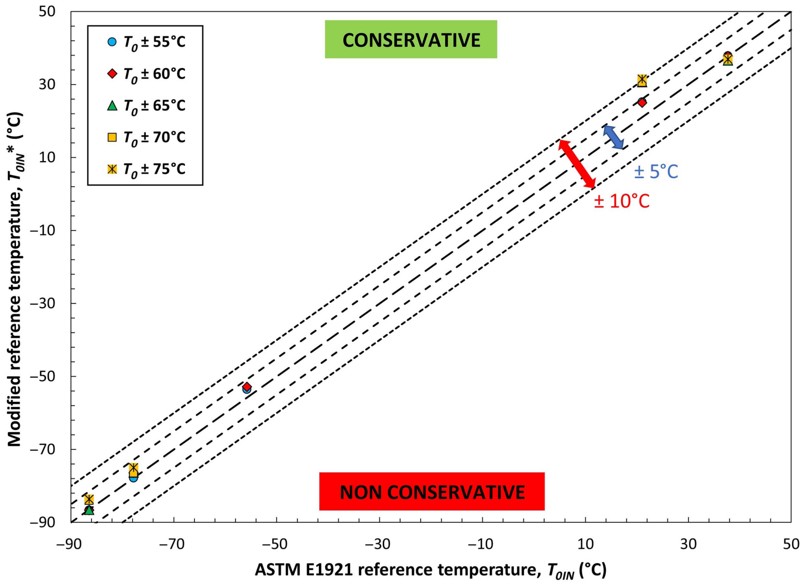
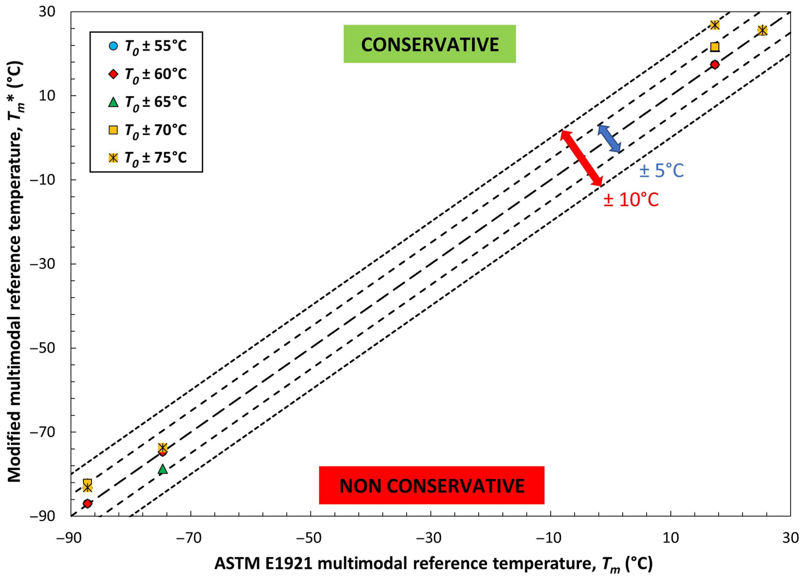


FIG. 12

Comparison between inhomogeneous reference temperatures calculated according to the multimodal method of ASTM E1921-22a and after symmetrically expanding the valid test temperature range.

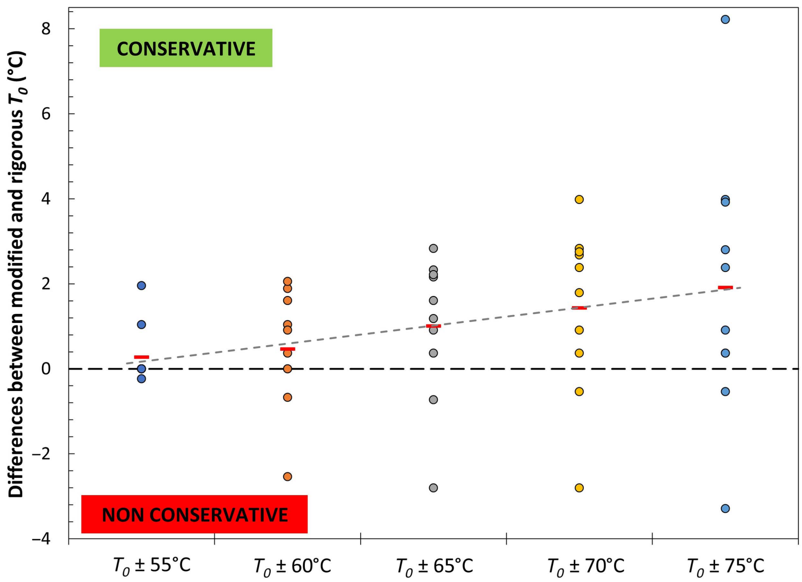


As the valid temperature range becomes wider, a clear increase in scatter and mean values of the recorded differences $T_0* - T_0$ can be observed from **figure 13**. The same trends were observed for $T_{0IN}* - T_{0IN}$ and $T_m* - T_m$ and are not shown here for brevity.

Appendix C in the supplementary material reports all the rigorous and modified reference temperatures, with the relevant differences.

FIG. 13

Differences between rigorous and modified homogeneous reference temperatures after symmetrically expanding the valid test temperature range.



Effects on the Homogeneity/Inhomogeneity of Data Sets

Of the 10 large data sets analyzed, four were deemed to be macroscopically inhomogeneous according to the screening criterion of ASTM E1921-22a:

$$T_{0scrn} - T_0 > 1.44\sqrt{\frac{\beta^2}{r}} \tag{2}$$

where $T_{0\text{scrn}}$ is determined by applying the homogeneity screening procedure of section 10.6, β is a sample size uncertainty factor which depends on the median fracture toughness of the data set, and r is the number of uncensored $K_{Jc,1T}$ values in the data set.

In a recent publication by the author,[7] a dimensionless parameter called Screening Criterion Index (*SCI*) was introduced, obtained by rearranging equation (2):

$$SCI = \frac{T_{0scrn} - T_0}{1.44\sqrt{\frac{\beta^2}{r}}} \tag{3}$$

According to equation (2), a material is screened macroscopically inhomogeneous when $SCI \geq 1$. Moreover, the higher is the value of *SCI* (or the larger the difference between T_{0scrn} and T_0), the more pronounced is the inhomogeneity of the material. We can therefore, in a totally arbitrary manner, establish the degree/level of inhomogeneity of each data set according to the value of *SCI*, based on the following (subjective) classification[*]:

- $SCI < 0.5$: strongly homogeneous
- $0.5 \leq SCI \leq 1$: moderately homogeneous
- $1 < SCI \leq 1.5$: moderately inhomogeneous
- $SCI > 1.5$: strongly inhomogeneous.

[*] A similar approach could also be applied based on the value of the *MLNH* parameter, which is used by E1921-22a to assess the likelihood that a data set is inhomogeneous, according to both the bimodal and multimodal approaches.

The inhomogeneity assessments for the 10 investigated large data sets, based on rigorous MC analyses, are summarized in Table 4. Based on these assessments, three of the four inhomogeneous data sets are strongly inhomogeneous ($SCI > 1.5$): 72W irradiated, EURO, Midland Unit 1 Weld irradiated. The fourth data set, Plate 13A C(T) specimens, is at the limit between moderately and strongly inhomogeneous ($SCI = 1.5$).

Two of the three strongly inhomogeneous data sets are irradiated weld materials, for which the effect of neutron irradiation adds up to the intrinsically heterogeneous nature of weld metals. In particular, the Midland 1 Weld data set displays a very high degree of inhomogeneity ($SCI = 14$). For this data set, inhomogeneity is most likely enhanced by the presence of different specimen/loading configurations (compact tension and pre-cracked Charpy specimens), as well as a large variation in specimen thickness, ranging from 1 in. = 25.4 mm (1TC(T)) to 4 mm (mini-C(T)).

Five of the remaining six data sets appear strongly homogeneous, with *SCI* values between 0.1 and 0.2, whereas the last one (72W unirradiated) is moderately homogeneous ($SCI = 0.8$).

The screening criterion of equation (2) was applied to all the investigated data sets after removing the valid temperature range. The comparison with the rigorous assessments of Table 4 is provided in Table 5.

The prevailing effect (6 out of 10) is to increase *SCI*, i.e., augment the degree of inhomogeneity in the data set. In two cases (72W unirradiated and 73W irradiated), the data set changes its nature (from homogeneous to

TABLE 4

Macroscopic inhomogeneity assessments for the 10 large data sets based on rigorous MC analyses

Data Set	Screening Result	*SCI*	*SCI*-Based Assessment
72W unirradiated	HOM	0.8	Moderately homogeneous
72W irradiated	INHOM	1.6	Strongly inhomogeneous
73W unirradiated	HOM	0.2	Strongly homogeneous
73W irradiated	HOM	0.2	Strongly homogeneous
Ingham et. al	HOM	0.1	Strongly homogeneous
EURO	INHOM	3.1	Strongly inhomogeneous
JSPS Round-Robin	HOM	0.2	Strongly homogeneous
Midland 1 Weld irradiated	INHOM	14.0	Extremely inhomogeneous
Plate 13A(C(T) specimens)	INHOM	1.5	Moderately inhomogeneous
Plate 13A(SE(B) specimens)	HOM	0.1	Strongly homogeneous

Note: HOM = homogeneous; INHOM = inhomogeneous.

TABLE 5

Comparison between macroscopic inhomogeneity assessments for the 10 large data sets before and after removing the valid temperature range

	Rigorous		After Removing Valid Temperature Range	
Data Set	Screening Result	*SCI*	Screening Result	*SCI*
72W unirradiated	HOM	0.8	INHOM	1.3
72W irradiated	INHOM	1.6	INHOM	2.7
73W unirradiated	HOM	0.2	HOM	0.1
73W irradiated	HOM	0.2	INHOM	2.4
Ingham et. al	HOM	0.1	HOM	1.0
EURO	INHOM	3.1	INHOM	1.3
JSPS Round-Robin	HOM	0.2	HOM	0.2
Midland 1 Weld irradiated	INHOM	14.0	INHOM	15.5
Plate 13A(C(T) specimens)	INHOM	1.5	INHOM	3.0
Plate 13A(SE(B) specimens)	HOM	0.1	HOM	0.0

TABLE 6
Macroscopic inhomogeneity assessments for the 10 large data sets after increasing the upper range limit

	Rigorous		Increased Upper Limit of the Valid Temperature Range									
	$T_0 + 50°C$		$T_0 + 60°C$		$T_0 + 70°C$		$T_0 + 80°C$		$T_0 + 90°C$		$T_0 + 100°C$	
Data Set	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*
72W unirr	HOM	0.8	INHOM	1.2	HOM	0.7	INHOM	1.1	INHOM	1.1	INHOM	1.1
72W irr	INHOM	1.6	INHOM	2.2	INHOM	3.3	INHOM	2.9	INHOM	2.8	INHOM	2.9
73W unirr	HOM	0.2	HOM	0.1	HOM	0.0	HOM	0.0	HOM	0.0	HOM	0.0
73W irr	HOM	0.2	INHOM	1.1	INHOM	1.7	INHOM	2.1	INHOM	2.2	INHOM	2.2
Ingham	HOM	0.1	HOM	0.0	HOM	0.6	HOM	0.9	HOM	0.9	INHOM	1.3
EURO	INHOM	3.1	INHOM	2.6	INHOM	2.3	INHOM	1.7	HOM	0.0	HOM	0.0
JSPS R-R	HOM	0.2	HOM	0.3	HOM	0.3	HOM	0.3	HOM	0.3	HOM	0.3
Midland Weld irr	INHOM	14.0	INHOM	14.3	INHOM	14.2	INHOM	14.2	INHOM	14.4	INHOM	14.5
Plate 13AC(T)	INHOM	1.5	INHOM	1.9	INHOM	1.7	INHOM	1.2	INHOM	1.7	INHOM	2.1
Plate 13ASE(B)	HOM	0.1	HOM	0.0	HOM	0.3	HOM	0.0	HOM	0.0	HOM	0.0

TABLE 7
Macroscopic inhomogeneity assessments for the 10 large data sets after decreasing the lower range limit

	Rigorous		Decreased Lower Limit of the Valid Temperature Range									
	$T_0 - 50°C$		$T_0 - 55°C$		$T_0 - 60°C$		$T_0 - 65°C$		$T_0 - 70°C$		$T_0 - 75°C$	
Data Set	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*
72W unirr	HOM	0.8	HOM	0.8	HOM	0.8	HOM	0.8	HOM	0.8	HOM	0.8
72W irr	INHOM	1.6	INHOM	1.6	INHOM	1.6	INHOM	1.6	INHOM	1.6	INHOM	1.6
73W unirr	HOM	0.2	HOM	0.2	HOM	0.2	HOM	0.2	HOM	0.2	HOM	0.2
73W irr	HOM	0.2	INHOM	1.1	INHOM	1.9	INHOM	1.4	INHOM	1.4	INHOM	1.4
Ingham	HOM	0.1	HOM	0.1	HOM	0.1	HOM	0.1	HOM	0.1	HOM	0.1
EURO	INHOM	3.1	INHOM	3.1	INHOM	3.1	INHOM	1.8	INHOM	3.1	INHOM	3.1
JSPS R-R	HOM	0.2	HOM	0.2	HOM	0.2	HOM	0.2	HOM	0.2	HOM	0.2
Midland Weld irr	INHOM	14.0	INHOM	13.6	INHOM	13.7	INHOM	13.5	INHOM	13.5	INHOM	13.6
Plate 13AC(T)	INHOM	1.5	INHOM	1.5	INHOM	1.5	INHOM	1.5	HOM	0.7	INHOM	1.8
Plate 13ASE(B)	HOM	0.1	HOM	0.1	HOM	0.1	HOM	0.1	HOM	0.1	HOM	0.1

inhomogeneous). This might also be caused by the fact that, outside the valid test temperature range, the experimental data do not follow the MC shape for some of the investigated data sets.

Table 6 shows the consequences of increasing the upper limit of the valid temperature range. In the majority of cases (6 data sets out of 10), the nature of the data sets does not change. As for the remaining data sets, inhomogeneity changes in two cases, but only for the highest upper limit values (Ingham and EURO). In just more case (72W unirradiated), the nature switches back and forth as the upper limit increases.

TABLE 8
Macroscopic inhomogeneity assessments for the 10 large data sets when using expanded valid temperature ranges

	Rigorous		Expanded Valid Temperature Range									
	$T_0 \pm 50°C$		$T_0 \pm 55°C$		$T_0 \pm 60°C$		$T_0 \pm 65°C$		$T_0 \pm 70°C$		$T_0 \pm 75°C$	
Data Set	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*	Screening Result	*SCI*
72W unirr	HOM	0.8	INHOM	1.4	INHOM	1.2	HOM	0.9	HOM	0.7	HOM	0.9
72W irr	INHOM	1.6	INHOM	2.3	INHOM	2.2	INHOM	3.1	INHOM	3.1	INHOM	2.9
73W unirr	HOM	0.2	HOM	0.1	HOM	0.1	HOM	0.0	HOM	0.0	HOM	0.0
73W irr	HOM	0.2	HOM	0.9	INHOM	1.6	INHOM	1.9	INHOM	2.1	INHOM	2.2
Ingham	HOM	0.1	HOM	0.4	HOM	0.0	HOM	0.0	HOM	0.6	HOM	0.5
EURO	INHOM	3.1	INHOM	2.6	INHOM	2.6	INHOM	1.8	INHOM	2.9	INHOM	3.3
JSPS R-R	HOM	0.2	HOM	0.2	HOM	0.3	HOM	0.3	HOM	0.3	HOM	0.3
Midland Weld irr	INHOM	14.0	INHOM	14.0	INHOM	14.2	INHOM	13.8	INHOM	13.9	INHOM	13.9
Plate 13AC(T)	INHOM	1.5	INHOM	1.5	INHOM	1.9	INHOM	1.7	INHOM	1.2	INHOM	1.6
Plate 13ASE(B)	HOM	0.1	HOM	0.0	HOM	0.0	HOM	0.0	HOM	0.3	HOM	0.0

The effects of decreasing the lower limit of the valid temperature range are shown in **Table 7**. For 6 of the 10 data sets, no consequences are observed up to T_0 – 75°C, as confirmed by constant values of *SCI*. Two of the remaining data sets (EURO and Midland) exhibit variations of *SCI* but no changes in their inhomogeneous nature. As far as the last two data sets are concerned, 73W irradiated becomes inhomogeneous as soon as the lower limit is decreased, whereas Plate 13A C(T) becomes slightly homogeneous ($SCI = 0.7$) but only for T_0 – 70°C. Obviously, there could be multiple variables determining the effects summarized in **Table 7**, such as the ratio between compact and bend specimens tested, through-thickness location of the samples, fluence differences in the case of irradiated data sets, and specimen location as a function of test temperature. Consideration of these factors is outside the scope of this work.

Finally, we examined the effects of using expanded symmetrical ranges, up to $T_0 \pm 75°C$ (**Table 8**). The overwhelming majority of the data sets (8 out of 10) does not change its nature. The exceptions are 72W unirradiated, which first becomes inhomogeneous as the temperature range is extended and then become homogeneous again with further expansion, and Plate 13A, which is generally inhomogeneous, except for $T_0 \pm 70°C$.

Data Set Homogeneity: Summary and Discussion

Of the 10 large data sets considered in this study, six screened homogeneous and four inhomogeneous according to the criterion set forth in ASTM E1921-22a, equation (2). Of the six homogeneous data sets, five were found to be "significantly homogeneous" based on the value of the parameter $SCI = 0.1 \div 0.2$, whereas the sixth one (72W unirradiated) was found to be "moderately homogeneous," as the calculated value of $SCI = 0.8$ is close to the threshold value $SCI = 1$. Note that the rigorous result for 73W irradiated, $SCI = 0.2$, can be considered surprising, as this is a weld material subject to neutron irradiation, a condition that normally entails material inhomogeneity.

As for the inhomogeneous data sets, three resulted "strongly inhomogeneous" ($SCI > 1.5$), and one of those (Midland Weld irradiated) was actually labeled "extremely inhomogeneous" ($SCI = 14.0$); the fourth one (Plate 13A C(T)) was found to be "moderately inhomogeneous," with a value of *SCI* just below 1.5.

After modifying or removing the valid temperature range and reapplying the screening criterion, in five cases, no change in the nature of the data sets is observed. All of these correspond to significantly homogeneous (three) or inhomogeneous (two) data sets.

For the remaining five data sets, changes were recorded for one or more modified temperature ranges: one was originally moderately homogeneous, one moderately inhomogeneous, two significantly homogeneous, and one significantly inhomogeneous. Let's look at these latter three cases in more detail:

- 73W irradiated ($SCI_{E1921\text{-}22a} = 0.2$) becomes inhomogeneous for most of the modified ranges, which lends support to the previously mentioned hypothesis that the E1921-22a rigorous analysis does not really capture the "true" nature of this data set.
- The Ingham data set ($SCI_{E1921\text{-}22a} = 0.1$) becomes inhomogeneous only for the highest upper limit of the temperature range, $T_0 + 100°C$.
- The EURO data set ($SCI_{E1921\text{-}22a} = 3.1$) becomes homogeneous only for the two highest upper limits of the temperature range, $T_0 + 90°C$ and $T_0 + 100°C$.

As for the last two data sets that initially screened moderately homogenous (72W irradiated) and moderately inhomogeneous (Plate 13A C(T)), the proximity of the rigorous *SCI* value to the $SCI = 1$ threshold appears to justify possible changes of their nature as more data points get added to the analyses.

In summary, if a data set is strongly homogeneous or inhomogeneous, it is likely that its nature will not change when the valid temperature range is expanded or removed. Conversely, if homogeneity or inhomogeneity is not very pronounced, changes of nature might happen when the range is extended or removed. However, exceptions are always possible.

MC Analyses of Subsets Outside of the $T_O \pm 50°C$ Range

In the last part of this investigation, we selected from each large data set a few subsets corresponding to test temperatures outside the original validity range of E1921-22a, $T_0 \pm 50°C$. The resulting reference temperatures (T_0*, T_{0IN}*, and T_m*) were compared with the results of the rigorous analyses, which can be considered "true"

FIG. 14 Differences between rigorous and modified homogeneous/inhomogeneous reference temperatures, calculated from subsets outside $T_O \pm 50°C$, as a function of the difference between (weighted average) test temperature, T_{test}, and $T_O + 50°C$ (T_{upper}).

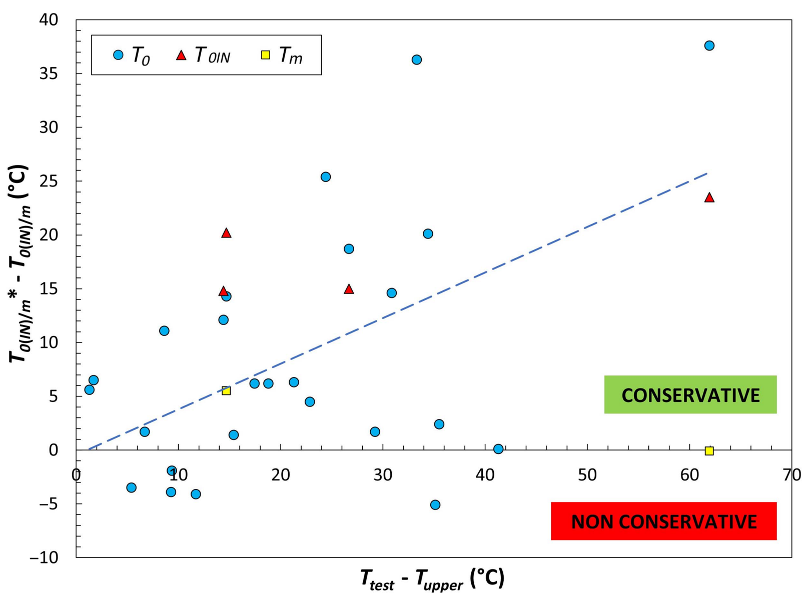


TABLE 9

Rigorous and modified reference temperatures calculated from subsets selected outside the E1921 valid temperature range

Data Set	N	T_0, °C	HOM/INHOM	T_{test}, °C	N^*	T_0^*, °C	ΔT_0, °C	HOM/INHOM	T_{0IN}, °C	T_{0IN}^*, °C	ΔT_{0IN}, °C	T_m^*, °C	T_m^*, °C	ΔT_m, °C
72W unirradiated	44	−58.8	HOM	−2, 0	11	−47.7	11.1	HOM	N/A			N/A		
				10	11	−52.6	6.2	HOM						
				20, 23	7	−57.1	1.7	INHOM		−43.0	N/A		N/A	N/A
				−2 to 23	29	−52.6	6.2	INHOM		−52.5	N/A		−48.1	N/A
72W irradiated	16	10.6	INHOM	75	7	22.7	12.1	INHOM		35.8	14.8		N/A	N/A
				85	16	36.0	25.4	HOM						
				95	11	30.7	20.1	HOM						
				75 to 125	39	29.3	18.7	INHOM		36.0	15.0		N/A	N/A
73W unirradiated	55	−60.4	HOM	−5	10	−63.9	−3.5	HOM	N/A			N/A		
				5	6	−59.0	1.4	HOM						
				−5 to 5	19	−62.3	−1.9	HOM						
73W irradiated	19	33.3	HOM	85	15	39.8	6.5	HOM	N/A			N/A	N/A	N/A
				95	6	29.2	−4.1	HOM						
				85 to 125	30	29.4	−3.9	INHOM		43.7	N/A		N/A	N/A
Ingham et al.	50	−105.0	HOM	−55 to 20	166	−110.1	−5.1	INHOM	N/A	−104.7	N/A	N/A	N/A	N/A
EURO	291	−91.3	INHOM	−40	92	−85.7	5.6	HOM	−86.5			−84.4		
				−20	126	−85.0	6.3	HOM						
				0	117	−91.2	0.1	HOM						
				−40 to 0	340	−86.8	4.5	HOM						
JSPS	105	−106.7	HOM	−50	50	−105.0	1.7	HOM	N/A			N/A		
Midland	84	−8.3	INHOM	75	8	28.0	36.3	HOM	37.7			25.4		
Weld irradiated				75 to 150	22	29.3	37.6	INHOM		61.2	23.5		25.3	−0.1
Plate 13A C(T)	64	−82.7	INHOM	−150	47	−66.8	15.9	INHOM	−77.8	−55.5	22.3	−73.9	N/A	N/A
				−18	8	−68.4	14.3	INHOM		−57.6	20.2		−68.4	5.5
				−18 to 24	13	−68.1	14.6	HOM						
Plate 13A SE(B)	52	−104.8	HOM	−51 to 20	162	−102.4	2.4	HOM	N/A			N/A		

Note: N/A = not available.

material properties, given the large number of available data points. These alternative reference temperatures were calculated without using any of the data points within the rigorous $T_0 \pm 50°C$ temperature range.

The results are illustrated in **figure 14**, where differences between modified and rigorous reference temperatures are plotted as a function of the difference between test temperature (or weighted average of test temperatures in case of multitemperature subsets) and the upper limit of the rigorous temperature range, $T_0 + 50°C$. Numerical values are reported in **Table 9**.

Calculated differences for T_0 range from −5°C to 37.6°C and in 80 % of cases, are positive (conservative). The largest differences correspond to the most inhomogeneous data set, Midland Weld irradiated. Despite considerable scatter, differences tend to increase with increasing distance between test temperature and $T_0 + 50°C$. Some of the largest differences could be due to the fact that the specific subsets may not follow closely the MC shape.

Very few differences are available for T_{0IN} or T_m, as only few inhomogeneous subsets could be extracted from already inhomogeneous data sets. Moreover, for most inhomogeneous subsets, the T0TEM software was unable to converge to a T_m value.

Only one subset was available for test temperatures below T_0 – 50°C (Plate 13A C(T), specimens tested at −150°C), for which relatively large positive differences were calculated ($T_0^* - T_0 = 15.9°C$ and $T_{0IN}^* - T_{0IN} = 22.3°C$).

Conclusions and Recommendations for the Revision of ASTM E1921

This study investigated the consequences of extending or removing the test temperature validity range (or window) for the data points used in the determination of reference temperatures in accordance with the MC methodology, for both macroscopically homogeneous and inhomogeneous data sets. Analyses were conducted on ten large "historical" data sets.

Both asymmetrical ranges (increased upper limit up to $T_0 + 100°C$ or decreased lower limit down to T_0 – 75°C) and symmetrical ranges (extended up to $T_0 \pm 75°C$) were considered, along with the option of not imposing any limits on test temperatures (which is however not advocated).

Examining the differences between modified and rigorous reference temperatures, both homogeneous and inhomogeneous, the following was observed for all the scenarios examined:

- The overwhelming majority of the calculated temperature differences are within ±5°C, which is of the order of the typical repeatability and reproducibility of the method according to the "Precision and Bias" section of ASTM E1921-22a. The largest recorded differences (all positive) are around 10°C–11°C.
- Most of the calculated differences (between 70 % and 80 %) are >0°C, indicating that the modified reference temperatures are higher than their rigorous counterpart. In other words, the effect of expanding or removing the temperature range is typically conservative.
- Differences tend to slightly increase as the width of the valid temperature range increases.

We also looked at the consequences of expanding the range on the macroscopically homogeneous or inhomogeneous nature of data sets, as indicated by the screening criterion of ASTM E1921-22a. If the data set is strongly homogeneous or inhomogeneous, it is unlikely that its nature would change when the range is modified. This might happen, particularly for the largest valid ranges, when the intrinsic homogeneity or inhomogeneity is only moderate.

Finally, when calculating reference temperatures on subsets corresponding to test temperatures outside of the $T_0 \pm 50°C$ interval, reference temperature differences up to almost 40°C (conservative) were obtained. The magnitude of the differences tends to increase as the test temperature moves further away from the upper limit of the temperature range ($T_0 + 50°C$).

These findings support a possible revision of the ASTM E1921 standard by expanding the allowable range of test temperatures for test results used in the calculation of reference temperatures. Based on the results obtained, it is probably advisable to limit this expansion to a lower limit of T_0 – 65°C and an upper limit of T_0 + 75°C. A symmetrical modified range corresponding to T_0 ± 65°C might represent a reasonable and prudent choice. It must be emphasized that for the 10 large data sets examined, relatively few data below T_0 – 50°C were available, so any statements concerning a decreased lower limit must be considered very preliminary.

Furthermore, it would be highly desirable to obtain a confirmation of these findings by performing a significant number of MC analyses (homogeneous and inhomogeneous—both simplified and multimodal) on many virtual fracture toughness data sets, generated through Monte Carlo simulations, and different types of valid temperature ranges.

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SUPPLEMENTARY INFORMATION

Appendixes for this paper are available at https://doi.org/10.6084/m9.figshare.22583953.

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