

Environmental dose rate determination using a passive dosimeter: techniques and workflow for α - $\text{Al}_2\text{O}_3\text{:C}$ chips -Supplementary Data-

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Abstract

The following figures and data supplement the main text and the given information therein. Furthermore, the full details on the, exemplarily, carried dosimeter analyses are provided. This includes the used **R** code and the obtained results.

1. Additional figures

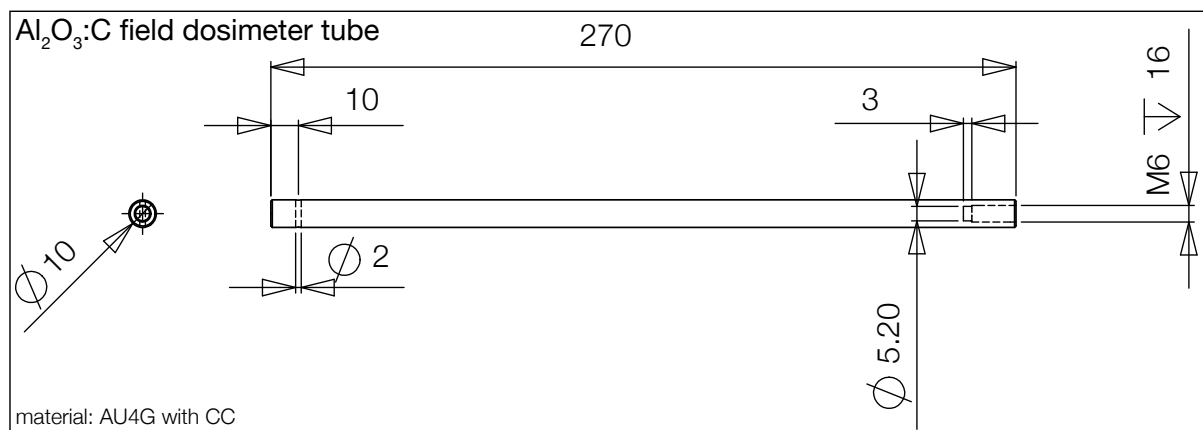


Figure S1: Technical drawing of the field container, gratefully provided by Meca Process (Gradignan, France). All distances are given in mm. Material compositions are, nylon screw: C (64 mass %), H (10 mass %), N (12 mass %), O (14 mass %), density: 1.24 g cm^{-3} ; rubber O-ring: C_5H_8 (100 mass %), density: 1.24 g cm^{-3} ; dosimeter tube: duralumin Al (92 mass %), Cu (4 mass %), Mg (3 mass %), Mn (1 mass %), density: 2.77 g cm^{-3} . Not shown: 3 chips $\text{Al}_2\text{O}_3\text{:C}$, density: 3.79 g cm^{-3} .

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Table S1: Reference sites cross-check results. For details see main text.

Reference site	Miallier et al. (2009)		This study		Variation to reference
	\dot{D}_γ [$\mu\text{Gy a}^{-1}$]	cv [%]	\dot{D}_γ [$\mu\text{Gy a}^{-1}$]	cv [%]	
LMP	641 ± 18	2.8	699 ± 19	2.7	+9
C341	849 ± 21	2.5	837 ± 64	7.6	-1.5
C347	$1,421 \pm 25$	1.8	$1,382 \pm 109$	7.9	-2.7
PEP	$2,536 \pm 110$	4.3	$2,204 \pm 189$	8.6	-13

Listed are 1σ uncertainties.

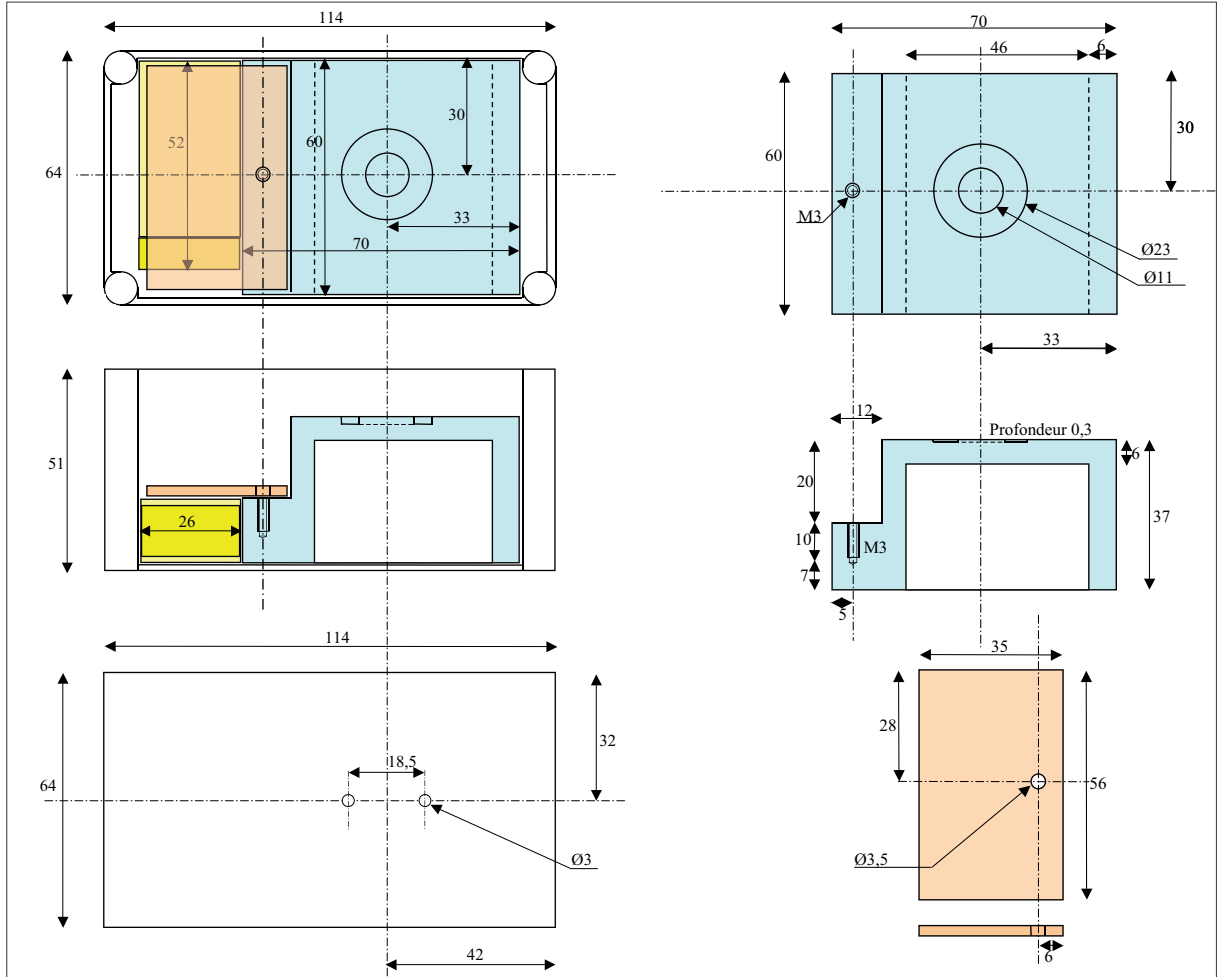


Figure S2: Technical drawing of the used bleaching box by Pierre Selva. The (empty) box is made out of aluminium alloy (ADC12) and was purchased from RS Components (<http://rs-components.com>), RS Stock NO: 5173822. LED used for the bleaching: *LuxeonTM-1* Watt Star, type number: LXHL-MRRC (royal-blue, batwing, low dome), λ_D at 25 °C and 350 mA: 455 nm (FWHM: 20 nm), maximum radiometric power: 100 mW (all technical information as delivered by the supplier). In the bleaching box, the LED is powered by a conventional 9 V block battery.

Stimulation Spectrum green-LEDs

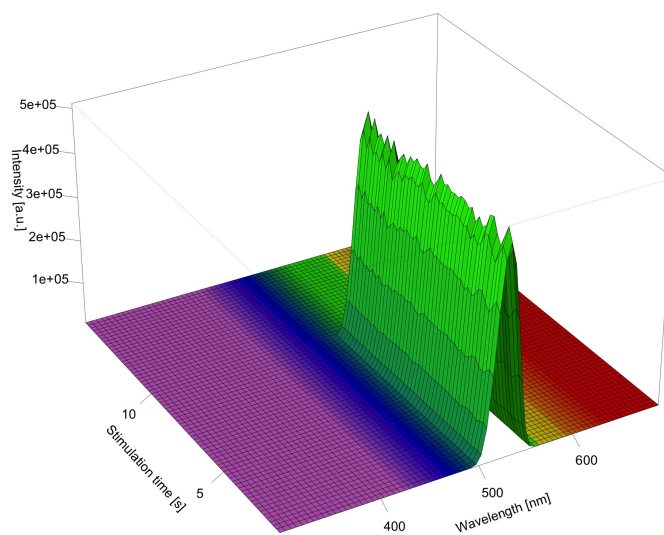


Figure S3: Stimulation spectrum of the green-LEDs as built-in in the operated *lexsyg SMART* reader. The stimulation spectrum was recorded on an identical stimulation unit installed in a *lexsyg research* at the Justus-Liebig-University Giessen, Germany in 2014. For recording the spectrum the in-built spectrometer of the system was used, the spectrometer system was energy calibrated using the spectrum of a conventional neon ceiling lamp.

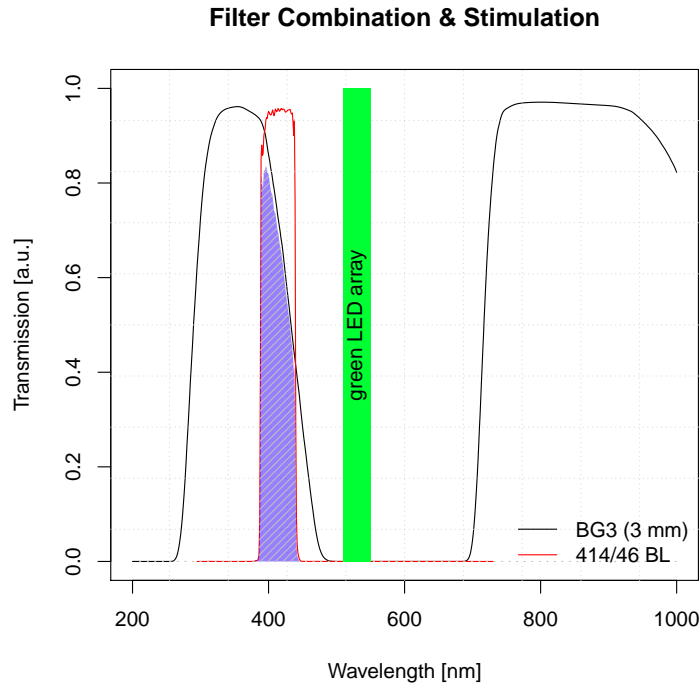


Figure S4: Filter transmission spectrum and stimulation wavelength as used for the experiments in the *lexsyg SMART*. The blue area shows the net transmission window; the LED emission is indicated by a green rectangle.

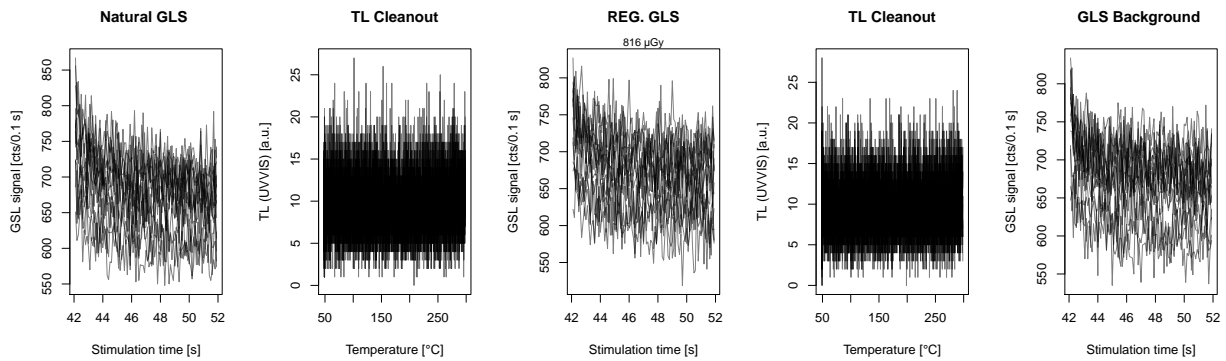


Figure S5: OSL and TL curves obtained from measuring 15 sample carriers as used for the experiments. The measurement sequence is identical to the one proposed in the main text. The shown curves follow the sequence structure. Before the measurement, the sample carriers were heated to 450 °C in N₂ within the reader. For all measured cups, no dose induced luminescence signal was observed. Even for different sample carriers, the signal is highly reproducible. The experiment further proves that the initial GSL signal decay is not related to the α -Al₂O₃:C chips as also shown with the background measurements in the main text.

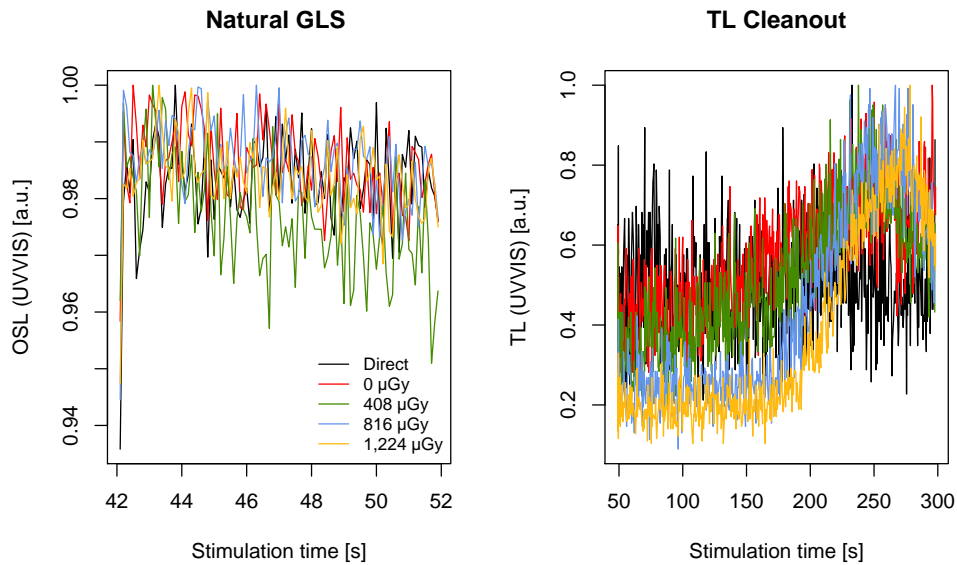


Figure S6: Shown are the results of the bleaching box performance test on 15 α - $\text{Al}_2\text{O}_3\text{:C}$ chips. All chips were previously reset in an external furnace in air (10 min, 950°C) and then split into five subsets á three aliquots. For all subgroups, the GLS (left plot) and TL curve (right plot) were measured (step 1 to 2 from the sequence proposed in the main text). The curves are normalised to the highest value of each curve. The pre-treatment differ for each subset. The subset (1) received no further treatment. The subset (2-5) received doses between $0\ \mu\text{Gy}$ (subset 2) and $1,224\ \mu\text{Gy}$ (subset 5) followed by a signal resetting in the bleaching box for 2 min. In the graphic, subsets are colour coded, showing the mean of each subset. Except for the GLS curves following a dose of $408\ \mu\text{Gy}$ (subset 3), the curves show no significant signal decay. However, the signal decay of subset 3 is even higher than the signal decay after $1,224\ \mu\text{Gy}$ (subset 5). The induced apparent dose results from technical difficulties during the handling of the chips, which stayed longer in the reader than the other chips. In summary, the results show that the (1) chips are susceptible (see also the subsequent TL curves, which show a small signal) and (2) the dose obtained during the transport of the dosimeter can be sufficiently reset in the bleaching box within 2 min. Please note that even the lowest dose applied here ($408\ \mu\text{Gy}$) is an order of magnitude higher than the typically expected maximum travel dose (e.g., 11.5 h flight from Paris to Tokyo: ca. $41\ \mu\text{Gy}$, cf. [Bottollier-Depois et al. 2003](#)).

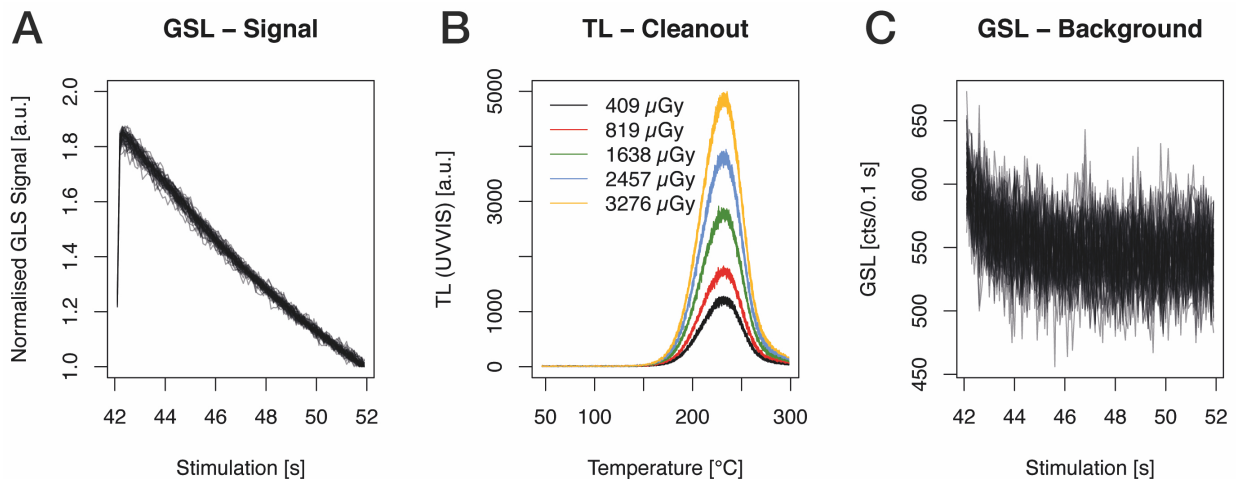


Figure S7: GSL and TL curves from the measurement obtained to correct the irradiation time for the additional dose uptake during the sample transport. Each plot shows the results for five repetitions of one aliquot. (A) Initial GSL curves, normalised to the highest count value each, (B) TL clean out curves (step 5, Table 3) and (C) background curves.

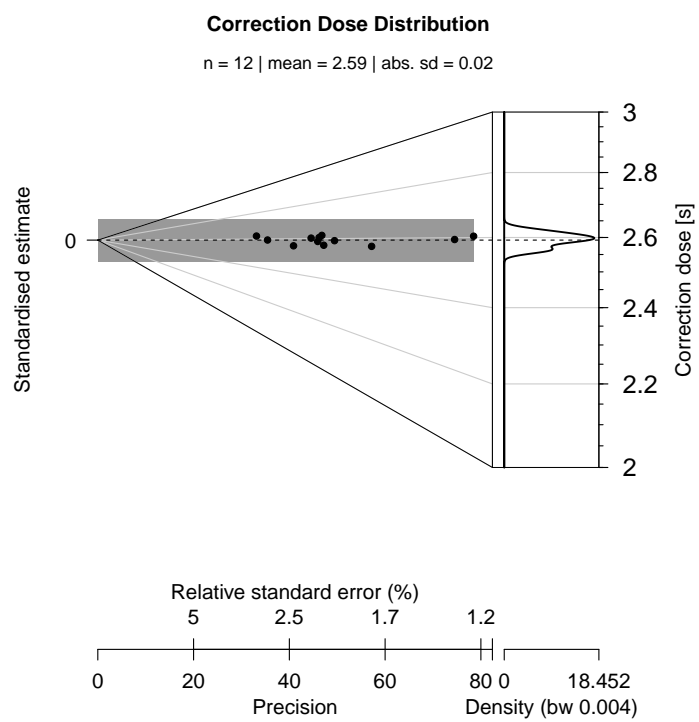


Figure S8: Abanico plot [Dietze et al. \(2016\)](#) showing the distribution of determined irradiation time correction values expressed in s. The summary quotes the error weighted mean and the absolute standard deviation.

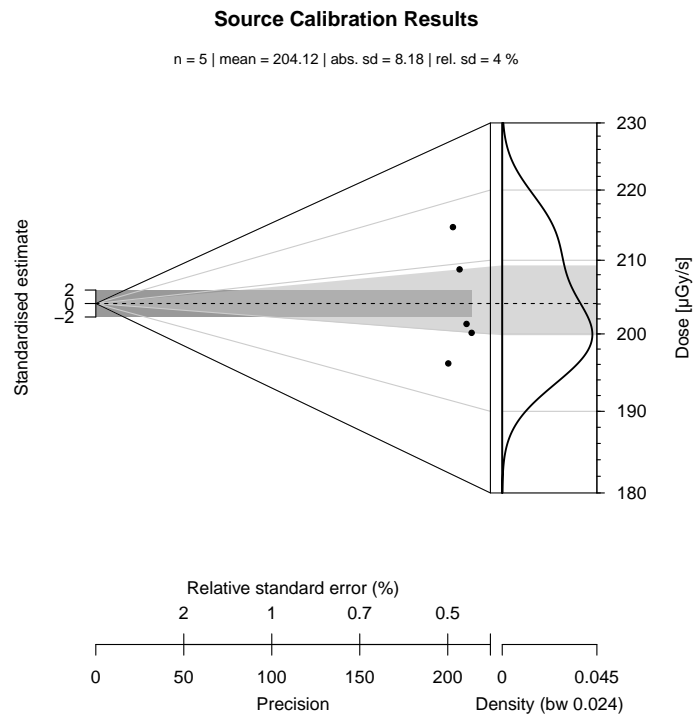


Figure S9: Calibration results for the β -source in the used *lexsyg SMART* reader. Shown are dose rate values in $\mu\text{Gy/s}$. Please note that the mean and the standard deviation differs slightly from the values reported in the main text. The values in the figures were obtained after the log-transformation, i.e. the mean here is not the arithmetic mean, but the geometric mean $\exp(\text{mean}(\log(x)))$. Furthermore, the standard error in the main text includes an additional error term from the estimation of the dose rate of the brick block used for the irradiation itself.

2. Application - Sierra de Atapuerca (Spain), site: Gran Dolina - full data analysis

The following pages are an example of analysing measurements carried out on α -Al₂O₃:C chips. For further information, not give below, please see the documentation of the **R** ‘Luminescence’ package.

Setup

The following page were produced using 'rmarkdown' and the following setup:

```
## R version: R Under development (unstable) (2018-01-20 r74146)
## 'Luminescence' package version: 0.8.0
```

Import data

```
##load R package 'Luminescence'
library(Luminescence)

##load pre-calculated values for irradiation cross-talk and
##irradiation time correction
load(A1203_CalculationData_path)

##import data
temp <- read_XSYG2R(file = data_path,
  fastForward = TRUE,
  verbose = FALSE
)
```

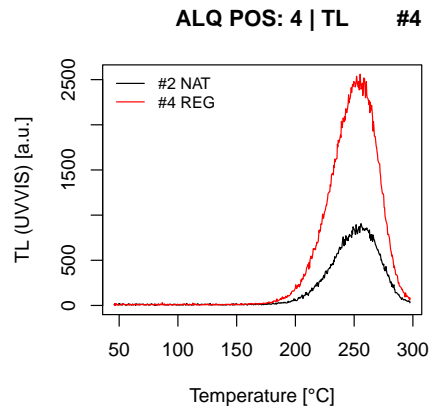
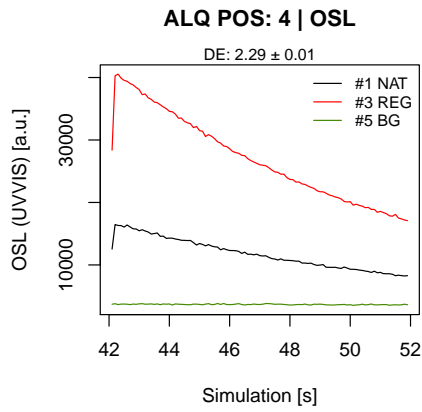
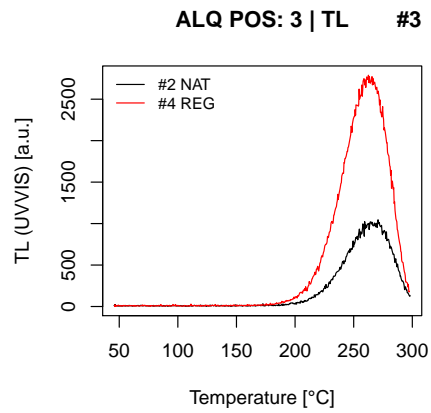
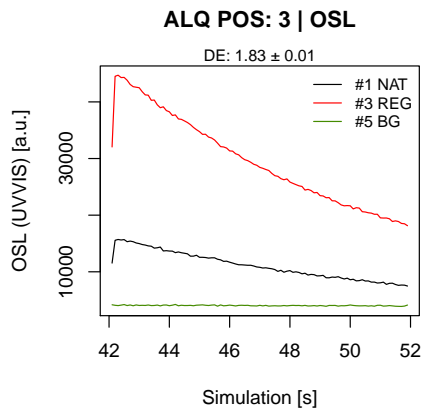
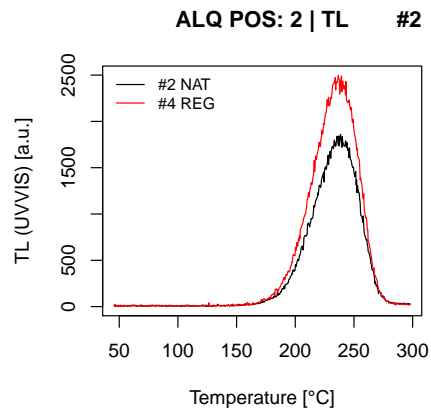
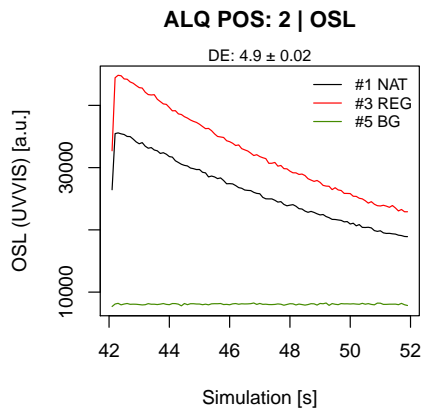
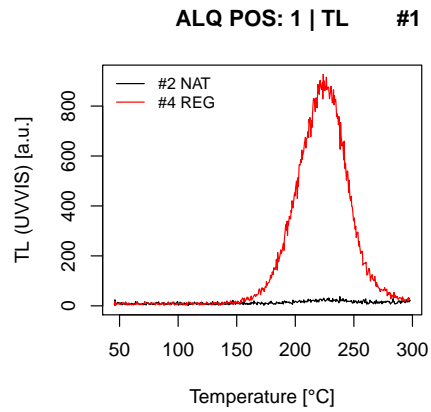
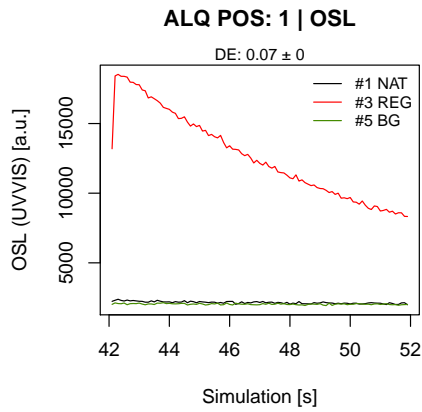
Please note that the values for the irradiation cross-talk, the irradiation time correction and the source calibration have been already obtained in previous experiments. Thus, the data processing uses the following datasets:

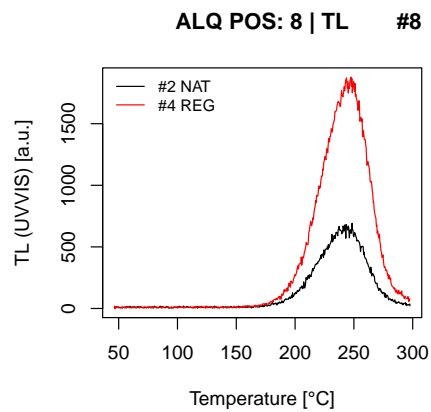
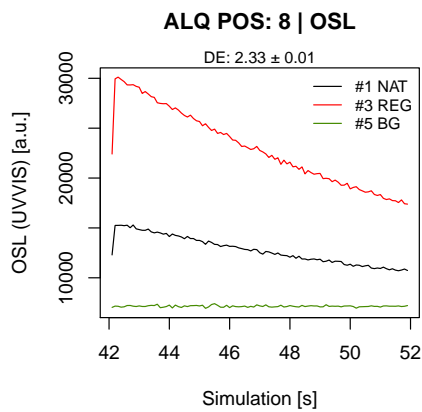
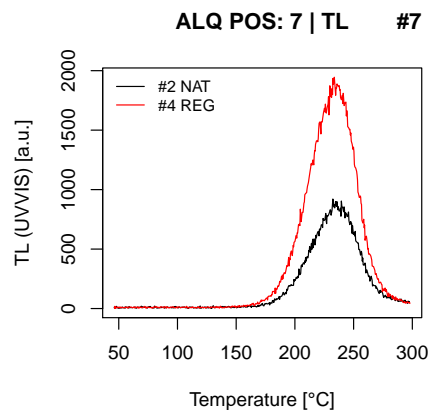
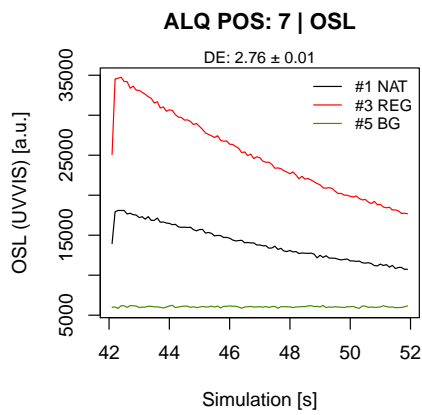
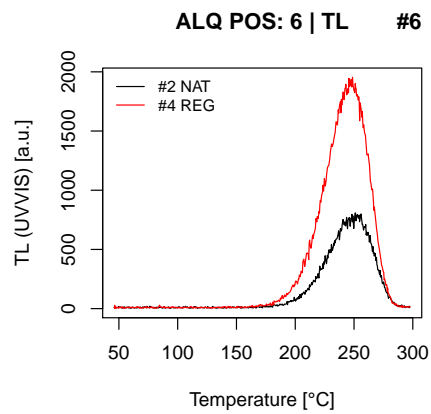
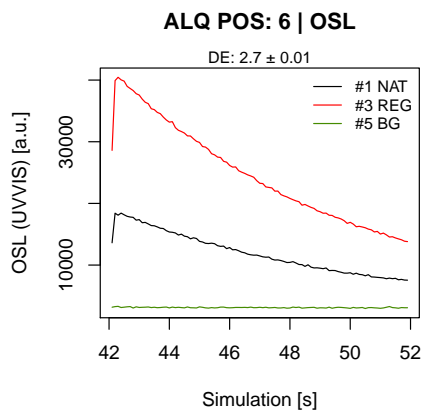
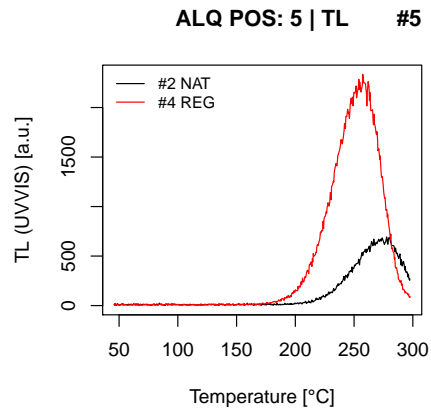
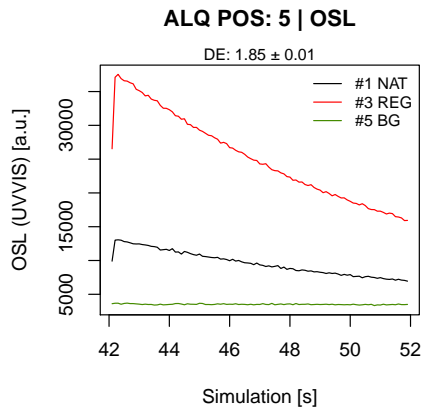
1. `results_ITC` (RLum.Results-object with the data for the irradiation time correction)
2. `results_CT` (RLum.Results-object with the radiation cross-talk data)
3. `sourceDR_FINAL` (the source calibration values)

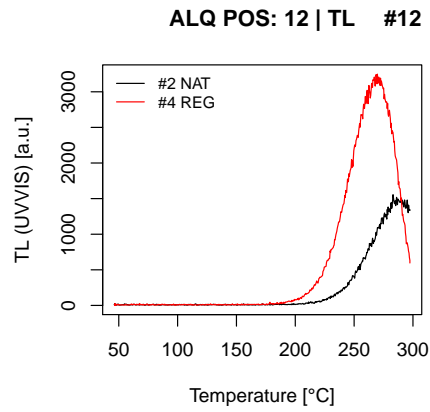
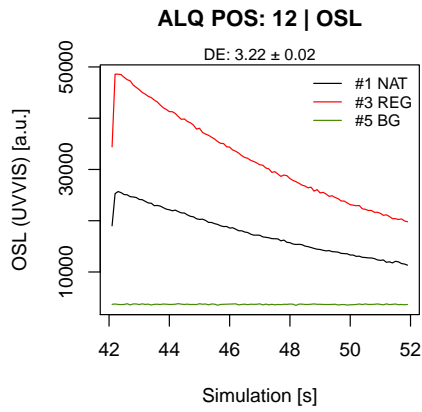
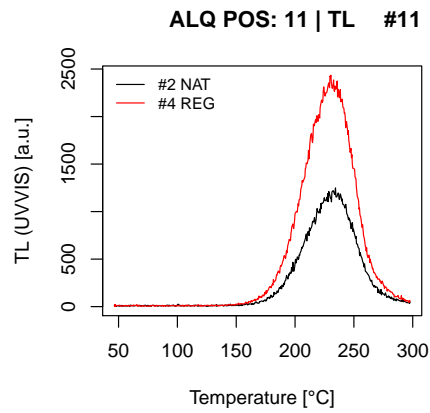
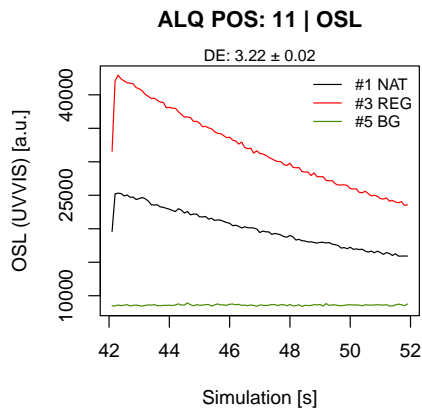
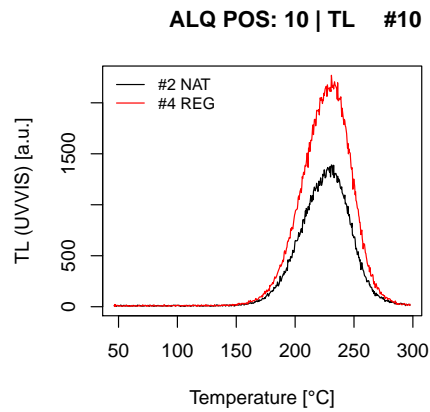
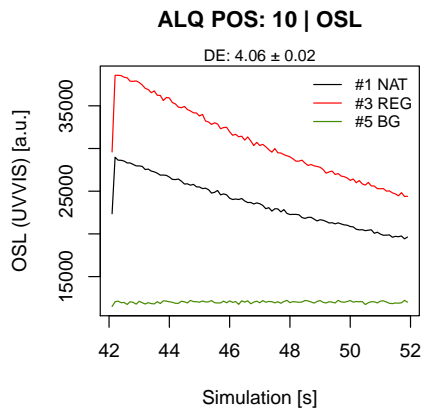
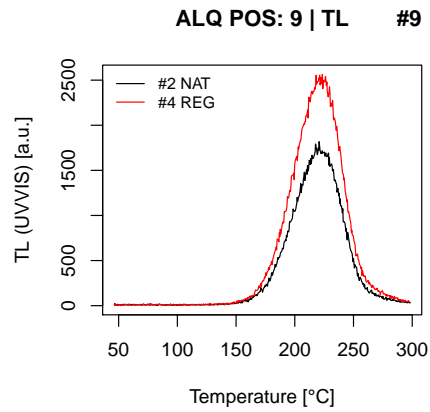
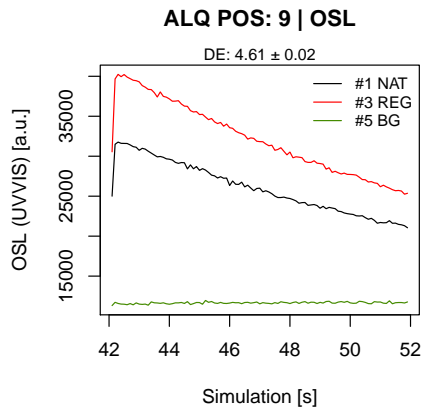
Analyse

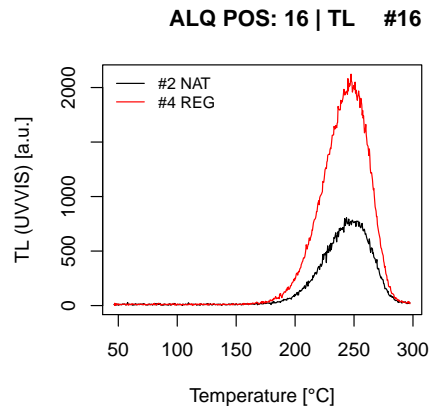
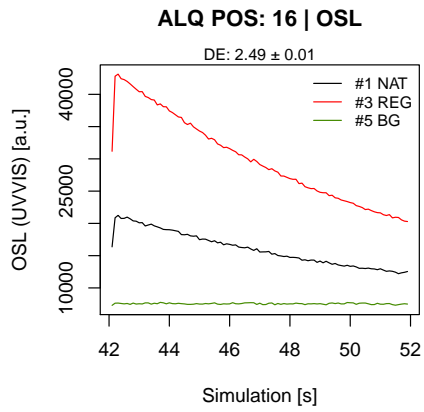
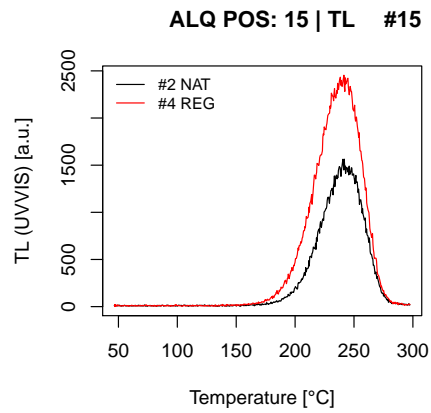
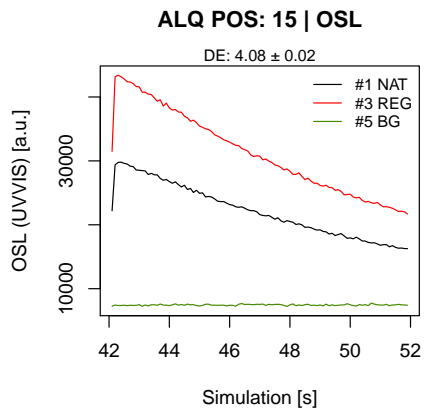
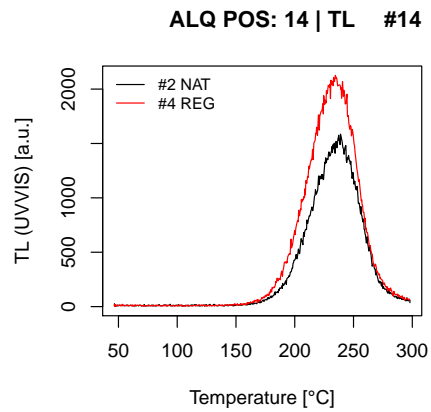
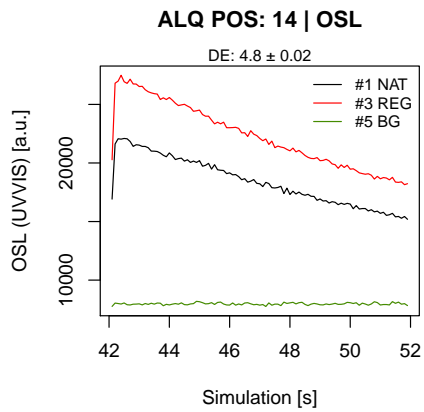
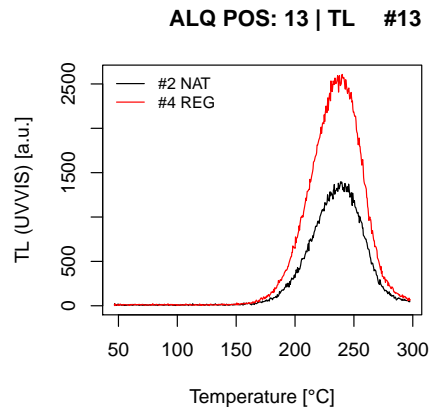
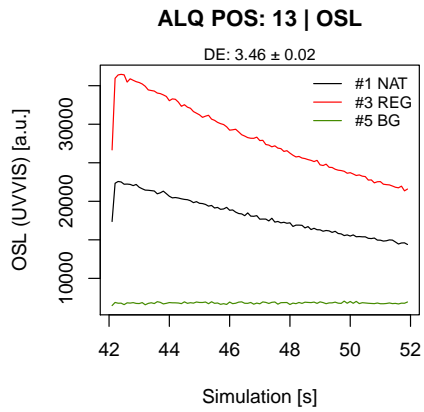
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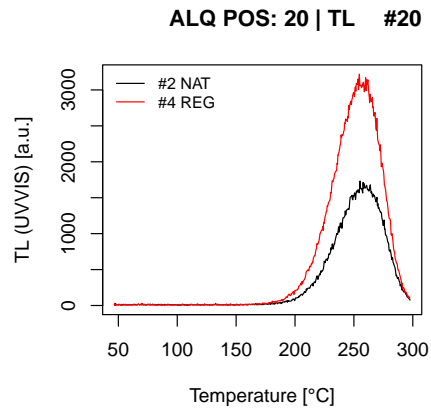
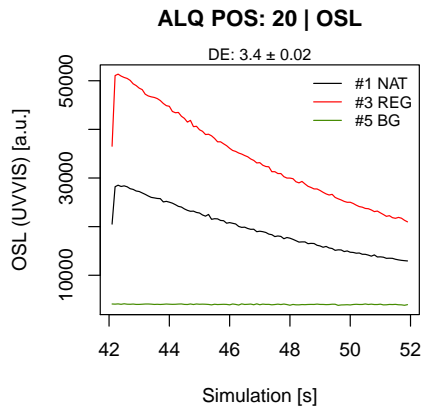
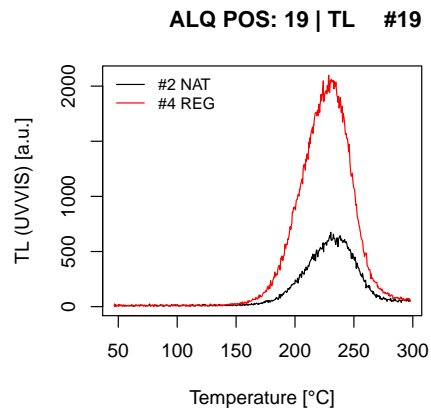
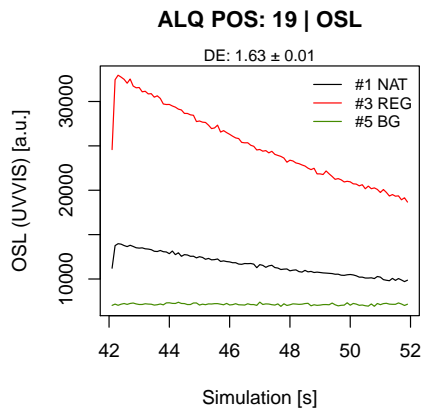
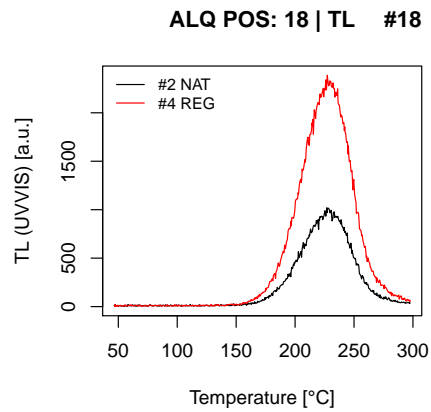
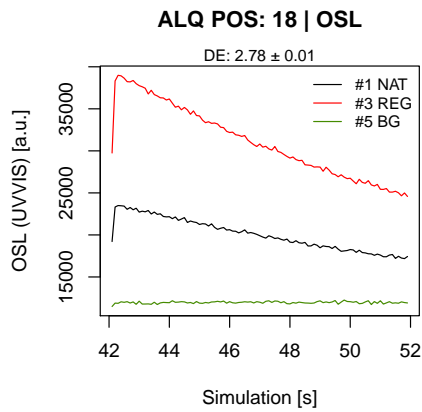
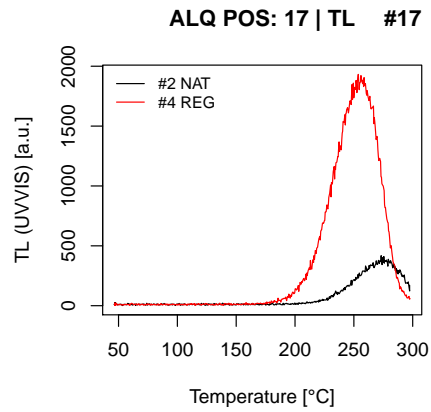
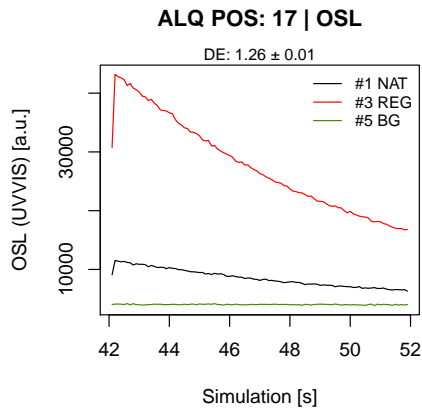
```
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  plot = TRUE
)
```

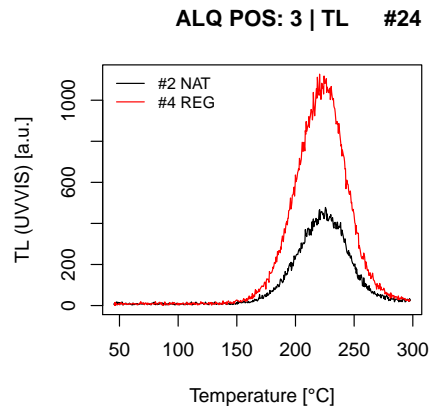
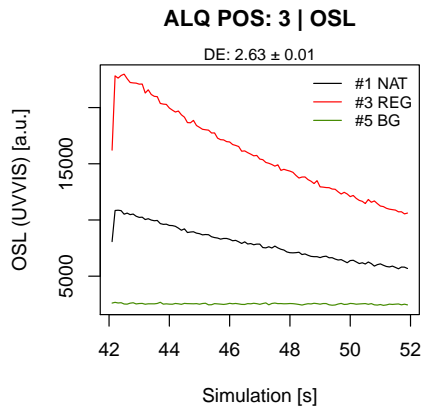
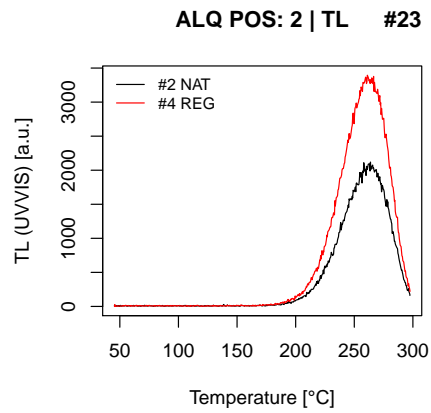
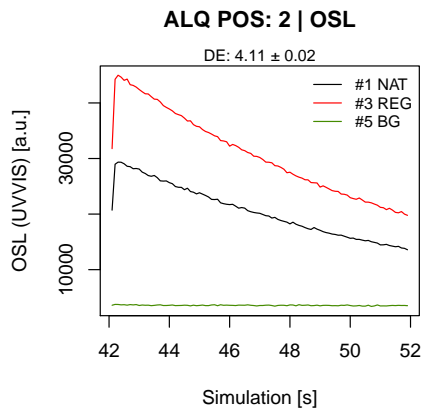
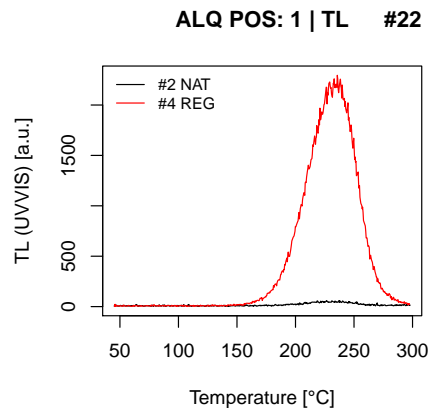
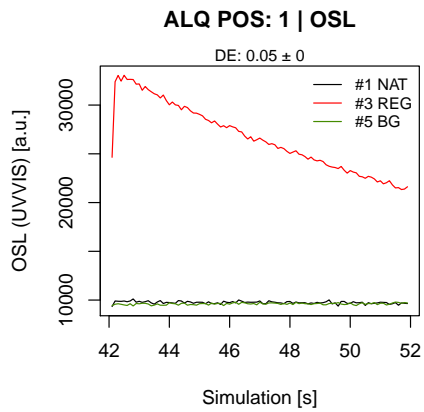
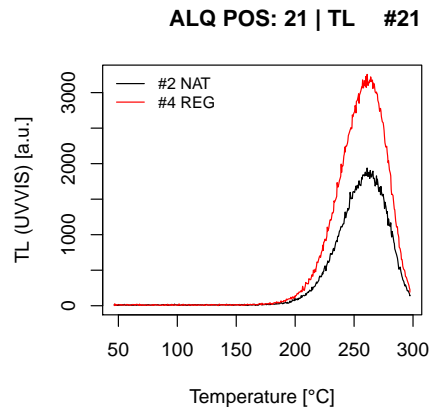
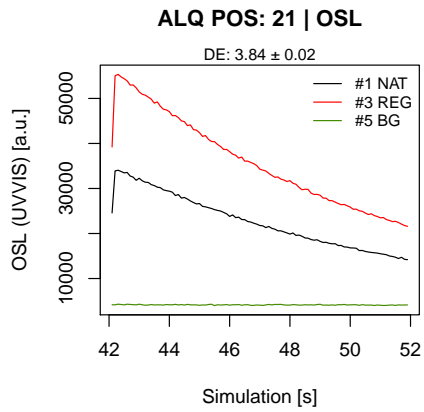


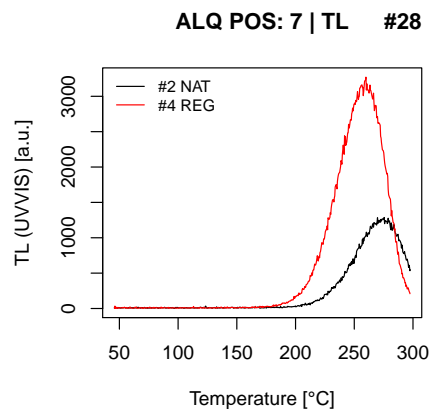
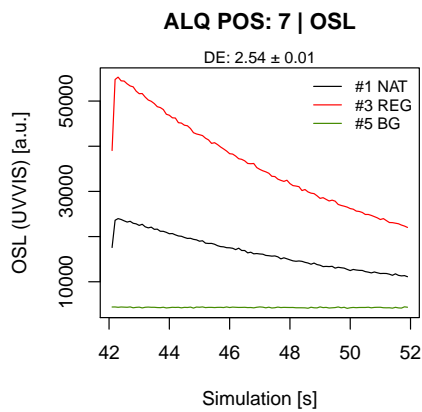
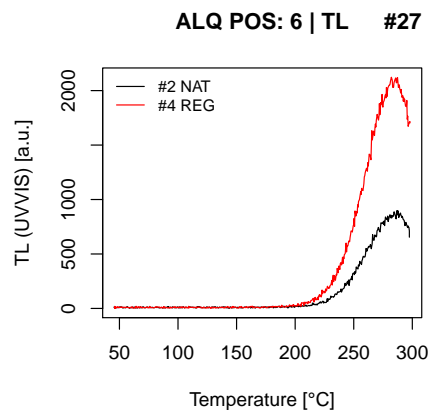
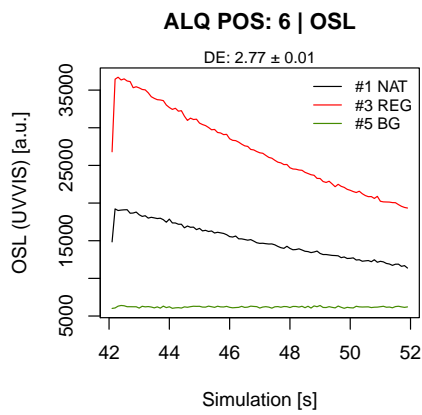
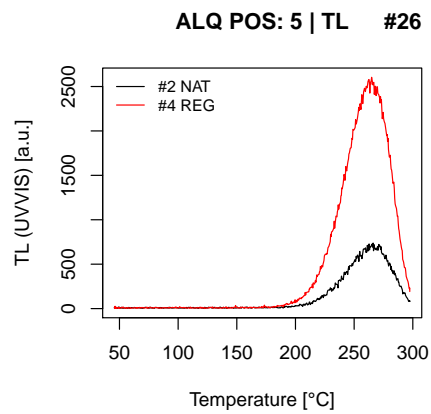
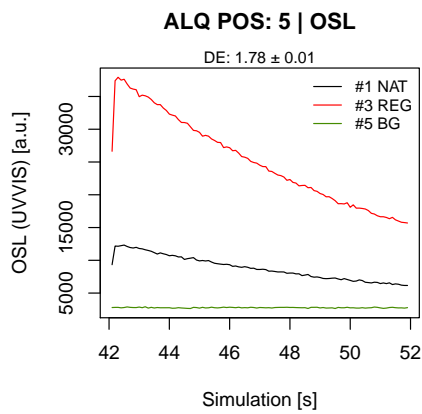
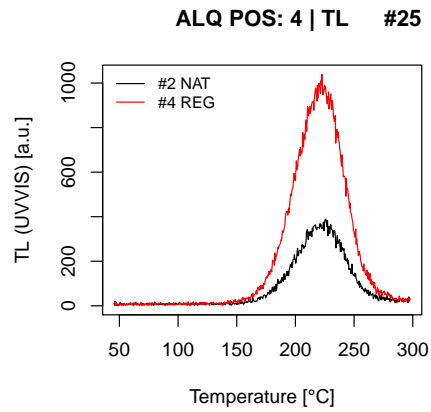
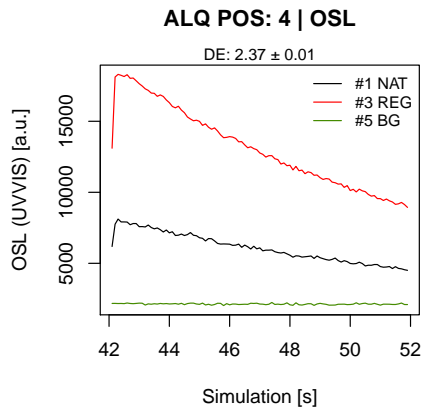


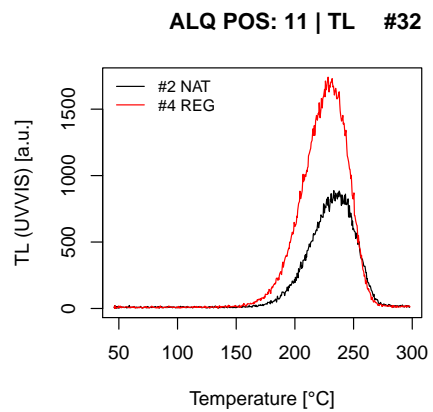
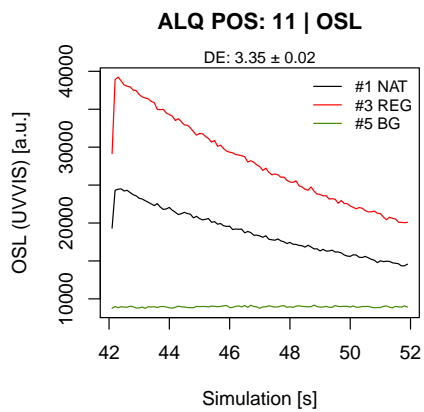
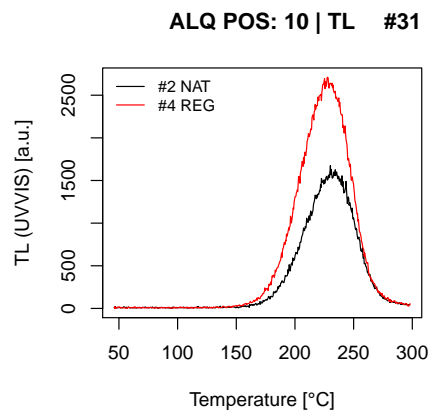
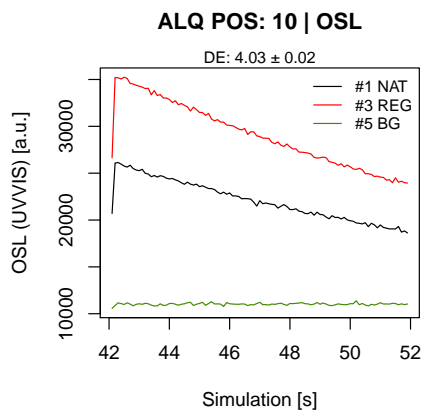
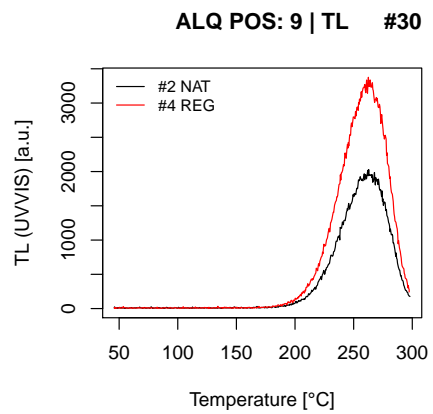
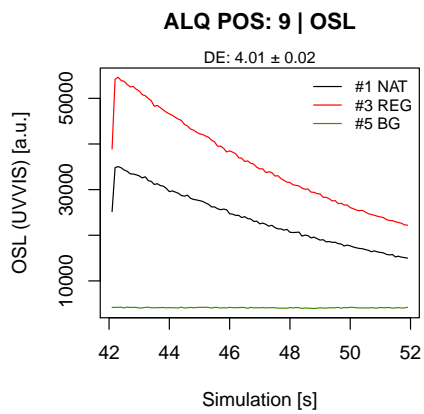
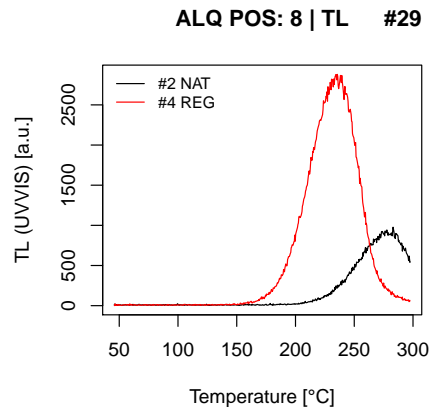
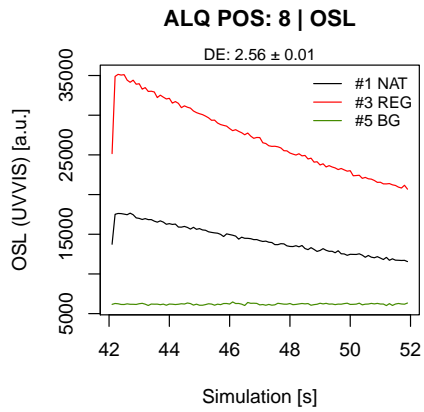


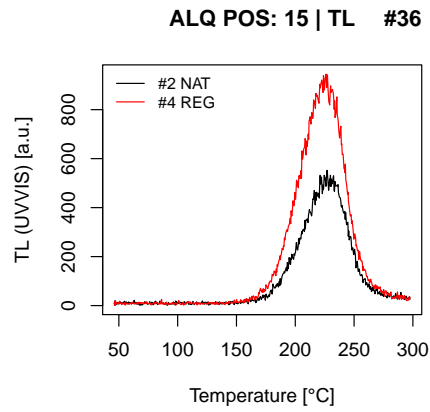
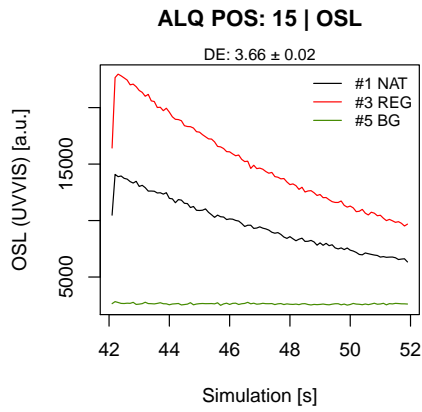
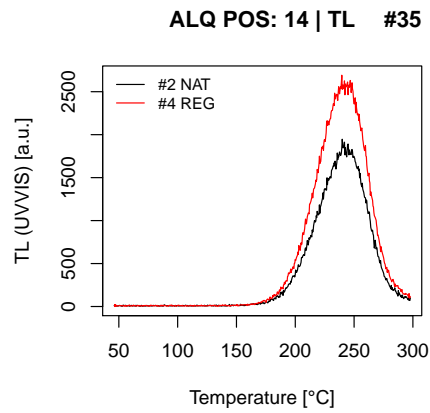
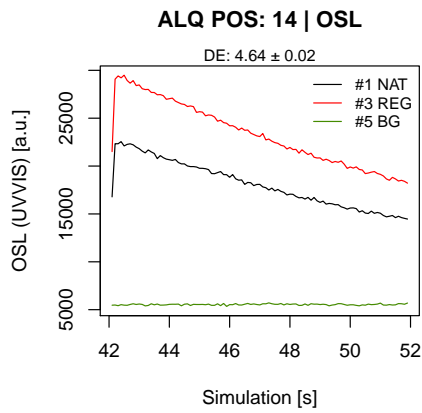
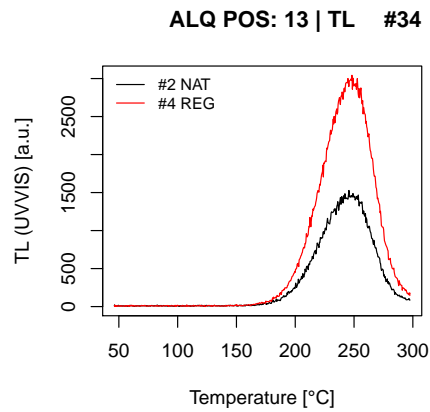
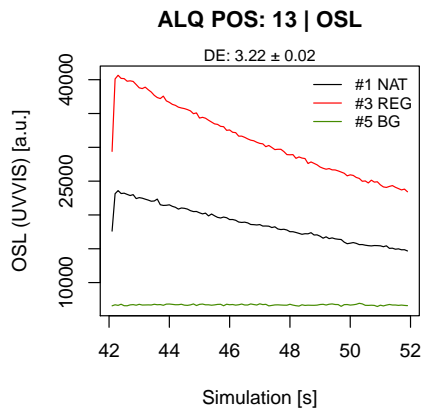
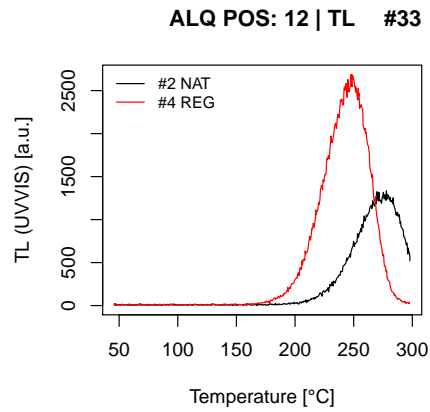
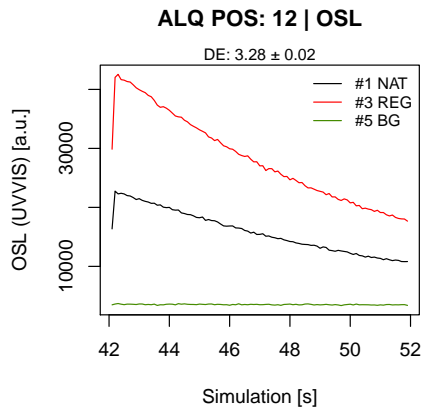


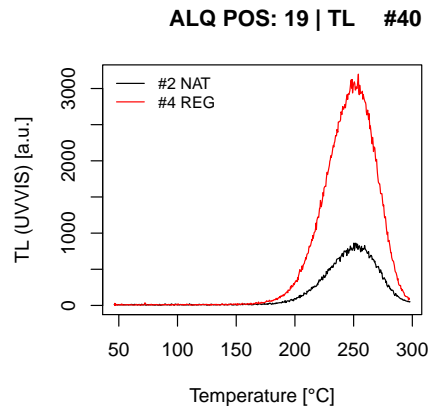
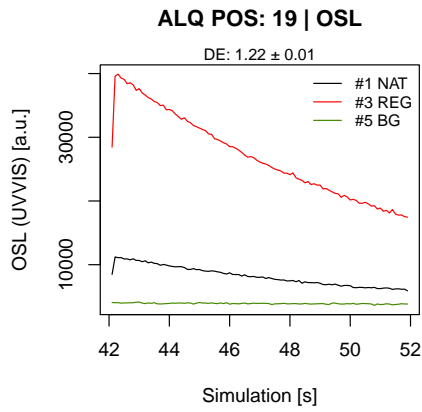
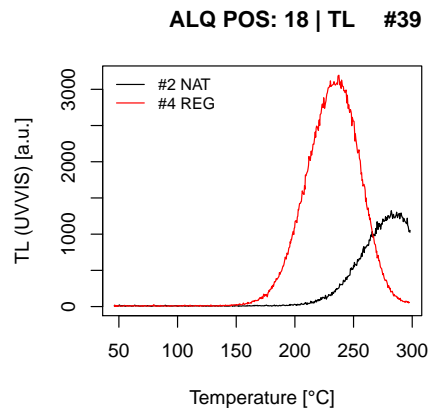
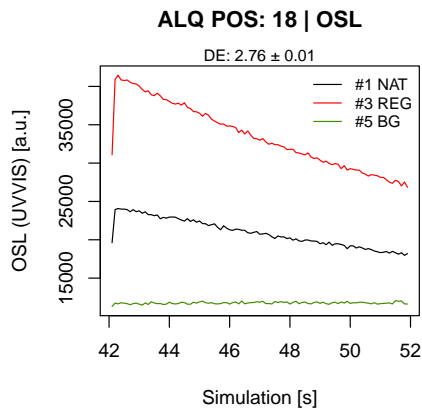
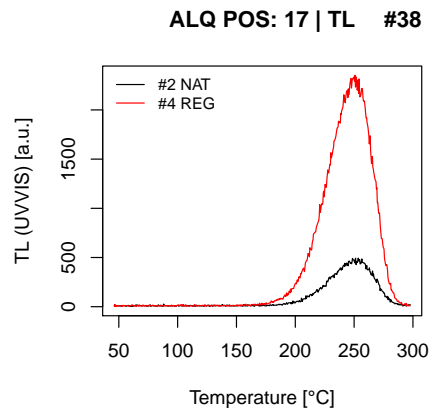
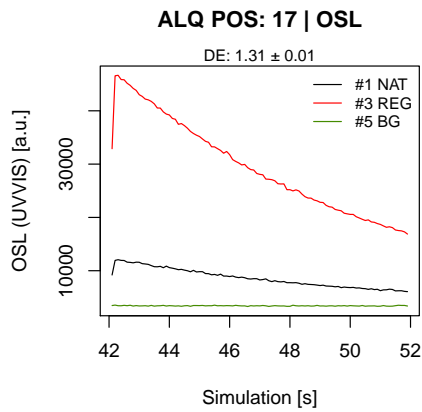
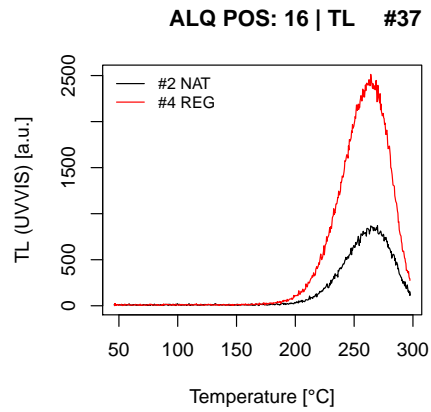
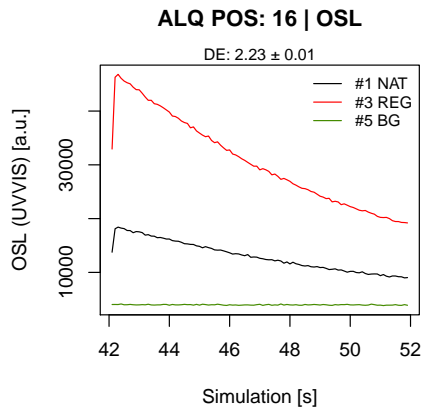


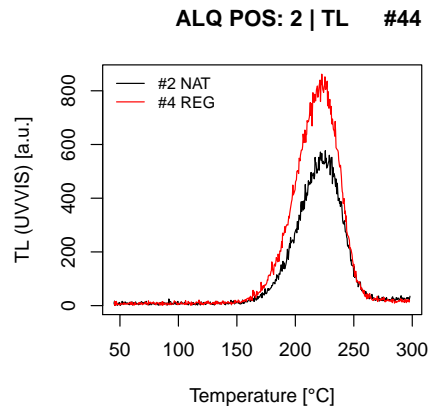
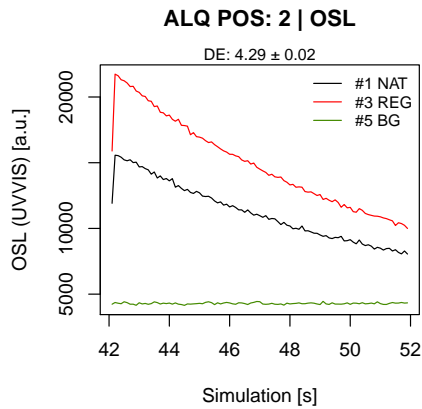
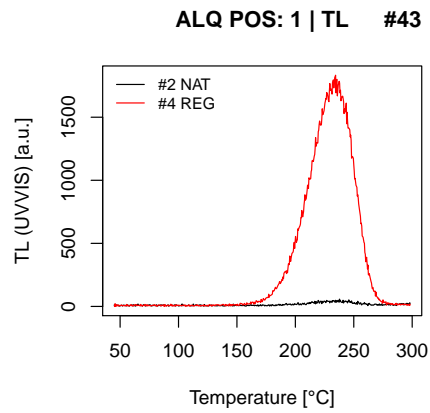
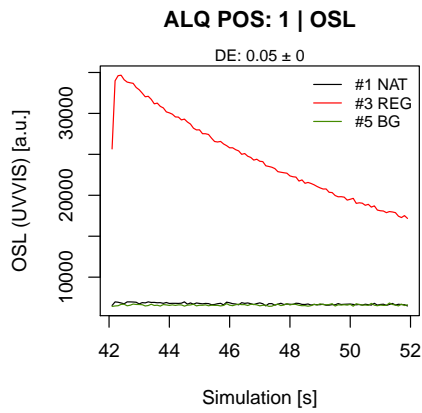
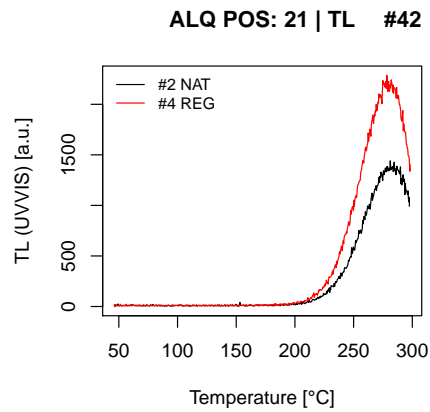
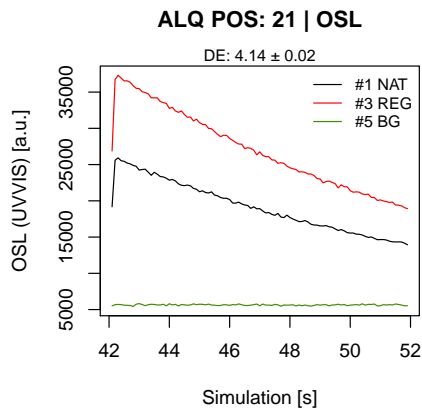
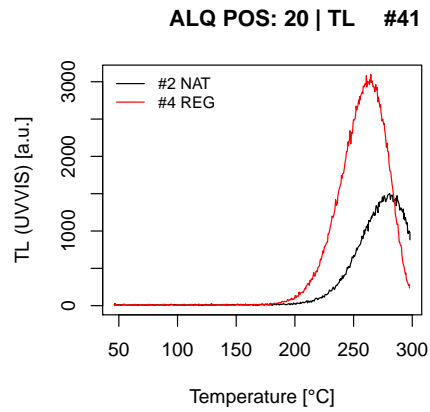
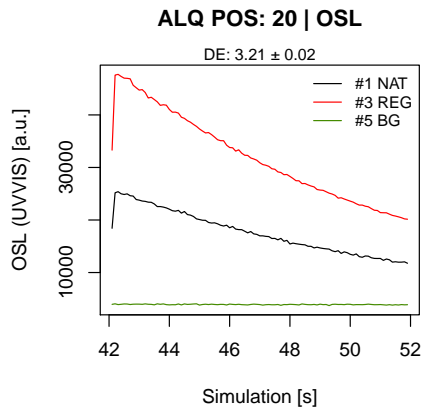


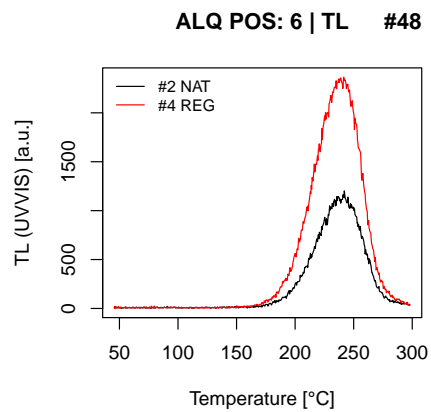
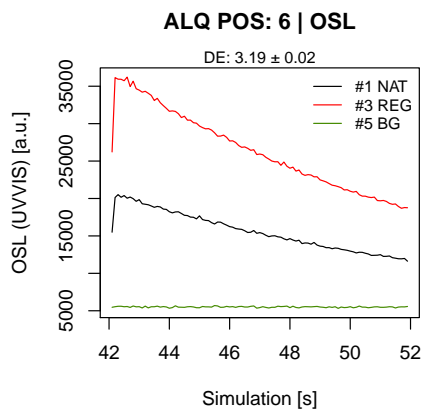
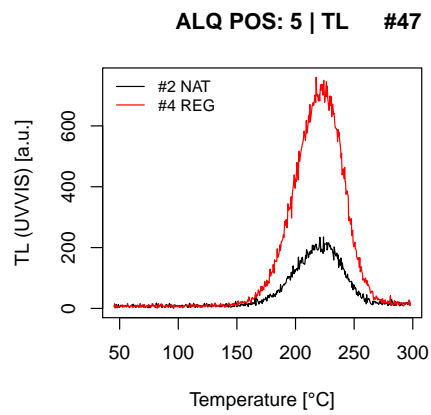
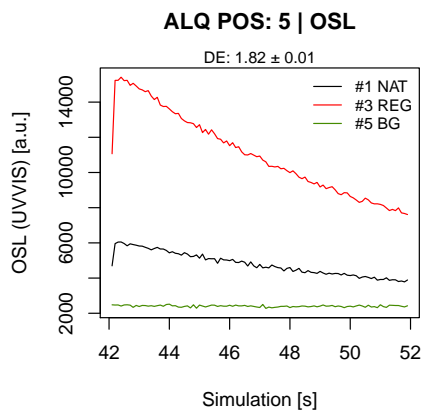
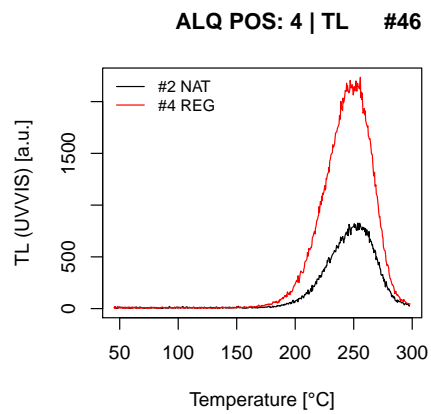
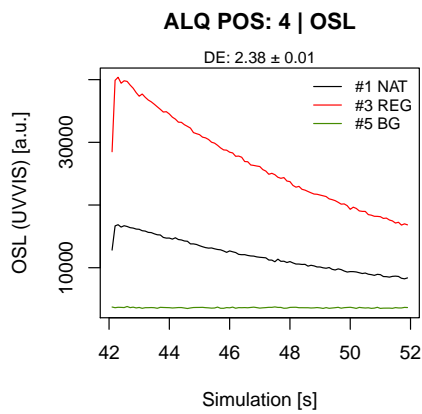
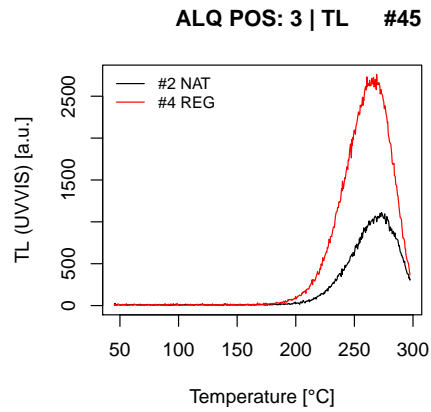
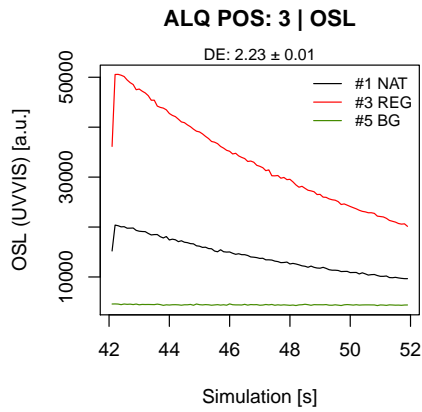


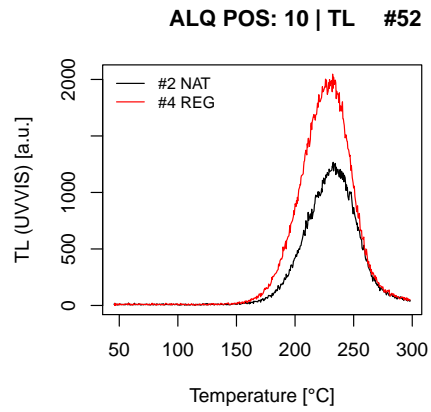
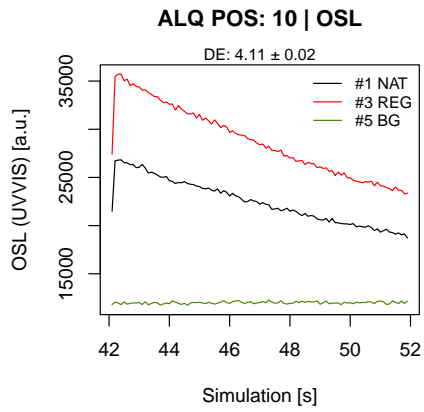
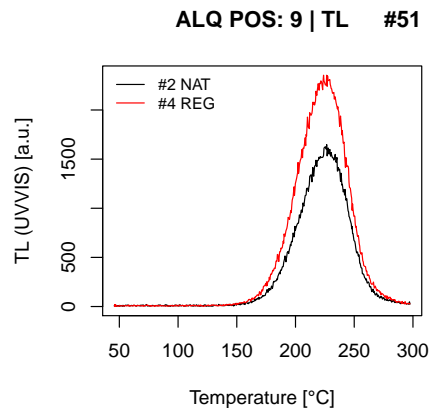
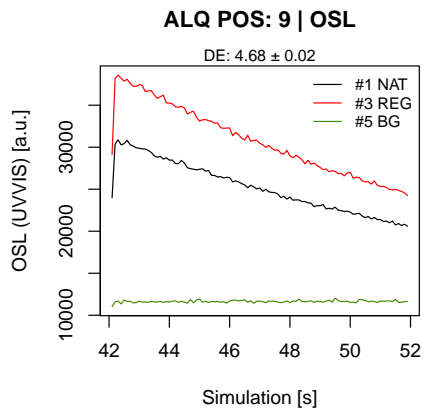
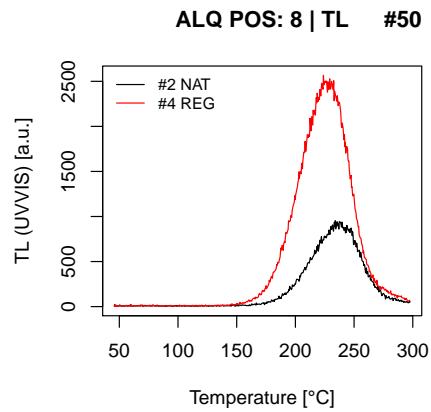
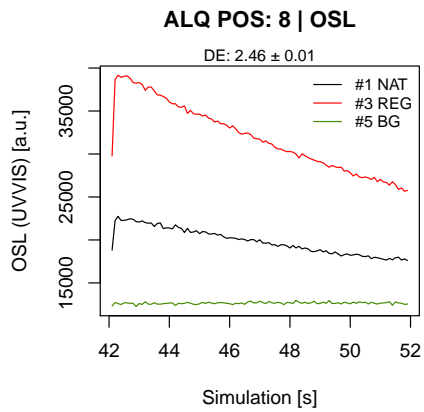
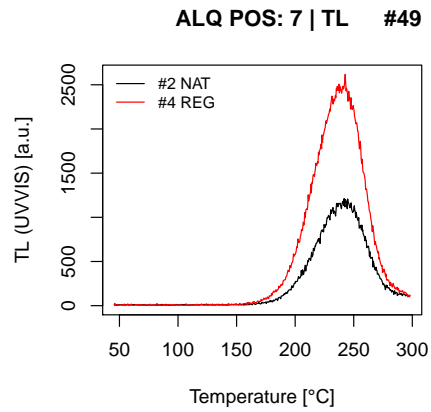
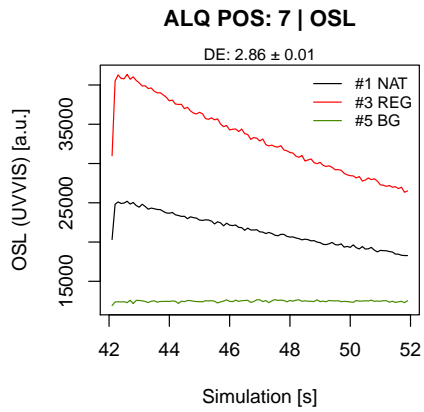


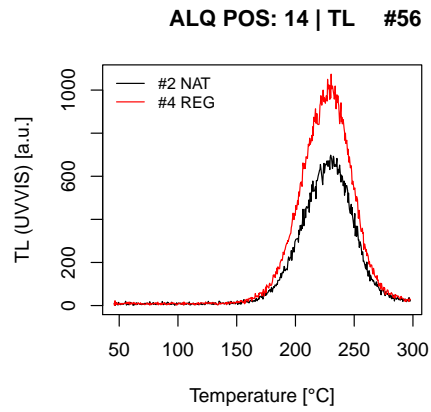
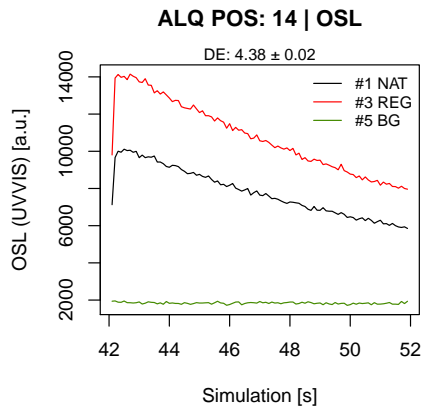
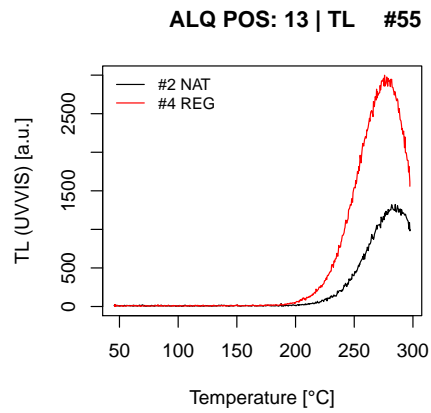
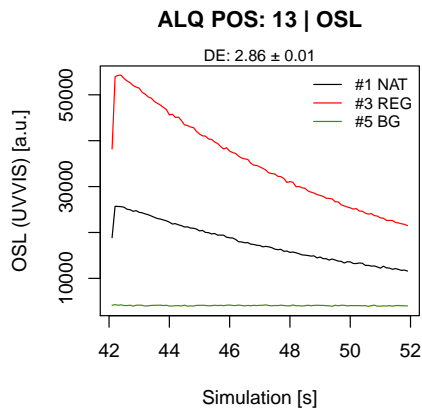
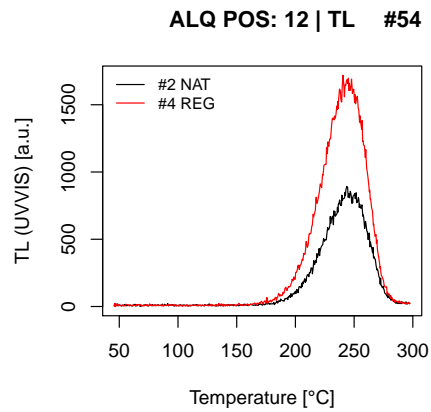
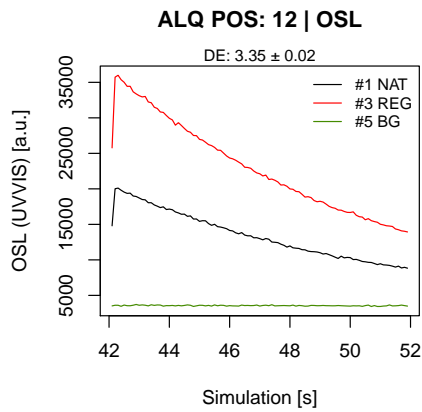
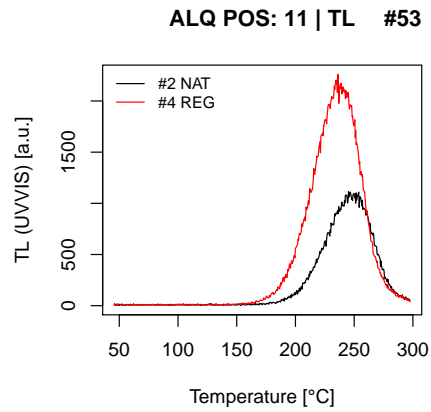
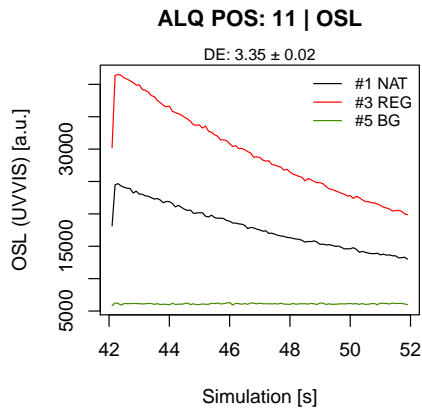


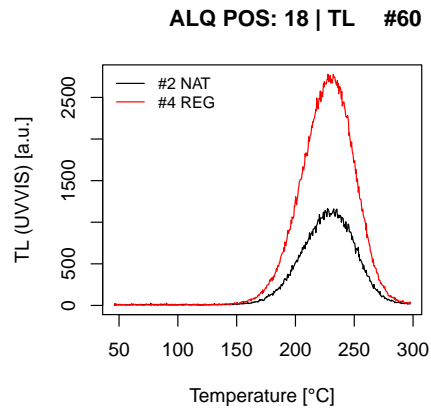
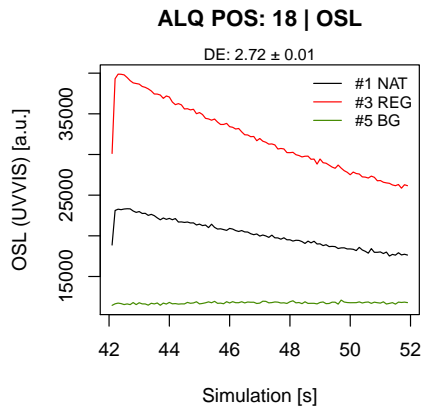
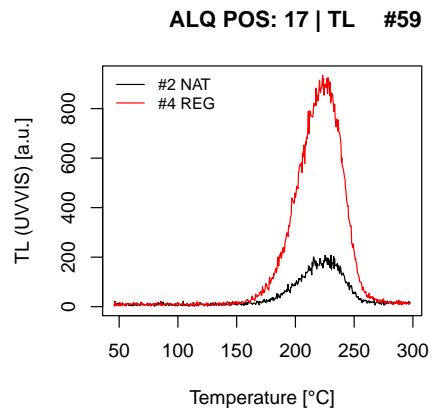
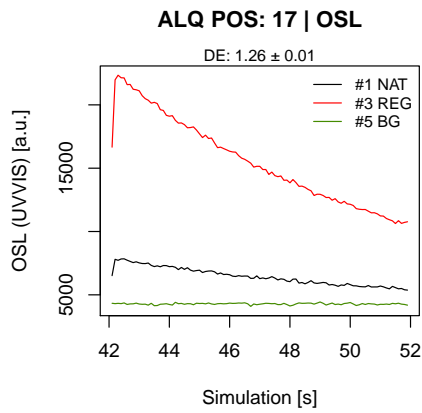
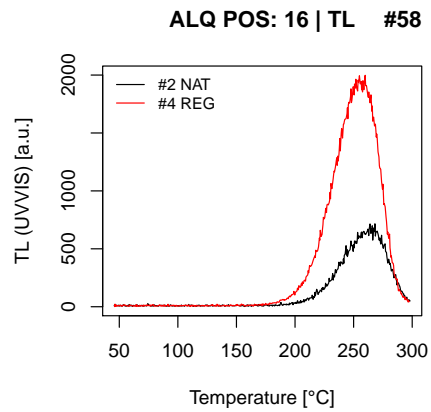
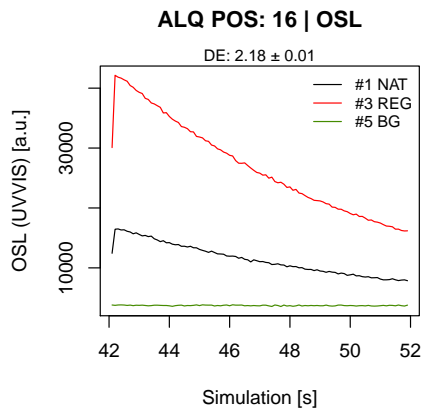
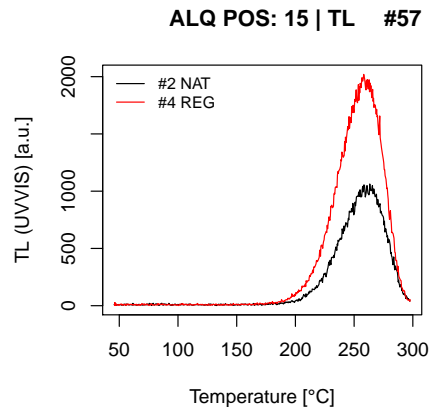
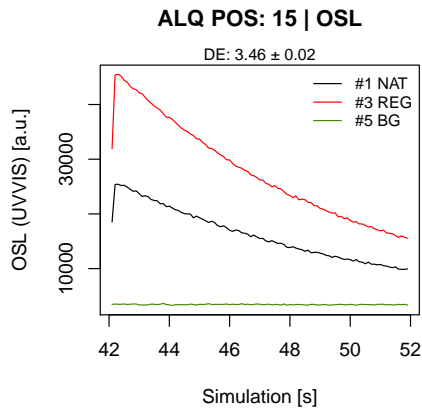


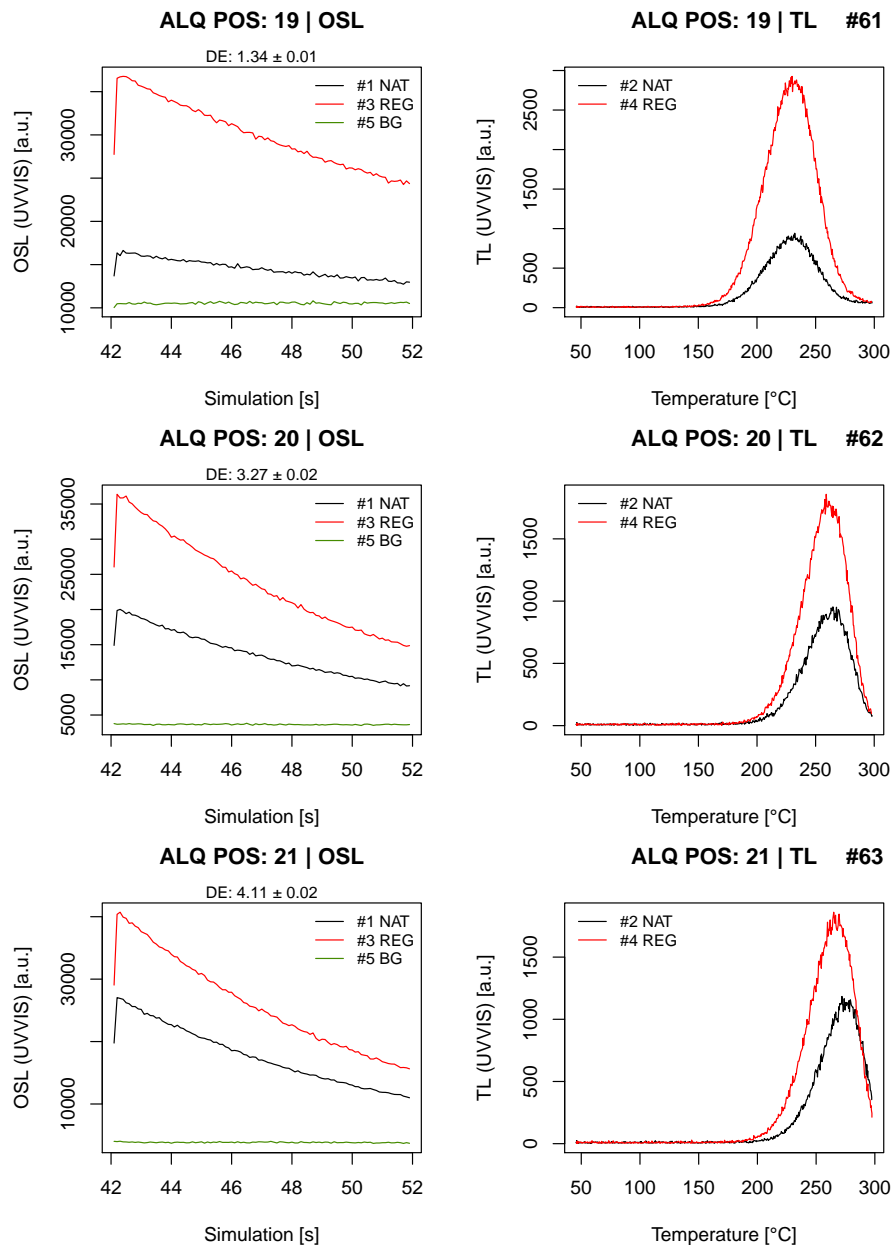












Summarise results and obtain final dose-rate

Extract data

The function `analyse_A1203C_Measurement()` returns an `RLum.Results`-object including the travel dosimeter corrected values (`results$data_TDcorrected`) for further processing, here in **R**, however, other programs like *MS ExcelTM* can be used as well.

At this point the measurement data might require a rejecting of individual aliquots; for this example nothing is rejecting.

```
##load package plyr
library(plyr)
```

```
##group data according to their position
results_grouped <- plyr::dply(results$data_TDcorrected, "POSITION", identity)

##calculate error weighted mean for each position,
results_summarised <- vapply(1:length(results_grouped), function(x){
  unlist(calc_Statistics(
    data = results_grouped[[x]][,c("DE", "DE_ERROR")],
    n.MCM = 1000)[["MCM"]][c("mean", "sd.abs")])
}, FUN.VALUE = numeric(length = 2))
```

Convert to μGy

The values needed to be converted to μGy using the source calibration value, here:

```
sourceDR_FINAL
```

```
##          DR DR_ERROR UNIT
## 1 204.2475 8.951548  $\mu\text{Gy/s}$ 
```

The conversion is a simple multiplication. Please note that the source calibration error, as a systematic error, needs to be considered in the final age calculation and is therefore not further taken into account here.

```
results_final <- results_summarised * sourceDR_FINAL[,1]
```

Correct for the anual fraction

The last step accounts for the fact that the dosimeter was stored for a fraction of a year, here, 258 days, but dose rates are usually given per year (or ka).

```
##final results
results_final <- results_final * 365.25 / 258
```

The final results for the obtained true dose recorded by the dosimeter are listed in the following table (expressed as dose rate):

```
df_final <- data.frame(
  POS = 2:21,
  DR = t(results_final)[,1],
  DR_ERROR = t(results_final)[,2],
  cv = t(results_final)[,2]/t(results_final)[,1] * 100)
```

Table 1: Final γ -dose rate values in $\mu\text{Gy/a}$; cv is given in %.

POS	DR	DR_ERROR	cv
2	1263.6803	97.423000	7.709466
3	626.9395	94.596618	15.088637
4	660.7887	13.179756	1.994549
5	507.3163	9.181574	1.809832
6	817.3762	61.786298	7.559102
7	769.3464	39.655032	5.154380
8	690.7183	26.869844	3.890131
9	1265.2729	87.093650	6.883388
10	1157.9356	12.089440	1.044051

POS	DR	DR_ERROR	cv
11	938.9186	18.996965	2.023281
12	932.5263	15.796971	1.693997
13	902.3959	72.205829	8.001569
14	1314.6045	49.779468	3.786650
15	1060.9771	74.639894	7.035015
16	647.9879	38.950597	6.011007
17	351.5619	7.557073	2.149571
18	779.4593	8.628355	1.106967
19	386.8038	50.308973	13.006327
20	934.7718	23.884300	2.555094
21	1147.9600	39.372109	3.429746

Further statistical measures:

```
##range DR
range(df_final$DR)
```

```
## [1] 351.5619 1314.6045
```

```
##mean cv
mean(df_final$cv)
```

```
## [1] 5.096638
```

```
##range cv
range(df_final$cv)
```

```
## [1] 1.044051 15.088637
```

```
##number of aliquots with cv >5%
table(df_final$cv > 5)
```

```
##
## FALSE TRUE
##    11    9
```

Please note that for obtaining the environmental dose rate (cosmic + γ -dose rate) every position needs to be corrected in three further steps:

1. Subtraction of the individual cosmic-dose rate per sample (e.g., by using the function `calc_CosmicDoseRate()`),
2. Correction of the remaining dose value for the container, in our case by multiplying by a factor of 1.065 (i.e. correct for the attenuation of the field container),
3. Adding again the individual cosmic-dose rate value to each sample.

Post-processing

The following post-processing was used to create figures shown in the main text.

```
## full data set merged
df <- merge(x = results$data, y = results$test_parameters, by = "UID")
```

```
##create matrix for positions (one column for each position)
results_grouped <- plyr::dply(df, "POSITION", identity)
```

```

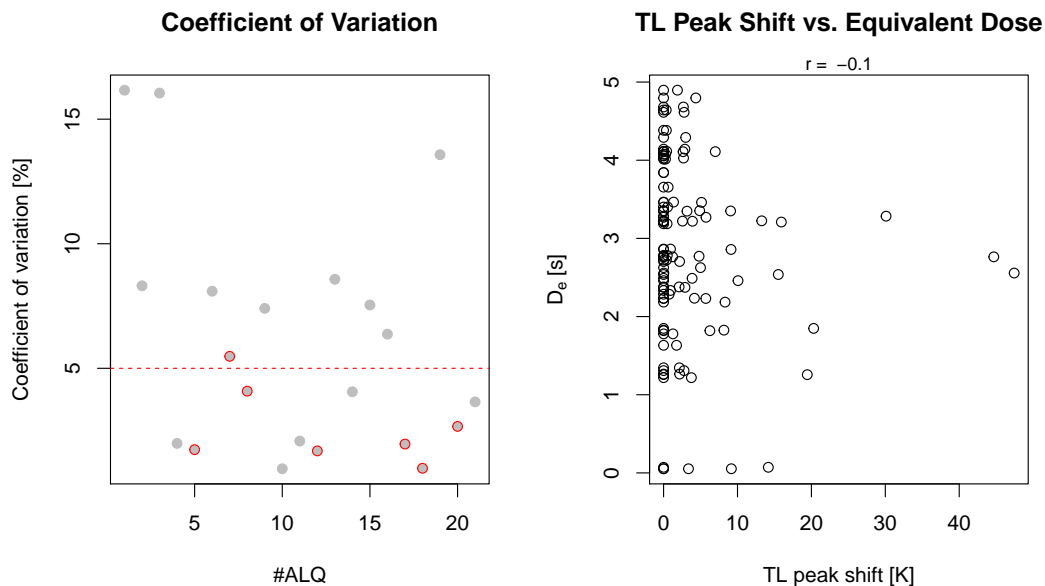
##create simple matrix
m <- do.call(cbind, lapply(results_grouped, function(x){x$DE}))

# Plotting -----
par(mfrow = c(1,2), cex = 1.2)

##plot1
plot(
  matrixStats::colSds(m)/colMeans(m) * 100,
  col = ifelse(unlist(lapply(results_grouped, function(x){any(x$STATUS)})), "red", "grey"),
  xlab = "#ALQ",
  ylab = "Coefficient of variation [%]",
  main = "Coefficient of Variation",
  bg = "grey",
  pch = 21
)
abline(h = 5, col = "red", lty = 2)

##plot2
plot(x = df$VALUE,
     y = df$DE,
     xlab = "TL peak shift [K]",
     ylab = expression(paste(D[e], " [s]")),
     main = "TL Peak Shift vs. Equivalent Dose"
)
mtext(side = 3, text = paste("r = ", round(cor(x = df$VALUE, df$DE),1)))

```



References

- Bottollier-Depois, J.F., Chau, Q., Bouisset, P., Kerlau, G., Plawinski, L., Lebaron-Jacobs, L., 2003. Assessing exposure to cosmic radiation on board aircraft. *Advances in Space Research* 32, 59–66.
- Dietze, M., Kreutzer, S., Burow, C., Fuchs, M.C., Fischer, M., Schmidt, C., 2016. The abanico plot: visualising chronometric data with individual standard errors. *Quaternary Geochronology* 31, 12–18.
- Miallier, D., Guérin, G., Mercier, N., Pilleyre, T., Sanzelle, S., 2009. The Clermont radiometric reference rocks: a convenient tool for dosimetric purposes. *Ancient TL* 27, 37–44.