CCRI(III)-S2.Hp(10):

Supplementary Comparison for the Calibration of Personal Dose Equivalent Meters in ISO Neutron Reference Fields

Technical Protocol

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1 Introduction

The monitoring of neutron personal dose equivalent is one of the most important tasks for the radiation protection of workers in the nuclear power plant and other places. The reliability of the monitoring of the neutron personal dose equivalent depends on the capability of the calibration of neutron personal dose equivalent meters. In practice, many difficulties lie in the fact that the sensitivities of neutron personal dose equivalent meters are generally small. This fact makes it difficult to make the comparison for the calibration of the neutron personal dose equivalent meters. If a transfer instrument has small sensitivity, it can be hard to distinguish between the statistical fluctuation of the measurand and the calibration capability of the participants. Unlike neutron ambient dose equivalent rate meters, neutron personal dose equivalent meters measure the dose equivalent rather than the dose equivalent rate. Reducing statistical uncertainties by the repeated measurements makes the measurement time long.

The procedure of the calibration of neutron personal dose equivalent is not written clearly in ISO 8529-3 [3]. One ambiguity is the method to subtract the contribution of the scattered neutrons in the neutron irradiation room. In ISO 8529-2 [2], four methods (Shadow-cone method, Generalized-fit method, Semi-empirical method, and Reduced-fitting method) are presented for the correction H*(10) for the influence of the scatted neutrons. However, there are no recommended methods to correct the scatter-contributions of $H_p(10)$. It is estimated to be about several percent for the neutron irradiation room with dimensions of 6.6 m x 7.6 m x 6.3 m surrounded by concrete walls [4]. Conversion coefficients $h_{p\Phi}(10)$ in the ICRU tissue slab phantom are evaluated for parallel neutron irradiation. Unlike conversion coefficient $h^*_{\Phi}(10)$ for ambient dose equivalent, $h_{p\Phi}(10,\alpha)$ is dependent for angles of incidence α. In practice, when the normal direction of the phantom surface coincides with the neutron source, $h_{p\Phi}(10{,}0°)$ can be used as $h_{p\Phi}(10)$.

Many national metrology institutes list the calibration of neutron personal dose equivalent in their CMC table and offer the calibration of neutron personal dose equivalent meters. But there is no CCRI comparison supporting the CMC because of the difficulties and complexity to realize the comparison for the neutron personal dose equivalent. Since 2017, a CCRI supplementary comparison for the calibration of neutron ambient dose equivalent (CCRI(III)-S1) is going on. A similar procedure could be applied the supplementary comparison for the calibration of neutron personal dose equivalent.

CCRI comparison for the calibration of neutron personal dose equivalent meter could be conducted using ISO neutron reference fields [1]. Two neutron personal dose equivalent meters will be used as transfer instruments and the calibration factors for two transfer instruments could be derived.

2 Participants

No.	Institute	Country	Contact person	Contact person (e-mail)
1	KRISS	Korea	Jungho Kim	jungho@kriss.re.kr
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Full contact information is given in Appendix A.

3 Schedule

Two transfer instruments will be circulated and the stability of the transfer instruments will be checked at the pilot laboratory (KRISS) during circulations.
One month is scheduled for the calibration measurement. The following month, the equipment will be shipped back to KRISS, which will be transported to the next participant after check of stability. If there is a problem with customs, participants will be given an additional month.

Start of the comparison **2022-02**

No.	Participant	Measurement at the participant	Transfer to next participant or to KRISS	Report of the results to pilot
1	KRISS (KR)	2022-02		
	KRISS*	2022-02	2022-02	
2	NIM (CN)	2022-03	2022-04	2022-07
3	BARC	2022-05	2022-06	2022-09
	KRISS	2022-07	2022-07	
4	CMI (CZ)	2022-08	2022-08	2022-11
5	IRSN (FR)	2022-09	2022-09	2022-12
6	NPL (UK)	2022-10	2022-10	2023-01
	KRISS*	2022-11	2023-11	
7	SCK/CEN (BE)	2022-12	2023-01	2023-04
8	PTB (DE)	2023-02	2023-04	2023-07
9	CIEMAT (ES)	2023-05	2023-05	2023-08
	KRISS	2023-06	2023-06	
10	NMIJ (JP)	2023-07	2023-09	2023-12
11	SMU (SK)	2023-10	2023-11	2024-02
12	VNIIM (RU)	2023-12	2024-01	2024-04
	KRISS	2024-02	2024-02	
13	NIST (USA)	2024-03	2024-03	2024-06
14	NRC (CA)	2024-04	2024-06	2024-09
	KRISS*	2024-07	2024-07	
15	NMISA (ZA)	2024-08	2024-09	2024-12
16	LNMRI/IRD (BR)	2024-10	2024-11	2025-02
	KRISS*	2024-12		

End of the comparison **2024-12**
Draft of Report **2025-03**
Comments of partners **2025-05**

* stability test

Participants should inform the pilot laboratory as soon as possible if the scheduled procedure has to be changed. In case of delays of more than one month, the whole schedule might be changed in accordance with the availability of the calibration facilities of the participants. The pilot laboratory will cover the expenses for shipping the equipment to the participants while the participants have to cover the costs of the return shipment or shipment to the next participant, respectively. After arrival of the transfer instruments the participant should inform the pilot about the reception. Before dispatching the package for delivery to the pilot or next participating laboratory, the participant should inform the contact person of the pilot laboratory or contact person of the next participant giving transportation details. Information on dimensions, content, and weight of the transport containers are given in Appendix B.

4 Measurements

The calibration factor of a personal dose equivalent meter is a unique property of the type of device. It depends on the neutron energy spectrum, the location of the phantom attachment, and the angle of incidence of the neutrons to the phantom surface. But it should not be a function of the characteristics of the calibration facility or experimental techniques employed.

ISO 8529, parts 1 to 3, [1-3] recommends several radionuclide sources for the calibration of neutron personal dose equivalent meters.

The calibration factor, N, is obtained by

$$N = h_{p\Phi}(10,\alpha)\, \Phi \;/\; M_c\,, \qquad (1)$$

where M_c is the measured reading corrected for all extraneous effects, Φ is the neutron fluence of the direct neutrons from the source to the point of test, and $h_{p\Phi}(10,\alpha)$ is the conversion coefficient of the neutron fluence-to-personal dose equivalent. The fluence is determined by the product of neutron irradiation time T and the fluence rate $\varphi = B_\Omega / l^2$ using the neutron angular source strength B_Ω and the distance l from the source axis of symmetry to the point of test. $h_{p\Phi}(10,\alpha)$ is dependent for angles of incidence α for parallel neutron radiation to the phantom surface normal. In practice, the phantom should be installed so as the normal direction of the phantom surface coincides with the neutron source and $h_{p\Phi}(10,0°)$ is used for the conversion coefficient, although the neutron radiation is not parallel.

The calibration procedure should follow the recommendations of ISO 8529, 1-3 [1-3], using those neutron reference fields of radionuclide sources available at the participating laboratory. The sources have to be characterized in terms of neutron source strength and anisotropy. No guidelines are provided for the scattering neutron correction, so the participants should follow their own methods used for nominal calibration of external customer device.

4.1 Quantity to be measured by the participants

The participants should determine the calibration factor in terms of neutron personal dose equivalent for the two transfer instruments using available radionuclide neutron sources recommended by ISO 8529. The operation of the instruments is briefly described in Appendix C. The calibration factor (eq. 1) should be determined for one direction of incidence as defined in Appendix C.

4.2 Neutron fields

ISO 8529 recommends the following neutron fields for the calibration of neutron personal dose equivalent meters:

- ^{252}Cf
- ^{241}Am-Be
- ^{252}Cf(D2O-moderated)
- ^{241}Am-B

Each laboratory should determine the calibration factor for the ISO recommended sources they have available, at least for those for which CMC entries exist and offered to customers.

4.3 Transfer instruments

The comparison will be performed with two identical transfer instruments, DMC3000 Neutrons, and one reader (LDM320D) manufactured by MIRION Technologies.

1) DMC3000 Neutron: S/N 09171430 – 00047A
2) DMC3000 Neutron: S/N 09172996 – 000493
3) LF LDM320D : S/N 18016806 (optional for reading)

Handling and usage advice are given in Appendix C. The pilot laboratory (KRISS) will determine the calibration factor for both devices at the beginning of the comparison. Before and after the calibration measurements of the participants, the stability of the reading of the devices will be checked with a ^{252}Cf source.

4.4 Calibration phantom

ISO 8529-3 recommends the specification of the calibration phantom. Measurements of the responses as a function of neutron energy and direction of neutron radiation incidence and calibrations of neutron personal dose equivalent meters should be carried out on a phantom of outer dimensions 30 cm x 30 cm x 15 cm made of PMMA walls (front wall 2.5 mm thick, other walls 10 mm thick) and filled with water, termed the ISO water slab phantom. The neutron personal dose equivalent meter is fixed on the front face of the phantom in such a way that the reference point of the meter is placed at the point of test. The participants can use a PMMA phantom instead of the ISO water slab phantom, but the outer dimensions should be equal to 30 cm x 30 cm x 15 cm.

4.5 Neutron irradiation and calibration conditions

Measurements should be carried out by positioning the reference point of the instrument at the point of test. Distance between the radiation source and the instrument should be taken as the perpendicular distance between the axis of symmetry of the radiation source and the reference point of the instrument. The instruments should be fixed on the phantom front face in such a way that their reference direction coincides with the normal to the front face.

The participants are encouraged to irradiate neutrons to the instruments until the reading of the instruments reaches 10 mSv in order to stabilize the reading. The uncertainty of the reading can be obtained by repeated measurements or evaluated using counts from DMC*User* program. The relative uncertainty of 10 mSv reading is estimated to be about 1.2 % (*k* = 1). The uncertainty of reading is $\sigma_{Dose}(\mu \mathrm{Sv}) = 1.246\sqrt{Dose(\mu \mathrm{Sv})}$. The coefficient 1.246 may be slightly different depending on the instrument. This Details on how to estimate uncertainty in a single measurement are given in Appendix E.

Participants who take a long time to irradiate due to weak source strength can set the minimum reading as 4 mSv for ^{252}Cf and 2 mSv for ^{241}Am-Be and $D_2O(^{252}Cf)$. The supplementary comparison mean value (SCMV) will be calculated for above 10 mSv for ^{252}Cf and above 4 mSv for ^{241}Am-Be and $D_2O(^{252}Cf)$. Any measurements not applied to the SCMV calculation are also included in the report. (See Appendix E.5)

	Minimum reading (mSv)	Minimum reading for SCMV (mSv)
^{252}Cf	4	10
^{241}Am-Be	2	4
$D_2O(^{252}Cf)$	2	4

The minimum distance *l* from the source axis of symmetry to the point of test should be 75 cm. If the shadow cone or the distance variation methods are applied, other distances can be chosen. The irradiations conditions and procedure used to determine the influence of scattered neutrons should be described in detail by the participants in their report.

The location where the instrument is attached on the phantom and how to align the instrument are given in Appendix C.

4.6 Reports from the participants

The participants should prepare a detailed report about the calibration procedure and the results. The report should contain all necessary details of:

- Date and place of calibration
- Description of the source employed (source strength, anisotropy, traceability, geometry…) For the ^{252}Cf(D2O-moderated) source the followings should be described: source strength of the ^{252}Cf source, diameter of the moderator, thickness of housing, drawing of the moderator (if available), information about H/D ratio in heavy water, thickness of Cd shell
- Description of the phantom (size, material, geometry…)
- Description of the neutron irradiation room (size, position of the source in the room, reference point, …)
- Description of the reference conditions, calibration conditions, and/or standard test conditions
- Description of the distance from the source axis of symmetry to the point of test
- Description of the method used for the correction of scattered neutrons and the uncertainty evaluation of the method
- Description of the calibration procedure and geometry
- Calibration factors *N* (eq. 1) in terms of $H_p(10)$ determined for the two transfer instruments and the neutron fields available.
- Description of the conversion factors $h_{p\Phi}(10)$ used with their uncertainties
- List of the uncertainties
- Any other necessary things to be commented.

The participants should send their final report to the pilot laboratory at the least three months after finishing their measurements.

Uncertainties should be calculated in accordance with the “Guide to Uncertainty in Measurement” (GUM) [5] for a coverage factor of $k = 1$.

5 Evaluation of the Results

The participants are asked to determine the calibration factor *N* in terms of personal dose equivalent for the two transfer instruments for the reference neutron fields available and used in routine service at their laboratory.
For the comparison, the calibration factors reported by the participants will be evaluated by the pilot laboratory. Since the evaluation of uncertainties is not uniform and differs for the participants and to avoid bias due to small uncertainties, the arithmetic mean will be used for

the determination of the reference values [6].

The evaluation of the results could proceed in the same way as in the technical protocol of CCRI(III)-S1 comparison [7].

As there are two transfer instruments, the single value for each participant and the supplementary comparison mean value (SCMV) have to be derived by combining the results obtained for the two instruments in every specific neutron field. If one instrument fails during the stability test or not be operational anymore, only one value will be evaluated and the procedure described below will be simplified.

In a first step the reference value $\bar{N}_j$ for the calibration factor of each transfer instrument *j* (*j*=1,2) is calculated by $\bar{N}_j = \frac{1}{n}\sum_{i=1}^{n} N_{i,j}$. For each participant *i* the deviation for each transfer instrument is calculated by $\bar{x}_{i,j} = \frac{N_{i,j}}{\bar{N}_j}$. A single value $\bar{x}_i$ for each participant *i* is derived by averaging the two results $\bar{x}_i = \frac{1}{2}\sum_{j=1}^{2} \bar{x}_{i,j}$. The supplementary comparison reference value $\bar{x}$ for the specific neutron field is then $\bar{x}$=1.
From the SCMV and the specified uncertainties, the degree of equivalence (DoE) will be calculated.

References

[1] International Standard ISO 8529-1 *Reference neutron radiations: Characteristics and methods of production* (2001).

[2] International Standard ISO 8529-2 *Reference neutron radiations: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field* (2000).

[3] International Standard ISO 8529-3 *Reference neutron radiations: Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence* (1998).

[4] V. Gressier and G C Taylor, *Calibration of neutron-sensitive devices*, Metrologia 48 S313-S327 (2011)

[5] JCGM 100:2008 *Evaluation of Measurement Data - Guide to the Expression of Uncertainty in Measurement*, www.bipm.org.

[6] G. Ratel, *Evaluation of the uncertainty of the degree of equivalence*, Metrologia 42 140-144 (2005)

[7] Désirée Radeck, *Technical Protocol of CCRI(III)-S1* (2017).

Appendix A : Full contact information of the participants

Institute	Address	Contact person
KRISS	Korea Research Institute of Standards and Science 267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Rep. of Korea Phone: +82-42-868-5788 / Fax: +82-42-868-5671	Jungho Kim jungho@kriss.re.kr
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NPL	National Physical Laboratory Hampton Road, Teddington, Middlesex, TW11 0LW, United Kingdom Phone: +44 20 8943 7087	Graeme Taylor graeme.taylor@npl.co.uk
CMI	Czech Metrology Institute Okružní 31, 638 00 Brno, Czech Republic Phone: +420 266 020 299 / Fax: +420 266 020 466 Shipping address: Czech Metrology Institute Radiová 1a, 102 00 Praha 10, Czech Republic	Zdenek Vykydal zvykydal@cmi.cz

Institute	Address	Contact person
SCK/CEN	SCK-CEN / Laboratory for Nuclear Calibrations (LNK) Boeretang 200, B-2400 Mol, Belgium Phone: +32 14 33 23 89 or +32 14 33 2005	Liviu-Cristian Mihailescu cristian.mihailescu@sckcen.be
CIEMAT	Responsable del Laboratorio de Patrones Neutrónicos [LPN] Laboratorio de Metrología de Radiaciones Ionizantes *[Ionizing Radiations Metrology Laboratory]* *[National Standards Laboratory, Associated to CEM]* E31.P1.11 (ext. 7811) CIEMAT Avenida complutense, 40. Madrid, 28040. Spain Phone: +34 91 346 0811 / 91 496 2606 Fax: +34 91 346 6442	Roberto Méndez Villafañe roberto.mendez@ciemat.es
SMU	Slovenský Metrologický Ústav (SMÚ) Karloveská 63 842 55 Bratislava, Slovakia Phone: +421260294282 / Fax: +421265429592	Pavol Blahušiak blahusiak@smu.gov.sk
NIST	National Institute of Standards and Technology 100 Bureau Dr., Stop 8461 Gaithersburg, MD 20899, USA Phone: 1-301-975-4666 / Fax: 1-301-926-1604	Alan K. Thompson akt@nist.gov
NRC	National Research Council Canada 1200 Montreal Road, Building M35 Ottawa, Ontario, K1A 0R6, Canada Phone: 613-993-2715 x252 / Fax: 613-952-9865	John Paul Archambault JohnPaul.Archambault@nrc-cnrc.gc.ca
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LNMRI/IRD	IRD - Instituto de Radioproteção e Dosimetria LN - Laboratório de Metrologia de Nêutrons Av. Salvador Allende, s/n - Barra da Tijuca 22783-127 - Rio de Janeiro – RJ, Brazil Phone:+55 21 2173-2870 / Fax: +55 21 2173-2709	Walsan Wagner Pereira walsan@ird.gov.br

Appendix B : Details on transport containers

One package will be sent with the following dimensions and weight.

Dimensions : 42 x 33 x 17 cm^3

Weight : 3.4 kg

Main contents : Two DMC3000 Neutrons, LF LDM320D, Torx screwdriver, USB

Fig. 1. Transport container

Appendix C : Instruction for the use of the equipment provided by the pilot laboratory

C.1 Equipments

1. Two DMC3000 Neutrons (neutron personal dose equivalent meter)
2. LF LDM320D (reader)
3. Torx screwdriver for battery replacement
4. USB with DMC*User* software, a manual of DMCUser and a manual of DMC3000 Neutron.
   DMC*User* is a program that can read readings from LF LDM320D reader.

Fig. 2. Equipments

The DMC3000 Neutron consists of two parts. One is a DMC3000, a gamma dosimeter, and the other is a neutron module. When replacing batteries, be careful not to mix the parts.

Fig. 3. DMC3000 S/N 09172996 (left) and neutron module S/N 000493 (right)

Fig. 4. DMC3000 S/N 09171430 (left) and neutron module S/N 00047A (right)

C.2 Description of reference conditions for the calibration

Reference point:

The neutron module of the DMC 3000 Neutron has a mark on the front surface and the side surface.

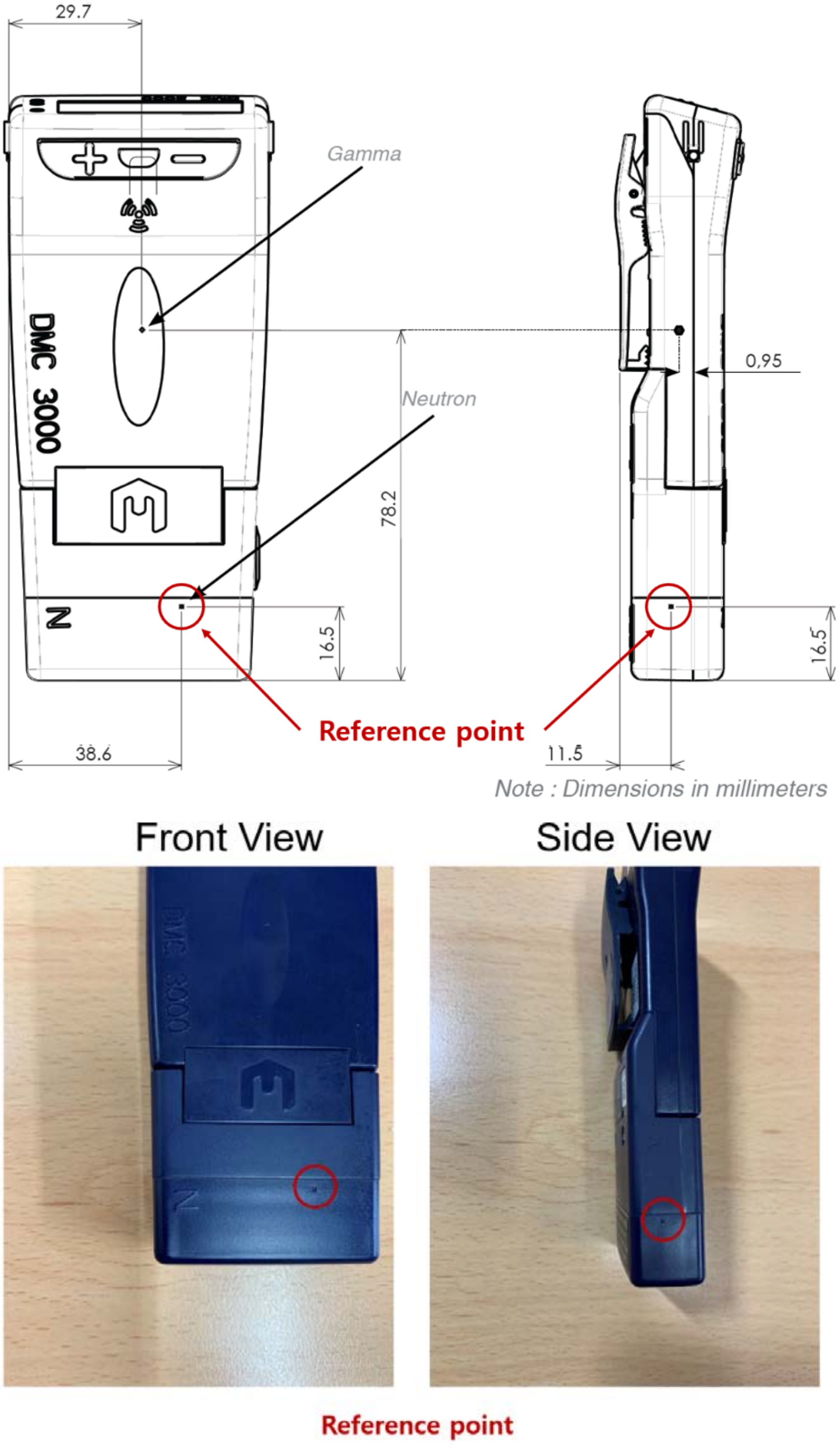


Fig. 5. Reference point of DMC 3000GN

C.3 Setup of the instrument

The instrument should be fixed and positioned on the phantom surface and installed so that the front reference point coincides with the center of the phantom. The phantom should be placed in such a way that the normal direction of the phantom front surface faces the source.

The minimum distance *l* from the source axis of symmetry to the point of test should be 75 cm.

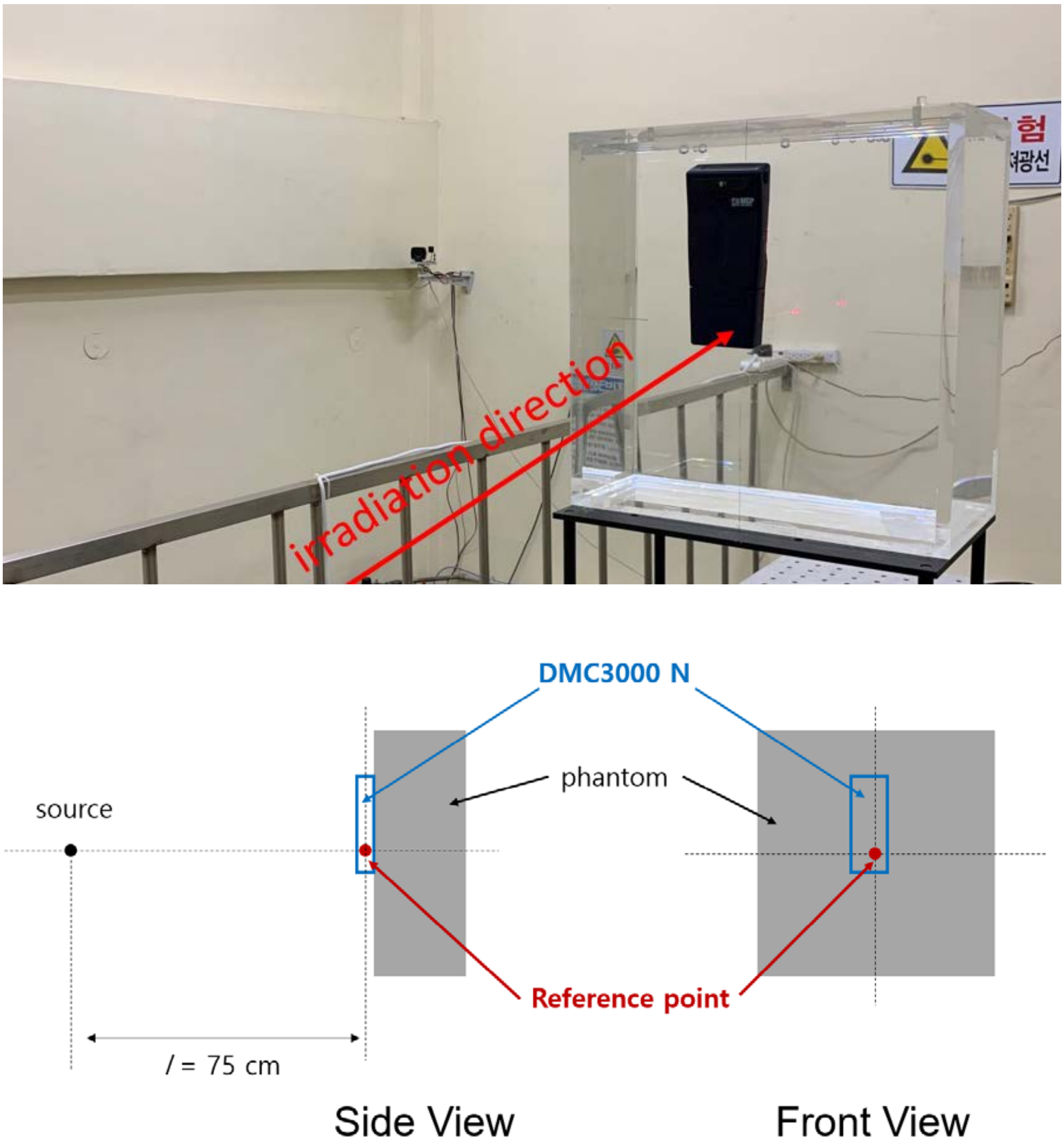


Fig. 6. Setup of the instrument

C.4 Brief instructions on how to use DMC3000 Neutron

Detailed instructions are given in the manual.

(1) Three modes; Sleep, Pause and Run

Sleep : a low-power consumption state.

Pause : You can check the data by pressing

Run : Data aquisition mode.

- Sleep mode to Pause mode 

When either button (“+” or “-”) on front face is pressed, the dosimeter automatically goes into Pause mode with a backlit display and all display segments activate for 2 seconds.

- Pause mode to Run mode 

In Pause mode, press “+” > 2 sec. “Enter” appears on the screen. Next go to “-” button and press shortly to enter Run mode.

- Run mode to Pause mode 

In Run mode, press “+” > 2 sec. “Exit” appears on the screen. Next go to “-” button and press shortly to enter Pause mode.

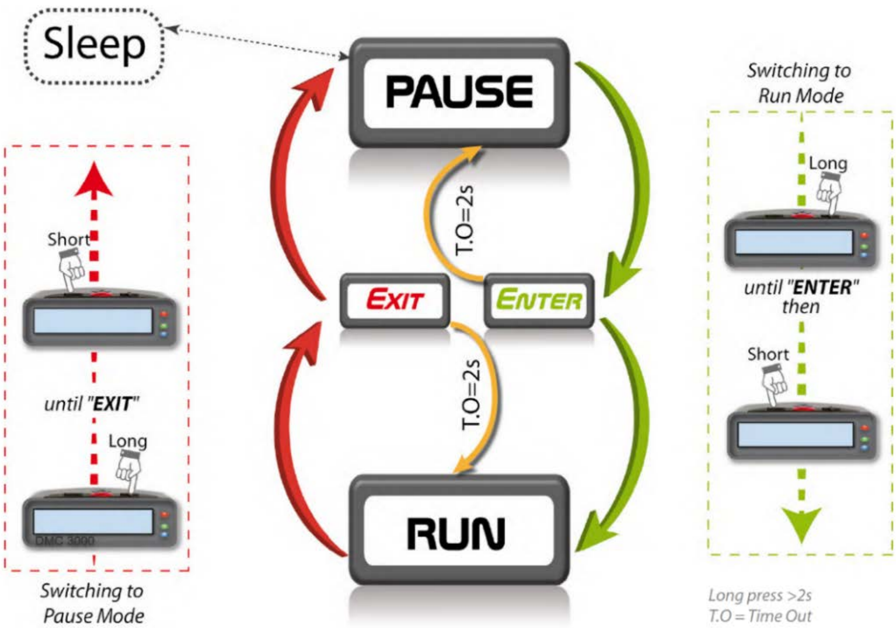


Fig. 7. Instructions of mode change

(2) Status monitoring of the dosimeter

Pause mode : You can check the status of the dosimeter by pressing “-” button. By pressing again, you can find other information. Data list is configurable with DMCUser.

Current setting is below.

last recorded dose (γ) → last maximum peak rate (γ) → last recorded dose (neutron) → last total dose (γ and neutron) → last duration in Run → current date

Run mode : You can check the status of the dosimeter by pressing “-” button. By pressing again, you can find other information. Data list is configurable with DMC*User*.

Appendix D : Data acquisition with DMC*User*

D.1 Installation of DMC*User*

If you have problems with history reading, try installing it in English version Windows. (See page 26)

(1) Double Click the installation program : DmcUserSetup 1.12.00 Full.exe (280 MB)

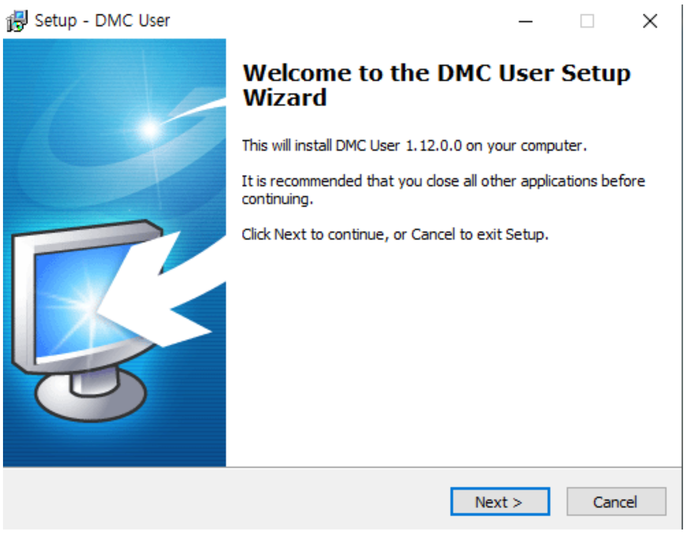


Fig. 8

(2) Select Destination Location

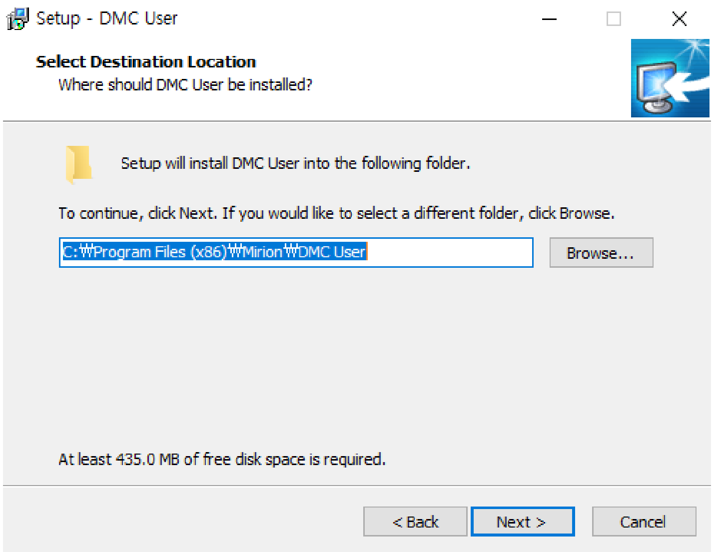


Fig. 9

(3) Select Additional Tasks : Select DMC User only – that's enough

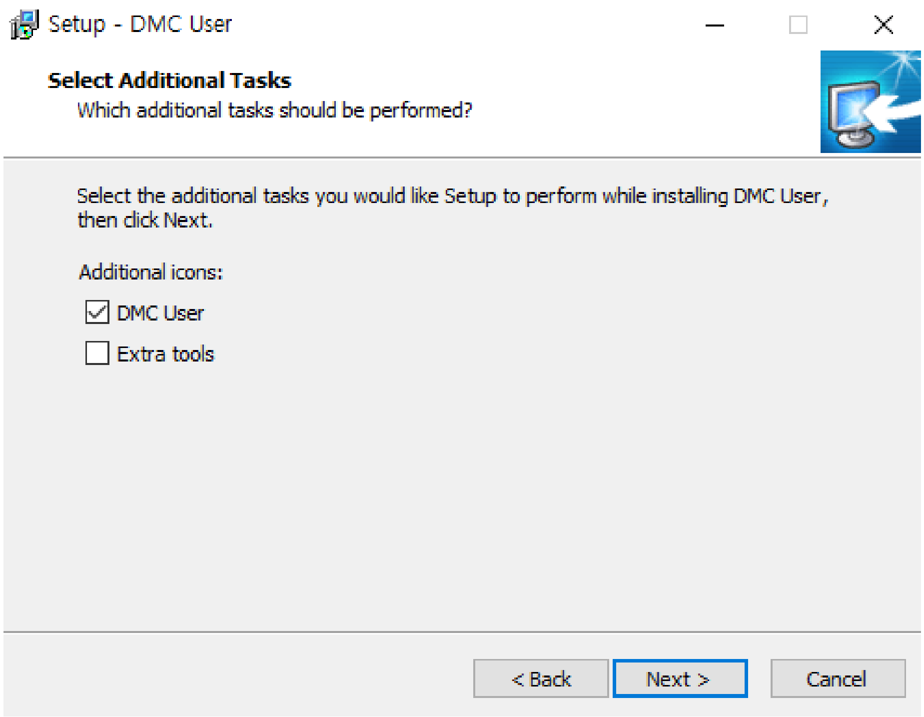


Fig. 10

(4) Ready to Install : Click Install to continue

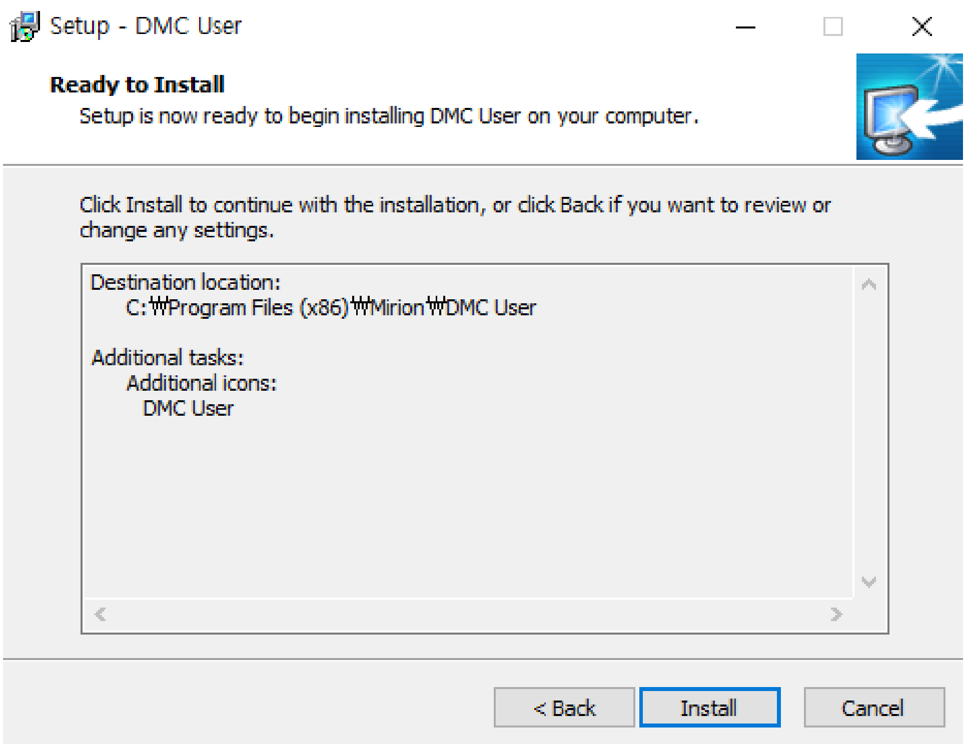


Fig. 11

D.2 Setup of the instrument

(1) Start DMCUser program and go to Technical support. Check License.

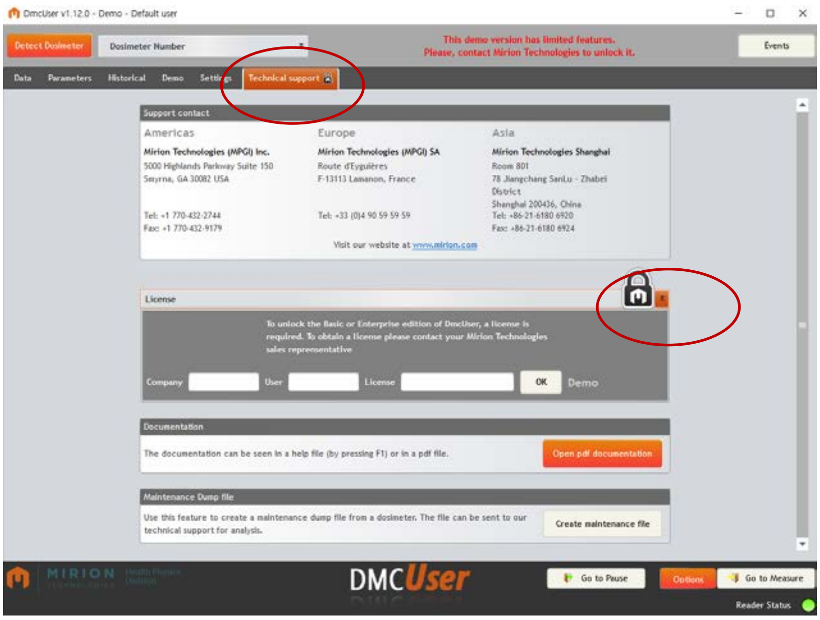


Fig. 12

(2) Input the following information and click OK. You have to restart the program.

Company: KRISS, User: JUNG HO KIM, License: MGP-BA6kq-3rsX-7p84HY

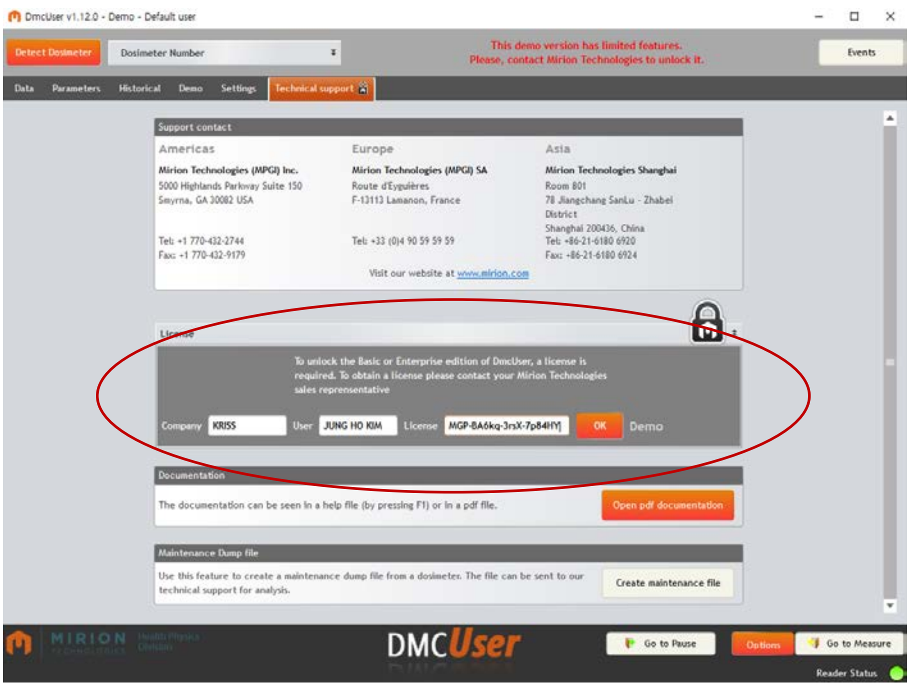


Fig.13

(3) (Optional) You can download new version.

Click blue icon on the top to download a new release and install it.

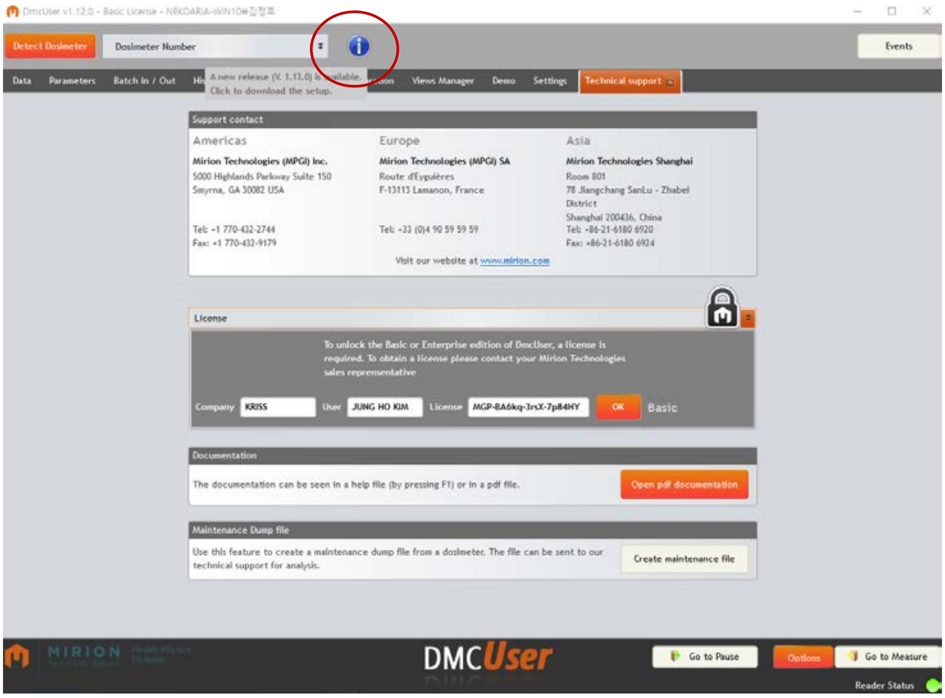


Fig.14

(4) After finishing the download, you can follow the same installation process.

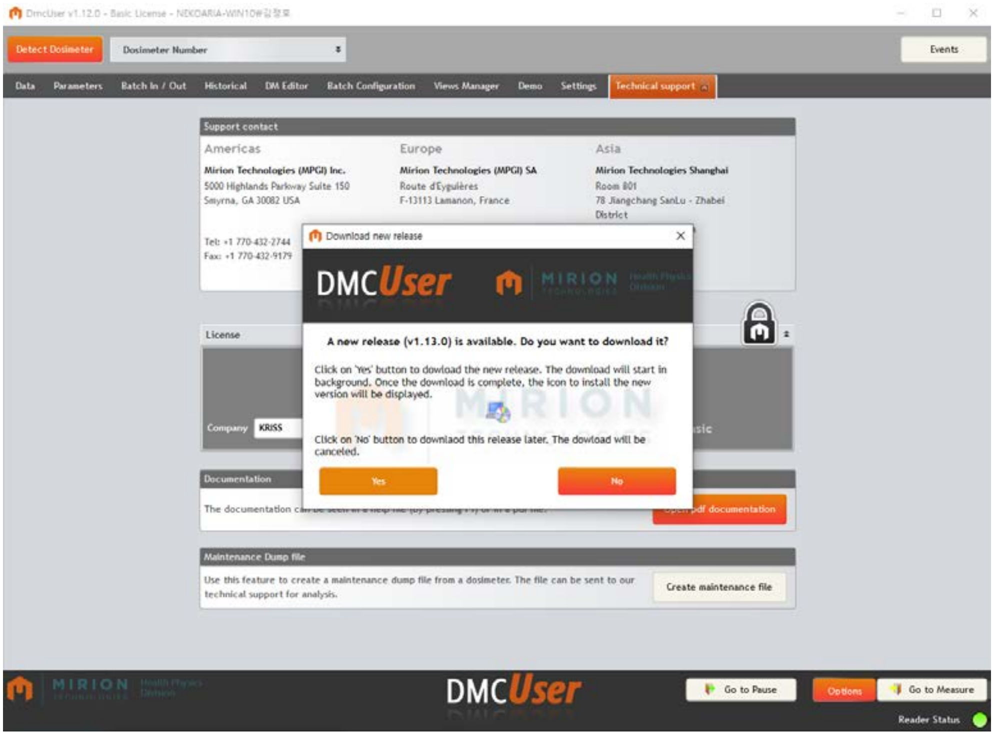


Fig.15

(5) Connect the dosimeter and detect dosimeter.

Click “Detect Dosimeter” shows the information of the dosimeter. Click “Read data” in Data menu and you can see the final data. Internal measures are for gamma and Additional measures for neutron.

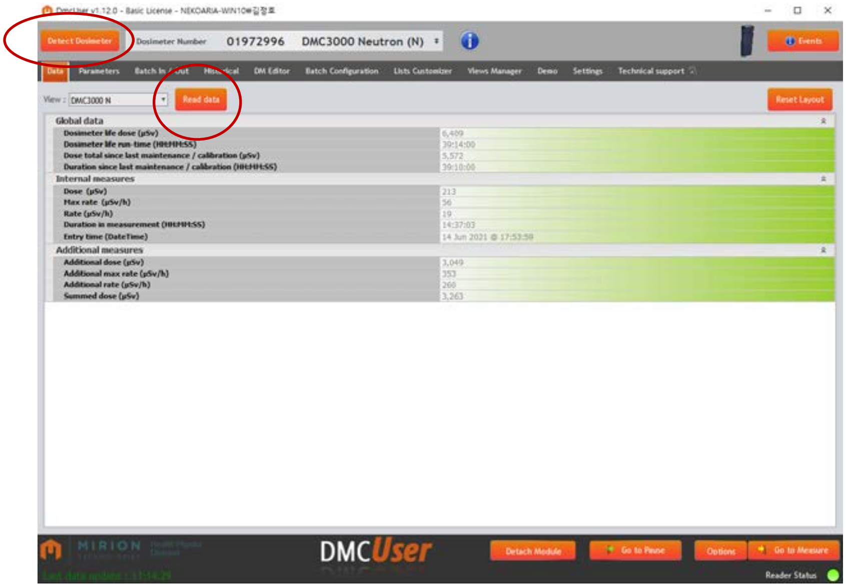


Fig.16

(6) Menu “Parameters” shows the parameters. You can read and change the parameters of the dosimeter by clicking “Read parameters”.

Please do not change the parameters except the “Histogram period”.

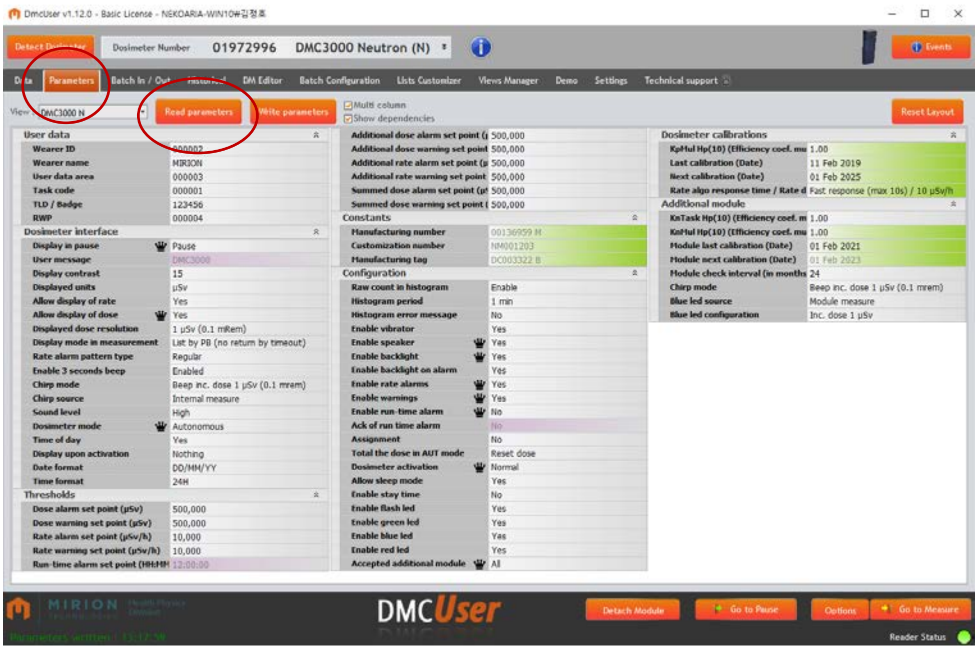


Fig.17

(7) Change “Histogram period”.

“Histogram period” is the time interval for reading history. Choose the time interval as you want. If history number exceeds 2000, it is overwritten. Therefore, 10 min or 1 hour is recommended. Click “Write parameters” and check the change using “Read parameters”.

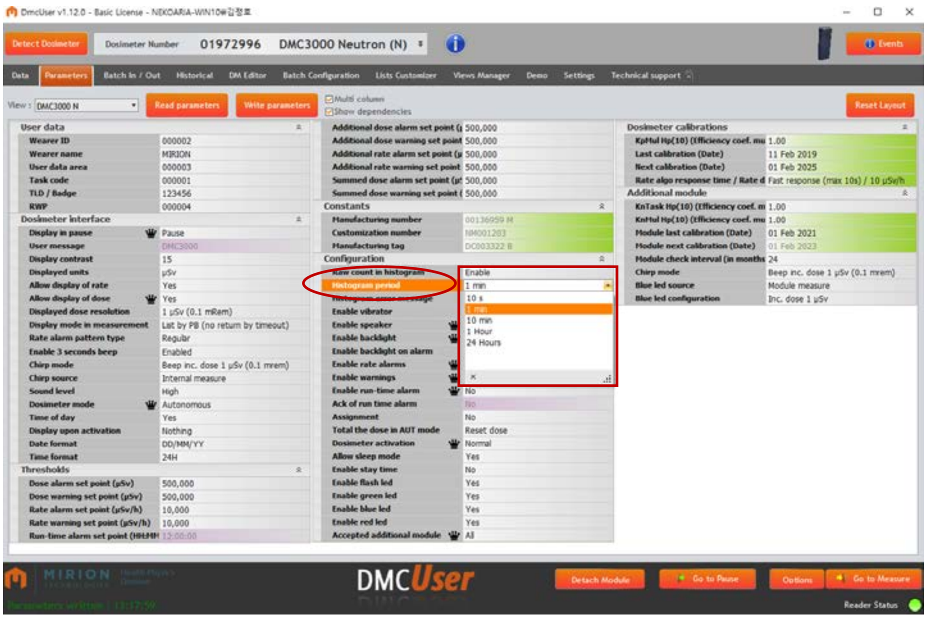


Fig.18

(8) Read histories of the readings.

Go to “Historical” menu.

Click “Get current” to get a current history. Be patient, it may take several miniutes.

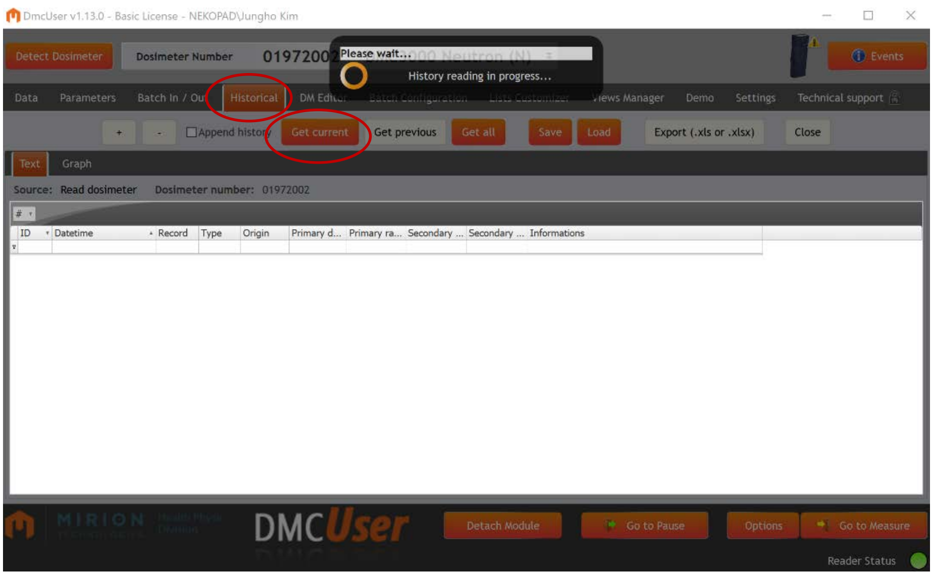


Fig.19

Doses and dose rates for primary (gamma) and secondary (neutron) are graphed.

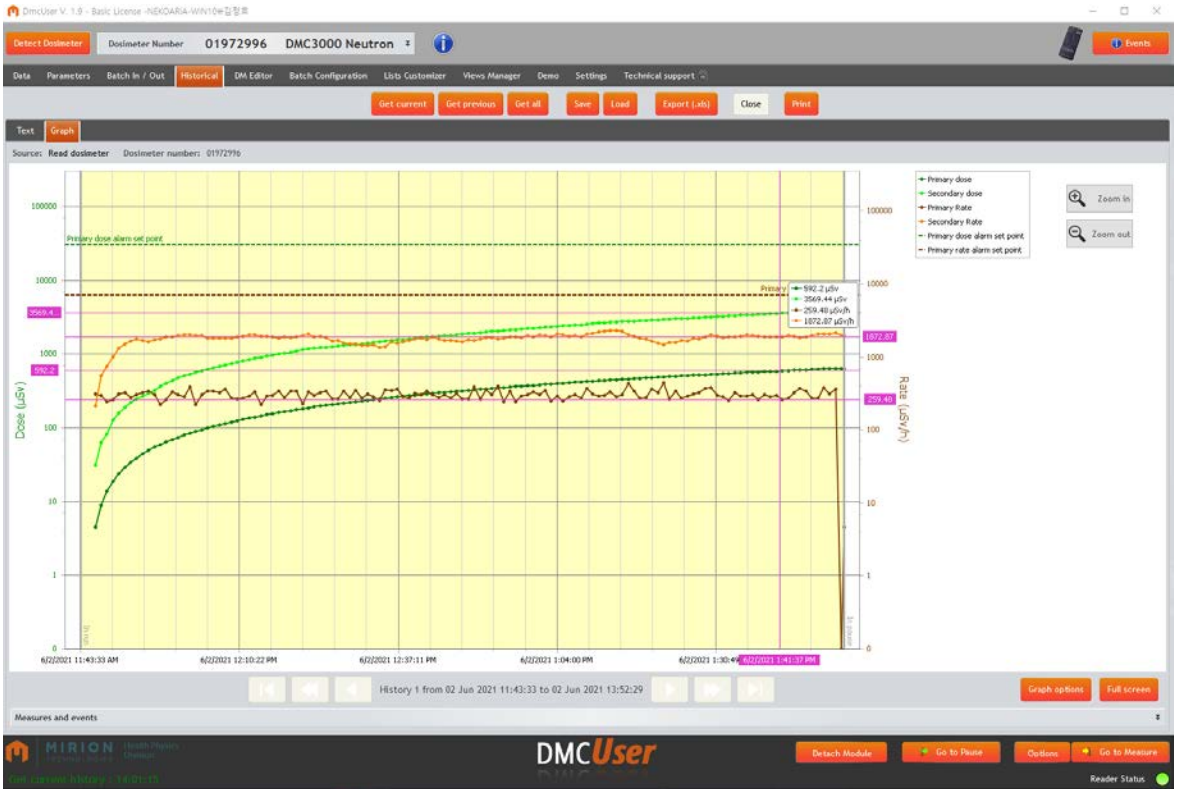
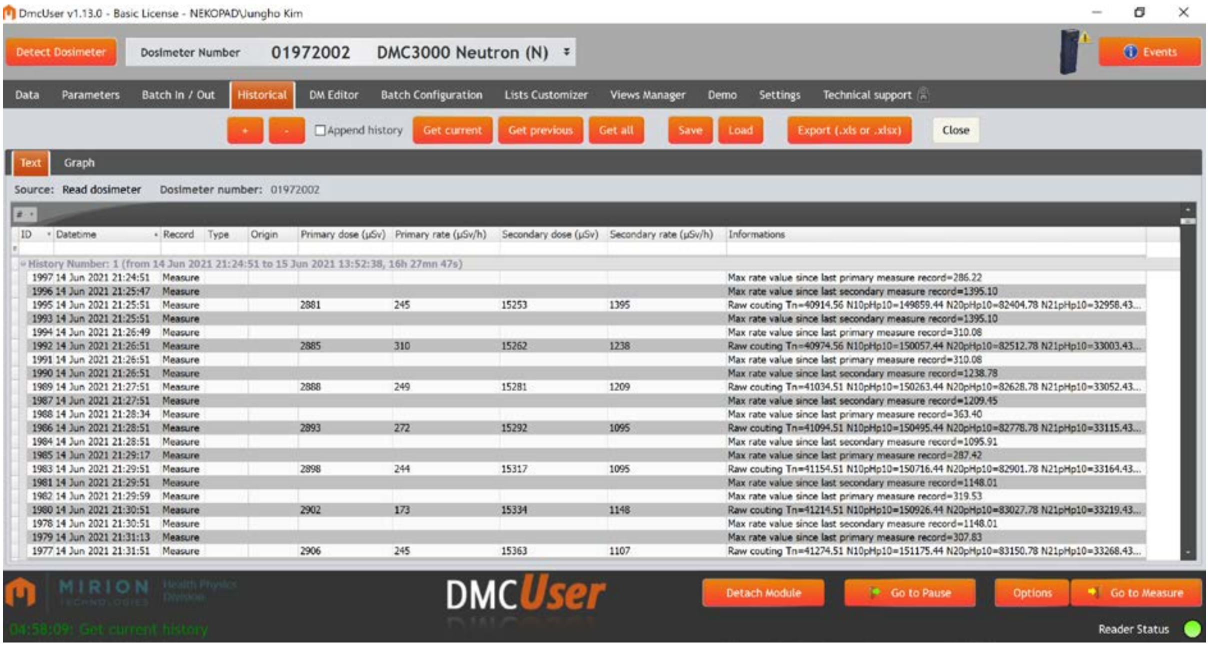


Fig.20

(9) Write the parameter.

Click “Export (.xls or .xlsx)” to save the history into Excel file.

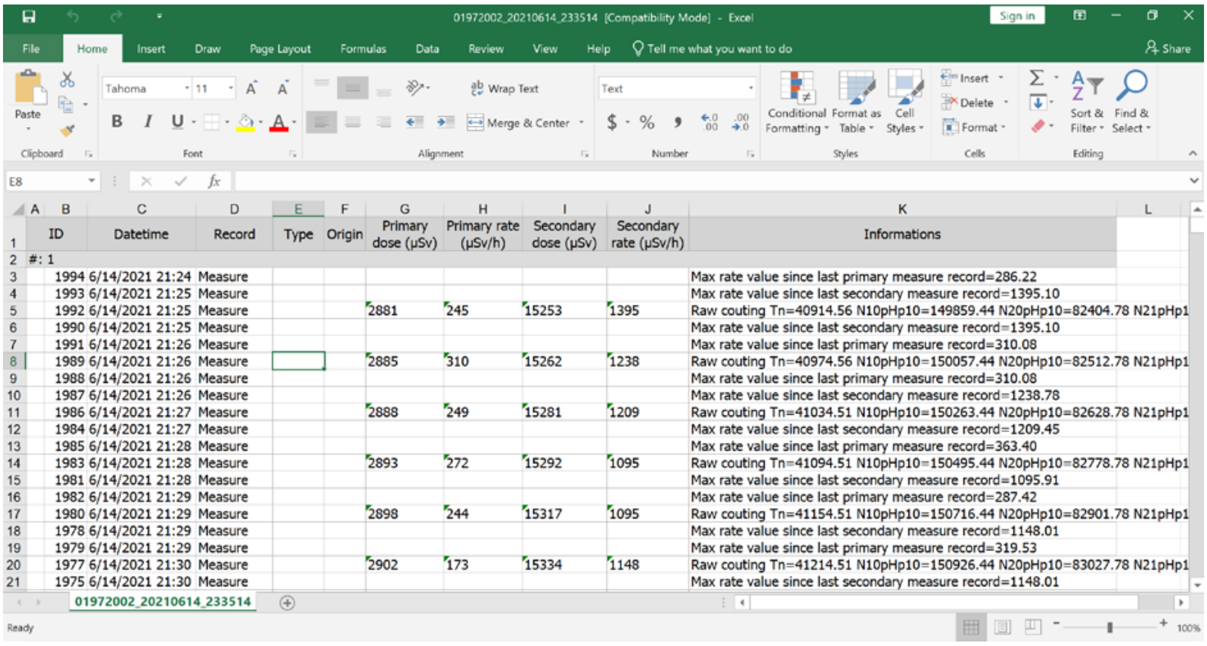


ID	Datetime	Record	Type	Origin	Primary dose (µSv)	Primary rate (µSv/h)	Secondary dose (µSv)	Secondary rate (µSv/h)	Informations
History Number: 1 (from 14 Jun 2021 21:24:51 to 15 Jun 2021 13:52:38, 16h 27mn 47s)									
1997	14 Jun 2021 21:24:51	Measure							Max rate value since last primary measure record=286.22
1996	14 Jun 2021 21:25:47	Measure							Max rate value since last secondary measure record=1395.10
1995	14 Jun 2021 21:25:51	Measure			2881	245	15253	1395	Raw couting Tn=40914.56 N10pHp10=149859.44 N20pHp10=82404.78 N21pHp10=32958.43...
1993	14 Jun 2021 21:25:51	Measure							Max rate value since last secondary measure record=1395.10
1994	14 Jun 2021 21:26:49	Measure							Max rate value since last primary measure record=310.08
1992	14 Jun 2021 21:26:51	Measure			2885	310	15262	1238	Raw couting Tn=40974.56 N10pHp10=150057.44 N20pHp10=82512.78 N21pHp10=33003.43...
1991	14 Jun 2021 21:26:51	Measure							Max rate value since last primary measure record=310.08
1990	14 Jun 2021 21:26:51	Measure							Max rate value since last secondary measure record=1238.78
1989	14 Jun 2021 21:27:51	Measure			2888	249	15281	1209	Raw couting Tn=41034.51 N10pHp10=150263.44 N20pHp10=82628.78 N21pHp10=33052.43...
1987	14 Jun 2021 21:27:51	Measure							Max rate value since last secondary measure record=1209.45
1988	14 Jun 2021 21:28:34	Measure							Max rate value since last primary measure record=363.40
1986	14 Jun 2021 21:28:51	Measure			2893	272	15292	1095	Raw couting Tn=41094.51 N10pHp10=150495.44 N20pHp10=82778.78 N21pHp10=33115.43...
1984	14 Jun 2021 21:28:51	Measure							Max rate value since last secondary measure record=1095.91
1985	14 Jun 2021 21:29:17	Measure							Max rate value since last primary measure record=287.42
1983	14 Jun 2021 21:29:51	Measure			2898	244	15317	1095	Raw couting Tn=41154.51 N10pHp10=150716.44 N20pHp10=82901.78 N21pHp10=33164.43...
1981	14 Jun 2021 21:29:51	Measure							Max rate value since last secondary measure record=1148.01
1982	14 Jun 2021 21:29:59	Measure							Max rate value since last primary measure record=319.53
1980	14 Jun 2021 21:30:51	Measure			2902	173	15334	1148	Raw couting Tn=41214.51 N10pHp10=150926.44 N20pHp10=83027.78 N21pHp10=33219.43...
1978	14 Jun 2021 21:30:51	Measure							Max rate value since last secondary measure record=1148.01
1979	14 Jun 2021 21:31:13	Measure							Max rate value since last primary measure record=307.83
1977	14 Jun 2021 21:31:51	Measure			2906	245	15363	1107	Raw couting Tn=41274.51 N10pHp10=151175.44 N20pHp10=83150.78 N21pHp10=33268.43...

Fig.21

(10) Read the data with Excel.

You can read the values by opening the file in the Excel program.



ID	Datetime	Record	Type	Origin	Primary dose (µSv)	Primary rate (µSv/h)	Secondary dose (µSv)	Secondary rate (µSv/h)	Informations
#: 1									
1994	6/14/2021 21:24	Measure							Max rate value since last primary measure record=286.22
1993	6/14/2021 21:25	Measure							Max rate value since last secondary measure record=1395.10
1992	6/14/2021 21:25	Measure			2881	245	15253	1395	Raw couting Tn=40914.56 N10pHp10=149859.44 N20pHp10=82404.78 N21pHp1
1990	6/14/2021 21:25	Measure							Max rate value since last secondary measure record=1395.10
1991	6/14/2021 21:26	Measure							Max rate value since last primary measure record=310.08
1989	6/14/2021 21:26	Measure			2885	310	15262	1238	Raw couting Tn=40974.56 N10pHp10=150057.44 N20pHp10=82512.78 N21pHp1
1988	6/14/2021 21:26	Measure							Max rate value since last primary measure record=310.08
1987	6/14/2021 21:26	Measure							Max rate value since last secondary measure record=1238.78
1986	6/14/2021 21:27	Measure			2888	249	15281	1209	Raw couting Tn=41034.51 N10pHp10=150263.44 N20pHp10=82628.78 N21pHp1
1984	6/14/2021 21:27	Measure							Max rate value since last secondary measure record=1209.45
1985	6/14/2021 21:28	Measure							Max rate value since last primary measure record=363.40
1983	6/14/2021 21:28	Measure			2893	272	15292	1095	Raw couting Tn=41094.51 N10pHp10=150495.44 N20pHp10=82778.78 N21pHp1
1981	6/14/2021 21:28	Measure							Max rate value since last secondary measure record=1095.91
1982	6/14/2021 21:29	Measure							Max rate value since last primary measure record=287.42
1980	6/14/2021 21:29	Measure			2898	244	15317	1095	Raw couting Tn=41154.51 N10pHp10=150716.44 N20pHp10=82901.78 N21pHp1
1978	6/14/2021 21:29	Measure							Max rate value since last secondary measure record=1148.01
1979	6/14/2021 21:29	Measure							Max rate value since last primary measure record=319.53
1977	6/14/2021 21:30	Measure			2902	173	15334	1148	Raw couting Tn=41214.51 N10pHp10=150926.44 N20pHp10=83027.78 N21pHp1
1975	6/14/2021 21:30	Measure							Max rate value since last secondary measure record=1148.01

Fig.22

In Column "Information", there is information such as Tn, Tm, N10pHp10, etc. MIRION company says these are used as raw data for the formula of evaluation of the personal dose equivalent (rate). The formula itself is not disclosed to customers.

The information received from the manufacturer is as follows. (Examples)

Tn=147.83	**(the value is: cumulated time 1)**
Tm=147.83	**(the value is: cumulated time 2)**
N10pHp10=266.02	**(the value is: gamma counter 1)**
N20pHp10=125.01	**(the value is: gamma counter 2)**
N21pHp10=45.00	**(the value is: gamma counter 3)**
N20pNeutron=33.00	**(the value is: neutron counter 1)**
N21pNeutron=8.00	**(the value is: neutron counter 2)**
N20bNeutron=5.00	**(the value is: neutron counter 3)**
M20pNeutron=33.00	**(the value is: neutron counter 4)**
M21pNeutron=8.00	**(the value is: neutron counter 5)**
M20bNeutron=5.00	**(the value is: neutron counter 6)**

(11) Error during reading Histrorical

When you use non-English Windows, no histories may appear. Click “Events” to check the messages. If you have such problem, please try English Windows to solve the problem.

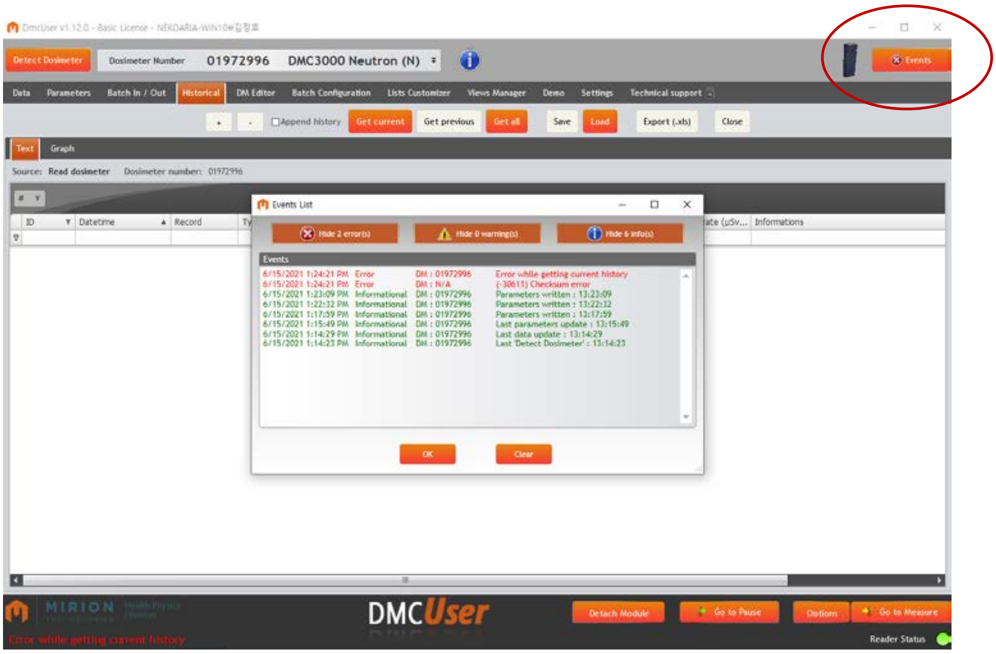


Fig.23

(12) DMC*User* Help

“F1” key navigates to Help.

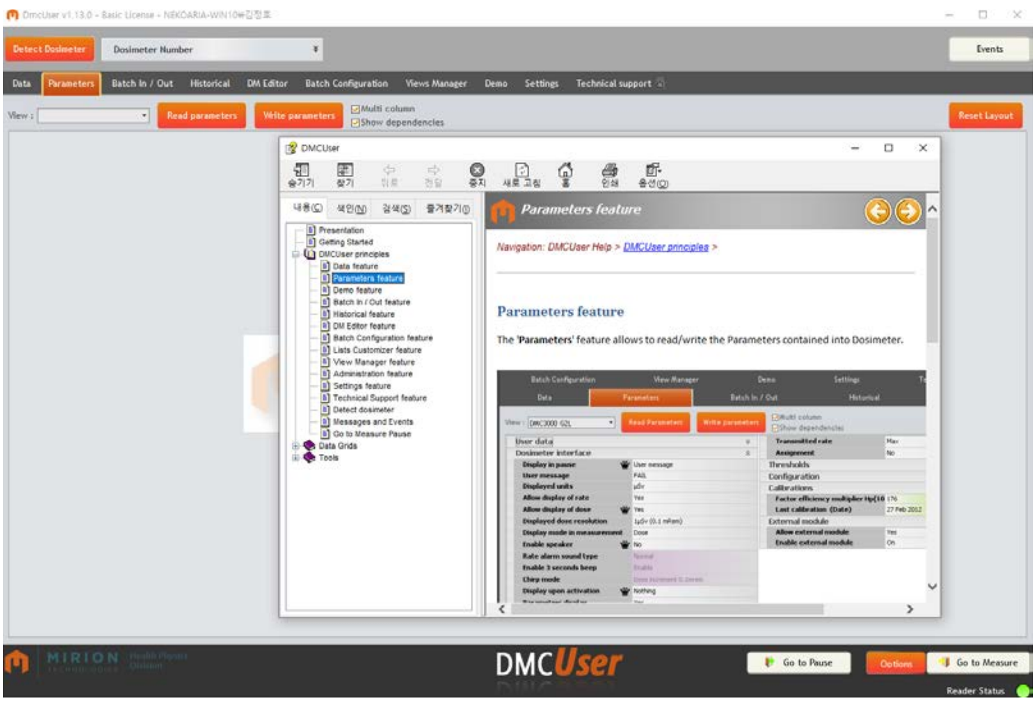


Fig.24

(13) Unit Settings

You can change units in the “Settings” menu. If readings are written in mrem and mrem/h, please change units to μSv and μSv/h.

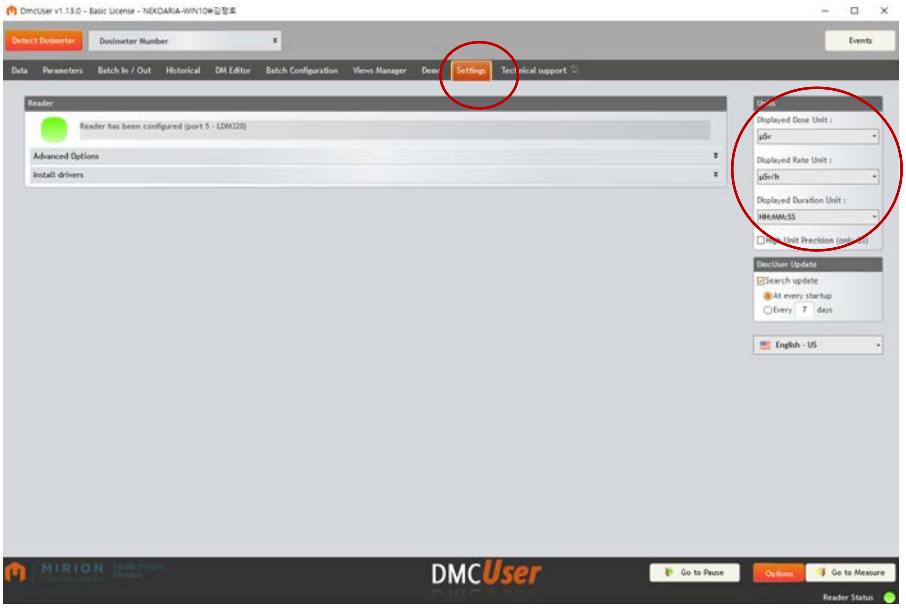


Fig.25

(14) Measure Options

In the bottom, there is “Go to Measure” menu. By clicking the menu, the dosimeter turns into measure state. There are three measure options. Default is “Go to measure (with dose reset)”.

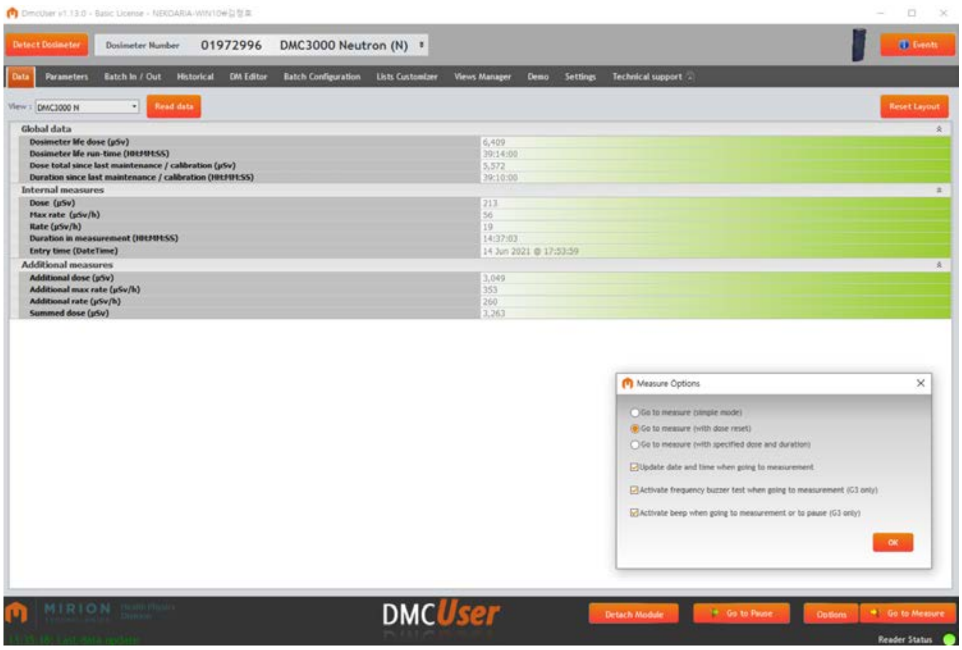


Fig.26

Appendix E : Reading uncertainty in one measurement

E.1 Principle of evaluating the neutron dose

On page 14 of the User Manual, there is a principle of evaluating the neutron dose.

$$\text{Neutron dose} = \frac{\text{N (counts)}}{\text{Kn } \times \text{KnMul } \times \text{KnTask}}$$

Kn is the factory efficiency coefficient and cannot be changed by the user.

KnMul is the Neutron efficiency coefficient multiplier and is set to 1.
KnTask is an optional neutron efficiency coefficient multiplier. This multiplier is managed by the dosimetry system or end user and may be used to adjust the neutron response of the dosimeter as a function of the energy spectrum related to the stask in which the dosimeter is used. Therefore, if the N used in the dose evaluation can be obtained, the uncertainty of neutron dose can be calculated from the uncertainty of N.

E.2 Evaluation of counts, N

In the above principle, N is set as counts. As shown in D.2 (10), three neutron counts (N20pNeutron, N21pNeutron and N20bNeutron) are available using the DMC*User* program. M20pNeutron, M21pNeutron and M20bNeutron are the same as N20pNeutron, N21pNeutron and N20bNeutron. It is not clear what is stored in the parameters N20pNeutron, N21pNeutron and N20bNeutron.
Dr. Zdenek Vykydal from CMI kindly provided his measurement data from DMC*User* (^{252}Cf source, ^{241}AmBe source and Thermal neutrons). The pilot laboratory analyzed the data and found the followings.

- N20pNeutron, N21pNeutron and N20bNeutron depend on the neutron fields.

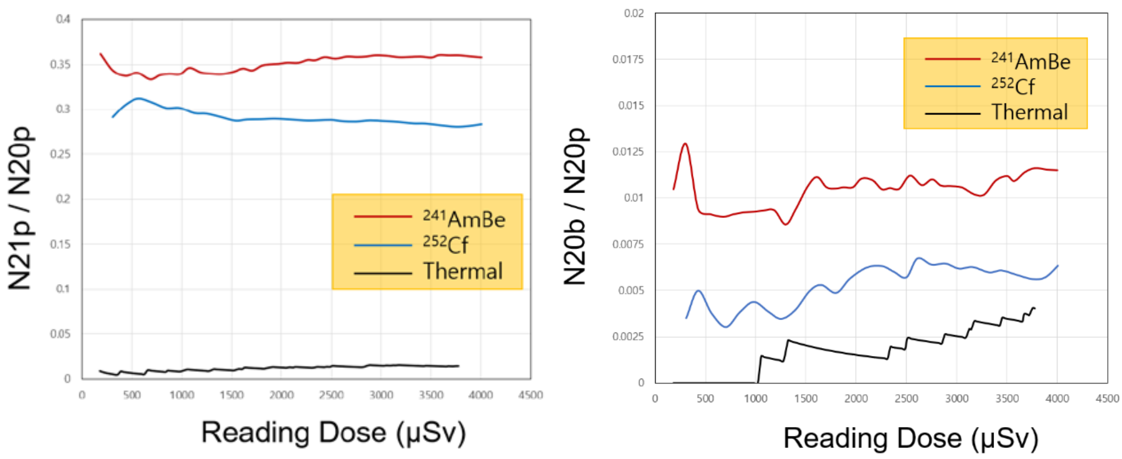


Fig. 27. Instructions of mode change

- Reading doses are almost proportional to N20pNeutron but not to N21pNeutron and N20bNeutron. This trend is well seen in the thermal neutron measurement.

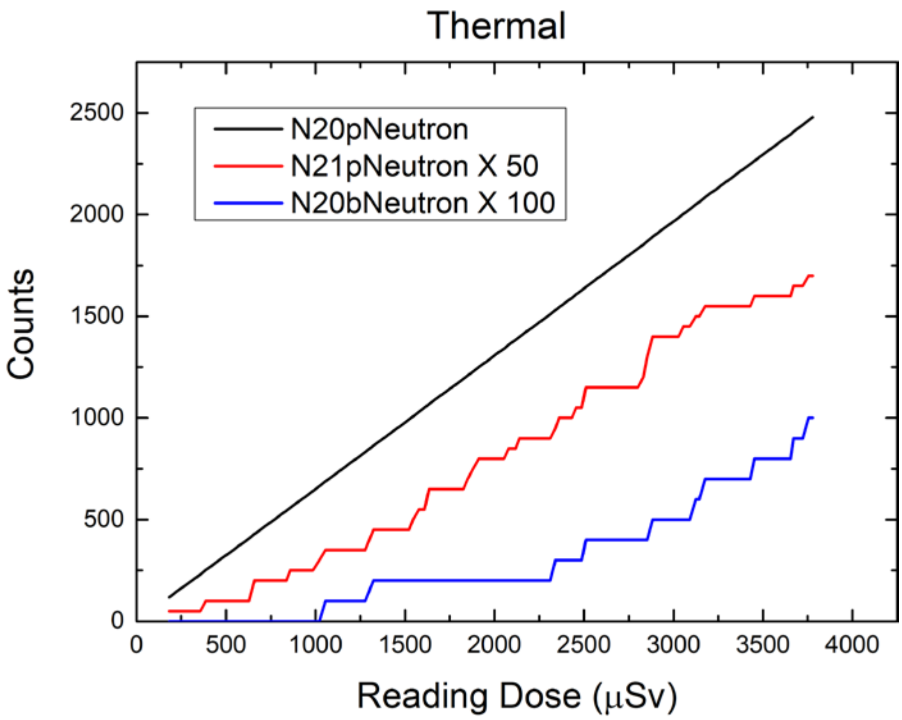


Fig. 28. N20pNeutron, N21pNeutron, and N20bNeutron for the reading dose in the thermal field

- Let N be N20pNeutron - N21pNeutron - N20bNeutron. Then the reading doses are linear to N and the slope is constant regardless of the neutron field. Reading doses and counts from three neutron reference fields and one field from ^{241}AmBe with PE moderator have a linear relationship as follows.

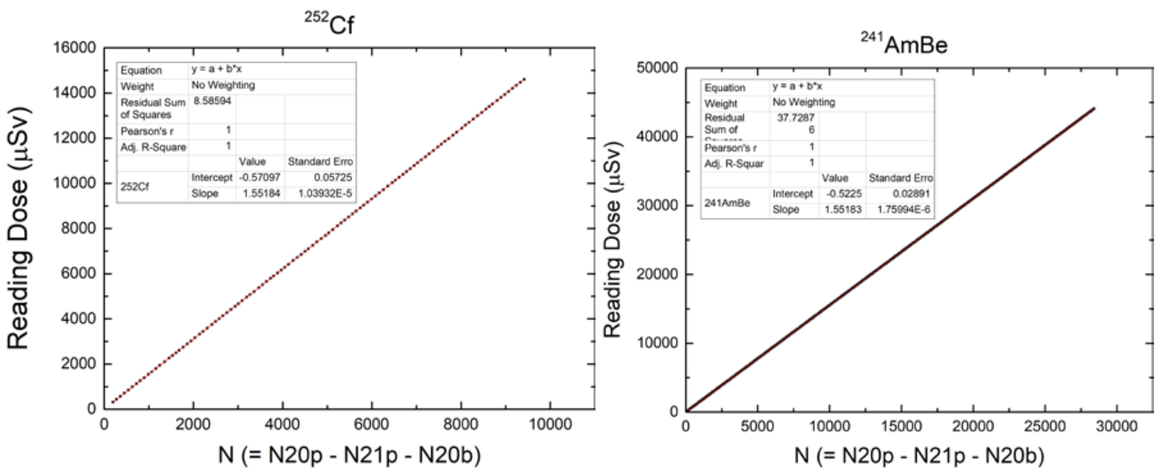


Fig. 29. Linearity between N and reading doses (left : ^{252}Cf, right : ^{241}AmBe)

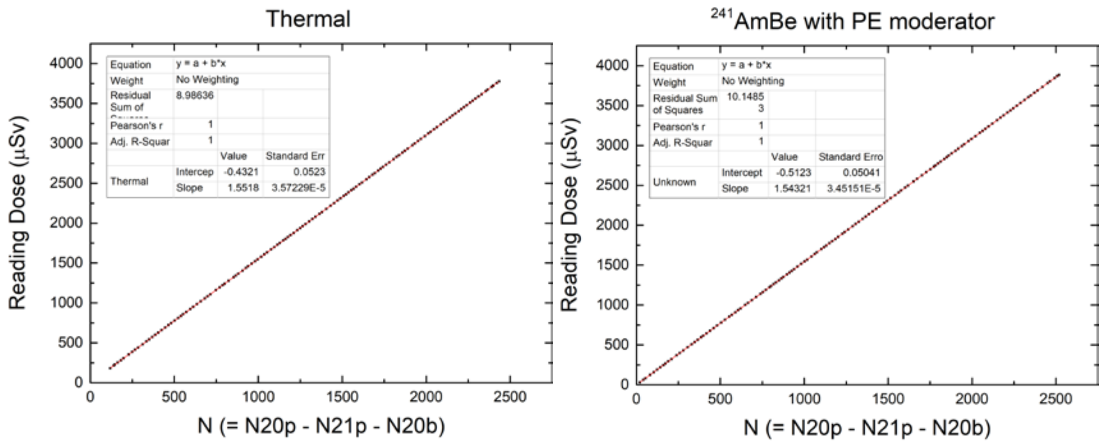


Fig. 30. Linearity between N and reading doses (left : thermal, right : ^{241}AmBe with PE moderator)

- The slope is 1/Kn in the formula of evaluating the neutron dose. In this case, Kn is 0.6444 for CMI DMC3000 Neutron (0.6480 for KRISS one). Kn is the factory efficiency coefficient and cannot be changed by the user. Kn may be different for each instrument. Neutron doses can be evaluated with Kn and N. The results for four neutron fields (^{252}Cf source, ^{241}AmBe source, Thermal neutrons and ^{241}AmBe with PE moderator) are shown in the graph below.

- It can be seen that the Reading dose and the calculated dose from N agree well in any case of the source. Note that the same Kn is used for ^{252}Cf source, ^{241}AmBe source, and Thermal neutrons.

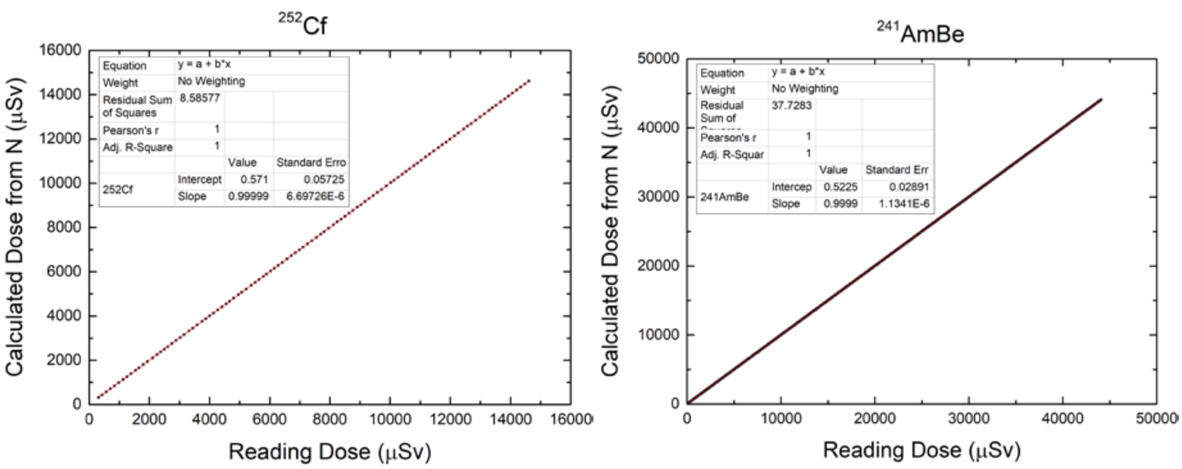


Fig. 31. Reading Dose .vs. Calculated Dose from N (left : ^{252}Cf, right : ^{241}AmBe)

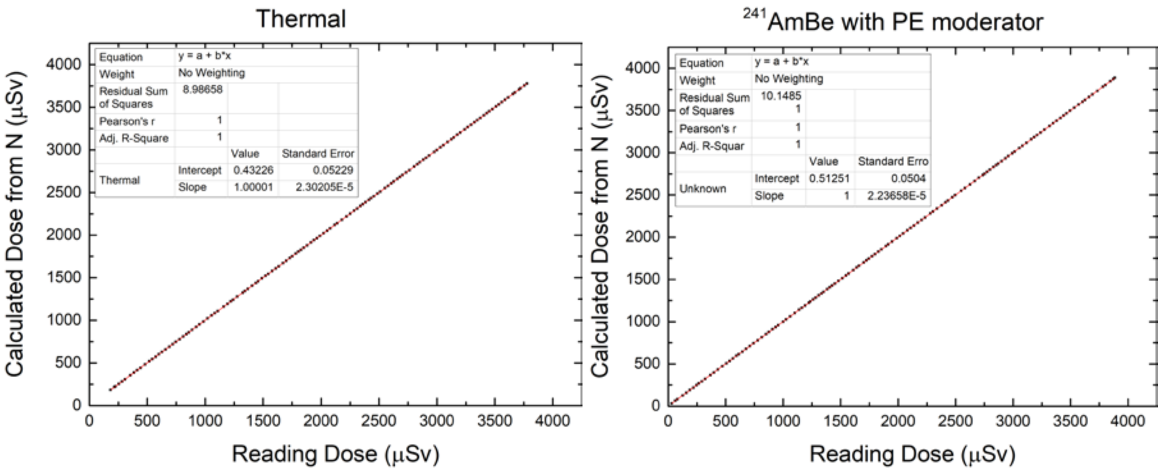


Fig. 32. Reading Dose .vs. Calculated Dose from N (left : thermal, right : ^{241}AmBe with PE moderator)

- The difference in dose by calculation and measurement is shown in the figure below.

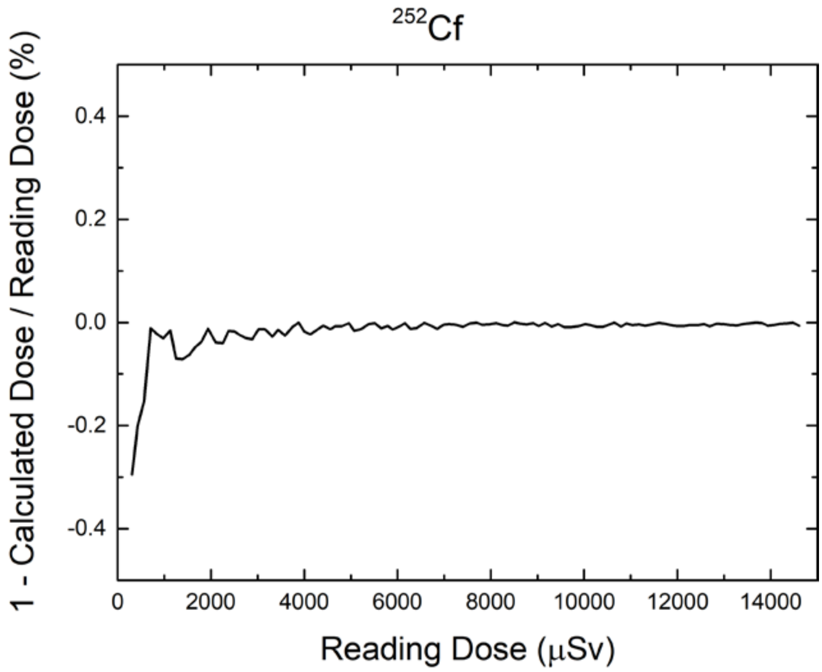


Fig. 33. Difference in dose by calculation and measurement for ^{252}Cf

E.3 Uncertainty of reading

Let N20pNeutron be abbreviated as N_{20p}, N21pNeutron as N_{21p}, and N20bNeutron as N_{20b}. The number of counts for evaluating the neutron dose is $N = N_{20p} - N_{21p} - N_{20b}$. It is not clear what is stored in the N_{20p}, N_{21p} and N_{20b} parameters, but N20p and N21p are proportional to each other, and N20b has a strong correlation, but not directly. The figure below shows the case of ^{241}AmBe.

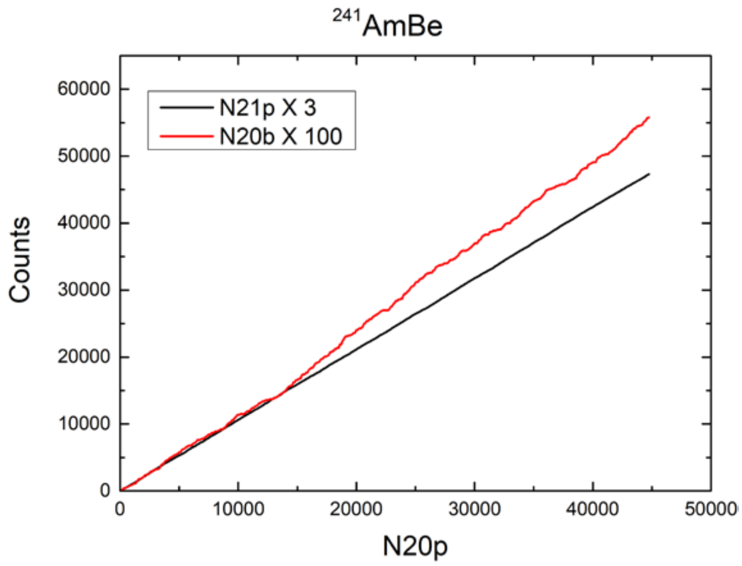


Fig. 34. N_{20p} .vs. N_{21p} and N_{20b} for ^{241}AmBe

There are three situations to consider.

Case 1. N_{20p}, N_{21p} and N_{20b} are independent. Assume that they follow the statistical uncertainty.

Case 2. N_{20p}, N_{21p} and N_{20b} are completely related to each other.

Case 3. Ignore the uncertainties of N_{20p}, N_{21p} and N_{20b}. And N follows the statistical uncertainty.

Case 1. The uncertainty of N can be expressed as

$$u(\mathrm{N}) = \sqrt{u(\mathrm{N_{20p}})^2 + u(\mathrm{N_{21p}})^2 + u(\mathrm{N_{20b}})^2} = \sqrt{\mathrm{N_{20p}} + \mathrm{N_{21p}} + \mathrm{N_{20b}}}$$

Let $N_{sum} = N_{20p} + N_{21p} + N_{20b}$. Then, the relative uncertainty of reading is

$$\frac{u(\mathrm{N})}{\mathrm{N}} = \frac{\sqrt{\mathrm{N_{20p}} + \mathrm{N_{21p}} + \mathrm{N_{20b}}}}{\mathrm{N_{20p}} - \mathrm{N_{21p}} - \mathrm{N_{20b}}} = \frac{\sqrt{\mathrm{N_{sum}}}}{\mathrm{N}}$$

Case 2. Let N_{21p} and N_{20b} be aN_{20p} and bN_{20p}. Then, $N = N_{20p} - N_{21p} - N_{20b} = (1 - a - b)N_{20p} = kN_{20p}$. The uncertainty of N can be expressed as $u(N) = k\sqrt{N_{20p}}$

Then, the relative uncertainty of reading is

$$\frac{u(N)}{N} = \frac{k\sqrt{N_{20p}}}{kN_{20p}} = \frac{1}{\sqrt{N_{20p}}}$$

Case 3. The relative uncertainty of reading is

$$\frac{u(N)}{N} = \frac{1}{\sqrt{N_{20p} - N_{21p} - N_{20b}}} = \frac{1}{\sqrt{N}}$$

To verify the above three cases, the uncertainty was evaluated using actual data. Since the readings from DMC*User* program are stored at the same time interval and the dose rate is constant, the average and standard deviation can be obtained by collecting the reading difference at each time interval. By increasing the time interval, another average and standard deviation can be evaluated.

Readings from ^{252}Cf, ^{241}Am-Be and thermal neutrons were analyzed. Dose averages and their standard deviations were given the following table. The relative uncertainties based on the experimental data and the relative uncertainties based on Case 1, Case 2, and Case 3 were calculated.

No. of data	Source	Dose average (μSv)	σ_{Dose} (μSv)	Relative uncertainty			
				Measurement σ_{Dose}/Dose	Case 3. $1/\sqrt{N}$	Case 1. $\sqrt{N_{sum}}/N$	Case 2. $1/\sqrt{N_{20p}}$
395	^{252}Cf	20.8	5.9	0.282	0.273	0.364	0.232
124	Thermal	29.0	6.7	0.232	0.231	0.236	0.229
197	^{252}Cf	41.6	8.1	0.194	0.193	0.258	0.164
62	Thermal	58.0	7.7	0.133	0.164	0.167	0.162
131	^{252}Cf	62.4	10.2	0.164	0.158	0.210	0.134
98	^{252}Cf	83.2	11.3	0.136	0.137	0.182	0.116
41	Thermal	87.1	9.7	0.112	0.133	0.136	0.132
427	^{241}AmBe	102.8	12.4	0.120	0.123	0.180	0.098
79	^{252}Cf	104.2	13.7	0.132	0.122	0.163	0.104
31	Thermal	115.9	11.8	0.102	0.116	0.118	0.115
65	^{252}Cf	124.9	13.5	0.108	0.111	0.149	0.095
105	^{252}Cf	136.2	14.5	0.106	0.107	0.145	0.090
56	^{252}Cf	145.7	17.2	0.118	0.103	0.138	0.088
49	^{252}Cf	166.5	16.8	0.101	0.097	0.129	0.082
43	^{252}Cf	187.0	18.6	0.100	0.091	0.121	0.077
213	^{241}AmBe	205.6	17.2	0.084	0.087	0.127	0.069

39	^{252}Cf	208.2	19.3	0.092	0.086	0.115	0.073
35	^{252}Cf	228.5	17.2	0.075	0.082	0.110	0.070
32	^{252}Cf	249.6	18.7	0.075	0.079	0.105	0.067
52	^{252}Cf	272.5	17.5	0.064	0.075	0.102	0.063
142	^{241}AmBe	308.4	21.6	0.070	0.071	0.104	0.057
106	^{241}AmBe	411.3	24.3	0.059	0.061	0.090	0.049
85	^{241}AmBe	514.1	27.5	0.054	0.055	0.081	0.044
71	^{241}AmBe	616.7	28.7	0.047	0.050	0.074	0.040
61	^{241}AmBe	719.7	34.1	0.047	0.046	0.068	0.037
53	^{241}AmBe	822.5	35.3	0.043	0.043	0.064	0.035
47	^{241}AmBe	925.5	40.2	0.043	0.041	0.060	0.033
42	^{241}AmBe	1028.0	35.4	0.034	0.039	0.057	0.031
38	^{241}AmBe	1131.2	38.1	0.034	0.037	0.054	0.030
35	^{241}AmBe	1233.7	37.6	0.030	0.035	0.052	0.028
32	^{241}AmBe	1336.2	42.5	0.032	0.034	0.050	0.027

In order to reduce statistical uncertainty, only more than 30 data were collected. Comparing with the measurement results, it can be seen that Case 1 is overestimated and Case 2 is underestimated. Case 3 seems to fit the experimental data best.

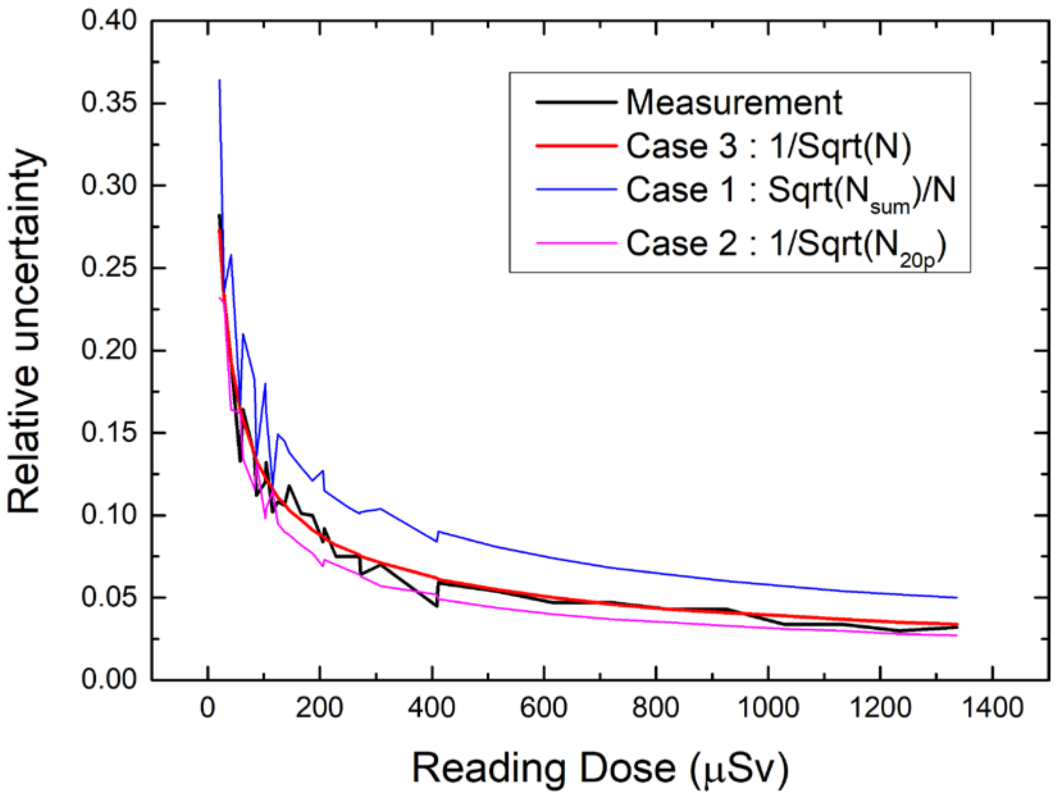


Fig. 35. Relative uncertainty changes for Reading Dose. Case 3 seems to fit the experimental data best.

Assuming that the relative uncertainty of the experimental data follows $\sqrt{Dose}$ (in case of Case 3), fitting was performed with a function $\sqrt{Dose}$.

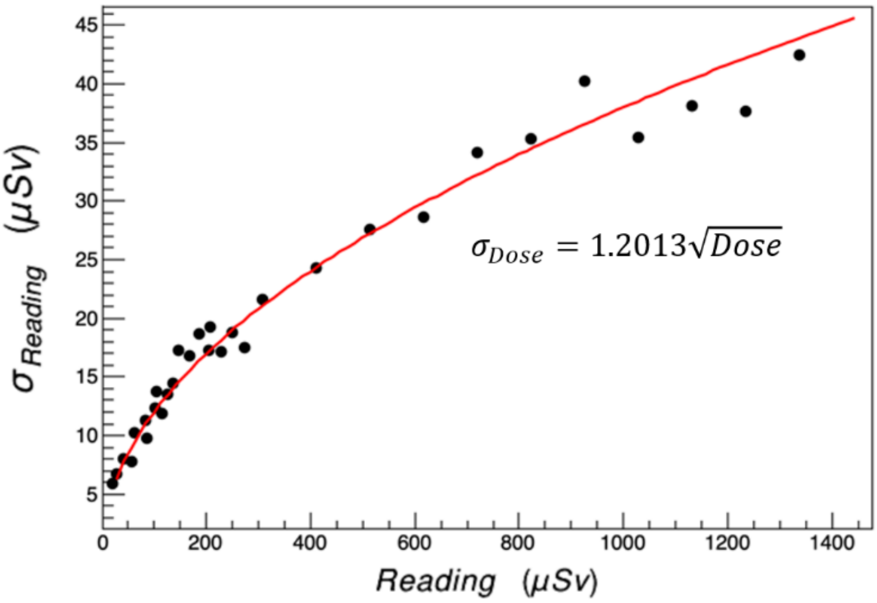


Fig. 36. Standard deviation for reading (current study)

This fitting result is in good agreement with the previous pilot study results. A similar study of estimating uncertainty from Reading Dose has been previously conducted. The fitting parameter obtained from measurements up to about 400 µSv is 1.192, which agrees with the above result within 1 %.

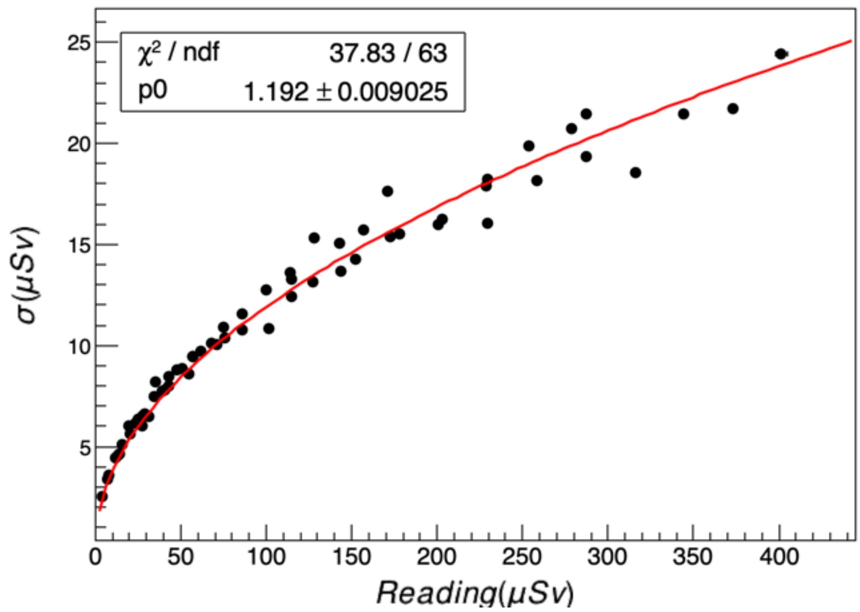


Fig. 37. Standard deviation for reading (previous pilot study)

In the pilot study, 30 repeated measurements were also performed using a ^{252}Cf source. The average is 724 μSv and the standard deviation is 37 μSv. The standard deviation is calculated as 32 μSv by the above equation $\sigma_{Dose}(\mu\text{Sv}) = 1.192\sqrt{Dose(\mu\text{Sv})}$. These results agree well within 10 %.

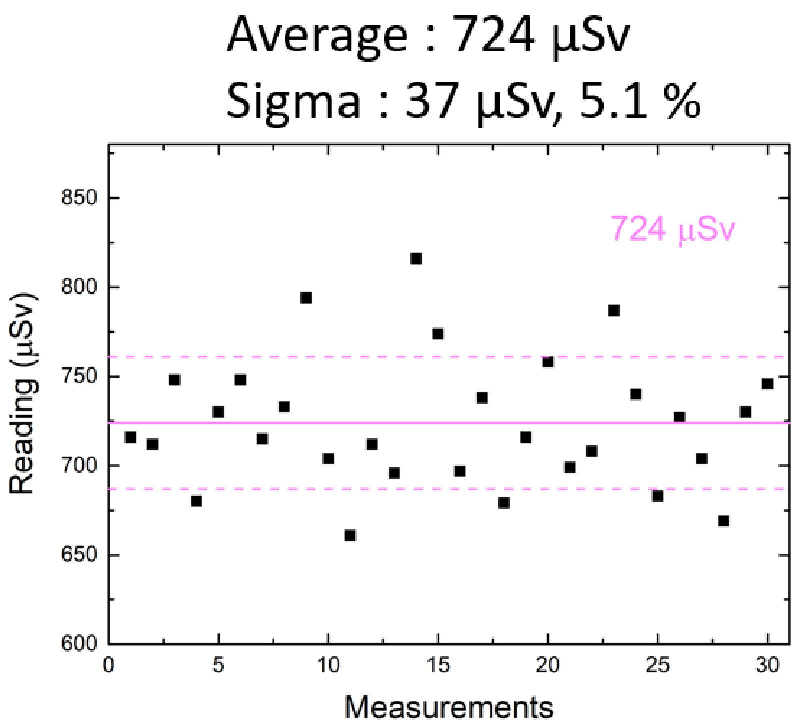


Fig. 38. Average and standard deviation by 30 repeated measurement (previous pilot study)

E.4 Uncertainty of reading in one measurement

Participants can evaluate the uncertainty of a single reading by using the DMC*User*. Proceed according to the procedure below. See Appendix D for how to use DMC*User*.

(1) Install the DMC*User* program.
(2) Read data of the dosimeter. histories of the readings.
(3) Read histories of the readings
(4) Find neutron dose, N20pNeutron, N21pNeutron and N20bNeutron.
(5) Calculate N = N20pNeutron - N21pNeutron - N20bNeutron.
(6) Calculate the relative uncertainty of the neutron dose as $1/\sqrt{\text{N}}$.

If participants have difficulty using DMC*User*, they can refer to the following. However, the recommended method is the above procedure.

Since Reading Dose is proportional to N and uncertainty is proportional to $1/\sqrt{\mathrm{N}}$, the relationship between Reading dose and uncertainty can be expressed as the graph below.
The result of fitting is $\sigma_{Dose}(\mu\mathrm{Sv}) = 1.246\sqrt{Dose(\mu\mathrm{Sv})}$. (See the picture below)

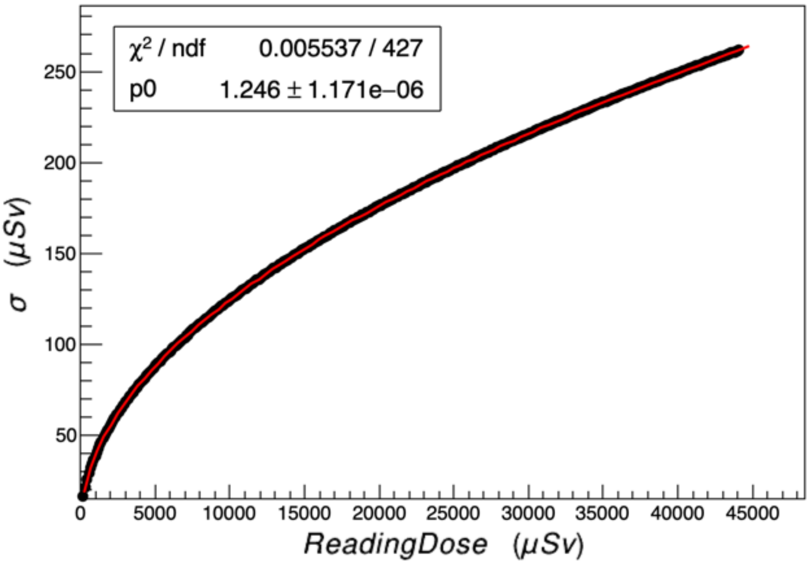


Fig. 39. Evaluation of standard deviation for single reading

E.5 Minimum readings for participation

With a neutron source whose source strength of 1 x 10^7 s^{-1} neutron source at 75 cm distance, the irradiation time can be evaluated as follows.

source	ϕ ($cm^{-2}s^{-1}$)	hp(10) (pSv cm^2)	Dose rate (μSv/h)	Time to reach (hour)			
				1 mSv	2 mSv	4 mSv	10 mSv
^{252}Cf	141.5	400	203.7	4.9	9.8	19.6	49.1
^{241}Am-Be	141.5	411	209.3	4.8	9.6	19.1	47.8
D_2O(^{252}Cf)	141.5	110	56.0	17.8	35.7	71.4	178.5

- **The recommended readings are 10 mSv for ^{252}Cf, ^{241}Am-Be and D_2O(^{252}Cf).**
- In general, the source strength of ^{241}Am-Be source is weaker than that of ^{252}Cf.
- At 75 cm distance, 49 hours (2.04 days) is required to reach 10 mSv for ^{252}Cf 178.5 hours (7.44 days) for D_2O(^{252}Cf) with a source strength of 1 x 10^7 s^{-1}.

The relative uncertainties of readings, u(*N*)/*N*, can be calculated by the following equation $\sigma_{Dose}(\mu \mathrm{Sv}) = 1.246\sqrt{Dose(\mu \mathrm{Sv})}$.

Reading (μSv)	Standard deviation (μSv)	Rel. unc
1000	39.4	3.9%
2000	55.7	2.8%
3000	68.2	2.3%
4000	78.8	2.0%
5000	88.1	1.8%
6000	96.5	1.6%
7000	104.2	1.5%
8000	111.4	1.4%
9000	118.2	1.3%
10000	124.6	1.2%

The relative uncertainty of the calibration factor $N = h_{p\Phi}(10, \alpha)\ \Phi\ / M_c$ can be represented by the following.

$$\frac{u(N)}{N} \sim \sqrt{\left(\frac{u(B)}{B}\right)^2 + \left(\frac{u(h_p)}{h_p}\right)^2 + \left(\frac{u(M_c)}{M_c}\right)^2}$$

Assume the the relative uncertainty of the source strength is 1.0 %. Then u(*N*)/N can be roughly calculated as in the following table.

M_c (mSv)	u(*B*)/*B* (%)	$u(h_p)/h_p$ (%)		$u(M_c)/M_c$ (%)	u(*N*)/N (%)	
		^{252}Cf	^{241}Am-Be / D_2O(^{252}Cf)		^{252}Cf	^{241}Am-Be / D_2O(^{252}Cf)
1	1.0	1.0	4.0	3.9	4.1	5.7
2				2.8	3.1	5.0
4				2.0	2.4	4.6
10				1.2	1.9	4.3

Unlike ^{252}Cf, since the uncertainty of hp(10) of ^{241}Am-Be and D_2O(^{252}Cf) is 4%, the influence of the uncertainty of the reading on the overall uncertainty is not large. For example, the difference between 4 mSv and 10 mSv is only 0.3%. Therefore, for ^{241}Am-Be and D_2O(^{252}Cf), it is considered reasonable to set the minimum readings to 4 mSv instead of 10 mSv in order to reduce the irradiation time. Of course, participants are encouraged to irradiate 10 mSv for ^{241}Am-Be and D_2O(^{252}Cf) if they have strong sources.

SCRV calculations will only include results from participants above 10 mSv for ^{252}Cf and above 4 mSv for ^{241}Am-Be and D_2O(^{252}Cf). However, the report will include all results for participants who meet the minimum readings.

For participants with a weak neutron source, the minimum readings are set as follows.

^{252}Cf : 4 mSv
^{241}Am-Be : 2 mSv
D_2O(^{252}Cf) : 2 mSv