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United States Navy nuclear accident dosimetry program: History and Current Status

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ABSTRACT

Federal Regulations of the United States require that installations possessing sufficient quantities of fissile material to potentially constitute a critical mass, such that the excessive exposure of individuals to radiation from a nuclear accident is possible, shall provide appropriate nuclear accident dosimetry. The American National Standard ANSl/HPS N13.3–2013 Dosimetry for Criticality Accidents provides technical, quality assurance, and performance requirements for nuclear accident dosimeters (NAD). In 2023 the U.S. Navy operated 82 nuclear-powered ships, with the fleet being composed of 11 aircraft carriers, 68 submarines, having a total number of 98 reactors. Since 1968 the U.S. Navy has used fixed nuclear accident dosimeters (FNAD) mounted to the bulkheads surrounding naval nuclear propulsion reactors. Since 1968 the US Navy has used two nuclear accident criticality dosimeters. The first Navy accident dosimeter DT-518/PD was introduced in 1968. It was developed by the Naval Radiological Defense Laboratory in San Francisco, California under leadership of Eugene Tochilin. This dosimeter contains two indium foils for quick dose assessments using shipboard gamma instruments available on nuclear powered vessels and two sulfur pellets/LiF TLD-700 powder for final dose determination at the Naval Dosimetry Center. The newest Navy NAD is the DT-723/PD, which contains indium foil, gold foil, cadmium shielded gold foil, sulfur pellet and a LiF TLD-700 chip. This paper provides a brief description of the measurement procedures, results of the testing of both NADs and comparison of their performance.

1. Introduction

According to The United States Naval Nuclear Propulsion Program, 2020 the US Navy has not had a single radiological incident since it has received the world's first nuclear powered submarine USS Nautilus (SSN-571) in 1955 and the world's first nuclear aircraft carrier USS Enterprise (CVN-65) in 1960. In 2019 U.S. Navy operated 82 nuclear-powered ships (11 aircraft carriers, 68 submarines) with total number of 98 reactors. This exceptional safety record can be attributed to the high level of standardization in naval power plants and their maintenance, and the high quality of the Navy's training and quality assurance programs. Though this is an enviable safety record, the U.S. Code of Federal Regulation (Code of Federal Regulation) 10, § 835.1304 still requires that installations having fissile materials sufficient to potentially constitute a critical mass shall provide appropriate nuclear accident dosimetry for personnel. Specifically, "nuclear accident dosimetry" shall include the following.

(1) A method to conduct initial screening of individuals involved in a nuclear accident to determine whether significant exposures to radiation occurred;
(2) Methods and equipment for analysis of biological materials;
(3) A system of fixed nuclear accident dosimeter units (aka FNAD); and
(4) Personal nuclear accident dosimeters (akaPNAD). "

A significant document providing additional detail on nuclear accident dosimetry is the American National Standard ANSI 13.3, 2013 (American National Standard ANSl/HPS N13.3-2013). According to this standard "The rapid and accurate assessment of personal absorbed doses resulting from a criticality accident may be of the utmost importance for exposed individuals and assisting with their medical treatment." Nuclear facilities need to have a dosimetry system capable of providing timely information following such an accident. Dose assessment personnel should use all available resources to ensure that any absorbed

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dose determinations are as accurate and timely as possible. ANSI 13.3, 2013 also provides criteria for the performance of nuclear criticality accident dosimetry systems (Table 1). If only fixed NADs are used ANSI 13.3, 2013 requires a method to determine (calculate) personal doses. In case of the Navy it can be done using deep photon dose reported by the Navy personal dosimeter DT-702/PD (see for detail Romanyukha et al., 2018) and neutron-to-photon dose ratio measured by the fixed NADs. Less common but technically qualified methods can also be used to measure dose, such as Electron Paramagnetic Resonance dosimetry in teeth and fingernails (see McKeever et al., 2019).

Where B = 100 × ((Measured Dose - Delivered Dose)/Delivered Dose)

Table 1
Performance testing criteria of criticality accident dosimeter systems, from ANSI 13.3

Total absorbed dose range	B, %
0.1–1 Gy (10–100 rad)	±50%
1–10 Gy (100–1000 rad)	±25%
>10 Gy (1000 rad)	Must give positive indication of >10 Gy (1000 rad)

2. Navy accident dosimeter DT-518/PD

2.1. Dosimeter description

Early reactor-related accident dosimeters were film-based. A change of paradigm in Navy dosimeters when the newer thermoluminescence and isotope activation-based dosimeters were introduced through the pioneering work of Eugene Tochilin, at the Naval Radiological Defense Laboratory in San Francisco, California.

The first modern non-film based Navy accident personal dosimeter (PD) DT-518/PD began use in 1968. This dosimeter is still in use until fielding of the new Navy accident will be initiated and completed.

The DT-518/PD contains two sulfur pellets, two indium foils, and thermoluminescent powder (LiF:Mg,Ti). The indium foil discs are to be used for accident on-scene evaluation of the neutron dose. The sulfur pellets (for definitive neutron dose determination; 0.10–500 Gy) and the thermoluminescent powder (for gamma dose determination; 0.01–100 Gy) to be evaluated by the Naval Dosimetry Center post-accident. These detectors are contained in a stainless-steel tube with diameter of 1.77 cm and 2.7 cm long (Fig. 1). Fig. 2 shows a disassembled DT-518/PD.

Sulfur pellets principally generates ^{32}P via fast neutrons (~3.0 MeV) by the reaction:

$^{32}S + n = {}^{32}P + \beta$, $^{32}P \rightarrow T_{1/2} = 14.27$ days, beta-emitter with E = 1.71 MeV

Indium foils produce isotopes via thermal and "fast" neutrons The reactions are:

Faster n: $^{115}In + n = {}^{115m}In + n + \gamma$; $T_{1/2} = 4.49$ h; main γ analysis energy $E_\gamma = 0.336$ MeV

Slower n: $^{115m}In + n = {}^{116m}In$ $T_{1/2} = 54.29$ min, main γ analysis energy $E_\gamma = 0.127$ MeV

^{116m}In branching ratio, $P_{g,}$ is equal to 0.823 as reported by Heft (1980).

The DT-518/PD accident dosimeter is used as an FNAD, mounted on secondary shielding surrounding naval nuclear propulsion plants. Similar sulfur pellets and indium discs were also contained in the end cap of another Navy personnel accident dosimeter, DT-526/PD, which is no longer issued.

The DT-518/PD readout can be conditionally split into four separate procedures.

Fig. 1. Assembled Navy accident dosimeter DT-518/PD.

Fig. 2. Disassembled Navy accident dosimeter DT-518/PD.

- Fast evaluation of neutron dose in the assembled DT-518/PD using multi-function RADIAC IM-265/PDQ (Geiger-Mueller counter);
- Partition of DT-518/PD;
- Measurements of accident neutron dose in sulfur pellets.
- Measurement of accident gamma dose in LiF:MgTi powder.

2.2. Fast evaluation of neutron dose in the assembled DT-518/PD

According to the Navy's Radiation Health Manual, Navy Medicine (NAVMED) P-5055 (NAVMED P-5055, 2011), an initial assessment can be performed on the posted DT-518/PD accident dosimeter. In the event of a suspected high dose (accident dose) to the posted dosimeter, the time at which the accident occurred is recorded. Then the accident dosimeter shall be placed against and parallel to the most sensitive gamma probe of multi-function radiation detector (e.g., IM-265/PDQ). The beta shield should be closed (if applicable) to prevent counting of the activated sulfur pellets. The highest reading of the detector meter observed at the accident dosimeter moved along the length of the probe shall be recorded as the gross reading. The background reading shall be subtracted from the gross reading. This difference is the net reading (nr), of the predominating isotopes at the time of the reading. An estimated neutron accident dose (±25%) is calculated for the point where the accident dosimeter was located at the moment of the accident as follows:

$$\text{Neutron Accident Dose (rads)} = \text{nr (mR/h)} \times 8 \times (F) \quad (1)$$

where nr is the background corrected IM-265/PDQ reading, 8 is empirically determined dose conversion factor to convert mR/h to rad, the Correction Factor (*F*) is obtained from Fig. 3 or from formula (2)

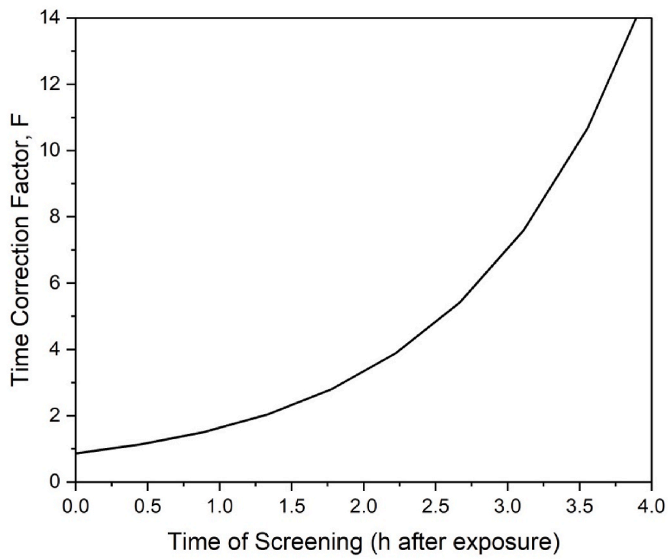

Fig. 3. Correction Factor (F) for field screening of Navy accident dosimeter indium disks.

using the time of screening (h after exposure) which is calculated as the time interval between the gross reading and the presumed time of the accident. Eq. (1) was verified by using irradiation of DT-518/PD with D_2O moderated ^{252}Cf which is recommended for personnel dosimeters calibration (Schwartz and Eisenhauer, 1980).

$$F = \exp\left(0.693(t - 0.5) / T_{1/2}\right) \quad (2)$$

Where F is time correction factor, $T_{1/2} = 0.9$ h, which is the half-life of ^{116m}In (the isotope having the largest activity so shortly after the excursion). There is an assumption in formula (2) that dosimeters will be available for the dose measurements within 0.5 h after nuclear accident.

Uncertainty, σ_F, associated with using correction factor F as function of time is equal to the time derivate of F. Then relative uncertainty associated with correction factor F as a function of time can be calculated with the following equation:

$$\sigma_F/F = (0.693/T_{1/2}) \times \sigma_t \quad (3)$$

For example, for $t = 3.00(4)$ h, $T_{1/2} = 0.9$ h; according to Eq (2) F at 3 h can be calculated as 6.855. Then Eq (3) will give $\sigma_F/F = 0.211$ or 21.1%. At 5 h relative uncertainty associated with correction factor F as a function of time as calculated by Eq (3) becomes 98%.

The last validation for the DT-518/PD dosimeter, formula (1) and the time correction factor (Fig. 3) was performed in the International Intercomparison Exercise for Nuclear Accident Dosimetry at the Nevada National Security Site Using GODIVA-IV in May 2016. The exercise consisted of three GODIVA burst irradiations at 70, 250 and 150 °C. For each burst, dosimeters were placed on stands for "free-in-air" dose measurements or placed on bottle manikin (BOMAB) phantoms or acrylic (PMMA) slab phantoms. The NAD stands accommodate up to 10 dosimeters per plate for a total of 40 dosimeters on the stands that have 2 plates (A-D locations only) or 80 dosimeters on the stands that have 4 plates (A-H locations). The BOMAB phantom accommodates up to 10 dosimeters on the front and 10 dosimeters on the back for a total of 20 dosimeters per BOMAB. The BOMABs contain saline solution simulating blood. More detail on design of the International Intercomparison Exercise for Nuclear Accident Dosimetry can be found in Heinrichs et al. (2014). Several sets of measurements were implemented to characterize the neutron and gamma fields at Godiva IV. The reference dose measurements were done by multiple Bonner spheres, calcium fluoride TLDs, and ion chambers. For details see Hickman et al. (2017).

Performance of DT-518/PD for the fast neutron dose measurements was done in the first burst (temperature 270 °C). Because the Navy uses DT-518/PD only as posted dosimeters five DT-518/PDs were put on the stands. There were two stands at 2 m from the GODIVA IV, one was placed at 197 cm high (position 2) and another was at 156 cm high (position 3). Table 2 provides the delivered doses during GODIVA IV Pulse #1.

The background measured by RADIAC IM-265/PDQ was 0.15 mR/h. The detector response varies depending on where the dosimeter is placed on the detector probe. It was important to place DT-518/PD on the probe so that the highest readings are obtained. All reported neutron doses from readings taken within 5 h of the irradiation agreed with the reference dose to within 50%, which is the maximum uncertainty limit recommended by the ANSI 13.3 2013 for initial dose screenings within the first 24 h. Table 3 provides obtained results of the fast neutron dose evaluation. The average reported dose was 1.70, $\sigma = \pm 0.43$ Gy, which is lower than reference doses in Table 2. It is unclear what specific dose terms were used and how the DT-518/PD was calibrated in 1968. The predicted neutron dose of DT-518/PD, using Equation (1) in the Godiva IV exercise can be evaluated as satisfactory.

2.3. Measurements of accident neutron dose in sulfur pellets

To evaluate the sulfur pellets performance, they were irradiated to known doses from a^{252}Cf source at the National Institute of Standards and Technology (NIST) and the Armed Forces Radiobiology Research Institute (AFRRI) research reactor. Mohaupt's thesis (Mohaupt, 1988) provides a detailed description of the fast neutron dose measurement based on the neutron activated sulfur pellets extracted from the DT-518/PD. He used gas proportional (GPC) and liquid scintillation counters (LSC) to count ^{32}P which is the product of the sulfur activation. Like Santry and Butler, 1963, Mohaupt used sulfur burning to increase counting efficiency. The sulfur in the activated pellets burns away and leaves the product of interest, ^{32}P (14.3 day half-life). Burning of the sulfur needs to be done under a ventilation hood since the fumes are radioactive and toxic. The burn process involved placing the planchet containing sulfur on a heated hot plate. When the flame burns out, a black, tarry residue remains. Part of the sulfur from each accident dosimeter capsule was prepared for counting on a gas proportional counter.

For LSC, the sulfur pellet was pulverized for maximum counting sensitivity. The sulfur was ground with a pestle to a course powder. The weight of the sulfur was measured by weighing the sample on the weighing paper and then reweighing the weighing paper once the sample was deposited into scintillation vials. The plastic vials had curved bottoms so that the sulfur accumulated around the outer edge of the vial rather than being uniformly distributed over the bottom. Ten ml of LS solvent was dispensed into counting vials. The solvent used was Hydrofluor (National Diagnostics, Inc, Manville, NJ), which was chosen because of the high efficiency counting of large or concentrated samples. The vial was sealed, and the cap labeled with the sample identification code. The prepared samples were placed in the refrigerated LSC for several hs before counting to allow the solution to equilibrate to the counter temperature and the sulfur to settle. The specific activities were calculated from average specific count rates corrected for background and decay by applying the counting efficiencies. The coefficient of variations of specific activities for each group ranged from 4 to 12%.

Despite the high counting efficiency achieved with the LSC, it was not the detector of choice for counting the activated sulfur because of its high background and anomalously low readings for samples with low activities. The preparation method of burning the sulfur and counting on the GPC gave consistent results for all dose levels. Counting of the sulfur is as not time critical as indium. Preparation may be delayed until the sample can be delivered to a facility capable of low-level counting of the high energy beta particles. Burning activated sulfur offers a convenient, reproducible method of preparing the sample for counting.

Observed agreement between neutron doses measured by the

Table 2
Delivered doses at 2 m during GODIVA IV Pulse #1.

Total Fluence, n/cm^2	Position, #	Distance, m	Height, cm	Tissue KERMA, Gy	ANSI 13.3 $D_p(10)$, Gy	ANSI 13.3 D*(10), Gy	Gamma Dose, Gy
9.89×10^{10}	2	2	197	1.58	2.02	1.96	0.24
1.04×10^{11}	3	2	156	1.64	2.10	2.03	0.21

Table 3
Results of fast evaluation of neutron dose in the assembled DT-518/PD using multi-function RADIAC IM-265/PDQ (Geiger-Mueller counter) with closed beta window to avoid an interference with neutron-activated sulfur beta exposure.

Dosimeter ID	Position #	Distance, m	Height, cm	RADIAC nr mR/h	NDC reported dose, Gy, predicted by Eq (1)
NDC#3	2	2	197	1.71	1.37
NDC#4	3	2	156	1.71	1.38
NDC#1	3	2	156	2.87	2.39
NDC#2	2	2	197	1.88	1.52
NDC#14	3	2	156	2.24	1.83

accident dosimeter DT-518/PD and reference doses was estimated as satisfactory, with 98% of the neutron doses agreeing within ±25% for doses higher than 0.25 Gy. Nearly half of these dosimeters indicated doses that were within ±10% of the reference neutron doses.

2.4. Measurement of accident gamma dose in LiF:MgTi powder

Measurement of the accident gamma dose in LiF:MgTi powder can be done with Model 3500 manual desktop Harshaw TLD reader. This reader uses contact heating with a closed loop feedback system that produces linearly ramped temperatures accurate to within ±10 °C up to 400 °C. The dose readout of LiF:MgTi powder requires about 30 s with maximum temperature 260°–300 °C, and heat rate 10 °C/s. Alternatively accident gamma dose can be obtained from the Navy personnel dosimeter DT-702/PD (for detail description see, Romanyukha et al., 2018).

2.5. Identified DT-518/PD deficiencies

- The accident dosimeter DT-518/PD is sensitive only to neutrons with two energies: ~0.3 MeV (indium foil) and ~3 MeV (sulfur pellets). Moreover, indium foil is used only for fast neutron dose evaluation, which is not very accurate.
- Formulas (1) and (2) evaluation of fast neutron doses is underestimated by approximately 20% and it does not provide neutron dose in the proper dose units according to the ANSl/HPS N13.3–2013. Formula (2) has an unjustified time shift from the time of the accident by 30 min, which is not considered, moreover this formula only accounts for one indium isotope, e.g., ^{116m}In ($T_{1/2}$ = 54.29 min), ignoring ^{115m}In ($T_{1/2}$ = 4.49 h). Gamma emission of ^{115m}In should be considered and additional dose can be obtained if needed. Fig. 3 from P-5055 is limited to 3.5 h post-accident and provides no additional guidance on dose assessment. It is impractical to receive the posted dosimeter from the site of criticality accident in such a short time. During Godiva IV intercomparison exercise the average time to receive dosimeters after irradiation was 4–5 h.
- The developed procedure for neutron dose measurement of the sulfur pellets requires burning on a heated hot plate under a ventilation hood. The burning process produces radioactive and toxic vapor product which must be controlled. It is time and labor consuming.
- NDC performed an inspection of several "aged" DT-518/PDs which revealed a significant oxidation (corrosion) of indium discs in some of the dosimeters. This can affect the accuracy of dose measurements due to the reduced amount of indium. Some sulfur pellets also had black stains possibly due to contact with water during storage or production.
- DT-518/PD dosimeters do not have a serial number, production date and space to indicate where and when it was placed for potential accident dose monitoring. This creates difficulties in tracking and accident dose assignment if it were to be used in the event of nuclear accident. It is also problematic to maintain the dosimeters inspection and recall records.
- The DT-518/PD does not have an approved standard for attaching to the wall or bulkhead aboard ships. This creates inconsistent attachment methods across the fleet. There is also no standard tool to open DT-518/PD.

Considering the above deficiencies and after conducting a fleet wide inspection in 2018, the Navy decided to replace DT-518/PD with a new accident dosimeter. Participation in the International Intercomparison Exercises for Nuclear Accident Dosimetry organized by Lawrence Livermore National Laboratory provided a unique opportunity to observe dose measurements conducted by different laboratories and compare the performance results of their accident dosimeters. Based on this understanding the Navy selected the commercially available criticality dosimeter NCL 03 which has received Navy designation DT-723/PD.

3. Navy accident dosimeter DT-723/PD

3.1. Dosimeter description

DT-723/PD (NCL 03) was originally developed at Harwell, United Kingdom in the 1950s (Fig. 4). The United States Navy acquired it through Rotunda Scientific Technologies® LLC (https://www.rotundascitech.com). This dosimeter has four neutron sensitive detectors: indium foil, gold foil, gold foil shielded by cadmium, and a sulfur pellet (Fig. 5). The sulfur pellet has a diameter of 22.0 mm, thickness of 2.41 mm, and a mass of 1.65 g. The gold foils have diameter of 10.0 mm, a thickness of 0.051 mm, and a mass of 0.077 g. The front (bare) gold foil has a section cut out to differentiate it from the cadmium shielded foil, which reduces the mass to 0.074 g. The indium foil is annular, with an outer diameter of 22.1 mm, inner diameter of 10.2 mm and a thickness of 0.165 mm, giving it a mass 0.37 g. The gold is specified to a purity of 99.96 %, the

Fig. 4. Assembled DT-723/PD.

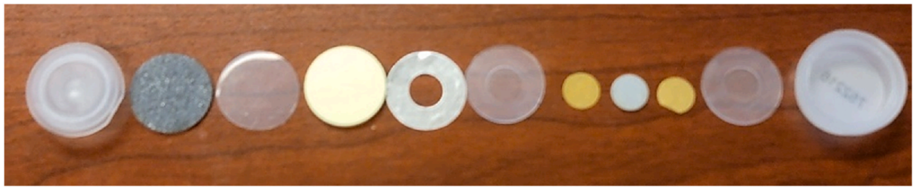

Fig. 5. Disassembled DT-723/PD.

indium to 99.95 % and the sulfur 99.25 %. For gamma dose measurement a single thermo-luminescent dosimeter (TLD) made from lithium fluoride doped with magnesium, copper and phosphor (^{7}LiF: Mg,Cu,P) is included. It is a standard TLD-700H pellet which is produced by Thermo Fisher Scientific and has a 0.381 mm thickness and a diameter of 3.6 mm. The DT-723/PD has many beneficial features including.

- Unique serial number for each dosimeter.
- A provided opener used for easy disassembly and reassembly for dose measurements or inspection.
- A water-resistant design and metal foils which are physically separated from the sulfur pellet to prevent degradation into indium sulfide and cadmium sulfide.

The following neutron reactions are utilized in DT-723/PD:

$^{32}S + n = {}^{32}P + \beta$, ^{32}P, $T_{1/2} = 14.29$ days, beta-emitter with E = 1.71 MeV.

$^{115}In + n = {}^{115m}In + n + \gamma$; $T_{1/2} = 4.49$ h; gamma-emitter with E = 0.336 MeV.

$^{115}In + n = {}^{116m}In$ $T_{1/2} = 54.29$ min, gamma emitter with E = 0.127 MeV.

$^{197}Au + n = {}^{198}Au$ $T_{1/2} = 2.69$ days, gamma emitter with E = 411.8 keV.

The addition of bare and cadmium shielded gold to the DT-723/PD has improved performance for neutron measurement of low (<1 eV) and intermediate (<0.1 MeV) energies as compared to the DT-518/PD. Moreover, ^{198}Au has a significantly longer half-life than ^{115m}In which gives more time for obtaining useful data for dose assessment. The other advantage of the DT-723/PD is the ability to measure activation activities using a High-Purity Germanium (HPGe) detector. In principle, NaI detector can be used for these measurements instead of HPGe one. The Naval Dosimetry Center uses an electric-cooled portable gamma spectrometer "Aegis" (Mirion Technologies) to determine the activity of gold and indium foils. This allows for improved accuracy of the dose measurements. A beta counter is used to determine the activity of the sulfur pellet. NDC uses an iSolo (Mirion Technologies) with Passivated Implanted Planar Silicon (PIPS) Detector which is the recommended instrument. The AWE developed a procedure that does not require burning or pulverization of the activated sulfur pellet. It is counted as a whole pellet (for detail see Wilson, 2015a) which significantly reduces the hazards and required counting time to 10 min per pellet. In principle, this technique can be also used for sulfur pellets counting of DT-518/PD.

Another improvement is the development of an algorithm that unfolds data from multiple detector elements of the DT-723/PD to calculate the most probable neutron spectrum and neutron dose. This was done at the United Kingdom Ministry of Defense research facility Atomic Weapon Establishment (AWE) by Chris Wilson in 2015. He embedded the developed algorithm in Microsoft® Excel® coded in Visual Basic. The software, known as "CRISIS Excel: A tool for Criticality Accident Dosimetry" is described in detail in Wilson (2015b).

To calculate neutron dose the following data needs to be entered into CRISIS.

- Dosimeter serial number,
- Date and time of the accident,
- Measured P-32 activity (Bq), date and time of measurement,
- Measured In-115m activity (Bq), date and time of measurement,
- Measured In-116m activity (Bq), date and time of measurement,
- Measured Au-198 (bare) activity (Bq), date and time of measurement,
- Measured Au-198 (cadmium shielded) activity (Bq), date and time of measurement.

CRISIS is capable of reporting dosimeter dose in several different terms.

- IAEA 211 Tissue Kerma (IAEA 211, 1982)
- IAEA 211 Recoil Absorbed Dose (IAEA 211, 1982)
- IAEA 211 Total Absorbed Dose (IAEA 211, 1982)
- LLNL Tissue Kerma (Deluca et al., 1985)
- ANSI N13.3 Personal Absorbed Dose (ANSI N13.3, 2013)
- ANSI N13.3 Ambient Absorbed Dose (ANSI N13.3, 2013)
- IAEA 211 H(n,g)D Absorbed Dose (IAEA 211, 1982)

The software will also provide a neutron energy spectrum for each dosimeter.

3.2. *Fast evaluation of neutron dose in the assembled DT-723/PD*

Like the DT-518/PD, a method to quickly perform a fast initial dose assessment using the assembled DT-723/PD is essential. A validation of the formula used for the DT-518/PD was performed by the Naval Dosimetry Center. This was done by irradiating five DT-723/PD dosimeters to a moderated and bare ^{252}Cf source at the Lawrence Livermore National Laboratory to known doses. Several Navy radiation detectors (RADIACs) were tested for their response and accuracy. The following three RADIACs were found suitable.

- RadEye G-20 (GM), measurements in μR/h,
- IM-265/PDQ with beta probe DT-304 (GM), measurements in counts per minute (CPM)
- AN/PDQ-79 with NaI detector, measurements in CPM.

For research purposes, the results of the activity measurements for the DT-723/PD were compared with the DT-518/PD dosimeter.

Results from the measurements show that the DT-723/PD produces about a factor of 2 higher activity for the same dose than DT-518/PD, which has numerical coefficient of 8 in formula (1). Table 4 shows numerical coefficients determined for different RADIACs and neutron sources. Shortly after exposure (<5 h) the main contributor in the activity of the assembled DT-723/PD is ^{116m}In, the same as for DT-518/PD. Therefore, expected uncertainty as a function of time for the DT-723/PD is similar to the one for DT-518/PD. However, the time correction factor for DT-723/PD has different from DT-518/PD time dependence because of contributions of the gold foils in total activity of the assembled DT-

Table 4
Numerical coefficients in formula (1) for tested RADIACs and neutron sources.

Source	RadEye G-20	IM-265/PDQ	AN/PDQ-79
D_2O moderated ^{252}Cf	4.32	0.75	0.0354
Bare ^{252}Cf	9.50	1.90	0.079

723/PD. Based on the time dependence of the time correction factor for DT-723/PD (Fig. 6) one can conclude that AN/PDQ-79 (NaI) has a biggest contribution from the gold activation which emits photons with E = 411.8 keV. RadEye G-20-10 (GM) has a biggest contribution from ^{116m}In which emits photons with E = 0.127 MeV. IM-265/DT-304 (GM) has similar contributions from both activated gold and indium. In principle, combined use of different RADIACs can allow to obtain information on the dominating energy of the neutron accidental exposure. The described method of the fast evaluation of neutron dose in the assembled DT-723/PD was developed in 2023 and not been verified yet in the exercises with blind dose measurements. This will be done during next exercise.

The neutron energy spectrum of D_2O moderated ^{252}Cf is more like the Naval nuclear reactor's spectrum compared to the Bare ^{252}Cf.

The experiment also allowed the determination of a time correction factor for these RADIACs. Fig. 6 shows results of the exponential fit of the averaged experimental data.

RadEye G-20-10: 5.41 + 1.18*exp((x+4.91)/2.87)

IM-265/DT-304: 1.9515+exp((x+2.01)/2.053)

AN/PDQ-79 (NaI): 2.07 + 1.75*exp((x+1.37)/2.73)

Average Best fit of all data: 3.15 + 1.31*exp(x+2.76)/2.55)

3.3. Results of DT-723/PD testing

In August 2022, the NDC team participated in the biennial International Blind Intercomparison Exercise for Nuclear Accident Dosimetry (IBIE) using the Godiva-IV reactor operated by Los Alamos National Laboratory and sited at the National Criticality Experiments Research Center at the Nevada National Security Site in Nevada (Tamashiro et al., 2023). A NAD intercomparison was conducted in August 2022 utilizing two prompt burst irradiations from the Godiva-IV critical assembly. Ten institutions participated in this exercise and nine institutions performed preliminary measurements at the Lawrence Livermore National Laboratory's (LLNL's) NAD lab. Nine institutions provided their results when they completed their analysis at their respective institution. These institutions were LLNL, Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), Savannah River Site (SRS), Hanford Site, Y-12 National Security Complex (Y-12), Naval Dosimetry Center (NDC), Atomic Weapons Establishment (AWE), and Institut de Radioprotection et de Sûreté Nucleaire.

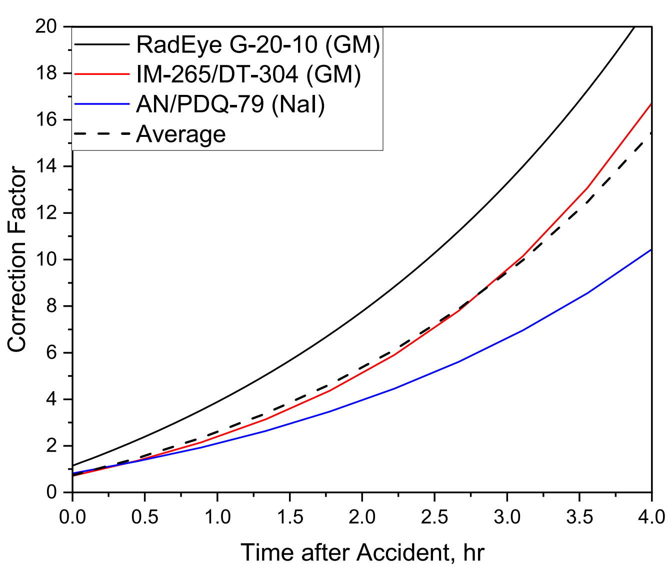

Fig. 6. Time correction factor for DT-723/PD for different RADIACs.

A total of 16 DT-723/PD dosimeters were exposed over the course of two different bursts on two different days. Eight dosimeters were exposed on the first day (24 Aug 22) and eight on the second day (25 Aug 22). The dosimeters were placed at varying distances of 2 m, 3 m, and 4 m, on various phantoms. The doses were reported in terms of IAEA 211 (International Atomic Energy Agency, 1982) Tissue Kerma, which is the first option in the CRISIS software. It is also important to mention that DT-723/PD used in this exercise did not have a TLD element. Therefore, gamma dose was not determined and only neutron dose was used to report total accident dose. The later obviously caused dose underestimation of the reported doses as compared to the delivered doses. The reported neutron doses are shown in Tables 5–8. Comparisons are made with the delivered doses as reported by exercise coordinators. As seen from Tables 5–8, the ANSI 13.3, 2013 dose terms generally provided better agreement with the delivered doses and this dose term is recommended for future measurements. The results were also compared with the performance testing criteria of criticality accident dosimeter systems provided by ANSI 13.3, 2013 (Table 1).

Comparisons between the results shown in Tables 5–8 and the testing criteria in Table 1 show that the DT-723/PD is a reliable indicator of neutron dose in accident scenarios. Negative bias is probably caused by the unreported gamma doses. It is also interesting to note if the NAD dose would be reported in the terms of IAEA 211, 1982 Total Absorbed Dose, then the average biases for Burst 1 and 2 would only be 6.75% and 6.77%, correspondently.

Fig. 7 shows an example of the neutron energy spectrum generated by CRISIS for NAD #752292, burst 1.

Gamma doses were not measured or reported because the DT-723/PD provided to NDC for this test did not include the LiF-700 TLD. Like the DT-518/PD Harshaw TLD, a manual TLD reader Harshaw Model 3500 can be used for its dose readout. The dose readout of ^{7}LiF: Mg,Cu,P dosimeter requires about 30 s with maximum temperature 240°–260 °C, and heat rate 10 °C/s. Alternatively accident gamma dose can be obtained from the Navy personnel dosimeter DT-702/PD (for detail description see, Romanyukha et al., 2018).

3.4. DT-723/PD holder

Due to the presence of cadmium shielding of gold foil in the DT-723/PD the dose determination is dependent on the dosimeter orientation, e.g., for accurate dose measurement the cadmium shielding of the gold foil shall face the incident irradiation. Therefore, NDC designed a special holder for DT-723/PD (Fig. 8) which can be printed by 3D printer at low cost. Developed DT-723/PD holder was not used in the intercomparison exercise because it was designed later upon request from the personnel responsible for the NAD placement in the reactor compartments.

4. Conclusions

The United States Navy accident dosimetry program is capable

Table 5
Reported doses in terms of IAEA 211 as compared with delivered doses for Burst 1.

Distance, m	Dosimeter ID	Reported IAEA 211, 1982 Tissue Kerma, Gy	Delivered dose, Gy	Bias %
2	752271	2.15	2.28	−5.70
2	752283	2.3	2.28	0.88
3	752293	1.05	1.35	−22.22
3	752281	1.19	1.35	−11.85
3	752282	1.01	1.35	−25.19
3	752291	1	1.35	−25.93
4	752268	0.719	0.99	−27.37
4	752292	0.824	0.99	−16.77
			Average	−16.77

Table 6
Reported doses in terms of IAEA 211 as compared with delivered doses for Burst 2.

Distance, m	Dosimeter ID	Reported IAEA 211, 1982 Tissue Kerma, Gy	Delivered dose, Gy	Bias %
2	752289	3.7	4.01	−7.73
2	752279	3.88	4.01	−3.24
3	752280	2.23	2.37	−5.91
3	752273	2.01	2.37	−15.19
3	752290	2.37	2.37	0.00
3	752301	1.87	2.37	−21.10
4	752262	1.46	1.74	−16.09
4	752270	1.21	1.74	−30.46
			average	−12.46

Table 7
Reported IAEA 211 Tissue Kerma averaged by distance for Burst 1.

Distance, m	Reported IAEA 211, 1982 Tissue Kerma, Gy	Delivered total dose, Gy	Bias %
2	2.225	2.28	−2.41
3	1.0625	1.35	−21.30
4	0.7715	0.99	−22.07
		average	−15.26

Table 8
Reported IAEA 211 Tissue Kerma averaged by distance for Burst 2.

Distance, m	Reported IAEA 211, 1982 Tissue Kerma, Gy	Delivered total dose, Gy	Bias %
2	3.79	4.01	−5.49
3	2.12	2.37	−10.55
4	1.335	1.74	−23.28
		average	−13.10

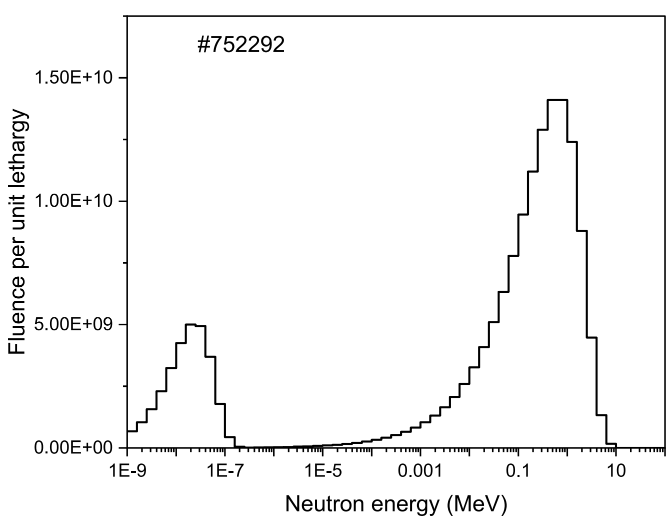

Fig. 7. Example of the neutron energy spectrum generated by CRISIS for dosimeter #752292.

providing an accurate dose measurement in the unlikely event of criticality accident. The newest Navy NAD DT-723/PD has many advantages when compared to the older DT-518/PD, which include following.

- Provides neutron dose measurements for a much broader neutron energy range, e.g., 10^{-3} - 10^{7} eV.
- Corresponding CRISIS software allows for accident dose calculations in an easy and reliable process.
- Combined with a spectrum generating software like CRISIS, the Neutron energy spectrum is provided.
- Capability to report accident dose in several different terms.
- Allows for a longer time for the dose measurements to be obtained, due to the gold foil longer half time.
- A unique serial number for each dosimeter is available.
- An opener is provided, with which the NAD DT-723/PD can be easy disassembled and assembled back for the dose measurements or inspection.
- A water resistant design with metal foils that are physically separated from the sulfur pellet prevents degradation into indium sulfide and cadmium sulfide.

The above listed features also make the DT-723/PD a valuable tool for neutron source and reactor characterization.

One of the limitations of the DT-723/PD dosimeter (and most of the other existing NADs), is that they only allow useful dose data to be obtained if the dosimeter is read within the time constraints associated with decay of the activation products and they provide no useful data if not analyzed during the first weeks following an accident occurrence. It is highly desirable to have a NAD which can be measured several times over the course of least one year, require simple, transportable, and inexpensive equipment to process and are inexpensive themselves. Recently proposed multiple alanine pellet accident dosimeters (Romanyukha, 2022; Romanyukha and Delzer, 2023) can potentially provide even better capabilities for the accident dose measurements.

Disclaimers

Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by NIST, nor does imply that the equipment are necessarily the best available for the purpose.

The views expressed in this paper are those of the authors and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U. S. Government.

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CRediT authorship contribution statement

Alex Romanyukha: Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Jessica Saunders:** Writing – review & editing. **David Boozer:** Software, Investigation, Data curation. **Keith Consani:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Jeff Delzer:** Writing – review & editing, Writing – original draft, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

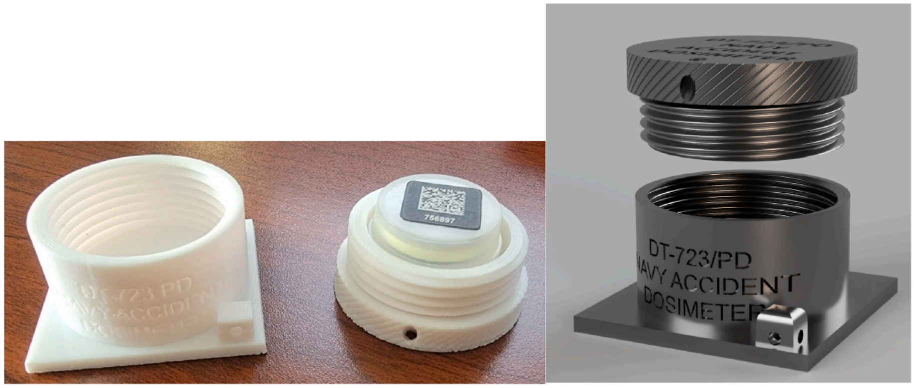

Fig. 8. DT-723/PD holder with dosimeter.

Data availability

Data will be made available on request.

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