



Defence Research and  
Development Canada

Recherche et développement  
pour la défense Canada



# **Development of an electronic neutron dosimeter**

*Project closeout report for CRTI 04-0029RD*

Carey L. Larsson and Trevor Jones

**Defence R&D Canada – Ottawa**

Technical Report  
DRDC Ottawa TR 2012-014  
May 2012

**Canada**



# **Development of an electronic neutron dosimeter**

*Project closeout report for CRTI 04-0029RD*

Carey L. Larsson and Trevor Jones  
DRDC Ottawa

**Defence R&D Canada – Ottawa**

Technical Report  
DRDC Ottawa TR 2012-014  
May 2012

Principal Author

*Original signed by Carey L. Larsson*

---

Carey L. Larsson

Defence Scientist/CARDS Section

Approved by

*Original signed by Julie Tremblay-Lutter*

---

Julie Tremblay-Lutter

Section Head/CARDS Section

Approved for release by

*Original signed by Chris McMillan*

---

Chris McMillan

DRP Chair/DRDC Ottawa

This work was funded in part by the CBRNE Research and Technology Initiative (CRTI) under project 04-0029RD.

© Her Majesty the Queen in Right of Canada, as represented by the Minister of National Defence, 2012

© Sa Majesté la Reine (en droit du Canada), telle que représentée par le ministre de la Défense nationale, 2012

## Abstract

---

The CBRNE Research and Technology Initiative (CRTI) funded the project CRTI-04-0029RD “Development of an Electronic Neutron Dosimeter” to produce a prototype electronic neutron dosimeter capable of meeting both civilian and military performance specifications, a feat that has not been achieved by any existing commercial device to-date. Significant technical hurdles were encountered throughout the development process, resulting in large schedule delays and increased development costs. Nonetheless, final prototype devices were delivered and tested, indicating good general performance, although several significant issues were encountered that will require further work to achieve desired performance levels.

## Résumé

---

L'Initiative de recherche et de technologies CBRNE (IRTC) a financé le projet de l'IRTC-04-0029RD « Développement d'un dosimètre électronique pour les neutrons » pour produire un prototype de dosimètre électronique pour les neutrons capable de répondre à des spécifications de performance à la fois civiles et militaires, un exploit qu'aucun appareil commercial existant à ce jour n'a pu réussir. D'importants obstacles techniques ont été rencontrés tout au long du processus de développement, entraînant des retards et des coûts de développement accrus. Néanmoins, les prototypes finaux ont été livrés et testés, indiquant une bonne performance générale, bien que plusieurs problèmes importants aient été rencontrés qui nécessitent davantage de travail pour atteindre les niveaux de performance souhaités.

This page intentionally left blank.

## Executive summary

---

### Development of an electronic neutron dosimeter: Project closeout report for CRTI 04-0029RD

Carey L. Larsson; Trevor Jones; DRDC Ottawa TR 2012-014; Defence R&D Canada – Ottawa; May 2012.

**Introduction or background:** Project CRTI-04-0029RD “Development of an Electronic Neutron Dosimeter” aimed to design, build, and test a small, wearable electronic neutron dosimeter capable of meeting civilian and military performance specifications. The project was carried out in three phases: conceptual design; construction and testing of a laboratory prototype; and fabrication and thorough testing of the final field prototype.

**Results:** The project encountered numerous technological hurdles during the development of this technology, resulting in major delays in project schedule and cost overruns that were covered by BTI as an unforecasted in-kind contribution to the project. In the end, the final prototype devices showed good general response, although several significant issues were identified preventing them from meeting desired performance specifications.

**Significance:** While this project has resulted in an electronic neutron dosimeter that provides improved dose response over a wide energy range compared to many of the commercially available ENDS, significant issues still remain to be overcome before the device can meet civilian and military performance specifications.

**Future plans:** Given the remaining issues that need to be addressed, as well as the schedule delays and much higher costs associated with bringing this technology to its current state, it is unclear whether additional efforts will be expended to further develop the technology. The decision to progress this work further will need to be made by the industry partner, BTI.

## Sommaire

---

### **Development of an electronic neutron dosimeter: Project closeout report for CRTI 04-0029RD**

**Carey L. Larsson; Trevor Jones ; DRDC Ottawa TR 2012-014 ; R & D pour la défense Canada – Ottawa; mai 2012.**

**Introduction ou contexte :** Le projet IRTC-04-0029RD « Développement d'un dosimètre électronique pour les neutrons » visait à concevoir, construire et tester un petit dosimètre électronique individuel pour les neutrons capable de satisfaire aux spécifications fonctionnelles civiles et militaires. Le projet a été réalisé en trois phases : la conception, la fabrication et la vérification d'un prototype de laboratoire et la fabrication et la vérification approfondie d'un prototype final.

**Résultats :** Le projet a rencontré de nombreux obstacles technologiques au cours du développement de cette technologie, entraînant des retards importants sur l'échéancier du projet et des dépassements de coûts qui ont été abordés par BTI comme contribution imprévue au projet. En fin de compte, le prototype final a montré une bonne réponse générale, bien que plusieurs problèmes importants aient été identifiés en les empêchant de rencontrer les caractéristiques de performance désirées.

**Importance :** Bien que ces projets ont produit un dosimètre électronique pour les neutrons qui fournit une réponse améliorée sur une large gamme d'énergie que beaucoup des dosimètres électroniques pour les neutrons sur le marché, des problèmes importants restent encore à surmonter avant que l'appareil puisse rencontrer les spécifications fonctionnelles civiles et militaires.

**Perspectives :** Compte tenu des problèmes résiduels qui doivent être réglés, ainsi que des retards et des coûts beaucoup plus élevés que prévu pour amener cette technologie à son état actuel, il est difficile de savoir si des efforts supplémentaires seront déployés pour développer davantage la technologie. La décision d'effectuer des travaux supplémentaires devra être prise par le partenaire industriel, BTI.



# Table of contents

---

Abstract .....	i
Résumé .....	i
Executive summary .....	iii
Sommaire .....	iv
Table of contents .....	v
List of figures .....	vii
List of tables .....	viii
Acknowledgements .....	ix
1 Introduction.....	1
2 Purpose .....	2
3 Methodology.....	3
4 Results.....	10
4.1 Neutron dose rate response.....	10
4.2 Neutron dose rate repeatability.....	12
4.3 Response time.....	13
4.4 Gamma dose rate response in a neutron field.....	14
4.5 Gamma free field dose rate response in a gamma field.....	16
4.6 Neutron and gamma angular response.....	16
4.7 Ancillary .....	17
4.7.1 Alarms .....	17
4.7.2 Buttons.....	18
4.7.3 Battery operation and charging system.....	18
4.7.4 Temperature effects .....	19
4.8 Results Summary.....	19
5 Transition and Exploitation .....	20
5.1 Follow-on Development.....	20
5.2 Transition to End Users .....	20
5.3 Intellectual Property Disposition .....	20
6 Conclusion .....	21
References .....	23
Annex A Project Team.....	25
Annex B Project Performance Summary.....	27
B.1 Technical Performance Summary .....	27
B.2 Schedule Performance Summary.....	27
B.3 Cost Performance Summary.....	29

Annex C Publications, Presentations, Patents.....	30
---	----

## List of figures

---

Figure 1: Concept 1 for the END high energy neutron sensor. ....	4
Figure 2: Concept 2 for the END high energy neutron sensor. ....	5
Figure 3: The final fast and thermal/epi-thermal neutron sensors chosen for the END. ....	6
Figure 4: Laboratory END prototype. ....	6
Figure 5: END2 laboratory prototype.....	8
Figure 6: The final END2 field prototype. ....	9
Figure 7: Dose rate response of END2 unit #2, 3, 7, and 9 compared to nProbe. ....	11
Figure 8: END2 measured to expected neutron dose rate for free-field target room exposures. ..	12
Figure 9: Scatter-corrected END2 dose rate response compared to expected neutron dose rate. .	12
Figure 10: END2 response for exposure to (rise time) and removal from (fall time) a neutron field. ....	14
Figure 11: END2 free field gamma dose rate response to neutron exposures.....	15
Figure 12: END2 and SVG2 free field gamma dose rate response to $^{60}\text{Co}$ and $^{137}\text{Cs}$ exposures. .	16
Figure 13: END2 unit 3 neutron and gamma angular response.....	17

## List of tables

---

Table 1: END2 neutron dose rate repeatability measurements for all units. ....	13
Table 2: Comparison of END2 and SVG2 measured gamma dose rates from Cf-252 exposures. ....	15
Table 3: Project team and project review committee (PRC) members. ....	26
Table 4: Original, revised, and final END project schedule. ....	28
Table 5: END project costs. ....	29

## Acknowledgements

---

This work was supported by Defence Research and Development Canada Centre for Security Science Chemical, Biological, Radiological/Nuclear, and Explosives Research and Technology Initiative (CRTI 04-0029RD) with project partners from Bubble Technology Industries (BTI), DND's Canadian Joint Incident Response Unit (CJIRU), and the Canadian Nuclear Safety Commission (CNSC). The author would like to acknowledge the scientists at Bubble Technology Industries for their significant efforts in the development of the technology resulting from this project.

This page intentionally left blank.

# 1 Introduction

---

In the years following September 11, 2001, much attention has been focused on the deployment of radiological dispersal devices (RDDs) as terrorist weapons. When considering which radiation sources may be incorporated into a dirty bomb, it was recognized that a number of neutron-emitting radioactive sources commonly used in industrial applications often have limited security precautions. For example, oil well logging and Troxler gauges employ Californium-252 ( $^{252}\text{Cf}$ ) or Americium-241/Beryllium ( $^{241}\text{Am}/\text{Be}$ ) sources, some with significant activity (in the case of the well logging gauge, as much as 0.85 TBq (23 Ci) is used). When not in use, these devices are often chained to the back of a flat bed truck and parked outdoors overnight. To support the limited security often associated with these devices, a review of NRC's Nuclear Materials Events Database for the period of 2001 through 2004 revealed that approximately 50 gauges were stolen per year and only about half of these were eventually recovered [1]. DRDC Ottawa (and other) calculations have shown that the threat from deliberate explosion or dissemination of even a small number of such sources could cripple a large urban infrastructure via contamination of many square kilometres to radiation levels well in excess of international regulatory limits. Such contamination is particularly serious because of the transuranic compounds involved, which are a major health threat once they enter the body [2].

Having a reliable assessment of radiation dose is paramount to the principles of radiation safety. Particularly with the high threat of radiological and nuclear terrorism, the need for accurate dosimetry in uncharacterized radiation environments is increased due to the potential exposure of non-nuclear energy workers such as emergency first responders. In the scenario described above, however, the readily-available commercial Electronic Personal Dosimeters (EPDs) of the type deployed with first responders will measure only the gamma ray dose and not the neutron dose, and hence will register only a small fraction (perhaps as low as 10 %) of the total effective dose from external radiation.

Neutron dosimetry is often regarded as the last frontier of radiation protection and it is well recognized that the development of a viable electronic neutron dosimeter (END) is an extremely difficult task [3]. Currently no electronic neutron dosimeter exists that will meet military or civilian performance specifications [4]. Experimental evaluations of existing and prototype devices have pointed out many deficiencies relative to the desired properties of a good END [5]. Specifically, a viable END should be a small wearable device that has appropriate sensitivity, a wide energy response, low power requirements, total neutron/gamma discrimination, and adequate environmental stability. In preparation for this project, a thorough assessment of existing sensor technologies and advances in technological development was performed and an alternative approach to producing a viable END was conceived. The objective of this project was therefore to successfully develop an electronic neutron dosimeter that meets all above-mentioned specifications.

## 2 Purpose

---

The electronic neutron dosimeter developed for this project was intended to provide responder communities with the ability to detect the presence of neutron sources, as well as monitor their associated exposure, ultimately improving their response capability. The END project aimed to address the requirements outlined in CRTI investment priorities of 2004/2005 for the development of “S&T in Support of Equipping and Training First Responders” and “Prevention, Surveillance and Alert Capabilities” as they pertain to the RN cluster [6]. In preparation for this project, a thorough assessment of existing sensor technologies and advances in technological development was performed and an alternative approach to producing a viable END was conceived. The objective of this research and development project was to successfully develop an electronic neutron dosimeter that meets international technical specifications as a leave-behind for the first response community, relevant to any scenario involving neutron-emitting radioactive material. The project consisted of three phases: conceptual design with input from all project partners; construction and testing of a laboratory prototype; and fabrication and thorough testing of the final field prototype. These are described in detail in the next section.



### 3 Methodology

---

To develop the electronic neutron dosimeter, three phases were identified covering conceptual design with input from all project partners, construction and testing of a laboratory prototype, and fabrication and thorough testing of a final field prototype. The conceptual design phase was to be the focus of the first project year. Dosimeter design features were to be discussed with all members of the project team, particularly focusing on the size, sensitivity, energy response, power requirements, neutron/gamma discrimination capability, and environmental suitability. Following this, necessary components of the device would be identified and procured, device subsystems designed and constructed, and each subsystem would then undergo performance testing. The main outcome for this stage of work was to be an approved conceptual design of the END, with tested subsystems of the design to base future laboratory and field prototypes upon.

The second phase of the project was to be focused on the construction and testing of a laboratory prototype capable of testing design performance and specification feasibility. The lab prototype would be built at BTI, employing lessons learned from the first phase of the project, with a focus on designing a device capable of meeting sensitivity, dose and energy range requirements, leaving size and weight requirements to be dealt with in the field prototype. Testing of the laboratory prototype would then be performed by DRDC Ottawa and Los Alamos National Laboratory (LANL) to investigate the device's sensitivity and energy response in a variety of neutron and mixed radiation fields. The main outcome for this work would be a working laboratory prototype meeting all technical specifications (ignoring physical ones), and a detailed report outlining end-user testing results.

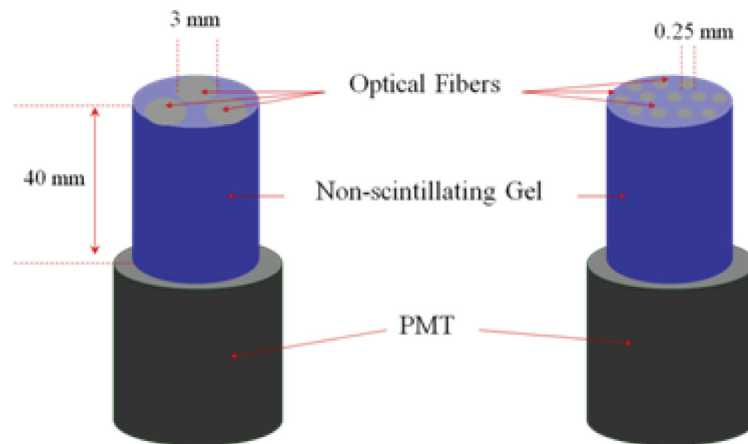
The third and last phase of the project was to be focused on the fabrication and thorough testing of a final field-ready electronic neutron dosimeter prototype against all physical, technical, and end-user specifications, improving on issues encountered during the laboratory prototype testing. Two field prototypes would be constructed and sent to DRDC Ottawa and LANL for a thorough assessment in relation to military and civilian specifications. This would be followed up by operational testing in a variety of possible use scenarios by end users from the Canadian Nuclear Safety Commission (CNSC), the Canadian Joint Incident Response Unit (CJIRU), and DRDC Ottawa.

To begin the first phase of the project, it was important to identify the technical specifications that the resulting END would strive to meet. To this end, a number of different international requirements for electronic neutron dosimeters were considered. The most stringent of these specifications are described in the International Electrotechnical Commission (IEC) specification 61526 [4]. From these, the following specifications were selected as the most important from our point view for the END prototype:

- Hp(10) dose with energy range: from thermal neutrons to 15 MeV.
- Size: all dimensions shall not exceed 15 cm in length, 8 cm in width, and 3 cm in depth. In addition, the volume shall not exceed 300 cm<sup>3</sup>.
- Mass: shall not exceed 300 g.
- Range for dose equivalent: from 1 µSv to 10 Sv.

- Range for dose equivalent rate: from 1  $\mu\text{Sv/h}$  to 1 Sv/h.
- Battery capacity: 100 h of continuous operation.
- Temperature range:  $-10^{\circ}\text{C}$  to  $+40^{\circ}\text{C}$  during operation.

A similar neutron sensor concept was presented in both the proposal and in the initial conceptual design phase. This concept considered the use of bundles of small scintillation fibres (either plastic or glass) encased in a non-scintillating gel, with light outputs viewed by small photomultiplier tubes (PMTs), as shown in Figure 1. The small diameter of the scintillators would allow anti-coincidence discrimination against long-range gamma ray interaction products (electrons) versus short-range neutron-interaction products (protons). The fibres in each bundle would be of different diameters, allowing different neutron energy ranges to be spanned. A unique signature received at the PMT would thus be assigned to each neutron-initiated event based on the tracking of reaction products, allowing for determination of the incident neutron energy and thence accurate assessment of dose via on-line convolution with the appropriate dose/energy response. A third sensor based on a boron-covered  $^6\text{Li}$  scintillator against a third PMT would be included to detect thermal and epithermal neutrons. A special method of operating PMTs based on voltage multipliers was to be developed in order to minimize power requirements. Unfortunately, attempts to develop this type of spectrometer for low energy neutrons (below 1 MeV) failed because of poor response function (exponential decrease with energy) and poor light collection. Also, the production of such a detector involved the handling of the many fine fibres, which was technically extremely challenging.

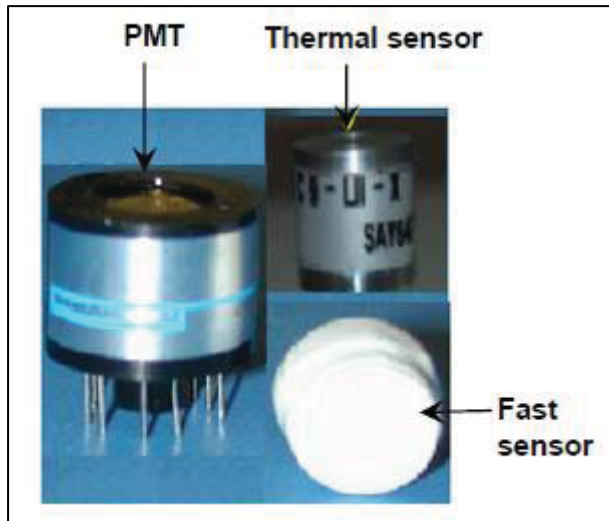


*Figure 1: Concept 1 for the END high energy neutron sensor.*

A second conceptual design was then proposed, shown in Figure 2, which consisted of a compact sensor with alternating layers of two different plastic scintillators (each emitting light at different wavelengths) and a third non-scintillating material sandwiched together. This sandwich would be viewed on one end with a small PMT, which detects both scintillator wavelengths, and on the other end with a photodiode, which only detects one, allowing for gamma discrimination. The non-scintillating layer would stop neutrons interacting in the edge of the scintillating materials from producing light outputs in the subsequent scintillator layers. The scintillators would have a thickness of a few tens of microns. Unfortunately, the poor response function and crosstalk observed between adjacent layers made this approach also technically unattractive.



A final conceptual design was settled on using the same type of neutron sensors as in the well-proven BTI N-probe [7]: a proton-recoil scintillator for fast neutrons and a specially-shielded thermal neutron detector for thermal and epithermal neutrons, shown in Figure 3. The fast neutron sensor is a special 1-cm<sup>3</sup> scintillator with excellent n/γ pulse-shape discrimination properties used with a tiny PMT. The thermal/epi-thermal sensor is a small <sup>6</sup>LiI scintillator used with a similar PMT. Like in the N-probe, this sensor is embedded within a specially-designed, thick, boron shell in order to alter the response of the <sup>6</sup>LiI detector. The shell “flattens” the response so that thermal neutrons do not overwhelm the response to epithermal neutrons. Calculations showed that small versions of such sensors are more than adequate to meet the desired performance specifications. The other technical challenges to minimize power consumption and device size to meet mechanical specifications had been addressed to a significant degree in the earlier work. Further improvements would be achieved using the latest low-power electronics along with small changes to the design of the high-voltage power supply and the analogue front-end pulse-processing circuitry.



*Figure 3: The final fast and thermal/epi-thermal neutron sensors chosen for the END.*

The END laboratory prototype, shown in Figure 4, weighed roughly 700 g with dimensions of 6.5 cm x 10.7 cm x 16.5 cm, and a volume of 1148 cm<sup>3</sup>. However, at this stage in the project, size and weight requirements were not the primary concern. Preliminary testing of the devices at BTI [8] was followed up with testing of the devices at DRDC Ottawa [9] and LANL [10] to assess device performance against the technical specification targets. Results and recommendations from this testing were provided to BTI for consideration in the next phase of END development.



*Figure 4: Laboratory END prototype.*

Due to the significant technical hurdles encountered during the design of an appropriate END, the project encountered delays in schedule and milestone delivery. In fact, delivery and testing of the laboratory prototype described above was completed at the originally-scheduled project completion timeframe of March 2009, with the third phase of the project not yet addressed. In addition, in the preceding months CRTI approved a follow-on project to 04-0029RD entitled “CRTI 07-0190TA – Extension of an Electronic Neutron Dosimeter to Detect Gamma Rays (END2)”, which proposed adding gamma dosimetry to the END prototype that resulted from the first project. Given the schedule delays, development of the final END and END2 prototype units were carried out concurrently, with all final prototype devices incorporating gamma dosimetry as

well as neutron dosimetry. These devices were all of the same design, referred to as END2, despite the two distinct projects. As such, methodology followed in the END2 project is detailed here due to their relevance in the delivery of the final field END prototypes.

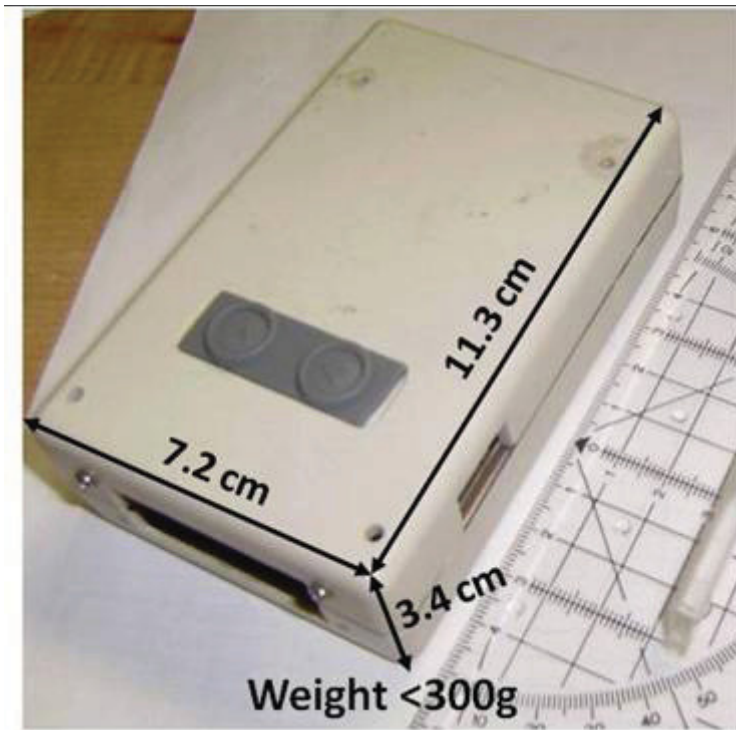
The END2 project followed a four-phase approach to the work, which included opportunities for end-users and other partners to provide feedback into the development and evaluation process to ensure the field prototypes were suitable for their requirements. The four phases of the project consisted of a “scintillator testing, review and preliminary design” phase, a “conceptual design” phase, a “fabrication and testing of laboratory prototype” phase and a “fabrication and testing of field prototype” phase. At the end of these four phases, two field END2 prototypes were to be delivered for each of the two projects (thus resulting in four END2 prototypes).

In the first phase of this project, an investigation was conducted into the applicability of a new scintillator known as CLYC ( $\text{Cs}_2\text{LiYCl}_6\text{:Ce}^{3+}$ ) for use in the END2 project, due to its potential use for combined neutron and gamma detection. Extensive testing and analysis determined that CLYC was a more appealing material than LiI from a scientific point of view. Superior properties for energy resolution and the capability to discriminate gamma events from neutron events favour CLYC for nuclear and particle physics research applications. However, the high cost and low availability of CLYC did not make it a suitable candidate for an affordable, easy to manufacture END2 device. For the purposes of this project, it was determined that the use of LiI as the detector material would be the most reasonable.

The second phase developed a conceptual design for the END2 prototypes. The detectors and their associated photomultiplier tubes (PMTs) were selected, preliminary schematics were produced, power requirements were assessed, preliminary graphical user interfaces were developed, and the initial mechanical design was generated. Multiple improvements based on lessons learned from the original END design were incorporated into the design of END2. The preliminary conceptual design was presented to the project partners and end-users and feedback was obtained regarding the LCD display, push buttons, alarming logic, backlight settings, neutron/gamma discrimination, and ruggedness and was subsequently incorporated into the final conceptual design for the END2 device. A final conceptual design was then developed, along with the initiation of algorithm development in preparation for fabrication of the prototypes.

In the third phase of the END2 development, two laboratory prototypes were manufactured, calibrated, and tested, shown in Figure 5. Notable achievements relative to the original END design included improvements to circuitry, miniaturized hardware, implementation of higher quantum efficiency PMTs, improved dose calculation algorithms, and development of firmware, software, and an offline replay tool. A significant reduction in size and weight was achieved relative to the original END prototype, with final dimensions of 11 cm x 7 cm x 3.3 cm. Once the laboratory prototypes were fully assembled, extensive testing was performed both in-house at BTI and by Los Alamos National Labs (LANL) and DRDC Ottawa. Testing and calibration included the use of neutron and gamma sources, as well as the DRDC Ottawa Van de Graaff accelerator, to evaluate the performance of the dosimeters. Results and recommendations from this testing were provided to BTI for consideration in the field END2 prototype development.





*Figure 5: Laboratory END2 prototype.*

The fourth and final phase of END2 development was focused on the construction and testing of the final field prototypes. The field END2 prototypes, shown in Figure 6, are based on the same technical and scientific principles as the laboratory prototype, including two detectors on mini PMTs to detect gamma and neutron radiation. The measured dose rates and total doses are displayed on an LCD screen. This screen also allows the user to toggle through different menus, silence alarms, and to turn on the backlight of the LCD display using the two push buttons located on the front face of the device. Based on end-user feedback, two multi-coloured LEDs were incorporated to indicate the battery and alarming status of the device. The mechanical design of the END2 enclosure was improved and a prototype customized enclosure was manufactured with a 3D printing technique. The dimensions of the field prototype of 12.5 cm in length, 8 cm in width, and 3 cm in height are similar to those of the laboratory prototype. Charging through a USB cable was enabled and the device can be charged either by a PC or an off-the-shelf wall charger. A total of four field END2 prototype units were delivered to DRDC Ottawa for final testing based on two variants of detectors (i.e. two units will have one variant of detector type, the other two will have the second variant). Testing of the devices, discussed in the next section, was the final major task for the two related END projects. Following this, project closeout activities were carried out.



*Figure 6: The final field END2 prototype.*

## 4 Results

---

Detailed testing reports of each stage of END and END2 prototypes were prepared at various stages of the project and can be found in the references, as well as in Annex C. This section presents a summary of the final testing carried out on the field END2 prototype units, which is also described in [11].

The four final END2 prototypes were tested at DRDC Ottawa, referred herein as units 2, 3, 7, and 9. During the testing, some general issues pertaining to the devices were encountered that prevented all desired tests to be carried out on all devices. These issues related to temperature problems and general functionality.

During early testing, the units appeared to be overheating causing them to fail. Originally, it was thought that the ambient temperature in the room was at fault; however, over the course of several days with varying room temperatures (20 – 30 °C), the failure was persistent. Eventually it was determined that the units were self-heating when used over extended periods of time (> 1 hour). The final solution to continue testing was to place a fan in a position to cool all units during testing. Due to this unfortunate problem, the END2s were not tested for temperature response.

Additional issues were encountered with units 2 and 7. Unit 7 was constantly giving neutron dose data higher than the other units ( $30 \pm 10\%$  over response compared to the other units). It was thought that this may be due to a calibration error in the firmware of that device. This device was therefore removed from further testing. In addition, Unit 2 was failing intermittently. Eventually it died completely and could not be used in any further tests. The cause is suspected to be due to a high voltage failure.

### 4.1 Neutron dose rate response

The four END2 devices and a reference a BTI nProbe [12] were exposed to three neutron sources at dose rates spanning two orders of magnitude. The ratio of END2 to nProbe reported dose rate versus theoretical dose rate is shown for units 2, 3, 7, and 9 in Figure 7. END2 unit 2 shows very good neutron dose rate response, with all measurements falling within  $\pm 20\%$  of the reference nProbe values. However, as described above, this unit only worked intermittently and eventually stopped working all together, so only limited data was collected with this unit. END2 unit 3 demonstrated fairly good response to AmBe and PuBe exposures, but the device seemed to over respond to  $^{252}\text{Cf}$  exposures. At the highest dose rate, this may have been due to deadtime effects in the nProbe, but this effect does not explain the over response seen at other dose rates. Overall, the response of this unit was slightly high. All measurements taken with END2 unit 7 show an over-response of approximately 40 % with respect to nProbe measurements. Comparison of these readings with those taken with units 3 and 9 also indicated that the unit was over responding. Response of END2 unit 9 was similar to that of unit 3, showing fairly good response to AmBe and PuBe exposures, but an over response to  $^{252}\text{Cf}$  exposures. Again, deadtime effects in the nProbe may have been a factor at the highest dose rates. As seen in unit 3, the response of unit 9 was slightly high, although not as high as that observed in unit 7. These over response issues may simply be an issue with the calibration factor entered in the firmware, but further investigation is



warranted. Note that testing with the  $^{252}\text{Cf}$  source was only performed on units 3 and 9 due to the issues identified above with the other two units.

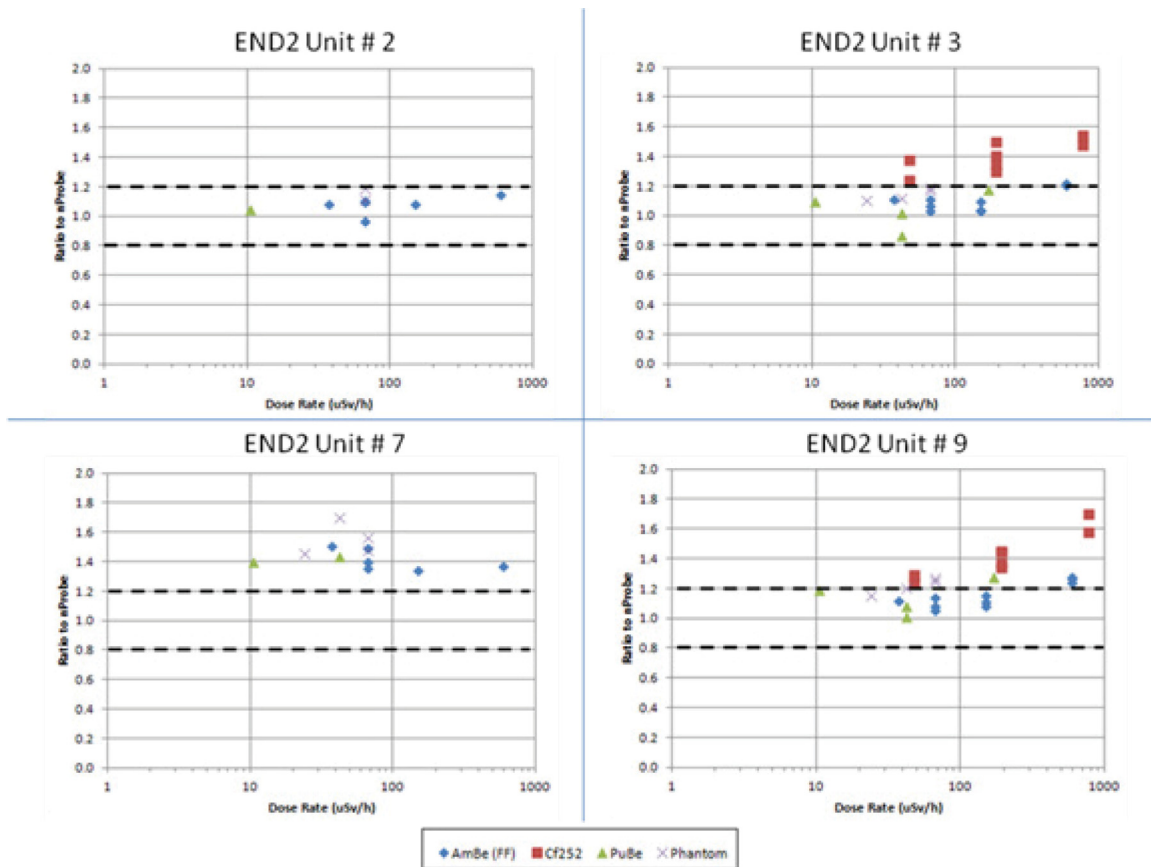


Figure 7: Dose rate response of END2 unit #2, 3, 7, and 9 compared to nProbe.

In order to directly compare END2 measured values to theoretical dose rates, neutron backscatter at the END2 units needs to be accounted for. This was calculated by applying a linear fitting to a plot of measured END2 neutron dose rate versus theoretical neutron dose rate, where the intercept of this fit provides a backscatter correction in units of  $\mu\text{Sv/hr}$ . An example of this linear fitting for free-field AmBe exposures is shown in Figure 8.

Using the backscatter correction determined for each neutron irradiation location, the scatter-corrected ratio of measured END2 dose rate to expected neutron dose rate plotted against the expected neutron dose rate is shown for units 3 and 9 in Figure 9. Overall, the dose rate response for these END2 units is very good, although a slight over-response is once again observed for both units.

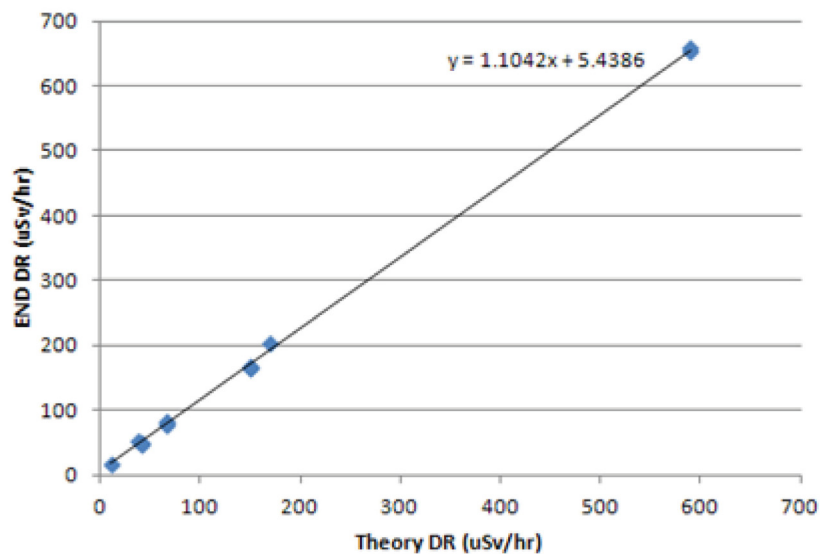


Figure 8: END2 measured to expected neutron dose rate for free-field target room exposures.

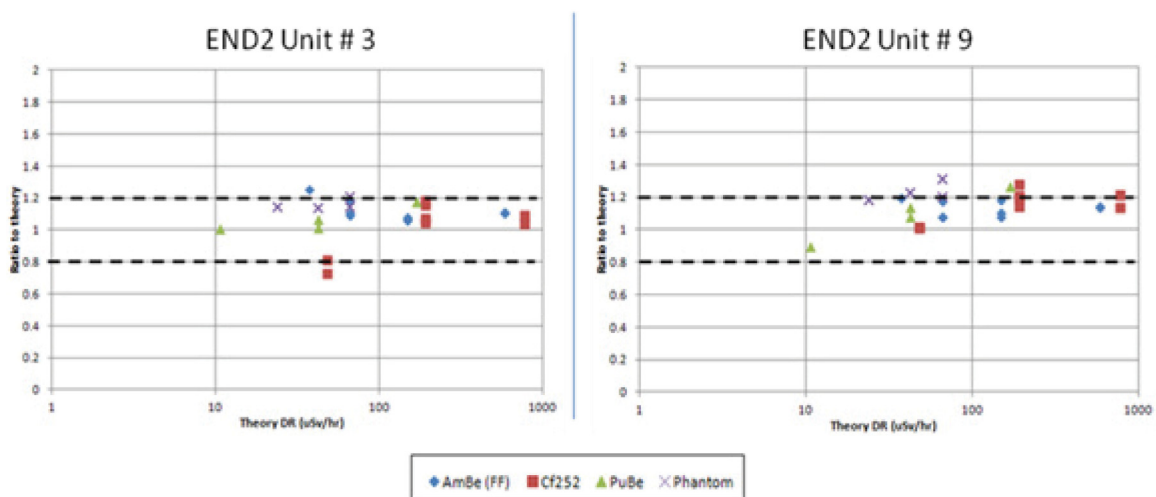


Figure 9: Scatter-corrected END2 dose rate response compared to expected neutron dose rate.

## 4.2 Neutron dose rate repeatability

Multiple neutron dose rate measurements were made for free-field irradiations using both AmBe and PuBe neutron sources in order to assess the repeatability of the reported END2 neutron dose rate. For each neutron source, neutron dose was measured for five identical irradiations (10 minute runs at 2 m for AmBe, 10 minute runs at 1 m for PuBe), as well as one additional longer duration run at the same distance. The results are shown in

Table 1 below, along with the calculated standard deviation of the dose rate. The repeatability of the END2s was very consistent, with an average variation between  $\pm 3.3\%$  to  $\pm 7.3\%$  for all units.

Table 1: END2 neutron dose rate repeatability measurements for all units.

Source	Run #	Unit 2 ( $\mu\text{Sv/hr}$ )	Unit 3 ( $\mu\text{Sv/hr}$ )	Unit 7 ( $\mu\text{Sv/hr}$ )	Unit 9 ( $\mu\text{Sv/hr}$ )	nProbe
AmBe	1	51.6	54.0	69.0	56.4	45.96
	2	51.0	52.8	74.4	53.4	47.94
	3	47.4	49.8	69.0	48.0	45.54
	4	52.2	51.6	69.6	53.4	44.7
	5	52.2	50.4	71.4	49.2	46.74
	6	50.8	52.3	70.7	52.5	47.08
	<i>Avg</i>	<b>50.9</b>	<b>51.7</b>	<b>70.7</b>	<b>52.1</b>	<b>46.3</b>
	<i>Std Dev</i>	<b>2.0</b>	<b>1.7</b>	<b>2.3</b>	<b>3.4</b>	<b>1.2</b>
PuBe	1	-	51.6	-	57.0	46.44
	2	-	56.4	-	61.2	48.96
	3	-	52.2	-	58.2	46.68
	4	-	49.2	-	51.0	46.74
	5	-	55.2	-	61.2	51.66
	6	-	50.6	-	53.6	50.6
	<i>Avg</i>	-	<b>52.5</b>	-	<b>57.0</b>	<b>48.5</b>
	<i>Std Dev</i>	-	<b>2.8</b>	-	<b>4.2</b>	<b>2.2</b>

### 4.3 Response time

END2 response time was assessed by examining the reported END2 and nProbe dose at specified time increments following placement (for rise time assessment) or removal (for fall time assessment) of the PuBe source at a distance of 1 m from the devices. These measurements provide an indication of how long the END2 will take to report neutron dose once a neutron field is entered and to report no dose following removal from the neutron field. The rise time and fall time response of the END2 is shown in Figure 10. The response time of the END2 device is quite slow, requiring approximately 150 seconds for the device to stabilize and report accurate readings.

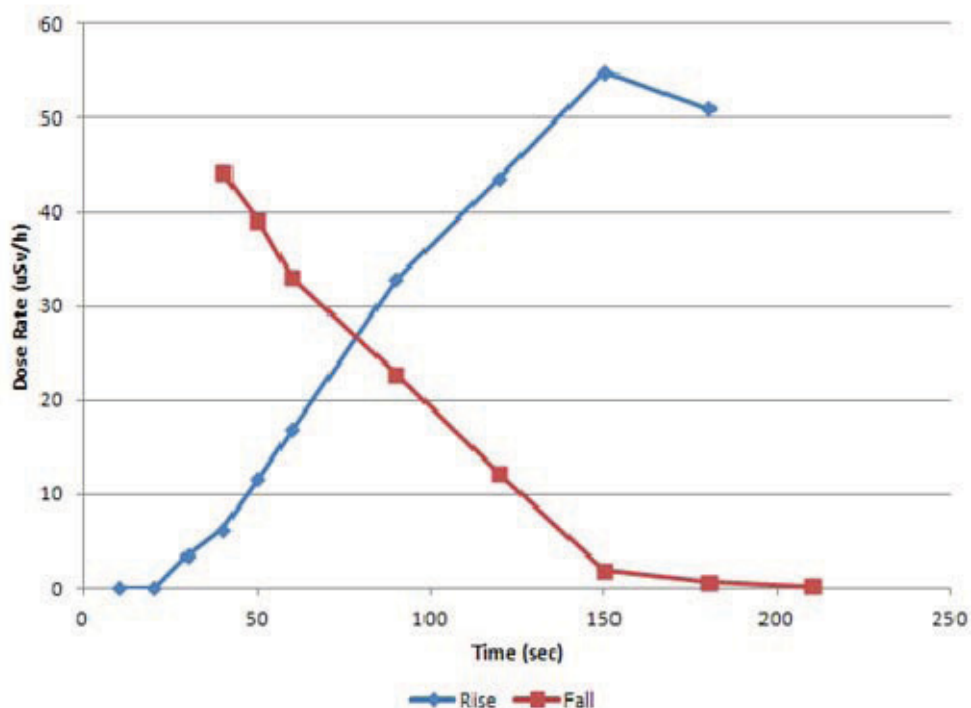


Figure 10: END2 response for exposure to (rise time) and removal from (fall time) a neutron field.

#### 4.4 Gamma dose rate response in a neutron field

Gamma dose rate response of the END2s was assessed for exposure to gamma fields from a variety of neutron sources. The units were irradiated for a preset time and total accumulated doses were used to determine unit response. The ratio of measured to expected dose rate is plotted against the expected dose rate for AmBe and PuBe exposures, both free-field and on-phantom, in Figure 11. Results show that the measured gamma dose is within  $\pm 20\%$  of the expected gamma dose for all END2 devices, except for unit 9, which seems to under respond for most of the exposures.

Due to difficulties in determining the theoretical gamma dose from a  $^{252}\text{Cf}$  source,  $^{252}\text{Cf}$  exposures were instead compared to SVG2 measurements, shown in Table 2. These results show extremely good agreement between END2 and SVG2 reported gamma dose rates, although in all cases the END2 reported a slightly lower gamma dose rate. It is also worth mentioning that SVG2 dose rates were also taken during AmBe and PuBe exposures, and these measurements were significantly higher than the END2 values (about 5x higher for AmBe and 1.4x for PuBe; data not shown). One explanation for this is the possibility of poor END2 neutron/gamma separation for AmBe and PuBe exposures, resulting in the low energy gamma dose being counted as a neutron dose. This would account for the slight over response seen for neutron dose rate response, but certainly does not account for such a large difference in values between the two detectors. This effect will need to be further explored to fully explain the observed response.

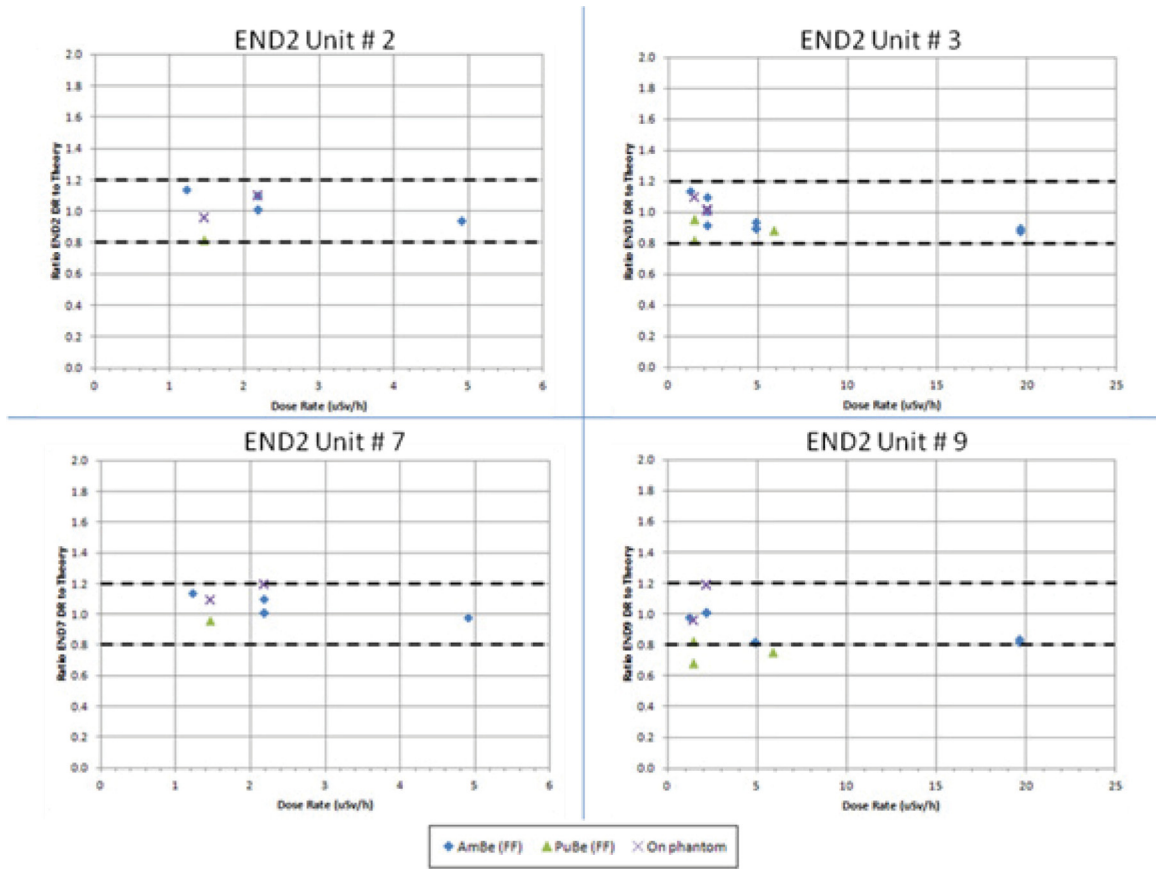


Figure 11: END2 free-field gamma dose rate response to neutron exposures.

Table 2: Comparison of END2 and SVG2 measured gamma dose rates from  $^{252}\text{Cf}$  exposures.

Measured SVG2 dose rate (μSv/hr)	Measured END2 unit 3 dose rate (μSv/hr)	Ratio END2 unit 3 to SVG2 measured dose rate	Measured END2 unit 9 dose rate (μSv/hr)	Ratio END2 unit 3 to SVG2 measured dose rate
2.32	2.2	0.95	2.0	0.86
2.30	2.2	0.96	2.0	0.87
2.23	2.05	0.92	1.99	0.89
8.31	7.9	0.95	7.7	0.93
8.60	7.6	0.88	7.52	0.87
8.80	7.92	0.90	7.6	0.86
8.16	8	0.98	7.48	0.92
28.96	26.8	0.93	27.7	0.96
28.72	26.4	0.92	28.0	0.97

## 4.5 Gamma free-field dose rate response in a gamma field

Gamma dose rate response of the END2 units 3 and 9 was assessed for exposure to both  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  at dose rates spanning 5.0 to 5000  $\mu\text{Sv/h}$ . As a reference, a Thermo SVG2 gamma survey meter was also exposed to the same gamma fields. The devices were irradiated for a preset time and total accumulated doses were used to determine unit response. The ratio of measured to expected dose rate is plotted against the expected dose rate in Figure 12 below. Results show that the free-field gamma dose response of the END2 devices is within  $\pm 20\%$  of the delivered gamma dose and the response is quite flat over three orders of magnitude for gamma dose rate.

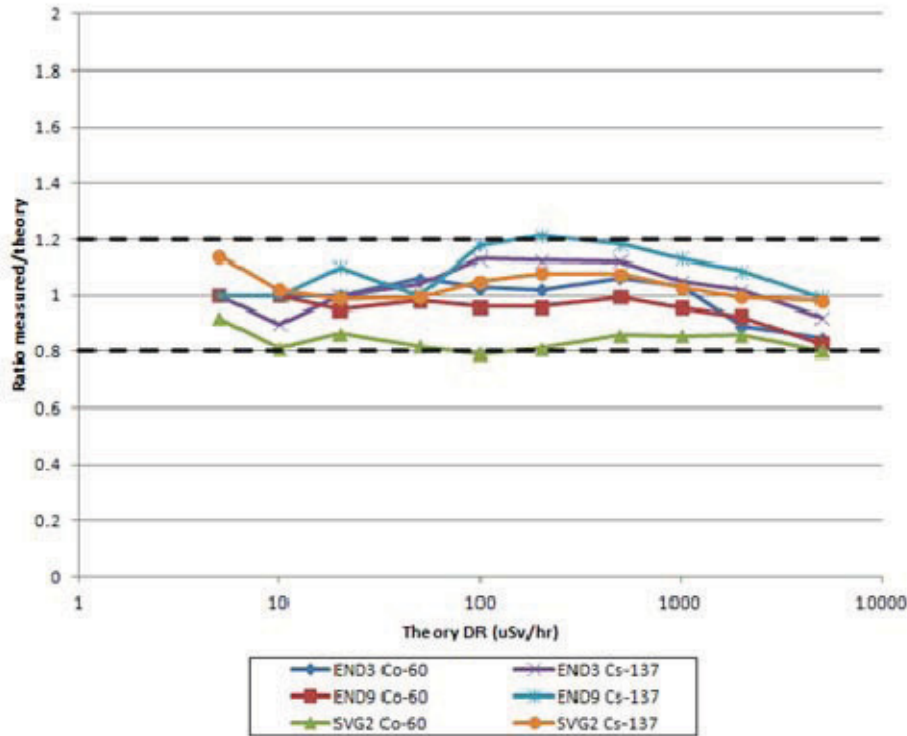


Figure 12: END2 and SVG2 free field gamma dose rate response to  $^{60}\text{Co}$  and  $^{137}\text{Cs}$  exposures.

## 4.6 Neutron and gamma angular response

The END2 unit 3 was exposed to a constant dose rate for both neutron (AmBe) and gamma ( $^{137}\text{Cs}$  and  $^{60}\text{Co}$ ) fields in a vertical orientation, as it would be if worn on the body. The unit was then rotated about the orientation axis, and readings taken every  $45^\circ$  through  $360^\circ$ . A ratio of each data point compared to the  $0^\circ$  reading was then plotted in a Radar plot, shown in Figure 13 for all exposures. The neutron and gamma angular response was very good, with only one exception: a reduction in gamma dose response was observed at the angle adjacent to the epi-thermal neutron sensor, which attenuated gamma rays.

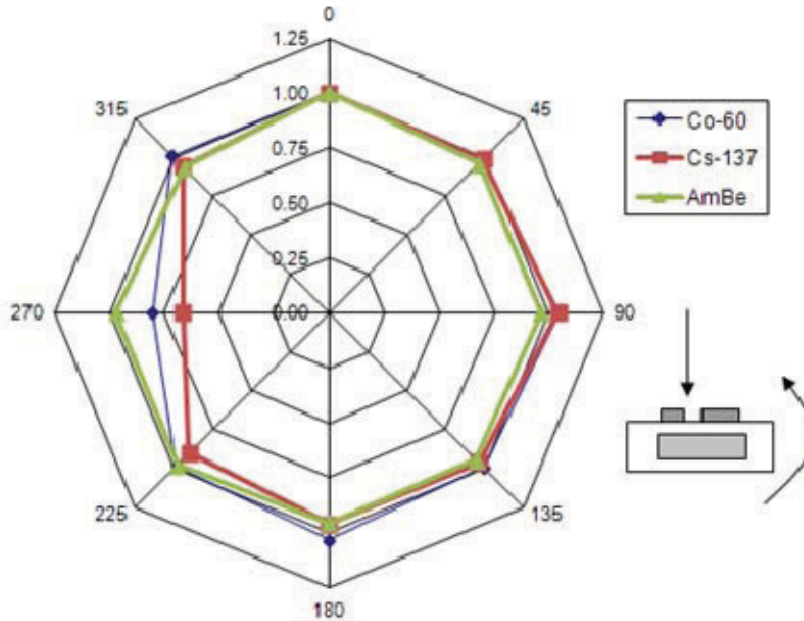


Figure 13: END2 unit 3 neutron and gamma angular response.

## 4.7 Ancillary

### 4.7.1 Alarms

The END2 has four alarm thresholds, two total dose alarms and two dose rate alarms. Alarms are indicated by both beeping and vibration of the unit, as well as an alert message on the LCD. When connected to the computer, the software will highlight the affected alarm with yellow when the first alarm threshold is exceeded and red when the second alarm threshold is exceeded. On the END2 units, the alarm can be acknowledged by pressing one of the buttons, at which point the audible and vibration alarms are ceased while the display alert remains active.

Alarm functionality of END2 unit 3 was tested using the PuBe source at 1 m, achieving a dose rate of 42.3  $\mu\text{Sv/h}$ . As was seen in the response time testing, the END2s take some time to report the actual exposed dose rate. It was, therefore, expected that dose rate alarms would be delayed, depending on the alarm level.

Three separate tests of both the END2 dose rate and total dose alarms were carried out, with a similar response observed for both sets of tests. For the dose rate alarm testing, the first test set the first dose rate alarm threshold to 60  $\mu\text{Sv/h}$  in order to assess whether the unit would give a spurious alarm when the END2 was placed in a dose rate level close to the threshold dose rate. The device functioned as expected with no alarm occurring.

In the second test, the first dose rate alarm threshold was set to 40  $\mu\text{Sv/h}$  to determine if the unit would alarm upon exceeding the dose rate threshold. The alarm (audible beep and pulsed



vibration) was activated after approximately 30 seconds, a significantly shorter time than expected from the previously reported response time of 100s to display the same dose rate. Upon alarm triggering, the displayed dose rate value jumped to 61.1  $\mu\text{Sv/h}$ , while the reference nProbe (in dose rate mode) was displaying approximately 45  $\mu\text{Sv/h}$ . Once the source was removed, the dose rate alarm took approximately 30 seconds to cease, at which point the displayed dose rate was 30  $\mu\text{Sv/h}$ . The jump in displayed dose rate following alarm activation should be noted as a possible firmware fault.

For the third test, the first dose rate alarm threshold was set to 40  $\mu\text{Sv/h}$  and the second dose rate alarm threshold was set to 50  $\mu\text{Sv/h}$ . After approximately 30 seconds of exposure, the first alarm was activated. Activation of the second alarm occurred after approximately 60 seconds from the start of the exposure (i.e. 30 seconds after activation of the first alarm). The displayed dose rate on the END2 following activation of the second alarm was 79.9  $\mu\text{Sv/h}$ , while the dose rate displayed by the nProbe was approximately 45  $\mu\text{Sv/h}$ . The unit was then left alone to see if the dose rate would rectify itself. After 2.5 minutes the reported dose rate was still 78.2  $\mu\text{Sv/h}$ ; after 3.0 minutes, the dose rate fell to 55.3  $\mu\text{Sv/h}$ ; after 3.5 minutes the displayed dose rate was 50.8  $\mu\text{Sv/h}$ . The source was then removed, and the second alarm ceased after approximately 30 seconds, followed by ceasing of the first alarm after an additional 30 seconds. As for the second test, the jump in displayed dose rate following, in this case, activation of both alarms should be noted as a possible firmware fault.

As stated above, the total dose alarms were tested in a similar fashion to the dose rate alarm testing. In these tests, the unit performed with no discernable difference from that noted in the dose rate alarm tests.

#### **4.7.2 Buttons**

The END2 devices have two buttons that are used to turn the unit on and off, to navigate the information on the LCD display, and to acknowledge alarms. The buttons performed their functions as laid out in the operating instructions for the unit. However, they were very difficult to operate, particularly when the unit was at an elevated temperature (i.e. after operation of about 30 minutes). The buttons worked better when the unit was cool. At times, it took a great deal of pressure on the buttons to make them work.

#### **4.7.3 Battery operation and charging system**

The unit was not tested exclusively for battery operation; however, several observations were made pertaining to the charging system and unit operation. When charged for an extended period of time, the units did not indicate 100% charge, instead reporting anywhere between 70-90% charge. When a unit was in the off mode for an extended period of time and then the charger was plugged in, the unit would spuriously turn on; when only off for a short period of time, this did not always occur. Also, when a unit did spuriously turn on, it did not always function properly. On several occasions it was noted that the unit did not report the correct dose or dose rate and the battery light would blink red. In these cases, the unit required being unplugged and reconnected or simply reset, which would result in correct functionality and the battery indication light displaying amber.



#### **4.7.4 Temperature effects**

As described at the beginning of this section, the END2 devices were not tested in the environmental chamber due to problems occurring with the unit “self-heating”. The reason for the excessive internal heat is not known and is a major problem. During the testing described above, a large external fan blowing on the END2 units was necessary in order to keep the END2s cool. This solution worked the majority of the time, although when the room temperature approached 30°C, even the large fan could not keep the units cool enough for them to continue operating.

### **4.8 Results Summary**

Testing of the END2 dosimeters has shown that there are still some significant technical hurdles that need to be overcome before commercialization can be considered. Consistency between the response and functionality of the four devices varied, which poses a concern for successful commercialization. Unexplained intermittent problems exhibited in some of the units are also a problem. However, the devices that did function reliably throughout the testing demonstrated good repeatability of measurements, excellent angular response, and good neutron and gamma dosimetry performance overall, with only slight over and under response reported, respectively. Unfortunately, the units were only able to function within an extremely limited temperature window, requiring the use of a large fan during the operation of the devices in order to overcome internal heating of the units. Issues with alarm, pushbutton, and battery indication functionality were identified requiring further investigation. In addition, the slow response time of the END2 presents a potential issue in terms of radiation safety, as a delay in reporting an elevated neutron dose would equate to an underestimate of neutron dose to the wearer.

Given that current devices for general neutron measurement are much bigger and heavier than the END2, the prototype development indicates a potential breakthrough for neutron detector systems. The additional benefit of yielding a gamma reading is also very important since there are no detectors currently on the market that provide a combined neutron and gamma dose rate measurement. However, the detectors are slightly large for a personal dosimeter system. While BTI did an excellent job in reducing the components to be as compact as possible, the size and weight are still larger than most dosimeters available in the general personal dosimetry market. Also, BTI reported a battery life time of approximately 5 days, which is not long enough for operation of a dosimeter in routine use. However, this represents a compromise between battery performance and device form factor—a larger battery would provide longer lifetime, but would further increase the size of the device. A possible better way-forward for this work may be to develop the technology into a general hand-held detector system instead of a dosimetry device. In fact, a slightly larger enclosure may address some of the temperature problems encountered with the END2.

## **5 Transition and Exploitation**

---

### **5.1 Follow-on Development**

The END2 project significantly advanced the state-of-the-art in neutron and gamma dosimetry technology. However, the technology would still require additional development in order to reach a maturity level suitable for a commercial product. There are two issues that would require further investigations: the device does not currently meet the desired dose accuracy performance over a wide temperature range and some of the devices appear to exhibit an intermittent problem which has not yet been resolved. These issues would need to be addressed before a commercial product could be launched.

### **5.2 Transition to End Users**

As highlighted above, further development of the END2 device is needed prior to commercialization and transition to end users. Two options for pursuing this additional development exist: funding of a third project with R&D funds (i.e. CRTI or other S&T funding sources), or industry development by BTI. Determination of the best approach will need to be made through discussions with BTI and DRDC Ottawa.

### **5.3 Intellectual Property Disposition**

Background intellectual property for this project largely resulted from work done previously at BTI during their past development of neutron detection systems, including the N-probe, and the ROSPEC. Foreground intellectual property resulting from this CRTI funded project, Development of an Electronic Neutron Dosimeter (CRTI-04-0029RD), rests with the Crown, as stipulated in the project charter and contract with BTI. Management and administration of this IP has been handled by DRDC Ottawa and made available to the Project team. Production of an END and commercialization of this IP will be carried out by BTI via the granting of licenses.

## 6 Conclusion

---

The development of the END device has been an extremely challenging task. Initial concepts proposed in the CRTI charter did not work due to physics limitations in trying to extend a technique proven for small cylinders (~3 mm in diameter) to thin fibers (<1 mm in diameter). The reduction in size created serious increases in surface-to-volume ratios which led to technical difficulties that could not be resolved. The design of the END had to be completely revised.

Another approach involving the use of 2 small scintillators, similar to the BTI N-probe but in a miniaturized form, had to be adopted. Fortunately, the prior developments involved the use of identical PMTs as used in the final design and miniature high voltage generators, that were a challenging task in their own right, were largely done. These simplified the undesirable problem of using completely different radiation sensors to continue the END development.

Nevertheless, these complications, which are not uncommon in R&D work, led to unavoidable delays and cost over-runs, which were difficult to accommodate within the CRTI program structure. Thus, the execution of this program, as judged by CRTI metrics, has not been very successful. However, from a technological development viewpoint, the END is undoubtedly a major advancement in terms of high detection sensitivity, good energy dependence over a broad range of neutron energies, and flexibility in terms of performance optimization. Unlike other similar devices, the END is basically a neutron spectrometer in miniature form. Such a task would be immediately recognized as a daunting task for all those who are familiar with neutron detection.

The execution of the final design of the END still encountered some technical difficulties. The most unfortunate was the discovery that tiny PMTs from reputable manufactures had much poorer resolution than conventional (larger) PMTs. Despite the use of “superbright” photocathodes, the resolution was still a factor of 2 worse than expected. According to the manufacturer, this is due to photocathode non-uniformity and the products are already at the limit of their technical capability. The poor resolution made it impossible for us to achieve the desired performance in the energy region below about 500 keV neutrons. Fortunately, neutrons in this region generally contribute only a negligible fraction of the neutron dose. Thus, the performance of END is not significantly compromised by this limitation.

Testing of the END2 dosimeters has shown that there are still some significant technical hurdles that need to be overcome before commercialization can be considered. The END2 testing results demonstrate a broad-range energy response, as well as good accuracy, repeatability of measurements, n/γ rejection, and angular response. However, the size and weight of the END2 prototype exceeds the IEC specifications, and performance is limited to a modest temperature range. Additional investigations would be required to identify a solution or workaround to the temperature-induced performance variations. Nonetheless, the END2 units still provide superior neutron dose accuracy than many existing electronic neutron dosimeters, which typically show spreads of factors of 10 to 100 in measured versus expected dose rates.

The END2 device requires relatively complex electronics in a small form factor. This makes the electronics challenging to design and troubleshoot. The field prototypes were delivered in prototype mechanical enclosures, which provide a representative impression of the overall device

size, but which are not ruggedized. A ruggedized yet lightweight enclosure would require an investment in an injection mould to produce the enclosures. While many improvements to the electronic and mechanical hardware were implemented, additional work would be required to achieve cost-effective manufacturing and high long-term reliability for field operations.

The END2 project significantly advanced the state-of-the-art in neutron and gamma dosimetry technology. The technology would still require additional development in order to reach a maturity level suitable for a commercial product.

## References

---

- [1] Nuclear Regulatory Commission: Regulatory Issue Summary 2007-28, from [http://adamswebsearch.nrc.gov/idmws/DocContent.dll?library=PU\\_ADAMS^pbntad01&LogonID=58838b9b1fed71e0a111a6f09d1f8966&id=073620772](http://adamswebsearch.nrc.gov/idmws/DocContent.dll?library=PU_ADAMS^pbntad01&LogonID=58838b9b1fed71e0a111a6f09d1f8966&id=073620772). Accessed 7 October 2011.
- [2] National Research Council (U.S.) Committee on the Biological Effects of Ionizing Radiations, 2005. Health Risks of Radon and Other Internally Deposited Alpha-Emitters. BEIR IV. National Academy Press, Washington, D.C.
- [3] Luszik-Bhadra, M., 2004. Electronic Personal Dosimeters: The Solution to Problems of Individual Monitoring in Mixed Neutron/Photon Fields? Radiat. Prot. Dosim. **110**, 747-752.
- [4] International Electrotechnical Commission, 2005. Radiation protection instrumentation – Measurement of personal dose equivalents Hp(10) and Hp(0,07) for X, gamma, neutron and beta radiations – Direct reading personal dose equivalent meters and monitor. IEC 61526, Geneva.
- [5] Luszik-Bhadra, M., 2007. Compliance of electronic personal neutron dosimeters with the new international standard IEC61526. Radiat. Prot. Dosim. **125**, 15-18.
- [6] CRTI – Call for proposals: guidebook for fiscal year 2005-2006. CRTI-M-2004-004, November 2004.
- [7] Ing, H. Djeflal, S., Clifford, T., Machrafi, R. and Noulty, R., *Portable Spectroscopic Neutron Probe*, Radiat. Prot. Dosim., Advanced Access published on June 16 (2007) doi:10.1093/rpd/ncm 049.
- [8] Bubble Technology Industries (BTI). *Electronic Neutron Dosimeter (END) Interim Report*, March 31, 2009.
- [9] Larsson, C.L., Jones, T., Voevodskiy, A., Andrews, H. R., and Ing, H., *How does it measure up? An assessment of a new electronic neutron dosimeter*. Radiation Measurements - special edition - proceedings of the 11th Neutron and Ion Dosimetry Symposium, in press, 4 pages.
- [10] McLean, T., *Evaluation of END device at LANL Central Health Physics Calibration Facility*, April 2009.
- [11] Larsson, C. L. and Jones, T., Final testing of a new electronic neutron and gamma dosimeter. DRDC Ottawa TM 2011-199, December 2011, Defence R&D Canada - Ottawa.
- [12] Ing, H. Djeflal, S., Clifford, T., Machrafi, R. and Noulty, R., *Portable Spectroscopic Neutron Probe*, Radiat. Prot. Dosim., Advanced Access published on June 16 (2007) doi:10.1093/rpd/ncm 049.

This page intentionally left blank.

## **Annex A Project Team**

---

This project was led and managed by DRDC Ottawa, with Bubble Technology Industries (BTI) as the prime contractor, and the Canadian Nuclear Safety Commission (CNSC), and the Canadian Joint Incident Response Unit (CJIRU) within Department of National Defence as project partners.

DRDC Ottawa was responsible for preparing all project management documentation, such as the project charter, satisfying CRTI project reporting requirements and managing the CRTI funds supplied to the project. In addition, DRDC Ottawa provided key scientific and technical support, including defining device requirements, provision of their facilities for device testing, and evaluation of the devices.

BTI was responsible for the detailed design and construction of the END, execution of software development, and testing of both the laboratory sub-systems and the completed device. BTI also provided liaison with Los Alamos National Laboratory, who worked in parallel to DRDC Ottawa in testing of the END prototypes.

The Technical and Emergency Programs Division at the CNSC contributed end-user input and device testing to this project. The CNSC's role in first responder training provided invaluable end-user feedback both from the perspective of R/N experts and first responders.

CJIRU provides a dedicated military capability to respond to CBRN terrorist activities as part of the National CBRN Response Team. Their inclusion in this project ensured direct end-user feedback in all phases of the project, providing end-user consultation and project review.

*Table 3: Project team and project review committee (PRC) members.*

<b>Position</b>	<b>Name</b>	<b>Title</b>	<b>Phone Number</b>
Project Champion	Ms. Maria Rey	Director General, DRDC Ottawa	(613) 998-2182
Portfolio Manager	Mr. Ian Summerell	R/N Portfolio Manager, CRTI	(613) 943-2504
Project Manager	Ms. Carey Larsson	Defence Scientist, DRDC Ottawa	(613) 991-4136
PWGSC Representative	Ms. Nancy Dobson	Supply Officer, PWGSC	(819) 956-1198
CNSC PRC Member	Mr. Luc Sigouin	Director, Emergency Management Programs Division, CNSC	(613) 943-7667
CNSC Partner	Mr. Diego Estan	CBRN Program Officer, CNSC	(613) 995-8083
CJIRU PRC Member	LCol Earl Vandahl	Commanding Officer, CJIRU	(613) 392-2811
CJIRU Partner	Sgt. Serge Perrault	Canadian Joint Incident Response Unit	(613) 392-2811 ext. 5132
BTI PRC Member and Partner	Dr. Harry Ing	President, BTI	(613) 589-2456
US Collaborator	Dr. Tom MacLean	Los Alamos National Laboratory	(505) 667-4254



## **Annex B Project Performance Summary**

---

### **B.1 Technical Performance Summary**

The objective of the project was to produce a field prototype electronic neutron dosimeter that also reports gamma dose and meets military and civilian performance standards. Significant engineering work was accomplished during the project and the majority of the design goals were achieved; however, additional development is still required to advance the field prototypes to a commercial-ready state. The current END2 prototypes are assessed to be at a TRL 6. The END2 prototypes achieved design goals of  $\pm 20\%$  dose accuracy for gamma radiation and  $\pm 30\%$  for neutron radiation over a broad energy range, while maintaining small size and weight. Additional development would be required, primarily to improve performance under varying temperature conditions. Other ENDs on the market shows spreads of factors of 10 to 100 in measured versus expected dose, and thus further development of the END2 technology would be warranted given the good performance thus far.

### **B.2 Schedule Performance Summary**

The original, two revised and final schedules for the DRDC Ottawa-led END project are shown in Table 4. Due to the significant technical hurdles encountered during the development process (described in Section 3 above), two revisions to the project charter were required during the course of this project. The first revision occurred in July 2008, due in large part to delays in device testing and a need to roll over funds associated with this activity. The second project charter and schedule revision, occurring in December 2009, was due to the fact that BTI had still not delivered the 2 final working prototypes. At this stage, the follow-on END2 project was well underway, and thus it was decided (officially at a PRC meeting held on 30 Nov 2009 but also in discussions held earlier) to allow the END1 project to remain open until which time BTI could deliver 2 working prototypes to DRDC Ottawa along with 2 additional units for DGNS.

Despite these changes in schedule, the dates for delivery of these devices kept slipping due to additional issues encountered by BTI, until March 31st, 2011 was highlighted as the “drop-dead date” due to the terms of BTI’s contract under END2. When the devices were finally delivered on this date, DRDC Ottawa was then tasked with testing the END devices, which was carried out over the summer of 2011. Despite the identification of continued issues with the END2s, given the significant delays and the large amount of in kind that BTI has already contributed in their development, the decision was made to close out the project.

Table 4: Original, revised, and final END project schedule.

Event	Original Date	Revised Date	2 <sup>nd</sup> revised Date	Final Date
Project Approval-in-principle	Apr 2005	Apr 2005	Apr 2005	Apr 2005
Project Approval	Aug 2005	Aug 2005	Aug 2005	Aug 2005
Project Implementation Begins	May 2005	May 2005	May 2005	May 2005
RFP Release	Aug 2005	Aug 2005	Aug 2005	Aug 2005
Contract Award	Sep 2005	Sep 2005	Sep 2005	Sep 2005
Kickoff Meeting	Sep 2005	Dec 2005	Dec 2005	Dec 2005
Preliminary sub-system testing complete	Mar 2005	Jul 2006	Aug 2006	Aug 2006
Year 1 project review & GO/NO GO decision	Apr 2005	Aug 2006	Aug 2006	Aug 2006
Device packaging complete	Nov 2006	Oct 2007	Oct 2007	Oct 2007
Complete construction of lab prototype	Feb 2007	May 2007	May 2007	May 2007
DRDC-O and LANL lab prototype testing complete	Mar 2007	Oct 2007	Oct 2007	Oct 2007
Year 2 project review meeting and GO/NO GO Decision	Apr 2007	Apr 2007	Nov 2007	Nov 2007
Two field prototypes constructed	Oct 2007	May 2008	Oct 2008	Oct 2008
Presentation at CRTI Summer Symposium	-	Jun 2008	Jun 2006/7/8/9	Jun 2006/7/8/9
Complete DRDC-O and LANL field prototype testing	Feb 2008	Aug 2008	Oct 2008	Apr 2009
Required device modifications complete	Apr 2008	Oct 2008	Jan 2010	Mar 2011
Complete 1st responder testing with CNSC and CJIRU	Jun 2008	Nov 2008	Nov 2009	Aug 2011
Project Close Out Meeting	-	Mar 2009	Mar 2010	Nov 2011
Final Report and Project Complete	Jun 2008	Mar 2009	Jun 2010	Dec 2011

### B.3 Cost Performance Summary

The original and final END project costs for each partner are shown in Table 5. CRTI funds were under spent for this project due to the delays discussed in the previous section, which prevented the device testing to take place in a timely manner. In kind contributions, on the other hand were much greater than projected due to additional development costs, expended by BTI.

*Table 5: END project costs.*

Partner		Projected	Expended	Delta
DRDC Ottawa	CRTI	\$76.7k	\$54.4k	-\$22.3k
	In Kind	\$247.7k	\$280.2k	+\$32.5k
BTI	CRTI	\$603.4k	\$603.4k	\$0
	In Kind	\$150.0k	\$296.6k	+\$146.6k
CNSC	CRTI	-	-	-
	In Kind	\$25.5k	\$1.3k	-\$24.2k
CJIRU	CRTI	-	-	-
	In Kind	\$7.1k	\$2.3k	-\$4.8k
TOTAL	CRTI	\$680.1k	\$657.8k	-\$22.3k
	In Kind	\$430.3k	\$580.3k	+\$150.0k

## **Annex C Publications, Presentations, Patents**

---

Larsson, C. L., 'Development of an Electronic Neutron Dosimeter – Technological Assessment and Way-Ahead'. Oral Presentation. TTCP CBR TP-13 Meeting, February 2004.

Larsson, C. L., et al., 'Development of an Electronic Neutron Dosimeter (END)'. Poster Presentation, Public Security Technical Program (PSTP) Bi-National Radiological Response R&D Workshop, November 2004.

Larsson, C. L., et al., 'Development of an Electronic Neutron Dosimeter'. Funded CRTI Full Project Proposal, March 2005.

Larsson, C. L., 'Development of an Electronic Neutron Dosimeter – Technological Assessment and Way Ahead'. Oral Presentation. NATO RND SG Team of Experts Meeting, September 2005.

Larsson, C. L., et al., 'Development of an Electronic Neutron Dosimeter'. CRTI Extended Abstract, October 2005.

Larsson, C. L., et al., 'Development of an Electronic Neutron Dosimeter'. CRTI Project Charter, October 2005.

Larsson, C. L., et al., 'CRTI-04-0029RD "Development of an Electronic Neutron Dosimeter"'. Extended Abstract, Proceedings of the 2006 CRTI Summer Symposium, June 2006.

Larsson, C. L., et al., 'CRTI-04-0029RD "Development of an Electronic Neutron Dosimeter"'. Poster Presentation, CRTI Summer Symposium, June 2006.

Larsson, C. L., et al., 'CRTI-04-0029RD "Development of an Electronic Neutron Dosimeter"'. Extended Abstract, Proceedings of the 2007 CRTI Summer Symposium, June 2007.

McLean, T., Preliminary evaluation of BTI END prototype device. November 2007.

Ing, H., Larsson, C.L., et al., A new Electronic Neutron Dosimeter (END) for reliable personal dosimetry. SPIE Defense Security and Sensing, March 2008.

Larsson, C.L., et al., CRTI 03-0029RD "Development of an Electronic Neutron Dosimeter". Extended Abstract in Proceedings of the 2008 CRTI Summer Symposium, June 2008.

Larsson, C. L., et al., 'CRTI 04-0029RD "Development of an Electronic Neutron Dosimeter"'. Oral Presentation, CRTI Summer Symposium, Edmonton, AB. June 2008.

Larsson, C.L. and Jones, T., Evaluation of an electronic neutron dosimeter prototype. Testing report. October 2008.

Bubble Technology Industries, Extension of an Electronic Neutron Dosimeter (END) to detect gamma rays (END-2) – Investigation of the Cs<sub>2</sub>LiYCl<sub>6</sub>:Ce<sup>3+</sup> (CLYC) crystal for combined gamma and neutron detection. March 2009.

Bubble Technology Industries, Preliminary conceptual design study for the Extension of an Electronic Neutron Dosimeter (END) to detect gamma rays (END-2). March 2009.

Bubble Technology Industries, Electronic Neutron Dosimeter (END) Interim Report, March 2009

McLean, T., Evaluation of END device at LANL Central Health Physics Calibration Facility, April 2009.

Bubble Technology Industries, Final conceptual design study for the Extension of an Electronic Neutron Dosimeter (END) to detect gamma rays (END-2). June 2009.

Ing, L., Andrews, H.R., and Larsson, C.L., CRTI 04-0029RD "Development of an Electronic Neutron Dosimeter". Oral Presentation, CRTI Summer Symposium, Ottawa, ON, June 2009.

Andrews, H.R., and Larsson, C.L., CRTI 04-0029RD "Development of an Electronic Neutron Dosimeter". Extended Abstract, Proceedings of the 2009 CRTI Summer Symposium, June 2009.

Achtzehn, T., Hugron, R., and Larsson, C.L., Extension of Electronic Neutron Dosimeter (END) to Detect Gamma Rays (END-2). Extended Abstract, Proceedings of the 2009 CRTI Summer Symposium, June 2009.

Achtzehn, T., Hugron, R., and Larsson, C.L., Extension of Electronic Neutron Dosimeter (END) to Detect Gamma Rays (END-2). Poster Presentation, CRTI Summer Symposium, Ottawa, ON, June 2009.

Larsson, C.L., et al., How Does it Measure Up? An Assessment of a New Electronic Neutron Dosimeter. Oral Presentation, 11th Neutron and Ion Dosimetry Symposium, Cape Town, South Africa, October 2009.

Larsson, C.L., et al., How does it measure up? An assessment of a new electronic neutron dosimeter. (U) Radiation Measurements - special edition - proceedings of the 11th Neutron and Ion Dosimetry Symposium, in press.

Bubble Technology Industries, END-II CRTI-07-0190TA – Test results report. March 2010.

Jones, T. and Larsson, C.L., Electronic Neutron Dosimeter II device testing report summary. May 2010.

Hugron, R., Larsson, C.L., and Achtzehn, T., CRTI 07-0190TA "Extension of Electronic Neutron Dosimeter to Detect Gamma Rays". Extended Abstract, Public Security S&T Summer Symposium 2010 proceedings, June 2010.

Jones, T., Larsson, C.L., and Hugron, R., END2 Performance Test Results. Testing report, January 2011.

Bubble Technology Industries, END-II End of Phase III Meeting. February 2011.

Jones, T., Larsson, C.L., and Hugron, R., END2 Final Testing Plan. Experimental plan, March 2011.

Bubble Technology Industries, Extension of an Electronic Neutron Dosimeter (END) to detect gamma rays (END-2) Field Prototype Test Results Report, March 2011.

Bubble Technology Industries, Extension of an Electronic Neutron Dosimeter (END) to detect gamma rays (END-2) Final Report, March 2011.

Hugron, R., Larsson, C.L., and Achtzehn, T., CRTI 07-0190TA "Extension of Electronic Neutron Dosimeter to Detect Gamma Rays". Extended Abstract, Public Security S&T Summer Symposium 2011 proceedings, June 2011.

Larsson, C. L. and Jones, T., Final testing of a new electronic neutron and gamma dosimeter. DRDC Ottawa TM 2011-199, December 2011.

Larsson, C.L., Development of an Electronic Neutron Dosimeter - Project Completion Report for CRTI-04-0029RD. DRDC Ottawa TR 2012-014, May 2012.

DOCUMENT CONTROL DATA		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)		
1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.)  Defence R&D Canada – Ottawa 3701 Carling Avenue Ottawa, Ontario K1A 0Z4	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.)  UNCLASSIFIED (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC JUNE 2010	
3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)  Development of an electronic neutron dosimeter: Project closeout report for CRTI 04-0029RD		
4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)  Larsson, C.L. and Jones, T.		
5. DATE OF PUBLICATION (Month and year of publication of document.)  May 2012	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)  48	6b. NO. OF REFS (Total cited in document.)  12
7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)  Technical Report		
8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)  Defence R&D Canada – Ottawa 3701 Carling Avenue Ottawa, Ontario K1A 0Z4		
9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)  CRTI-04-0029RD	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)	
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)  DRDC Ottawa TR 2012-014	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)	
11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)  Unlimited		
12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.)  Unlimited		

13. **ABSTRACT** (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

**The CBRNE Research and Technology Initiative (CRTI)** funded the project CRTI-04-0029RD “Development of an Electronic Neutron Dosimeter” to produce a prototype electronic neutron dosimeter capable of meeting both civilian and military performance specifications, a feat that has not been achieved by any existing commercial device to-date. Significant technical hurdles were encountered throughout the development process, resulting in large schedule delays and increased development costs. Nonetheless, final prototype devices were delivered and tested, indicating good general performance, although several significant issues were encountered that will require further work to achieve desired performance levels.

L'Initiative de recherche et de technologies CBRNE (IRTC) a financé le projet de l'IRTC-04-0029RD « Développement d'un dosimètre électronique pour les neutrons » pour produire un prototype de dosimètre électronique pour les neutrons capable de répondre à des spécifications de performance à la fois civiles et militaires, un exploit qu'aucun appareil commercial existant à ce jour n'a pu réussir. D'importants obstacles techniques ont été rencontrés tout au long du processus de développement, entraînant des retards et des coûts de développement accrus. Néanmoins, les prototypes finaux ont été livrés et testés, indiquant une bonne performance générale, bien que plusieurs problèmes importants aient été rencontrés qui nécessitent davantage de travail pour atteindre les niveaux de performance souhaités.

14. **KEYWORDS, DESCRIPTORS or IDENTIFIERS** (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

neutron dosimetry; radiological and nuclear terrorism





## **Defence R&D Canada**

Canada's leader in Defence  
and National Security  
Science and Technology

## **R & D pour la défense Canada**

Chef de file au Canada en matière  
de science et de technologie pour  
la défense et la sécurité nationale



[www.drdc-rddc.gc.ca](http://www.drdc-rddc.gc.ca)