Determination of W_{air} value in high energy electron beams

by

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Physics

Specialization in Medical Physics

Ottawa-Carleton Institute for Physics

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Ottawa, Ontario, Canada

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They give me five years five years

It's my turn

[...]

Hope you don't two-time

It'll be the best time

There won't be no next time

It's show time

Sinéad O'Connor, *Jerusalem, The*

Lion and the Cobra, Chrysalis

Records, 1987

Abstract

Purpose: The mean energy expended by a charged particle slowing to a stop in air to create an ion pair, W_{air} , is a key value in radiation dosimetry standards. It is used to convert the charge created into the energy deposited. The ICRU report 90 has reaffirmed the accepted value to be 33.97(12) eV and to be energetically independent above 10 keV. However, a recent publication by Tessier *et al.* (DOI: 10.1002/mp.12660) has shown a possible energy dependence. The present work aims to determine the value of W_{air} in high-energy electron beams and to investigate the assumption that W_{air} is energy independent.

Methods: W_{air} can be evaluated by combining ionometric and calorimetric measurements with a calculated ratio of the absorbed dose in the detectors. Graphite and aluminum detectors were used and the dose ratio was calculated using the EGSnrc Monte Carlo code. A range of average energies at the measurement point were obtained by inserting absorber plates in the primary beam.

Results: The overall standard uncertainty in the determination of W_{air} was approximately 0.5 %, and similar for both sets of detectors. Good agreement was obtained between the two separate experiments, but the data appear to separate into two sets. The smaller (9 points) yielding a value for W_{air} of 33.76(16) eV, consistent with the current consensus value of 33.97(12) eV; the larger (31 points) reproducing the energy dependency observed by Tessier *et al.*.

Conclusion: This investigation cannot rule out a possible energy dependence of W_{air} in high-energy electron beams of -0.18(3) % per MeV. Although not supported by theory, a systematic review of the methods used and the parameters influencing the overall result did not identify any experimental error that could explain the unexpected energy dependence.

Acknowledgments

To my supervisor:

Now I believe in what you say

Is the undisputed truth

*But I have to have things my own way*¹

Thank you for this amazing project, I did enjoy every part of it, even the rabbit hole. To say that you are an incredible supervisor and mentor, would be an understatement.

Frédéric, j'ai rarement rencontré une personne aussi généreuse de son temps et d'esprit. Toutes nos discussions m'ont vraiment aidé pour mon projet, et pas seulement pour le Monte Carlo, merci à l'infini. Kim, thank you very much for your friendship, you may not have directly contributed to the science in this project, but you certainly contribute to my happiness, therefore to the project. John Hanna, thank you very much for the very meticulous work on machining the pieces for this project. I would like to thank Bryan, Claudiu and Feridoun for their help with the project and Steward and James for the comments on the thesis.

To m-35 group:

The bird a nest, the spider a web, (wo)man friendship.

William Blake

Thank you for making me feel like home. I'll miss you all.

¹Supertramp, *Goodbye stranger, Breakfast in America*, A&M Records, 1979

Statement of originality

This thesis summarizes the most significant portions of the author’s research over the course of her doctoral studies. This work has been published in the peer-reviewed papers and conference presentations listed below. Dr. Malcolm McEwen supervised this project, giving input on many aspects of the research, and provided comments on the published manuscript. The author made most of the experimental measurements, performed all of the computational work, analyzed the results, wrote and prepared the manuscript and revised them based on comments from referees.

Peer-reviewed papers

I. A. Bourgouin, C. Cojocaru, C. Ross, and M. McEwen, “Determination of W_{air} in high-energy electron beams using graphite detectors”, *Medical Physics* **46**, 5195 – 5208 (2019).

II. A. Bourgouin, A. Schüeller, R.-P. Kapsch, T. Hackel, R. Kranzer, D. Poppinga, and M. McEwen, “Calorimeter as active detector for dosimetry in ultra-high pulse dose rate electron beams”, *Frontiers in Physics* (2020) under peer review.

Conference abstracts (* indicates presenting author)

I. A. Bourgouin* and M. McEwen, “Ion chamber dose measurements: problems with the temperature-pressure correction factor (P_{TP})”, Oral presentation at the American Association of Physicists in Medicine (AAPM) Meeting, Washington, D. C., U. S., Aug. 2016.

II. A. Bourgouin* and M. McEwen, “Vacuum current: a possible systematic error in absolute dose/kerma measurements with ion chambers”, Oral and poster present-

ation at the Council on Ionizing Radiation Measurements and Standards (CIRMS) Meeting, NIST, Gaithersburg, Maryland, U. S., Mar. 2017. Won first place of the Student Grant Awards Program.

III. A. Bourgouin* C. Cojocaru, C. Ross and M. McEwen, “Challenges in measuring absorbed dose with a simple open-to-atmosphere graphite calorimeter”, Oral presentation at the Canadian Organization of Medical Physicists (COMP) Meeting, Ottawa, Ontario, Canada, Jul;. 2017.

IV. A. Bourgouin* C. Cojocaru, C. Ross and M. McEwen, “Investigation of the energy dependence of W_{air} in high energy electron beams”, Oral and poster presentation at the Council on Ionizing Radiation Measurements and Standards (CIRMS) Meeting, NIST, Gaithersburg, Maryland, U. S., Apr. 2018. Won first place of the Student Grant Awards Program.

V. A. Bourgouin* C. Cojocaru, C. Ross and M. McEwen, “Investigation of the energy dependence of W_{air} in high energy electron beams”, Oral presentation at World Congress on Medical Physics & Biomedical Engineering (IUPESM) Meeting, Prague, Czech Republic, Jun. 2018.

VI. A. Bourgouin* C. Cojocaru, C. Ross and M. McEwen, “Improving radiation dosimetry through an investigation of the mean energy required to create ionisation in dry air.”, Oral presentation at Women in Physics Canada (WIPC) Conference, Sherbrooke, Canada, July. 2018.

VII. A. Bourgouin* and M. McEwen, “Determination of W_{air} in high-energy clinical electron beams using Aluminum detectors.”, Oral and poster presentation at the Council on Ionizing Radiation Measurements and Standards (CIRMS) Meeting, NIST, Gaithersburg, Maryland, U. S., Apr. 2019. Won fourth place of the Student

Grant Awards Program.

VIII. A. Bourgouin* and M. McEwen, “Determination of W_{air} in high-energy clinical electron beams using aluminum detectors”, Oral presentation at the International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS-2019) at the International Atomic Energy Agency Headquarters, Vienna, Austria, Jun. 2019.

IX. M. McEwen*, A. Bourgouin and A. Schüeller “Investigation of a Simple Calorimeter Design for the Dosimetry of Ultra-High Pulse Dose Rate (FLASH) Electron Beams”, Oral presentation at the 2020 Joint AAPM—COMP Virtual Meeting, July. 2020

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Table of Symbols

$\beta, \beta(T)$	thermistor sensitivity parameter, see Equation 4.5
ΔR	change in resistance in one arm of the AC bridge
ΔR_{th}	change in the combined resistance of the thermistors in the calorimeter
Δt	defined duration of time
ΔT	radiation-induced temperature rise in the calorimeter core
ΔV_{out}	calorimeter bridge output (voltage)
ϵ_{im}	energy imparted
ρ	density of the medium in question
c_{al}	specific heat capacity of aluminum
C_{gen}	coefficient of general (volume) recombination
c_{gr}	specific heat capacity of graphite
C_{init}	constant of initial ion recombination
c_{med}	specific heat capacity of a medium
D_{air}	absorbed dose deposited in the sensitive volume of the ion chamber
D_{med}	absorbed dose deposited/measured in a dense medium
D_w^Q	absorbed dose to water for a specific radiation beam of quality Q
$(\overline{\mu_{\text{en}}}/\rho)_{\text{wall}}^{\text{air}}$	spectrum averaged ratio of mass energy absorption coefficients
$(D_{\text{air}}/D_{\text{med}})_{\text{MC}}$	Monte Carlo-calculated absorbed dose ratio
E	energy
E_{max}	maximum energy of the electron spectrum
$\bar{g}_{\text{air}}$	fraction of the secondary charged particle energy lost through radiative events
I	lowest ionization potential of a particle
I_{gr}	mean excitation potential of graphite

$K_{\Omega/\text{mV}}$	conversion coefficient between bridge output ΔV_{out} and the thermistor resistance change ΔR_{th}
K_{air}	air kerma (the kinetic energy transfer from ionizing uncharged particles to charged particles)
k_{dd}	correction factor for non-uniformity in lateral dose profile
k_{hc}	correction factor for conductive heat loss
k_{HD}	correction factor for the heat defect in the calorimeter medium
k_{hum}	humidity correction factor
k_{hv}	correction factor for convective heat loss
$k_{\text{n-gr}}$	correction factor for non-graphite material within the calorimeter core
$k_{\text{n-med}}$	correction factor for components within the calorimeter core made of a different material than the core
k_{p}	perturbation of the radiation field due to non-homogeneity of the detector
k_Q or k_{Q,Q_0}	beam quality conversion factor
$(\bar{L}/\rho)_{\text{hum}}^{\text{air}}$	ratio of the mass electronic stopping powers of dry air to humid air
$(\bar{L}/\rho)_{\text{air}}^{\text{wall}}$	ratio of the mass electronic stopping powers of the ion chamber wall material to dry air
$(\bar{L}/\rho)_{\text{air}}^{\text{water}}$	ratio of the mass electronic stopping powers of water to dry air
m_{air}	mass of dry air in the sensitive volume of the ion chamber
m_{hum}	mass of humid air in the sensitive volume of the ion chamber
N	number of . . .
n_{ϵ}	number of particles of energy ϵ in the cavity
$N_{D,w}^{60\text{Co}}$	calibration coefficient that converts the reading of an ion chamber to the absorbed dose to water in a reference ^{60}Co beam
P	pressure
P_{cel}	correction factor for the presence of the ion chamber central electrode

P_{repl}	correction factor which accounts for the radiation perturbation, fluence and gradient, from the presence of the air cavity of the ion chamber
P_{wall}	correction factor for the presence of non-water equivalent material of the wall of the ion chamber
P_{elec}	correction factor for the electrometer efficiency
P_{ion}	ion recombination correction factor
P_{leak}	correction factor for ion chamber leakage
P_{MCp}	correction factor for the effect on the dose deposited due to a change in pressure (calculated using Monte Carlo)
P_{pol}	polarity correction factor
P_{rp}	correction factor for the lateral variation of the beam intensity profile
P_{SEE}	slow electron emission correction factor
P_{TP}	correction factor for the change in density of the air in the ion chamber cavity from reference conditions (commonly referred to as the temperature-pressure correction)
P_m	air pressure within the cavity of the ion chamber during measurement
Q	beam quality
Q_{VC}^-	vacuum current measured for negative charge collected
Q_{VC}^+	vacuum current measured for positive charge collected
$Q_{(p)}$	raw charge measurements for a cavity pressure p
$Q_{(p_0)}$	raw charge measurements at the reference pressure p_0 101.325 kPa
Q_{air}	charge created by ionizing particles in the sensitive volume of the ion chamber (fully corrected, dry air)
Q_{hum}	charge created by ionizing particles in the sensitive volume of the ion chamber (fully corrected, humid air)
Q_{pp}	charge created in the ion chamber per linac pulse
Q_{raw}	raw ion chamber charge measurement

Q_{raw}^-	raw measurement for negative charge collection
Q_{raw}^+	raw measurement for positive charge collection
Q_{sat}	ideal charge reading that would be obtained without ion recombination
Q_{VC}	vacuum current
Q_0	reference beam of quality
Q_H	measured charge for a high polarizing voltage applied between the ion chamber electrodes (two voltage technique to determine P_{ion})
Q_L	measured charge for a low polarizing voltage applied between the ion chamber electrodes (two voltage technique to determine P_{ion})
$R_{\text{precision}}$	precision fixed resistor in the AC bridge for calorimeter read-out
R_{var}	precision variable resistor in the AC bridge for calorimeter read-out
R_0	resistance of the thermistor beads at the reference temperature
R_1	precision resistor #1 in calorimeter bridge
R_2	precision resistor #2 in calorimeter bridge
R_{th}	combined resistance of the two thermistors in the calorimeter core
S	sensitivity of the thermistor
S_ϵ	energy spectrum of the particles going through the cavity
T	temperature
T_m	temperature of air in the ion chamber during measurement
T_0	reference temperature
V_H	high polarizing voltage applied between the ion chamber electrodes (two voltage technique to determine P_{ion})
V_L	low polarizing voltage applied between the ion chamber electrodes (two voltage technique to determine P_{ion})
$w_{\text{air},\epsilon}$	differential form of W_{air}
W_{air}	mean energy required to create an ion pair in dry air as electron slows to a stop

W_{hum} mean energy required to create an ion pair in humid air as electron slows to a stop

Table of Abbreviations

AAPM	American Association of Physicists in Medicine
ALECS	NRC-built symmetric plane-parallel aluminum ion chamber
BIPM	Bureau International des Poids et Mesures
C552	Air-equivalent plastic
CIRMS	Council on Ionizing Radiation Measurements and Standards
CMM	Coordinate-measuring machine
COMP	Canadian Organization of Medical Physicists
CPE	charged particle equilibrium
DFS	Design and Fabrication Services (branch of the NRC)
DMM	Digital Multimeter
ECUT	Electron kinetic energy cut-off (EGSnrc)
EGSnrc	A software toolkit to perform Monte Carlo simulation developed and maintained at the NRC
FAC	Free-Air Chamber
FEM	Finite element method
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Units and Measurements
IDOS	International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry
IRS	Ionizing Radiation Standards (branch of the NRC)
IUPESM	International Union for Physical and Engineering Sciences in Medicine
<i>I</i> -value	The mean excitation potential
KEL-F [®]	PCTFE (polychlorotrifluoroethylene)
Kerma	Kinetic Energy Released per MAss

LET	Linear energy transfer
linac	Linear accelerator
MARKIII	NRC-built symmetric plane-parallel graphite ion chamber
NIST	National Institute of Standards and Technology
NPL	National Physical Laboratory
NRC	National Research Council Canada
NTC	Negative-Temperature-Coefficient (thermistor probes)
PCUT	Photon kinetic energy cut-off (Monte Carlo)
PEEK®	Polyether ether ketone
PMMA	Poly(methyl methacrylate)
PTW	Physikalisch-Technische Werkstätten (company)
Python	Programming Language
SDD	Source-to-detector distance
SPR	Stopping power ratio
TG-21	AAPM task-group protocol number 21
TG-51	AAPM task-group protocol number 51
TRS-277	IAEA International Code of Practice report number 277
TRS-398	IAEA International Code of Practice report number 398
WIPC	Women in Physics Canada

Chapter 1: Introduction

Les gens aiment bien quand ça fait mal, Et y a pas de mal à s'faire du bien

Jean Leloup¹

The primary characterization of ionizing radiation is its ability to ionize the matter through which it passes. It can be directly ionizing, such as a proton or electron, or indirectly ionizing, such as photon and neutron. The parameter that describes how much energy is required to create an ionization event in a specific material is the W -value, and W_{air} is, therefore, the mean energy required to create an ion pair in dry air as it slows to a stop.

The parameter W_{air} is very important in radiation dosimetry because one of the oldest and most widely used detectors is the air-filled ionization chamber. An ion chamber is the less-sensitive relative of the Geiger-Müller tube and is very useful because the obtained signal is directly proportional to the energy deposited in the air cavity of the chamber. Energy deposited is the quantity of interest in the majority of applications of ionizing radiation, because it is the energy (or more correctly the energy density, referred to as the absorbed dose) that drives chemical and biological effects. For example, in radiation therapy, where ionizing radiation is used to treat cancerous tumours in the body, the absorbed dose is a good physical analogue for the biological damage caused in human tissue. Ion chambers can be used to detect

¹Jean Leloup, *Faire des enfants, Le Dôme*, Audiogram, 1996

and characterize these beams used for radiation therapy, and the link between the charge that can be measured with a chamber and the energy is the parameter W_{air} .

This parameter features in many of the primary air-kerma standards and absorbed-dose standards operated by National Measurement Institutes. In the area of radiation therapy, the field where the highest accuracy dose measurements are required, these standards are disseminated through calibration chains and dosimetry protocols to end users in cancer centres, where air-filled ionization chambers are used to characterize the output of radiation devices prior to patient treatment. As a result, W_{air} has been the focus of research for decades and has been extensively measured for low-energy beams, under 2 MeV, for both photon and electron sources. Measurements in high-energy beams (where the majority of radiation therapy treatments are currently delivered) are lacking, with only one data set published, each, for high-energy electron and photon beams as shown in Table 5.6 of ICRU report 90 [1]. The underlying theory for how W_{air} should vary with particle energy suggests that it should be a constant for particles with energies above 10 keV, and the majority of the experimental data in the literature confirms this. However, a recent publication has suggested a possible energy dependency, up to 2 %, of W_{air} for electron beams with energies greater than 5 MeV [2].

This apparent inconsistency between the presently-understood theory of the energy dependence of W_{air} and this recent publication, combined with the lack of accurate data for energies above 2 MeV, is the catalyst for this project. W_{air} is a key value in radiation dosimetry, affecting both air-kerma and absorbed dose measurements and impacting application areas from radiation protection to industrial dosimetry, but with a specific focus on the dosimetry of radiation therapy beams. W_{air} can be viewed as one of the “fundamental constants” of ionizing radiation dosimetry and therefore it is very important to determine both its absolute value and

its energy dependence in the region of interest for practical applications. The aim of this PhD project is to determine W_{air} for a range of high-energy electron beams.

The layout of this thesis is as follows. In Chapter 2, the rationale of this project will be presented, along with the theory of how W_{air} can be determined and the design constraints for detectors. Chapter 3 is an investigation of a contaminant electrical current that could potentially have a significant impact not only on the determination of W_{air} , but also for ionization chamber dosimetry in general. Chapters 4 and 5 present the method, materials and results for the first part of the W_{air} project, which used graphite detectors. Chapter 6 presents an improved experiment to determine W_{air} , building on what was learnt in the first investigation, using aluminum detectors instead of graphite. The data is synthesised in Chapter 7 and compared with the current understanding and the conclusions of the project, including suggestions for future work, are given in Chapter 8.

The project to measure W_{air} at the National Research Council Canada (NRC) predated this thesis work and measurement data had already been acquired prior to the author joining the project. The author was involved in obtaining all of the results presented in this thesis, although not always to the same degree. The following paragraphs detail the contributions made by research and technical staff in the Ionizing Radiation Standards group at NRC, and place the significant contributions of the author within the overall project.

An initial, limited, investigation into ion chamber responses at reduced air pressures (Chapter 3) was carried out by McEwen *et al.* [3] and their results for the MARKIII graphite-walled ionization chamber are presented in Figure 3.7. The author is solely responsible for all the other ion chamber data presented and has reanalyzed all experimental data to provide a consistent analysis of results.

The measurements using graphite detectors, described in Chapter 4, were acquired prior to the author joining the project (in fact, these first results were the impetus for the PhD). The graphite ion chamber, type MARKIII, was designed, constructed and commissioned by Dr W.(Bill) H. Henry and Mr. George Smith in the 1970s. The graphite calorimeter was constructed by Dr. Malcolm McEwen and the measurement data comparing the calorimeter and ion chamber in electron beams from the NRC Vickers linac were acquired by Dr. Malcolm McEwen, Dr. Claudiu Cojocaru and Dr. Carl Ross. The last two authors also carried out the first thermal simulations, using an energy source calculated using EGSnrc and FEM calculations using FlexPDE. The author took over all the analysis at this point, and looked at all aspects of the equation required to determine W_{air} : calculation of the calorimeter/ion chamber dose ratio; more detailed thermal simulations using both FlexPDE and COMSOL; validation of the Monte Carlo geometry (Fano test); development of algorithms using Python to consistently analyze calorimeter data; and a detailed sensitivity analysis.

The author was responsible for the re-design of the experiment, as described in Chapter 6, and provided detailed guidance to the expert machinists from the NRC Design and Fabrication Services (DFS) – Luc Martin and John Hanna. Hugo Breton was responsible for digitization of the original 1970s blueprints, on which the new ion chamber design was based. The calorimeter was entirely assembled by the author, after discussions with David Marchington. The aluminum ion chamber was assembled by the author with assistance from Feridoun Farahvash for the critical step of a reliable electrical connection. All of the experimental data using the aluminum detectors was acquired solely by the author and, as for the graphite data, they were responsible alone for all the analysis and calculation steps to yield a value of W_{air} .

Chapter 2: Theory and Method

*The place where I come from is a small town, They think so small,
They use small words, But not me*

Peter Gabriel¹

2.1 W_{air} , definitions and reference dosimetry

The mean energy expended by a charged particle to create an ion pair in dry air as it slows to a stop, W_{air} , is defined by the International Commission on Radiation Units and Measurement (ICRU) report 31 [4] as the total number (N) of ion pairs set in motion in an air cavity by a charged particle that expends all its kinetic energy (E) in the cavity.

$$W_{\text{air}} = \frac{E}{N}. \quad (2.1)$$

The report also defines its differential form, $w_{\text{air},\epsilon}$, to be the ratio of the kinetic energy loss (dE) and the number of ion pairs created (dN) by an ionizing particle of energy E passing through a volume of matter of thickness dx .

$$w_{\text{air}} = \frac{dE}{dN}. \quad (2.2)$$

¹Peter Gabriel, *Big Time, So*, Geffen Records, 1986.

The relationship between W_{air} and the differential form $w_{\text{air},\epsilon}$ is given by the following equation:

$$W_{\text{air}} = E / \int_I^E \frac{d\epsilon}{w_{\text{air},\epsilon}}, \quad (2.3)$$

where ϵ is the instantaneous energy of the particles that go through dx losing dE energy and I in this equation is the lowest ionization potential.

W_{air} is a key value in both air kerma and absorbed dose standards formalisms, as it will be shown in the following equations. W_{air} converts the number of charges created by ionization of air (the measured quantity) into the energy imparted, ϵ_{im} , that the charge particles expended (quantity of interest). The quantity obtained during ionometry is therefore the dose deposited through W_{air} and is defined by the following equation:

$$D_{\text{air}} = \frac{d\epsilon_{\text{im}}}{dm} = \frac{Q_{\text{air}} W_{\text{air}}}{m_{\text{air}}}, \quad (2.4)$$

where D_{air} is the dose deposited by the ionizing particles in the sensitive volume of the ion chamber, Q_{air} is the charge created and m_{air} is the mass of the sensitive volume. The Equation 2.4 is the fundamental equation of ionometric measurement.

The air kerma, K_{air} , is the Kinetic Energy Released per MAss by an indirectly ionizing particle (uncharged particle; photon or neutron). The relationship between the energy released, or transferred, and the energy imparted is through the fraction of the secondary charged particle energy lost in radiative events (primary energy transferred to secondary charge particles that leave the sensitive volume through tertiary uncharged particles). For a low-energy photon beam, the air kerma is measured using free-air chambers (FAC). These ion chambers are designed so the wall of the chamber does not affect the measurement. The other consideration for these ion chambers is to create charged particle equilibrium (CPE), i.e. all the secondary charged particles of energy ϵ leaving the detector's sensitive volume will be replaced

by the same type of particle with an energy ϵ created outside the sensitive volume. A FAC diagram is illustrated in Figure 2.1.

Figure 2.1: Diagram of a free-air chamber. The secondary electron e_2 set in motion by a primary photon in the sensitive volume (grey area) is replaced by a secondary electron emitted from outside the sensitive volume (e_1). The electron e_1 enters the sensitive volume with the same energy as e_2 left it (illustration of CPE). The ions created by the ionization of air from the secondary electron e_1 are going toward opposite electrodes due to the presence of an electric field. Note that the direction of the positive and negative ion could be reversed, depending on the polarizing voltage.

If CPE conditions are fulfilled, the energy imparted is equal to the energy transferred, and therefore, the air kerma for FAC is calculated using the following equation:

$$K_{air} = \frac{D_{air}}{(1 - \bar{g}_{air})} = \frac{Q_{air}}{m_{air}} W_{air} \frac{1}{(1 - \bar{g}_{air})} \Pi K, \quad (2.5)$$

where Q_{air} is the charge created by the ionization of air, m_{air} is the mass of the irradiated sensitive volume, ΠK are correction factors and $\bar{g}_{air}$ is the fraction of the secondary charged particle energy lost in radiative events, the interaction resulting in the creation of a photon that escapes the cavity.

For higher-energy photon beams such as ^{60}Co beam, the use of a FAC ion chamber is no longer practical due to the range of the secondary electron. The photons emitted from the ^{60}Co source have an energy of 1.17 MeV or 1.33 MeV. The dominant interaction for this energy range is the Compton effect and the energy transfer to the secondary electron can be approximated on average to half of the initial photon energy [5], about 0.6 MeV which has a range of three meters [6] in air. For such a beam, a cavity chamber is used, however, the particles do interact with the ion chamber wall and therefore the equation is more complex than for the FAC ion chamber. The air kerma formalism for ^{60}Co beam using cavity ion chamber is:

$$K_{\text{air}} = \frac{Q_{\text{air}}}{m_{\text{air}}(1 - \bar{g}_{\text{air}})} W_{\text{air}} \left(\frac{\bar{L}}{\rho} \right)_{\text{air}}^{\text{wall}} \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_{\text{wall}}^{\text{air}} \Pi K, \quad (2.6)$$

where Q_{air} and m_{air} and $\bar{g}_{\text{air}}$ are the same as defined earlier. $(\bar{L}/\rho)_{\text{air}}^{\text{wall}}$ is the ratio of the mass electronic stopping powers of the ion chamber wall material to dry air. $(\overline{\mu_{\text{en}}}/\rho)_{\text{wall}}^{\text{air}}$ is the ratio of mass energy absorption coefficients ratio of dry air to wall material and ΠK are correction factors.

The Equation 2.6 is directly used in primary standards of air kerma and dosimetry formalisms based on such standards (e.g. AAPM TG-21 [7] protocol and IAEA TRS-277 [8]). However, the absorbed dose formalism (e.g. AAPM TG-51 protocol (1999) [9] and IAEA TRS-398 (2000) [10]) which related the ion chamber charge created by ionization of air, Q_{air} , to the dose in water, D_w^Q , for a specific radiation beam of quality Q use the following equation:

$$D_w^Q = Q_{\text{air}} k_Q N_{D,w}^{60\text{Co}}, \quad (2.7)$$

where Q_{air} is the charge created, $N_{D,w}^{60\text{Co}}$ is a calibration coefficient that converts the charge released in the air cavity to the dose in water for the reference ^{60}Co beam. The k_Q , or k_{Q,Q_0} , conversion coefficient transforms an ionization chamber calibration

coefficient obtained in one radiation quality (usually ^{60}Co) for use in a clinical beam of quality Q .

It is in this latest conversion factor that W_{air} is implicitly included as a ratio of W_{air} values for the two beams in question. The k_Q factor can be measured, or calculated using the following equation where W_{air} is explicitly shown:

$$k_Q = \frac{\left[W_{\text{air}} \left(\frac{\bar{L}}{\rho} \right)_{\text{air}}^{\text{water}} P_{\text{wall}} P_{\text{repl}} P_{\text{cel}} \right]_Q}{\left[W_{\text{air}} \left(\frac{\bar{L}}{\rho} \right)_{\text{air}}^{\text{water}} P_{\text{wall}} P_{\text{repl}} P_{\text{cel}} \right]_{^{60}\text{Co}}}, \quad (2.8)$$

where $\left(\frac{\bar{L}}{\rho} \right)_{\text{air}}^{\text{water}}$ is the ratio of the restricted mass electronic stopping powers of the ion chamber water to dry air, P_{wall} is the wall correction factor for the presence of non-water equivalent material of the ion chamber in the beam. P_{repl} , the replacement correction factor, used to account for the radiation perturbation (fluence and gradient) from the presence of the air cavity of the ion chamber at the point of measurement. P_{cel} is the correction factor to account for the presence of the ion chamber central electrode.

The air kerma formalism directly depends on the absolute value of W_{air} as shown in Equation 2.5 and 2.6. The dependence of the absorbed dose to water formalism on W_{air} value is relative as shown in Equation 2.8. If W_{air} is the same for both beams of quality Q and Q_0 , then the absolute value of dose measurement using a calibrated ion chamber does not depend on the absolute value of W_{air} . On the other hand, if W_{air} does depend on the energy (or quality) of the beam, the variation of W_{air} would impact the absorbed dose to water measurement accuracy, depending on the method used to obtain the k_Q factor. While a measured k_Q would directly take account of any W_{air} energy dependency, a calculated k_Q [11, 12] factor would not *unless explicitly included*. The addendum to TG-51 (2014) [13] uses Monte-Carlo-calculated k_Q factors and includes the assumption that W_{air} has no energy dependency above 10 keV.

It should be noted that in all the discussions of W_{air} and its application to reference dosimetry, the composition of air is assumed to be constant, with any variation having an insignificant impact on the energy required to produce an ion pair. The only exception is the water vapour content (humidity), which is discussed later.

2.2 Literature review

The International Commission on Radiation Units and Measurements, ICRU, carried out a critical review of the key data used for ionizing radiation dosimetry and summarized the results in ICRU Report 90 (2016), Key Data for Ionizing-Radiation Dosimetry: Measurement Standards and Applications [1]. The report has reaffirmed the accepted value of W_{air} to be 33.97(12) eV for electron energies above 10 keV. The W_{air} value is considered to follow an asymptotic equation with a constant value for high-energy particles [14]. Therefore, the report indicates that this “constant” of radiation dosimetry does not depend on the incident beam energy above 10 keV since there is no theoretical nor experimental evidence to the contrary. The ICRU Report 90 has adopted the following equation, firstly proposed by Buhr *et al* (2012) [15]:

$$W(T) = \frac{W_{\infty}}{1 - (T/A_1)^{A_2 + A_3 T}}, \quad (2.9)$$

where $A_1=14.393(18)$ eV, $A_2=-0.8179(87)$, $A_3=-3.4(1.5)\times 10^{-5}$ [1] and T is the kinetic energy of the particle in eV. The W_{∞} is by definition the value of W_{air} , 33.97(12) eV, measured in a ^{60}Co beam and remains constant above this energy. The equation is shown in the Figure 2.2 along with the published data sets on which the equation is based. As it can be seen in Figure 2.2 and in Equation 2.9, W_{air} has an energy dependency at low energy, under 10 keV. The energy dependency comes from the stochastic nature of radiation, when the energy of the particle comes closer to the W_{air} value, as it is an average value, there is a chance that the particle would not

create an ion pair. The opposite is possible too, a particle with lower energy than 33.97(12) eV could produce an ion pair.

The obtained Equation 2.9 is based on three sets of data published for energy below 10 keV and 17 published W_{air} values using beta and gamma sources and high-energy beams (three measurements using ^{35}S , one measurement using ^{137}Cs , nine measurements using ^{60}Co , four measurements using a high-energy photon and electron beam). From the listed measurements of table 5.6 [1] of the ICRU Report 90, it can be noted that W_{air} was mostly measured in ^{60}Co and only two published data sets were from investigations at higher energies.

Figure 2.2: The published results of W_{air} value on which Equation 2.9 is based. References; Combecher [16], Waibel and Grosswendt [17], Büermann *et al.* [18], ^{35}S beta rays [19], ^{137}Cs gamma rays [20], ^{60}Co gamma rays [19–21], Burns *et al.* [22] and the empirical fit [1].

Burns *et al.* [22] have measured W_{air} using a combination of a vacuum-sealed graphite calorimeter and graphite-walled ion chamber in MV photon beams, as part of an investigation of primary absorbed dose standards. They obtained a constant

value of 34.04(7) eV. However, since they used MV photon beams, the average energy of the electrons depositing energy in the ion chamber sensitive volume was quite low, a few MeV. The value of W_{air} obtained by Cojocaru and Ross in high-energy electron beams was based on a reanalysis of a set of measurements published in the 1970s [23]. This data set was initially reanalyzed by Svensson and Brahme [24] and will be discussed below.

In 1986, Svensson and Brahme [24] extracted a value of W_{air} from a reanalysis of measurements obtained by Domen and Lamperti [23]. The original data were the measured ratios of a graphite calorimeter and graphite ionization chamber in high-energy electron beams, from 15 MeV to 50 MeV (incident energy), with various buildup thicknesses. Svensson and Brahme found a 2 % variation of W_{air} in the electron energy range investigated. As mentioned earlier, there is no theoretical reason to believe that W_{air} would be dependent on particle energy above 10 keV. It was believed that this unexpected trend could be a result of inaccurate estimation of the restricted mass electronic stopping powers, which is a key-value to obtain W_{air} from the signal ratio between a calorimeter and an ion chamber measurement.

In 2018, Tessier *et al.* [2] repeated the work of Svensson and Brahme, using modern Monte Carlo techniques with the most up-to-date interaction data. They included all perturbation factors in the experiment and carried out a detailed sensitivity analysis, looking at possible systematic errors in the original experiment. This reanalysis of the Domen and Lamperti data suggested a variation of up to 3 % in W_{air} in the clinical energy range (1 MeV to 25 MeV), surprisingly similar to the cruder calculations of Svensson and Brahme. However, they did identify that this energy dependence could be an artifact, due to potential uncertainties in the density of the graphite buildup plates used in the original experiment.

In the TRS-398 [10] report, authors included an uncertainty component for the

potential variation in W_{air} , but this was based solely on the Svensson and Brahme reanalysis of the Domen and Lamperti data. Muir *et al.* [25] published a comparison of consistent measured and calculated k_Q data sets and suggested a possible variation of up to 1.0021(9) for a 25 MV photon beam compared to the reference ^{60}Co beam.

These above-cited published W_{air} values (or a variation with energy) in a high-energy beam are, however, obtained indirectly or analysis has been carried out decades after the initial investigation. MV photon beams were used in 2014 by Burns *et al.* [22], but as mentioned earlier, the average energy of the secondary electrons in the cavity remains low as the MV photon beam was used. There is no investigation of W_{air} in high-energy electron beams to refute or confirm the energy dependency observed by Tessier *et al.* [2]. The present work aims to determine the absolute value of W_{air} in high-energy electron beams and to investigate the assumption that W_{air} is energy-independent in the clinical range.

This project has a scope of energy in the few tens of MeV and the CSDA range in air of an electron with a kinetic energy of 35 MeV (the maximum anticipated) is more than 100 m. Measuring W_{air} in a high-energy beam, according to its ICRU definition, would require an impractical ion chamber air cavity. The differential form of W_{air} , $w_{\text{air},\epsilon}$, is more suitable for measurement in this context. However, producing a perfectly monoenergetic high-energy electron beam is not realistic since the beam interacts with matter before entering the ion chamber cavity.

In this project, the value obtained would be for a specific energy spectrum and therefore, strictly corresponds to neither W_{air} nor $w_{\text{air},\epsilon}$ definition. The obtained W_{air} value is mathematically defined by:

$$W_{\text{air},S_\epsilon} = \frac{\int_I^{E_{\text{max}}} n_\epsilon \cdot w_{\text{air},\epsilon} d\epsilon}{\int_0^{E_{\text{max}}} n_\epsilon d\epsilon}, \quad (2.10)$$

where S_ϵ is the energy spectrum of the particles going through the cavity, I is the lowest ionization potential of air, E_{max} is the maximum energy of the spectrum and n_ϵ is the number of particles of energy ϵ in the sensitive volume.

It should be noted that if W_{air} is, indeed, energetically independent above 10 keV, then W_{air} and $w_{air,\epsilon}$ would be equal for electron energies well above 10 keV. Therefore, since the absolute value of W_{air} would be theoretically the same as $w_{air,\epsilon}$ value in the range investigated, the term W_{air} will be used in this document. Also, by convention, the term W_{air} is used in the literature, although the quantity measurement is more closely related to the definition in Equation 2.10.

2.3 Methods

Using the definition of W_{air} in Equation 2.1, and the absorbed dose in an ion chamber air cavity defined in Equation 2.4, the W_{air} equation can be rewritten as:

$$W_{air} = \frac{E}{N} = \frac{D_{air}m_{air}}{Q_{air}}, \quad (2.11)$$

where Q_{air} is charge set in motion by charged particles, m_{air} and D_{air} are the mass of, and the dose deposited in, that volume respectively.

The term Q_{air} in Equation 2.11 can be determine using an ion chamber charge measurement (which would require correction factors, see Section 2.4) and m_{air} would be the mass of air of the ion chamber sensitive volume. The undetermined parameter of Equation 2.11 is D_{air} since direct measurement of the dose deposited in the ion chamber sensitive volume is not practical without using ionometry (which would lead to a circular argument), as air is a low density medium. It is, however, possible to measure the dose deposited in a dense medium, D_{med} . Therefore, a second dosimeter exposed to the same radiation field is added to the method and the dose measurement would need to be converted from measured D_{med} to calculated D_{air} . This is possible

using Monte Carlo radiation transport simulations. Therefore, W_{air} can be obtained using Equation 2.12.

$$W_{\text{air}} = \frac{D_{\text{med}}}{Q_{\text{air}}/m_{\text{air}}} \left(\frac{D_{\text{air}}}{D_{\text{med}}} \right)_{\text{MC}}, \quad (2.12)$$

where the dose ratio in brackets, $(D_{\text{air}}/D_{\text{med}})_{\text{MC}}$, is a Monte Carlo dose simulation ratio. The detailed methods used to obtain the various components in Equation 2.12 will be discussed in the following sections. In addition to the three measured or simulated quantities, m_{air} , the mass of the air, is critical to obtaining W_{air} . It is generally obtained from the mechanical volume of the air cavity and the known density of air, but strictly speaking it is the collecting volume (i.e., that defined by the electric field between the ion chamber electrodes, excluding any “dead” volumes where any charge created is not collected). This will not be discussed below as it is specific to each particular ion chamber, and so will be covered in more detail in Chapters 4 and 6.

The above method of measuring W_{air} was used by Burns *et al.* [22] and Tessier *et al.* [2]. This thesis is distinguished from the two above-cited publications as the technique is applied in a new context; using different tools, detectors, and radiation beams. The research presented in this thesis is similar to the original experiment carried out by Domen and Lamperti [23] and uses the same approach to obtain W_{air} as presented by Tessier *et al.* [2]. However, in this work, each step has been designed to obtain a value of W_{air} .

2.4 Ionometry, Q_{air}

The number of ion pairs created in the sensitive volume of the ion chamber by ionizing radiation, Q_{air} , has to be known with a high level of precision and accuracy to determine the value of W_{air} , as shown in Equation 2.12. The efficiency of charge

collection of an ion chamber is not perfect and requires correction factors. The raw charge measurement, Q_{raw} , has to be corrected for ion recombination P_{ion} , polarity effect P_{pol} , electrometer calibration coefficient P_{elec} , and the effect of any leakage current P_{leak} . In addition, since W_{air} is defined for dry air, Q_{raw} has to be corrected for humidity in air cavity, k_{hum} . The corrected charge reading, Q_{air} , is found using the following equation:

$$Q_{\text{air}} = Q_{\text{raw}} P_{\text{TP}} P_{\text{ion}} P_{\text{pol}} P_{\text{elec}} P_{\text{leak}} P_{\text{rp}} P_{\text{SEE}} k_{\text{hum}}, \quad (2.13)$$

where P_{TP} is the pressure-temperature correction factor and P_{rp} is a correction factor for the lateral variation of the beam intensity profile within the sensitive volume. These correction factors will be discussed in turn in the next section.

2.4.1 Correction factors

During this investigation, P_{rp} is taken to be unity as the effect of the beam profile is taken into account explicitly in the Monte Carlo dose ratio calculation (Equation 2.12). The pressure-temperature correction factor is applied to correct the change in mass of the sensitive volume due to temperature and pressure changes. Since by convention it is applied to the charge collection and defined to be used this way [9], the correction factor will be applied to the charge collection rather than the mass, m_{air} . The pressure-temperature correction factor, P_{TP} , is based on the ideal gas law and is obtained using the following Equation [9]:

$$P_{\text{TP}} = \frac{m_0}{m_m} = \frac{P_0}{P_m} \frac{T_m}{T_0} = \frac{101.325}{P_m} \frac{(T_m + 273.15)}{295.15}, \quad (2.14)$$

where the pressure and the temperature during measurement, P_m and T_m , are in kPa and °C. In Equation 2.14 the temperature is explicitly defined to be 22° C, the chosen reference value for North America. The choice of reference temperature is

not critical as long as the density of air used in the calculation of m_{air} is taken at the same temperature.

A voltage is applied between the electrodes of the ion chamber to create an electric field to collect the charges created. The voltage applied is limited to a specific range due to ion collection efficiency and charge multiplication. If the voltage applied is too low, the charges created will recombine before been collected, on the other side, if the voltage is too large, there will be charge multiplication due to free electrons gaining enough energy from the electric field to ionize the air [26]. This is not desirable as charges collected will become strongly dependent on the voltage applied between the ion chamber electrodes [27].

The three main types of recombination are; initial, general, and ionic recombination. The ionic recombination occurs due to thermal diffusion. The initial recombination is defined by the recombination of ion charge within the same primary particle track and general when the recombination occurs between two ion charges created on different tracks [26]. The initial recombination depends on the linear energy transfer (LET) of the ionizing particles; a high LET particle will create more charges in a single track. The general recombination will depend on the density of particle tracks, therefore, the dose rate or dose per pulse. The theory of ion recombination in an ion chamber has been summarized by Boag [27].

The ion recombination correction factor, P_{ion} is used to correct for the lack of full charge collection during measurement. The ion recombination factor is therefore defined by:

$$P_{ion} = \frac{Q_{sat}}{Q_m}, \quad (2.15)$$

where Q_{sat} is the charge where the saturation point has been reached (all the ions created by the ionization of air are collected) and Q_m is the charge measured. The challenge to obtain P_{ion} is to determine Q_{sat} . In a pulsed electron beam, the gen-

eral and initial recombination are linearly dependent on V^{-1} . The absorbed dose formalisms (e.g. AAPM TG-51 protocol (1999) [9] and IAEA TRS-398 (2000) [10]) recommend the two voltage technique which consist of measuring charges, Q_L and Q_H , for an applied low (V_L) and high (V_H) potential respectively. However, the TG-51 addendum protocol (2014) [13] has changed this recommendation and advises a characterization of the charge collected versus the voltage applied on the ion chamber for a range of potential and charge-per-pulse values.

The P_{ion} factor can be obtained for a specific beam by plotting V^{-1} vs Q^{-1} , a Jaffé plot [28], for a range of potentials applied to the ion chamber and extrapolate the linear portion to the ordinate axis to obtain Q_{sat} . The correction factor is then calculated using Equation 2.15. For pulsed beams, the ion recombination depends on the density of radiation tracks, therefore, if P_{ion} is obtained for a range of charge measured per pulse (proportional to the dose per pulse), the correction factor can be interpolated using the following linear Equation [13, 29]:

$$P_{\text{ion}} = 1 + C_{\text{init}} + C_{\text{gen}}Q_{\text{pp}}, \quad (2.16)$$

where C_{init} is the initial recombination, whereby ion pairs recombine in the same radiation tracks, which can be determined by measuring P_{ion} in a beam source such as ^{60}Co or by linear interpolation of a range of measurements at different charges per pulse, Q_{pp} .

The polarity correction factor, P_{pol} , is a correction factor that accounts for the change in measurement magnitude when the ion chamber polarizing voltage is reversed. The correction factor is calculated using the following equation:

$$P_{\text{pol}} = \left| \frac{(Q_{\text{raw}}^+ - Q_{\text{raw}}^-)}{2Q_{\text{raw}}} \right|, \quad (2.17)$$

where Q_{raw}^+ is the raw measurement for a positive charge collection, Q_{raw}^- is the raw

measurement for negative charge collection and Q_{raw} is the raw charge collected at the polarity that would be used during measurement.

The leakage correction factor, P_{leak} , is determined from the measured current while the bias is applied to the ion chamber, but the ion chamber is not exposed to any radiation field. This correction factor is shown as a multiplying correction factor, however, the current is considered constant during measurement and independent of the radiation charge measurement, therefore, it is subtracted from the raw charge measured before applying the other correction factors.

The slow electron emission correction factor, P_{SEE} is a correction factor that has been added in this investigation to account for an observed “vacuum current” that was described in the 1950s and ‘60s. This effect has generally been considered as being insignificant compared to the current due to air ionization. However, as this current is not from the ionization of the air in the cavity, it is a potential source of systematic error in the determination of W_{air} . As this correction factor was investigated during this project, it will be discussed in detail in Chapter 3.

The relative humidity in the air cavity is corrected using the k_{hum} correction factor which is applied to the charge collected as shown in Equation 2.13. However, the accepted k_{hum} value [30] is a correction factor that includes the effect of humidity on three factors: the change in the mass of air due to the presence of water molecules, the effect on the interaction of the particles (restricted mass electronic stopping power) and the W -value as the average energy required to create ion pairs will be different due to the presence of water molecules.

As k_{hum} partly accounts for the change in the energy required to create an ion pair in humid air, it can be asked if the original correction factor should be modified for this project. The humidity correction factor was investigated by Rogers and Ross and they define it in equation 12 [30]. Reversing their equation 12, we obtained the

following:

$$W_{\text{air}} = \frac{W_{\text{hum}}}{k_{\text{hum}}} \frac{m_{\text{air}}}{m_{\text{hum}}} (\bar{L}/\rho)_{\text{hum}}^{\text{air}}, \quad (2.18)$$

where W_{hum} is the energy required to create an ion pair in humid air, m_{air} and m_{hum} are the mass of the cavity when filled with dry air and humid air respectively, and $(\bar{L}/\rho)_{\text{hum}}^{\text{air}}$ is the restricted mass electronic stopping powers ratio of dry air to humid air. The W_{hum} can be defined using the same equation as W_{air} , Equation 2.12:

$$W_{\text{hum}} = \frac{D_{\text{med}}}{Q_{\text{hum}}/m_{\text{hum}}} \left(\frac{D_{\text{hum}}}{D_{\text{med}}} \right)_{\text{MC}}. \quad (2.19)$$

Taking the assumption that any perturbation corrections are independent of humidity then the Monte Carlo dose ratio can be simplified to a mass collision restricted stopping power ratio. Combining equations Equation 2.20 and 2.19 then yields:

$$W_{\text{air}} = \frac{D_{\text{med}} m_{\text{hum}}}{Q_{\text{hum}}} (\bar{L}/\rho)_{\text{med}}^{\text{hum}} (\bar{L}/\rho)_{\text{hum}}^{\text{air}} \frac{m_{\text{air}}}{m_{\text{hum}}} \frac{1}{k_{\text{hum}}}, \quad (2.20)$$

$$W_{\text{air}} = \frac{D_{\text{med}} m_{\text{air}}}{Q_{\text{hum}} k_{\text{hum}}} (\bar{L}/\rho)_{\text{med}}^{\text{air}}, \quad (2.21)$$

$$W_{\text{air}} = \frac{D_{\text{med}} m_{\text{air}}}{Q_{\text{air}}} (\bar{L}/\rho)_{\text{med}}^{\text{air}}. \quad (2.22)$$

As shown in the above equation, the humidity correction factor should not be modified for this investigation as Equation 2.22 is the same as Equation 2.12 (mass restricted SPR being equivalent to the Monte Carlo dose ratio).

2.4.2 Ion chamber performance criteria

It would be useful to have some objective criteria against which the performance of an ion chamber can be judged, to give confidence that it will be reliable in using

Equation 2.12. The minimum must be that any chamber used for this investigation meet the reference-class specification of the AAPM TG-51 Addendum [13]. The requirements are listed in appendix A table III of the task group report and are repeated here.

Table 2.1: Reference-class-ionization chamber requirements as specified in appendix A table III of AAPM TG-51 Addendum [13].

Parameter	Requirement
P_{leak}	Should be smaller than 0.1 % of the ion chamber signal measured
P_{pol}	Should be a correction smaller than 0.4 % and should have an energy dependency smaller than 0.5 %
P_{ion}	Should be linear with Q_{pp}
C_{init}	Should be less than 0.2 % and the difference in value for opposite polarities should be smaller than 0.1 %

The TG-51 addendum states that the leakage has to be under 0.1 % of the signal measured. However, due to the high level of accuracy and precision required for this experiment, 0.1 % of the signal coming from leakage is considered too high. It has been decided that the portion of charge measurement coming from leakage should be well below the standard deviation of measurement, therefore, negligible. Typically, 0.05 % is the type A uncertainty attributed to ion chamber charge measurement, and leakage under 0.01 % would be an acceptable value.

2.5 D_{med} , Calorimetry

As mentioned earlier and stated in Equation 2.12, the dose in a dense medium, D_{med} , has to be measured so the dose deposited in the ion chamber, D_{air} can be obtained using a Monte Carlo dose ratio simulation. There are different options, such as

Fricke dosimetry, calorimetry or the use of scintillator, however, calorimetry has the big advantage of being accepted as a standard in radiation physics. A calorimetric dosimeter is a detector optimized to measure the temperature rise in matter due to the energy absorption by radiation. It is considered to be the most direct method to measure the dose, as it does not rely on other radiation-derived values, such as W_{air} for ionometric measurements. The absorbed dose in a calorimeter is obtained using the following equation:

$$D_{\text{med}} = c_{\text{med}} \cdot k_{\text{n-med}} \cdot \Delta T \cdot k_{\text{hc}} \cdot k_{\text{hv}} \cdot k_{\text{p}} \cdot k_{\text{dd}} \cdot \frac{1}{1 - k_{\text{HD}}}, \quad (2.23)$$

where D_{med} [$\text{J} \cdot \text{kg}^{-1}$] is the absorbed dose in the core of the calorimeter, ΔT [K] is the temperature increase induced by charged particle energy deposition in the calorimeter core, c_{med} [$\text{J} \cdot \text{kg}^{-1} \text{K}^{-1}$] is the specific heat capacity and $k_{\text{n-med}}$ is a correction factor for components within the calorimeter core made of a different material than the core. The correction factors are: k_{hc} and k_{hv} for conductive and convective heat loss which can be calculated using finite element method (FEM), k_{p} is for the perturbation of the radiation due to non-homogeneity of the material in the calorimeter, k_{dd} is for non-uniformity of the lateral dose profile and k_{HD} is a correction for the heat defect in the calorimeter medium. Both correction factors for radiation perturbation, k_{p} and k_{dd} , are taken to be unity since any radiation perturbations are accounted for by the Monte Carlo dose ratio, Equation 2.12.

Although a wide variety of calorimeter absorbers are possible and have been used in the past for beam calorimetry measurement [31–33], the calorimeters used for reference dosimetry are now typically based on tissue-equivalent material (mainly water and graphite). The water calorimeter design is typically a sealed vessel of an aqueous system with a known heat defect, usually, N_2 -saturated or H_2 -saturated highly purified water. The vessel, which contained the thermistors, is immersed in a large water tank at 4°C to avoid heat convection.

The water calorimeter is the most widely used calorimeter type in national metrology institutes, however, graphite calorimeters have been in use for much longer as there is no challenge related to heat defect and convection. Graphite calorimetry can simplify to a multibody system where the temperature is measured in the core (central body) by temperature sensors. The core is separated from the surrounding bodies by vacuum or air gaps to limit the heat loss through conductivity, as illustrated in Figure 2.3.

Figure 2.3: Example of a multibody graphite calorimeter. A) Beam view of the calorimeter in a phantom, B) Side view of the multibody calorimeter inserted in the phantom and C) zoom on the core and jacket of the calorimeter.

The three main operating modes are quasi-adiabatic, heat loss compensated and isothermal. In a quasi-adiabatic operating mode, the core and the jackets are uniformly irradiated. This ensures a uniform temperature rise in the calorimeter, which minimizes the heat loss from the core. In a heat loss compensated calorimeter, the signal of the core is summed to the signal in the jackets to quantify the heat loss from the core. In an isothermal calorimeter, the temperature is maintained at a constant temperature to produce a constant heat loss rate in the core.

The calorimeter used in medical physics are usually operated at 4° C in the case of water calorimeters and at room temperature for graphite calorimeters. The advantage of operating a graphite calorimeter at low temperature using liquid nitrogen or helium would be theoretically interesting as it would lower the noise and the specific heat capacity (increase of radiation-temperature rise). However, this possibility was explored at the National Physical Laboratory (NPL) in 2006 [34], the project didn't go any further than the feasibility stage.

The temperature rise measurement depends on the dose rate, the length of radiation exposition, and the specific heat capacity of the medium. The typical radiation-induced temperature rise is of the order of a few hundred μK . The calorimeter measurement is performed in three phases as illustrated in Figure 2.4.

Figure 2.4: A typical raw temperature-time traces measurement of a graphite calorimeter. The radiation-induced temperature rise is determined by extrapolating the pre- and post-drift to the centre point of the irradiation.

First, the background temperature is measured, this is the pre-drift measurement (from point A to B). In the second phase, the radiation source is turned on for a fixed amount of time (from point B to D). The third and last phase is the measurement of the post-drift (from point D to E). In water calorimetry, the full measurement length

is about 5 minutes, while graphite calorimetry is about 2 minutes. The calorimetric measurements using graphite are shorter since the specific heat capacity of graphite is about six times smaller than water, therefore, the radiation time can be shorter for the same temperature rise.

2.6 Monte Carlo simulation

The Monte Carlo method is a numerical technique to solve mathematical integrals by sampling points randomly, instead of deterministic algorithms. For radiation transport, the particle is explicitly tracked and randomly samples its interaction probability distributions in a given material to model its fate: scattering, absorption, and the possible creation of secondary particles. Such secondary particles are in turn followed individually, to yield a cascade or shower of particles representing one possible history starting from one initial particle. This history ends when all the energy has been dissipated in the material or has escaped the geometry. By repeating this sampling process a large number of times, the expected experimental response of the material to a beam of incident particles is thus properly modelled.

Monte Carlo techniques use the microscopic interaction probability of radiation particles to simulate their interactions with matter. The photon interactions are: Compton and photoelectric effect, pair production, Rayleigh (coherent) scattering, and photonuclear interaction. The four types of interactions of electrons with matter are the: soft collision, hard collision (knock-on electron), Coulomb-force interactions with the external nuclear field, and the bremsstrahlung production. These interactions are macroscopically described by attenuation, energy transfer, and absorption for the photon interactions and by the radiative yield, stopping and scattering power for electrons. These matter properties are based on theoretical derivations (photon

cross-section and stopping power) and experimental values (e.g. mean excitation potential, I -value). The Monte Carlo accuracy is therefore dependent on the way that the theory is modelled for the Monte Carlo software and the precision of the experimental values. From a user perspective, these considerations will lead the choice in the software selected for the simulation. The user has also an impact on the accuracy of the simulation as it is the user that has to reproduce the experimental geometry and the source of the particles accurately.

There are multiple Monte Carlo algorithms available specifically developed for radiation transport calculation. The three main ones used in medical physics research are: EGSnrc, Geant4, and PENELOPE. The Geant4 software suffers from an electron step size artifact which may result in a larger difference between simulation and measurement compared to the two other algorithms [35]. The simulation in Geant4 can be improved by adjusting the maximum step size allowed, however, it suffers from an efficiency loss [36]. EGSnrc and PENELOPE yield similar agreement with measurement, however, EGSnrc shows a higher efficiency [36]. As the project will require multiple geometry simulations, faster simulation software is desirable. EGSnrc has been shown to be accurate within 0.1 % with respect to its own cross-sections [37], it is efficient and is considered to be the gold standard in medical physics. As this project was held at the National Research Council Canada where the EGSnrc algorithm is developed and is maintained, combined with the fact it is fast and shows accuracy, it went without saying to choose EGSnrc for the Monte Carlo simulation.

EGSnrc, standing for Electron Gamma Shower, is an open-source general-purpose software toolkit for the simulation of electron and photon transport through matter. The energy range that can be simulated is from 1 keV to 10 GeV. EGSnrc is known for its efficiency, it is capable of fast simulation speed without accuracy sacrifice

as mentioned earlier. This is possible because of condensed history and variance reduction techniques available for applications that will be used in this project. In the condensed history technique, the large number of electron interactions with matter is condensed in a single effective electron step [38, 39].

The EGSnrc software toolkit can be conceptually separated into two components; the radiation transport algorithms that handle the interaction probability to ensure the physical meaning of the simulation and the applications such as `egs_chamber`. The applications are used to define the geometry in which the radiation particles will be created and transported. The applications are also used to score the quantities of interest. In this project, three main quantities are of interest: the dose deposited in the sensitive volume of the detector simulated, the dose mapping in the calorimeter, and the energy spectrum in the ion chamber cavity. In the EGSnrc package, two applications were used to score those quantities; `cavity` for energy spectrum and `egs_chamber` for dose calculations.

To obtain a Monte Carlo simulation using `egs_chamber` or `cavity`, the user will have to first create an input file, the `.egsinp` file. This file will contain the description of the geometry with the media, the particle source, the scoring options, the transport parameters, the variance reduction techniques to be used, and the random seed number and run control. The run control is there to state the number of particles to be simulated, which affects the final precision. The scoring options are to state the volume in which the dose will be scored. For transport parameters, the important options for the simulation in this project are the so-called “Ecut” and “Pcut” which stand for Electron and Photon cut-off energy. As mentioned earlier, the particles are tracked down until all their kinetic energy has been dissipated in the material. The cut-off energy is the energy at which the particles are “killed”, i.e. the particle reaches its terminus and remaining energy (“Ecut” or “Pcut”) is

deposited in the region in which the particle is located. These parameters affect both the efficiency and the accuracy of the Monte Carlo results. The computational time increases for lower cut-off energy, however, if the cut-off energy is too large, the accuracy will be affected. The approximation of “killing” the particle once it reaches the cut-off energy is valid only if the selected energy represents the range of the particle in the region with the lowest mass thickness. This will ensure that the particles will not stop in a region when it could have reached the next one. The lowest cut-off energy that can be selected in EGSnrc is 1 keV. This represents a range smaller than 0.05 mm in air and 1000 times less in water.

In the `egs_chamber` application of the EGSnrc package, there are different variance reduction techniques available [40]. As an electron beam will be used for this project, only the range-based Russian roulette [41] technique will be discussed, but there are variance reduction techniques available for photons such as photon cross-section enhancement. As mentioned earlier, the electron will be tracked down until reaching the cut-off energy E_{cut} . As the geometry increases in size, the ratio between the number of particles that will deposit energy in the scoring volume versus the total number of particles that are simulated can drastically decrease, therefore, affecting the simulation efficiency. The range-based Russian roulette technique aims to increase the simulation efficiency as it reduces the number of particles tracked down to the cut-off energy by terminating electrons histories based on their range. These terminated particles are considered to have practically no chance to reach the scoring volume, therefore, do not contribute to the energy deposited in the scoring volume. However, some of these electrons could generate photons in radiative events that would potentially deposit energy in the scoring volume. Therefore, before terminating electrons histories that are considered to have no chance to reach the scoring volume, the electron will be submitted to a Russian Roulette “game”. If the elec-

tron survives the game and is not terminated, it will carry a larger statistical weight representative of the chance to survive the Russian Roulette.

The particle source is created using the **egs++** particle sources class library, which allows creating different source shapes and states the particle energy. It is possible to use a tabulated spectrum rather than a monoenergetic beam. The particle trajectory is initially defined by the particle source class which can be modified using angular spread. For simple source modelling, it is useful to declare the source geometry and parameter in the same input file as the other parameters since all the information is found in the same file. However, for a more complex geometry such as a clinical linear accelerator (linac), the use of another EGSnrc application, **BEAMnrc**, helps to improve the efficiency of the simulation and simplify the input file.

In the input file, the geometry will be created using the **egs++** geometry class library which offers a large variety of geometric shapes. While creating the geometry, the user will have to consider the efficiency of the simulation. The first consideration should be the type of geometry class selected, e.g. a translated object in the geometry could considerably slow down the simulation. The second consideration is the level of accuracy in reproducing the actual experimental geometry. To reproduce with high detail the experimental set-up that is far from the dose scoring volume would slow down the simulation without impacting the results. For EGSnrc to adequately simulate the particle interactions in the medium, some information on media has to be given such as: the atomic composition and mass weight, the density, the mean excitation potential (I -value), and the density correction. In the EGSnrc package, there are large variety of media already tabulated with appropriate density correction files. In the media section of the **.egsinp** input file, the user has to state the name of the density correction file to be used. It is also possible for the user to create their own density correction file if the medium is not included in the EGSnrc package, or

if the data in the files are outdated.

2.7 Detector design consideration

The design of the detectors will be detailed in the Chapters 4 and 6, however, general consideration can be listed for the method chosen for this investigation. As it is shown in Equation 2.12, the obtained W_{air} relies on the accuracy of the Monte Carlo calculation. The accuracy of the Monte Carlo calculation relies on the knowledge of particle-interaction probability distributions, the accuracy of the generated geometry, and particle's source. It is, therefore, preferable to have a similar design for both detectors and where both are made from the same material. The use of a water calorimeter can be, therefore, excluded as an ion chamber cannot be built out of water. A solid calorimeter design will be based on a multibody concept, as explained earlier. The central element of the calorimeter is the core, usually having a cylindrical shape, the axial symmetry being perpendicular to the beam axis, surrounded by a gap, most likely air or vacuum.

There are multiple designs available for the ion chamber, however, the closest design to the above-described calorimeter design is the plane-parallel chamber. This ion chamber design typically has two co-planar plates perpendicular to the beam axis as shown in Figure 2.5 A). The calorimeter core would be the analog of the central collector, however, the calorimeter is surrounded by an air gap, above and under as shown in Figure 2.3. In the case of the ion chamber, there is typically only one air gap above the central collector (lower plate). For the calorimeter design, the air gap is crucial and can't be removed, however, it would be possible to add an air cavity under the central collector without affecting the functioning of the ion chamber, as shown in Figure 2.5 B).

Figure 2.5: A) Example of a plane-parallel chamber where the grey zone is the sensitive volume of the ion chamber. B) Example of an ion chamber where the central collector is placed in the middle of the sensitive volume, creating two volumes.

In Section 2.5, it was mentioned that vacuum could be used to reduce the heat loss during measurement. The vacuum system is the most effective way to reduce heat loss for a solid-based calorimeter. A review of the literature and discussion with some calorimeter experts indicated that the challenges of building a vacuum calorimeter were significant. Calorimeters with vacuum gaps have generally been optimized for photon beam measurements and designed for a limited number of measurement situations. At the outset of this project, it was determined that a flexible calorimeter design would be needed to allow some iteration of the experimental design. A vacuum system would significantly restrict that flexibility. It was also found from a review of the literature that, for the electron beams that were likely to be used in the W_{air}

determination, a calorimeter operating at standard ambient pressure in a quasi-adiabatic mode would achieve the necessary accuracy and precision [42].

Chapter 3: Slow electrons emission

Every day for us something new, Open mind for a different view,

And nothing else matters

Metallica¹

As stated in theory Chapter 2, and more specifically shown in Equation 2.1, to determine the value of W_{air} , the charge collected should only come from the ionization of the air in the sensitive volume by charged particles passing through the ion chamber cavity. The output of an ionization chamber is assumed to be uniquely due to ionization of the air within the cavity once the charge measurement is corrected according to the following equation:

$$Q_{\text{air}} = Q_{\text{raw}} P_{\text{TP}} P_{\text{ion}} P_{\text{pol}} P_{\text{elec}} P_{\text{leak}} P_{\text{rp}} k_{\text{hum}}, \quad (3.1)$$

which has been presented in Chapter 2. The raw measurements, Q_{raw} , includes charges from the ionization of the air, but also some contaminating current that is assumed to be corrected by the polarity correction factor P_{pol} . This factor aims to rectify the change in the magnitude of the charge measured when the polarizing voltage is reversed. This effect is thought to be due to several factors, which are listed and well explained by Boag [27]. From that list, most of the potential source of contaminating current are considered to be independent of the collecting polarity

¹Metallica, *Nothing else matters*, Metallica, Blackened Recordings, 1991

in magnitude and sign, therefore, the average of the absolute charge measurements would corrects for it (P_{pol} shown in Equation 2.17). However, at least one item in the list, more specifically the low-energy electron emission (or slow electron emission), is dependent in magnitude and sign on the polarizing voltage and would not be corrected for by the polarity correction factor.

This effect would be theoretically dependent on the polarity applied to the ion chamber. In the case of an ion chamber measurement collecting positive charge, the polarity of the central collector is negative. The slow electrons emitted from the wall would most likely be reabsorbed due to the electric field, the wall of the ion chamber being positively charged, and would have no impact on the charge measurement. On the other hand, the slow electrons emitted from the central electrode would create an extra positive charge measurement while leaving the collector. For negative charge measurement, the ion chamber polarity is reversed. The slow electrons emitted from the wall would be collected by the central electrode and the slow electrons emitted from the central collector would most likely be reabsorbed immediately, resulting in an extra negative charge measurement.

The number of slow electrons emitted and collected would depend on the design of the ion chamber. For a cylindrical chamber, it would be expected to observe a larger signal for negative charge collected as the central collector is smaller than the wall surface area facing the sensitive air volume. In the case of a parallel-plate ion chamber, as the surface area of both collector and walls facing the sensitive volume is the same, it would be expected to see a similar signal, but opposite sign, for both polarities if both the wall (front window) and central collector are exposed to the same radiation fluence. It would also depend on the material of both walls and collector, expected to be larger for denser and higher-Z material.

A so-called “vacuum current”, i.e. a non-zero current measure for a zero pressure

in an ion chamber cavity, was observed and investigated by Wilson *et al.* [43] in the 1950s and the '60s by Burlin and Husain [44]. This current was considered to be consisting of slow electrons emitted from the electrodes [45]. The slow electron emission would be secondary, but most likely tertiary electrons, emitted from the walls and the central electrode of the ion chamber with low energy, below 50 eV. These electrons would not ionize the air due to their low energy but would be collected due to the electric field in the ion chamber. This effect has been ignored for several decades and considered to be insignificant compared to ionization current or to be cancelled out between chamber calibration and use.

In the mid-2000s La Russa *et al.* [46] acquired data as part of an investigation of the validity of the pressure-temperature correction factor. They found a deviation with pressure that was explained by a breakdown of the Bragg-Gray theory and found that it could be avoided by an air-equivalent ion chamber. However, McEwen *et al.* [3] carried out preliminary measurements in high-energy electron beams. Their results indicated that another significant effect would be involved in the break-down of the temperature-pressure correction factor and was consistent with slow-electron emission. As the aim of this project required a precise evaluation of the charge created by the ionization of air in the ion chamber sensitive volume, and this vacuum current could significantly affect the evaluated value of W_{air} , the preliminary research from McEwen *et al.* was extended to a much larger number of ion chambers and radiation sources.

3.1 Methods and material

To investigate the slow electron emission, six different ionization chambers were studied. Two cylindrical and four plane-parallel designs were investigated and are

listed in Table 3.1 with some design specifications. A range of chamber designs was chosen because the geometry of the chamber, along with the materials of the collecting electrode and chamber body, has an impact on the magnitude of the slow electron emission effect.

The two cylindrical ion chambers; the FC65-G and Exradin A19, have a similar design as their volumes are of the same order and their walls are made of low Z elements (graphite and plastic). However, the central collector of these chambers is made of aluminum and plastic respectively. The ion chamber A19 was also selected as it was one of the chambers studied by La Russa *et al.* [46] in a low energy KV beam and they concluded that this ion chamber was ideal as it is made of air-equivalent material. The two commercial plane-parallel ion chambers, the Markus[®] and Roos[®] from PTW have similar materials for both the window and the collector, but with different collecting radii: yielding a larger electrode area to sensitive volume ratio for the Roos[®] ion chamber.

The ion chamber types MARKIII and ALECS are two NRC-built symmetric plane-parallel ion chambers (symmetric in the beam axis). The two ion chambers have the same design with minor differences. The body, collector, and guard ring are respectively made of graphite and aluminum, as stated in Table 3.1. The technical drawing of the ion chambers and the electrical connection is shown in Figure 4.1. The results obtained with both ion chambers could be directly compared to study the material dependence of the slow electron emission. Also, because of the particular design of the central collector “floating” in the middle of the air cavity and made of the same material as the body, the theory would predict that the magnitude of the “vacuum current” would be the same for both collecting polarities, but with an opposite sign if exposed to the same radiation fluence.

Table 3.1: List of ion chambers used in the slow electron emission investigation with some design specification.

Ion chamber Model <i>Manufacturer</i>	Material		Sensitive volume (cm ³)	Surface area (approximative, cm ²)	
	Body / window	Central collector		Body / window	Collector
FC65-G <i>IBA</i> (London, United Kingdom)	Graphite	Aluminum	0.65	4.50	0.73
Exradin A19 <i>Standard imaging</i> (Middleton, WI, USA)	C552 Shonka air-equivalent plastic		0.62	4.14	0.68
Markus [®] <i>PTW</i> (Freiburg, Germany)	Polyethylene	PMMA (graphited)	0.055	0.22	0.22
Roos [®] <i>PTW</i> (Freiburg, Germany)		PMMA (graphited)	0.35	1.91	1.91
MARKIII <i>NRC-built</i>	Graphite		0.86	7.31	7.31
ALECS <i>NRC-built</i>	Aluminum		0.86	7.38	7.38

The ion chambers were positioned in a polymethylmethacrylate (PMMA) air-tight vessel of 30 cm diameter, 0.65 cm thick walls and 50 cm height as shown in Figures 3.1 and 3.2. The ambient pressure was varied from 0.1 to 1.0 atmospheres using a vacuum pump. Initial investigations had shown that the measurements were very sensitive to the accuracy of the pressure measurement, therefore two electronic barometers (stated accuracy of 0.1 % and 0.05 %) were used. It was initially thought that the adiabatic changes in pressure within the vessel could result in changes in

the air temperature but this was found to be not significant.

Figure 3.1: Picture of the radiation set-up for ^{90}Sr sources, A) for cylindrical ion chamber measurement and B) plane-parallel ion chamber measurement.

Three different radiation fields were used; ^{90}Sr , ^{60}Co and MeV electron beams. The setups used for the ^{90}Sr source measurements are shown in Figure 3.1 A) and B) as two different sources, PTW ^{90}Sr sources model 48002 and 48010, were used to accommodate both cylindrical and plane-parallel chambers. For cylindrical chamber measurement with ^{90}Sr source, no additional phantom was required as the source is self-shielded. For plane-parallel ion chamber measurements using a ^{90}Sr source, the ion chamber and the source were positioned in an aluminum phantom for positioning reproducibility and to maintain a stable temperature. The PMMA protective cap was used during measurement with the Markus[®] ion chamber.

The set-up used with a Gammabeam X200 ^{60}Co unit (manufactured by Therat-

ronics), is shown in Figure 3.2. The clinical NRC Elekta Precise linear accelerator was used for the MeV electron beams. For ^{60}Co and MeV electron beams, the ion chambers were set in expanded polystyrene foam to provide positioning stability, see Figure 3.2. The ion chambers were positioned at 115 cm from the source and the field size used was $10\text{ cm} \times 10\text{ cm}$ at a distance of 100 cm from the source.

Figure 3.2: Picture of the radiation set-up at the NRC ^{60}Co source, a Gammabeam X200 ^{60}Co unit (manufactured by Theratronics).

A protocol was developed to ensure that the pressure and temperature within the chamber were at equilibrium with the measured vessel pressure and temperature. All external read-out connections were via vacuum-sealed feed-throughs. The ion chambers were connected to a calibrated Keithley 6517A for the MeV electron beams and a SuperMAX Electrometer (Standard Imaging) for the ^{90}Sr and ^{60}Co source. Leakage measurements were performed before and after irradiation measurements. Measurements were repeated multiple times to investigate hysteresis/cycling effects. During this investigation, the ion recombination was also measured at different pressures for

one ion chamber to ensure it behaved as expected. It was measured at 0.3, 0.5, 0.8, and 1.0 atmospheres for the aluminum ion chamber ALECS using a 18 MeV electron beam. The measurement was carried out following the recommended procedure [13] described in Chapter 2, Section 2.4.

Extensive Monte Carlo dose calculations were carried out to reproduce the measurement set-up and investigate possible second-order effects from changes in the pressure within the vessel, as La Russa *et al.* [46] observed. The EGSnrc radiation transport system was used with the user code `egs_chamber`. The change in pressure within the vessel was simulated using custom density correction files. For all geometries investigated, simulations were run to reach a statistical uncertainty of 0.1 %. The range-based Russian-roulette technique, a well known and tested variance reduction technique [41], was used to optimize computational time. Electrons and photons were tracked down to a kinetic energy of 1 keV. Manufacturer's technical drawings of each ion chamber were used in the geometry implementation. For the ^{90}Sr source, an accurate description of the source was simulated. For ^{60}Co source, a diverging point source to create a 10 cm $\times$ 10 cm at 100 cm was simulated with the spectrum calculated by Mora and Rogers [47]. For linear accelerator electron beams, it was deemed sufficient to use a diverging point source with a simple spectrum.

3.2 Results and Analysis

Figure 3.3 shows the Monte Carlo simulated variation in the absorbed dose to air as a function of air pressure and its reciprocal for the radiation source used in this investigation with the Exradin A19 ion chamber. The effect is generally small, ≤ 1.0 % at $\Delta P = 0.1$ atm.) and with limited dependence on the radiation field. A Monte Carlo pressure correction factor (P_{MCp}) was added to the Equation 3.1

to account for the observed dose deposition dependence on pressure highlighted by the Monte Carlo simulation. The correction factor is the reciprocal value of the relative dose calculated. In the following section, the focus is on the Exradin A19 cylindrical chamber, rather than the purpose-built plane-parallel chambers, because the measurements revealed that the impact of this slow electron emission correction factor has implications beyond this project. Also, the A19 is a detector that has been extensively studied by various groups.

Figure 3.3: Relative dose deposited in the cavity of the Exradin A19 calculated by Monte Carlo for the sources and beams used in this investigation for the range of pressure used in this investigation.

Figure 3.4 A) illustrated the deviation of the temperature-pressure corrected charge measurement from the theoretical value. The P_{MCp} correction factor has been applied to the measurement shown in Figure 3.4 A) and the results are shown in Figure 3.4 B). The observed curvatures of the corrected temperature-pressure charges shown in Figure 3.4 A) are not explained by the dose deposition dependence on pressure.

Figure 3.4: A) Dependence of the charge measurement of the Exradin A19 ion chamber as a function of air pressure corrected for the standard temperature-pressure and B) with additional correction for the observed air pressure dose deposition dependence calculated by Monte Carlo.

The raw negative charge measurements using the Exradin A19 chamber, $Q_{(p)}$, normalized to the signal at 1 atm., $Q_{(p_0)}$, for the different radiation fields are shown in Figure 3.5 A). Figure 3.5 B) shows that there is a residual current even at a null pressure inside the cavity, a vacuum current, as observed by Wilson *et al.* [43].

To extract this current to obtain a correction factor, the different pressure-dependent correction factors of Equation 3.1 have to be considered in the analysis, while the correction factors that are constant with pressure can be ignored. The resulting equation is:

$$Q_{\text{air}} = (Q_{(p)} - Q_{\text{VC}})P_{\text{TP}}P_{\text{ion}}P_{\text{MCp}}, \quad (3.2)$$

where $Q_{(p)}$ is the measured charge at air pressure p , Q_{VC} is the charge due to the vacuum current, P_{TP} is the air temperature-pressure correction factor, P_{ion} is the ion recombination correction factor and P_{MCp} is the Monte Carlo pressure correction factor discussed above. The leakage current correction factor, P_{leak} , not included in the above equation, was applied to $Q_{(p)}$ prior to the analysis. The ion recombination

correction factor, P_{ion} , was kept in the equation since for pulsed beams (MeV electron beams) it is dependent on the charge created per pulse [13], therefore, dependent on the pressure in the cavity. To ensure it behaved as expected, the ion recombination was measured in an electron beam for the aluminum ion chamber ALECS at different values of pressure. The results obtained were all within the uncertainty of the expected value for both collecting polarities. As it can be noted, Q_{VC} was added in the Equation 3.2 to account for the vacuum current measured, considered to be constant with pressure.

Figure 3.5: The Exradin A19 ion chamber signal measurement, $Q(p)$, normalized shown in A) for a range between 0.1 atm. to 1 atm. and for a zoom from 0.0 atm. to 0.2 atm. in B) with the linear fit extrapolated to zero pressure to illustrate the vacuum current.

Equation 3.2 can be inverted to extract Q_{VC} and Q_{air} from the measurement using the following equation:

$$Q(p) = \frac{Q_{\text{air}}}{P_{\text{TP}} P_{\text{ion}} P_{\text{MCp}}} + Q_{\text{VC}}, \quad (3.3)$$

where Q_{air} would be the slope and Q_{VC} the intercept of the $Q(p)$ as a function of $(P_{\text{TP}} P_{\text{ion}} P_{\text{MCp}})^{-1}$. The obtained corrected measurements as a function of the cavity air pressure for the Exradin A19 ion chamber are shown in Figure 3.6.

Figure 3.6: The dependence of the charge measurement of a Exradin A19 ion chamber as a function of air pressure corrected for the standard temperature-pressure, Monte Carlo pressure dependence and the slow electron emission P_{SEE} . A) negative charge collected and B) positive charge collected.

In the Figure 3.6, it can be observed that the subtraction of the vacuum current from the raw measurement corrects the curvature observed in Figure 3.4 for all beams down to a pressure of 0.25 atm. Below this pressure it can be observed that there is significant deviation for continuous radiation beams (^{90}Sr , ^{60}Co) when collecting negative charge (Figure 3.6 A)). This is not observed when collecting positive charge, as shown in Figure 3.6 B). This difference was also observed for all of the ion chambers investigated, both cylindrical and plane parallel.

The relative values obtained, $Q_{VC}/|Q_{air}|$ for all the ion chambers and radiation sources used in this investigation are shown in the Table 3.2 for both collecting polarities. The uncertainties stated in Table 3.2 are the propagation of the linear fit uncertainty combined with the uncertainty evaluated from data reproducibility and the impact of the range selected for the analysis. For the source ^{90}Sr and ^{60}Co sources, it is evaluated to be 0.1 % and for the MeV electron beam, 0.05 %. The uncertainty of the MeV beam was considered smaller as the signal-to-noise ratio was

larger and the pressure range selected for the analysis had a smaller impact on the results.

Table 3.2: The relative values of vacuum current to ionization current at standard temperature and pressure, $Q_{VC}/|Q_{air}|$ using the Equation 3.3 in percent (%). The stated uncertainties ($k = 1$) are the propagation of the linear fit uncertainty combined with the uncertainty evaluated from data reproducibility and the impact of the range selected for the analysis.

Radiation type	Collecting charge	Scanditronix FC65-G	Exradin A19	PTW Markus [®]	PTW Roos [®]	NRC MARKIII	NRC ALECS
⁹⁰ Sr	+	0.00(10)	0.33(11)	-0.72(11)	-0.46(11)		
	-	-0.28(10)	-0.39(11)	-0.66(10)	-0.13(10)		
⁶⁰ Co	+	0.36(10)	0.19(10)	0.27(10)	0.13(11)		
	-	-0.22(10)	0.09(10)	-0.20(10)	-0.01(10)		
4 MeV	+		0.41(7)			-0.53(5)	-1.33(6)
	-		-1.38(9)			-0.63(5)	-1.67(5)
8 MeV	+					0.06(5)	0.01(5)
	-					-0.27(8)	-0.54(5)
12 MeV	+					0.18(5)	0.31(5)
	-					-0.29(5)	-0.45(5)
18 MeV	+		0.97(9)			0.31(5)	0.44(5)
	-		-1.33(10)			-0.24(5)	-0.40(5)

From the results shown in Table 3.2, it can be observed that the extra current measured is of the opposite sign for positive and negative charge collection, therefore, it would not be corrected by the standard polarity correction factor P_{pol} . An additional correction factor should be added to the Equation 3.1 to account for this slow electron emission, P_{SEE} :

$$P_{SEE} = 1 - \frac{(Q_{VC}^+ + |Q_{VC}^-|)}{2}, \quad (3.4)$$

where the Q_{VC}^+ is the vacuum current measured for positive charge collected and Q_{VC}^- for negative charge collected. The results obtained for the ion chambers and radiation sources and beams investigated are shown in Table 3.3.

Table 3.3: The calculated slow electron emission correction factor, P_{SEE} at standard temperature and pressure.

Radiation type type	Scanditronix FC65-G	Exradin A19	PTW Markus [®]	PTW Roos [®]	NRC's MARKIII	NRC's ALECS
⁹⁰ Sr	0.9986(7)	0.9964(8)	1.0003(8)	1.0016(7)		
⁶⁰ Co	0.9971(7)	0.9995(7)	0.9977(7)	0.9993(8)		
4 MeV		0.9910(6)			0.9995(4)	0.9982(4)
8 MeV					0.9984(5)	0.9973(4)
12 MeV					0.9976(4)	0.9962(4)
18 MeV		0.9885(7)			0.9973(4)	0.9958(4)

The values obtained in this investigation using the aluminum and graphite plane-parallel ion chamber were compared to the obtained values by McEwen *et al.* [3] in that preliminary investigation. The values obtained show agreement within 0.02 % and 0.10 % for the beam energy of 12 MeV and 18 MeV respectively. The slow electron emission correction factor obtained in this investigation using the aluminum and graphite ion chamber; ALECS and MARKIII ion chamber respectively, are shown in Figure 3.7. The shown results from McEwen *et al.* [3] have been reanalyzed using the same procedure as the data obtained in this investigation. This reanalysis did not change the results at the level of the uncertainties.

Figure 3.7: The slow electron emission correction factor calculated for ALECS and MARKIII ion chambers compared with the reanalyzed data obtained by McEwen *et al.* [3] for MeV electron beams.

3.3 Discussion

From the results shown in Table 3.2, it can be observed that the vacuum current measured is of the same sign as the collecting charge, with some exceptions that will be discussed below. The analysis of the data obtained indicates that at least three effects were contributing to the ion chamber response:

- A change in the energy deposition due to the variation in air density (ideal gas law, P_{TP} , applied in Figure 3.4 A)).
- A variation in the dose deposition dependent with air pressure due to ion chamber design characteristics (P_{MCP} , determined from Monte Carlo calculation, examples shown in Figure 3.3).
- A pressure-independent effect, consistent with the vacuum current (Q_{VC}) meas-

ured by Wilson [43] and with the slow electron emission from walls proposed by Greening [45].

For the cylindrical ion chambers, FC65-G and Exradin A19, the results indicate a non-symmetry in the magnitude of the vacuum current measured, as expected due to the non-symmetry of the electrodes. For the ^{90}Sr source measurements, the magnitude of the vacuum current is larger for negative charge collection as predicted by the theory. The number of slow electrons emitted from the cylindrical wall of the ion chamber should be larger than from the central collector. It was expected that the extra positive charge measured would be larger for the FC65-G compared to the Exradin A19 as the central electrode is made of aluminum and air-equivalent plastic C552 respectively. However, the results indicate a negligible difference between the two ion chambers. For the negative charge measurement, a larger current is observed for the Exradin A19 while it was expected to see the same magnitude of extra negative current since the wall surface area to sensitive volume ratio are similar and both ion chamber walls are made of low-Z material.

For ^{60}Co source measurements with commercial cylindrical ion chambers, the results indicate a larger extra positive vacuum current for the FC65-G. This observation was expected since the central collector is made of aluminum compared to plastic C552 for the Exradin A19. For the negative charge collection, a positive vacuum current is measured for the Exradin A19. This result was not expected, however, the current measurement is about the same order as the uncertainty.

For the commercial plane-parallel chambers, a negative vacuum current is measured for both ion chambers and collecting polarities for the ^{90}Sr source, an electron source. This could be explained by primary electrons stopping in the cavity. However, the magnitude of the negative vacuum current measured for negative charge collected is smaller than for positive charge collected for the Roos[®] chamber. This is

unexpected as the theory would predict that the magnitude of the vacuum current would be of the same order or larger than that measured for positive charge collection. For ^{60}Co source measurement, the PTW Roos[®] chamber shows no significant vacuum current measured for both collecting polarities. For the PTW Markus[®] chamber, a smaller current is measured compared to the result with ^{90}Sr source.

As it can be observed in the Table 3.2, for the two symmetric ion chambers (MARKIII and ALECS) measured at higher MeV electron beams (12 MeV and 18 MeV), the magnitude of the vacuum current is of the same order, but opposite sign as expected due to the particular design. For the 4 MeV beam, a negative vacuum current is measured at both polarities. This could be explained by primary or secondary electrons stopping in the central collector. This would also explain the smaller positive current measured for 8 MeV compared to the negative vacuum current.

For electron beam measurements, the cylindrical ion chamber A19 does reproduce the observation made for the plane-parallel ion chambers; the magnitude of the vacuum current increases with an increase of beam energy for positive charge collection and the opposite is observed for the negative charge collection.

From the results in Table 3.2 and Figure 3.7, it can be observed that the magnitude of the vacuum current, therefore the slow electron emission correction factor, is larger for the aluminum chamber than the graphite chamber. This result was expected as it would be predicted that a larger number of slow electrons would be emitted from a high-Z material.

3.4 Conclusions and implications

The extra ion chamber signal observed at low pressures was not explained, nor corrected for, by the polarity correction factor. The extra signal was also not explained by a change in ion recombination as the measurements were consistent with the predicted value. The dose deposition dependence on pressure, highlighted by Monte Carlo simulation, did not explain nor reproduce the measurement, which was the case in the investigation in kV beam by La Russa *et al.* [46].

However, the measured signal was consistent with the 50-year-old concept of a vacuum current and found to be significant when considering the stated uncertainties in primary ionometric measurements. The results show that the effect is somewhat dependent on the chamber design and construction, and can be up to 1 % for MeV electron beams. However, even for ^{60}Co , where cavity chambers are the primary standard for air kerma, the effect could be as large as 0.3 %. However, secondary instruments that are calibrated against a primary standard will only show a differential effect, e.g. due to small pressure (altitude) differences. It is often assumed that ionization chambers are old technology and therefore well understood, but there is still much in their functioning that is not fully explained.

The measurements using both graphite and aluminum NRC-built ion chambers, which will be used in this W_{air} investigation, have shown effects that are significant for this project. The largest calculated correction factor is for the aluminum ion chamber, as expected, and larger for the higher-energy beam. For both ion chambers, the rate of change of the correction factor with energy indicated that the correction factor would have an asymptotic behavior with energy. It was decided to use a constant value for high-energy electron beams, 18 MeV and above. For beam energies lower than 18 MeV, a linear fit of the results would be used.

Chapter 4: Graphite detectors, methods and material

Envy is the bond between the hopeful and the damned

Pink Floyd¹

4.1 Medium

The medium chosen for the first stage of this project was graphite. It has been selected for the following reasons;

- Graphite exposed to high-energy electron beams has shown a negligible heat-defect [48–51].
- It is a conductive material, which is fundamental for the ion chamber, but also very useful for the calorimeter as it prevents undesirable electric fields due to charge accumulation during radiation.
- Graphite has a low specific heat capacity at ambient temperature, six times smaller than water; it would therefore yield a radiation-induced temperature-rise six times larger for the same dose deposited.

¹Pink Floyd, *Green is the colour, More*, EMI Columbia, 1969

4.2 Ion chamber

The ion chamber used in this investigation is a graphite-walled symmetric plane parallel chamber. This graphite ion chamber is the third design, MARKIII, of a series of five symmetric plane-parallel ion chambers designed for ^{60}Co air kerma measurements at the National Research Council of Canada (NRC) in the 1970's. The ion chamber chosen for this investigation is very similar to the fourth design, MARKIV, as used and described by McCaffrey *et al.* [52].

The procedure to perform ionometric measurements is standard and has been described in detail in Chapter 2, Section 2.4 and will not be repeated here. The ion chamber was connected to a calibrated Keithley electrometer model 6517A. The electrometer calibration factor was measured using a charge-injection system [53] and found to be 1.0003(2). The full equation used to obtain Q_{air} is:

$$Q_{\text{air}} = (Q_{\text{raw}} - Q_{\text{leak}})P_{\text{TP}}P_{\text{ion}}P_{\text{pol}}P_{\text{elec}}P_{\text{SEE}}k_{\text{hum}}, \quad (4.1)$$

where Q_{raw} is the ionometric raw measurement, Q_{leak} is the measured ion chamber leakage, P_{ion} is the ion recombination correction factor, P_{pol} is the polarity correction factor, P_{elec} is the electrometer calibration coefficient, and k_{hum} the humidity correction factor. The correction for slow electrons, P_{SEE} , was discussed in detail in Chapter 3.

4.2.1 Design

This ion chamber has been selected for this investigation since its design is very similar to a calorimeter graphite core surrounded by a one millimeter air gap. The technical drawing of the ion chamber with the electrical connection is shown in Figure 4.1. The graphite (Ultra Carbon Corporation, Michigan, USA) used for machining

the ion chamber pieces had a stated density of $1.706(2) \text{ g}\cdot\text{cm}^{-3}$, which has been re-measured in 2019 using machined graphite cylindrical pieces from the original rod. The physical dimensions of the ion chamber's pieces have been measured prior to the assembly and are listed in the Table 4.1, as labeled in Figure 4.2.

Figure 4.1: The ion chamber technical drawing with its associated electrical connection using a coaxial cable and a ground wire.

Figure 4.2: Schematic and labels of the sensitive volume of the ion chamber and its surrounding. Greek and Latin letters are for radial and length dimension label respectively (used as reference for Table 4.1).

Table 4.1: Dimensions of the graphite parts of the ion chamber used. Parts labeled are illustrated in Figure 4.1 and labeled in 4.2.

Dimension label	Description	Value (<i>mm</i>)
a	Gap body/window	0.08(5)
b	Window thickness	1.009(1)
c	Thickness front cavity	1.19(2)
d	Gap collector/guard ring	0.009(5)
e	Thickness collector	2.012(1)
f	Thickness guard ring	2.013(3)
g	Thickness back cavity	1.14(2)
h	Thickness back window	1.01(3)
α	Collector radius	10.7859(2)
β	Guard ring inner radius	10.9158(1)
γ	Guard ring outer radius	13.2229(1)
δ	Body radius	15.469(7)
ξ	Gap collector/guard ring	0.1298(2)
ψ	Length of guard ring	2.3071(2)
ω	Gap body/guard ring	0.252(7)

4.2.2 Cavity air mass

Evaluation of the air cavity mass, through the volume and density is a crucial step in the determination of W_{air} . Any error in the evaluation of the sensitive volume of the ion chamber would lead to a systematic error in the absolute value of W_{air} . Using the mechanical dimensions of the ion chamber (the standard method used for primary standard ^{60}Co air kerma cavity chambers), the sensitive volume was

found to be $0.8629(14) \text{ cm}^3$. The parallel-plate design of the chamber lends itself to an alternative route to determining the air volume, through a measurement of the capacitance. The advantage of this method is that it is accomplished once the chamber is completely assembled and operational. The measurements were carried out in 1976, correcting for cable effects and the impact of the guard and collector not being perfectly planar (which modifies the electric field edge). The capacitance-based sensitive volume was found to be $0.86266(21) \text{ cm}^3$, which is 0.03 % lower than the mechanical measurement which has a 0.16 % uncertainty. Prior to using the chamber for this experiment, a series of QA tests were performed, to compare the response of the chamber in ^{60}Co to other cavity ionization chambers with known volumes. These tests indicated no changes in the sensitive volume at the 0.1 % level since construction and commissioning in the 1970s. Note that the ion chamber could not be dis-assembled to mechanically validate the results obtained from air kerma measurement.

4.3 Calorimetry, D_{med}

The calorimetric absorbed dose Equation 2.23 for this project can be rewritten as:

$$D_{gr} = \Delta T \cdot c_{gr} \cdot k_{hc} \cdot k_{n-gr}, \quad (4.2)$$

where c_{gr} is the specific heat capacity of graphite, ΔT is the measured temperature rise induced by radiation, k_{hc} is the heat loss correction factor and k_{n-gr} is a correction factor for non-graphite material within the calorimeter core. This last correction factor takes into account the differences between the specific heat capacity of pure graphite and the core, altered by the presence of the temperature sensor within the core. The radiation perturbations from air gaps and dose profile correction factor, Equation 2.23, have been ignored since they will be implicitly included in the

Monte Carlo dose ratio. The calorimeter design and the method used to obtain each parameter of Equation 4.2 will be detailed in the following subsections.

4.3.1 Design

The calorimeter used for this investigation is based on an open-to-atmosphere calorimeter design originally developed at the NPL [54] and is shown in Figure 4.3. The calorimeter is operated at standard ambient pressure in a quasi-adiabatic mode, i.e., there is no active control of the calorimeter core temperature and heat exchange between the calorimeter core and its surroundings is observed through heat loss after irradiation. The choice of this simple design was made after reviewing the literature, which demonstrates that for high-energy electron beams with dose rates of $5 \text{ Gy}\cdot\text{min}^{-1}$ or greater, the calorimeter could achieve a suitable level of precision and accuracy, comparable to more complex calorimeters using vacuum systems and active temperature control [42]. This convenient design could be quickly built for the initial stage of this project. It was also simple to modify the calorimeter design to match the dimensions of the ion chamber selected for this project, which should decrease the uncertainty of the Monte Carlo dose ratio.

The calorimeter graphite core, density $1.686(10) \text{ g}\cdot\text{cm}^{-3}$, is a disk of radius $10.803(4) \text{ mm}$ and thickness $2.692(1) \text{ mm}$. The graphite core is enclosed in a graphite phantom, as shown in Figure 4.3. The core is held in place by expanded polystyrene foam spacers of millimetric cube size. Polystyrene foam was chosen since it has a low density, about $0.02815 \text{ g}\cdot\text{cm}^{-3}$ and a small heat conductivity, $0.032(3) \text{ Wm}^{-1}\text{K}^{-1}$ [55].

Figure 4.3: Schematic of the graphite calorimeter detector and AC bridge. The drawing shows a single thermistor, but two thermistors in series were actually used in this investigation. R_1 , R_2 and $R_{\text{precision}}$ are fixed resistances of 10 k Ω , 10 k Ω and 15 k Ω respectively. R_{var} is a variable resistance used to balance the bridge. All dimensions in mm.

4.3.2 Temperature sensor

The temperature sensors selected for this project are thermistors, for two main reasons: their small volume and high sensitivity to temperature changes. A small volume temperature sensor is desirable to minimize the non-graphite correction factor, $k_{\text{n-gr}}$. This correction factor is proportional to the volume of the non-graphite material compared to the total volume. As the thermal properties of the material used for temperature sensors can have large uncertainty, the minimal volume of the temperature sensors ensures a smaller uncertainty of the non-graphite correction factor. The second reason comes out of the purpose of the calorimeter in radiation dosimetry, which is the measurement of temperature change due to radiation. Thermistors are

also resistant to radiation and can receive up to several MGy [49], therefore we can assume no radiation damage of the temperature sensor during this project.

The graphite calorimeter core temperature sensors were two negative-temperature-coefficient (NTC) thermistor probes (Micro-Betachip GA10K3MCD1, Measurement Specialties, Boston, MA, USA) with a resistance of approximately 10 k Ω at 25° C. Each thermistor probe was embedded in a 0.72 mm³ hole in the calorimeter core. The dimensions of the thermistor probes are 0.5 mm diameter and length of 3.3 mm, which results in a correction factor, k_{n-gr} , of 1.0009.

The approximate relationship between a NTC thermistor's temperature and resistance is shown in the following equation [56]:

$$R_{th}(T) = R_0 e^{\beta(\frac{1}{T} - \frac{1}{T_0})}, \quad (4.3)$$

where R_{th} is the resistance of the thermistor, T_0 is a reference temperature, R_0 is the resistance of the thermistor beads at T_0 , β is the exponential calibration factor and T is the thermistor temperature. To find the exponential calibration factor β of the thermistor and the reference resistance R_0 , a calibration was required. The thermistor calibration procedure used in this project follows that used at NRC for water calorimeter thermistor calibration, described by Seuntjens *et al.* [56], with minor differences as described below.

For calibration, each thermistor is embedded in a drilled hole slightly larger than the thermistor bead, in a mass (cubic centimeter size) of graphite. This set-up is then inserted into a waterproof bag which is placed in a mixture of water and ethylene glycol contained in an insulated box. The insulated box is connected through a pipe system to a computer controlled bath (Thermofisher Scientific, Haake AC25). The thermistor resistance is measured by a Keithley 2001 multimeter set to 4-wire ohm mode. The temperature of the water mixture in the insulated box is measured

using platinum resistance temperature detectors (RTDs) traceable to NRC's primary temperature standards. The resistance of the NTC thermistor is measured for a 18° C to 25° C range with step of 0.5° C. The calibration is repeated four times, two times from 18° C to 25° C and two times from 25° C to 18° C, alternately. The calibration measurement shows a quadratic relationship between the natural logarithm of the thermistor resistance and the inverse of the temperature as shown below:

$$\ln(R_{th}(T)) = a_0 + \frac{a_1}{T} + \frac{a_2}{T^2}. \quad (4.4)$$

The exponential calibration factor β of the thermistor can be derived from Equation 4.3 and 4.4 and is found to have a small temperature dependency:

$$\beta(T) = a_1 + \frac{2 \cdot a_2}{T}, \quad (4.5)$$

The temperature dependence of $\beta(T)$ implies a temperature dependence of $R_0(T)$. From previous calibrations of thermistors, the parameter $\beta(T)$ has shown a change of value between 0.06 % to 0.09 % per ° C and $R_0(T)$ of 0.002 % per ° C. However, using a constant value of $\beta(T)$ and $R_0(T)$ leads to an error under 0.04 % in the evaluation of the radiation-induced temperature rise.

4.3.3 Calorimetric measurement

As described above, the radiation-induced temperature rise is measured via the change in resistance of the thermistor. For the thermistor calibration, the resistance is measured using a 7.5 digit digital multimeter (DMM). However, the signal-to-noise ratio of the DMM is not sufficient to achieve the required uncertainty of the temperature rise measurement for dose measurements. For calibration, averaging at each fixed calibration temperature over a long period of time is possible, but for dose measurements, it is not possible. The alternative is to indirectly measure the resistance change of the thermistor using a system such as a Wheatstone bridge, which

offers increased signal-to-noise. However, it requires an additional experimentally-determined factor to convert the change in the measured bridge output to the change in the thermistor resistance. The primary standard water calorimeter at the NRC initially used a standard AC Wheatstone, but now uses an active version, as illustrated in Figure 11 in *Primary standards of absorbed dose for electron beams* by McEwen and DuSautoy [57].

A number of other standards laboratories have reported using direct measurements of the thermistor resistance (DMM-based) during a radiation measurement [58, 59]. A brief investigation of this approach was carried out as it does not require an additional experimentally-determined factor to convert the measured signal to resistance. Measurements were performed on the graphite calorimeter using an Agilent/HP 3458A and compared with the standard NRC bridge-based measurement system. The results indicated that the signal-to-noise ratio for the DMM was half of that obtained using the bridge and therefore it was decided to continue with the standard NRC acquisition system.

The calorimetric measurement is performed in three phases, as shown in Figure 4.4. The bridge output is measured for 30 seconds, which is called the pre-irradiation trace (from point A to B), to determine the background temperature drift. The calorimeter is then irradiated for a specific time (in this case 15 seconds or 30 seconds, from points B to D). Once the beam is turned off, the bridge output is measured for 60 seconds to evaluate the post-radiation temperature drift (to point E). To extract the radiation-induced temperature-rise, ΔT , from the temperature-time traces measured, the gradient (dT/dt) at points B and D has to be found and extrapolated to the mid-radiation (point C) as illustrated in Figure 4.4 A).

The gradient is usually taken to be the linear fit of the pre- and post-radiation traces and this extrapolation technique has been used to extract the radiation-

induced temperature-rise for the analysis in this project. However, in this project, the time constant of the calorimeter is about the same order of time as the measurement duration, due to the open-to-atmosphere design. As illustrated in Figure 4.4 B), the ΔT calculated using this numerical approach is not sufficient to account for heat loss. The heat loss correction factors are calculated using thermal simulations and will be discussed in more details in Section 4.6.

Figure 4.4: Thermal simulation of calorimeter temperature-time traces representing typical measurement (realistic) and its associated ideal case where there is no heat loss. B) Panel shows a zoom of A) to illustrate the technique for extracting the radiation induced temperature rise, ΔT , and the heat loss correction factor, k_{hc} .

4.3.4 Thermistor resistance rise measurement, ΔR_{th}

As mentioned earlier, the calibration of the thermistor is independent of the bridge used to measure the radiation-induced temperature increase. The advantage of this method is a better flexibility of the system, as the thermistors are easily interchangeable. As the output signal of the bridge is a potential difference, a conversion factor, $K_{\Omega/mV}$, from the difference in potential output ΔV_{out} into thermistor resistance change ΔR_{th} is required.

The bridge calibration coefficient is obtained by measuring the electrical potential

variation (ΔV_{out}) induced by a known resistance change in the opposing arm of the bridge, ΔR_{var} . To obtain $K_{\Omega/\text{mV}}$, the bridge is initially balanced by changing the value of R_{var} , see Figure 4.3. The bridge output is measured during 30 seconds to minimize noise and measure the drift. R_{var} is then increased by 5Ω for 30 seconds and returned to the initial value for another 30 seconds of measurement, as illustrated in Figure 4.5. ΔV_{out} is obtained as shown in Figure 4.5 A). The individual calibration coefficient is then $\Delta V_{\text{out}}/\Delta R$.

Figure 4.5: Example of bridge calibration, A) a single calibration, B) the linearity of the bridge calibration in relation with the bead thermistor temperature.

As $K_{\Omega/\text{mV}}$ depends linearly on the thermistor probe resistance, as shown in Figure 4.5, the bridge calibration has to be measured several times for a range of thermistor temperatures. As both calibration and measurement are performed with a balanced bridge, the calibration coefficient $K_{\Omega/\text{mV}}$ can be considered to be dependent on the initial value of R_{var} . The bridge calibration coefficient can be written as:

$$K_{[\Omega/\text{mV}]}(\Omega) = a \cdot R_{\text{var}} + b, \quad (4.6)$$

where a and b are respectively the slope and intercept of the linear fit of the measured conversion coefficients.

4.3.5 Temperature rise, ΔT

As the bridge ΔV_{out} would be known from the extrapolation of the temperature-time trace as described in the Subsection 4.3.3, one last step is required to convert the bridge ΔV_{out} into radiation induced temperature rise, ΔT . As explained earlier, by means of the bridge calibration coefficient, ΔV_{out} is converted into ΔR_{th} using Equation 4.6. Once the radiation induced resistance change is calculated, it is converted into radiation induced temperature change using the following equation:

$$\Delta T = \frac{\Delta R_{th}}{R} \frac{1}{S}, \quad (4.7)$$

where ΔR_{th} is evaluated as explained above, R is the total resistance which can be evaluated to be the sum of the opposite arms when the bridge is close to balance, and S is the sensitivity of the thermistor, which is defined as:

$$S = \frac{\Delta R_{th}}{R} \frac{1}{\Delta T} = \frac{\beta}{T^2}, \quad (4.8)$$

where β is the exponential calibration factor of the thermistor, Equation 4.5 and T is the temperature of the thermistor at mid-irradiation time.

4.3.6 Thermistor temperature

As shown in Equation 4.8, the temperature of the core is required to calculate the thermistor sensitivity. The thermistor's temperature can be evaluated by using the calibration coefficient and the thermistor resistance, using the following simplified bridge equation (see Figure 4.3) (ignoring the internal impedance of the lock-in amplifier):

$$V_{out} = V_{supplied} \cdot \left(\frac{R_1}{R_1 + R_2} - \frac{R_{var} + R_{precision}}{R_{var} + R_{precision} + R_{th}} \right), \quad (4.9)$$

which can be simplified, considering the fixed resistances R_1 and R_2 , see Figure 4.3, to be exactly the same value, to:

$$V_{\text{out}} = \frac{V_{\text{supplied}}}{2} \cdot \frac{R_{\text{th}} - (R_{\text{var}} + R_{\text{precision}})}{R_{\text{var}} + R_{\text{precision}} + R_{\text{th}}}. \quad (4.10)$$

The total resistance of the two thermistors is therefore:

$$R_{\text{th}} = (R_{\text{var}} + R_{\text{precision}}) \left(\frac{2 \cdot V_{\text{supplied}}}{V_{\text{supplied}} - 2 \cdot V_{\text{out}}} - 1 \right) \quad (4.11)$$

Using Equation 4.11 and the thermistor calibration coefficients, the thermistor temperature is evaluated by solving analytically the following equation (using a Python script):

$$R_{\text{th}} = R_{th01} e^{\beta_{01}(\frac{1}{T} - \frac{1}{T_0})} + R_{th02} e^{\beta_{02}(\frac{1}{T} - \frac{1}{T_0})}, \quad (4.12)$$

where R_{th01} and β_{01} are the calibration coefficients of the first thermistor and R_{th02} and β_{02} of the second thermistor.

4.3.7 Specific heat capacity of graphite, c_{gr}

The specific heat capacity is a key parameter for calculating the dose deposited in the calorimeter core, and therefore a key parameter to obtain W_{air} . The specific heat capacity of graphite has been measured at the National Physical Laboratory (NPL) by Williams *et al.* [60] and the Bureau International des Poids et Mesures (BIPM) by Picard *et al.* [61]. The specific heat capacity is considered to be linear with temperature in the range of the measurement, around 295.15 K, and can be found using the following equation:

$$c_{\text{gr}} = a \cdot (T - T_0) + b, \quad (4.13)$$

where T is the temperature of the core during the measurement in Kelvin and a , b and T_0 are the constants in Table 4.2 for both publications quoted above.

Picard *et al.* [61] used two methods, direct and differential measurement, to obtain the specific heat capacity while Williams *et al.* used the direct method on a larger group of graphite samples. The stated value in Table 4.2 from the Picard *et al.* [61] publication is the average of both methods. They concluded that the obtained value with the differential method should be considered the final value of the specific heat capacity since it was felt that there was less systematic error, loss from heating wire, involved in the method. However, the sample-to-sample reproducibility observed by Williams *et al.*, is better than 0.04 %, and the negligible variation of the heat capacity obtained with different rates of energy input suggests that the systematic error from heat loss via the wire should be smaller than 0.04 %. However, Picard *et al.* [61] observed a difference of 0.12 % between the two methods. Also, the difference in the value obtained using the direct method between the two laboratories, 0.3 %, is larger than the difference between the two methods.

Table 4.2: The parameters of Equation 4.13 measured by Williams *et al.* [60] and by Picard *et al.* [61]. The difference in b is mostly due to the difference in T_0 . The uncertainty stated in the last column is the total standard uncertainty ($k = 1$).

Publication	a $J \cdot kg^{-1} K^{-2}$	b $J \cdot kg^{-1} K^{-1}$	T_0 K	Heat capacity at 22° C $J \cdot kg^{-1} K^{-1}$
Williams <i>et al.</i>	2.94	644.9	273.15	709.6 ± 0.6
Picard <i>et al.</i>	2.95	707.4	295.15	707.4 ± 1.1

As both specific heat capacity values, from Williams *et al.* and Picard *et al.* results, does not agree within the stated uncertainties, the value used in this project was the average of both values found using Equation 4.13 with constants from Table 4.2. The standard uncertainty was the square root of the quadratic sum of each standard uncertainty, $1.2 J \cdot kg^{-1} K^{-1}$, equal to the half of the values difference.

4.3.8 Heat loss correction factor, k_{hc}

The heat loss correction factor, k_{hc} , is obtained using two simulated temperature-time traces, calculated by the finite-element method (FEM). The realistic traces were simulated by modeling the calorimeter and its immediate surrounding in a 2D radial (rz) geometry. To simulate the idealized temperature-time trace, the heat conductivity of the immediate medium surrounding the core was deactivated. The heat loss correction factor is calculated using the same extrapolation technique for both thermal simulations as for the measured temperature-time traces. The heat loss correction factor is the ratio between the temperature rises calculated for the idealized and realistic traces shown in Figure 4.4 B). More details on FEM and thermal simulation are provided in Section 4.6.

4.4 Radiation and phantom apparatus

The ionometric and calorimetric measurements have been performed using high-energy electron beams provided by the NRC Vickers linear accelerator (linac), which have been characterized by Ross *et al.* [62]. The energy spectrum at the linac exit window approximates a Gaussian shape with an 0.4 % uncertainty of the mean and a sigma of 0.4 %. The dose rate was $\sim 5 \text{ Gy} \cdot \text{min}^{-1}$ for both incident energies used. A pure aluminum scattering plate was positioned at 3.5 cm from the exit window to spread the primary beam. The beam was then collimated using a standard clinical 6 cm $\times$ 6 cm applicator at 0.5 cm from the exit window, the scattering plate being positioned between the first and second layers of the collimator (see Figure 4.6).

Two transmission chambers were installed after the electron applicator for beam monitoring and dose rate normalization purposes. The first was a PTW7862 chamber (PTW Freiburg) and the second was an NRC-built device. The PTW chamber

consists of four graphite-coated polyimide electrodes ($28 \text{ mg}\cdot\text{cm}^{-2}$ in total) while the NRC chamber has two aluminum-coated polyethylene terephthalate electrodes and three gold-coated polyimide electrodes ($56 \text{ mg}\cdot\text{cm}^{-2}$ in total). In addition, two Farmer-type field monitoring chambers were positioned at the edges of the primary beam in front of the detector phantom assembly, 1.5 m from the linac exit window. By monitoring the ratio of these two chamber readings, it was possible to determine if there was any significant variation in the lateral beam position.

Figure 4.6: Schematic of the radiation apparatus (upper drawing) with the detector phantom assembly and picture of the radiation set-up (lower pictures).

The ion chamber and the calorimeter core were each enclosed in a graphite slab, approximately 150 mm square, to provide side and backscatter. A detailed list of

graphite plates used in each detector's phantom is found in Table 4.3). The graphite phantom was placed in an polystyrene foam box to provide thermal isolation (shown in Figures 4.7 and 4.8. The use of the polystyrene foam box was unnecessary for the ion chamber apparatus, but was used to mimic the calorimeter apparatus.

Figure 4.7: Pictures of the expanded polystyrene foam box with the calorimeter and graphite phantom inserted as shown in A). The final assembly of the calorimeter in the expanded polystyrene foam box (insulating box) is shown in B) where the detachable parts are labelled as in A). The red dotted box show the relevant part for the discussion.

Table 4.3: Geometric characteristics for insulating polystyrene foam box and graphite phantoms as illustrated in Figure 4.7. All values are in cm. Z refers to the beam axis.

	Ion chamber			Calorimeter		
	X	Y	Z	X	Y	Z
Insulating phantom	24.65		15.525	25.075		15.225
Insulating hole (instrument space)	15.3	19.9	5.100	15.5	20.1	5.200
Graphite phantom	15.249		Front 0.100	15.255		Front 0.098
			Side 0.637			Side 0.476
			Back 0.419			Back 0.474

A typical procedure consisted of a series of 10 measurements with each detector. To minimize the systematic effect of any drift in the linac output, the calorimeter and ion chamber were mounted on a translation stage and were alternated in the beam on a 5-minute cycle. Irradiation times for the ion chamber and the calorimeter were kept similar to avoid effects related to beam start-up.

Figure 4.8: Detector phantom assembly. The “null” listing in Table 4.3 indicates no additional build-up material, just the front plate. The “back filling” is made of a low density material to ensure good thermal contact between the plates. Both buildup positions are illustrated, buildup “in” is positioned directly in front of the detector graphite phantom and the buildup “out” is positioned at 2.5 cm from the polystyrene box.

The radiation and buildup apparatus have been varied in terms of thermal and radiation conditions to identify any systematic error that could be produced during the analysis process through computer simulation (Monte Carlo or thermal modeling). To compare two similar radiation apparatuses while changing the thermal condition, the graphite buildup has been positioned inside or outside of the insulating box at 2.5 cm from the phantom. Another way to maintain the radiation

apparatus, but to modify the thermal condition is to change the radiation duration. The list of the different apparatuses used during this project is given in Table 4.4.

Table 4.4: Radiation and buildup apparatus variation. Buildup position refers to Figure 4.8 whether it is positioned in front of the detector phantom (Inner) or at the front of the polystyrene box (Outer).

Radiation			Buildup		
Energy [†] <i>MeV</i>	Scatterer <i>mm</i>	Duration <i>s</i>	Position (-)	Thickness <i>mm</i>	Mass thickness <i>g·cm⁻²</i>
20	4	15	Inner	Null	-
		30			
		15		9.513(7)	1.7502(3)
		30			
		15	Inner	19.028(11)	3.3453(53)
		30			
35	7	30	Inner	Null	-
		30			
		15		19.028(11)	3.3453(53)
		30			
		15	Inner	38.056(13)	6.6907(74)
		30			
		30	Outer	39.873(14)	7.0754(16)

[†]at the exit windows of the beam line, before the Al. scatterer

As stated in the Table 4.3, a thin backscatter was used compared to the recommended thickness for high-energy electron beam [54]. The backscatter should be at least 15 cm for a 35 MeV and 0.5 cm was used in this investigation. The thick-

ness used is a concession between minimizing the heat loss and dose equilibrium as illustrated in Figure 4.9 and Figure 4.10.

Figure 4.9: Experimental dependency with backscatter thickness. A) Depth dose curve at 20 MeV in a graphite cylinder of 30 cm thick simulated by Monte Carlo. B) Comparison of normalized temperature change of the calorimeter core at 4 cm depth in graphite irradiated by a 20 MeV during 30 sec. with 0.5 cm and 15 cm backscatter thickness.

Figure 4.10: Dose and heat loss correction factor dependence with backscatter thickness. A) Monte Carlo dose simulation of the core for two different thickness of front plate (0.1 cm and 4.0 cm). B) Heat loss correction factor simulated for two different thickness of the front plate (0.1 cm and 4.0 cm).

As shown in Figure 4.10, the variation of the dose deposition in the calorimeter core does not change by more than 0.26 % for backscatter thickness larger than

0.5 cm. However, the thickness of the backscatter has an impact on the heat loss correction factor, order of ten percent as shown in Figure 4.10 B). The percentage depth dose shown in Figure 4.9 A) illustrates the problem with a thick backscatter. While the calorimeter core is in the dose plateau, the thick backscatter is in the tail of the depth dose. This would create a cold mass which would drain the core heat and would increase k_{hc} .

4.5 Monte Carlo dose ratio

The dose ratio is used to convert the dose deposited in the calorimeter core to the dose in the sensitive volume of the ion chamber. In the energy range investigated, the dose in the sensitive volume of the ion chamber is expected to be between 15 to 25 % higher than the calorimeter core. This ratio depends on the geometric difference between the calorimetric and ionometric measurements since it has an impact on the radiation in the sensitive volume. The major geometric difference is that the medium of the sensitive volume of both detectors is not the same, bulk graphite versus air. Due to the difference in the medium, the Monte Carlo dose ratio calculation is highly dependent on the mass restricted stopping power ratio (SPR) between air and bulk graphite. While the stopping power is well known in dry air at 1 atmosphere, the stopping power of bulk graphite is less certain. The most recent ICRU report on stopping power in graphite, ICRU 90 [1], has reevaluated the I -value (mean excitation energies) in graphite to be 81 eV instead of 78 eV. Also, even if the graphite used in this experience is a bulk type, the stopping power should be evaluated using the grain type graphite for its impact on the density correction. These uncertainties regarding the graphite stopping power are the main reason why this experiment was conducted in a high-energy electron beam while the energy range used in radiation therapy is lower. The impact of the uncertainty in

the density correction and the I -value tend to be mitigated in higher-energy range.

Monte Carlo simulations for dose ratio calculation have been performed using the `cavity` and `egs_chamber` application from EGSnrc software [63] (released version 2017, commit 9266877). Electrons and photons have been tracked down to a kinetic energy of 1 keV (cut-off). Range-based Russian roulette [41], which is a well-known and tested variance reduction technique, has been used to increase the efficiency of the simulation. Custom density correction files have been generated for every graphite plate since the density of plates varied between $1.75 \text{ g}\cdot\text{cm}^{-3}$ and $1.86 \text{ g}\cdot\text{cm}^{-3}$. The files have been created with the density effect parameter of the crystalline (grain) graphite form (density $2.265 \text{ g}\cdot\text{cm}^{-3}$, $I_{\text{gr}} = 81 \text{ eV}$) using ESTAR data [6].

The beam source was simulated using `EGS_GaussianSpectrum Class Reference` with a mean energy of 20 MeV or 35 MeV and a sigma of 0.4 %. The source was started outside the geometric domain with a circular beam of 0.01 cm radius and with an angular spread, sigma of 0.25 degree [62]. The geometry began with the $41.2 \mu\text{m}$ thick window of titanium alloy (Ti 90 %, Al 6 %, V 4 %). The electron applicator was positioned downstream the exit window, 5 mm away. The simulated electron applicator geometry consists of four layers of aluminum and lead in square shapes based on the measured dimensions of the one used. The pure aluminum scattering foil was positioned downstream the exit window, 35 mm away, between the 2 first layers of the electron applicator, with a radius of 25 mm and a thickness of 4.0 mm or 7.0 mm depending on the beam energy (20 MeV and 35 MeV respectively). The detector geometry has been modelled following the details given in Figures 4.3 and 4.1. The four monitoring ion chambers were not simulated since it was assumed they would not significantly perturb the radiation field.

4.6 Thermal simulation

The heat loss correction factor, k_{hc} , is obtained using two simulated temperature-time traces, calculated by the finite-element method (FEM). The FEM software used during this investigation was COMSOL Multiphysics v.5.2. (COMSOL AB, Stockholm, Sweden) and FlexPDE (version 6, PDE Solutions Inc., WA, USA). FEM requires four components: geometry, material properties, energy source and the boundary condition. The boundary condition was set as an adiabatic system. This boundary condition is realistic as long as the simulated geometry is sufficiently large. This condition can be simply tested by increasing the size of the geometry till no significant differences are observed. The heat source implemented was a dose deposition mapping obtained using the `DOSXYZnrc` application calculated for every radiation set-up. Different types of interpolation are available, with both FEM software, between the defined points in the mapping energy map file (file created from Monte Carlo simulation). A quick study has shown no significant impact on the simulated interpolation calculation. To decrease computation time for both the thermal simulation and Monte Carlo simulation of the energy deposition mapping, the calorimeter apparatus has been simplified to a 2D radial geometry. Initial investigations did not demonstrate improvements using a 3D thermal simulation model compared to a 2D geometry.

To simulate the idealized temperature-time trace, the heat conductivity of the immediate medium surrounding the core was turned off. The heat loss correction factor is calculated using the same extrapolation technique for both thermal simulations as for the measured temperature-time traces. The heat loss correction factor is the ratio between the radiation temperature-rise calculated for the idealized and realistic trace shown in Figure 4.4 B). The simulated and measured temperature-time

traces of a calorimeter were compared as part of the validation. The COMSOL simulations were compared to results obtained using FlexPDE. FlexPDE also uses the finite element method, but the technique for describing the geometry, the differential equations and the boundary conditions are different from that of COMSOL.

Chapter 5: Graphite detectors, results and analysis

It seemed the answers were so easy to find
Supertramp¹

5.1 Ion chamber measurement

5.1.1 Validation

As stated in Section 2.4.2, the ion chamber used to measure W_{air} should meet some requirement to demonstrate suitable behavior. The measured leakage of MARKIII has shown to be smaller than 0.005 % of the typical charge measurement. The polarity correction factor has been measured to be 0.9988 in a ^{60}Co beam and has been measured for every set-up (energy and buildup thickness), the results are shown in Figure 5.1. It was found to vary between 1.00116(12) and 1.00338(20) for the energy range used to investigate W_{air} . These results meet the recommendations of the TG-51 addendum criteria for reference-class ion chambers, as the correction remained under 0.4 % and the variation with energy was smaller than 0.5 %. A small dependency with energy has been observed, as expected due to the small thickness

¹Supertramp, *Fool's Overture, Even in the Quietest Moments...*, A&M Records, 1977

of the sensitive volume [25, 29]. The relative humidity of the air ranged from 20 to 59 % during ionometric measurements. A constant value of 0.997 for k_{hum} was applied to all measurements, with an estimated uncertainty of 0.05 % [64].

Figure 5.1: Measured P_{pol} for a bias of -75 V (positive charge collected) measured for the graphite ion chamber as a function of the energy of the particle in the cavity.

The ion recombination correction has been measured in 8 MeV, 12 MeV and 18 MeV electron beams from an Elekta Precise linac for a range of charge created per pulse, Q_{pp} values. An example of a Jaffé plot obtained for a range between -15 V to -150 V is shown in Figure 5.2 A). As it can be seen in the lower panel of Figure 5.2 A), the inverse collected charge is not linear at any applied potentials, but the deviations from the linear fit is below the measurement uncertainties for a range from -15 V to -75 V ($0.06\bar{6}$ V to $0.01\bar{3}$ V⁻¹). Therefore, the bias potential applied to the ion chamber was selected to be -75 V.

The ion recombination correction factor should be linear with the charge created in the ion chamber cavity per linac output pulse, Q_{pp} , and the initial recombination should be less than 0.1 %. To evaluate the initial recombination, the following

equation [13] was used to fit the plot shown in Figure 5.2 B):

$$P_{\text{ion}} = 1 + C_{\text{init}} + C_{\text{gen}} \cdot Q_{\text{pp}}. \quad (5.1)$$

The initial recombination C_{init} was evaluated to be 1.00153(4) for an applied polarizing voltage of -75 V, a correction smaller than the maximum of 0.2 % stated in table III of the TG-51 addendum [13]. The initial recombination has been measured for positive polarity, +75 V, to be 1.00132(4) %. The difference between the initial recombination at opposing polarities is smaller than 0.001, as stated in the TG-51 addendum.

Figure 5.2: An example of a Jaffé plot obtained in A) (x axis is in absolute value) with the ion recombination correction factor over a range of charge created per pulse, Q_{pp} , in B) for an applied bias of -75 V.

5.2 Calorimetric dose measurement

5.2.1 Results

Temperature-time traces of a calorimeter measurement set are illustrated in Figure 5.3 A) with its associated averaged traces, compared to the thermal simulation in B). In a perfectly controlled temperature environment, it would be expected to observe an increase of the post-radiation trace curvature through successive measurements as the temperature difference between the calorimeter and its surrounding increases with each irradiation. However, the post-radiation traces, Figure 5.3 A), show no distinctive trend and appear to be random. This is most likely due to the back-and-forth procedure swapping the calorimeter and the ion chamber in the beam, which disturbs the thermal environment.

Figure 5.3: A typical set of measured calorimeter temperature-time traces in A), M-*th* represent the order in which the temperature-time trace has been measured and in B), the corresponding normalized average compared to the simulated temperature-time trace.

Figure 5.4: Dependence of the heat loss correction factor k_{hc} on buildup thickness, irradiation time and primary beam energy; 20 MeV beam (E20) and 35 MeV beam (E35). The error bar is the uncertainty evaluated by comparing the measured temperature-time curve with the simulated one.

The heat loss correction factors, k_{hc} , obtained for each radiation set-up listed in Table 4.4 are shown in Figure 5.4. The simulated thermal model was a single radiation run. It was decided to simulate it as a single run rather than a full simulation of the measurement (10 sets of irradiation with approximately 10 minutes between each irradiation) due to the insufficient characterization of the thermal environment to correctly simulate such a series. This approach was reasonable given the random distribution of the experimental post-irradiation traces.

As shown in Figure 5.4, the heat loss correction factor increases with the thickness of the buildup material. This result was expected due to the increase in the non-uniformity of the energy deposition in the graphite calorimeter and phantom as a function of buildup thickness as illustrated in Figure 5.5. The correction factor is also smaller for a shorter irradiation time since the rate of heat loss is driven by the difference of the core temperature and its surrounding medium. It is also larger for

the 35 MeV beam compared to the 20 MeV beam even while using small buildup thickness. This result was not expected, based on the similarity of the depth-dose curves for the two energies at a depth smaller than 3 cm. It shows the importance of the lateral dose uniformity in the graphite phantom. As the linear accelerator used for this part of the project is a research linac, the field does not show lateral uniformity. A 20 MeV beam scatters more in the lateral direction, providing better uniformity, compared to a 35 MeV beam at the same buildup thickness.

Figure 5.5: Dose distributions map implemented in the FEM software for the simulation of the temperature-time trace of a 20 MeV beam for A) no buildup and B) 2 cm buildup. The calorimeter geometry simulated include the calorimeter in the graphite phantom embedded in polystyrene foam. The label number are relative dose deposited.

5.2.2 Validation

The validation of the graphite calorimeter with another absolute dosimeter could have been performed using the NRC primary standard water calorimeter. The dose conversion from the graphite calorimeter measurement to the water calorimeter would have required additional Monte Carlo calculations. However, due to the very

different designs of the two calorimeters, the uncertainty in the Monte Carlo dose conversion would impact the value of the comparison. Similar graphite calorimeters have been previously tested and showed to yield accurate results [42]. The bridge used for this investigation was the same as the one used for the NRC water calorimetry and thermistors were calibrated using the same equipment. Therefore, self-consistency and reproducibility were considered a sufficient validation of the graphite calorimeter.

There is no obvious way to independently validate the thermal simulation. The heat loss correction factor calculated using thermal simulation computed with COMSOL Multiphysics, a graphical user interface based software, was compared to a second set of thermal models simulated using FlexPDE which is a scripted FEM solver. The calculated difference between both k_{hc} was, on average, 0.07 % which is less than the average statistical standard deviation of the calculated calorimeter dose deposited, see Table 5.4. The comparison is not a strict independent validation of the thermal model since both FEM software simulations were based on the same physical elements such as the energy source and energy map derived from EGS-nrc. However, it indicates consistency in the results obtained by the FEM software. The agreement between the post-irradiation curvature of the measurement and the thermal simulation was also considered as a self-consistency validation, see Figure 5.6.

The uncertainty in the heat loss correction factor was evaluated by comparing the measured temperature-time curve with the simulated one. The simulated realistic temperature-time trace was normalized with the maximum of the ideal trace (no heat loss). The measurement trace was then normalized so the maximum of both measurement and realistic simulation traces were the same. Using the same technique of analysis for both measured and simulated curves, k_{hc} values were calcu-

lated and compared. The difference between the two was then considered to be the uncertainty in the heat loss correction factor calculated using thermal simulation. The uncertainty was evaluated for each measurement set and ranged from 0.04 % to 0.79 % with an average of 0.3 %. The largest uncertainty was evaluated for the 20 MeV beam using 0.951 cm buildup. Interestingly, the second and third largest uncertainties were evaluated for the null buildup used for both energies. From the comparison between simulation and measurement post-irradiation traces in these particular cases, an underestimation of the heat loss correction factor k_{hc} is more likely than the converse.

Figure 5.6: Comparison between measured and simulated temperature-time curves for 30 seconds of irradiation at 35 MeV for different buildup thickness (B). The circular symbols are the measured values at 0.5 s intervals. The curves are normalized in 2 steps. First the realistic thermal simulation is normalized to the maximum value obtained from the ideal thermal simulation (no heat loss), then the measured temperature-time trace is normalized so the maximum of the curve, around point D (Figure 2.4), matches the maximum of the simulated one. The value of k_{hc} is also given for each situation.

5.2.3 Sensitivity analysis

As it can be observed in the lower panel of Figure 5.3, the point where the radiation stops is not as obvious in the measured data as in a perfect system or in thermal modeling. The rounded shapes of the traces around the point D are a consequence of the time lags due to heat transport between the core and the temperature sensor. This artifact could lead to an error in fitting the overall post-irradiation traces. Therefore, the gradient (dT/dt) at the point D of Figure 4.4 would be determined using a fitting between a point D' and point E. The point D' is defined from the irradiation starting, point B with the radiation length and a time-lag. This time-lag has been selected to be 2 seconds, based on an estimate of the time constant for thermistor-core heat transfer.

As mentioned in Chapter 4, Section 4.3, the fitting temperature-time gradient (dT/dt) at the point B and D, see Figure 4.4, is extrapolated to the mid-radiation time to calculate the radiation induced temperature-rise. The pre-irradiation traces appear linear for all calorimetry measurements, therefore, the gradient at the point B has been taken to be the linear fit of the full length pre-irradiation trace. For the post-irradiation traces, as shown in Figure 5.3, it is not as straightforward. The traces have a quadratic shape and there is a low frequency noise observed. These two elements make it less clear as to which kind of fitting should be used. A quadratic fit would be a better fit for the measurement post-radiation traces, however it is more noise sensitive. As it would potentially impact the calculated radiation-induced temperature rise, ΔT , as well as the heat loss correction factor, different fitting approaches have been tested and compared and are listed below:

- Single linear fit between D' and E, which would not be representative of the gradient at D, but robust against low frequency noise.

- Multiple linear fits over a varying fit range of $D' + \Delta t$, where Δt is ranged between 1 second and $D' - E$, the full length of the post-radiation drift. The gradient at point D is then evaluated by extrapolating the linear fit parameters to $\Delta t = 0$.
- Calculation of the gradient at point D using the derivative of the quadratic fit of the post-radiation drift (linearization) between the point D' and E.

The quadratic fit of the post-radiation drift and the multiple linear fits technique are more dependent on the data obtained around the point D than the single linear fit. The obtained type A uncertainty, the standard deviation between measurement runs, for both the quadratic fitting and the multiple linear fits technique were twice as large as obtained for the single linear fit. The evaluated type B uncertainty from the heat loss correction factor was also larger for quadratic fitting and the multiple linear fit techniques.

The difference between the dose calculated using the listed techniques above has shown to be within uncertainties. This result shows that the exact determination of the gradient at point D has less impact on the final results. This can be understood because the radiation-induced temperature-rise is corrected using k_{hc} and both are evaluated using the same technique. As the use of the quadratic fit or the multiple linear fits would have led to an apparent overestimation of the uncertainty, the results shown in this section have been obtained using the single linear fit of the post-radiation traces. The values obtained from the other techniques were used as an evaluation of the validity of the selected technique and an uncertainty has been added to the final value calculated of W_{air} in consequence, see Table 5.4.

5.3 Monte Carlo dose ratio

5.3.1 Results

Statistical (type A) uncertainties of 0.05 % were obtained after typically 10^{10} histories for the ionometry dose calculation, and 0.04 % after 10^9 histories for the calorimetry dose calculation. The electron spectra in the sensitive volume of the ion chamber were calculated using the `cavity` application, as shown in Figure 5.7.

Figure 5.7: Normalized electron energy spectra calculated by Monte Carlo using the `cavity` application in the ion chamber sensitive volume for the different measurement configurations listed in Table 4.4.

At the incident beam energy of 20 MeV without buildup, the spectrum shows a double peak. This is due to the separation of the sensitive volume of the ion chamber by the collector. The double peak is not visible for other configurations due to broadening of the spectra. However, it would be visible if the spectra were scored separately for the two sensitive volumes.

5.3.2 Validation

The Monte Carlo simulations have been tested using the recommended Fano test method [39, 65]. The Fano test is usually used to test the transport algorithm self-consistency. The Fano test is also very useful to validate the geometry and the volume calculation. To perform the test, some modifications to the Monte Carlo input files are required. First, the atomic composition has to be uniform. Therefore, the composition of the medium should be set uniformly with the same density correction file, but at the density of the original medium. Secondly, the medium has to be infinite. To fulfill this condition, the entire geometry is duplicated around itself to recreate an infinite medium, no particles would “die” at the geometric boundary. Thirdly, the field should also be uniform, and this is achieved by using an `egs_fano_source` Class Reference which is available in the EGSnrc distribution. The modification of the original input files to carry out the Fano test also highlights the limitation of the test. The Fano test will not validate the medium used for each region (density, I -value, etc.), nor validate the source. The dose scored in the regions of interest, the ion chamber air cavity and the calorimeter core, were respectively within 0.06(3) % and 0.006(20) % of the theoretical Fano value.

As pointed out with the Fano test, the source is not tested using the Fano test. To validate the beam source and modeling of the scattering foil with an applicator, a comparison of measured and simulated lateral beam profiles is a useful tool. The beam line simulation has been compared to a profile measurement obtained using a linear array of 47 ion chambers, the Victoreen THEBES II Model 7020 (Elimpex-Medizintechnik GesmbH, Austria). The results of both measurement and simulation are shown in Figure 5.8.

As can be seen in Figure 5.8, the measured profile is not completely symmet-

ric, the right side being slightly sharper than the left. This is consistent with the measurement of Ross *et al.* [62] and likely due to small asymmetries in the beam spot exiting the accelerator and minor deviations of the beam incident angle and position relative to the defined beam axis. Since the difference between simulated and measured profiles within the dimensions of the detector's sensitive volume (~ 1 cm radius) was smaller than the combined uncertainties ($< 0.4\%$) no modification was implemented in the beam simulated by Monte Carlo to account for this. As for the difference within the dimension of the graphite phantom (15 cm width), it was considered insignificant since the average difference was zero: the right and left sides would balance in the thermal simulation input source. The vertical profile was not measured as the results of Ross *et al.* [62] indicated that the horizontal profile was the one with the largest asymmetry and it was considered to be insignificant considering the size of the detector.

Figure 5.8: Normalized 20 MeV A) and 35 MeV B) radial beam profiles measured and simulated at 1.5 m from the Vickers exit window and their relative difference: C) 20 MeV, D) 35 MeV. The vertical dashed lines represent, respectively, the limit of the sensitive volume of the detectors and the limit of the graphite phantom.

5.3.3 Sensitivity analysis

A sensitivity analysis of the calculated dose ratio has been performed by changing the mass thickness and/or incident electron beam energy, within their stated uncertainty $k = 1$ (see Chapter 4). The position on the transverse beam axis was also investigated within a 1 mm displacement. All the different simulated scenarios are listed in Tables 5.1 and 5.2 with the impact on the average calculated W_{air} .

In Section 4.5 it was noted that a 1 keV cut-off was used for the Monte Carlo dose ratio. For the sensitivity analysis, however, a cut-off of 10 keV was used to reduce the calculation time. It was known that using a higher cut-off energy would impact the absolute dose ratio (by up to 1 %), but since the same cut-off was used in all investigated scenarios for the sensitivity analysis, any impact should completely cancel. The simulations have been run to achieve an uncertainty of 0.1 % in the sensitive volume for both detectors. Therefore, the uncertainty of the values in Table 5.1 is estimated to be 0.13 %.

Table 5.1: Sensitivity analysis scenarios simulated with Monte Carlo for a displacement of the detector in relation to the beam axis by 1 mm.

Displacement		Deviation of W_{air}
Calorimeter	Ion Chamber	Avg. (%)
1 mm	1 mm	0.08
center	1 mm	0.09
1 mm	center	-0.01

Table 5.2: Sensitivity analysis scenarios simulated by Monte Carlo and their relative impact on the average calculated W_{air} value. “Nom.” indicates that the value used is the one stated, the plus sign indicates the nominal value is increased by $k = 1$, reduced by $k = 1$ for minus sign. The density of both detector and phantom were increased or decreased in parallel.

Energy	Graphite Density		Deviation of W_{air}
	Calorimeter	Ion Chamber	Avg. (%)
Nom.	-	-	0.03
Nom.	+	+	0.21
Nom.	-	+	0.07
Nom.	+	-	0.11
-	Nom.	Nom.	0.12
-	-	-	0.07
-	+	+	0.02
-	-	+	0.02
-	+	-	0.08
+	Nom.	Nom.	0.19
+	-	-	0.23
+	+	+	0.01
+	-	+	-0.10
+	+	-	0.34

The average deviation in W_{air} obtained is smaller than the uncertainty of the calculated dose ratio (0.13 %). The largest deviation is 0.34 % for a beam energy increase by 0.4 %, the calorimeter detector and phantom density increase by $k = 1$, and the ion chamber density decreases by $k = 1$. While the impact of such a

case is significant for this investigation, the probability of this scenario occurring is low. The result is nonetheless useful as it indicates the extreme situation. One plausible scenario with larger deviation than the uncertainty is when the energy is underestimated by 0.4 %, which would lead to an underestimation of 0.19 % in W_{air} . For the displacement of the detector, the average W_{air} obtained is within the uncertainty. An uncertainty of 0.1 % has been added to the W_{air} uncertainty budget to account for these possible experimental uncertainties.

5.4 W_{air}

The mean energy required to create an ion pair in air, W_{air} , obtained in this investigation is shown in Figure 5.9 and in more detail in Table 5.3. The uncertainty bars in Figure 5.9 are the type A standard uncertainty ($k = 1$) combined with the heat loss correction uncertainty evaluated for each measurement set (i.e., the uncorrelated uncertainties). In Table 5.3, in column 5, the uncertainty in brackets is the combined uncertainty (type A and B), which is detailed in Table 5.4 and discussed below. In the last column, W_{air} has been averaged for every data set with the same energy at the point of measurement. In the last row, the average value for each column is presented. The value in parentheses for the last row, column 5, is the average uncertainty for each experiment and in column 6 is the standard deviation between experimental set-ups. The W_{air} values obtained at different electron energies in this investigation are consistent with a constant value of 33.87(18) eV. The data obtained here do not show any significant trend with energy (see Figure 5.9).

The evaluation of the uncertainty is listed in the Table 5.4. The value for the heat loss correction factor in the table represents the average. The temperature extrapolation type B uncertainties reflect the observation from the sensitivity analysis.

The influence quantities in the Monte Carlo section also reflects the results of the sensitivity analysis.

Figure 5.9: The mean energy required to create an ion pair in dry air, W_{air} , obtained in this investigation compared to the ICRU 90 recommendation, results of Tessier *et al.* [2] (Figure 5) and Burns *et al.* [22]. The uncertainty bars are only the type A uncertainties (uncorrelated) for each measurement set up combined with the heat loss correction uncertainty evaluated for each data set.

Note that there is a minor difference in the stated data in this thesis (Table 5.3) compared to the published data, Bougouin *et al.* [66] table IV, for the 20 MeV and 35 MeV for the 1.90 cm buildup. Looking at the consistency of the thermal simulation, it appears that the energy mapping of the 20 MeV and 35 MeV for the 1.90 cm buildup was inverted. As the differences are all within uncertainty and the conclusion does not change, no corrigendum has been sent to the journal editor.

Table 5.3: Detailed W_{air} values obtained in this investigation. Single values are for each specific experiment with the combined uncertainties of type A and B.

Incident energy (MeV)	Buildup thickness (mm)	Mean energy in IC cavity (MeV)	Irradiation length (sec.)	W_{air} (eV)	W_{air} avg. (eV)
20	19.03	7.7	30	34.11(12)	34.08(14)
			15	34.06(15)	
	9.51	10.4	30	33.85(28)	33.87(22)
			15	33.90(16)	
	0.00	14.0	30	33.46(22)	33.55(17)
			15	33.64(11)	
35	39.87	11.4	30	33.84(11)	33.84(11)
			15	33.81(12)	
	38.06	11.4	30	33.89(13)	33.85(12)
			15	33.89(13)	
	19.03	16.8	30	34.05(11)	34.07(12)
			15	34.10(13)	
	3.17	23.2	30	33.87(09)	33.87(11)
			30	33.88(12)	
	0.00	24.5	30	33.87(11)	33.87(11)
			30	33.67(17)	
			Avg.	33.87(14)	33.85(18)

Table 5.4: Relative standard uncertainties in the determination of W_{air} expressed in percent. The approach of the ISO Gum [67] is followed.

Component of Eq. 2.12	Type A (%)	Type B (%)
D_{med}		
Statistical standard deviation of ΔT	0.09	
Normalization ion chamber	0.06	
Specific heat capacity		0.15
Impurity correction factor		0.02
Thermistor calibration		0.05
Temperature extrapolation		0.22
Heat loss correction		0.30 [†]
Q_{air}/m_{air}		
Statistical standard deviation of Q_{air}	0.02	
Normalization ion chamber	0.07	
Mass of air	0.02	0.10
Polarity effect	0.02	
Ion recombination		0.03
Slow electron emission	0.05	
Relative humidity		0.05
Monte Carlo dose ratio		
Statistical standard deviation	0.05	
Influence quantity		0.10
Combined standard deviation	0.46	

[†] There is some correlation between the components for temperature extrapolation and heat loss correction, but for the purposes of this work, a correlation coefficient of zero is assumed.

5.4.1 Discussion

The average value obtained for W_{air} , 33.87(18) eV, is consistent with the recommended value of the ICRU 90, 33.97(12) eV. This value agrees with the result of Burns *et al.* [22], 34.03(7) eV, in photon beams ranging from 6 MV to 25 MV using a similar approach. The obtained data are consistent with the hypothesis of the energy independence of W_{air} .

The data are self-consistent in that the standard deviation between experimental set-ups is 0.18 eV while the average uncertainty for each data set is approximately the same: 0.14 eV. Also, at an energy around 11 MeV there is agreement between data obtained with the two incident energies of 20 MeV and 35 MeV. The uncertainty budget in Table 5.4 indicates that overall uncertainty is at the original target level of around 0.5 % and that the majority of uncertainty components are under control. However, the investigation revealed that the simplicity of the open-to-atmosphere design of the calorimeter made the determination of the heat-flow correction rather challenging. It is recommended that for any future investigation, the calorimeter design should be revised to reduce the impact of the thermal simulation.

The experiment is time-consuming (as with many calorimeter investigations) and so it was only possible to acquire a limited number of data points at different electron energies. It is recommended that any future investigation should focus on lower energies (in the range 6 MeV to 10 MeV) and also higher energies (above 30 MeV) as this would provide data to assess more conclusively the apparent energy dependence reported by Tessier *et al.* [2].

Another improvement would be to redesign the phantom, absorber and polystyrene foam box. A radial symmetry of the phantom should improve the agreement between the thermal simulation and measurements. Although no improvement was

seen by simulating the geometry using a full 3D simulation, designing a cylindrical phantom would reduce the number of approximations implemented in the thermal simulation. The insulation could also be improved by reducing the amount of conductive material around the detector by moving the absorber material outside the insulating box. This would be also very useful as it would be possible to improve the sealing of the polystyrene foam box: it would no longer be required to open and close it between each set-up.

A change of material should be considered to avoid issues of variable graphite density. The production process of graphite means that it is difficult to control the density through a rod or slab, the grain size can be variable, and impurity concentrations are not always well known. These variations can't easily be simulated meaning that the simulation may not represent the actual graphite calorimeter and ion chamber. The use of a pure material would avoid such issues.

Chapter 6: Aluminum detectors

*Parce que j'suis libre comme l'air, Libre de faire demi-tour,
J'avais continuer, continuer*

Daniel Bélanger¹

As mentioned in the discussion of the graphite results, changes could be made to improve the experiment; in particular, the design and the material of the detector along with a focus on using a lower-energy range (6 MeV to 10 MeV). The first half of this chapter will focus on the changes that have been made to the experiment to determine W_{air} . In the second half, the obtained results will be presented.

6.1 Methods and materials

6.1.1 Medium

Based on the analysis and review of the graphite measurements in the Chapter 5, the new material should preferably fulfill the listed properties;

- Pure element
- Conductor (thermal and electrical)

¹Daniel Bélanger, *Le Parapluie, Quatre saisons dans le désordre*, Audiogram, 1996

- Naturally found as an amorphous solid (non-crystalline form)
- Low Z material
- Machinable and not toxic
- Low reactivity with air

Some of these properties are essential to the functioning of the detectors, others are for convenience, such as being machinable, but at the same time non-toxic during machining (dust toxicity). The material should be an amorphous solid and have low reactivity with air. The first point is to avoid nonisotropic heat propagation, such as in pure graphite crystal, and avoid any crystal dislocation, transient energy absorption or lattice displacements in crystalline materials, which would potentially lead to a heat defect. The low reactivity with air is important to avoid oxidation which would potentially limit the conductivity, but could also lead to a heat defect. For the same reason, a pure element is preferable and would also potentially reduce the uncertainty of the Monte Carlo dose calculation. The element should be a low Z material to avoid activation of the detector during irradiation.

The element chosen for the experiment was aluminum. It fulfills the above list and has some additional advantages. It is an abundant element and widely used in industry. Therefore, the pricing is low compared to rarer elements, and the physical properties required for the experiment would likely be known at a lower uncertainty level. Aluminum is reactive with air, however, a thin passivation layer is rapidly created on the surface which prevent further oxidation [68]. The pure aluminum sublayer will no longer been in contact with air, or any other compound, which would exclude the possibility of heat defect in the calorimeter core. The impact of a possible heat defect in the aluminum oxide layer on the overall calorimeter core would be negligible as the layer is of few nm and aluminum oxide is not very reactive

with air or water vapour. A disadvantage is that aluminum is a soft metal, which can make it harder to machine thin pieces. The possibility of using an alloy with high purity was therefore investigated. After a review of a wide range of aluminum alloys, type 6061 was identified as the preferred option, since it was one of the hardest, higher-purity alloys easily available, had a long history of use (it was developed in the 1930s) and the Design and Fabrication Services branch of the NRC were very familiar with working with the material. The nominal composition of 6061 alloy is 97.9 % Al, 1.0 % Mg, 0.6 % Si, 0.3 % Cu and 0.2 % Cr.

The impact of using aluminum alloy compared to pure aluminum for the different detector component on the dose deposited in the sensitive volume of the ion chamber was studied using Monte Carlo calculations prior to any machining being carried out. The Monte Carlo study showed that the dose deposited in the ion chamber air cavity was sensitive to the metal used in parts directly surrounding it. However, the use of pure aluminum or alloy for the phantom (back and side-scatter) showed no significant impact, 0.06(13) %. The Monte Carlo investigation also showed that only the medium directly surrounding the sensitive volume was having a significant impact on the dose deposited. As the medium surrounding the calorimeter core was an air volume and it would not change in any scenarios, it was decided that a similar investigation for the calorimeter was not required. The only scenario of concern would have been to use alloy for the calorimeter core, but for thermal properties reasons, that possibility was already rejected.

6.1.2 Ion chamber

The ion chamber design was copied from the graphite chamber with a few minor modifications. The body was a ring where the two windows would be joined with a friction (press) fit, instead of a body in a cup shape with a single window press

fit. All the KEL-F[®](Polychlorotrifluoroethylene) parts, see Figure 4.1, have been changed to PEEK[®]plastic. All the pieces of the ion chamber were manufactured in pure aluminum 99.999 %.

The dimension of each part has been measured and validated by the NRC DFS branch, using a coordinate measuring machine (CMM), prior to assembly. These parts have also been measured using standard mechanical tools (micrometer, Vernier caliper). After the assembly of the body, guard ring and the collector, the dimensions and position of these three parts were measured by the Dimensional Metrology Team at NRC using a metrology-quality CMM. The details of the dimension and positions are listed in Table 6.1, following from Figure 6.1. The ion chamber has been commissioned and ion recombination, secondary electron emission, leakage and polarity effects have been evaluated.

Figure 6.1: Schematic and label of the sensitive volume of the aluminum ion chamber and its surrounding. Greek and Latin letters are for radial and length dimension label respectively (used as reference for Table 6.1).

Cavity mass

Using the mechanical dimensions of the ion chamber, the sensitive volume was found to be 0.8639(39) cm³. A series of QA tests were then carried out, comparing the

Table 6.1: Dimensions of the aluminum parts of the ion chamber used. The dimension labels (first column) are taken from Figure 6.1. The number in brackets represents the standard uncertainty of the value.

Dimension label	Description	Value <i>mm</i>
a	Gap body/window	0.060(5)
b	Front window thickness	0.939(6)
c	Thickness front cavity	1.230(7)
d	Front gap collector/guard ring	0.018(36)
e	Thickness collector	2.006(4)
f	Thickness guard ring	2.005(6)
g	Thickness back cavity	1.241(8)
h	Thickness back window	0.944(7)
i	Back gap collector/guard ring	0.024(36)
j	Thickness of ion chamber (body)	6.358(3)
j'	Thickness of ion chamber (center)	6.258(15)
j''	Thickness of ion chamber (window)	6.216(2)
α	Collector radius	10.835(1)
β	Guard ring inner radius	10.869(3)
γ	Guard ring outer radius	13.219(1)
δ	Body radius	15.462(4)
χ	Gap collector/guard ring	0.033(4)
ψ	Length of guard ring	2.348(6)
ω	Gap body/guard ring	0.251(5)

response of the chamber in ^{60}Co to other cavity ionization chambers with known volumes. These tests, combined with Monte Carlo dose calculations, lead to a volume of $0.8628(33) \text{ cm}^3$. As the aluminum ion chamber was compared to the graphite ion chamber, the uncertainty stated for this volume included the uncertainty in the I -value of both aluminum and graphite. Combining these two volumes, the sensitive volume was taken to be $0.8634(25) \text{ cm}^3$.

6.1.3 Calorimetry

Calorimeter design

As mentioned in Chapter 5, the core mounting of the calorimeter could be improved. The expanded polystyrene foam beads used in the graphite calorimeter provide the lowest-mass mounting system between core and surround. Unfortunately, it adds two kinds of uncertainty, positioning and heat conductivity. The beads are made out of the foam by cutting small parts; however, the cutting process compresses the foam which increases the conductivity of it by an unknown amount. Since it is not a very precise process, it does contribute to some uncertainty in the final positioning of the core within the gap. Considering a worst case uncertainty of positioning of 0.5 mm, for a set-up positioned at 100 cm from the source, it would increase the uncertainty by 0.1 % to the dose deposited.

To improve positioning, without increasing heat loss, a “hard” mounting system with minimal contact with the core has been designed and is shown in Figure 6.2. The design of the core jacket was also slightly modified to match the size of the ion chamber body. In this design, the core would be the same size as the ion chamber central collecting electrode.

Figure 6.2: Schematic of the aluminum calorimeter detector and its immediate surrounding. The core holder is made of PEEK[®] or aerogel. All dimensions shown in the figure are in mm and have been measured prior to assembly.

A study of the heat loss correction factor for graphite measurements has highlighted one possible problem with using buildup to change the particle's energy in the cavity. There is a correlation between the heat loss correction factor and the buildup used. Since the point of the experiment is to determine the possible energy dependency of W_{air} with energy, it would be preferable to avoid as much as possible an energy dependent parameter in Equation 2.12. However, the use of variable buildup thickness to change the particle's energy in the ion chamber cavity has the advantage of being reproducible and easy to implement. It was decided to reproduce

the measurement for two calorimeter set-ups with an important change in the heat loss. The calorimeter core holder has been therefore made out of two materials with very different densities.

The “low” density material chosen was silica-based aerogel (Airloy[®]X103M, Aerogel Technologies, LLC). The density is $0.2 \text{ g}\cdot\text{cm}^{-3}$ with a specific heat capacity approximately $1.0 \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ and a heat conductivity of $0.029 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$. Even if the specific heat capacity is 10 % larger than aluminum, as the piece is a tenth of the mass of the aluminum core, the aerogel core holder would have a low impact on the temperature of the core.

The “high” density material was Polyether ether ketone (PEEK[®]). It has low thermal conductivity, with a density of $1.3 \text{ g}\cdot\text{cm}^{-3}$ which brings the mass of the core holder to 57 % of the core mass, with a specific heat capacity of $1.13 \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ compared to $0.897 \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ for aluminum. The energy required to increase the temperature of the holder piece would be 15 % more than for the core. However, from Monte Carlo studies, the holder is expected to absorb 35 % less energy than the aluminum core. It would therefore change considerably the heat loss correction factor compared to a holder made of aerogel.

Thermal properties

The specific heat capacity of aluminum has been calculated at 22° C from 5 different publications [69–73], giving a value of $0.8969(10) \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$. The uncertainty was calculated using the standard deviation of the values from the different publications divided by the square root of $N-1$ ($s/\sqrt{N-1}$). The specific heat capacity of the aluminum alloy 6061 is stated to be 0.07 % lower [74] than pure aluminum at 20° C , therefore the specific heat capacity of the alloy at 22° C was considered to be $0.8976 \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ with the same uncertainty as pure aluminum.

The heat conductivity of pure aluminum is $237 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ [75]. The heat conductivity of the alloy is dependent on the heat treatment (temper) used by the manufacturer. The tempering used for the aluminum alloy rod purchased for the phantom was a T6511 and the heat conductivity for a temper T6 is $167 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ [74]. The heat conductivity uncertainty was considered to be $13 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ based on the heat conductivity variation between the different 6061 alloy tempers [74]. The uncertainty is conservative as it represents the range limits of the temper heat conductivity, however, it had low impact on the sensitivity analysis.

Silica-based aerogel has been studied since the 1930s. Despite the fact that this material is mainly used for its particular thermal properties, the specific heat capacity can be hard to find for a specific sample as it varies with the density of the aerogel. Scheuerpflug *et al.* [76] showed that an aerogel of density of $0.262 \text{ g}\cdot\text{cm}^{-3}$ would have a specific heat capacity approximately 25 % larger than vitreous silica. They measured the specific heat capacity of vitreous silica to be around $0.850 \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ which is larger than the value found in literature [75] ($0.74 \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ at 22° C). The specific heat capacity of the aerogel used in this study was considered to be $1.0 \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ with an uncertainty of $0.1 \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$.

The heat conductivity of silica-based aerogel has been measured and published more widely. The manufacturer of Airloy X103 gives a value of $0.029 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ for the aerogel used (density of $0.2 \text{ g}\cdot\text{cm}^{-3}$). For the other possible densities that can be bought, 0.1 , $0.4 \text{ g}\cdot\text{cm}^{-3}$ and $0.55 \text{ g}\cdot\text{cm}^{-3}$, the manufacturer states a value of $0.023 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$, $0.043 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ and $0.056 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$. As the value stated by the manufacturer aligns with the value found in literature, $0.024 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ [77–79], for comparable density, the value was taken to be $0.029 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ with an estimated uncertainty of $0.003 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$.

The thermal properties of PEEK[®](Polyether ether ketone), after a literature review, was found to be $1.130(50) \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ for the specific heat capacity and $0.25 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ for heat conductivity. The heat capacity value was found using equation (4) of Cheng *et al.* [80]. The uncertainty was evaluated to be about 5 % as it is the average difference found in comparison with the theoretical value reported by Zannoni *et al.* [81] quoted in [82]. The specific heat capacity and the heat conductivity of the expanded polystyrene foam (density of $0.02815 \text{ g}\cdot\text{cm}^{-3}$) is estimated to be $1.280(50) \text{ J}\cdot\text{g}^{-1}\text{K}^{-1}$ and $0.032(3) \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ from [55].

Temperature measurement and correction factor

As the procedure and analysis of the temperature measurement are the same as for the graphite measurements, they will not be repeated here. The temperature sensor used for this project was the same type as for the graphite calorimeter, thermistor NTC probe (Micro-Betachip GA10K3MCD1, Measurement Specialties, Boston, MA, USA). The resulting correction factor for impurity, $k_{\text{n-al}}$, was found to be $1.00047(29)$. The aluminum oxide layer was not included in the calculation of the $k_{\text{n-al}}$ as the relative volume (in regard of the total volume of the core) was insignificant, $\approx 0.001 \%$. The heat loss correction factor has been determined using a 2D radial model calculated using the FlexPDE version 6.4. The source file has been created using the `egs_chamber` application from EGSnrc software [63] on a radially divided geometry. A sensitivity analysis has been performed on the thermal properties of every material in the calorimeter apparatus for both calorimeter set-ups, “low” and “high” density materials for the core holder. The thermal model simulated was a single radiation run as for graphite calorimetry.

6.1.4 Radiation and detector phantom apparatus

The ion chamber and the calorimeter were each enclosed in an aluminum cylinder of 7.6 cm diameter to provide side and backscatter. The aluminum phantom and the buildup have been made out of aluminum alloy 6061. The alloy is harder, therefore easier to machine, and also economical. A single expanded polystyrene box was used to improve the rigidity and the positioning reproducibility of the two detectors, rather than the separate boxes used for the graphite experiment. Schematic and pictures of the detectors set-up are shown in Figures 6.3 and 6.4.

Figure 6.3: The detector assembly in the phantom and polystyrene foam box.

Figure 6.4: A) Inside view of the expanded polystyrene foam box. B) Picture of the expanded polystyrene foam box placed in the radiation set-up with aluminum buildup.

The ionometric and calorimetric measurements have been performed using clinical electron beams provided by the NRC Elekta Precise linear accelerator. It was decided to use the Elekta Precise as it offered the lower energies that were of interest and at the time of this part of the project, the NRC research accelerator, the Vickers, was unavailable. The beam was then collimated using a standard clinical $10\text{ cm} \times 10\text{ cm}$ applicator. Two Farmer-type field monitoring chambers mounted on the applicator were used for normalization purposes as shown in Figure 6.5. The first one is the FC65G SN1683 and the second chamber was a PTW30012 SN447, each connected to a calibrated Keithley 6517A electrometer. By monitoring the ratio of these two chamber readings it was possible to determine if there was any drift in the beam energy and/or beam position.

Figure 6.5: A) Radiation apparatus with the detectors phantom assembly (polystyrene foam box on the left) and B) Inside view of the electron applicator.

Typical measurements consisted of a series of 10 measurements with each detector. To minimize the systematic effect of any drift in the linac output, the calorimeter and ion chamber were mounted on a translation stage and were alternated in the beam on a 3-minute cycle. Irradiation times for the ion chamber and the calorimeter were kept similar to avoid effects related to beam start-up. The radiation beam energy and buildup thickness have been varied to modify the thermal

and radiation field conditions with the aim of identifying any systematic bias that could be produced during the analysis process through computer simulation (Monte Carlo or thermal modeling). Two materials for calorimeter core holders have been used and the irradiation time as well as the source to detector distance (SDD) has been changed. The different configurations are given in Table 6.2.

Table 6.2: Radiation, calorimeter and buildup apparatus variation. The number in brackets for the buildup represent the difference in the buildup thickness used for the ion chamber versus the one used for the calorimeter. Generally, the match is of few micrometers.

Energy <i>MeV</i>	SDD <i>cm</i>	Duration <i>s</i>	Core holder (-)	Buildup thickness <i>mm</i>
8	110	60	PEEK [®] and Aerogel	Null, 1.993(5) and 3.981(1)
12	110	60	PEEK and Aerogel	Null, 1.993(5) and 4.974(15)
12	150	30	PEEK [®]	Null
18	110	60	PEEK [®] and Aerogel	Null, 1.993(5), 4.974(15) and 9.996(4)
18	150	30	PEEK [®]	Null, 1.993(5), 4.974(15) and 9.996(4)
22	110	60	PEEK [®]	Null, 1.993(5), 4.974(15) and 9.996(4)
22	150	30	PEEK [®]	Null, 1.993(5), 4.974(15) and 9.996(4)

The procedure has been repeated twice for each set-up on different days, with the exceptions of 12 MeV and 22 MeV at an SDD of 150 cm. To avoid potential systematic errors from heat accumulation in the calorimeter (increase in heat gradi-

ent between the detector and the ambient air), the order of the measurements was reversed from day one to day two. For example, if the null buildup was the first measurement of day one, for the duplicate measurement, it was the last measurement taken on the second day. The measurement using the PEEK[®] core holder has been repeated using the aerogel core holder, with the exception of 22 MeV because of a linear accelerator operating issue.

6.1.5 Monte Carlo dose ratio

Monte Carlo simulations for the dose ratio calculation have been carried out using the `cavity` and `egs_chamber` applications of the EGSnrc package [63] (released version Oct. 2018, commit d0b1ec9). The beam line, including the accelerator head and electron applicator, have been modeled using `BEAMnrc` up to 95 cm from the point source. The accelerator model used was the same as that used by Muir and Rogers [83]. Electrons and photons have been tracked down to a kinetic energy of 1 keV (cut-off). Custom density correction files have been generated for PEEK[®], aluminum alloy, aerogel and expanded polystyrene foam: the details used to create the files are in Table 6.3. The stated density was measured on a large piece of each material.

The detector geometry has been modeled according to the details given in Figures 6.2 and 4.1 and Table 6.1. The buildup and the phantom have been modeled to be the exact size as measured. The monitoring ion chambers were not simulated since it was assumed they would not significantly perturb the radiation field due to their positions which do not intercept the primary beam, as shown in Figure 6.5. Sensitivity analyses have been performed for the I -value of aluminum, 166.0(2) eV [84], and air, 85.7(1.2) eV [1].

Table 6.3: Material information used to calculate the density correction from ESTAR application [6] used for Monte Carlo calculation (density correction file). The stated density and I -value are the same as used in the density correction file.

Material name	Fraction by weight	I -value (eV) [6]	Density ($g \cdot cm^{-3}$)
Aluminum alloy 6061	Mg 0.0120	166.3	2.708
	Al 0.9755		
	Si 0.0080		
	Cr 0.0040		
	Cu 0.0005		
PEEK [®]	H 0.042	75.3	1.30
	C 0.792		
	O 0.166		
Expanded polystyrene (97.5 % air, 2.5 % polystyrene)	H 0.00197	85.4	0.0282
	C 0.02360		
	N 0.73605		
	O 0.22588		
	Ar 0.01250		
Aerogel (91.4 % air, 8.6 % silica)	C 0.04566	90.7	0.200
	N 0.04019		
	O 0.69052		
	Si 0.21191		
	Ar 0.01173		

6.2 Results, sensitivity analysis and validation

6.2.1 Ion chamber measurement

Validation

The polarity effect has been measured prior to each set-up measurement of W_{air} . The results presented in Table 6.4 are the average of each set-up measurement and the results show good reproducibility. The energy dependency observed with the aluminum measurement in Figure 6.6 was also observed with the graphite ion chamber.

Figure 6.6: P_{pol} for a bias of -100 V (positive charge collected) measured for the aluminum ion chamber as a function of the energy of the particle in the cavity.

The aluminum ion chamber has been tested against the requirement stated in table III of the TG-51 addendum regarding criteria for reference-class chambers. The results are summarized in Table 6.4. The ion chamber measurements were performed using a calibrated [53] Keithley electrometer model 6517A with a calibration factor of 1.0001(2).

Table 6.4: The leakage, polarity and ion recombination correction factors of the aluminum ion chamber compared to the requirement stated by the TG-51 addendum [13]. The range of value for P_{pol} is for the value obtained at different buildup thickness at the stated nominal beam energy used in this investigation.

	Measured	Requirement
Leakage	0.004 %	< 0.01 %
P_{pol}		
8 MeV	1.0027(2) to 1.0047(4)	
12 MeV	1.0009(4) to 1.0022(6)	> 0.996
18 MeV	1.0001(4) to 1.0010(4)	< 1.004
22 MeV	0.9997(1) to 1.0001(1)	
Energy var.	0.50(4) %	< 0.5 %
P_{ion}		
Behavior with Q_{pp}	linear	linear
C_{init} , -100 V	1.00085(11)	> 0.998, < 1.002
C_{init} , +100 V	1.00088(14)	> 0.998, < 1.002
Polarity diff.	0.00(2) %	< 0.1 %

The ion recombination correction has been measured at 8 MV, 10 MV and 18 MV photon beams from an Elekta Precise linac for a range of values of the charge created per pulse, Q_{pp} . An example of a Jaffé plot obtained for a range between -25 V to -300 V is shown in Figure 6.7 A). As it can be seen in the lower panel of Figure 6.7 A), the uncertainty of the linear fit is below the measurement uncertainties for a range from -25 V to -100 V. Therefore, the bias potential applied on the ion chamber was selected to be -100 V. It was decided to not use -75 V, as with the graphite ion chamber, to increase compatibility with different electrometer models (not all can

supply a voltage magnitude smaller than 100 V).

The ion recombination is known to be dependent on the electric field strength. As both the graphite and the aluminum ion chambers have very similar cavity thickness, they should, in theory, have very similar ion recombination correction (for the same bias applied) and this is illustrated in Figure 6.7 B).

Figure 6.7: An example of a Jaffé plot obtained in A) (x axis is in absolute value) and in B) the ion recombination correction factor over a range of charge created per pulse, Q_{pp} , for both the graphite and the aluminum ion chambers calculated for an applied bias of -100 V (positive charge collected).

The relative humidity in air ranged from 18 to 54 %. As for the graphite ion chamber, the humidity correction factor was considered to be a constant value of 0.997 for all measurements with an associated uncertainty of 0.05 %. The charge measured was also corrected for the slow electron emission. As the correction shows an energy dependency at lower energies, the correction factor was calculated using a linear fit between 8 MeV and 18 MeV of the values obtained in Chapter 3 .

6.2.2 Calorimetric dose measurement

Temperature-time traces for an 18 MeV measurement using 2 mm of buildup are shown in Figure 6.9. As was expected, the curvature of the post-irradiation trace is larger when the core holder is made out of PEEK® as the heat loss is greater. The average standard deviation of the radiation induced temperature-rise using the aluminum calorimeter was 0.1 %, similar to graphite measurement. The temperature sensor type and read-out electronics used was the same for both calorimeter measurements. However, the linear accelerator used was different. For aluminum calorimetry, the set-up was closer to the radiation source, therefore closer to a potential source of electronic noise, but the noise measured for aluminum calorimetry was similar. As the signal of the measurement at a source-detector distance of 150 cm is 4 times smaller (irradiation time is half of SDD 110 cm), the relative standard deviation between measurements is also larger, 0.22 % on average compared to 0.10 % for graphite and aluminum calorimetry (SDD of 110 cm). As shown in Figure 6.9 C), the noise seems larger for measurement at 150 cm, however, the absolute noise measurement is at the same level as other calorimetry measurement runs.

Figure 6.8: Dependence of the heat loss correction factor, k_{hc} , on build-up thickness, irradiation time and nominal beam energy.

Figure 6.9: Temperature-time traces of a 18 MeV measurement set with 2 mm of aluminum buildup, M-th represent the order in which the temperature-time trace has been measured. The idealized temperature-time trace is a simulation without heat loss in the core and realistic is the simulation closest to the reality. A) at an SDD of 110 cm with the aerogel core holder, B) at an SDD of 110 cm with the PEEK[®] core holder, and C) at an SDD of 150 cm with the PEEK[®] core holder.

The heat loss correction factor, k_{hc} , obtained for each radiation set-up listed in Table 6.2 is shown in Figure 6.8. The heat loss correction factors calculated for measurement using the PEEK[®]core holder are larger than for the graphite measurements, but the k_{hc} calculated for the aerogel core holder is slightly smaller. The heat loss correction factor increases with the thickness of the buildup material, as in graphite calorimetry, due to the increase in the non-uniformity of the dose deposition as a function of depth in the phantom. Contrary to the graphite calorimeter, the heat loss correction factors do not increase with energy. As the linear accelerator used for this part of the project is a clinical machine, the field shows better lateral uniformity and the aluminum alloy phantom is within the field size. Therefore, the heat loss correction factor is driven by the depth dose uniformity (or nonuniformity). As the electron energy increases, for the same depth, the uniformity within the aluminum phantom increases, therefore, a smaller correction factor is expected.

The comparisons between the thermal simulation representing the measurement (realistic) and the experimental calorimeter runs are shown in Figure 6.10. As shown in the figure, the best agreement was for the measurement at 110 cm for the source with the PEEK[®]core holder. For the SDD of 150 cm, the agreement between the thermal simulation and the average experimental post-irradiation trace was at the same level as the spread of the experimental traces.

During the sensitivity analysis, it was noted that a larger deviation between the thermal simulation post-irradiation curves and measurements was observed for the calorimeter set-up using aerogel for the core holder compared to the set-up using PEEK[®]. The comparison between measurement and thermal simulation shows that the heat loss during and after irradiation was overestimated for aerogel, but not for PEEK[®], as illustrated in Figures 6.9 and 6.10.

Figure 6.10: Comparison between measured temperature-time curves and simulations. The circular symbols are the measured values at 1.0 s intervals. The curves are normalized in same way as for graphite calorimeter. BLD th represents the absorber thickness in mm. A) at an SDD of 110 cm with the aerogel core holder, B) at an SDD of 110 cm with the PEEK[®] core holder, and C) at an SDD of 150 cm with the PEEK[®] core holder.

The implemented energy source mapping from Monte Carlo calculations for aerogel and PEEK® core holders were very similar and interchanging them had no or minimal impact on the post-irradiation trace or the calculated k_{hc} . It was then decided to study the impact of varying the thermal properties of the aerogel within their stated uncertainties. Since only very small variations of the post-irradiation curve were observed when this was done, extreme values of the aerogel thermal parameters were then used in the attempt to close the gap between simulated and measured traces. It was noted that if the heat conductivity of the aerogel was set to zero, the simulated post-irradiation trace was very similar to the measured one.

The thermal simulation of the calorimeter with aerogel core holder led to two options that were both physically wrong; a thermal simulation with the conductivity of aerogel stated by the manufacturer, but not representative of the measurement and a thermal simulation matching the measurement, but with a non-realistic value of the aerogel thermal conductivity. Therefore, due to the limited available data on aerogel, the most pragmatic decision was to take the average of both simulations. The resulting simulated post-irradiation trace was within the spread of the measured post-irradiation trace. In most cases, the difference between both simulated heat loss correction factors were smaller or very close to the evaluated uncertainty of k_{hc} and for the case where it was larger, the uncertainty was increased accordingly.

Sensitivity analysis

The sensitivity analysis of the post-radiation trace fitting equation, using the same techniques as with graphite calorimetry, led to the same conclusion: linear fitting is more robust against low frequency noise and the simplest to implement, and the fitting equation selected had little or no impact on the calculated dose considering the average uncertainty of the calorimetry dose measurement. As in graphite calori-

metry, the sensitivity analysis was used to calculate a type B uncertainty related to the fitting equation of the post-irradiation trace, as shown in Table 6.7.

A sensitivity analysis of the range used for the post-irradiation fit has been performed. The sensitivity analysis has shown that the length of time discarded, to account for the time-lag, has no significant impact (under 0.05 %) between 1 to 10 seconds. Therefore, the first 2 seconds were discarded from the post-irradiation trace analysis, the same value as used for the graphite analysis.

An extensive sensitivity analysis of the implemented thermal simulation parameters has been performed. The size of the voxel used in Monte Carlo as well as in the energy deposition source file implemented in the FEM were optimized to the point where no differences were seen in the heat loss correction factor obtained, but the point density and the voxel size minimized the computational time. The size of the expanded polystyrene foam simulated in the FEM was also studied and optimized to minimize the computational time, without having any impact on the calculated heat loss correction factor. It was found that more than a 2 cm thickness of expanded polystyrene foam around the aluminum phantom had no additional impact on the heat loss correction factor.

For each material used and simulated, the heat conductivity and the specific heat capacity were varied in the simulation within $k = 1$ of the stated uncertainty (see Section 6.1.3). It was found that the thermal properties of the core holder was the parameters having the largest impact on the heat loss correction factor for both the PEEK® and aerogel (a maximum effect of 0.3 %).

Uncertainties and reproducibility

The difference between the dose obtained for each set-up has been compared to the duplicate measurement, carried out on a separate day. The dose differences obtained

have been compared to the type A uncertainty, standard deviation of the calorimetry measurements, combined with the type B uncertainty related to the monitoring ion chamber, 0.05 %. For the 28 set-ups that have been measured twice, the dose difference obtained was smaller than $k = 1$ for 75 % of the set-ups, 93 % were smaller than $k = 2$. As the distribution follows a normal curve, these results demonstrate reproducibility, and show that the uncertainty estimations are reasonable.

The improvement in the design of the aluminum calorimeter and phantom allows the sensitivity analysis of the thermal properties to be used for the evaluation of the uncertainty of the heat loss correction factor. This approach has the advantage of removing the correlation between uncertainty due to the use of the measurement in the evaluation of the type B uncertainty. This technique also implicitly includes the FEM solving precision. The impact of the thermal properties was calculated for each set-up and the averaged uncertainty of the heat loss correction factor was evaluated to be 0.33 %. The agreement of the thermal simulation with the measurement was also investigated using the evaluation technique used as for the graphite calorimetry measurement and it was found to be of the same order, 0.30 %.

6.2.3 Monte Carlo

Statistical (type A) uncertainties of 0.08 % were obtained after typically 10^9 histories for the ionometry dose calculation, and 0.06 % after 10^8 histories for the calorimetry dose calculation. The electron spectra in the sensitive volume of the ion chamber were calculated using the `cavity` application. The lowest and highest incident energy beam spectrums calculated are shown in Figure 6.11. At the incident beam energy of 8 MeV without buildup, the spectrum shows a double peak. This is due to the separation of the sensitive volume of the ion chamber by the collector.

Figure 6.11: Normalized electron energy spectra calculated by Monte Carlo using the `cavity` application in the ion chamber sensitive volume for some of the different measurement configurations listed in Table 6.2. The spectra have been normalized so the integral is equal to unity.

Validation and Sensitivity analysis

The Monte Carlo simulations have been tested using the recommended Fano test method [39, 65]. The dose scored in the regions of interest, the ion chamber air cavity and the calorimeter core, were within 0.02(4)% and 0.04(4)% of the theoretical Fano value, respectively.

A sensitivity analysis of the Monte Carlo dose ratio has been made for the aluminum experiment. As the medium was aluminum (no density variation), the sensitivity analysis has been performed over the uncertainty of the I -value of the sensitive materials, aluminum and air. The results are presented in Figure 6.12.

As the results presented in Figure 6.12 show no obvious trend with energy for both the aluminum and air, the impact of the uncertainty of the I -value was considered to be constant in the energy range of this investigation. The impact of the I -value uncertainty on the dose ratio calculated was similar for both media and was evaluated

to be on average 0.20(16) %. Although the uncertainty of the dose ratio obtained in this sensitivity analysis is almost as large as the deviation observed, the ratio obtained is systematically larger, or smaller, so the deviation observed is considered significant and was used as a type B uncertainty of the Monte Carlo calculation.

Figure 6.12: Monte Carlo dose ratio obtained from varying ($k = 1$) the I -value of both A) air and B) aluminum. The y-axis is the dose ratio difference between the obtained dose ratio using the I -value stated in the label and the accepted value, 85.7(1.2) eV and 166(2) eV for air and aluminum respectively. The dotted lines represent the average values obtained.

6.3 W_{air} , results and discussion

The mean energy required to create an ion pair in dry air, W_{air} , obtained in this investigation using aluminum detectors is shown in Figure 6.13 and in more detail in Tables 6.5 and 6.6. The uncertainties in Figure 6.13 are the type A standard uncertainty ($k = 1$) combined with the heat loss correction uncertainty evaluated for each measurement set. In Tables 6.5 and 6.6, in columns 5 to 8, the uncertainties in the brackets are the combined uncertainties (type A and B), which are detailed in Table 6.7 and discussed below. In column 9, W_{air} has been averaged for every data

set with the same electron energy in the ion chamber cavity and the last column is the standard deviation between experimental set ups of the same energy.

Figure 6.13: The mean energy required to create an ion pair in air, W_{air} , obtained in this investigation with an aluminum calorimeter. The uncertainty bars are only the type A uncertainties (uncorrelated) for each measurement set up combined with heat loss correction uncertainty evaluated for each data set.

The evaluation of the uncertainty is listed in the Table 6.7. The value of the heat loss correction factor in the table represents the average of the individual uncertainty evaluated each set-up. The variation between set-ups ranged from 0.13 % to 0.55 %. The temperature extrapolation type B uncertainties reflect the results of the sensitivity analysis on the post-radiation drift fitting technique (see sensitivity analysis Subsection 6.2.2). The I -value uncertainty in the Monte Carlo section represents the impact of I -value, varied within $k = 1$, on the calculated dose ratio (see sensitivity analysis Subsection 6.2.3).

In Figure 6.13, it is shown that both aluminum measurement sets, using different

core holders, are in general consistent with each other. However, it is also seen that seven data points measured using the PEEK[®] core holder are lower by about 1 % than that measured with the aerogel core holder. They do not appear to be consistent with the rest of the measurements using PEEK[®] either. These seven data points were measured using no buildup and represent the measurement at each incident energy for the two different SDD values.

The most likely source of error in the range of 1 % would be the heat loss correction factor; however, the post-irradiation curvature fits well with the measurement as shown in Figure 6.10 B). Also, comparing the average measurement curve with the thermal simulation tends to indicate that an overestimation of the heat loss correction factor is more likely than an underestimation for these data points, except for the 8 MeV incident beam measurement. In that case, by comparison to the measurement, an underestimation of the 0.4 % would be the extreme case. The conservative approach would be not to exclude those data points simply based on the fact that the W_{air} value is not consistent with the rest of the data set. A review has not indicated any specific error in the experiment or fault in the methodology, and it is very unlikely that the 1 % difference has occurred by some specific combination of factors, all acting in the same direction. However, the same trend can be observed with the graphite measurement where the measurement using no buildup was, for both incident energies, lower than the average.

Overall, the aluminum experiment was a success as it improved the investigation and meets most of the goals set at the end of Chapter 5. The change in material was the biggest improvement; it considerably reduced the amount of work on the sensitivity analysis of the Monte Carlo dose ratio and gave increased confidence in the value obtained as less parameters were varied. The improvement in the set-up by positioning the buildup outside the insulator polystyrene foam box has shown to

be very useful as it improved the work flow, with no need to reopen the insulated box between measurements. It was therefore possible to increase the number of data points taken which was one of the goals set at the end of the graphite experiment. It also improved the workflow for the thermal simulations as a single geometry had to be created rather than multiple ones, the only difference was the dose mapping used. The increased number of measurement points highlighted the issue of the no buildup set-ups, which was not possible with the graphite measurement due to the low number of measurement points.

The determination of the heat-flow correction was still challenging and the impact of the uncertainty in the thermal simulation was not significantly reduced. The uncertainty of the overall experiment remained in the target range, 0.5 %. It should be noted, however, that the spread of the measurements with the aerogel core holder was smaller than for the graphite measurements. The obtained W_{air} value in Figure 6.13 and the calculated heat loss correction factor between set-ups shown in Figure 6.8 indicated that the uncertainty evaluated for the heat loss correction factor is most likely to be overestimated.

The use of two different core holder materials did increase the amount of work, however, it has shown to be very useful and gave better confidence in the data presented. The good agreement between the PEEK[®] core holder with the measurement using an aerogel core holder has demonstrated the validity of the calorimetric measurement since the calculated heat loss correction factor was very different. The measurements have also shown agreement between measurements at the two SDD despite the low signal and the smaller signal-to-noise ratio, as shown in Figure 6.9.

Table 6.5: Detailed W_{air} values obtained in this investigation using a source-to-detector distance of 110 cm.

Incident energy	Buildup thickness	Mean energy		W_{air}		W_{air}	
		in IC cavity	SDD	PEEK	Aerogel	avg.	standard dev.
(MeV)	(mm)	(MeV)	(cm)	(eV)	(eV)	(eV)	(eV)
8	0	5.12	110	34.00(13), 34.07(14)	34.65(15), 34.78(15)	34.37(14)	0.40
8	2	4.41	110	34.98(20), 34.99(20)	34.83(21), 34.88(21)	34.92(20)	0.08
8	4	3.69	110	35.41(22), 35.46(22)	34.93(23), 35.00(23)	35.20(22)	0.27
12	0	8.67	110	33.65(14), 33.65(14)	34.43(14), 34.51(14)	34.06(14)	0.47
12	2	7.42	110	34.14(19), 34.22(19)	34.54(16), 34.56(16)	34.37(17)	0.21
12	5	6.22	110	34.59(20), 34.62(22)	34.78(18), 34.66(18)	34.66(20)	0.08
18	0	12.27	110	33.56(14), 33.61(15)	34.32(14), 34.32(14)	33.95(14)	0.42
18	2	11.29	110	34.05(17), 34.12(18)	34.48(15), 34.45(15)	34.27(16)	0.22
18	5	9.98	110	34.34(17), 34.29(18)	34.33(18), 34.39(18)	34.34(18)	0.04
18	10	7.87	110	34.39(18), 34.46(18)	34.50(18), 34.41(18)	34.44(18)	0.05
22	0	15.25	110	33.69(14), 33.66(14)		33.68(14)	
22	2	14.21	110	34.02(19), 34.08(19)		34.05(19)	
22	5	12.82	110	34.19(17), 34.24(18)		34.22(18)	
22	10	10.67	110	34.52(23), 34.31(22)		34.41(23)	

Table 6.6: Detailed W_{air} values obtained in this investigation using a source-to-detector distance of 150 cm.

Incident energy (MeV)	Buildup thickness (mm)	Mean energy in IC cavity (MeV)	SDD (cm)	W_{air}		W_{air}	
				PEEK (eV)	Aerogel (eV)	avg. (eV)	standard dev. (eV)
12	0	8.34	150	33.69(19)			
18	0	12.42	150	33.68(15), 33.81(16)		33.74(15)	
18	2	11.38	150	34.19(18), 34.27(19)		34.23(19)	
18	5	10.03	150	34.25(21), 34.18(22)		34.22(21)	
18	10	7.90	150	34.34(22), 34.23(22)		34.27(22)	
22	0	15.53	150	33.65(18)			
22	2	14.38	150	34.03(19)			
22	5	12.94	150	34.04(21)			
22	10	10.74	150	34.09(22)			

Table 6.7: Relative standard uncertainties for the determination of W_{air} expressed in percent.

Component of Eq. 2.12	Type A (%)	Type B (%)
D_{med}		
Statistical standard deviation of ΔT	0.11	
Normalization ion chamber	0.05	
Specific heat capacity		0.12
Impurity correction factor		0.03
Thermistor calibration		0.02
Bridge calibration		0.08
Temperature extrapolation		0.16
Heat loss correction		0.33
$Q_{\text{air}}/m_{\text{air}}$		
Statistical standard deviation of Q_{air}	0.01	
Normalization ion chamber	0.05	
Mass of air		0.29
Polarity effect		0.02
Ion recombination		0.03
Slow electron emission		0.05
Relative humidity		0.05
Monte Carlo dose ratio		
Statistical standard deviation	0.10	
I -value uncertainty		0.20
Combined standard deviation		0.56

Chapter 7: W_{air} , synthesis and discussion

You'll have to take me just the way that you find me

Peter Gabriel¹

In this chapter, the obtained W_{air} values in this investigation will be compared to the published data in the same energy range and the recommended ICRU 90 [1] values. The W_{air} value obtained using aluminum detectors, the published W_{air} value using graphite detectors by Burns *et al.* [22], Tessier *et al.* [2] and the graphite measurements presented in Chapter 5 together with the recommended ICRU 90 [1] values are shown in Figure 7.1. It can be noted that the spread of the measurements using the PEEK[®]core holder is in the same range as the graphite measurement and consistency has been improved by the use of aerogel, since the spread of the individual W_{air} values obtained is smaller.

As mentioned in Chapter 6 Section 6.3, the W_{air} value obtained using no buildup for both graphite and aluminum (using PEEK[®]core holder) detectors are systematically lower. As the results obtained in this investigation indicate two different trends, the values have been explicitly separated in Figure 7.2.

¹Peter Gabriel, *I Don't Remember*, Peter Gabriel, Charisma Records, 1980.

Figure 7.1: The mean energy required to create ion pair in air, W_{air} , obtained in this investigation compared to the investigation using the graphite detector, ICRU 90 recommendation (grey areas), results of Tessier *et al.* [2] (Figure 5) and Burns *et al.* [22]. For this work, the uncertainty bars are only the type A uncertainties (uncorrelated) for each measurement set-up combined with heat loss correction uncertainty.

Figure 7.2: Presented data of Figure 7.1, but separated to highlight the two apparent trends; A) W_{air} is indeed a constant value in high energy, the green shaded region represent the $k=1$ uncertainty of the value obtained in this investigation and B) W_{air} has an energy dependency in high energy.

As it can be observed in the Figure 7.2 A), the obtained values in this investigation are consistent and indicate a constant value. These measurements would lead to the conclusion that W_{air} has a constant value of 33.76(16) eV. As shown in the Figure 7.2 A), the obtained value in this investigation is consistent with the recommended ICRU 90 value of 33.97(12) eV, illustrated by the overlap of the blue and grey areas (representing the uncertainty of this investigation uncertainty and ICRU value uncertainty respectively). The values obtained are also consistent with the published value of Burns *et al.* [22].

For the second trend observed in this investigation, Figure 7.2 B), the results are consistent with Tessier *et al.* [2]. It can be observed that the obtained W_{air} values using aluminum detectors are systematically larger than the value obtained by Tessier *et al.* [2] (Figure 5) and the obtained value using graphite measurements presented in Chapter 5. There are two constant parameters in Equation 2.12 that have a systematic effect on all measurements which could explain the offset between the value obtained by Tessier *et al.* [2] and the aluminum measurements. The first constant is the mass of air in the aluminum ion chamber with an uncertainty of 0.21 % and the second is the specific heat capacity of aluminum with an uncertainty of 0.12 %. There is a third parameter that appears to have a systematic effect on the obtained W_{air} value that does not explicitly appear in the Equation 2.12. This parameter is the I -value of aluminum which impacts the Monte Carlo dose ratio, as mentioned in subsection 6.2.3, which contributes an uncertainty of 0.2 % to the W_{air} value. The combined effect of these three parameters is 0.37 % (square root of the quadratic sum) which would explain the difference between the obtained value of Tessier *et al.* [2] and the aluminum measurements.

The slope of the energy trend observed with the aluminum detector measurement is consistent with the one observed for the Tessier *et al.* [2] results. In the energy

range of 5 MeV to 15 MeV, the slope of Tessier *et al.* [2] is -0.15(2) % per MeV and in this investigation, using aluminum detector, the slope was calculated to be -0.18(3) % for the same particle energy range. These results give a strong hint of energy dependency of the W_{air} value. The Equation 2.12 and the listed factors in Table 6.7 will now be dissected to understand how the observed energy trend can be explained.

The calorimetric dose equation used in this investigation is shown in Chapter 2 Equation 2.23 and Chapter 4 Equation 4.2 and is repeated here:

$$D_{\text{med}} = \Delta T \cdot c_{\text{med}} \cdot k_{\text{hc}} \cdot k_{\text{n-med}}, \quad (7.1)$$

where c_{med} is the specific heat capacity of the material used, ΔT is the temperature increase due to radiation, k_{hc} is the heat loss correction factor calculated using thermal simulation and $k_{\text{n-med}}$ is a correction factor for material within the calorimeter core with a different specific heat capacity than the main material used.

In Chapters 5 and 6, the impact of the technique (fitting equation) used to obtain ΔT has shown to have a negligible effect on the obtained D_{med} measurement and did not show any impact on the W_{air} energy dependencies observed. For the specific heat capacity, in the temperature range that the measurements were performed, the specific heat capacity can be considered constant. The same conclusion can be drawn on the correction factor $k_{\text{n-med}}$ as it corrects the specific heat capacity of the calorimeter core. From Equation 7.1, the only possible source of the energy trend observed would be that the heat loss correction factor has an energy dependence, due to an error in the thermal model or a missing component.

Figure 7.3: Dependence of the heat loss correction factor, k_{hc} , on the average electron energy.

Figure 7.3 shows the data for the two core holder materials. Although an energy trend is observed for the heat loss correction factor, extensive sensitivity analyses have been performed on the heat loss correction factor, showing consistency in the obtained value. To obtain a constant W_{air} value, the measurements in the 8 MeV and 12 MeV beams would have to be reduced by 2 % to 5 %. This shift is, in the case of aerogel measurement, larger than the heat loss correction factor and, in the case of PEEK[®] measurement, of the same order as the correction itself. There is also the fact that aerogel and PEEK[®] core holder measurement have very different heat loss correction factors, see Figure 7.3, but the two measurement set-ups are consistent with each other, see Figure 7.1. Therefore, the observed W_{air} energy dependency cannot be explained by an error in the assessment of the heat loss correction factor.

The ionometric measurement equation used in this investigation is shown in Chapter 2 Equation 2.13 and Chapter 4 Equation 4.2 and repeated here:

$$Q_{air} = Q_{raw} P_{TP} P_{ion} P_{pol} P_{elec} P_{leak} P_{SEE} k_{hum}, \quad (7.2)$$

where Q_{raw} is the raw charge measurement that was acquired using a calibrated electrometer, P_{ion} and P_{pol} are the ion recombination and polarity correction factors respectively, P_{elec} and P_{leak} are the correction factor for the electrometer efficiency and leakage measurement, k_{hum} and P_{TP} are the humidity correction factor and the pressure-temperature correction factor. The slow electron emission correction factor, P_{SEE} was added consequently to the results obtained and shown in Chapter 3. There is also the mass of air m_{air} , which is not explicitly included in the equation, but as mentioned earlier, it is a constant value with energy and would therefore not explained the apparent energy dependence of W_{air} .

In Equation 7.2, most of the parameters are not energy dependent, but would be dependent on other factors. For the environmental correction factor, k_{hum} and P_{TP} , as the temperature, pressure and humidity of the air in the ion chamber cavity randomly varied between measurements, the effect on W_{air} would not correlate with the average electron energy in the cavity, Figure 7.2 B). The electrometer correction factor, P_{elec} , depends on the electrometer and the range selected, but has no energy dependencies and the P_{leak} was smaller than 0.005 % of the signal. The ion recombination correction factor depends on the charge created per pulse, but has no dependencies on the particle's energy and varies by no more than 0.4 % between measurement set-ups. For both the polarity and slow electron emission correction factor, P_{pol} and P_{SEE} , these correction factors change by less than 0.4 %.

In the case of the Monte Carlo calculation, it has been tested using the standard Fano test, showed self-consistency, and a full sensitivity analysis was performed. Tessier *et al.* [2] had suggested that the range of densities found for bulk graphite plates could be a possible explanation for the apparent energy dependence seen in the Domen and Lamperti data. In the case of the aluminum measurement, the density does not have any significant variability, but beam energy could be a possible source

of error. However, the measurements using PEEK[®] core holder and aerogel core holder were performed almost a year apart and the linac was calibrated between the two measurements. Therefore, as the two sets of measurements agree with each other, it is less likely that the energy of the beam was significantly different than the simulated one.

From this investigation, two conclusions can be drawn. First, the assumption that W_{air} is a constant value of 33.97(12) eV can't be excluded. However, it should be noted that the data indicating a constant value were not consistent with the other measurement points. This observation would suggest the possibility that there is an unknown significant effect not included in the analysis. The second conclusion is that the energy dependency observed by Tessier *et al.* [2] is consistent with the measurement made with aluminum and graphite measurements and could not be explained.

Chapter 8: Conclusion

The time is gone, the song is over, thought I'd something more to say

Pink Floyd¹

8.1 Background and purpose of the project

The mean energy expended by a charged particle to create an ion pair, W_{air} converts the number of charges created by ionization of air (the measured quantity) into the energy deposited that the charged particles expended (quantity of interest). The energy deposited is an important quantity in radiation physics as it is directly related to the dose deposited, which is for example the quantity prescribed by the oncologist for a patient undergoing radiotherapy treatment. W_{air} is a key value in radiation dosimetry; it enters directly in the equation for air kerma (Eq. 2.5) and it is also implicitly present in radiation therapy absorbed dose formalisms (e.g., AAPM TG-51 protocol (1999) [9] and IAEA TRS-398 (2000) [10]). The k_Q (or k_{Q,Q_0}) approach in these protocols uses a conversion factor to transform an ionization chamber calibration coefficient obtained in one radiation quality (usually ^{60}Co) for use in another. The calculation used to obtain these k_Q factors includes a ratio of W_{air} values for the two beams in question.

¹Pink Floyd, *Time, The Dark Side of the Moon*, Harvest Records, 1973.

The International Commission on Radiation Units and Measurements (ICRU) carried out a critical review of the key data used for ionizing radiation dosimetry and summarized the results in ICRU Report 90 [1]. This report has reaffirmed the accepted value of W_{air} (for dry air) of 33.97(12) eV. The report also indicates that this “constant” of radiation dosimetry does not depend on the incident beam energy above 10 keV, since there is no theoretical nor experimental evidence to the contrary. W_{air} has been extensively measured for low-energy beams, under 1 MeV, for both photon and electron sources, but measurements with megavoltage beams are limited, with only one data set each published for high-energy electron and photon beams as shown in table 5.6 of ICRU report 90 [1]. Cojocaru *et al.* [85] reported a single value of W_{air} 33.84(14) eV in high-energy electron beams (15 MeV to 50 MeV) and Burns *et al.* [22] obtained 34.03(7) eV in high-energy photon beams (6 MV to 25 MV).

There are therefore two, related, issues for clinical radiation dosimetry: the absolute value of W_{air} and its energy dependence over the energy range of interest for photon and electron beams. The latter is specifically a concern for dosimetry protocols and the k_Q formalism. If W_{air} is constant for both the beam of quality Q and the reference beam of quality Q_0 , then the absorbed dose measured using a calibrated ion chamber does not depend on the absolute value of W_{air} . On the other hand, if W_{air} does depend on the beam quality, the variation of W_{air} may impact the absorbed dose to water measurement accuracy, depending on the method used to obtain the k_Q factor. While a measured k_Q would directly take account of any W_{air} energy dependency, a calculated k_Q factor [11, 12] would not, unless explicitly included. The addendum to TG-51 (2014) [13] uses Monte Carlo-calculated k_Q factors and includes the assumption that W_{air} has no energy dependency above 10 keV. This is a simplification that is often missed in comparing dosimetry protocols, or comparing measured and calculated k_Q factors.

Muir *et al.* [25] published a comparison of consistent measured and calculated k_Q data sets and suggested a possible variation of W_{air} of up to 1.0021(9) for a 25 MV photon beam compared to the reference ^{60}Co beam. A recent re-analysis by Tessier *et al.* [2] of measured calorimeter to ion chamber ratios obtained in high-energy electron beams by Domen and Lamperti [23] has shown a possible energy dependence of W_{air} and an extreme interpretation of that data set would suggest a variation of up to 2 % [24] in the clinical energy range (although the physical basis for such a large variation is unclear). The present work aimed to determine the absolute value of W_{air} in high-energy electron beams and to investigate the assumption that W_{air} is energy independent in the clinical range.

8.2 Review of the results

W_{air} is defined by the International Commission on Radiation Units and Measurements (ICRU) report 31 [4] as the measurement of the total number (N) of ion pairs set in motion in an air cavity by a charge particle that expends all its kinetic energy (E) in the cavity. To determine the total number (N) of ion pairs created from the ionization of air in the sensitive volume, the air cavity of an ion chamber for example, the charge measurement is corrected to account for different factors such as the polarity effect, ion recombination and the temperature and pressure of the air in the cavity. A breakdown of the temperature-pressure correction factor was observed in in low-energy, kV x-ray beams [46]. Preliminary investigation in high-energy beams by McEwen *et al.* also indicated a breakdown in the temperature-pressure correction factor and could be explained by slow electrons emitted from the ion chamber electrodes (body and collecting electrode). It would result in an excess of charge measurement, a so-called “vacuum current”, i.e. a non-zero current measure for a zero pressure in an ion chamber cavity.

To investigate this potential effect, six different ionization chambers were studied, two cylindrical type and four plane-parallel type, using three different radiation fields: ^{90}Sr , ^{60}Co and MeV electron beams. The detail of this investigation is presented in Chapter 3. It was observed that the slow electron emission was dependent on the ion chamber design and the radiation beam. The signal was consistent with the 50-year-old concept of a vacuum current and found to be significant when considering the stated uncertainties in primary air kerma determinations in photon beams. These measurements suggest that calibrated chambers could be in error by up to 1 %. In the light of the obtained results, an additional correction factor, P_{SEE} , was added to the ion chamber charge measurement equation. In high-energy electron beams (between 8 MeV and 22 MeV), it was found that the correction for two specific plane-parallel chambers were smaller than 0.4 % and showed a small energy dependency, about 0.2 % for the range investigated. However, to apply this correction factor to ionization chambers in general, the study should be considerably extended. The intent of the work presented here was purely empirical, and there was not the opportunity to investigate the effect in detail, beyond obtaining a consistent correction for the ion chambers of interest for measuring W_{air} . Some questions still remain, including the deviations from the applied model for continuous radiation beams and further investigations are warranted.

In Chapter 4, the method and material using graphite detectors – a calorimeter and a plane-parallel ion chamber – to determine W_{air} in high-energy electron beams, using the NRC Vickers linear accelerator, was presented. The determination of W_{air} was performed using two incident beam energies, 20 MeV and 35 MeV, with variable graphite buildup thickness for a total of seven measurement sets. The results of this investigation were presented in Chapter 5. The obtained value for different mean energies are shown in Figure 5.9 and the data presented was consistent

with the hypothesis of the energy independence of W_{air} . The average value was determined to be 33.87(18) eV, consistent with the recommended value from ICRU Report 90, 33.97(12) eV. This new value also agrees with the result of Burns *et al.* [22], 34.03(7) eV, in photon beams ranging from 6 MV to 25 MV using a similar approach.

In light of the results obtained, it was concluded that further investigations should extend to lower energies (in the range 6 MeV to 10 MeV), as this would provide data to more conclusively assess the apparent energy dependence reported by Tessier *et al.* [2]. Another recommendation was to redesign the experimental apparatus to improve the thermal environment of the calorimeter and simplify the procedure for changing the measurement depth. A change of material was also an improvement highlighted by the investigation using graphite detectors. Graphite is a material with variable density, which increases the uncertainties and the degree of approximation required for the simulations (both radiation transport and thermal). It was therefore concluded that the use of a pure material would be advisable.

In Chapter 6, the changes made to the experimental set-up were described. The major change was to use pure aluminum as the main material for both detectors – calorimeter absorber and ion chamber. The design of the calorimeter was changed to use a holding system for the core using two different materials to assess its impact on the heat loss correction factor. The obtained results are shown and discussed in Chapter 7.

The results obtained show two distinct trends. A set of data, using no buildup with the higher density core holder, shows a constant, independent of electron energy, which was consistent with the graphite measurement also using no buildup. The average W_{air} value obtained, for this set of data, was 33.76(16) eV which is consistent with the recommended value of 33.97(12) eV [1] but lower than the value obtained

in photon beam (within $k = 2$) by Burns *et al.* [22], 34.03(7) eV.

The majority of the data obtained using the aluminum detectors showed an energy dependence that was similar to that reported by Tessier *et al.* [2]. In the energy range of 5 MeV to 15 MeV, the slope of Tessier *et al.* [2] is -0.15(2) % per MeV and in the investigation, using aluminum detectors, the slope was calculated to be -0.18(3) % for the same particle energy range. A systematic review of Equation 2.12 and the parameters influencing the overall result did not identify a possible experimental error that could explain the observed energy dependence.

8.3 Future work

The improvement of the design and material of the experiment in the second part of the investigation has shown promising results, especially using a low-density core holder made from aerogel. The results are more consistent with each other, showing a smaller spread in the results and a reduced heat-loss correction factor. However, in light of continued thermal simulation uncertainties, there is still room for improvement in the method to thermally isolate the calorimeter core from the surrounding material. The use of pure aluminum was a good decision as it reduced the uncertainty in the Monte Carlo dose ratio, compared to graphite, but an unexpected challenge was found in machining the material and assembling the detectors. Manipulation of pure aluminum is not straightforward as it can be damaged by hand tools or even fingernails. This led to an increase in the uncertainty in the determination of the sensitive volume, compared to the previous graphite detector, which was not anticipated. The manufacture of the new ion chamber also highlighted the excellence of the scientists and machinists who constructed the original graphite detector in the early 1970's. In light of the Monte Carlo investigation into the effect of con-

taminants, it would appear that a better option would be to use an aluminum alloy. If a machinable alloy with a high aluminum fraction ($> 97\%$) were used for the ion chamber and calorimeter core and the exact composition could be determined (e.g., from chemical analysis) then a higher overall experimental accuracy should be possible.

The determination of the mass of air, which is directly dependent on the determination of the sensitive volume, of the ion chamber, is a component that could be improved. Although a capacitive measurement can be used to confirm the mechanical volume, a chamber where the volume could be accurately varied offers opportunities for investigating potential systematic errors. This approach was successfully used by Burns *et al.* [86] for a primary standard cavity chamber for ^{60}Co and during this project a similar chamber was constructed. In this case, the starting design was the chamber used by Domen and Lamperti [23]. The ion chamber was constructed from pure aluminum and was intended as a back-up to the fixed-volume aluminum chamber described in Chapter 6. The ion chamber presented in Chapter 2, Figure 2.5 A) is based on the technical drawing of the ion chamber. In the end, the project timeline did not allow for the characterization and use of this second chamber, and therefore it would be interesting in future work to compare the two detectors. This is not simply an experimental comparison of two ion chambers, however, as the Monte Carlo dose calculations are geometry dependent.

The approach taken in this investigation was to carry out a combined Monte Carlo calculation of the medium/air dose ratio. Although this provided increased efficiency it resulted in a loss of information on the relative perturbation corrections of the four detects (two calorimeters, two ion chambers). Additional insight may be gained from carrying out individual calculations to determine these perturbation corrections. However, the self-consistency of the experiments, and the agreement

between different materials and geometries, would suggest that this will provide insight into detector response rather than identify an error.

In the light of the results obtained during this project, there are a few recommendations that could be addressed in a future project. In this investigation, the obtained results were not consistent, within $k = 1$, with the obtained results by Burns *et al.* [22]. That measurement was performed using photon beams. It should be straightforward to do measurement using photon beams as the NRC clinical accelerators can provide different photon beam energies ranging from 6 MV to 25 MV. A complete redesign of the calorimeter to operate with vacuum gaps (such as used by Domen and Lamperti [23] or Burns *et al.* [22]) is possible but would require significant effort and would limit the ease-of-use of the current calorimeter.

Unfortunately, both the detailed analysis of the Domen and Lamperti [23] experiment by Tessier *et al.* [2] and the review of influence quantities in the experiment described here using aluminum detectors have not identified any obvious avenue of investigation to explain the similar energy dependencies of the two experiments separated by more than 40 years. Given the assertion in ICRU 90 that there is no theoretical reason for an energy dependence above ^{60}Co energies, it is tempting to assume that what is seen is an experimental artifact, but there are no common features of the two experiments beyond the overall concept. Further measurements are clearly necessary to resolve the apparent contradiction and the suggestions given above – refine the calorimeter core design, use aluminum alloy instead of pure aluminum, and compare different ion chamber designs – are a good starting point.

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