MEASUREMENT OF COSMIC RADIATION EXPOSURE TO CANADIAN FORCES AIRCREW

Bernard M. Ellaschuk
Department of Chemistry and Chemical Engineering, Royal Military College of Canada,
P.O. Box 17000, Station Forces, Kingston, Ontario, K7K 7B4, ellaschuk-b@rmc.ca

ABSTRACT

The International Commission on Radiological Protection (ICRP) recommended in its Publication 60 (1990) that radiation exposure limits for personnel be reduced, that aircrew be acknowledged as occupationally exposed and that their exposure levels be monitored. In 1999/00, the Royal Military College developed a semi-empirical computer model, PC-AIRE, to predict the ambient dose equivalent (H*(10)) for global flight routes. The model was based on data spanning altitudes from 8,800 to 11,900 m. Regulations identify exposure limits in effective dose (E) and, consequently, in this research, an E/H*(10) scaling factor was developed for PC-AIRE. The model was further modified to enable its application in a batch mode for the simulation of a database of 1111 flights for Canadian Forces aircrew flying onboard the Airbus A310 aircraft. This was done to ascertain each aircrew's annual exposure for 1999 and enable a comparison to the proposed regulations. Additionally, a means of applying PC-AIRE as an exposure prediction and monitoring tool for any air carrier was developed.

I. INTRODUCTION

In 1990, the ICRP published various recommendations as a result of further study of the Hiroshima and Nagasaki atomic bomb survivors. These recommendations included: (1) a reduction in the exposure limits for occupational workers from 50 mSv yr^{-1} to 100 mSv over 5 years (i.e., 20 mSv yr^{-1}); (2) a reduction in the exposure limits for the general population from 5 mSv yr^{-1} to 1 mSv yr^{-1}; and (3) a consideration given to jet aircraft crew where they are recognized as being occupationally exposed (1). Transport Canada has reacted to the ICRP's recommendations and is producing a Commercial and Business Aviation Advisory Circular (CBAAC) recommending that Canadian airlines: (i) adopt the ICRP recommendation to consider their aircrews as occupationally exposed, (ii) recognize the ICRP's dose level of 20 mSv y^{-1}; and (iii) adopt an intervention level of 6 mSv y^{-1}. The Canadian Department of National Defence (DND) is not bound to Transport Canada regulations, but instead has its own Nuclear Safety Orders and Directives that stipulate the Department will endeavour to ensure its nuclear policy is consistent with the civilian program.

II. DESCRIPTION OF COSMIC RADIATION

Cosmic radiation originates beyond the boundary of our solar system and hence is given the name Galactic Cosmic Radiation (GCR). Sporadic bursts of energetic particles from our own sun also occur as Solar Particle Events (SPE) in the form of solar flares and coronal mass ejections. Both SPEs and GCRs have ionizing properties and thus pose a biological hazard (2).

As this ionizing radiation approaches the Earth, inelastic collisions between the incident particles and atmospheric nuclei produce a number of secondary charged particles (e.g., neutrons, protons, charged pions, electrons, positrons and gamma rays) in a cascading and buildup effect (3).

Radiation exposure is proven to be dependent upon three factors: solar cycle, geomagnetic position and altitude.

The solar wind, consisting of charged particles emanating from the sun, produces a magnetic field that attenuates incoming primaries from outside the solar system. As such, the GCR contribution acts in an anticoincident fashion with the solar cycle where it is at a maximum during a solar minimum situation and vice versa (4). This effect is quantified via a heliocentric potential (5).

Cosmic radiation that penetrates the Sun's magnetic field next encounters the Earth's magnetic field, which can deflect some of the lower-energy GCRs. The depth to which a particle can penetrate is characterized by its rigidity (i.e., ratio of the particle's momentum and charge to the speed of light). If the particle's rigidity exceeds the vertical cut-off rigidity (R_c) of the Earth's magnetic field at the point of entry, penetration can occur.

The last barrier to the incident GCR is the shielding effect of the Earth's atmosphere with an increasing thickness of atmosphere providing increased attenuation (via scattering and absorption). The cascade of secondary charged particles competes with their depletion (via decay, energy loss, and absorption), and a buildup of secondary particles occurs. Consequently, the dose rates from the secondary particles will increase with altitude, reaching a maximum at approximately 20 km above sea level (known as the Pfotzer maximum) (6).

III.AIRCREW EXPOSURE ASSESSMENT

In order to assess aircrew exposures, RMC personnel flew a TEPC on 64 global flights that spanned the entire cutoff rigidity of the Earth, at altitudes ranging from 9500 to 11900 m. The data from these flights (~20,000 points) were used to develop a semi-empirical model, PC-AIRE, that utilizes correlations as a function of the heliocentric potential, latitude and altitude in order to to compute the ambient dose equivalent for a great circle flight path between any two global positions (7,8). The code operates on a flight-by-flight basis, with keyboard entry of the following flight parameters: departure/arrival locations, ascent/descent times, altitudes flown and time at-altitude. This code was validated against a separate set of flight measurements at the RMC and was also in good agreement with separate measurements made by the Physikalisch Technische Bundesanstalt.

IV.CODE DEVELOPMENT

This paper describes the development of an effective dose (E) to ambient dose equivalent (H*(10)) scaling ratio for use in the program PC-AIRE. An application of the revised program to DND's Airbus A310 flight database for 1999 is also considered. The results of this application are then compared to current models in order to demonstrate the feasibility of the PC-AIRE model for the prediction of aircrew annual exposure in light of the proposed limits. DND is particularly interested in this latter point, given the reduced annual limits and the recommendations of Transport Canada.

A.SCALING RATIO DEVELOPMENT

PC-AIRE's output, H*(10) is specifically an operational quantity, whereas the dose limits established by the ICRP are defined in terms of the protection quantity effective dose, E. To produce an effective dose estimate from an ambient dose equivalent measurement, a scaling ratio of E to H*(10) was required. For this ratio a series of E and H*(10) values were obtained for identical altitudes and latitudes during the same phase of the solar cycle. Currently there exist two accepted transport codes upon which to base the E/H*(10) ratios: FLUKA (a Monte Carlo based transport code) and LUIN (a deterministic code based upon solutions to the Boltzmann transport equation.). Since there is a discrepancy of ~ 20% in the output of these two codes which remains unexplained, E/H*(10) ratios were developed from both models.

The data for the FLUKA-based E/H*(10) ratios were obtained from the published work of Ferrari and Pelliccioni (9) and from personal correspondence (10). From these data, best-fit curves were determined for the bounding conditions and a Lagrange interpolating polynomial produced for intermediate values (Figure 1). The FLUKA-based E/H*(10) ratio is given by the expression:

$$f_{E/H^*(10)}^{FLUKA}(R_c,A)=\begin{cases} f_1(A) & ; \quad R_c \le 0.4GV \\ \sum_{i=0}^{2} f_i(R_c)\cdot p_i(A); & 0.4GV < R_c < 12GV \\ f_3(A) & ; \quad R_c \ge 12GV \end{cases} \qquad [1.a]$$

where the bounding conditions are given by:

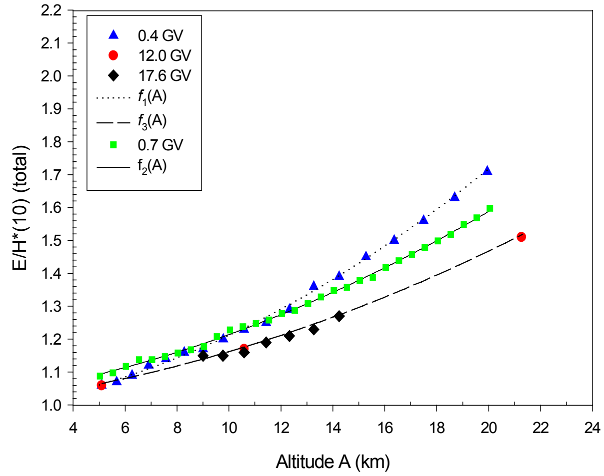


Figure 1: E/H*(10) ratio derived from FLUKA calculations.

$$f_1(A)=E/H^*(10)_{R_c=0.4GV} = 1.3634x10^{-3}A^2+9.4307x10^{-3}A+9.7972x10^{-1} \qquad [1.b]$$

and

$$f_3(A)=E/H^*(10)_{R_c\ge 12GV} = 9.1674x10^{-4}A^2+3.7872x10^{-4}A+1.0822 \qquad [1.c]$$

and the multiplicative (interpolation) function isgiven as the simple quadratic polynomials:

$$f_i(R_c)=c_{i1}R_c^2+c_{i2}R_c+c_{i3} \qquad [1.d]$$

and

$$p_i(A)=s_{i1}A^2+s_{i2}A+s_{i3}. \qquad [1.e]$$

The coefficients, c_{ij} and s_{ij} in equation [1] are listed in Tables 1 and 2 respectively.

Table 1: Coefficients of c_{ij} (a)

i	j		
	1	2	3
0	2.8736x10^{-1}	-3.6494	2.4138
1	-2.9498x10^{-1}	3.6578	-1.4159
2	7.6289x10^{-3}	-8.3918x10^{-3}	2.1361x10^{-3}

(a) R_c is expressed in GV.

Table 2: Coefficients of s_{ij} [(a)]

i	j		
	1	2	3
0	1.3634×10^{-3}	9.4307×10^{-3}	9.7972×10^{-1}
1	9.2095×10^{-4}	9.7771×10^{-3}	1.0169
2	9.1674×10^{-4}	3.7872×10^{-4}	1.0822

(a) A is expressed in km.

Similar to the FLUKA-based ratios, E/H*(10) ratios were developed using results from LUIN. Data for these calculations were obtained from LUIN simulations (11) conducted using the original PC-AIRE database (Figure 2). A Lagrange interpolation polynomial was used to develop the following LUIN-based E/H*(10) ratio:

$$f^{LUIN}_{E/H^*(10)}(A,R_c) = 9.901x10^{-3}A + f_5 \qquad [2.a]$$

where

$$f_5 = -4.170x10^{-4}R_c^2 + 1.188x10^{-2}R_c + 0.8816 \qquad [2.b]$$

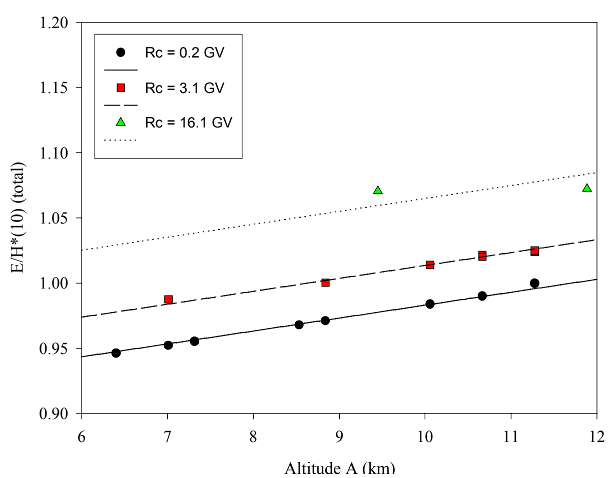


Figure 2: E/H*(10) ratio derived from LUIN calculations.

In general, the FLUKA correlation (Equation [1]) provides a more conservative estimate (by up to ~ 20%) at normal subsonic altitudes, compared to the LUIN correlation (Equation [2]) (where the E/H*(10) ratio is closer to unity).

B.APPLICATION OF PC-AIRE TO AIRBUS FLIGHT DATA

Determination of the annual effective dose (E) of the CF personnel flying onboard the Airbus A310 aircraft utilized archived A310 flight data records for January through December, 1999. These data contained the flight origin, flight destination, flight date, departure time, arrival time and names of all crewmembers onboard. With estimates of altitude, and ascent/descent times, these archive data were used as input to the improved PC-AIRE model which provided a route (effective) dose prediction for each flight. Subsequently, each individual's annual effective dose was obtained by summing the route dose estimates on each flight over the year.

Archived flight record data for the CF Airbus A310 aircrew consisted of 1111 flights with 175 aircrew. To expedite data entry, a C++ program (EXPOSURE) was written which enabled batch file input/output (in ASCII format) for use by the PC-AIRE C++ program.

The archived A310 flight data was originally resident in an electronic database called the Mission Management Application. An electronic copy of the data was unavailable for use and its output format was also incompatible with the requisite PC-AIRE code input. Given the quantity of data and the requirement to repeatedly manipulate such data, a relational database was created and populated with the archived A310 flight data. For the current application, MS-ACCESS® was chosen for the database software.

When the database was populated with the archived data, a query was conducted on the tables and the result exported to produce a file with the necessary input parameters as required by EXPOSURE/PC-AIRE.

The incomplete nature of the archive data required assumptions to be made regarding altitudes flown at and ascent/descent times, with the premise of producing a conservative route dose estimate. These assumptions were added to EXPOSURE in the form of "if-then-else" statements. Depending upon the total flight duration provided by the archived data, EXPOSURE selected an appropriate altitude and determined the ascent and descent times along with the subsequent at-altitude time.

PC-AIRE also required input in ASCII text format (for batch file application). As such, an input file was created wherein each row was established as a separate flight and consisted of the following tab-delimited information: (i) heliocentric potential, (ii) total time, (iii) departure latitude, (iv) arrival latitude, (v) departure longitude and (vi) arrival longitude. The file was saved as a simple text file with ASCII characters. Data for this file was exported from an electronic database that had contained the archived A310 data.

The program EXPOSURE opened the ASCII text "input" file, read a line of data consisting of the six items mentioned above, and then computed the remaining four data items, i.e., the altitude, ascent time, descent time and at-altitude time, via the if-then-else statements. It then called PC-AIRE to compute the ambient dose equivalent for that point in the flight. Looping through the data file and summing the H*(10) values, enabled computation of the route dose. The two E/H*(10) ratios described previously, were also applied for effective dose prediction. The results were saved as ASCII text in an output file and imported into the database.

Executing EXPOSURE produced an output file (ASCII text) containing the ambient dose equivalent, altitude, time-at-altitude and the effective dose values. These values were incorporated into the database.

With a fully populated database, queries were conducted to yield the values of the annual effective dose for each member. These queries were based first on the FLUKA ratio and then on the LUIN ratio. Additional criteria were added to the queries to enable a review of only pilots or flight attendants, for example.

V. RESULTS AND DISCUSSION

The above queries identified the number of personnel whose annual effective dose exceeded the CBAAC limit of 1 mSv y^{-1}. These results are listed in Table 3 along with estimates produced using the US FAA CARI-6 code and a simple model proposed by Ferrari (12). Table 4 summarizes the percentage of A310 aircrew that exceeded specified exposures from 1 to 6 mSv y^{-1} based upon annual effective doses computed by the more conservative FLUKA-based E/H*(10) ratio. The highest annual exposures determined were for two personnel, one a load master and the other a flight attendant, with values of 4.67 and 4.68 mSv y^{-1}, respectively, as calculated with the FLUKA-based E/H*(10) ratio. The LUIN-based E/H*(10) ratio yielded values ~ 11% lower for these same individuals.

Figure 3 contains 1111 points corresponding to the effective doses produced by the two ratios for each flight in the archived Airbus A310 data. Superimposed upon the plot is a perfect correlation line. The relative differences between the values of E range from ~ 30% for low dose values to ~ 18% for high dose values. As expected, the use of the FLUKA ratio provides a highr route dose value.

Table 3: Number of personnel whose annual effective dose exceeded 1 mSv yr^{-1} [(a)]

Model	Total Aircrew (175)	Pilot (26)	Flight Steward (20)	Flight Attendant (25)	Load Master (32)	Other Crew (72)
$E/H^*(10)_{FLUKA}$	83	18	18	23	21	3
$E/H^*(10)_{LUIN}$	80	18	18	22	19	3
CARI-6	80	18	18	22	19	3
Ferrari	84	18	18	23	22	3

(a) Number of personnel within the occupation is listed in brackets.

Table 4: Percentage of Airbus aircrew that exceeded the stated number of mSv y^{-1}

Specified Exposure (mSv y^{-1})	Total Aircrew (%)	Pilot (%)	Flight Steward (%)	Flight Attendant (%)	Load Master (%)	Other Crew (%)
1	48	68	90	92	66	6
2	33	64	80	52	38	2
3	22	40	45	44	25	2
4	6	24	5	4	9	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0

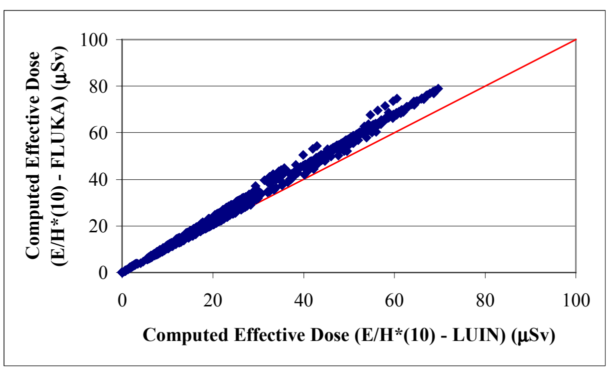
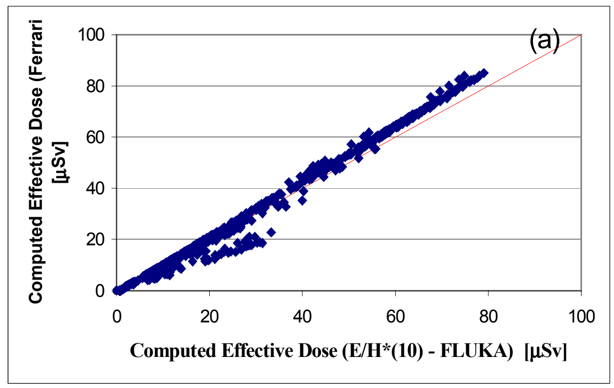


Figure 3: Comparison of effective doses as computed using LUIN and FLUKA-based E/H*(10) scaling ratios.

The effective dose values obtained by employing the E/H*(10) ratios developed were compared via a sensitivity analysis (Figure 4) to a simple model proposed by Ferrari (12). Approximately 90% of the effective dose values generated by the E/H*(10) ratios are within 20% of those predicted by the Ferrari model. The uncertainties associated with values generated by Ferrari's model were reported to be within 10 to 15%, or better, of calculated values (12).



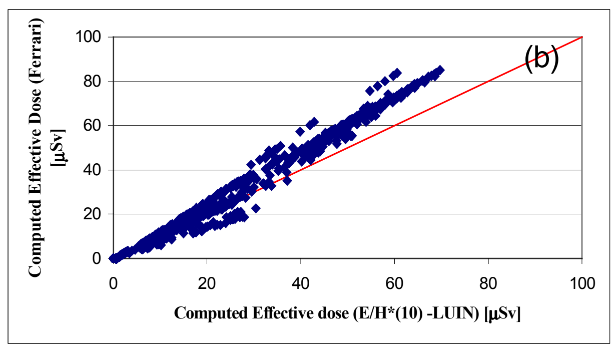
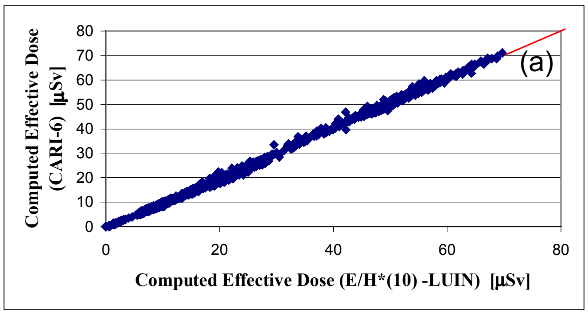


Figure 4: Comparison of effective doses as computed by Ferrari's model and the (a) $E/H^*(10)_{FLUKA}$, and (b) $E/H^*(10)_{LUIN}$ ratios.

A comparison of the effective dose values determined by the E/H*(10) ratios of this work were also compared to the US FAA's CARI-6 model (Figure 5). A strong correlation is noted between the LUIN-based E/H*(10) ratio and the CARI-6 model with ~ 90% of the results having a relative difference of < 20%.

The comparison to CARI-6 demonstrated, once again, that both E/H*(10) ratios provide effective dose values (E) that are reasonably consistent with published theoretical work and hence provide an endorsement for using these techniques with PC-AIRE.



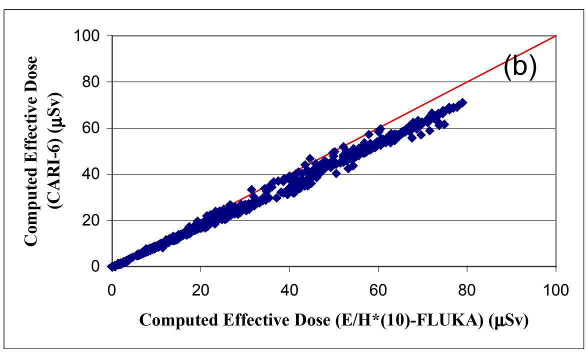


Figure 5: Comparison of effective doses as computed by CARI-6 and the (a) $E/H^*(10)_{FLUKA}$, and (b) $E/H^*(10)_{LUIN}$ ratios.

Although Table 4 suggests that flight attendants and flight stewards are the most at risk with ~ 90% of both groups exceeding the 1 mSv y^{-1} dose limit, their average annual exposure as determined by PC-AIRE for 1999, is ~ 2.47 and 2.75 mSv y^{-1}, respectively (Table 5). When juxtaposed with pilots, it is apparent that these three groups have a similar occupational risk due to cosmic radiation exposure.

Table 5: Mean and median dose values[(a)]

Annual Effective Dose	Pilot (26)	Flight Steward (20)	Flight Attendant (25)	Load Master (32)	Other Crew (72)
Mean (mSv)	2.44 ± 0.83	2.75 ± 0.94	2.47 ± 0.84	1.71 ± 0.58	0.29 ± 0.10
Median (mSv)	2.59	2.92	2.70	1.39	0.17

(a) Number of personnel in the occupation is listed in brackets.
(b) Error is taken as ± 1σ

A comparison of the annual exposures calculated for pilots of the Airbus aircraft was made to that determined for pilots of the Boeing 707 aircraft during the Canadian Forces Pilot Survey (CFPS, July 1995 through October 1996) (Table 6) (13). The difference between the Annual dose equivalent of the CFPS and the Mean effective dose for this study was ~ 7%, which shows good consensus for the exposure of aircrew flying at altitudes of 7600 to 8800m feet.

Table 6: Comparison of CFPS and PC-AIRE results

CFPS[(a)(b)]			EXPOSURE/PC-AIRE[(d)]			
Typical Pilot Hours[(c)] (h y^{-1})	Annual Dose Equivalent (mSv y^{-1})	Annual Dose Equivalent (upper bound) (mSv y^{-1})	Mean Pilot Hours[(c)] (h y^{-1})	Mean Effective Dose[(c)] (mSv y^{-1})	Median Pilot Hours (h y^{-1})	Median Effective Dose (mSv y^{-1})
355 ± 121	1.2 ± 0.3	2.3	404 ± 137	2.4 ± 0.8	440	2.6

(a) taken from reference (13)
(b) heliocentric potential, U ~ 512MV
(c) error taken as ± 1σ
(d) heliocentric potential, U ~ 710MV

The analysis conducted on the archived Airbus A310 data revealed that DND's

Mission Management Application (MMA) currently tracks the majority of the information required for PC-AIRE to assess the annual exposure of the Airbus aircrew. The MMA is a database written using the software Powerbuilder® (version.6.5). This research has shown that it is entirely possible for PC-AIRE to be incorporated into the program executing the MMA database, thereby enabling real-time calculations of the aircrews' exposure and, with applicable assumptions added to the program, predictions of their future exposure.

All other air groups within DND also use the MMA and as such, implementation of the PC-AIRE model into the MMA database of all air groups would enable continued assessment of personnel exposures no matter what airframe or squadron they may be assigned to. Indeed, there is no reason why this program could not also be used in the fully automated flight planning system of any airline, be it military or commercial.

VI. CONCLUSION

Effective dose to ambient dose equivalent scaling ratios were developed and successfully incorporated into the program PC-AIRE. The results of the modified program were validated and found to be in excellent agreement with current FLUKA and LUIN based models. Subsequent application of the modified program to DND's Airbus flight database revealed that in 1999, ~ 48% of the A310 aircrew exceeded Transport Canada's limit of 1 mSv y^{-1}, but that none exceeded the intervention level of 6 mSv y^{-1}. It revealed that the average annual effective dose rate for A310 aircrew is between 2.47 and 2.75 mSv y^{-1}.

This work demonstrates hat current methodology could be applied to both military and indeed commercial aircrew databases in order to manage aircrew exposure, particularly in light of pending regulations.

ACKNOWLEDGEMENTS

The author would like to thank Dr. B. Lewis, Dr. L. Bennett and Dr. A. Green of the Royal Military College for their assistance in this study, along with Dr. S. Roesler (Stanford, CA) and E. Felsberger (University of Graz, Austria). Lastly, the author would like to express his gratitude to the crewmembers of 437 Squadron, Trenton. Financial support for this study was received from the Director General Nuclear Safety of the Department of National Defence.

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