Radiation Protection Dosimetry
Vol. 99, Nos 1–4, pp. 435–438 (2002)
Nuclear Technology Publishing

THE EVALUATION AND USE OF A PORTABLE TEPC SYSTEM FOR MEASURING IN-FLIGHT EXPOSURE TO COSMIC RADIATION

G. C. Taylor†, R. D. Bentley‡, T. J. Conroy§, R. Hunter‖, J. B. L. Jones*, A. Pond* and D. J. Thomas†
†National Physical Laboratory, Queens Road, Teddington, Middlesex, TW11 0LW, UK
‡Mullard Space Science Laboratory, Holmbury St Mary, Dorking, Surrey, RH5 6NT, UK
§Far West Technology, 330 South Kellogg Avenue, Suite D, Goleta, CA 93117, USA
‖Civil Aviation Authority, Aviation House, Gatwick Airport South, Gatwick, West Sussex, RH6 0YR, UK
*Virgin Atlantic Airways Ltd, Manor Royal, Crawley, West Sussex, RH10 2NU, UK

Abstract — A recent EC directive has called for all member states to introduce legislation covering the assessment and restriction of air crew exposure to cosmic radiation. In the UK the Civil Aviation Authority, in conjunction with the Department of the Environment, Transport and the Regions issued guidelines suggesting the use of a predictive code such as CARI for this purpose. In order to validate the use of calculated route doses, an extensive programme of measurements is being carried out on long haul routes in conjunction with Virgin Atlantic Airways, using a prototype HAWK TEPC developed by Far West Technology. This programme began in January 2000 and by the end of February 2001 had resulted in the accumulation of data from 74 flights. In this paper the instrument design is discussed, together with the calibration programme. An overview of the in-flight results is also presented, including comparisons between measurements and calculations, which indicates that CARI under-predicts the route doses by approximately 20%.

INTRODUCTION

Prior to the publication of ICRP 60[1], exposure to naturally occurring radiation was considered outside the remit of radiation protection legislation. However, some groups of workers are exposed to significantly increased levels of radiation as a direct consequence of their work. In the case of air crew, the change in philosophy put forward in ICRP 60 is especially welcome as their exposure levels are on a par with workers in the nuclear industry[2]. The European Union began the process of enshrining this change in law in 1996, when it published a directive giving the member states four years to implement the necessary legislation at a national level[3]. In the UK, this was achieved when the Department of the Environment, Transport and the Regions, or DETR (now called the Department of Local Government, Transport and the Regions) amended the Air Navigation Order to include the requirement that dose assessments be made for all air crew liable to exceed an effective dose of 1 mSv per year as a result of flying. The UK Civil Aviation Authority (CAA), in conjunction with the DETR suggested the use of a predictive code such as CARI for this purpose, provided any such code was backed up by experimental validation.

AIM OF WORK

Many groups have performed measurements on board aircraft with a variety of dosemeters, both active and passive, since the publication of ICRP 60 (see, for example Schrewe, 2000[4]). However, the aim of this study is to compile a substantial body of measurements using well-characterised tissue-equivalent proportional counters (TEPCs), not only to validate predictive codes, but also to generate a self-consistent set of data using what is considered to be the best instrument for cosmic ray dosimetry at aircraft altitudes[5].

INSTRUMENTATION

The specific instrument used in this study was a prototype of the commercially-available Hawk TEPC, supplied by Far West Technology, California. The Hawk TEPC is ideal for this work (see Lewis *et al* 2000[6]), as the entire system fits into a small suitcase.

The prototype system used in this study collects data in two MCA cards, with lineal energy ranges between ~2 keV.μm^{-1} and ~1000 keV.μm^{-1} (1024 channels) and between ~0.4 keV.μm^{-1} and ~ 17 keV.μm^{-1} (256 channels), and the data is stored every minute. The dose contribution below 0.4 keV.μm^{-1} is estimated by linear extrapolation. The conversion from dose to dose equivalent used the revised Q(L) relationship published in ICRP 60.

One enhancement over the original prototype employed for this work involved replacing the existing power pack with heavy duty batteries which enabled the instrument to collect data continuously for 5–7 days at a time.

INSTRUMENT CALIBRATION

The TEPC was characterised in a variety of radiation fields, namely photon (3 X ray qualities), neutron

Contact author E-mail: graeme.taylor@npl.co.uk

(monoenergetic and radionuclide sources) and high-energy mixed field (the CERF facility at CERN[7]). The instrument responses in terms of Ambient Dose Equivalent (H*(10)) are shown in Table 1. There are several points worth noting about the H*(10) responses shown in Table 1. Firstly, the response of the TEPC to low energy X rays is very poor. This is due to the stainless steel housing of the instrument, which is several millimetres thick. A similar observation may be made regarding the thermal neutron response, which is significantly lower than for traditional TEPCs. MCNP simulations indicate that the stainless steel shell of the instrument is responsible for attenuating the thermal neutrons by roughly 50%, which explains the discrepancy. However, the rest of the responses are somewhat higher than expected, and investigations revealed the use of an inappropriate factor embedded in the analysis software, which was high by a factor of 1.17. In addition, it was noted that the proton edge of the spectra occurred at a lineal energy of 150 keV.μm^{-1} rather than 136 keV.μm^{-1}, which is the more appropriate value[8]. The effect of correcting the dose equivalent value for this shift introduces a second factor of 1.12. Decreasing the values reported in Table 1 by these factors decreases the results for the TEPC by a single factor of 1.31, bringing them into close agreement with results for the NPL laboratory TEPC[9]. Finally, the result from the CERF facility at CERN was corrected for the muon background.

Given that the CERF radiation field is the most appropriate for cosmic ray dosimetry[10], it was decided to use the factor of 1.30 obtained at that facility as the calibration factor for the in-flight measurements.

Table 1. H*(10) response of the TEPC.

Radiation field	H*(10) response R_H
X ray (Narrow series)	
N–40	0.05
N–150	0.84
N–250	1.03
Neutron	
Thermal	0.28
144 keV	0.74
565 keV	1.34
1.2 MeV	1.50
2.5 MeV	1.62
5.0 MeV	1.40
14.8 MeV	1.16
^{252}Cf	1.46
^{241}Am-Be	1.57
CERF	
Low LET	1.41
High LET	1.28
Combined	1.30

IN-FLIGHT MEASUREMENT PROGRAMME

To date, the TEPC has recorded the doses on 74 flights, covering 13 different routes, courtesy of Virgin Atlantic Airways. The date, route and dose equivalent (DE) for each of these flights are listed in Table 2. The statistical uncertainties associated with the data presented in Table 2 range from ~2% for the highest values to ~4% for the lowest values. However, these are dwarfed by the systematic uncertainty associated with the CERF calibration field, which is of the order of 10%[11].

Mean values for the route doses are presented in Table 3, together with the standard deviations associated with those route doses. The effects of including the data collected during the Forbush decrease of the week following the flare of 14 July 2000 are also shown. In each case, a substantial reduction in the mean dose for that route is observed.

Table 2. Route doses measured with the TEPC listed by date.

Date	Route	DE (μSv)
17/01/2000	Lon-S/H	45.6
18/01/2000	S/H-Lon	56.8
18/01/2000	Lon-NY	36.1
19/02/2000	Lon-S/H	41.1
29/02/2000	Lon-LA	53.2
23/03/2000	Lon-Joh	24.8
24/03/2000	Joh-Lon	22.0
26/03/2000	Lon-LA	48.4
27/03/2000	LA-Lon	48.9
27/03/2000	Lon-NY	31.6
28/03/2000	NY-Lon	30.6
02/04/2000	Lon-Joh	24.9
03/04/2000	Joh-Lon	21.4
04/04/2000	Lon-Tok	47.1
05/04/2000	Tok-Lon	62.2
05/05/2000	Lon-Joh	24.7
06/04/2000	Joh-Lon	26.2
16/04/2000	Lon-LA	52.9
17/04/2000	LA-Lon	46.8
17/04/2000	Lon-NY	33.7
18/04/2000	NY-Lon	28.9
18/04/2000	Lon-Ath	12.5
19/04/2000	Ath-Lon	12.2
19/04/2000	Lon-Ath	10.9
19/04/2000	Ath-Lon	13.1
19/04/2000	Lon-HK	42.9
20/04/2000	HK-Lon	55.0
22/04/2000	Lon-Joh	27.3
23/04/2000	Joh-Lon	28.3
24/04/2000	Lon-Tok	53.1
25/04/2000	Tok-Lon	58.9
25/04/2000	Lon-Ath	10.6
26/04/2000	Ath-Lon	13.5
26/04/2000	Lon-Ath	11.7

COMPARISONS WITH CARI

A preliminary analysis of the CARI-6 predictions for 51 of the above flights has been carried out. However, care has to be taken when comparing measurements with CARI, as the predicted results are for *effective dose* rather than for ambient dose equivalent. Nevertheless, comparisons are possible if the predicted effective doses are scaled down by a factor of 1.25, a figure derived from Bartlett's statement that the effective dose at flight altitudes is 20%–30% higher than the ambient dose equivalent[(2)]. The results of this comparison are shown in Figure 1, which demonstrates that the TEPC is measuring a route dose 22% higher than CARI predicts. It should be noted that the CARI predictions were produced using monthly figures for the heliocentric potentials rather than daily figures. However, given that virtually all the points fall above the unity line implies that a move to daily potentials would not improve matters, as the probability that the heliocentric potential on the

Table 2. Continued.

Date	Route	DE (μSv)
26/04/2000	Ath-Lon	13.2
26/04/2000	Lon-Joh	27.7
28/04/2000	Lon-Tok	54.8
29/04/2000	Tok-Lon	56.8
29/04/2000	Lon-Joh	24.4
30/04/2000	Joh-Lon	27.3
01/05/2000	Lon-Tok	54.8
07/07/2000	Lon-SF	47.8
08/07/2000	SF-Lon	41.1
08/07/2000	Lon-Bos	27.6
09/07/2000	Bos-Lon	27.8
09/07/2000	Lon-Mia	34.1
09/07/2000	Mia-Lon	27.7
10/07/2000	Lon-Mia	27.5
14/07/2000[1]	Lon-HK	37.7[2]
15/07/2000	HK-Lon	40.2[2]
16/07/2000	Lon-LA	40.2[2]
17/07/2000	LA-Lon	37.3[2]
17/07/2000	Lon-NY	26.2[2]
18/07/2000	NY-Lon	26.4[2]
19/07/2000	Lon-Chi	34.1[2]
19/07/2000	Chi-Lon	30.4[2]
20/07/2000	Lon-Tok	43.5[2]
21/07/2000	Tok-Lon	46.4[2]
21/07/2000	Lon-HK	37.3[2]
27/10/2000	Lon-Bos	36.3
28/10/2000	Bos-Lon	21.2
28/10/2000	Lon-SF	45.8
29/10/2000	SF-Lon	34.8
29/10/2000	Lon-Bos	31.6
30/10/2000	Bos-Gla	19.9
14/01/2001	Lon-Orl	35.6
15/01/2001	Orl-Lon	28.0
15/01/2001	Lon-Orl	37.0
16/01/2001	Orl-Lon	29.8
07/02/2001	Lon-Bos	30.7
08/02/2001	Bos-Lon	26.9
08/02/2001	Lon-Bos	28.2
09/02/2001	Lon-Bos	29.8
10/02/2001	Bos-Lon	27.8

KEY:
Ath = Athens, Greece; Bos = Boston, USA; Chi = Chicago, USA; Gla = Glasgow, UK; HK = Hong Kong, China; Joh = Johannesburg, RSA; LA = Los Angeles, USA; Lon = London, UK; Mia = Miami, USA; NY = New York, USA; Orl = Orlando, USA; S/H = Shanghai, China; SF = San Francisco, USA; Tok = Tokyo, Japan.
NOTES:
1. Date of major solar event. TEPC flown on aircraft approximately 9 h after peak of flare.
2. Forbush decrease

Table 3. Mean route doses, listed by decreasing dose for the outward-bound flight.

Route	No of flights	Mean route dose (μSv)	Std Dev. (μSv)
Lon-Tok	4	52.5	3.7
	5*	50.7*	5.1*
Tok-Lon	3	59.3	2.7
	4*	56.1*	6.8*
Lon-LA	3	51.5	2.7
	4*	48.7*	6.1*
LA-Lon	2	47.9	1.5
	3*	44.3*	6.2*
Lon-SFO	2	46.8	1.4
SFO-Lon	2	38.0	4.5
Lon-S/H	2	43.4	3.3
S/H-Lon	1	56.8	–
Lon-HK	1	42.9	–
	2*	39.3*	3.1*
HK-Lon	1	55.0	–
	2*	47.6*	10.5*
Lon-Orl	2	36.6	1.0
Orl-Lon	2	28.9	1.3
Lon-Chi	1*	34.1*	–
Chi-Lon	1*	30.4*	–
Lon-NY	3	33.8	2.3
	4*	31.9*	4.2*
NY-Lon	2	29.8	1.2
	3*	28.6*	2.1*
Lon-Mia	2	30.8	4.7
Mia-Lon	1	27.7	–
Lon-Bos	6	30.7	3.1
Bos-Lon	4	25.9	3.2
Bos-Gla	1	19.9	–
Lon-Joh	6	25.6	1.5
Joh-Lon	5	25.0	3.1
Lon-Ath	4	11.4	0.9
Ath-Lon	4	13.0	0.6

KEY: See Table 2.
NOTE:
The flights during the flare week 14–21 July 2000 have been omitted from the first entry, but have been included where marked*.

day of each and every measurement is lower than the averaged monthly figure must be infinitesimal. Nevertheless, given the 10% uncertainty in the TEPC calibration factor and the uncertainty inherent in converting CARI-6's predictions from effective dose to ambient dose equivalent, the comparison is reasonable.

CONCLUSIONS

A stand-alone TEPC system was flown with Virgin Atlantic Airways on 74 flights during the period January 2000 to February 2001, sampling 13 flight routes. Preliminary comparisons of the results with predictions from CARI-6 indicate that CARI-6 is low by approximately 20% *when those predictions are converted to ambient dose equivalent (H*(10))*. These early findings will be investigated in more detail in the near future. Further measurements are planned for at least the next two years using a new Hawk TEPC, which is currently being flown in parallel with the one used in the above study to ensure the continuity of the data.

With the solar cycle just passing solar maximum, it is hoped that during the next phase of the measurement programme, the TEPC will be flying during a solar particle event that leads to a significant increase in the dose recorded at flight altitudes. It is anticipated that any such measurement, analysed in conjunction with satellite and ground-based data, will be able to shed light on the future prediction of such events.

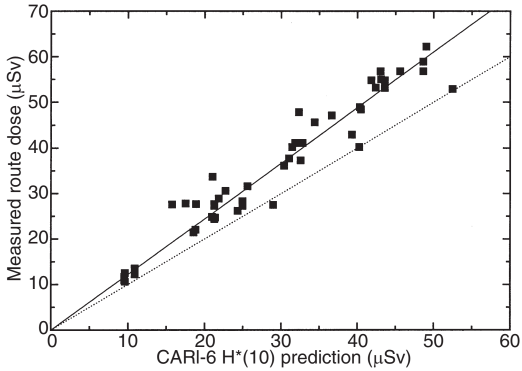

Figure 1. Comparison of measured route doses with CARI-6 predictions, scaled to give H*(10). Dashed line: unity line, CARI = Measurement. Solid Line: linear fit with zero intercept. Value of slope: 1.221 ± 0.017.

ACKNOWLEDGEMENTS

The authors would like to thank Marco Silari and his team at the CERF Facility, Andrew Bennett, Nicky Horwood, Peter Kolkowski and John Winnington at the National Physical Laboratory and the UK Particle Physics and Astronomy Research Council (PPARC) for funding the continuation of this measurement programme.

REFERENCES

1. ICRP. *1990 Recommendations of the International Commission on Radiological Protection*. Publication 60 (Oxford: Pergamon Press) (1991).
2. Bartlett, D. T. *Radiation Protection Concepts and Quantities for the Occupational Exposure to Cosmic Radiation*. Radiat. Prot. Dosim. **86**, 263–268 (1999).
3. Council Directive 96/29/EURATOM of 13 May. *Laying Down the Basic Safety Standards for Protection of the Health of Workers and the General Public Against the Danger Arising from Ionizing Radiation*. Official Journal of the European Communities **19**, L159, 1–114, Article 42 (June 1996).
4. Schrewe, U. J. *Global Measurements of the Radiation Exposure of Civil Air Crew from 1997 to 1999*. Radiat. Prot. Dosim. **91**, 347–364 (2000).
5. Lindborg, L., Kyllönen, J. E., Beck, P., Bottollier-Depois, J. F., Gerdung, S., Grillmaier, R. E. and Schrewe, U. J. *The Use of TEPC for Reference Dosimetry*. Radiat. Prot. Dosim. **86**, 285–288 (1999).
6. Lewis, B. J., McCall, M. J., Green, A. R., Bennett, L. G. I., Pierre, M., Schrewe, U. J., O'Brien, K. and Felsberger, E. *Aircrew Exposure from Cosmic Radiation on Commercial Airline Routes*. Radiat. Prot. Dosim. **93**, 293–314 (2001).
7. Aroua, A., Hoefert, M., Sannikov, A. V. and Stevenson, G. *Reference High Energy Neutron Fields at CERN*. CERN Report CERN/TIS-RP/TM/94–12 (1994).
8. Waker, A. J. *Principles of Experimental Microdosimetry*. Radiat. Prot. Dosim **61**, 297–308 (1995).
9. Taylor, G. C. *Neutron Response Characteristics of the NPL Tissue-Equivalent Proportional Counter*. NPL Report CIRM 26 (March 1999).
10. ISO. *Reference Neutron Radiations — Characteristics and Methods of Production of Simulated Workplace Neutron Fields*. ISO 12789:2000 (Geneva: ISO) (2000).
11. Nava, E., Otto, T. and Silari, M. *Reference Dose Equivalent Values for the 1997 CERN-EC runs*. European Organization for Nuclear Research Technical Memorandum TIS-RP/TM/97–22. (August 1997).