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Tissue Equivalent Proportional Counter Microdosimetry Measurements Aboard High-Altitude and Commercial Aircraft

Brad Gersey[1] and Richard Wilkins[2]
Center for Radiation Engineering and Science for Space Exploration,
Prairie View A&M University, Prairie View, Texas 77446

William Atwell[3]
Boeing Research & Technology, Houston, Texas 77059

W. Kent Tobiska[4]
Space Environment Technologies, Pacific Palisades, CA 90272

Christopher Mertens[5]
NASA Langley Research Center, Hampton, VA 23681

Nomenclature

FAA	=	Federal Aviation Administration
NASA	=	National Aeronautics and Space Administration
TEPC	=	Tissue Equivalent Proportional Counter
ARMAS	=	Automated Radiation Measurements for Aviation Safety
SBIR	=	Small Business Innovative Research
ER-2	=	Earth Resource – 2, a variant of the Lockheed U-2 aircraft
KC-135	=	Kerosene Cargo – 135, a reduced gravity aircraft operated by NASA
EMF	=	Electromagnetic Field

High-altitude and commercial aircraft crew members are occupationally exposed to a complex and variable radiation environment during flight. Components of the galactic cosmic and solar particle radiation spectra penetrate and interact with both the upper atmosphere of the Earth and the aircraft structure itself to create this radiation environment. The level of radiation exposure received by crew members during a flight can vary greatly due to a variety of factors including the altitude, latitude, and duration of the flight as well changes in the level of recent solar activity. In this work, a Hawk style Tissue Equivalent Proportional Counter (TEPC) microdosimeter was used to measure the radiation exposure in terms of absorbed dose and dose equivalent during ER-2, KC-135, and commercial aircraft flights. The data represents expected radiation exposure to flight crew and

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[1] Research Scientist Leader, NASA Center for Radiation Engineering and Science for Space Exploration, Prairie View A&M University, P. O. Box 519, Prairie View, TX 77446, and AIAA Member Grade: non-member.
[2] Professor, Department of Electrical and Computer Engineering, Prairie View A&M University, P. O. Box 519, Prairie View, TX 77446, AIAA Member Grade: non-member.
[3] Technical Fellow, Boeing Research & Technology, 13100 Space Center Blvd, MS: HB 2-30, Houston, TX. 77059-3556, , AIAA Member Grade: Associate Fellow.
[4] Chief Scientist, Space Environment Technologies, Space Weather Division, 1676 Palisades Dr., Pacific Palisades, CA 90272, AIAA Member Grade: Associate Fellow.
[5] Senior Research Scientist, NASA Langley Research Center Science Directorate, Chemistry and Dynamics Branch, 21 Langley Blvd., Mail Stop 401B, Hampton, VA. 23681-2199, AIAA Member Grade: non-member.

passengers during long range commercial flights, as well as higher altitudes from the ER-2 flights. Results from these radiation exposure measurements as well as pertinent flight profile information will be presented. This presentation will emphasize the efficacy and flexibility of the Hawk TEPC system for use in measuring the radiation exposure aboard diverse aircraft platforms and flight environments. Recent measurements onboard commercial flights support NASA efforts related to characterizing and modeling the atmospheric radiation environment.

I. Introduction

A complex and changing spectrum of galactic cosmic and solar particle radiation continually bombards the Earth's upper atmosphere. Components of this cosmic radiation spectrum interact in different ways with the atmosphere producing secondary radiation[1,2]. The measureable amount of radiation exposure caused by this primary and secondary radiation in the atmosphere increases with increasing altitude. At common commercial aircraft altitudes, the radiation dose received by flight crew members or frequent flyer passengers can be significant from a radiation protection and safety standpoint. "The FAA estimates annual subsonic aircrew exposures to range from 0.2 to 9.1 mSv compared to 0.5 mSv exposure of the average nuclear power plant worker in the nuclear industry"[3]. Awareness of this radiological safety issue by the scientific community, individuals associated with the air travel industry, as well as the general public has led to a host of studies over a period of decades which have been designed to measure, model and predict the radiological environment and risks posed during air travel. Presented in this work are results from three flight dosimetry studies performed by researchers at the National Aeronautics and Space Administration (NASA) Center for Radiation Engineering and Science for Space Exploration (CRESSE) at Prairie View A&M University, Prairie View, Texas. The specific focus of each of these studies concerned dosimetry measurements of the ambient aircraft radiation environment onboard different aircraft platforms. The KC-135 'Weightless Wonder' study was conducted to test the efficacy of dosimetry results measured by a TEPC under conditions of high and low acceleration, fluctuating EMF fields, and alterations of altitude and vibrations incident upon the device. The ER-2 High Altitude study was performed in order to measure the absorbed dose and dose equivalent as measured by two TEPCs at flight altitudes in the vicinity of 65 000 feet. The commercial flight measurements (under the NASA ARMAS SBIR project) is an ongoing study, and TEPC dosimetry measurements have been taken on heavily traveled common carrier routes.

II. Methodology

A. The Tissue Equivalent Proportional Counter (TEPC) Flight Dosimeter

A TEPC is an active dosimeter that has been used to detect space radiation aboard the space shuttle and the International Space Station (ISS)[4-6]. This same type of instrument is also used to detect the radiation environment onboard aircraft. There were two different TEPC designs used in the studies presented here. The fundamental difference between the two designs rests in the shape and size of the active volume of each detector. The first TEPC design is designated a 'shuttle style' and it had an active volume that was a right cylinder 1.78 cm long and 1.78 cm in diameter (illustrated in Figure 1). The walls of this right cylinder were fabricated from tissue equivalent A-150 plastic and were 1.9 mm thick. The right cylinder was enclosed in stainless steel walls of 0.89 mm thickness. The active volume was then enclosed in an aluminum cylinder which measured 2 in. in diameter and was 12 in. long (henceforth, the active volume chamber, including the 2x12 aluminum enclosure, will be referred to as 'chamber'). The active volume of the TEPC was filled with low-pressure propane gas to simulate a right cylinder with a 2-micron diameter and length. An anode wire runs the length of the cylinder and is kept at a potential of 640 volts relative to the cylinder walls. The Shuttle Style TEPC was used in the KC-135 study. The second TEPC design is designated a 'Hawk style' and it had a spherical active volume 5 inches in diameter with A-150 plastic walls 1.9 mm thick. The active volume of the Hawk Style TEPC simulated a 2-micron diameter sphere of tissue by utilizing a low pressure propane gas in the active volume. An anode wire surrounded by a fine helix wire ran the entire length of the diameter of the active volume. The Hawk Style TEPC was used in the ER-2 and Commercial Airline studies. With the exception of the different size and shape of the TEPC active volumes, the remainder of the components (hardware and software) of these two style devices was virtually identical.

When energy is deposited in the TEPC active volume, charge is collected at the anode wire and is processed by a pre-amplifier. The signal then moves from the pre-amplifier to two shaping amplifiers. These two shaping amplifiers have a difference in gain of approximately a factor of 50. After shaping amplification, the two signals are converted to a digital pulse height by means of an analog to digital converter (ADC). These pulse height signals are then integrated for 1 minute and then stored with a time stamp on a flash-ROM card for later analysis. A variety of instrument 'health and status' information (including temperature, voltage, current draw, dead time estimate) as well as GPS coordinate data are stored every minute with the time stamped pulse height data. The electronics for the TEPC are housed in an aluminum cylinder 6 inches (in.) in diameter and 6 in. long (henceforth the electronics container will be referred to as 'the spectrometer').

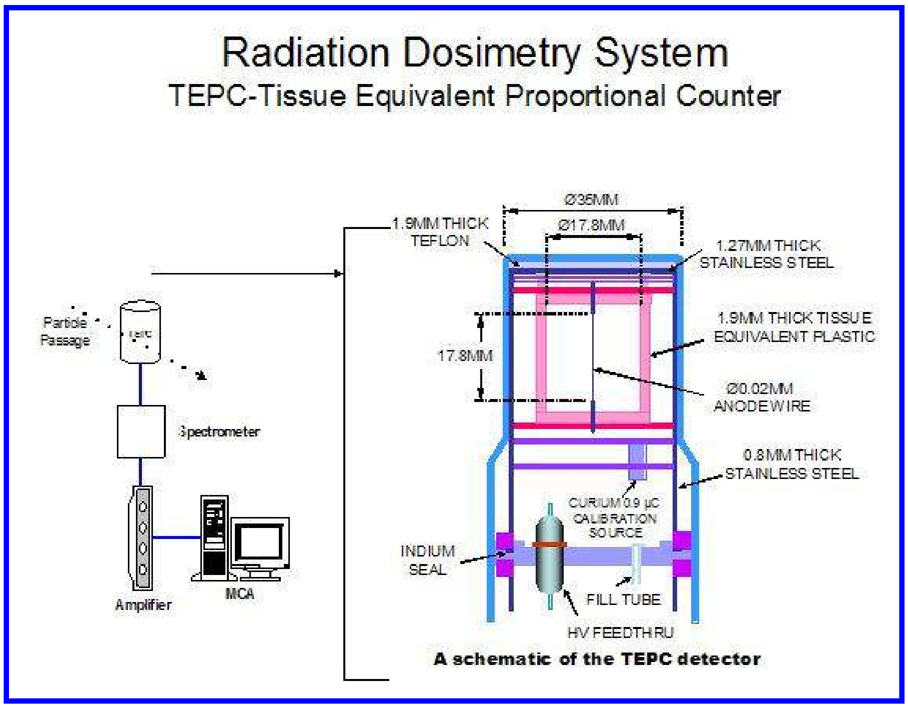

Figure 1: Diagram of the Space Shuttle style TEPC active volume**.**

During data analysis, the pulse height signals collected during each flight from the TEPC were combined to form a pulse height distribution. This distribution was then converted into a lineal energy (y) deposition distribution (f(y) versus y). Lineal energy is defined as the energy deposited in the active volume by a single energy deposition event divided by the mean chord length through the active volume. Units of lineal energy are keV/micrometer. The TEPC measured a lineal energy (y) deposition spectrum ranging from 0.4-1024.0 keV/micrometer. The f(y) versus y spectrum was used to calculate the absorbed dose to tissue from the radiation incident upon the microdosimeter using the formula[7].

$$\text{Absorbed Dose} = \int C * yf(y)dy \quad (1)$$

Where C is a constant to convert the energy deposited (keV/micrometer) into absorbed dose (Gy).

By making the assumption that *y* was equal to the LET of the radiation field, this same spectrum was used to approximate the LET spectrum of the incident radiation. This LET spectrum was then used to calculate absorbed dose, dose equivalent, and an average quality factor (Q) of the radiation in tissue[7]. The dose equivalent from the radiation field was determined using the values for the average quality factor and the absorbed dose.

B. Flight Platforms

i. KC-135 'Weightless Wonder'

The Reduced Gravity Program, operated by NASA Lyndon B. Johnson Space Center (JSC) out of Ellington Field near Houston, TX, utilized a KC-135A aircraft to offer a flight platform that, by performing maneuvers known as "parabolas", could replicate various gravitational environments (0 to 1.8 gravities). Two flight experiments were performed aboard the aircraft on April 8th and April 9th of 2004, flight week three of NASA's Reduced Gravity Student Flight Opportunities Program. The nature of the experiments involved the characterization of the response of a Tissue Equivalent Proportional Counter (TEPC) to cosmic and alpha particle radiation during the accelerations offered by the KC-135 platform.

The primary objective of this experiment was to determine if the TEPC had a different response to alpha particle radiation while in a zero gravity environment as opposed to being in a one gravity environment or a 1.8 gravity environment. Two identical TEPC systems were flown aboard the KC-135. The first TEPC (TEPC I) had an internal calibration alpha particle source running continuously during the flight. This produced a calibration peak with a known energy deposition in the detector. After the flight, the response function produced by TEPC I was analyzed to determine if the calibration peak had changed while it was in the different gravity environments.

The secondary objective of this experiment was to determine the absorbed dose and dose equivalent received by flight participants from the radiation field found onboard the KC-135. The second TEPC (TEPC II) ran during the flight without a calibration source. The response function from TEPC II was used to calculate the absorbed dose and dose equivalent from the radiation field present aboard the KC-135 during the flight.

The hypothesis of this experiment was that the TEPC response function may have a systematic error associated with the different gravity environments. If this error exists, it must be quantified through controlled experiments so that the TEPC response function produced during future radiation dosimetry aboard spacecraft and aircraft can be corrected.

It has been shown that both strong vibration and strong electromagnetic fields (EMF) may alter the response function of a TEPC. This experiment utilized both a vibration detector and an EMF detector to record the levels of vibration and EMF aboard the KC-135. During the post-flight data analysis phase of this experiment this information was used to insure that any change in the TEPC response function was not due to these two factors.

Two TEPCs were used aboard each flight. The first TEPC (TEPC I) had an internal calibration alpha particle source running continuously during the flight. This produced a calibration peak with a known energy deposition in the detector. The second TEPC (TEPC II) ran without a calibration source.

The lineal energy, y, response function of the two TEPCs were analyzed together to produce two sets of results. The first result was a determination of the absorbed dose and dose equivalent received by flight participants from the radiation field found onboard the KC-135 (TEPC II). The second result was to determine if the instrument has a different response to alpha particle radiation (see Figure 2) while in a zero gravity environment as opposed to being in a 1 gravity environment or a 1.8 gravity environment (TEPC I).

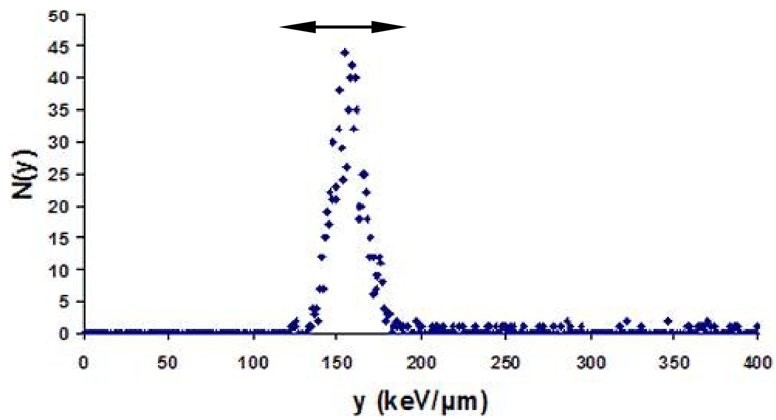

Figure 2: Standard energy deposition calibration peak including illustration of possible shift during different gravity environments. Units for the X-axis is lineal energy (y) in keV/µm. Units for the Y-axis are number of counts.

In conjunction with the response to the varying gravitational environment, the TEPC responses were also characterized with respect to possible effects from electromagnetic field (EMF) and vibration frequency and magnitude onboard the KC-135. This was done to ensure that any shift in the calibration peak of TEPC I and any abnormal data received from TEPC II would not be misinterpreted as being caused by gravitational acceleration if it was caused by vibration or EMF.

ii. ER-2

This ER-2 High Altitude study was performed to address one of the primary scientific goals of the Atmospheric Ionizing Radiation (AIR) project. Specifically, this goal concerned increasing the accuracy of radiological exposure measurements for radiation safety monitoring of future flight crews and passengers of the planned High Speed Civil Transport (HSCT). The average cruising altitude for these ER-2 flights was 65000 feet, and the average duration of each flight was 200 minutes. Dosimetry measurements were performed during the ER-2 High Altitude study using two Hawk style TEPCs for each flight. During each of the flight performed, the TEPCs were located below the wings of the plane (one TEPC under each wing) in containment vessels called superpods. Also during each flight, the housing of just one of the TEPCs was surrounded by a candidate shielding material in order to ascertain any effect the shield had on the absorbed dose and dose equivalent measurements during the flight. Candidate shielding materials included aluminum, high density polyethylene and titanium. Results for an ER-2 flight with one of the TEPCs surrounded by aluminum will be presented in this work.

iii. Commercial Aircraft (ARMAS)

Flight dosimetry measurements were conducted aboard Federal Express aircraft by Brad B. Gersey and Richard Wilkins from The Center for Radiation Engineering and Science for Space Exploration (CRESSE) at Prairie View A&M University in support of the ARMAS Phase I SBIR. These dosimetry measurements were performed utilizing a HAWK Tissue Equivalent Proportional Counter (TEPC) microdosimetry system that was specifically designed and constructed for use aboard commercial aircraft.

The basic test protocol for the flights presented in this document involved packaging the HAWK TEPC in a stainless steel case with the GPS antenna attached to the outside of the containment case. This stainless steel case with GPS antenna attached was placed inside a larger cardboard FEDEX box and was then shipped via overnight Federal Express carrier to the given destination. Once the package was received at the destination, the dosimetry data was analyzed and correlated to the time/date/GPS information and results were reported in both graphical and table format.

III. Results and Discussion

A. KC-135 Reduced Gravity Flight Experiments:

After analysis of the data from the two flights, it was determined that the response of the two TEPCs, the vibration detector, and the EMF detector was virtually identical for the two flights. Results from flight II will be used to illustrate the results for this study.

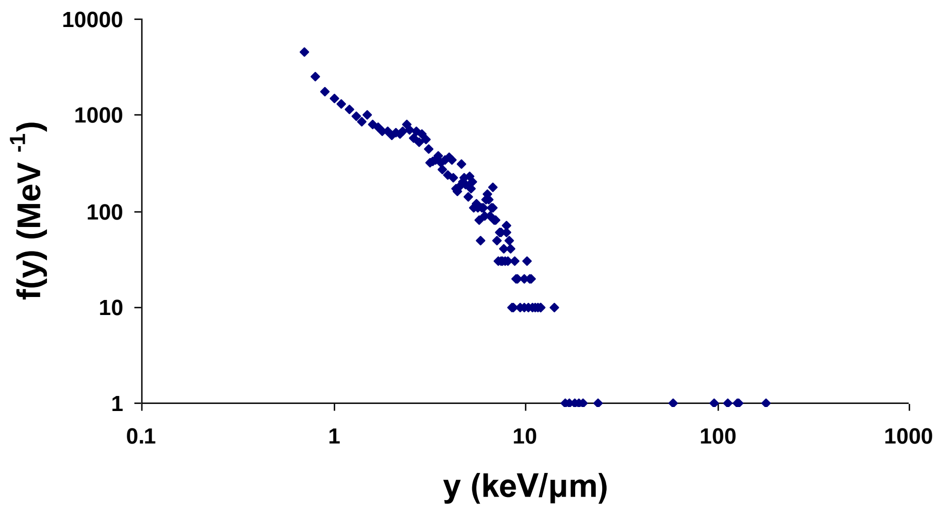

Figure 3: Illustrates the lineal energy response spectrum from TEPC II, flight II. Units for the X-axis: lineal energy (y) in keV/um. Units for the Y-axis are frequency of counts.

The lineal energy response function spectrum shown in Figure 3 was used to calculate the absorbed dose and dose equivalent for flight II using the procedure outlined in Section A of the Methodology section of this paper. For the duration of flight II the measured absorbed dose was 4.4 µGy and the dose equivalent was 11.86 µSv. The total flight duration was approximately three hours, and the altitude was far too variable to assess. This was due to the unique necessity for the aircraft to climb and dive (parabolas) for the majority of the flight. The virtually constant changes in altitude makes it difficult to make a reasonable comparison of the flight dosimetry for the KC-135 mission with commercial airline or ER-2 high altitude flights.

The lineal energy spectrum from TEPC I was plotted for the time frame of the entire flight and saved for analytical comparisons with the lineal energy spectra resulting from shorter time frames of the same flight. The specific segments of time chosen for closer examination and comparison with the overall flight spectrum corresponded to the times when the following activities were transpiring.

1. *Takeoff and ascent*
2. *Parabola dives*
3. *Parabola climbs*
4. *Decent and landing*

There was no discernible change in lineal energy calibration peak between each of these times. The output from TEPC I and TEPC II were correlated with the vibration and EMF data on a time basis. This was checked for each phase of the flight (1-4 above). In addition, any vibration or EMF spikes and the time that they occurred were noted. The lineal energy spectra from TEPC I and TEPC II were examined during these times to note any anomalies or deviations in them. None were detected. Because there did not appear to be any large vibration spikes, it was expected that vibration would not impact the TEPC results. However, even the very large EMF (Figure 4) spikes did not appear to effect the TEPCs proper functioning. There was not a discernible shift in the calibration peak of TEPC I between each of these times for flight I or flight II.

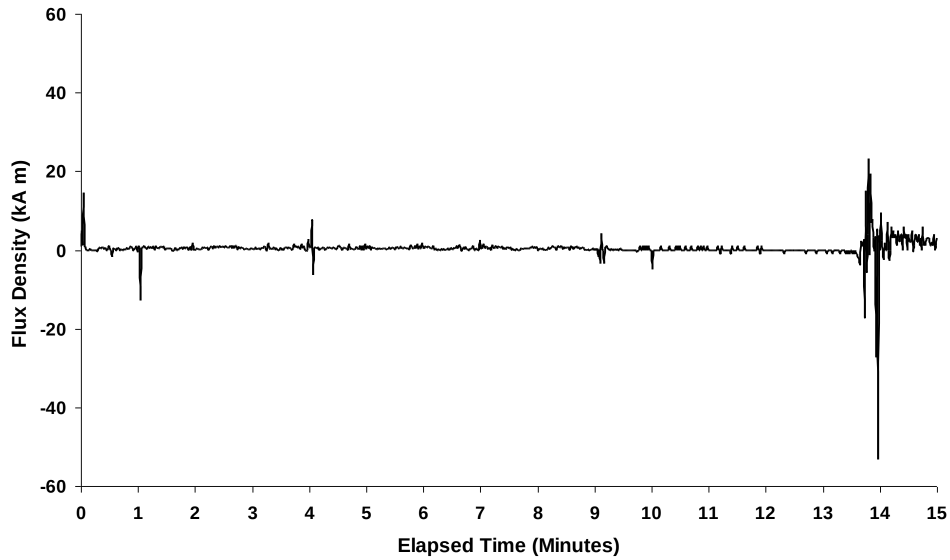

Figure 4: Illustrates a sample of the EMF data from flight II presented as a time series. Noticeable EMF spikes occurred at approximately $\Delta t = 0$, $\Delta t = 1$, $\Delta t = 4$, $\Delta t = 9$, $\Delta t = 10$ and $\Delta t = 14$ (minutes).

B. ER-2 High Altitude Study

A total of seven flights with two functioning TEPCs on board each flight were performed in this study. The majority of the data is in the process of being analyzed by the authors of this work. Presented here are results from a flight performed aboard the ER-2 at NASA Dryden Flight Research Center on March 19, 2002.

Table I. Dosimetry results from measurements taken with a TEPC during an ER-2 flight

	Absorbed Dose Rate (µGy/hr)	**Dose Equivalent Rate (µSv/hr)**	**Average Quality Factor (Unitless)**
TEPC	**2.99**	**7.31**	**2.63**
TEPC + Al Shield	**2.56**	**6.93**	**2.71**

The dosimetry results for this flight are found in Table I. The absorbed dose and dose equivalent measured by the TEPC without any shield covering was 2.99 µGy/hr and 7.31 µSv/hr respectively. The TEPC that was surrounded by an aluminum shield measured an absorbed dose rate that was 15% lower than the uncovered TEPC, and a dose equivlanet rate that was approximately 5% lower. Further analysis of the remaining ER-2 flights will lend insight into the effect of this and other shields on the radiation environment found aboard the ER-2.

C. ARMAS Commercial Aircraft

Dosimetry results for three separate flights are presented in Table I. While a total of seven dosimetry flights were performed during the ARMAS SBIR Phase I, it was determined after data analysis procedures that only the three flights for which results are presented in Table II were fully useful for this study.

The measured absorbed dose rate at flight altitude (estimated to be 32 000 feet) was less than 20% different between the 3 flights. However, there was up to 46% variation in the measured dose equivalent rate at flight altitude between the 3 flights. In addition the variability in the minute by minute flight dosimetry results (illustrated for one of the flights in Figure 5) show that each flight had a unique time profile.

Table II. Dosimetry results from measurements taken with a TEPC during three commercial airline flights

Flight Origin			Flight Destination			Flight Total Absorbed Dose	Absorbed Dose Rate At Cruise Altitude	Total Dose Equivalent	Dose Equivalent Rate At Cruise Altitude	Average Quality Factor
Date	Time (PST)	Location	Date	Time (PST)	Location	(µGy)	(µGy/Hour)	(µSv)	(µSv/Hour)	At Cruise Altitude
04/28/11	5:26 AM	Holbrook, NY	04/28/11	7:43 AM	Memphis, TN	2.34	1.28	5.88	3.29	2.55
06/15/11	6:56 PM	Holbrook, NY	06/15/11	8:40 PM	Indianapolis, IN	1.19	1.17	2.63	2.70	2.24
08/25/11	12:06 AM	Houston, TX	08/25/11	3:07 AM	Los Angeles, CA	2.20	1.03	3.96	1.81	1.72

Due to the fact that both the dates of the flights as well as the flight paths were different for each of these flights, variability in the dosimetry results is to be expected. Comparisons of the measured dosimetry results between these three flights are of limited usefulness except to illustrate the consistency of the HAWK response function to the ambient radiation field aboard aircraft. It is not surprising moreover (given the large difference in average flight altitude) that the measured absorbed dose rate and dose equivalent rate is more than twice as great aboard the ER-2 flight as opposed to an average commercial carrier flight.

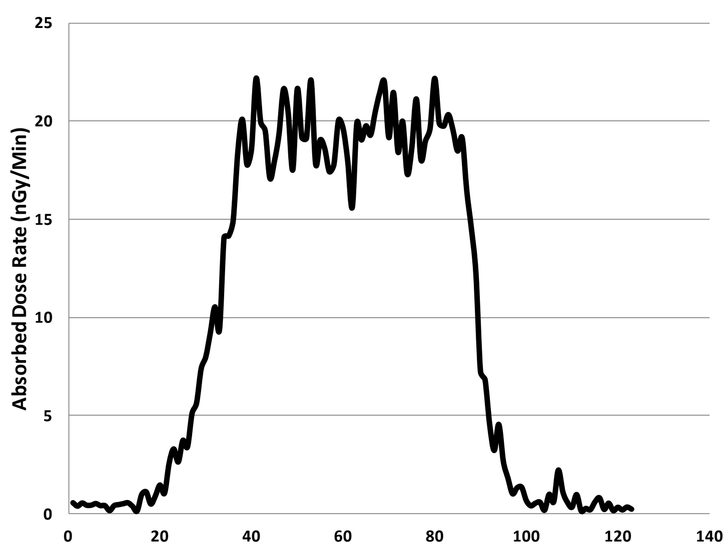

Figure 5: Measured absorbed dose rate (nGy/Min) as a function of elapsed time in minutes for flight from Holbrook, NY to Indianapolis, IN.

IV. Conclusions

A TEPC is a proportional counter microdosimeter that is currently used to measure absorbed dose and dose equivalent aboard space craft and aircraft. The KC-135 Reduced Gravity experiment was conducted to test whether a calibration peak in the lineal energy spectra from a TEPC was shifted when the TEPC was under zero, one and 1.8 gravities. There was not a discernible shift in the calibration peak when the lineal energy spectra for each of these conditions were compared.

A second goal of the KC-135 experiment was to measure the absorbed dose and dose equivalent from the radiation exposure received during each KC-135 flight. This was successfully accomplished.

It is known that excessive vibration and excessive EMF can interfere with the proper functioning of a TEPC. Devices were used in this experiment to quantify the vibration and EMF that the TEPCs were exposed to on each flight. It was determined that neither vibration nor EMF contributed to any anomalous results in the lineal energy spectrum from either TEPC during flight I or flight II.

The results from the KC-135 Reduced Gravity study confirmed the utility of the TEPC to successfully perform accurate flight dosimetry measurements in a challenging flight environment that included external stressors (EMF, vibration, acceleration) that are known to interfere with the proper functioning of other radiation detectors.

The ER-2 High Altitude Flight Dosimetry study successfully performed a total of seven separate flights with two TEPCs onboard. Dosimetry results were presented for one of these flights. In addition to the ambient absorbed dose and dose equivalent measurements, these results included measurements of these same quantities behind an aluminum shield. Selected results from the ARMAS Commercial Aircraft study were presented and it is noted that the absorbed dose and dose equivalent rates measured aboard three commercial aircraft flights were less than half in magnitude than these quantities measured during an ER-2 flight.

Data analysis for the ER-2 High Altitude and the ARMAS Commercial Flight studies is ongoing. In addition, new dosimetry measurements are currently being made under the ARMAS study while future ER-2 dosimetry flights are being planned.

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