HEALTH PHYSICS AND AVIATION: SOLAR CYCLE 23 (1996–2008)

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Abstract—**We continue our description of the scientific and professional activities that were initiated by the classification of airline flight crewmembers as occupational radiation workers in 1994, specifically looking at the period between 1996 and 2008. During this period, radiation measurement programs were conducted on numerous commercial aircraft flights. Epidemiological studies have looked at the incidence of cancer in pilots and flight attendants, with mixed conclusions. The Federal Aviation Administration (FAA) released revised versions of its CARI software, the computer program designed to evaluate radiation exposures received on user-defined flight plans. Additional dose-evaluation programs have been made available by other entities. In May 2000, member states of the European Union (EU) adopted regulations that apply to the air carriers in all twenty-seven nations requiring education on health risks of in-flight radiation as well as dose assessment for all EU flight crewmembers. The National Oceanic and Atmospheric Administration (NOAA) revised its classification scheme for space weather events including radiation-producing solar storms. In 2005, the FAA created a Solar Particle Alert system to warn aircraft of high radiation levels caused by significant events of this type. There is now an early-warning system for potentially harmful solar particle events. This new system depends on the earlier arrival time of relativistic electrons compared with the heavier particulate radiation.**

Health Phys. 96(4):456–464; 2009

Key words: radiation risk; radiation, atmospheric; radiation, technological enhancement; occupational safety

INTRODUCTION

IN PREVIOUS articles in *Health Physics*, we discussed the subject of in-flight radiation exposure of airline crewmembers and passengers (Barish 1990, 1995). To briefly summarize, it had been recognized for some time that exposure to cosmic radiation at airliner altitudes results in an occupational dose for many pilots and flight attendants that is at the high end of those values reported for groups of radiation workers exposed in more conventional settings such as medical or industrial facilities (FAA 1990; U.S. NRC 2007). As the regulatory authority for commercial aviation in the United States, the Federal Aviation Administration (FAA) had encouraged personnel who are members of its Radiobiology Research Team, in cooperation with outside consultants, to develop educational materials and analytical tools to help the airline industry recognize and fulfill its responsibilities to those workers who receive cosmic radiation exposure during the performance of their duties. These materials have included advisory publications and scientific papers (FAA 1990, 1994; Friedberg et al. 1992, 1999, 2000, 2002; Nicholas et al. 2000; Friedberg and Copeland 2003) as well as a computer program, which can be used by crewmembers to evaluate their accumulating exposures on a flight-by-flight basis (O'Brien et al. 2003).

In the preceding paper in this series (Barish 1995), the author expressed optimism that, following ten years of concern in the health physics community for flight crewmembers as an occupationally exposed worker group, the advisory action taken by the FAA would lead to "an educational program that would be equivalent to the radiation training provided to radiation workers in the ground-based industries regulated by other Federal agencies" (Barish 1995). With the passage of 13 years, such optimism appears to have been misplaced. No U.S. based air carrier has systematically instituted such training, although at least one airline has created a document, available at the request of any crewmember, that supports the FAA advisories with further information should it be specifically sought (AACMD 1996). Notwithstanding this failure of the industry to universally adopt the FAA's recommended program of crewmember education, added impetus for action in this area may have been produced by the requirement that all nations in the European Union (EU) adhere to regulations that became effective in May 2000 as a result of recommendations in a report on the subject published in 1996 (EURADOS 1996). These regulations require that air carriers of the twenty-seven

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(*Manuscript accepted* 1 *October* 2008)

0017-9078/09/0

member states provide all flight crewmembers with appropriate training and dose assessment (EU 1996).

The implementation of this European law has been partly responsible for a number of the programs of radiation measurement that have been carried out on aircraft of European nations as well as U.S. and Canadian air carriers. These programs were undertaken by a number of very different organizations with interests and agendas that were not necessarily in common. The groups included the German Airline Pilots Association (in collaboration with Lufthansa Airlines), Air France, the National Institute of Occupational Safety and Health (NIOSH), the Canadian Military College, and others (EURADOS 1996; Goldhagen 2000; Lewis et al. 1994, 1999; O'Sullivan et al. 1999, 2001). In February 1998, the Medical University of South Carolina sponsored a 3-day conference. The topic was "Cosmic Radiation, Electromagnetic Fields, & Health Among Aircrews." A number of speakers reported on the measurements made with radiation detectors carried in ordinary passenger aircraft flying their normal routes. These measurements were made using a variety of detectors including tissue-equivalent proportional counters (TEPC), "rem-meters," bubble detectors, thermoluminescent dosimeters (TLDs), and other instruments, often used in a tandem configurations to separately measure the low-linear energy transfer (LET) and high-LET components of the radiation field at aircraft altitudes. Results of these measurements were compared with the dose equivalent values predicted by the then-current versions of the software used to model these doses.

The 1998 NCRP Meeting

In April 1998, the National Council on Radiation Protection and Measurements (NCRP) held its 34th Annual Meeting. The topic was "Cosmic Radiation Exposure of Airline Crews, Passengers and Astronauts." At that meeting, presentations were made on the assessment of radiation exposure on commercial aircraft, factors affecting cosmic ray exposure in civil aviation, measurements performed by an assortment of international researchers, and epidemiological studies of commercial aircraft crews (NCRP 2000). In addition to these papers, a session was held concerning current regulatory programs. At that session, the FAA specifically cited requirements of the Federal "Guidance" document on occupational radiation exposure that individuals exposed to radiation and their managers should be instructed on the basic risks to health from ionizing radiation and on basic radiation protection principles (U.S. EPA 1987). They discussed the materials that they had made available including their advisory circulars, scientific publications, and their computer program for estimating dose equivalent for any specific flight plan. They indicated that they would continue to make this material available for voluntary use by the air carriers.

During a panel discussion that included representatives of the FAA, the Airline Pilots Association, and the Association of Professional Flight Attendants (a union representing American Airlines employees), the FAA panelist was specifically questioned about the apparent failure of any American carrier to implement the suggested program of flight crewmember education that had been presented in an advisory circular a full four years earlier (FAA 1994). The response was that, rather than enacting new regulations, the FAA felt that it was the affected constituency (i.e., pilots and flight attendants) who should bring appropriate pressure on their employers to comply with the FAA recommendations. In the same regulatory session several European attendees remarked that the most recent European Directive on Basic Standards of Radiation Protection set out requirements for all member states of the European Union to assess and regulate the exposure of aircrew to cosmic radiation within two years (EU 1996).

The 1998 International Conference

A few months after the NCRP meeting, the European Commission and the Radiological Protection Institute of Ireland held an international conference on the subject of cosmic radiation and aircrew exposure (Anonymous 1999; Talbot 1999). Many of the presentations mirrored those presented earlier at the U.S. meeting. An important difference was based on the legal requirement that all aircrew receive mandatory radiation training and dose assessment under the laws of the European Communities that would go into effect in mid-May 2000. Of particular interest were the available options for dose assessment. Several presentations at the meeting were concerned with the various existing computer models that could be used as the basis for such assessments. A common theme was the relative simplicity of using these computer-generated dose estimates instead of relying on more costly instrumentation that would potentially introduce problems of equipment failure as well as possibly confusing measurement differences between competing devices. Adopting a standard computer model would allow for consistency of route doses among the various European airlines, with the software subject to independent scrutiny and revision, as required. It was generally agreed that, for flight crew making a significant number of trips over the same routes, the differences in dose rates as flight altitudes changed would be reasonably approximated with a single average number for cruising altitude, thus eliminating the requirement for extremely detailed in-flight data.

Another major element of the European meeting, in contrast with its American predecessors, was the amount of time allotted for the presentation of the views on this subject by the affected constituency, pilots and flight attendants. These presentations revealed a much greater familiarity with these issues by the European unions than that demonstrated by their U.S. counterparts. Included in the presentations were ideas for such changes as limiting of ceiling altitudes in air travel (as an approach to ALARA or "as low as reasonably achievable" for this group) and adopting various social and economic changes to allow for protection of pregnant crewmembers with preservation of the financial benefits afforded by "flight pay."

The 2006 request from AFA

The Association of Flight Attendants (AFA) represents over 55,000 employees at 20 airlines. In May 2006, the President of that union, Patricia Friend, wrote a letter to Marion Blakey, the Administrator of the FAA, requesting that new regulations be put in place to promote the awareness of radiation risks for the union membership (Friend 2006). This followed 6 years during which flight attendants from European carriers were all subject to the EU requirements on radiation training and dose assessment. In that letter Friend specifically asked that three things be incorporated into new regulations. These were mandatory (rather than voluntary) training programs on the health risks of in-flight radiation, tracking of employee doses using the CARI software or equivalent methods together with an estimate of increased doses caused by solar particle events, and a solar flare awareness program to provide an additional level of safety during solar particle events, awareness that might usefully prompt the airlines to make changes in altitude or latitude to lower radiation levels should a radiation event of that nature occur.

The FAA response to the to letter from AFA was less than they had hoped for. Rather than receiving a direct reply from the Administrator herself, they heard from the Associate Administrator for Aviation Safety, Nicholas A. Sabatini. He stated that the FAA had made available sufficient information on in-flight radiation issues through the Advisory Circulars and Web-based training manual that we have discussed here earlier. His response specifically said that *"the FAA itself is not currently disposed to initiate the rulemaking"* that had been requested by AFA (Sabatini 2006).

Epidemiology and the NIOSH study

In our previous *Health Physics* paper we reported on the initiation of a project under the auspices of the National Institute of Occupational Safety and Health (NIOSH) with the general title "Study of Reproductive Disorders in Flight Attendants" (Barish 1995). Subsequently, the study was divided into two sections. The first part has the title "Evaluation of Cosmic Radiation and Cabin Environment Exposures of Flight Attendants." That part of the study has two objectives: to provide descriptive and statistical evaluation of cosmic radiation levels as a function of altitude, distance/duration, and changes in flight latitude and longitude, and; to compare the cosmic radiation dose equivalent data measured with a particular TEPC for specific flight segments with cosmic radiation dose equivalents predicted by the FAA computer model (then CARI version 3-Q; now CARI-6) (O'Brien et al. 2003).

The first years of this study were devoted to the acquisition of dose data for representative flight as a means of establishing the validity of using the FAA CARI program as the fundamental method of assigning career dose values to study participants (Waters et al. 2000). Measurements were made using an instrument from Battelle Pacific Northwest Laboratories that had been well described in concept in several forums over a period of years (Chee et al. 2000). The second part of the project, currently underway, consists of the comparative evaluation of two groups of women matched into statistical cohorts, each containing 4,000 individuals. The first group is flight attendants, the second, schoolteachers. At the time of this writing, study results have not yet been published.

More than thirty papers looking at the possible relationship between cosmic radiation exposure and cancer incidence in aircrew have been published. In the period 1996–2008, in addition to studies on airline pilots, considerable attention was generated by several papers that found a statistically significant increase in the incidence of breast cancer in female flight attendants compared with women of the same ages in the general population of a number of Northern European countries, and through meta-analysis of previously published studies (Pukkala et al. 1995; Lynge 1996; Band et al. 1996; Grayson and Lyons 1996; Wartenberg and Stapleton 1998; Gundestrup and Storm 1999; Rafnsson et al. 2000, 2001, 2003; Buja et al. 2006; Salhab and Mokbel 2006; Tokumaru et al. 2006). Other authors found the relationship between in-flight radiation exposure and cancer to be either statistically uncertain or negatively correlated, particularly as it related to the predominantly male pilot cohort where the "healthy worker syndrome" may have had some influence on outcomes (Irvine and Davies 1999; Haldorsen et al. 2001; Blettner et al. 2003; Pukkala et al. 2003; Zeeb et al. 2003; Langner et al. 2004; Sigurdson and Ron 2004; Kojo et al. 2005).

Some investigators have proposed alternative causes of the increased incidence of breast cancer in female flight attendants. Specifically, they have advocated the importance of disruptions in the circadian cycle as a result of crossing through several time zones and the impact of these rapid time-zone changes and sleep-cycle disruptions on hormone levels. They have emphasized the possible impact of an observed suppression of melatonin, a hormone that has been shown to be associated with cancer regulatory processes, particularly for breast cancer (Megdal et al. 2005; Pandi-Perumal et al. 2008).

Validation of computer models

In addition to the CARI-6 program developed by the FAA, nations in the EU, in connection with the requirement for dose assessment of all aircrew, have made available their own computer dose estimation programs. One is called EPCARD, *E*uropean *P*rogram Package for the *C*alculation of *A*viation *R*oute *D*oses. This software was developed by the German Research Center for Environmental Health (GRCEH 2008). The French have their own computer code called SIEVERT (Systeme d'information a d'evaluation par vol de l'exposition au rayonnement cosmique dans les transport aeriens) that is available to subscriber airlines (Bottollier-Depois et al. 2007), and a research group in Canada has developed their own program named PCAIRE (*P*redictive *C*ode for *Ai*rcrew *R*adiation *E*xposure) that essentially performs the same task for an annual subscription fee of $25 (International Safety Research 2008). A fifth code, FREE (*F*light *R*oute *E*ffective Dose *E*stimation), has been developed by researchers in Austria in collaboration with an American partner and is now used primarily in Austria and Germany (Felsberger et al. 2004). Of these five, only CARI-6 and EPCARD are freely available, without charge, for use by anyone interested in performing a dose calculation by entering a simple flight plan.

In order to validate and refine these programs, a significant number of in-flight radiation measurement programs were completed in the latter part of the twentieth century and the results of those measurements were compared with the results predicted by calculation (Lewis et al. 1994, 1999, 2005; O'Sullivan et al. 1999, 2001; Schrewe 1999; Zhou et al. 2003; Lindborg et al. 2004; Takada et al. 2007; Beck et al. 2008). A side-by-side comparison of the predicted doses from the five major computer models was published under the auspices of the European Communities (EURADOS 2004). The report stated: "Results of measurements and calculations presented in this report show that there is good agreement between different methods of experimentally determining ambient dose equivalent rates at aircraft altitudes for the galactic component of cosmic radiation." Recent papers have pointed out deficiencies in the underlying physics of some of these models that may have been responsible for the variations that were found in the comparison of dose estimates using the several different programs (O'Brien 2004, 2008).

The NOAA space weather scales

In November 1999 the National Oceanic and Atmospheric Administration (NOAA) announced a new classification scheme for their space weather alert system. The Space Weather Prediction Center (SWPC) in Boulder, CO, monitors solar activity with a variety of sensors including satellites that have multichannel radiation detectors; they issue alerts and warnings that are useful to operators of systems such as power, communications and satellites. All of these systems are subject to damage or disruption in the event of significant solar flares. In a manner similar to the familiar system of grading the intensity of hurricanes or earthquakes with numbers, NOAA introduced analogous scales for geomagnetic and particle radiation events. Their initial radiation scale significantly underestimated the doses that might be received by passengers and crew in commercial aircraft (Barish 2000). This error was subsequently corrected (Heckman 2000).

The radiation levels associated with the Solar Radiation Storm scale (S-scale) are grouped into five intervals, each representing an increase of one order of magnitude above the previous. They are based on the measured integral proton flux values of particles with energies equal to or greater than 10 MeV, as detected by their satellites. At level S1 there might be minor impacts on radio reception or transmission over the polar regions. Level S5 indicates extreme radiation hazards to astronauts, possible permanent damage to orbiting satellites and the possibility of complete blackout of radio communications in polar areas. It also indicates increased radiation risk to passengers and crewmembers on commercial aircraft.

Unfortunately, the S-scale is, at present, based on the increased incidence of radiation particles of modest energies. Although particles of those energies will certainly influence systems outside of the Earth's atmosphere, the impact on commercial aircraft radiation levels is more dependent on increased levels of higher-energy particles. In other words, a particle event that might be extremely significant as a radiation hazard at the altitude of the International Space Station might be of little consequence, or of lesser significance, at airliner altitudes.

The FAA has attempted to rectify this situation by introducing its own alert system (Copeland et al. 2005). During a solar particle event that causes a significant increase in the radiation dose rate at airliner altitudes, the FAA scientists compute a maximum flight altitude at which the dose rate is less than 0.02 mSv per hour. This information is made available through the National Weather Wire Service (NWWS) to all commercial aviation companies through their own weather monitoring stations. The intention of the alert system is that air carriers will have adopted a policy that will keep passenger and crew exposure rates below that 0.20 mSv per hour level by descending to the specified altitudes and/or changing flight latitudes away from more-polar flight routes where the anisotropy of the radiation intensity always produces higher dose rates.

Solar flare alerts

A common theme in virtually every meeting devoted to cosmic radiation exposure of air crewmembers is the subject of these particle-producing solar flares. The large event of October 1989 was estimated to have produced radiation dose equivalent rates as high as 0.1 mSv per hour at airliner altitudes over polar routes. Discussions of the implementation of systems that would notify aircraft in flight about these events had been underway for the past ten years. During the quiet period between solar cycles 22 and 23, i.e., late 1995 until late 1997, there were no significant particle events to remind those parties concerned with these issues that they needed to be addressed prior to the rise in activity that would be expected as cycle 23 headed toward its predicted peak in 2001. Solar cycle 23 lasted from May 1996 through June 2008. In that 12-y period there were 93 solar particle events (NOAA 2007). Of these 93, seven were classified as Ground Level Events (GLE) (NOAA 2008). In order to become a GLE, the secondary particles (primarily neutrons) released from proton interactions in the upper atmosphere must cause a sudden sharp increase in the measured radiation levels in a network of monitoring stations at ground level. There are more than 125 such stations run by a number of academic centers or governmental agencies, essentially covering the globe, with locations on every continent (including Antarctica).

Remarkably, three large events in cycle 23 occurred late in 2003 (*"The Halloween Storm"*) and again late in 2004 and early 2005. These late-cycle events dispelled the notion that there would be a particularly *"quiet sun"* as the sunspot minimum approached. On 20 January 2005, the largest solar proton event in 50 years occurred. The event started at 06:50 universal time (GMT) and at 5 min after it began, dose rates at 60,000, 50,000, 40,000, and 30,000 feet (relative to mean sea level) were reported to have reached maximum values of 1.70, 0.87, 0.35, and 0.10 mSv per hour at those respective altitudes. During a 1-h period, the integrated doses were 0.90, 0.42, 0.16, and 0.05 mSv at the same altitudes. For a 10-h flight at high latitudes during that event, the estimated doses to passengers or crewmembers (the highest altitudes used only by certain military aircraft) were, at those same altitudes, 2.2, 1.0, 0.39, and 0.12 mSv (Copeland et al. 2008). Due to a very strong anisotropy in the dose pattern, the maximum dose in polar regions has also been reported at 0.125 mSv per hour while at the same time it was only 0.002 mSv per hour at mid-latitudes (Beck et al. 2005; Smart et al. 2005). During this event, the dose equivalent rate at airliner altitudes was increased by as much as a factor of 15 to 20. One group that analyzed the data recently reported a maximum increase in the effective dose rate at flight altitude as a result of this event of almost 1,000 times greater than normal in the south-polar region, at a latitude of around 70 degrees south and a longitude of 130 degrees east (Bütikofer et al. 2008). During the solar proton alert of 29 and 30 September 1989, the highest effective dose rates at airliner altitudes could have been as much as 0.57 mSv per hour, more than ten times the normal value (Copeland et al. 2008).

Following the first significant solar proton event of cycle 23, on 6 November 1997, an independent company, In-Flight Radiation Protection Services, Inc., initiated a program to providing warnings in the case of future significant particle events. The concern here was primarily for pregnant passengers or crewmembers, but any travelers sensitive to these issues could acquire the information. In this regard, in September 1999, a telephone advisory service was put into place. By telephoning an 877 (toll free) phone number accessible from anywhere in the United States, a traveler received a message informing them if a solar storm was in progress or expected. When an increased radiation level was occurring, the severity was simply described as "minor" or "major." The caller was advised in the first case to "consider" and in the second case to "strongly consider" postponing their travel until conditions returned to levels below a particular dose threshold. The service operated for a period of just over a year before it was discontinued due to lack of sufficient public interest (Wald 2000). During the period of its operation, there were two solar proton events that significantly raised the dose rates at airliner altitudes. The first occurred on 14 June, the second on 9 November. The latter was the fourth largest event recorded in the previous 25 years.

Recently, researchers announced a method of predicting, in real time, the arrival of high-energy particulate radiation associated with a solar particle event (Posner 2007). The method relies on the earlier arrival of relativistic electrons that reach an orbiting satellite of the European Space Agency (ESA), the Solar and Heliospheric Observatory (SOHO), and are measured by an onboard detector called the Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP). A Web site that is a collaborative effort between ESA and our own National Aeronautics and Space Administration (NASA) has been set up with claims that it is able to provide a "reliable early warning sign of hazardous radiation ahead" (SOHO 2008). It is stated that warning of the arrival of the more damaging particles will be given somewhere between seven minutes and an hour before they actually impact the terrestrial environment. This manuscript is being prepared at the time of solar minimum—the period of transition from solar cycle 23 to solar cycle 24. There have been no solar particle events since late in 2006, so the ability of this new warning system to actually deliver on its representation of early warning has yet to be tested.

New polar routes

In 1999, air carriers were given permission by the Russian government to fly over their airspace, thus allowing for shorter "great circle" routes between the United States and Asia. On 4 July 1998 Cathay Pacific Airways flew the first non-stop New York to Hong Kong flight in somewhat more than 15 hours—a full 5 hours less than if they had followed the traditional route. Subsequent to that test flight, over the following two years, other major air carriers initiated regular service on polar routes as the air traffic control system in the Russian Federation was upgraded with appropriate satellite-based communications systems to allow for safe travel over these remote areas. Polar flights now connect major U.S. cities with China and India. Although the flying time is reduced, with a significant saving in fuel cost, the in-flight radiation environment at polar latitudes is subject to both a generally increased dose rate under normal conditions and a possibly very significant increase during a solar particle event.

Using the CARI-6 program, it can be calculated that the 1 mSv exposure recommended as a maximum during pregnancy (or as an annual dose for a member of the public) can be exceed by as few as six round trips between, say New York and Tokyo (Barish 2004). If one of those trips happens to be at a time of a solar particle event, when the polar dose rate could rise by a factor of ten or more, the total amount of air travel that would result in an integrated value of 1 mSv would, of course, be reduced. Several air carriers have made it their corporate policy to eliminate polar flights if a radiation alert is announced (Cameron 2007). The possibility of exceeding the recommended annual public exposure limit of 1 mSv with as few as one transpolar flight every two months again raises a question first proposed earlier (Barish 1995). Should business travelers whose work requirements include significant air travel be formally recognized as occupationally exposed persons? And, if so, should they be required to have some form of education about their exposure to cosmic radiation in flight?

CONCLUSION

Perhaps the most surprising element of the story of health physics involvement with airline crewmembers and passengers over the 12-y period since 1996 has been the apparent lack of concern among these affected workers in the United States in comparison with their European counterparts. Given that there are tens of thousands of American aircrew who receive exposures in the range of 2–6 mSv per year, it might be expected that the strong demand for "radiation protection" that the health physics community sees from other elements of society who are usually exposed at far lower levels would have, by now, manifested itself. This has clearly not been the case. A possible explanation is the lack of knowledge about this issue. As long as the air carriers choose not to accept the FAA's recommendations regarding education of the workforce, then it is possible that any increase in appreciation of the risks will only come with a concerted effort by the employee unions or professional associations to add this issue into the agenda of employee-management issues. With the dramatic increase in airline financial problems caused by the increase in fuel prices that began in 2007, it seems unlikely, however, that there will be any available resources that would allow U.S. based airlines to invest in radiation training or dose monitoring programs for their employees any time soon. The 2006 decision by the FAA to abstain from rulemaking in this area may be the final word on the subject as far as flight crew working for U.S. carriers is concerned.

Whether the subject of in-flight radiation and its relationship to employee health will expand to business frequent flyers is a matter of speculation. It should be noted however there may come a time when the "failure to warn" flight crewmembers and business travelers who are occupationally exposed to cosmic radiation about their health risks may have repercussions in the legal arena. The following quote is taken from a paper presented by leading experts from the FAA, NASA, the U.S. Department of Energy and several academic centers: "It appears the situation justifies that U.S. aircrews are probably due illness compensatory legislation, but insufficient data exist on which to write such legislation. It is imperative that U.S. aircrew epidemiological studies are expanded to correct the current lack of data on cancer incidence and mortality among U.S. aircrew in preparation of required legislation. This impetus follows since it is clear that there are health risks associated with a career of flying" (Wilson et al. 2002).

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