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Abstract

An analysis of the radiation hazards that are anticipated on an early Human Lunar Return (HLR) mission in support of NASA deep space exploration activities is presented. The HLR mission study emphasized a low cost lunar return to expand human capabilities in exploration, to answer fundamental science questions, and to seek opportunities for commercial development. As such, the radiation issues are cost related because the parasitic shield mass is expensive due to high launch costs. The present analysis examines the shield requirements and their impact on shield design.

Introduction

The Human Lunar Return (HLR) study examined the basic rationale, the required technologies, and the mission development for a return to the Moon. The basic thrust of the HLR mission study is to make humanity a multi-planet society, to open new opportunities for commercialization, and to answer fundamental questions about Earth and solar system science. Since these goals are mainly futuristic in orientation, the attempt is to lay the foundation for human space activity over the next three decades. The near term objectives will hinge mainly on the current cost of space exploration and emphasize the possibility of a low cost return to the Moon. Radiation protection systems (shielding, monitoring, and medical supplies) impact mission cost, and uncertainty in past shield databases is inadequate for the present design study. Recent advances in shield design technologies require a regeneration of the necessary design database (refs. 1 through 6). For example, a progression of aluminum shield attenuation characteristics is shown in figure 1. The lower curve is that generated by the code of Letaw, Silberberg, and Tsao (ref. 1) and was used in the National Council on Radiation Protection (NCRP) report 98 (ref. 7). The nuclear fragmentation (NUCFRG1) curve used the first generation of the Langley Research Center (LaRC) database (ref. 2) and

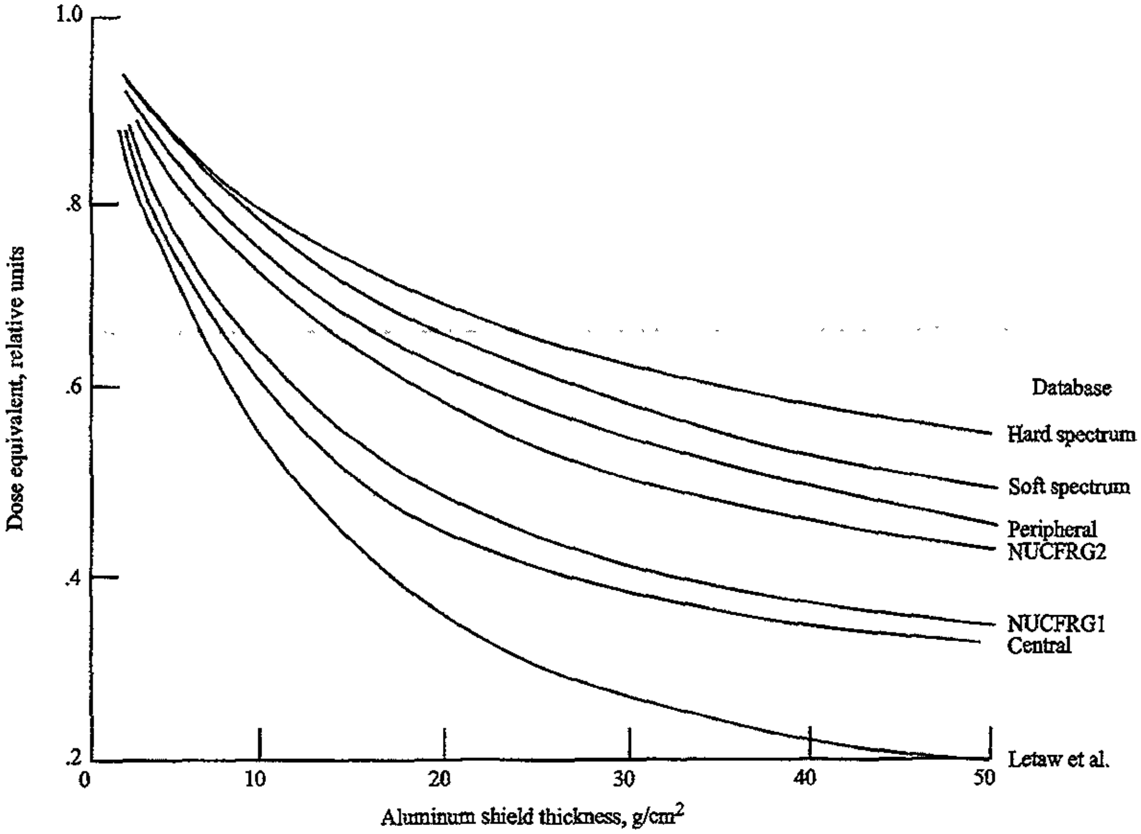

Figure 1. Shield attenuation for solar minimum galactic cosmic ray dose equivalent resulting from nuclear fragmentation (NUCFR) models G1 and G2.

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the corresponding first version space radiation transport code (ref. 3). The peripheral and central limits (curves) are the unitary limits on the projectile fragmentation which ensure charge and mass conservation, not including the direct target knockout contributions to the transmitted fluence (ref. 4). The NUCFRG2 (curve) is the revised database that resulted from the 600 *A* MeV experiments at the Bevalac facility (ref. 5). The two upper curves (labeled *hard spectrum* and *soft spectrum*) include improved nuclear data for the knockout of light fragments from projectile and target nuclei and the uncertainty in their production spectra (ref. 6). These data encompass our best current estimate of the attenuation of dose equivalent in aluminum. Clearly, large changes in the nuclear data and transport procedures have occurred in the last several years. Only the completion of the transport code with the as yet neglected radiation components (with added laboratory and flight testing) will allow a final evaluation of the expected astronaut exposure.

In returning to the Moon, we first note that in addition to great changes in technology, our understanding of space radiation protection practice has improved since the first lunar missions. The Apollo program was recognized as a high risk, exploratory venture in which the radiation risks were a direct trade-off against the other mission risks (ref. 8). As a result, the protection standards were mainly concerned with early biological effects associated with high exposures that may directly impact mission safety. The late biological effects such as cancer induction and cataract formation were of secondary concern. Thus, the low level galactic cosmic rays (GCR) were neglected in the design process. The important solar particle events (SPE) of the time were those of solar cycle 19, including 23 February 1956, 16 July 1959, and 12–13 November 1960, for which it was estimated that serious exposures could impact mission safety, but that early lethality was unlikely. During the Apollo program, between missions 16 and 17, the 4 August 1972 event occurred. This event had significantly higher exposures within typical space structures than prior events, bringing to mind the potential lethality of solar particle events (ref. 9). In addition to an improved knowledge of the environment, the whole texture of the space program changed with the development of the Skylab and shuttle operations, in which access to space became routine, and the need for revised space radiation standards developed (ref. 10). As a result of the routine access to space, the neglect of the galactic cosmic ray background was reevaluated and identified as a critical element in future NASA radiation concerns (ref. 11). No standards have been established to protect astronauts from the high charge and energy (HZE) particles of galactic cosmic rays. In addition to changes in protection practices, the technology base has improved, and mission costs may change radically as the result of new space transportation methods, the use of a space-based staging area (provided by the developing International Space Station), and new spacecraft materials. Such new materials may provide added protection compared with an equal mass of aluminum (the standard construction material in the Apollo program).

In this report, we examine the attenuation characteristics of potential shield materials for use in the early return to the Moon and assess the shield requirements that protect the astronauts.

Radiation Protection Standards

Currently, no radiation limits have been accepted or even recommended for exploration class missions. However, for *planning purposes only*, the National Council on Radiation Protection (NCRP) suggests that the limits established for astronauts in low-Earth orbit (LEO) may be used as guidelines for other missions if the principle of ALARA (as low as reasonably achievable) is followed (ref. 7). LEO exposure limits are currently given as dose equivalents to specific organs for short-term (30-day) exposure, annual exposure, and total career exposure. LEO limits for the skin are 150, 300, and 600 cSv (1 cSv = 1 rem), respectively. LEO limits for the ocular lens are 100, 200, and 400 cSv, respectively. LEO limits for the blood-forming organs (BFO) are 25, 50, and 100 to 400 cSv, respectively (with career limits, depending on age and gender). Note that the exposure limits for the BFO reflect the exposure limitation to prevent all cancer, assuming that the BFO dose is indicative of whole body exposure. The NCRP is currently revising the LEO recommendations as a result of larger estimates of cancer risk coefficients (ref. 12).

The current limits are based on a 3-percent lifetime excess fatal cancer risk, which is comparable to the fatal risk of moderately safe occupations (ref. 7). A lower acceptable risk may be required due to the improved safety record, in recent years, of these moderately safe industries. Furthermore, it is unlikely that special high risk limits for exploratory class missions will be approved in the current social context. In the current context, risk management for Human Lunar Return (HLR) may be even more restrictive and may lead to more stringent, or at best unchanged, shield requirements.

Even if designs are adequate for protection from a solar event, an accidental exposure could occur. In the event of accidental exposure, methods to deal with the potential astronaut health problems must be part of the planning process, and there must be reasonable assumptions as to the worst case scenario to allow for medical treatment plans and to provide adequate dosimetry to

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diagnose the expected severity for medical intervention during the course of the mission. This planning requires the specification of adequately complex dosimetry systems capable of estimating organ dose rates. Well-established biological response models must be validated for treatment planning in the space environment (ref. 13).

Radiation Environmental Models

For exploration calculations of radiation effects in free space, we use environmental input models and two transport codes. For galactic cosmic ray (GCR) environments, we now use the model of Badhwar and O'Neill (ref. 14). Our earlier work during the Space Exploration Initiative (SEI) time period used the CREME model (ref. 1) for the GCR environment and an earlier version of the HZETRN code that was developed at Langley Research Center (LaRC) (ref. 2). For solar proton event environmental data, we use a variety of inputs: the fluence (time integrated flux) of the four largest flares that have occurred during the last 40 years—February 1956, November 1960, August 1972, and October 1989 (refs. 9, 15, and 16); flux data from the GOES-7 satellite for a series of 1989 flares, including October 1989; and IMP-5 and IMP-6 data for the August 1972 event. In addition, we have inputs of smaller flare data from IMP-7 and IMP-8 satellites.

For the transport of GCR and solar proton events through various materials, LaRC has developed HZETRN and BRYNTRN, respectively. The transport codes and the database are tested in laboratory experiments performed by the Lawrence Berkeley Laboratory and others. Both codes are well-known and are used widely in the radiation community. We also model the effects of biological response and electronic response to the radiation environment for incorporation into the transport code analysis systems.

Our engineering design tools can model various configurations of spacecraft/habitats to determine the shielding that is provided by the structure, the internal and external equipment, and the consumables. Those results, combined with the transport results, will provide us an estimate of the radiation environment within the spacecraft/habitat. Then we can investigate the optimum placement of equipment to minimize parasitic shield requirements. We are currently validating this procedure with detectors onboard the LEWIS spacecraft that will be launched in May 1997 (ref. 17).

Currently, large uncertainties exist in biological response, spacecraft shielding properties, and transport properties of body tissues to HZE (high charge and energy) particles, such as those which comprise the galactic cosmic rays. The uncertainty in astronaut risk to HZE particles consists of the biological response with uncertainties up to a factor of ~5 and to the transport properties of materials with uncertainties up to a factor of ~2 (fig. 1). The NASA Life Sciences Division is funding projects to reduce these factors. Uncertainties in the GCR background environment are estimated to be about 10 to 15 percent, while the solar event spectra are variable, and the appropriate design spectrum is controversial. For this analysis, we will use the 4 August 1972 event as the most hazardous single event for space exposures yet observed.

Statistical Odds of Encountering a Major Solar Proton Event

Although the statistical odds of encountering a major solar proton event such as the February 1956, July 1959, November 1960, August 1972, or October 1989 event is statistically very low, with only 5 *major* events in the last 40 years (probability for a 16-day mission is about 1 in 200). Serious exposures to the crew would occur if no provisions for a major solar event were provided. For example, the 30-day exposure limit of 25 cSv is greatly exceeded by any of these events without special provision. Some have suggested that early lethality may occur within 45 or more days after an extremely intense event. Clearly, such an event cannot be ignored on the basis that it is unlikely. One need only to recall that with a slight change in schedule, either Apollo 16 or Apollo 17 would have encountered the August 1972 event, which is the most important event ever observed with regard to space radiation safety. Furthermore, one must consider the negative impact on the developing space program if adequate provision is not made to protect the astronauts from a potentially debilitating injury.

If the solar particle event can be predicted from solar observation, crew members will have a minimum warning time of 20 minutes before the arrival of energetic particles (ref. 15). The October 1989 flare came in three main pulses and lasted about 10 days (ref. 16). The limiting dose for the October 1989 flare was the 30-day ocular lens dose (assuming LEO limits), which would be reached only 17 hours after receiving warning (assuming that the crew member on the lunar surface was wearing a space suit). In comparison, one extravehicular activity (EVA) shift may last between 6 and 8 hours. For flares such as the October 1989 event, crew members will have a number of hours to seek shelter before any of the 30-day limits are exceeded. These time limits would determine the safe distance for a crew member to venture from the protection of the habitat or storm shelter. For example, during the August 1972 event, the ocular lens limit would have been reached in about 7 to 8 hours (ref. 9).

The time development of the particle fluence can be very different. The February 1956 event delivered its

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dose within hours. Twenty minutes after the optical flare and radio noise were seen at Earth, energetic particles arrived from the February 1956 event. From the ground-based measurements, the event's intensity was seen to have peaked 30 minutes later, followed by a decay with a mean time of 1 hour (ref. 15). Thus, the entire flare lasted only a few hours. Crew members would have had significantly less time to reach a flare shelter before limits were exceeded (compared with the October 1989 event). The time development of the February 1956 event was also characteristically very different from the other recorded large flares of November 1960 (ref. 15) and August 1972 (ref. 9).

Only minor doses in free space were predicted by space weather forecasters for the August 1972 event; however, it was the largest event ever observed for space exposures. By 0700 Universal time (UT), the accumulated dose at a 1-cm depth was 2.7 cGy, climbing rapidly to 10 Gy over the next several hours (1400 UT). Astronauts (nominally shielded in free space) would have had only ~3.5 hours to reach a storm shelter from the time of particle onset at 1 AU (astronomical unit) to the time that 30-day exposure limits (assuming LEO limits) were exceeded (ref. 9). Clearly, very high levels of exposure can be received in a short time (a few hours) with possibly inadequate warning, leading to the possibility of early radiation syndrome. Some attention needs to be given to the prediction and control of biological effects which could occur during such an accidental exposure (ref. 13).

Radiation Protection From Various Shielding Thicknesses

Estimates of exposures made in 1992 by using the galactic cosmic ray CREME model and the sum of the 1989 flare events (October, September, and August) are substantially different from the exposure estimates of more recent models of the GCR by Badhwar and O'Neill (ref. 14) and the recent reevaluation of the nuclear databases in the HZETRN code (ref. 18). The solar flare results have changed mainly because of reevaluation of the particle fluence. New tables for GCR exposures behind regolith and polyethylene shields are shown in tables 1 and 2 for solar minimum and maximum, respectively.

Overall, the dose and the dose equivalent are substantially higher because the CREME model underestimated the fluence of important components (ref. 14). In addition to the more intense environmental model, the cross sections for fragmentation and particle production are substantially greater than those represented in prior codes (fig. 1). Also, the atomic interactions are more accurately accounted for than in the Letaw, Silberberg, and Tsao procedure (ref. 1) and in Wilson and Badavi (ref. 19). All these factors compound to increase the estimated astronaut exposure with the latest values given in tables 1 and 2. A factor-of-three reduction in exposures is seen near solar maximum for moderate-to-thin shielding. This ratio of solar minimum to solar maximum decreases to slightly over two at large depths.

We have recalculated the dose and the dose equivalent for the solar particle event of 4 August 1972 with the BRYNTRN code. The results are presented in table 3. We have used two representations of the 4 August 1972 event spectra: one prepared by King (ref. 20) and the other by Wilson and Denn (ref. 9). The relative advantage of a hydrogenic polymer, as opposed to regolith, is clearly apparent in the table. The geometry used is a spherical shell with a tissue sample within a 0-cm and a 5-cm radius. Reducing the values by a factor of 2 approximates self-shielding provided by the human geometry for the skin or lens (0 cm) or the BFO (5 cm). These values are in reasonable agreement with the older values by Simonsen, Nealy, Sauer, and Townsend (ref. 16) and are in good agreement with Wilson and Denn for polyethylene (ref. 9). Doses to the lens or to the skin on the lunar surface are further reduced to about a factor of 4 smaller than the 0-cm values, and the BFO is about a factor of 4 smaller than the 5-cm value given in table 3.

Galactic Cosmic Ray Dosage for 16-Day Exploration Missions

Compared with the other inherent risks of spaceflight, the risks of a 16-day exposure to galactic cosmic rays would not be a concern. We use the following assumptions in estimating GCR exposure:

- 6 days in free space and 10 days on the lunar surface
- 5 g/cm^2 aluminum shield typical of Apollo-type spacecraft
- estimate of blood-forming organ dose as 5-cm water depth dose

The GCR dose estimate would be 1.3 to 3.4 cSv to the skin and 1 to 2.4 cSv to the BFO when the range of values depends on whether the mission is at solar maximum or solar minimum. (Using a computerized anatomical man model would lower these estimates, but the developing transport database will increase the estimates.) These estimates could be compared with the annual allowed exposure of 50 cSv or the 30-day allowed exposure of 25 cSv used for the space station, although these limits do not apply strictly for these radiations. If the mission is planned for 2001, the environment will be near solar maximum, and the minimum GCR environment is appropriate.

Crew Dosage Expected on Lunar Missions During Past Solar Proton Events

The October 1989 event was a series of particle increases lasting 10 days. Exposure estimates (ref. 16) for the October 1989 event during the 3-day trip to or from the Moon, behind a shield thickness of 2 cm of water (lightly shielded module) in free space is between 65 and 80 cSv to the blood-forming organ (BFO) (by using a 5-cm depth dose as the estimated BFO exposure). By using the same assumptions for a 10-cm water shield (typical of a storm shelter), the dose equivalent to the BFO is estimated to be between 10 and 17 cSv. For a lunar surface stay, assuming a 2-cm water shield for the entire 10-day fluence, in which the lunar surface provides additional protection, the estimated BFO dose equivalent is 50 to 65 cSv. For 10 cm of water shielding on the lunar surface for the 10 days, the estimated dose equivalent to the BFO is 8 to 14 cSv. The shielded volumes are assumed to be cylindrical.

In estimating the dose equivalent to the BFO, the lens, and the skin for the August 1972 event, we have used self-shielding factors which substantially reduce the organ dose by about a factor of 2 and an average quality factor of 1.3 (ref. 9). In addition, there is a further reduction on the lunar surface to a factor of 2 because of the lunar shadow. The dose equivalent from the August 1972 event is somewhat higher and is accumulated over a shorter period of time (about 10 to 16 hours). During the three-day transit time, the August 1972 event would result in exposures within a simple pressure vessel (approximately 1 g/cm^2 equivalent water) of 15.6 Sv (skin and lens) and 2.2 Sv (BFO). By moving into an equipment related area (5 g/cm^2 equivalent water, compared to the Apollo command module of 4.5 g/cm^2), the exposures are 2 Sv (skin and lens) and 0.46 Sv (BFO). To meet the 30-day limit, one will require a storm shelter (about 10 g/cm^2) in which 0.6 Sv (skin and lens) and 0.2 Sv (BFO) would have been received.

In a space suit on the lunar surface, the accumulated exposure is about 13 Sv (skin and lens) and 1.1 Sv to the BFO. Moving into a simple pressure vessel on the surface (minimum habitat wall of approximately 1 g/cm^2) reduces the estimated exposures to 7.8 Sv (skin and lens) and 0.85 Sv (BFO). The exposures in an equipment room (5 g/cm^2) within the habitat are still lower, yielding 1 Sv (skin and lens) and 0.23 Sv (BFO), which satisfy the 30-day exposure limitation requirements for the LEO exposure limits.

Using the ALARA principle (keeping exposure as low as reasonably achievable), one would attempt to provide as much shielding as reasonably possible. The following requirements are necessary to meet currently accepted space station limits as applied to this mission:

- a storm shelter of at least 10 g/cm^2 of water equivalent shield during transit to the Moon (note that this is equivalent to about 14 g/cm^2 of aluminum)
- a region that has at least 5g/cm^2 water equivalent shielding (7 g/cm^2 of aluminum) that all astronauts can reach in a timely fashion (within a few hours) during lunar operations
- improved biological understanding that could possibly relax the current 30-day limit, result in great reductions in the shield requirements, and reduce mission costs
- exploration of dynamic shielding concepts in which movable equipment and materials can be used to make the most effective temporary use of onboard mass

Radiation Protection Properties of Materials

The GCR background during a 16-day mission is not more than 3.4 cSv. The primary protection problem for the HLR is that the possibility of solar particle event exposures may be quite large, with a 0.5-percent probability within a 16-day mission. Although the probability of occurrence is small, the potentially serious illness which could result is a cause for concern. There are two important parameters in determining space shield properties in a solar particle event: stopping the low energy protons by atomic collision, and to a lesser extent, stopping the production of particles in collision with the shield nuclei. In both respects, hydrogen is a preferred material constituent; the higher the hydrogen content per unit mass of material, the better the shield properties (both the atomic and nuclear properties). Thus, polyethylene, other polymers, water, compressed methane (a possible rocket fuel), and LiH are all good materials. Shield attenuation results are shown in table 4 for several materials for the October 1989 event (ref. 16). Of the materials listed, only the regolith contains no hydrogen-bearing molecules. Water and magnesium hydride are likely materials for life support systems. Polyethylene is used as a high performance shield and shows significant advantage over regolith. Adding boron to the polyethlene to deplete the low energy (thermal) neutrons appears to be counterproductive because the added production of secondaries and the change in the atomic cross sections usually increase the dose. Lithium hydride is probably a better alternative.

Protecting the astronaut from space radiation is dependent on the local distribution of materials. Much protection will be derived from materials and equipment that is onboard the spacecraft for other purposes. The choice of materials used to construct the spacecraft systems is very important, and some attention should be given to materials that will be used in future spacecraft technology. For example, materials designed primarily for water and food storage also could be useful for other purposes. Removable polymeric flooring and other equipment could be temporarily rearranged for protection from a solar event. Parasitic shielding is expensive, but polyethylene is a good material if added shield material is required. However, polyethylene has limited material properties and poses a flammability issue that must be resolved. Polymer composites are the next most useful materials, but the preferred material would have a high binder-to-fiber ratio to maintain a high hydrogen content. Careful consideration should be given to the other onboard materials.

Concluding Remarks

For the short-term missions to the Moon, the shielding against the galactic cosmic ray (GCR) background is negligible. Longer missions (to establish a permanent base) will be limited by the GCR exposures, and the latest results on shielding properties will require added shield mass over prior estimates. The solar energetic particle events require special consideration and protection of at least 10 g/cm^2 of water or polyethlene during transit to the Moon and 5 g/cm^2 on the Moon's surface. The shield mass requirements to protect astronauts from a solar event are about 40 percent higher if regolith or aluminum is used. In the event of an accidental exposure by a solar event, some provision for medical treatment needs to be provided. The accurate prediction of accidental exposure levels is necessary to allow proper prognosis and medical treatment. Appropriate design criteria for protection against solar events are still lacking.

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Table 1. Annual Dose (*D*) and Dose Equivalent (*H*) for Galactic Cosmic Rays Behind Slab Shield Amounts (*x*) at the 1977 Solar Minimum

Lunar regolith,	*D*, cGy/yr for—		H_{60}, cSv/yr for—	
x, g/cm^2	0 cm	5 cm	0 cm	5 cm
0	19.44	20.41	120.13	94.63
1	21.92	20.37	132.26	91.06
2	22.20	20.33	126.62	87.76
5	22.25	20.17	111.38	79.43
10	21.94	19.91	93.74	69.36
25	20.93	19.20	68.66	53.89
50	19.46	18.10	56.32	45.78
75	18.05	16.99	52.54	43.21

Polyethylene,	*D*, cGy/yr at—		H_{60}, cSv/yr at—	
x, g/cm^2	0 cm	5 cm	0 cm	5 cm
0	19.44	20.41	120.13	94.63
1	20.52	20.18	118.39	88.63
2	20.39	19.96	108.86	83.33
5	19.71	19.40	86.61	70.78
10	18.79	18.69	64.09	57.30
25	17.27	17.38	38.92	41.18
50	15.84	15.88	30.82	35.20
75	14.45	14.38	28.18	32.43

Table 2. Annual Dose (D) and Dose Equivalent (H) for Galactic Cosmic Rays Behind Slab Shield Amounts (x) at the 1970 Solar Minimum

Lunar regolith, x, g/cm^2	D, cGy/yr at—		H_{60}, cSv/y at—	
	0 cm	5 cm	0 cm	5 cm
0	6.12	6.97	37.90	34.47
1	7.21	7.02	44.01	33.66
2	7.44	7.06	43.33	32.87
5	7.74	7.15	40.55	30.72
10	7.93	7.24	36.42	27.84
25	8.04	7.36	28.98	22.80
50	7.94	7.37	24.77	20.02
75	7.72	7.25	23.76	19.43

Polyethylene, x, g/cm^2	D, cGy/yr at—		H_{60}, cSv/yr at—	
	0 cm	5 cm	0 cm	5 cm
0	6.12	6.97	37.90	34.47
1	6.63	6.94	39.09	32.77
2	6.69	6.90	37.07	31.21
5	6.66	6.80	31.40	27.25
10	6.51	6.66	24.51	22.59
25	6.23	6.41	15.36	16.47
50	6.03	6.16	12.35	14.39
75	5.77	5.83	11.69	13.71

Table 3. Dose (*D*) and Dose Equivalent (*H*) for 4 August 1972 Event Spectra by King and LaRC

Lunar regolith, x, g/cm^2	*D*, cGy King		*H*, cSy King		*D*, cGy LaRC		*H*, cSy LaRC	
	0 cm	5 cm	0 cm	5 cm	0 cm	5 cm	0 cm	5 cm
1	3250.5	242.55	5696.6	332.73	2613.7	254.1	4491.4	346.57
2	1722.2	183.48	2843.8	251.55	1472.7	198.02	2391.3	269.98
5	495.2	86.0	772.5	119.0	480.84	100.66	740.36	137.84
10	117.2	29.10	179.7	41.3	132.59	38.20	200.75	53.57
25	6.08	2.39	11.27	4.69	9.34	3.96	16.04	6.91
50	0.2932	0.23	1.42	0.95	0.5	0.35	1.79	1.92
75	0.0732	0.083	0.5232	0.39	0.099	0.12	0.61	0.47

Polyethylene, x, g/cm^2	*D*, cGy King		*H*, cSy King		*D*, cGy LaRC		*H*, cSy LaRC	
	0 cm	5 cm	0 cm	5 cm	0 cm	5 cm	0 cm	5 cm
1	2437.4	221.82	3714.4	322.20	2013.4	234.63	3022.5	338.18
2	1188.7	155.5	1727.9	225.36	1055.0	170.84	1515.8	245.76
5	287.4	60.41	401.09	88.0	295.83	73.48	410.2	106.09
10	55.31	16.1	76.14	24.44	67.96	22.55	93.77	33.54
25	1.96	0.874	3.27	2.03	3.33	1.56	5.20	3.09
50	0.125	0.0898	0.36	0.367	0.18	0.13	0.49	0.47
75	0.04	0.0317	0.13	0.13	0.054	0.04	0.16	0.17

Table 4. Dose (D) and Dose Equivalent (H) for 1989 Large Solar Particle Events Behind Slab Shield Amounts (x)

Material	x, g/cm^2	D, cGy		H_{ICRP26}, cSv	
		0 cm	5 cm	0 cm	5 cm
Lunar regolith	1	3761.76	208.09	7435.22	306.24
	2	1586.95	163.96	2792.31	239.48
	5	391.73	88.28	615.87	127.24
	10	109.88	39.65	164.00	57.03
	25	13.67	7.66	20.71	11.68
	50	1.75	1.22	3.13	2.24
	75	0.40	0.32	0.89	0.70
Water	1	2830.31	198.52	5099.28	291.77
	2	1176.81	150.11	1922.11	218.56
	5	276.48	73.68	411.37	105.56
	10	73.68	30.07	105.56	42.88
	25	8.22	4.90	12.00	7.29
Magnesium hydride	1	3286.85	204.37	6166.85	300.69
	2	1383.24	157.76	2336.36	230.15
	5	333.30	81.26	508.18	116.74
	10	91.02	34.93	132.66	49.99
	25	10.89	6.28	16.19	9.45
Polyethylene	1	2587.62	195.67	4552.52	287.47
	2	1065.36	145.79	1706.01	212.10
	5	245.81	69.35	360.31	99.23
	10	64.21	27.42	90.89	39.05
	25	6.91	4.23	10.02	6.30
Borated polyethylene	1	2957.96	201.52	5346.73	296.48
	2	1239.37	153.69	2029.53	224.13
	5	295.16	76.87	439.73	110.38
	10	79.37	31.96	113.69	45.72
	25	9.03	5.35	13.18	7.99
Lithium hydride	1	2822.50	199.70	4979.57	294.08
	2	1184.89	151.50	1903.08	221.22
	5	282.09	74.90	415.17	107.75
	10	75.67	30.71	107.58	43.97
	25	8.49	4.99	12.27	7.39

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An analysis of the radiation hazards that are anticipated on an early Human Lunar Return (HLR) mission in support of NASA deep space exploration activities is presented. The HLR mission study emphasized a low cost lunar return to expand human capabilities in exploration, to answer fundamental science questions, and to seek opportunities for commercial development. As such, the radiation issues are cost related because the parasitic shield mass is expensive due to high launch costs. The present analysis examines the shield requirements and their impact on shield design.

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OVERVIEW OF ATMOSPHERIC IONIZING RADIATION (*AIR*) RESEARCH: SST-PRESENT

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ABSTRACT

The Supersonic Transport (SST) program, proposed in 1961, first raised concern for the exposure of pregnant occupants by solar energetic particles (SEP), and neutrons were suspected to have a main role in particle propagation deep into the atmosphere. An eight-year flight program confirmed the role of SEP as a significant hazard and of the neutrons as contributing over half of the galactic cosmic ray (GCR) exposures, with the largest contribution from neutrons above 10 MeV. The FAA Advisory Committee on the Radiobiological Aspects of the SST provided operational requirements. The more recent (1990) lowering of recommended exposure limits by the International Commission on Radiological Protection with the classification of aircrew as "radiation workers" renewed interest in GCR background exposures at commercial flight altitudes and stimulated epidemiological studies in Europe, Japan, Canada and the USA. The proposed development of a High Speed Civil Transport (HSCT) required validation of the role of high-energy neutrons, and this resulted in ER-2 flights at solar minimum (June 1997) and studies on effects of aircraft materials on interior exposures. Recent evaluation of health outcomes of DOE nuclear workers resulted in legislation for health compensation in year 2000 and recent European aircrew epidemiological studies of health outcomes bring renewed interest in aircraft radiation exposures. As improved radiation models become available, it is imperative that a corresponding epidemiological program of US aircrew be implemented.

INTRODUCTION

After the discovery of radiation emanating from certain materials, the source of background radiation observed in the atmosphere was thought to have exclusively originated from the ground, however Hess's series of balloon flights from 1911-1913 showed that an additional component originating from the sky was also present in this background. In 1925, Millikan coined this newly discovered radiation as cosmic rays.

The fact that the cosmic rays consisted in part of charged particles was directly demonstrated by coincidence experiments using Geiger-Mueller tubes and resolving individual charged particle tracks within a Wilson cloud chamber. The cloud chamber lead to the discovery of the positron as part of the cosmic rays, followed by the discovery of the charged mesons, and further shed light on the important neutron component of cosmic radiation in the atmosphere (Bethe et al. 1940). Worldwide surveys of cosmic ionization during the years 1931-1932 were made by several groups and Hess of Austria studied time variations associated with solar activity cycle on a mountaintop from 1931-1937. Global radiation levels correlated well with the expected effects of the geomagnetic deflection of cosmic radiation. A worldwide network of stations began to develop leading to observed short-term fluctuations in the global ionization rates simultaneously in both the southern and northern hemispheres and was correlated with solar disturbances (Hess and Eugster 1949). Observed large increases in the ionization rates would be attributed to particles coming directly from the solar events (Fig. 1). More modest decreases over a few days, as seen for the July-August 1946 event, were attributed to disturbance of the local interplanetary medium by which approaching cosmic rays were excluded from the local Earth environment (Forbush decrease). It was now clear that extraterrestrial radiation from both the sun and the galaxy were contributing to the atmospheric ionization levels. The next-to-last piece of important evidence from a human exposure perspective was the discovery of heavy ion tracks by Phyllis Frier and coworkers (1948) using nuclear emulsion track detectors in high altitude balloon flight. Although the initial emphasis of this discovery was the ability to sample cosmic matter, attention would turn to the possibility of human exposure by these ions in high-altitude aircraft and future space travel (Armstrong et al. 1949, Schaefer 1950, 1952, 1959, Allkofer and Heinrich 1974).

When the possibility of high-altitude supersonic commercial aviation was first seriously proposed, Foelsche brought to light a number of concerns for the associated atmospheric radiation exposure due to penetrating cosmic rays (CR) from the galaxy (GCR) and the sun (SCR, also referred to as solar particle events, SPE) including the secondary radiations produced in collision with air nuclei (Foelsche 1961, Foelsche and Graul 1962, Foelsche 1965). Subsequently, a detailed study of the atmospheric ionizing-radiation components at high altitudes was conducted from 1965 to 1971 at the NASA Langley Research Center (LaRC) by Foelsche et al. (1969, 1974). Prior to that study the role of atmospheric neutrons in radiation exposure was generally regarded as negligible (ICRP 1966). The LaRC studies revealed the neutron radiation to be the major contributor to commercial aircraft GCR exposure. Still the exposure levels were comfortably below allowable exposure limits for the block hours typical of airline crews of that time except during a possible solar particle event (less than 500 block hours were typical of the 1960's although regulations allowed up to 1000 hours). As a result, the US Federal Aviation Agency (FAA) Advisory Committee on the Radiobiological Aspects of the SST issued recommendations that crew members will have to be informed of their exposure levels, maximum exposures on any flight be limited to 5 mSv, development of airborne radiation monitors, development of a satellite monitoring system, and development of a solar event forecasting service (FAA 1975, see also Foelsche et al. 1974).

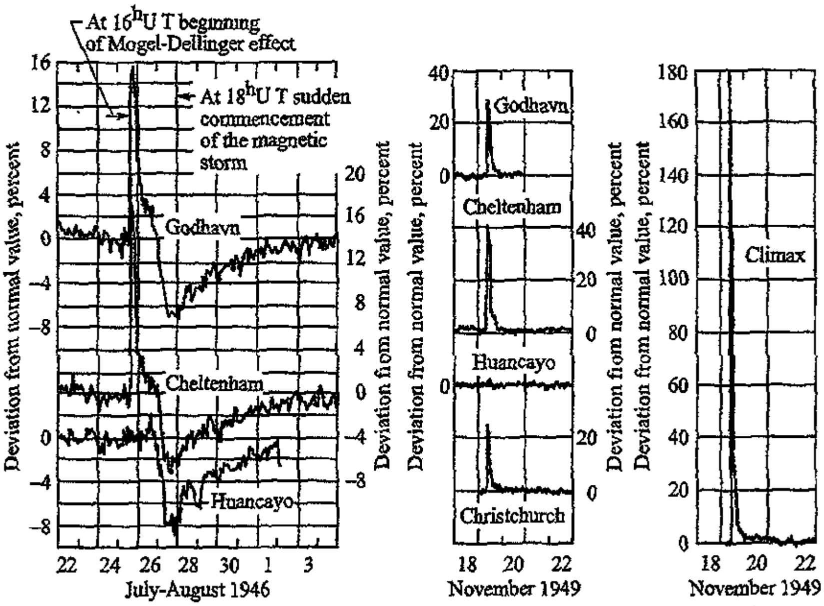


Fig. 1 Ground level ion chamber observations of solar particle events of 1946 and 1949. (From Foelsche et al. 1974)

Several factors have changed since those early studies: (a) the highly ionizing components are found to be more biologically damaging than previously assumed and the associated quality factors for fatal cancer have been increased (ICRU 1986, ICRP 1991); (b) recent studies on developmental injury in mice embryo indicate larger quality factors are required for protection in prenatal exposures (Jiang et al. 1994); (c) recent epidemiological studies (especially the data on solid tumors) and more recent A-bomb survivor dosimetry have resulted in higher radiation risk coefficients for γ rays (UNSCEAR 1988, BEIR V 1990, ICRP 1991) resulting in lower proposed permissible limits (ICRP 1991, NCRP 1993); (d) "an urgent need is recognized for better estimates of the risk of cancer from low levels of radiation" (anon. 1993); (e) subsequent to deregulation of the airline industry, flight crews are logging greatly increased flight hours (Bramlett 1985, Wilson and Townsend 1988, Friedberg et al. 1989, Barish 1990); (f) a new class of long haul commercial aircraft is being developed on which personnel for two crew shifts will be simultaneously aboard a single flight leading to increased exposures for a fixed number of flight duty hours (Lebuser 1993); (g) US airline crew members are now classified as radiation workers (McMeekin 1990, ICRP 1991); (h) NASA is developing technology for a High Speed Civil Transport (HSCT) to begin service in the twenty-first century; and (g) there are plans to introduce a revolutionary commercial transport (Mach 0.98 Sonic

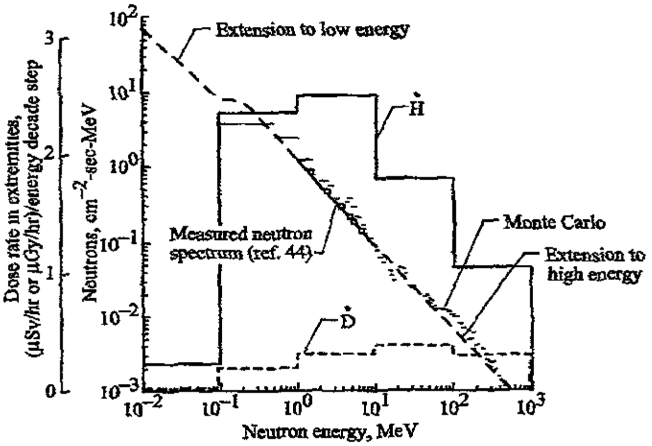
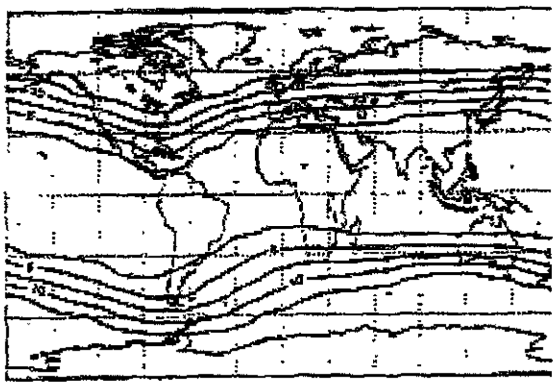


Fig. 2 Neutron spectrum at 70,000 ft over Ft. Churchill on August 3, 1965.

Cruiser) with operating altitudes from 45,000-51,000 ft (Boeing 2002). In recognition of the potential impact of several of these factors on present day crew exposures, the Commission of the European Communities organized a Workshop on Radiation Exposure of Civil Aircrew (Reitz et al. 1993). The workshop conclusions (mainly for subsonic exposures) are that the environment is not adequately known for reliable estimates of dose equivalent resulting mainly from uncertainty in the neutron spectra at high energies and a re-evaluation of the heavy ion component should be made. More recently the International Civil Aviation Organization (ICAO) has recommended that "All airplanes intended to be operated above 15 000 m (49 000 ft) shall carry equipment to measure and indicate continuously the dose rate of total cosmic radiation being received (i.e., the total of ionizing and neutron radiation of galactic and solar origin) and the cumulative dose on each flight. The display unit of the equipment shall be readily visible to a flight crew member" (ICAO 1995). More recently Japanese flight crews have requested from their government, health benefits on the basis that their exposures are "far greater than the exposure of the average nuclear power plant worker" (Fiorino 1996). Added emphasis comes from epidemiological studies of health outcomes among Department of Energy contractors (NEC 2000) leading to the *Energy Employees Occupational Illness Compensation Program Act of 2000*. Finally, it is clear that the development of advanced high-altitude commercial aircraft (such as the HSCT) requires some attention to the past concerns of high-altitude flight but in terms of current day knowledge and uncertainty in that knowledge (Wilson et al. 1995). In a prior report, we reviewed the status of knowledge of human occupational exposures and related uncertainties in health risks (Wilson 2000). It was clear that exposures among aircrew were generally higher than other terrestrial occupationally exposed groups and the aircrew risk uncertainties were high since a large fraction of the exposure is from high-LET radiations.

H, mSv/1000 hr at 40 000 ft



H, mSv/1000 hr at 50 000 ft

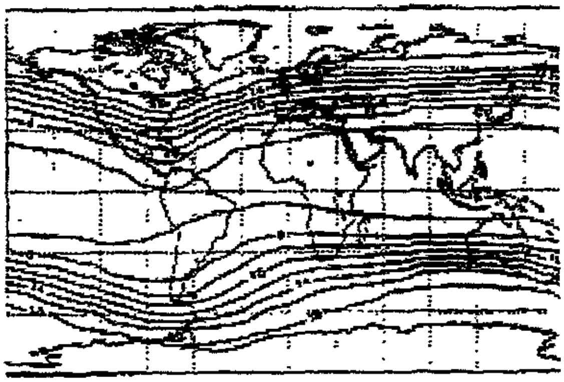


Fig. 3 Background exposure levels (*AIR* model) in atmosphere at solar minimum (1965).

In this paper we will review key historical developments in our understanding of atmospheric ionizing radiation and its impact on commercial operations. Although such a review cannot be made without reference to work outside the US, we leave the thorough review of European research to O'Sullivan et al. (2003) in this issue. A brief overview of ongoing research in the US is given with special emphasis on future requirements.

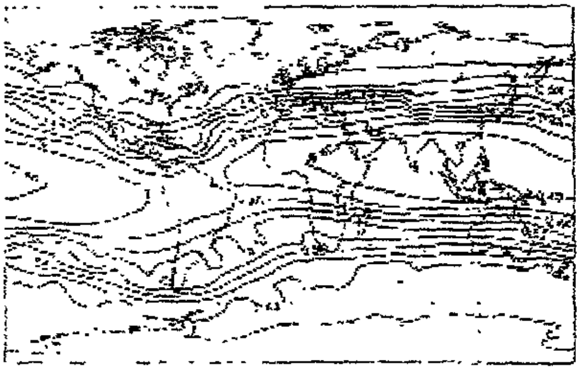
PAST *AIR* STUDIES

The primary concern for commercial aircraft radiation exposures began with the Supersonic Transport with a projected high operating altitude (20-km) for service on transoceanic flights. Foelsche raised concern on vulnerability on the high-latitude routes from the US eastern seaboard to Europe where extraterrestrial particles easily penetrate the geomagnetic field and intense solar particle events could induce unacceptable exposures on a single high-altitude flight. It was assumed that the neutrons produced in nuclear reactions with atmospheric nuclei would play an important role in carrying the dose equivalent deeper into the atmosphere and potentially contribute to background exposures. A measurement program was initiated by NASA at the Langley Research Center (LaRC) to resolve these issues in July 1964.

The LaRC commissioned over 300 flights over most of the duration of solar cycle 20 on high-altitude aircraft and balloons to study both background radiation levels over the solar cycle and to make measurements during a solar particle event. The Langley flight package consisted of a 1–10 MeV neutron spectrometer, tissue equivalent ion chamber, and nuclear emulsion for nuclear reaction rates in tissue. Monte Carlo calculations (Wilson et al. 1970, Lambiotte et al. 1971) for incident GCR protons were used to extend the neutron spectrum to high energies (Fig. 2). Also shown in Fig. 2 are the contributions to dose and dose equivalent from neutrons on individual energy decades. The measured data was integrated into a parametric Atmospheric Ionizing Radiation (*AIR*) model scaled with Deep River neutron monitor count rate and geomagnetic vertical cutoff rigidity (Wilson et al. 1991). The solar minimum global exposures are shown in Fig. 3 at two altitudes. Over half of the neutron dose is from neutrons above 10 MeV and an accurate knowledge of the high-energy neutron quality factors is critical to evaluation of dose equivalent. About half of the dose equivalent is from neutrons as shown in Fig. 4. Additional high-LET components come from the nuclear reactions caused by the charged hadrons so that well over half of the exposures in commercial operations are from high-LET events which leaves large uncertainties in the associated health risks (Wilson 2000, Cucinotta et al. 2001) even if the radiation levels are accurately known.

The only solar particle events of interest are those capable of ground level observations with ion chambers (Fig. 1) or neutron monitors. The rates of occurrence of such events (Shea and Smart 1993) are shown in Fig. 5. The ground level events vary greatly in intensity and only the most intense events are important to high-altitude aircraft protection. The largest ground level event yet observed occurred on Feb. 23, 1956 in which neutron count rates rose to 3,600 percent above background. Two of the afore mentioned over 300 flights were made out of Fairbanks, Alaska during the event of March 30-31, 1969 with results shown in Fig. 6. If the ground level increase for the March 1969 event is used to scale other historical ground level events, we conclude that high-levels (1 cSv or more) of radiation exposure were present at aircraft altitudes in the past. The uncertainties in the proton spectra for the Feb. 1956 event are large but upper and lower bounds estimated by Foelsche result in dose equivalent rates from Monte Carlo calculations (Foelsche et al. 1969, Wilson et al. 1970, Armstrong et al. 1969) in qualitative agreement with those derived from simply scaling the March 1969 data. The Monte Carlo results are shown in Fig. 7 as

$H_{neutron}/H$ at 40 000 ft



$H_{neutron}/H$ at 50 000 ft

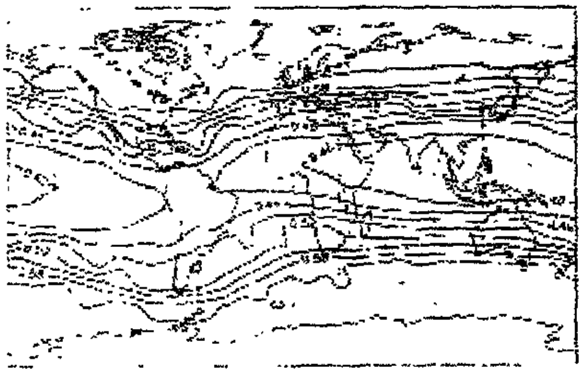


Fig. 4 Fraction of dose equivalent (AIR model) due to neutrons at solar minimum (1965).

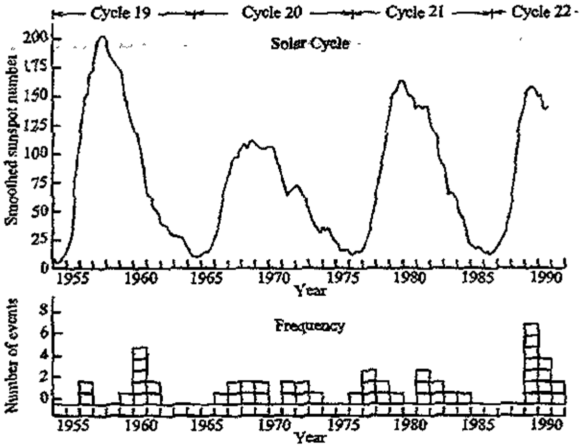


Fig. 5 Temporal distribution of ground level solar particle events for the past 40 years. (Shea and Smart

calculated by the Langley code (Wilson et al. 1970) and Armstrong et al. (1969) at Oak Ridge National Laboratory using the High Energy Transport Code (HETC). The results in the figure use the maximum surface dose equivalent conversion factors for a 30-cm tissue slab geometry. Dose equivalent averaged over the 30-cm slab is approximately a factor of 2-3 lower for solar particle events (Foelsche et al. 1974). It was clear from these results that exposures to crew and passengers on high-latitude routes of the SST flying at 58 g/cm^2 would be unacceptable unless descent to subsonic altitudes was possible to minimize exposures during such a large event. The importance of such events is limited to the Polar Regions.

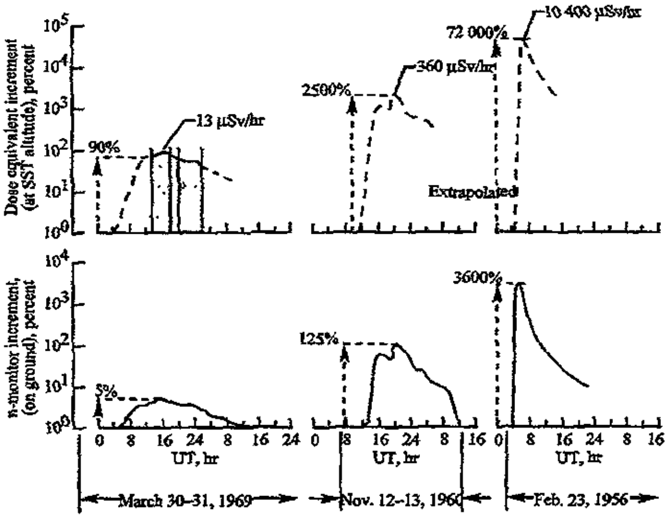


Fig. 6 . Energetic solar events measured on the ground and at SST altitude.

The main concern of these early studies was the potential prenatal injury in high-altitude flight especially during such a possible large solar event since crew and passengers included women of childbearing age. It is seen in Fig. 3 that flights from the US northeast to Europe fly along the edge of the polar region and are subject to solar particle event exposures (Wilson et al. 1995). An advisory committee to the Federal Aviation Administration (FAA 1975) recommended that a satellite early-warning/monitoring system be established, active onboard monitoring devices be included in the aircraft design, and that operational procedures be developed to insure that exposures on a given flight be limited to 5 mSv. Although many ground level events occur, only a few have been of such intensity as to be of concern to near term high-altitude air traffic. The *second* largest ground level event observed over the last 60 years is the event on September 29, 1989. This event was similar to the February 23, 1956 event in its time course and spectral content but of an order of magnitude lower intensity (on the order of 1 mSv/hr) and of less concern to supersonic operations. Since the February 23, 1956 event is the only outstanding event, it leaves a heavy operational overhead requirement for such an unlikely occurrence. Yet, it is likely such an event will occur again and perhaps an even larger event. It is fortunate that high-altitude aircraft requirements are largely met by the space program and weather service requirements providing potential cost sharing (Wilson 1981).

RECENT *AIR* STUDIES

Many factors relative to aircraft exposures have changed over the last decade as recounted in the introduction. There are continued studies of a possible hypersonic air transport, which will bring a host of new issues as reviewed elsewhere (Wilson 2000). Two key events had an important impact on requirements for atmospheric ionizing radiation research over the last decade: the ICRP (1991) included aircrew among the defined occupationally exposed and NASA initiated a technology assessment for a possible second-generation supersonic transport (High Speed Civil Transport, HSCT).

Although a consistent data set over much of the Earth's surface and most of solar cycle 20 has been measured by the LaRC SST program, many of the individual components were not resolved due to instrument limitations at the time of measurement (circa 1964) and the major portion of the neutron spectrum depended on theoretical calculations for proton interactions with the atmosphere (Foelsche et al. 1974). Hewitt et at. (1978) measured the neutron spectrum using a

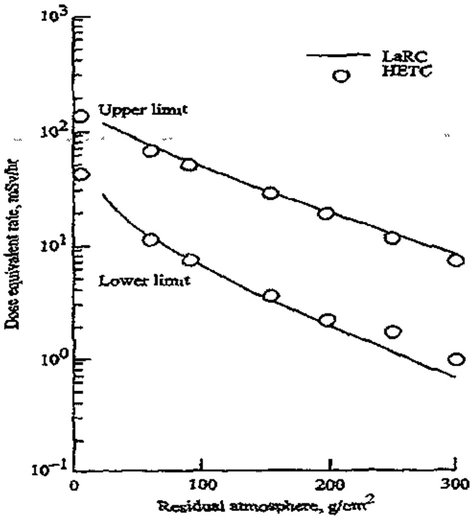


Fig. 7 Calculated upper and lower limits for dose equivalent rate at high latitude for the Feb 23, 1956 event

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Bonner sphere set up at subsonic altitudes and analyzed the data assuming a simple power spectrum and confirmed the importance of the high-energy neutrons but left the exact nature of the spectrum uncertain due to limitations of the analysis methods. Ferenc Hajnal of the DOE Environmental Measurements Laboratory developed new analysis techniques for unfolding Bonner sphere neutron spectral data and found important structural features in Hewitt's data near 100 MeV (see Fig. 8) that have important implications for aircraft exposures (Hajnal and Wilson 1991, 1992). A quick survey of published atmospheric neutron spectra shows considerable uncertainty in our knowledge and the impact of these uncertainties are analyzed elsewhere (Wilson et al. 1995, Wilson 2000). The status of knowledge of atmospheric ionizing radiation was reviewed by the NCRP (1996) providing a basis for continued studies in support of the HSCT technology assessment activity.

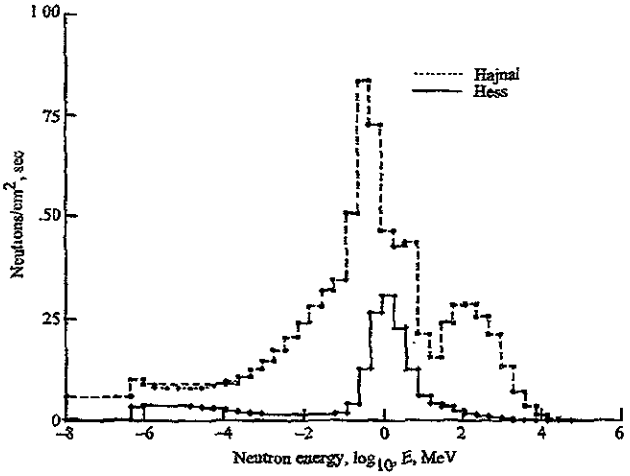

Fig. 8 Hajnal unfolded neutron spectrum from Hewitt data measured at 17.46°N at 23.5 km compared to Hess et al. (1961) spectrum.

Further studies were started at the Langley Research Center. An instrument package was developed in accordance with the NCRP recommendations through an international guest investigator collaborative project, thereby ensuring the availability of the numerous instruments required measuring the many components of the radiation spectra and providing a calibration platform for dosimetry. Selection criteria included: (a) the instruments had to fit within the cargo bay areas of the ER-2 airplane and be able to function in that environment, (b) the instruments had to be provided at no cost to meet budget constraints, (c) each instrument must have a principal investigator with independent resources to conduct data analysis, and (d) the instrument array must be able to measure all significant radiation components for which the NCRP (1996) had established minimal requirements. Also, the flight package had to be operational and the first flight to occur before or near the maximum in the galactic cosmic ray intensity (spring/summer 1997) and continued through the next cosmic ray minimum.

The flight package was a collaboration of fourteen institutions in five countries and consisted of eighteen instruments able to separate the various physical components and tested various dosimeters (Goldhagen et al. 2000). The flight plan was established using the first *AIR* model (Tai et al. 1998) and concentrated on north/south surveys with an altitude profile at the northern extremity. The first flight series in June 1997 met with considerable success with the loss of only one instrument in the data flow. The flight program ended with the decision that technology was not ready to develop a competitive high-speed civil transport but the data analysis continues to this day including corrections for the ER-2 flight platform structure. Preliminary neutron spectra (Goldhagen et al. 2002) are shown in Fig. 9 and tend to confirm the results of Hajnal's analysis (Fig. 8). Note that the neutron spectra of the northern and southern flight extremes, where the geomagnetic cutoffs differ by more than an order of magnitude, are similar in spectral content with different magnitude. This corresponds well with the more limited results of Foelsche et al. (1974), who likewise concluded that the spectrum has negligible differences in the upper atmosphere as a function of altitude and latitude.

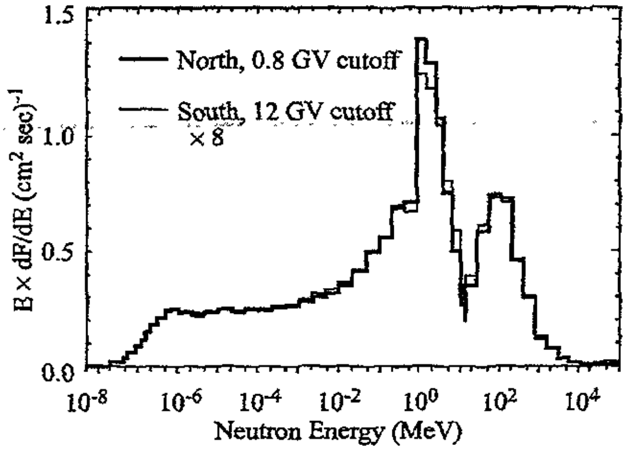

Fig. 9. Cosmic-ray neutron spectra measured at the northern end (54°N, 117°W, 0.8 GV cutoff, 56 g cm^{-2} atmospheric depth) and at the south end (19°N, 127°W, 12 GV cutoff; 54 g cm^{-2} atmospheric depth). The south spectrum is multiplied by 8.

A preliminary comparison of the first *AIR* model with the high-pressure argon ion chamber is given in Fig. 10. This was approximately a six and one-half hour flight starting June 13, 1997 at 15:52 from NASA Ames Research Center on a prescribed sequence of northern, western, and southern headings. This was the second northern flight and the aim was to approximately repeat the radiation measurements as a function of geomagnetic latitude to as far north as possible with altitude excursions along a constant-radiation, geomagnetic latitude line near Edmonton, Canada. During the westward portion of the flight, an altitude excursion was made as an altitude survey as evident in the figure. The AIR model using the recorded flight trajectory is shown in the figure for comparison with the measured flight data.

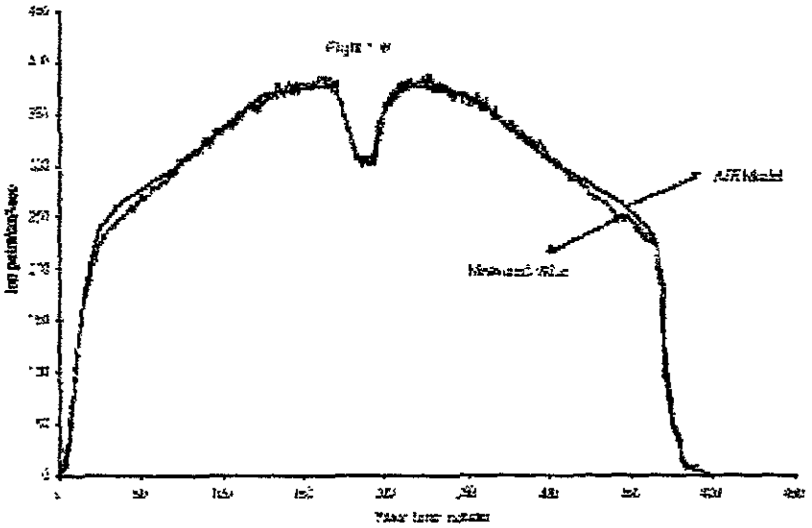

Fig. 10 Predicted and measured value of Air Ionization Rate as function of time for Flight 97-108, June 13, 1997.

A preliminary summary of European activity is given by McAulay et al. (1996). Further study of the atmospheric neutron spectrum lead by H. Schraube of GSF in Neuherberg has been funded by the Directorate General XII. The experimental component consists of a Bonner sphere spectrometer with a ^{3}He proportional counter (Schraube et al. 1998) on a mountaintop (Zugspitze). The theory portion of the study uses the FLUKA code, currently maintained at CERN, and the known cosmic rays incident on the atmosphere (the multiple charged ions are assumed to be dissociated into nucleonic constituents (Roesler et al. 1998). It is interesting to note that the structure expected from the analysis of Hajnal at 100 MeV (Fig. 8) appears in both the measurements and the FLUKA calculation (see Fig. 11). Note that this feature was absent from the LUIN code available at the time of the study. LUIN then depended on the Hess et al. (1961) spectrum for guidance as to the shape of the neutron spectrum at low energies. Thus the LUIN code is not a basic physics model in that it contains information outside the basic LUIN transport model (O'Brien and Friedberg 1994). Schraube et al. (1998) showed that the neutron ambient dose equivalent is about a factor of two larger than that estimated by LUIN; the added contributions are from high-energy neutron interactions with tissue nuclei resulting in an array of high-LET reaction products at each collision event. LUIN99 and LUIN2000 (O'Brien et al., 2003) address this issue by using Rösler et al. (1998) neutron-spectrum results. Very little biological data exist on such radiations (Wilson et al. 1990, Wilson 2000, Cucinotta et al. 2001).

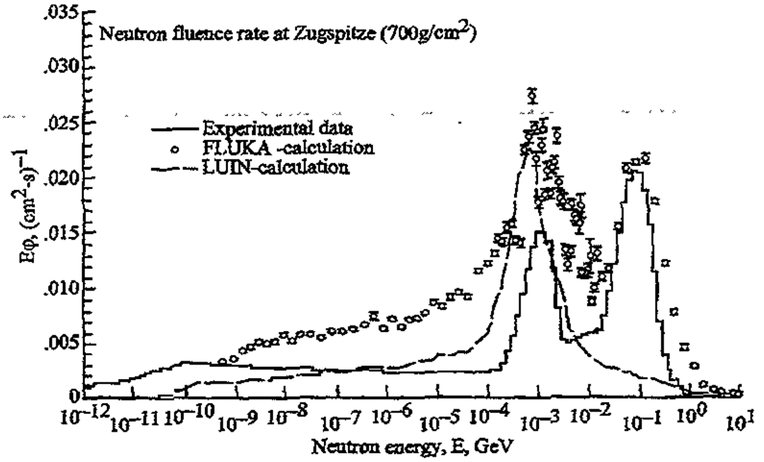

Fig. 11 Spectral neutron fluence rate obtained by measurements and calculations on top of Zugspitze (by permission of Schraube et al. 1998).

It was determined by Foelsche et al. (1974) using simultaneous flight measurements with a research aircraft and a balloon that local neutron production in materials of a small research aircraft added 10 percent to the measured neutron field. Later measurements by Wilson et al. (1994) onboard commercial subsonic transports found that the radiation levels varied by up to 30 percent within the aircraft cabin space. These results give incentive to evaluation of aircraft materials as a means to providing limited control of the interior environment. Evaluation of aircraft design alternatives requires a physics-based *AIR* model for which the transmission properties of aircraft materials can be folded into the design process.

POLICY & EPIDEMIOLOGY

Aside from the question of more restrictive regulatory requirements resulting in a FAA advisory (McMeekin 1990) there is increased concern for potential health outcomes among the crew in commercial aviation. The health outcomes are undoubtably related to environmental factors including radiation. Studies continue to expand giving greater statistical resolving power (De Angelis et al. 2001a). Although as a group the health risks of this select group of individuals are low (healthy worker effect, for the specific case of aircrew members, see De Angelis et al. 2001b), Band (1990) found increased risks of several types of cancer among Canadian commercial pilots. Further concern for some of the most sensitive occupants of commercial aircraft, the US National Institute for Occupational Safety and Health continues a study of early pregnancy outcomes among commercial flight attendants (Grajewski et al. 1994, Whelan 2002).

Table 1. *Cancer Sites with significant positive association for civilian airline flight personnel crewmembers. Confidence limits are 90 or 95 percent depending on study.*

Cancer Site	Sex	Job	Type	Confidence Limits		Source
All Sites*	M	CA	SIR	1.3	2.2	Haldorsen et al. (2001)
Bone	F	CA	SIR	1.8	54.4	Pukkala et al. (1995)
Brain	M	P	SIR	1.2	7.9	Band et al. (1990)
Brain	M	P	SMR	1.4	9.5	Band et al. (1990)
Breast	F	CA	SIR	1.2	2.2	Pukkala et al. (1995)
Breast	F	CA	SIR	1.0	4.3	Wartenberg et al. (1998, 1999)
Breast	F	CA	SIR	1.09	1.83	Reynolds et al. (2002)
Esophagus	M	CA	SIR	2.7	11.4	Haldorsen et al. (2001)
Hodgkin Lymphoma	M	P	SIR	1.2	11.7	Band et al. (1990)
Kidney and Pelvis	M+F	P	PMR	1.18	3.06	Nicholas et al. (1998)
Leukemia – AML	M	P	SIR	2.1	9.3	Band et al. (1996)
Leukemia – Myeloid	M	P	SIR	1.4	5.5	Band et al. (1996)
Liver*	M	CA	SIR	1.3	39.2	Haldorsen et al. (2001)
Prostate	M	P	SIR	1.4	2.5	Band et al. (1996)
Rectum	M	P	SMR	1.2	11.2	Band et al. (1990)
Skin – Melanoma	M	P	SMR	1.5	6.3	Irvine & Davies (1999)
Skin – Melanoma	M	PE	SIR	1.1	2.7	Haldorsen et al. (2000)
Skin – Melanoma	M	P	SIR	5.0	36.5	Rafnsson et al. (2000)
Skin – Melanoma	M	CA	SIR	1.1	6.4	Haldorsen et al. (2001)
Skin – Melanoma	M	P	SIR	2.85	4.23	Nicholas et al. (2001)
Skin – Melanoma	F	CA	SIR	1.2	6.7	Rafnsson et al. (2001)
Skin—Melanoma	M	P	SIR	1.27	4.54	Hammar et al. (2002)
Skin--Melanoma	F	CA	SIR	1.28	4.38	Reynolds et al. (2002)
Skin – Other Cancers	M	P	SIR	1.1	2.2	Band et al. (1990)
Skin – Other Cancers	M	PE (jets)	SIR	2.1	4.2	Gundestrup & Storm (1999)
Skin – Other Cancers	M	P	SIR	1.3	4.0	Haldorsen et al. (2000)
Skin – Other Cancers*	M	CA	SIR	4.5	18.8	Haldorsen et al. (2001)
Prostate#	M	P	SIR	1.19	2.29	Ballard et al. (2000)
Skin – Melanoma#	M	P	SMR	1.02	3.82	Ballard et al. (2000)

*cancer outcome possibly related to lifestyle only; # results from meta-analysis of previous studies, then adjusted for socio-economical status; AML = Acute Myeloid Leukemia; CA = Cabin Attendants;
P = Pilots only; PE = Pilots and flight Engineers; PMR = Proportional Mortality Ratio;
SIR = Standardized Incidence Ratio; SMR = Standardized Mortality Ratio

Although not a study of commercial aircrew, the report of the National Economic Council (NEC) Panel on *Occupational Hazards Associated with Nuclear Weapons Production* (NEC 2000) has important implications for commercial aviation. The US President requested the NEC to assess "whether there is evidence of occupational illness in current and former contract workers at the US Department of Energy (DOE) from exposures to occupational hazards unique to nuclear weapons production and evaluate the strength of that evidence." The NEC Panel (Task Group 1) found only modest average annual exposures of the DOE contractor workforce, 1.5 to 2 mSv to 1960, a slow decline from 1.5 mSv to 1 mSv in 1978 through 1988, followed to a rapid decline to a few tenths of a mSv past 1990 (compared to an estimated annual aircrew exposure (e.g., Chicago-to-NY) of 2.72 mSv, Friedberg et al. 2002). Mortality studies among the DOE contractors showed a healthy worker effect but increased standard mortality and incident ratios (SMRs, SIRs) with 90-95 percent confidence intervals above unity (statistically significant) for cancer of the thyroid, breast, pharynx, esophagus, stomach, small intestine, pancreas, bile ducts, gall bladder, and liver as well as leukemia, multiple myeloma, and lymphomas (except Hodgkin's) as identifiable work related illnesses as concluded by the panel. A compensation program for this entire list of illnesses was set up with some limitations related to possible causality. Furthermore, several cancer sites showed positive correlations with radiation exposures while other cancer sites were assumed to be related to other environmental factors. As a result, the NEC recommended legislation for worker compensation for this restricted list of illnesses which were found with statically significant elevated SMRs and SIRs, leading to the *Energy Employees Occupational Illness Compensation Program Act of 2000* passed by the US Congress and signed into law.

A few studies of populations in high-altitude cities have concluded an inverse effect with radiation exposure although Weinberg et al. (1987) argues that oxygen effects may be the source of decreased adverse health risks at *high* altitudes. More recently studies of US Air Force pilots showed statistically significant elevated risks of cancer in genitals, testis, and urinary systems (Grayson and Lyons 1996). A recent study of mortality among US commercial pilots and navigators found statistically significant elevations of kidney and pelvic cancers (Nicholas et al. 1998). Many European epidemiological studies on health outcomes of aircrew have been in progress for several years (see e.g. Rafnsson et al. 2000, 2001, Ballard et al. 2002, and for reviews Ballard et al. 2000, De Angelis et al. 2001a, 2001b) and provide additional concern for the need for further studies in the US. It is well established that elevated standard mortality and incidence ratios with 90 to 95 percent confidence intervals above unity is observed among European aircrew as shown in Table 1 along with limited US studies. Even so, one might argue that the SMR and SIR depend on the control group and there are even regional differences as observed in the DOE contractor studies (NEC 2000) and the data still rests on relatively few occurrences in many cases (Friedberg et al. 2002). Still, establishment of policy and science are different issues and the data in Table 1 meets the selection criteria of the NEC panel for compensation (NEC 2000). It is anticipated that US crews who fly generally closer to the magnetic pole than European crews will have both different radiation exposure patterns and distribution of cancers with elevated SMRs. It appears the situation justifies that US aircrews are probably due illness compensatory legislation but insufficient data exists on which to write such legislation. It is imperative that US aircrew epidemiological studies are expanded to correct the current lack of data on cancer incidence and mortality among US aircrew in preparation of required legislation. This impetus follows since, "it is clear that there are health risks associated with a career of flying."
(Friedberg et al. 2002)

CONTINUING US ACTIVITY

Three issues continue to be addressed within the US: development of the basic *AIR* model including experimental validation, testing of potential aircraft material transmission properties, and epidemiological studies. The extent of the ongoing activity will be briefly reviewed in this section.

The continued analysis of the ER-2 flight data has concentrated on establishing corrections to the neutron spectrum due to packaging into the flight racks and the surrounding aircraft structure (Goldhagen et al. 2003). This will be followed by analysis of the other instruments used on the flights including the high-pressure ion chamber,

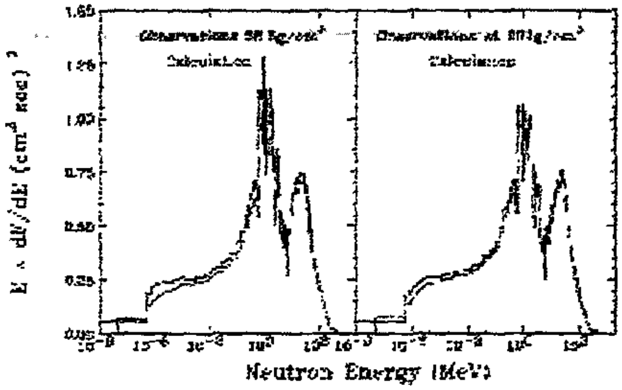

Fig. 12 Comparison of the augmented FLUKA evaluated neutron spectra at the northern extreme of June 1997 ER-2 flight measurements.

the various scintillators, and particle telescopes. Collaboration with the Bartol Research Institute at the University of Delaware and their unique augmentation of FLUKA to include collisional source terms for multiple charged ions is being evaluated for use in deriving a new physics-based *AIR* model (Clem et al. 2003). Preliminary comparisons of the altitude survey at the northern extreme of the ER-2 flight shown in Fig. 12 are encouraging. The new *AIR* model will include a dynamic geomagnetic transmission model for years 1945 to 2020 including geomagnetic storm effects (De Angelis et al. 2003). The fundamental model will be for the particle fields allowing introduction of aircraft geometry and human geometry for final exposure evaluation. One use of the model will be to evaluate single event effects on avionics in future aircraft design. With the historic variation of the geomagnetic transmission factors, the model will enable exposure assessment in retrospective health outcome studies.

The transmission properties of materials in such a complicated environment are poorly understood. The effects of the surrounding aircraft materials and payload on the exposures within the cabin space and on the flight deck are largely unknown. As a result we have designed a flight experiment for the ER-2 aircraft for evaluation of material effects on the local radiation environment. The experiment uses cross-calibrated TEPCs to measure effects on the lineal energy spectra as a function of material type. One rack of the basic apparatus is shown in Fig. 13. There are two such racks that fill the two well-isolated superpod tailcones mounted on the midwings of the ER-2. The measured change in lineal energy spectral content as a function of shield material will give us a degree of measure of the change in the physical fields within the shielded region to evaluate computational shielding models. Fundamental to this usage is an improved understanding of the TEPC response in such mixed radiation fields (Shinn et al. 2001).

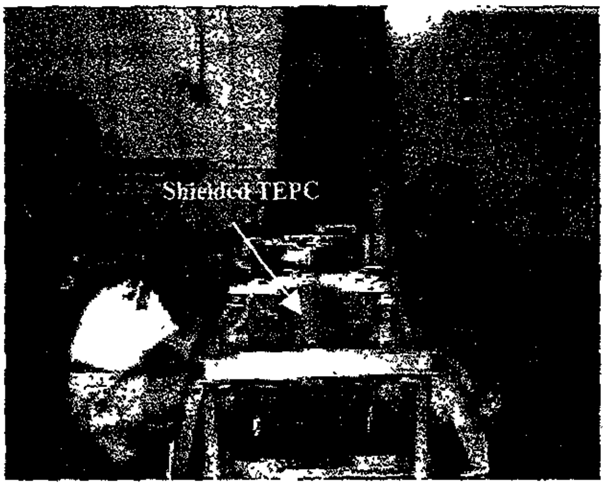

Fig. 13 Aircraft shield materials experiment rack being prepared for ER-2 flight.

The NIOSH/FAA Study of Reproductive Disorders in Female Flight Attendants remains as the only US led epidemiological effort of which we are aware. The study is in three parts: data on reproductive outcomes by questionnaire, ovulation function study using hormone testing, and an environmental assessment of the cabin space (Whelan 2002). Primary school teachers of the same age distribution are being used as a control group for the study.

CONCLUDING REMARKS

SST related studies of atmospheric ionizing radiation quantified the exposure fields, established neutrons as the dominant component of radiation health hazard, and identified solar particle event exposures of pregnant occupants as a major health issue. Even then it was recognized that background exposures of commercial aircrew placed them among the most highly exposed occupational groups. As cancer risk coefficients were revised to greater values and corresponding new safety standards implemented, concern over potential health risks led to a number of studies of the radiation environment and corresponding studies of health risks at subsonic commercial transport altitudes. Although unrelated, identifiable added health risks were found in epidemiological studies of nuclear weapons workers, who were generally less exposed to ionizing radiation than commercial aircrew. The resulting legislation for the US nuclear weapon contractors has strong implications for aircraft safety. Extensive studies of European aircrews have resulted in a database adequate for compensation of European aircrew. However, the corresponding database on US aircrew is lacking. An accurate physics based *AIR* model is required to evaluate reference exposures for epidemiological studies and evaluation of potential design features of future aircraft to improve safety. The development of such a model has been the focus of the NASA Langley Research Center for the last several years. A comprehensive flight measurements program is required to validate the *AIR* model and evaluate the transmission properties of aircraft materials.

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Cross Section for C^{12}(*alpha* , *alpha n*)C^{11} at 920 MeV

Jonathan Radin
New York University, Bronx, New York 10453

Received 30 October 1969; revised 21 May 1970

Plastic scintillators were exposed in the external 920-MeV *alpha* -particle beam at the 184-in. cyclotron at Lawrence Radiation Laboratory. The beam-flux monitor was Ilford 100-μ L4 pellicles. The cross section for C^{12}(*alpha* , *alpha n*)C^{11} was found to be 49.4 ± 1.8 mb.

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High Altitude Radiations Relevant to the High Speed Civil Transport (HSCT)

J. W. Wilson[1], P. Goldhagan[2], D. L. Maiden[1], H. Tai[1]
[1]NASA Langley Research Center, Hampton, Virginia
[2]DOE Environmental Measurements Laboratory, New York, New York

The Langley Research Center (LaRC) performed atmospheric radiation studies under the SST development program in which important ionizing radiation components were measured and extended by calculations to develop the existing atmospheric ionizing radiation (AIR) model. In that program the measured neutron spectrum was limited to less than 10 MeV by the available 1960-1970 instrumentation. Extension of the neutron spectrum to high energies was made using the LaRC PROPER-3C monte carlo code. It was found that the atmospheric neutrons contributed about half of the dose equivalent and approximately half of the neutron contribution was from high energy neutrons above 10 MeV. Furthermore, monte carlo calculations of solar particle events showed that potential exposures as large as 10-100 mSv/hr may occur on important high latitude routes but acceptable levels of exposure could be obtained if timely descent to subsonic altitudes could be made. The principal concern was for pregnant occupants onboard the aircraft [1]. As a result of these studies the FAA Advisory Committee on the Radiobiological Aspects of the SST recommended [2]:

1. Crew members will have to be informed of their exposure levels
2. Maximum exposures on any flight to be limited to 5 mSv
3. Airborne radiation detection devices for total exposure and exposure rates
4. Satellite monitoring system to provide SST aircraft real-time information on atmospheric radiation levels for exposure mitigation
5. A solar forecasting system to warn flight operations of an impending solar event for flight scheduling and alert status

These recommendations are a reasonable starting point to requirements for the HSCT with some modification reflecting new standards of protection as a result of changing risk coefficients.

One result of the SST studies was the realization that subsonic aircrew members are among the most high occupationally exposed groups [1,3] which prompted the FAA to develop methods to further study exposures resulting in the CARI exposure estimation code (named after the Civil Aeronautical Research Institute) based on the LUIN transport model (developed by the DOE Environmental Measurements Laboratory) to generate the database [4]. The estimated risk of serious illness to the child of a subsonic aircrew member during pregnancy is on the order of 1.3 per thousand [5] and the FAA recommended that air carriers begin a program of training of their employees on the risks of inflight subsonic exposures [6]. The dose rates at the HSCT altitudes are a factor of 2-3 higher than for subsonic operations and the HSCT crew annual flight hours will have to be reduced by this same factor to maintain exposure levels comparable to the subsonic crews.

Regulations on exposure limitation are based mainly on the estimated cancer risk coefficients. These coefficients have increased significantly over the last decade as solid tumor appearance is higher among the WW2 nuclear weapons survivors than initially anticipated [7-10]. As a result, new recommendations for reducing regulatory limits have been made by national and international advisory bodies [10,11]. Whereas subsonic crew exposures were well under the older regulatory limits, the substantial reductions (by factors of 2.5 to 5) in exposure limitations recommended by these advisory bodies resulted in the need to improve aircrew exposure estimates [12]. Hence, a workshop on Radiation Exposure of Civil Aircrew held in Luxembourg on June 25-27, 1991 was sponsored by the Commission of the European Communities Directorate General XI for Environmental Nuclear Safety and Civil Protection [12]. To be noted in the workshop is the closure of the gap between subsonic aircrew exposures and the newly recommended regulatory limits and in fact some concern that limits may be exceeded in some cases. Thus uncertainty in exposure estimates becomes a critical issue and emphasis on the numbers of and spectral content of high energy neutrons as well as the penetrating multiple charged ions were identified as a critical issue for subsonic flight crews. More recently Japanese flight crews have requested from their government, health benefits on the basis that their exposures are "far greater than the exposure of the average nuclear power plant worker" [13]. The issues for HSCT commercial air travel are compounded by the higher operating altitudes (higher exposure levels) and the possibility of exposures to

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a large solar particle event wherein annual exposure limits could be greatly exceeded on a single flight [1,14].

As a result of the higher expected exposures in high altitude flight, the US congressionally chartered federal advisory agency on radiation protection, NCRP, examined the data on atmospheric radiation and made recommendations [15] on the need for future studies as follows:

1. Additional measurements of atmospheric ionizing radiation components with special emphasis on high energy neutrons
2. A survey of proton and neutron biological data on stochastic effects and developmental injury for evaluation of appropriate risk factors
3. Develop methods of avoidance of solar energetic particles, especially for flight above 60,000 ft
4. Develop an appropriate radiation protection philosophy and radiation protection guidelines for commercial flight transportation, especially at high altitudes of 50,000 to 80,000 ft

Clearly, these recommendations must be addressed before the HSCT goes into commercial service to ensure the safety of the crew and passengers. The current effort in this assessment is the use of an experimental flight package to reduce the uncertainty in AIR models in direct response to the NCRP recommendations.

An instrument package was developed in accordance with the NCRP recommendations through an international guest investigator collaborative project to acquire the use of existing instruments to measure the many components of the radiation spectra. Selection criteria was established which included: (a) the instruments had to fit into the cargo bay areas of the ER-2 airplane and able to function in that environment (Some high quality laboratory instruments were rejected because of their large size or inability to operate in the ER-2 environment.), (b) the instrument had to come at no-cost for use by the project to meet budget constraints, (c) the instrument must have a principal investigator with their own resources to conduct data analysis, and (d) the array must include all significant radiation components for which the NCRP had made minimal requirements. The flight package must be operational and the first flight occur before or near the maximum in the galactic cosmic ray intensity (ca. spring/summer 1997) and extend through the next cosmic ray minimum.

The flight package developed uses all of the available space in the ER-2 cargo areas. The primary instruments in the package consist of neutron detectors, scintillation counters, and an ion chamber from the DOE Environmental Measurements Laboratory and charged particle telescopes from Institute of Aerospace Medicine of Deutsche Forschungsanstalt fur Luft- und Raumfahrt (DLR), and Johnson Space Center. Ten other instruments from Germany, Italy, the United Kingdom, and Canada make up most of the remainder of the flight package. These include passive track detectors from Institute of Aerospace Medicine, DLR, and University of San Francisco; TEPCs from Boeing and Defence Research Establishment Ontario; and dosimeters from Boeing, Royal Military Academy in Ontario and National Radiological Protection Board (NRPB) in the UK. The existing primary instruments and data system were modified for operation on the ER-2. A data acquisition system was incorporated to control operation of the entire instrument package, and to record data from the primary instruments during flight. Data from the other instruments are recorded separately by each instrument and recovered after a flight. The AIR model was modified for diurnal and solar rotational corrections as shown in figure 1a with the results for the ion chamber in a northern flight into Canada shown figure 1b. The dosimetry of the neutron component is being updated with ambient dose and dose equivalent for comparison with the TEPC data. Preliminary bonner sphere functions are likewise being used for preliminary flight comparisons.

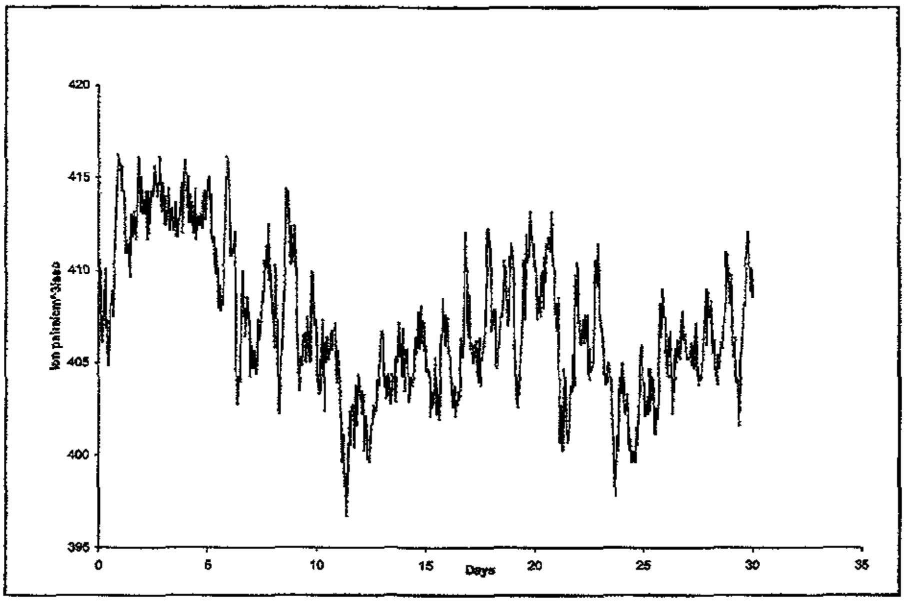

Figure 1a. Ionization rate in the month of June, 1997, at 19.8 KM near polar region. Atmospheric pressure = 55.2 mb.

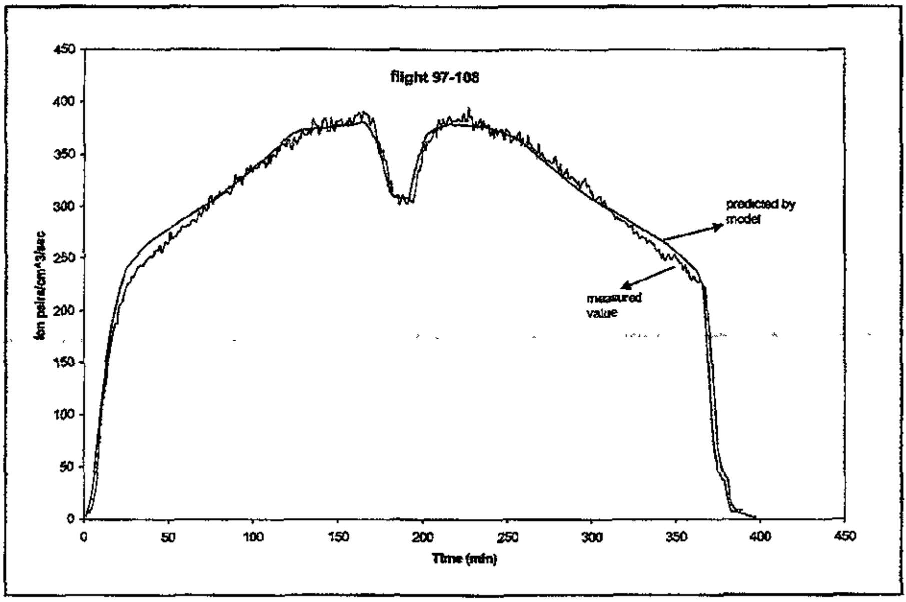

Figure 1b. Predicted and measured values of Air Ionization Rate as function of time for Flight 108.

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Alpha-spallation cross sections at 920 MeV (230 MeV/*N*) in ^{27}Al, ^{16}O, ^{12}C, and ^{9}Be, and application to cosmic-ray transport

Jonathan R. Radin*
Tel-Aviv University, Department of Physics & Astronomy, Ramat Aviv, Israel

Alan R. Smith and Nickey Little
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

Received 29 November 1973

We investigated the effects on cosmic rays from spallation reactions between cosmic rays and interstellar helium. The spallation cross sections were measured by exposing thin-sandwich targets to the 920-MeV (230-MeV/*N*) external *alpha*-particle beam of the 184-in. cyclotron at Lawrence Berkeley Laboratory. Cross sections were measured for the production: from ^{27}Al of ^{18}F (12.5±0.5 mb); from ^{16}O of ^{15}O (46.4±2.7 mb), ^{13}N (6.75±0.5 mb), ^{11}C (18.5±0.9 mb), and ^{7}Be (18.5±1.3 mb); from ^{12}C of ^{7}Be (20.0±1.2 mb); and from ^{9}Be of ^{7}Be (12.6±0.8 mb). We constructed spallation cross-section ratios for the ratio of *alpha*-particle-induced to proton-induced reactions (= *Sigma* $^{alpha}{}_{p}$). We parametrized this ratio by the nucleon difference (*Delta A*) between the target initial and final states and we fitted this ratio [*Sigma* $^{alpha}{}_{p}$(*Delta A*)] to a linear function in *Delta A*. We used this function [*Sigma* $^{alpha}{}_{p}$(*Delta A*)] to obtain all of the *alpha*-particle-spallation cross sections from the corresponding proton-spallation cross sections for targets and products in the elemental range 3 <= *Z* <= 8, and we applied these cross sections to a cosmic-ray transport calculation wherein we investigated the sensitivity of the cosmic-ray *L* / *M* ratio [=(Li + Be + B) / (C + N + O)] and of the abundances of the *L* and *M* elements to the helium fraction of the interstellar gas.

[NUCLEAR REACTIONS ^{27}Al(*alpha* ,*x*)^{18}F; ^{16}O(*alpha* ,*x*)^{15}O, ^{13}N, ^{11}C, ^{7}Be; ^{12}C(*alpha* ,*x*)^{7}Be; ^{9}Be(*alpha* ,*x*)^{7}Be, *E*=920 MeV; measured *sigma* ; NaI detector. Examined effect interstellar He on cosmic rays.]

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[*] Work performed in part while at New York University, Department of Physics, New York City, N. Y. 10003.

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Sub-luminal pulses from cosmic-ray air showers

J Linsley
Dept. of Phys. & Astron., Univ. of New Mexico, Albuquerque, NM, USA

Print publication: Issue 8 (August 1984)

Abstract. Some signals produced by air showers of energy greater than 10^{19} eV in scintillators at impact parameters greater than 1 km possess a distinctive feature, a 'sub-luminal pulse' (SLP) following the normal one with a time delay of approximately 1.5 r/c. The average amplitude of the SLP corresponds to an energy deposit of about 50 MeV, three times as much as is deposited by a vertical minimum ionising muon. The SLP account for approximately 5% of the energy deposited in the atmosphere by such air showers at these distances.

doi.10 1088/0305-4616/10/8/005
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Descriptive Summary

Creator:	Korff, Serge Alexander, 1906-
Title:	Papers.
Dates:	1928-1989
Abstract:	Serge A. Korff was a prominent cosmic ray physicist active in academic, governmental and international settings whose tenure at NYU was from 1941-1989. The collection encompasses Korff's professional career and includes correspondence with leading American, South American and European physicists, graduate students and post-doctoral fellows, academicians from other disciplines, professional scientific organizations, government agencies, military personnel, commercial equipment suppliers, and publishing concerns. Also included in the collection is information on research projects and expeditions; grant proposals and reports; materials on scientific conferences; students' theses and dissertations; administrative records pertaining to NYU and its physics department; and reprints of scholarly articles by Korff and others.
Quantity:	12 linear feet (8 boxes)

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Historical/Biographical Note:

Sergei Alexander Korff was born in Helsingfors, Finland, in 1906. Immigrating to the United States with his family in 1917, he became a citizen in 1927. Korff attended Princeton receiving his A.B. in 1928, M.A. in 1929 and Ph.D. in 1931. Between 1932 and 1940, he completed research fellowships at the Mt. Wilson Observatory, the California Institute of Technology, the Carnegie Institute of Washington, and the Bartol Research Foundation. Collaborating with eminent physicists in his early work, Korff investigated topics such as optical dispersion, proportional counters and neutron measurements in cosmic radiation. Korff began his tenure at New York University in 1941, and continued there until his death in 1989. He helped train at least three generations of students, taking many on research expeditions as far away as the North Pole and the South Seas.

In addition to his teaching and research, Korff lent his efforts to the international scientific community. He compiled the report of the Joint Commission on High Altitude Research for ICSU-UNESCO; served on the Cosmic Ray Technical Panel for the International Geophysical Year, 1957-58; organized the pole-to-pole Rockwell Scientific Round-the-World Flight in 1965; and encouraged and secured support for scientific work around the world, particularly in Central and South America. Notable among his numerous professional affiliations were his terms as president of the Explorer's Club (1955-1958); the American Geographical Society (1966-1971); and New York Academy of Science (1972). For his efforts to transfer surplus scientific equipment to the decimated laboratories of France after World War II, in 1952 Korff was decorated Chevalier of the Legion of Honor. For the contribution of his radiation detection devices to the study of cancer, he was awarded the Curie Medal of the International Union Against Cancer.

Korff's Counter Project and Cosmic Ray Project attracted numerous students to NYU; many later achieved prominence as physicists. The project also brought the university substantial funding from government agencies, such as the National Air and Space Agency and the National Science Foundation. Author of over 150 scientific papers and books, as well as a number of works on exploration, geology and stamps, Korff's contributions to science went beyond the study of cosmic rays. His ability to render complex scientific issues exciting and clear to the general public in encyclopedia and newspaper articles, and to expose the subtleties of science to his students and peers marked Korff as an outstanding figure in 20th century physics.

Scope and Content Note

The collection reflects the work and perspective of a scientist whose life work was devoted to understanding the universe and sharing that knowledge with as wide an audience as possible. The Korff Collection documents the work of a prominent cosmic ray physicist active in academic, governmental and international settings. The collection contains 10 linear feet of correspondence, notes, photographs, manuscripts, and printed material documenting research grants, academic activities, professional organizations, conferences, and publications. Korff's work from 1928 to 1989 is reflected; the bulk of the material representing the period 1950-1980. There is a largely undocumented area in this collection: the first is Korff's work prior to his affiliation with NYU, while the second coincides with World War II.