Chapter 1: Atmospheric Ionizing Radiation and the High Speed Civil Transport

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Preface

Atmospheric ionizing radiation is produced by extraterrestrial radiations incident on the Earth's atmosphere. These extraterrestrial radiations are of two sources: ever present galactic cosmic rays with origin outside the solar system and transient solar particle events that are at times very intense events associated with solar activity lasting several hours to a few days. Although the galactic radiation penetrating through the atmosphere to the ground is low in intensity, the intensity is more than two orders of magnitude greater at commercial aircraft altitudes. The radiation levels at the higher altitudes of the High Speed Civil Transport (HSCT) are an additional factor of two higher. Ionizing radiation produces chemically active radicals in biological tissues that alter the cell function or result in cell death. Protection standards against low levels of ionizing radiation are based on limitation of excess cancer mortality or limitation of developmental injury resulting in permanent damage to the offspring during pregnancy. The crews of commercial air transport operations are considered as radiation workers by the EPA, the FAA, and the International Commission on Radiological Protection (ICRP). The annual exposures of aircrews depend on the latitudes and altitudes of operation and flight time. Flight hours have significantly increased since deregulation of the airline industry in the 1980's. The FAA estimates annual subsonic aircrew exposures to range from 0.2 to 9.1 mSv compared to 0.5 mSv exposure of the average nuclear power plant worker in the nuclear industry. The commercial aircrews of the HSCT may receive exposures above recently recommended allowable limits for even radiation workers if flying their allowable number of flight hours. An adequate protection philosophy for background exposures in HSCT commercial airtraffic cannot be developed at this time due to current uncertainty in environmental levels. In addition, if a large solar particle event occurs during flight at HSCT altitudes then passengers and crew may greatly exceed allowable limits unless means are available to reduce exposures.

Introduction

The impact of ionizing radiation on the High Speed Civil Transport was not examined in High Speed Research Program Phase 1 where environmental issues were first addressed as it was not considered a first-priority environmental concern at that time. Although aircrews are recognized by the FAA, the EPA, the NCRP, and the ICRP as radiation workers (occupationally exposed), there are no US regulations for ionizing radiation exposures in commercial transports (unless they carry radioactive materials). Indeed, the concern over subsonic airtraffic commenced only after the latest report on greatly increased cancer risk coefficients and recommendations by national and international advisory bodies to significantly reduce the allowable exposure levels by factors of 2.5 to 5. There is an FAA Circular that recommends air carriers educate crewmembers on the hazards of ionizing radiation. The circular reports that pregnant crewmembers may run a risk as high as 1.3 per thousand births of severe illness to their children as a result of background radiation exposure. This has prompted a study of problems in early pregnancy of aircrews by the National Institute of Occupational Safety and Health (NIOSH).

The impetus to examine the impact of ionizing radiation stems from: (1) recent reductions in recommended radiation exposure limits by the ICRP and the National Council on Radiation Protection and Measurements (NCRP), and (2) recent scientific experimental results confirming the uncertainty in the amount of aircraft radiation exposure. The NCRP examined the state of knowledge of atmospheric radiation in high altitude flight and made recommendations on the need for improved information in order to develop a protection philosophy for high-altitude commercial flight operations. The HSR Environmental Impact radiation element developed the Atmospheric Ionizing Radiation (AIR) project to respond to the need for reduction of uncertainties in measurements applicable to HSCT based commercial operations after which an adequate protection philosophy can be developed.

Background

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 theoretical models. Furthermore, theoretical models of solar particle events showed that potentially high exposures may occur on important high latitude routes but acceptable levels of exposure could be obtained if timely descent to subsonic altitudes can be made. The principal concern was for pregnant occupants onboard the aircraft (Foelsche et al. 1974). As a result of these studies the FAA Advisory Committee on the Radiobiological Aspects of the SST (1975) recommended:

1. Crewmembers 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 highly occupationally exposed groups (Foelsche et al. 1974, Schaefer 1968) which prompted the FAA to develop methods to further study exposures resulting in the development of the CARI exposure estimation code (named after the Civil Aeronautical Research Institute) based on the LUIN transport code (developed by the Department of Energy (DOE) Environmental Measurements Laboratory) to generate the database (O'Brien and Friedberg 1994). The estimated risk of serious illness to the child of an aircrew member during pregnancy is on the order of 1.3 per thousand (Friedberg et al. 1992) and the FAA recommended that air carriers begin a program of training of their employees on the risks of in-flight subsonic exposures (White 1994). 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. One may assume that similar instruction of aircrew will be required for HSCT operations and restrictions on crew utilization of the HSCT will by necessity be different than on subsonic transports.

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 (ICRP 1991). As a result, new recommendations for reducing regulatory limits have been made by national and international advisory bodies (ICRP 1991, NCRP 1993). 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 (Reitz et al. 1993). 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 (Reitz et al. 1993). 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" (Fiorino 1996). The issues for HSCT commercial air travel are compounded by the higher operating altitudes (higher exposure levels) and the possibility of exposures to a large solar event wherein annual exposure limits could be greatly exceeded on a single flight (Foelsche et al. 1974, Wilson et al. 1995).

Impact of *AIR* on HSCT environmental assessment

As a result of the higher expected exposures in high-altitude flight, the congressionally chartered federal advisory agency on radiation protection, NCRP, examined the data on atmospheric radiation and made recommendations (NCRP 1996) on the need for future studies. We summarize their recommendations 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 issues 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 development of an experimental flight package to reduce the uncertainty in AIR models in direct response to the NCRP recommendations.

Goals

The focused goal of this project is to develop an improved *AIR* model with uncertainties in the atmospheric radiation components reduced to twenty percent or less to allow improved estimation of the associated health risks to passengers and crew. Special emphasis will be given to the high-energy (10 to 1000 MeV) neutrons in the altitude range of 50,000 to 70,000 ft. The results will be expressed in terms of an environmental *AIR* model able to represent the ambient radiation components including important spectral and angular distributions that will allow evaluation of aircraft shielding properties and the geometry of the human body. The model must be capable of representing the atmospheric radiation levels globally as a function of solar modulation. The model must furthermore be capable of evaluating radiation levels during solar particle event increases in near real-time using data from available satellite systems to allow risk mitigation and flight planning in the case of a large solar event.

Following the development of the *AIR* model, studies of impact of radiation exposure limitations on crew utilization and impact on passengers (especially frequent flyers) will be made to assess the need of developing a specific philosophy to control exposures in HSCT operations. These will result in requirements for study of the economic impact on operations costs. For example, it has been suggested that the HSCT crew be utilized at one third to one half the number of block hours as now utilized by subsonic aircraft to minimize exposures, which requires more crews at increased cost. The other possibility is to rotate crews to less exposed routes for a portion of each year and especially during a declared pregnancy. The need for and the extent of such exposure control measures must await the improvement of the *AIR* model.

Current predictive methods and impact on HSCT operations

The first model developed for atmospheric ionizing radiation was empirically based on the global measurements program under the LaRC SST study (Foelsche et al. 1974). The instrumentation consisted of tissue equivalent ion chambers, fast neutron spectrometers, and nuclear emulsion. Limited flights were made with tissue equivalent proportional counters (TEPCs), Bonner spheres, and the Concorde prototype radiation-monitoring instrument. The flights were made over most of solar cycle 20 with altitude surveys, latitude surveys, and measurements during the solar particle event of March 1969. Unfortunately the program was terminated in the year prior to the largest solar event observed during solar cycle 20, the 4 August 1972 event. The data set was augmented by the decades of measurements of air ionization rates using argon filled steel-walled ion chambers. The high-energy neutrons were estimated using Monte Carlo calculations as an extension of the measured 1 to 10 MeV flux from the fast neutron spectrometers. These theoretical high-energy neutron flux calculations indicated that over half of the neutron dose is from neutrons of energy above 10 MeV and are quite uncertain in their spectral content and intensity as was noted in the LaRC study (Foelsche et al. 1974), concluded by the Luxembourg workshop (Reitz et al. 1993), and by the

NCRP (1995). The solar particle event predictions are based on Monte Carlo calculations using the Bertini nuclear model and the United Kingdom nuclear data files (Foelsche et al. 1974).

In a recent report by LaRC, a survey was made of measurements and calculations of the neutron flux spectra for which large uncertainties in the resulting neutron dose were estimated (Wilson et al. 1995). The effects of these uncertainties on subsonic and HSCT flight crews are shown in figure 1. The exposure limits recommended by the ICRP and NCRP as a result of the now known higher cancer risk coefficients and new standards for pregnancy (table 1 columns 3 and 4, note that foot note *b limits* the average annual exposure to about 10 mSv), leave subsonic flight a concern to aircrews throughout the world (Reitz et al. 1993, Fiorino 1996) and an emphasis on reducing the uncertainties for development of an adequate radiation protection philosophy is most appropriate (NCRP 1995).

This is especially true for the HSCT with its much higher exposure rates as shown. However, the concern for frequently flying passengers is more for the slower subsonic flights (fig. 2) than the HSCT unless there is a large solar event. Diplomatic and business couriers may be more exposed on subsonic flights if their number of trips is fixed but the HSCT exposures would be higher if their flight hours are fixed. Clearly any advice to be given on control of individual exposures to either crew/passengers is limited by the exposure uncertainties in figures 1 and 2.

A second model has appeared from the FAA using the LUIN transport code to generate the necessary database. Although the LUIN code was initially in poor agreement with the LaRC measurements (Friedberg and Neas 1980), the last several years have shown substantial improvements in the LUIN code to describe dose and dose equivalent rates. A recent examination of the LUIN model in comparison with more advanced transport codes is shown in figure 3. Shown are results of the FLUKA code, a Monte Carlo code (Merker) developed under the LaRC project, and the 1997-1998 version of the LUIN code. Note that the differences in the range from 10 to 1000 MeV are as large as an order of magnitude. Recall that the neutrons in this range contribute over half of the total neutron dose so that these differences are quite important to exposures. To better understand the meaning of these comparisons, a limited Bonner sphere measurement on Mount Zugspitze (Schraube et al. 1997) is shown in figure 4 with the FLUKA results and emphasizes the large uncertainty in the present radiation model used by the FAA.

An informal December 1995 report on "HSCT Radiation Exposure" by Steven L. Baughcum and James R. Gillis examined mission radiation exposures for four city-pairs. It is interesting to note that the same exposure was calculated with the Seattle to Tokyo route which traverses from 55 degrees N to 25 degrees N geomagnetic latitude and the Los Angeles to Tokyo route which traverses from about 40 degrees N to 25 degrees N, which is due to the differences in flight times. A northern route from New York to London indicated that the northern routes are more critical to high altitude radiation exposure. Baughcum and Gillis calculated 3.7 millirems for the 3-hour NYC to London trip. If this exposure is converted to millisieverts and scaled up for a maximum annual 900 block hour duty (actual duties could be less), the crewmember would have received 11.1 mSv (or 6.2 mSv for 500 block hours). Wilson et al (1995) indicate that the same 900 block hours should produce a minimum cumulative exposure of about 11.4 mSv (or 6.3 mSv for 500 block hours) at solar minimum but with current uncertainties that it could be as high as 21 mSv (or 11.7 mSv for 500 block hours). The ICRP 60 recommended exposure limit for occupational exposures is 20 mSv per year and the new NCRP recommendation is for 10 mSv per annum for new designs to assure that lifetime exposures do not exceed 10 x age (mSv). The lower value calculated by the CARI code could be due to differences in solar modulation, in intensity/spectra of high-energy neutrons, in other radiation components, and in the dosimetric evaluations.

A route from Los Angles to London was examined [Friedberg letter] using CARI-2 by Dr. Wallace Friedberg at the FAA Civil Aeromedical Research Institute. His estimate was for a 6.3-hour mixed-Mach number flight that avoided supersonic flight over the landmass. He estimated the radiation dose for the HSCT flight to be 49 microSv. For 900 block hours this would accumulate to be approximately 7 mSv (or 3.9 mSv for 500 block hours). Baughcum and Gillis examined the same city pair for a similar 6.53-hour flight and came up with 5.5 mrem. Converting this to millisieverts and for 900 block hours this is approximately 7.59 mSv (or 4.2 mSv for 500 block hours). Wilson did not do a similar city pair estimate. Both of these estimates are within the ICRP 60 limit of 20 mSv per year, but push the new NCRP recommendation of 10 mSv per annum for new designs for those crew members which fly near their maximum allowable block hours. Numerous comparisons of the *AIR* model with other measurements and calculations are given elsewhere (Wilson et al. 1991).

AIR model development

The basic quantities of the present *AIR* model are the air ionization rate, the 1 to 10 MeV neutron flux, and the rate of nuclear star events in nuclear emulsion. These quantities were measured over a complete set of altitudes, geomagnetic latitudes, over the solar cycle, and scaled according to known procedures to allow a total time-dependent mapping of the global radiation field as a function of time. The limitations of the model concern the high-energy neutron spectrum, the quality factor of the ionic components, and the relative contribution of the nuclear stars.

The first step in improved model development is to add estimates of the proton and light ion flux using available transport models and databases. An international agreement with the Japan Atomic Energy Research Institute is being negotiated to provide computational support for adding improved results for the radiation-induced fields from the galactic cosmic ray protons. These results will be augmented by the light and heavier galactic cosmic ion components using the LaRC cosmic ray transport codes. Global fields as a function of time will be generated using the world wide vertical cutoff database and high-latitude neutron-monitor count rates. Model validation will require a definition of the mapping of the model field quantities to the ER-2 instruments. Although each investigator is responsible for the definition of their own instrument response functions, the LaRC team will assist in these definitions to the extent possible within funding and manpower limitations.

AIR flight measurements

An instrument package has been 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 elements 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 which had 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 (ca. June 2000 ± 13 months, Wilson et al. 1999).

The flight package developed uses all of the available space in the ER-2 cargo areas. The instrument layout is shown in Figure 5. The primary instruments in the package consist of neutron detectors, scintillation counters, and an ion chamber from the Environmental Measurements Laboratory of the Department of Energy 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; tissue equivalent proportional counters (TEPC) from Boeing and Defence Research Establishment Ottawa; and dosimeters from Boeing, Royal Military College of Canada in Ontario and National Radiological Protection Board (NRPB) in the UK. The existing primary instruments and data systems 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.

Status of regulatory process

The inherent assumption in regulating occupational exposures is that society and the individual worker obtains benefits from the execution of said occupation. The issue is the determination of the risks incurred by these occupations and the acceptability of those risks to both the individual worker and the society at large. The individual's decision to accept an at-risk occupation has to be made on a case by case basis with adequate information on the risks to be assumed (informed consent). At the same time it is a matter of law that the employer is to keep exposures as low as reasonably achievable (the ALARA principle) and is a function of the means at the employer's disposal. With respect to the general public, it is inherently assumed that these individuals are exposed without direct personal benefit and indeed without their consent. For this reason, the allowable exposures for the general public are normally set by regulators to be an order of magnitude lower than the exposure limits for the occupationally exposed.

The regulatory process is peculiar to each country. The process in the US is shown in figure 6. The ICRP is an international advisory body composed of members of various national advisory bodies among its committees. The NCRP is a congressionally chartered federal advisory council utilized by the national regulatory agencies in setting standards. The recommendations of the NCRP typically result in changes in US regulations about 5 to 7 years later. The latest changes in recommendations on exposure limitations are contained in the ICRP report 60 (1991) and the report NCRP 116 (1993). Although there are no current regulations within the US governing aircrew exposures, the FAA has published an advisory circular recommending training of aircrews on radiation exposure risks (White 1994) and the ICRP has recommended that aircrews be recognized as an occupationally exposed group with the usual regulatory requirements (ICRP 1991).

The status of current US regulations on exposures is discussed elsewhere (Fed. Reg. 1991, OSHA 1996, EPA 1994) and in recently proposed changes to mainly cover pregnancy (Cool and Peterson 1991), and recent proposed exposure limitations (ICRP 1991, NCRP 1993) are shown in table 1. It is anticipated that US and foreign regulations will follow the NCRP 116 (1993) and ICRP 60 (1991) more closely by the end of the decade. Indeed, the FAA advisory circular on the training of aircrew refers exclusively to the ICRP 60 (1991) recommendations with obvious implications.

The European regulatory process is more complicated due to the inter-relation through the Commission of European Communities (CEC). The process in the UK is shown in figure 7 as compiled by C. K. Wilson (1993). The CEC has held a workshop on aircrew exposures (Reitz et al. 1993) which was a driving factor in the present project as well as in various international organizations (Three of whom are collaborators in the ER-2 flight project). It is anticipated that aircrew in Europe will be treated on the same level as other radiation workers and methods of exposure estimates are being explored. For example, the NRPB in figure 7 is a government agency in the UK developing dosimetric methods for use on commercial subsonic aircraft and a partner in the present ER-2 flight project.

At present we have no clear picture of the Japanese regulatory process but the Japanese Aircrew Unions have petitioned the government to treat their members on the same level as the other occupationally exposed workers within their country (Fiorino 1996).

The above statements apply to mainly subsonic airtraffic and are driven by the lowering of the ICRP recommended exposure limits as a result of the increased cancer risk estimates as determined from studies of the WW2 nuclear weapons survivors. The exposures at HSCT altitudes are substantially higher during ordinary days due to the higher operating altitudes and in addition may suffer from a solar particle event exposure in which high exposures may occur on a single flight, affecting not only the crew but also the passengers. For example, OSHA (1996) defines a "high radiation area" as one in which an hourly dose of 1 mSv is present (a level easily exceeded by a major solar event in an HSCT at high latitudes) and requires a "conspicuous sign" reading "Caution, High Radiation Area." The NCRP has cited a need for future studies to develop a radiation protection philosophy for risk mitigation and exposure control for which the present project is in direct response. A simplified listing of the NCRP recommendations is given in an earlier section of this report.

Relationship to other Government Entities

The most cost-effective means of performing this project was to utilize available equipment and personnel to make the necessary measurements and data analysis. This required us to look beyond the bounds of the US and the resulting team is international in character. The work will be accomplished under various interagency, national, and international agreements as follows:

- United States
  - DOE Environmental Measurements Laboratory
  - DHHS National Institute of Occupational Health and Safety
  - FAA Civil Aeromedical Institute
  - NCRP National Council on Radiation Protection
  - NASA Johnson Space Center
  - Hampton University
  - Prairie View A&M University
  - Yale University
- Canada
  - Royal Military College
  - Defence Research Establishment-Ottawa
- Germany
  - DLR Institute of Aerospace Medicine
  - University of Kiel
- United Kingdom
  - National Radiological Protection Board
- Italy
  - University of Pisa
  - Istituto Superiore di Sanita'
- Japan
  - Japan Atomic Energy Research Institute

Assessment of impact on HSCT

Studies have identified a substantial market for a future supersonic airliner--or High Speed Civil Transport-- to meet the rapidly growing demand for long haul travel, particularly around the Atlantic and Pacific rim. Over the period from 2005 to 2040, this market, without any environmental restrictions, could support over 1000 aircraft. The current HSCT is designed to carry 300 passengers at Mach 2.4 on transoceanic routes over distances up to 5,000 nautical miles.

The current Mach 2.4 aircraft design will cruise at altitudes between 53,000 to 65,000 feet (16.8 to 19.2 km). Studies have indicated a utilization rate of at most 15 hours per day. If an average flight time of 4 hours is assumed, an HSCT will fly at most four flights per day or 1460 flights per year. If a down time of 10 percent for maintenance is assumed, the annual flights will be reduced to approximately 1314. For a load factor of 70 percent the number of passengers on board per flight will be 210 with an on board crew of about 12 (pilot, co-pilot, and 10 flight attendants). Therefore the number of person flights (passengers and crew) per HSCT per year is approximately 291,708. Assuming the crew flies 8 hours a week then the required crew size per aircraft consists of 168 members for which the majority are women of child bearing age (Reitz et al. 1993). One can further say that if there are 1000 units operating, the number of person flights per year would be 291,708,000 including the flights of the 168,000 crewmembers. Assuming a western distribution of ages, about 1 percent of the people flown will be pregnant, which totals 2,917,080 pregnant person flights including the flights of the 1,680 pregnant crew members. Of the 2.9 million pregnancies flown, 972,360 will be in the first trimester, the most critical time in the development of the fetus.

Background exposures of pregnant occupants- The FAA had estimated that subsonic crew exposures could result in as much as a 1.3 per thousand incidence rate of severe illness to the developing child by working during pregnancy (McMeekin 1990). This realization is in part the basis for the NIOSH/FAA study of pregnancy termination of women in the airline industry (Grajewski 1997). The background radiation levels at HSCT altitudes are a factor of 2 to 3 higher (Foelsche et al. 1974, Wilson et al. 1991) and incidence of severe illness could be as high as 3-4 per thousand assuming subsonic work patterns apply (McMeekin 1990). In this assessment we assume the crew will fly only one round trip per week so exposures are more comparable to subsonic exposures and the rate of severe illness is 1.3 per thousand. Assuming a western distribution of population (including children) among the 168,000 crew members which underestimates the pregnancy rate, one would anticipate 2 or more births with severe radiation induced developmental injury per year among the crewmembers. There is a clear need for development of a radiation protection philosophy and counseling of crewmembers on their personal exposures (NCRP 1995).

Solar particle event exposures- Assuming 15 hours of operation of 1000 aircraft with a 10 percent down time places 563 aircraft aloft at any time during the day. Utilization studies places 72 percent on high latitude routes with approximately 104,895 occupants. If a solar particle event occurs and assuming western population distributions, there could be as many as 1049 pregnancies on high latitude routes which could receive up to 10 to 20 mSv on a single flight unless means of controlling exposures is implemented. The number of individuals expected with serious health effects can be quite high if adequate precautions are not taken during large solar event. Clearly, some provision for protection of passengers and crew from such events needs to be developed (Reitz et al. 1993, NCRP 1995).

Exposures of the Crewmembers- The risk of health effects of greatest concern is excess fatal cancer. The excess risk of fatal cancer from background radiation among the crew (excepting pregnancy discussed in the preceding subsection) can be found by using the risk coefficient of 6.3 per 100,000 per mSv (White 1994). The annual exposure for flights from New York to London is as high as 21 mSv for 900 block hours (or 12 mSv for 500 block hours) which is a little over a factor of two higher than the subsonic exposures estimated by the FAA (9.1 mSv for 950 block hours). Assuming a 20-year career, the lifetime excess risk of fatal cancer for 500 block hours is 20 x 12 x 6.3 = 1512 per 100,000 which is comparable to risks of subsonic flight given by the FAA (White 1994) assuming 950 block hours per year. The expected number of excess cancer deaths among the 168,000 crewmembers is 2,540 compared to the normally expected number of naturally occurring cancer deaths of 36,960.

Exposures of the Frequent Flyer- For present purposes we have taken the frequent flyer to be an individual who makes ten round trips per year. Business and courier passengers may greatly exceed these values and would be treated as occupationally exposed, as is the crew. The health concerns (excepting pregnancy) of the frequent flyer are similar to the health concerns of the crew (fatal cancer) and depends strongly on the number of flights per year. The frequent flyer on an HSCT will incur significantly less risk than corresponding flights on subsonic carriers unless a large solar event occurs. The excess risk of fatal cancer from background radiation among the frequent flyers can be found by using the risk coefficient of 6.3 per 100,000 per mSv. The annual exposure for flights from New York to London is at most about 1 mSv for ten round trips which is almost a factor of two lower than the corresponding subsonic exposures. Assuming a 20 year career, the lifetime excess risk of fatal cancer is 20 x 1 x 6.3 = 126 per 100,000. We have no reliable estimates of the number of such travelers or their work patterns.

Be^7 as a maintenance hazard- Be^7 is a radioactive by-product of the interaction of cosmic rays with atmospheric constituents. It decays by electron capture with a half-life of 54.5 days emitting a 0.479 MeV gamma in 10 percent of the decays. The main source terms are in the stratospheric altitude range of 40,000 to 100,000 ft (Dutkiewicz and Husain 1985) and at high latitudes (above 55 degrees magnetic). The transport in the atmosphere is of considerable interest to atmospheric circulation studies and the DOE Environmental Measurements Laboratory has developed a database on Be^7 concentrations. The Be atom is an open electron shell structure and is expected to have a large sticking coefficient to surfaces. The rate of adherence (mainly to leading edge surfaces, Fishman et al. 1991) will depend on the atmospheric Be^7 concentration along the trajectory, air flow, and surface properties and reach a steady state in the 54.5 day time frame since the loss is mainly through decay to Li^7 which is not radioactive. It has been reported (A. Mortlock) that work crews on the Concorde wear radio-protective gear in servicing that aircraft. Given data on the Concorde contamination levels and the DOE/EML source database, one could scale to the HSCT flight conditions using a linear kinetics model.

Single Event Upsets- Single event upsets (SEU) from radiation found at high altitudes have been measured in present day avionics technologies based on microelectronic devices (Normand et al. 1994). Such electronic devices are sensitive to the sudden introduction of charge into an active element of their circuits. The amount of such charge that is sufficient to change the state of a logic circuit is called the critical charge. As shown in figure 8, there is a rough relationship between critical charge Q_c and the device feature size L (note Q_c is proportional to L^2).

The critical charge also depends on chip design factors and operating voltage. The charge released in the device is proportional to the energy deposited by the particle (1 pico-coulomb of charge is released for every 22.5 eV deposited in silicon). The charge released is not the charge collected since ionization within charged particle tracks is very dense in the track center (Cucinotta et al. 1995) and recombination occurs on a very short time scale (Shinn et al. 1995). Single event upsets in the device are then dependent on the charge collected in comparison to the critical charge. The energy deposit depends linearly on the feature size while the critical charge depends on the feature size squared. Decreasing the feature size by a factor of 2 reduces the charge collected by a factor of 2 while the device sensitivity to upset increases by a factor of four. As the feature size decreases, new physical processes resulting in small energy deposition are able to upset the device. For cosmic ray heavy ions that are directly ionizing, the SEU rate is directly proportional to the cross sectional area of the sensitive region of each device (approximately proportional to L^2), and inversely proportional to the square of Qc (Qc^{-2}, therefore to L^{-4}); thus overall it is strongly inversely proportional to L. For protons and neutrons that ionize indirectly, through nuclear reactions with the device, the SEU rate may, very approximately, be taken to vary directly with the heavy ion SEU rate. Thus for protons and neutrons too, the SEU rate variation is strongly inversely proportional to feature size.

One example of the importance of this effect to aircraft is in avionics. Whereas older devices with feature sizes on the order of 4 microns were insensitive to nuclear reactions within the chip, smaller devices of <1 micron are sensitive to such effects. This is shown in figure 9 where the energy regions of various ion types to which a device upsets is shown in the figure along with the reaction products from high energy reactions in silicon. Note that the sensitive region lies to the right hand side of the indicated curve for each feature size. These types of upsets are caused by high-energy protons and neutrons (Normand et al. 1994). SEUs have been measured during flight by computers in conventional aircraft that were protected by error correction and detection (EDAC) circuitry (Tabor and Normand 1993).

These SEUs have been shown to be dominated by the atmospheric neutrons as shown in figure 10 (Normand 1996) since the altitude and latitude variations of the upsets correlate with the corresponding variations of the atmospheric neutron flux. For HSCT flight at higher altitudes, the SEU rate is still expected to be dominated by the neutrons, but protons and even primary cosmic rays, may also contribute very significantly to the SEU rate, especially in the polar regions.

The next generation of computers have feature sizes that are fractions of a micron feature size and are expected to be greatly more sensitive to these types of upsets than current technologies. Improved estimates of the intensity and spectral distribution of atmospheric neutrons and protons are important to evaluation of the expected upset rates which will be needed in the design of upset tolerant systems.

Materials Effects- The flight of the aircraft at 15 hours per day for 30 years will accumulate a dose of 164,250 x 1 mrad per hour = 164 rad = 1.64 Gy. Materials degradation effects in polymers from ionizing radiation thresholds are 10,000 Gy and no effects are anticipated. Metallic materials effect thresholds are even higher. Although the effects of the radiation on materials are expected to be negligible, the effects of construction materials on the radiation fields within the interior are measurable. For example, the measurements on board the RB-57F of 1-10 Mev neutrons were ten percent higher than on the balloon flights (Foelsche et al. 1974, Wilson et al. 1991). Measurements of variations in radiation levels on subsonic air transports of up to 30 percent have been observed (Wilson et al. 1994). The use of polymer composites especially those with neutron absorbing (carbon cored) boron fibers is expected to lower the interior environment below that for metallic construction. In addition to the basic wall materials, large metal structures (for example the wing box) may have a significant effect on the internal environment (amplification) and needs to be evaluated.

Recommendations and future plans

The progress needed to provide for the radiation safety of the HSCT and develop a radiation protection philosophy for future HSCT operations is given by the NCRP recommendations. Those recommendations embody in part the recommendations of the FAA Advisory Committee on the Radiobiological Aspects of the SST but go beyond those recommendations in recognition that the much higher fatal cancer risk coefficients found in recent analysis of the WW2 exposures needs to be addressed. To develop a comprehensive safety procedure it was recognized by the NCRP that improved estimates of the exposure levels need to be made. This is the main emphasis of the current task. In addition to this main task, the development of procedures for control of exposure levels on high latitude routes during a solar particle event is also to be addressed. This is being accomplished by implementing transport procedures to use GOES satellite data to provide real-time mappings of the solar particle event induced radiation levels to provide guidance in exposure avoidance. Important solar events of the past will be examined to test methods of reducing exposure through adjustments in the flight path. In support of these requirements we recommend the following steps.

Improvements of AIR model- The *AIR* flight package was flown during the peak galactic cosmic ray intensities in June 1997. The process of improvement and validation of the *AIR* model using this flight data needs to continue. The flights need to resume near the next galactic cosmic ray minimum (2000-2001).

The *AIR* model development should continue in parallel to the flight program and will utilize state of the art transport codes and databases to generate input data to the *AIR* model. The response functions of each instrument need to be modeled for validation of the *AIR* model by comparison with the flight data. The Bonner sphere, scintillation counters, particle telescopes, and nuclear track detectors will be used to improve the model spectral intensities.

To further utilize the results of the flight measurement program on the ER-2, a parallel effort to fly an SEU experiment should be considered. It would consist of an electronics board on which upsets would be detected, corrected and recorded, allowing direct correlation with the detector and dosimetry data from the instruments on the ER-2.

Develop methods of evaluating solar particle induced radiation- A solar particle event routine will be developed for conversion of the GOES satellite data into atmospheric radiation levels. An interagency agreement should be established with NOAA Space Environmental Laboratory for integration of the AIR model and the satellite real-time data stream. A geomagnetic storm field model based on horizontal storm field component needs to be developed since geomagnetic storms may occur during particle event arrival.

The need for instrumentation to monitor the radiation levels will be met by some of the instruments included in the ER-2 flight package. Both passive and active dosimetric device candidates are being flown for comparison with the more detailed evaluations of the physical field measurements. The cross calibration of the several dosimetric devices flown with the actual environment will provide a basis for a future HSCT monitoring system.

Advocate solar particle event forecasting- Develop HSCT requirements for solar event forecasting. An advocacy package needs prepared for the Office of Space Sciences on needs for solar physics studies to meet HSCT requirements.

Develop Be^7 model from Concorde operational experience- The Concorde should have a database on Be^7 accumulation from flight operations. This data can then be scaled to HSCT altitudes and operation schedules using the DOE/EML source database on Be^7 concentrations and a linear kinetics model.

Reduce the biological uncertainties- The peculiarity of atmospheric ionizing radiation is that the exposure is dominated by heavily ionizing particles. The risk coefficients associated with such radiations are the main source of uncertainty especially for prenatal exposures. The NCRP should be funded to survey biological data for evaluation of risk factors for stochastic and developmental injury in neutron and proton exposures.

Develop a philosophy for radiation safety of the HSCT- With a validated *AIR* model and updated information on the associated risk coefficients and available instrumentation for solar forecasting and monitoring, the NCRP should be funded to develop a philosophy for radiation safety of high altitude commercial aircraft operations.

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Table 1. Current and Projected Maximum Allowable Exposure Limits (Wilson et al 1995)

Exposure condition	Maximum allowable exposure, mSv			
	Present United States 10 CFR Part 20 (1991)	Proposed United States NUREG/BR-0117 (Cool and Peterson 1991)	Proposed NCRP Rep. 116 (1993)	Proposed ICRP Publ. 60 (1991)
Occupation:				
Annual	[a]50	50	50	20
Lifetime	[50 (Age - 18)]		[b]10 × Age	
Pregnancy (total)	5	5		[c]2
Pregnancy (monthly)			0.5	
Public:				
Annual, many years	[d]1	1	1	1
Annual, occasional		5	5	
Pregnancy (total)		5		[c]2
Pregnancy (monthly)			0.5	

[a] Not to exceed 30 mSv in any quarter year.

[b] Recommended limit for new designs in 10 mSv/yr.

[c] Abdomen surface for x-rays, 1 mSv in *utero*.

[d] 5 mSv allowed with prior approval of NRC.

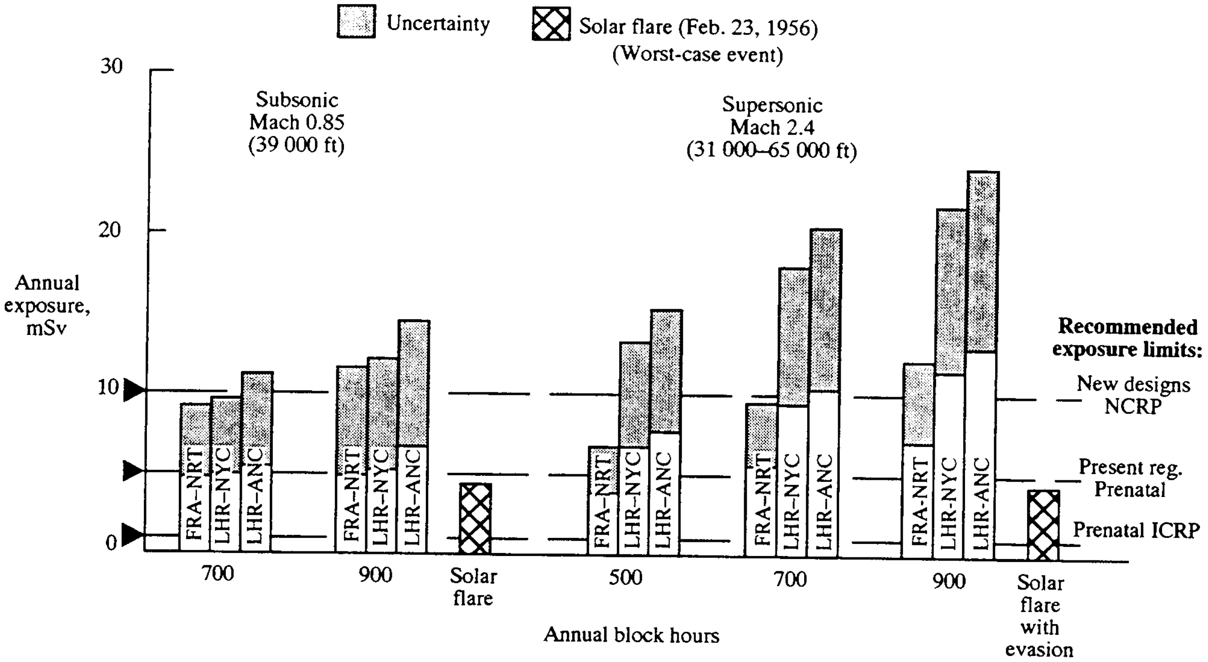

Figure 1.- Annual crew exposures of subsonic and Mach 2.4 flights along specific air routes for assumed number of block hours.

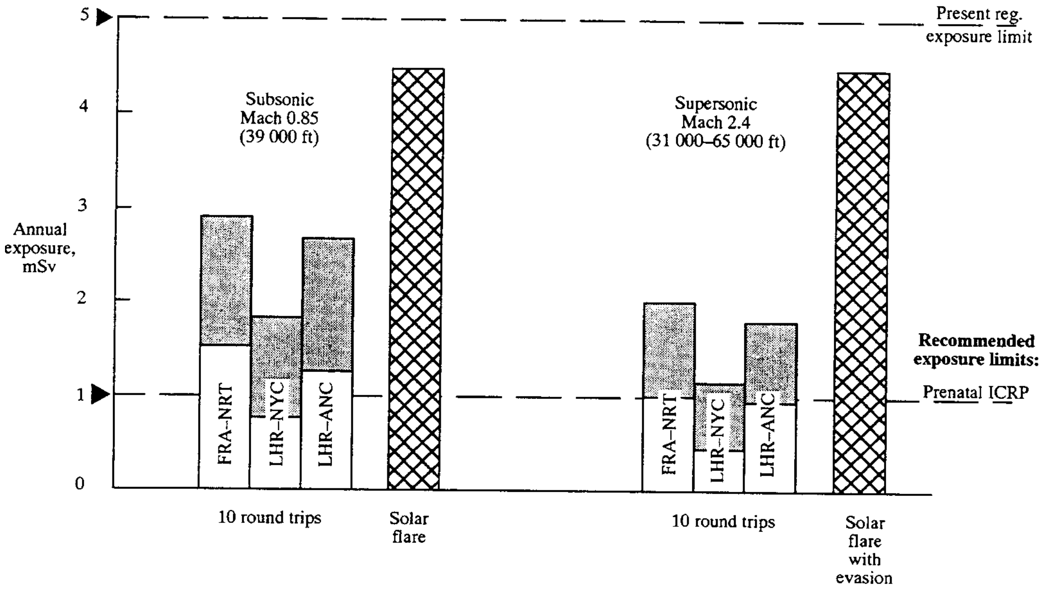

Figure 2.- Frequent Flyer annual exposure for subsonic and Mach 2.4 flights along specific air routes for 10 round trips.

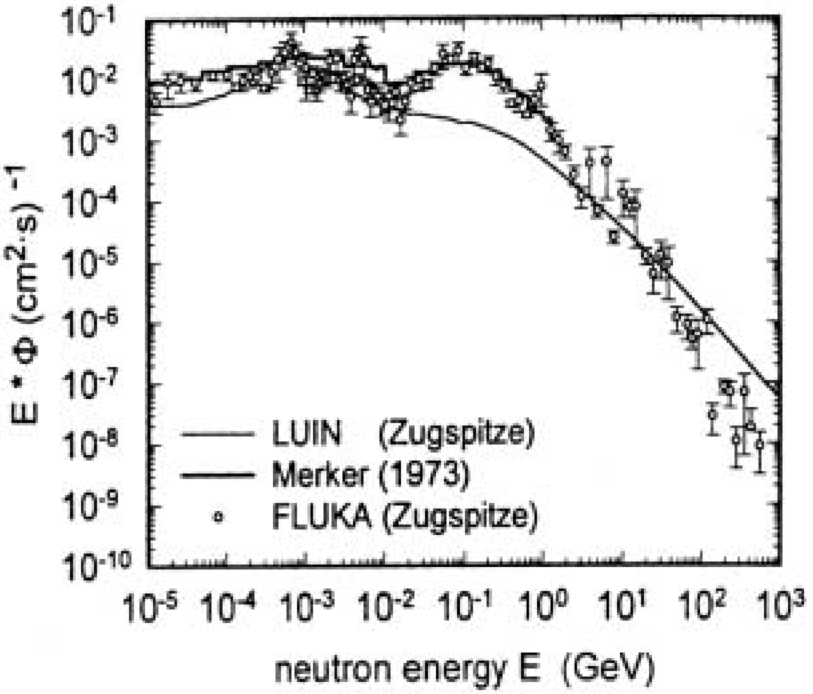

Figure 3.- The calculated cosmic ray neutron spectrum on the top of mount Zugspitze. (From Schraube et al. 1997)

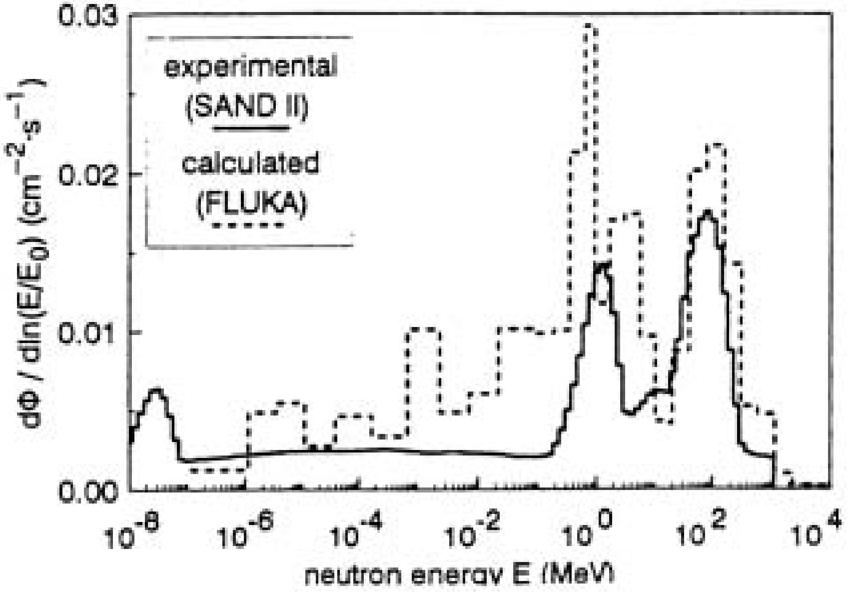

Figure 4.- The cosmic ray induced neutron spectrum on top of mount Zugspitze. (Schraubbe et al. 1997)

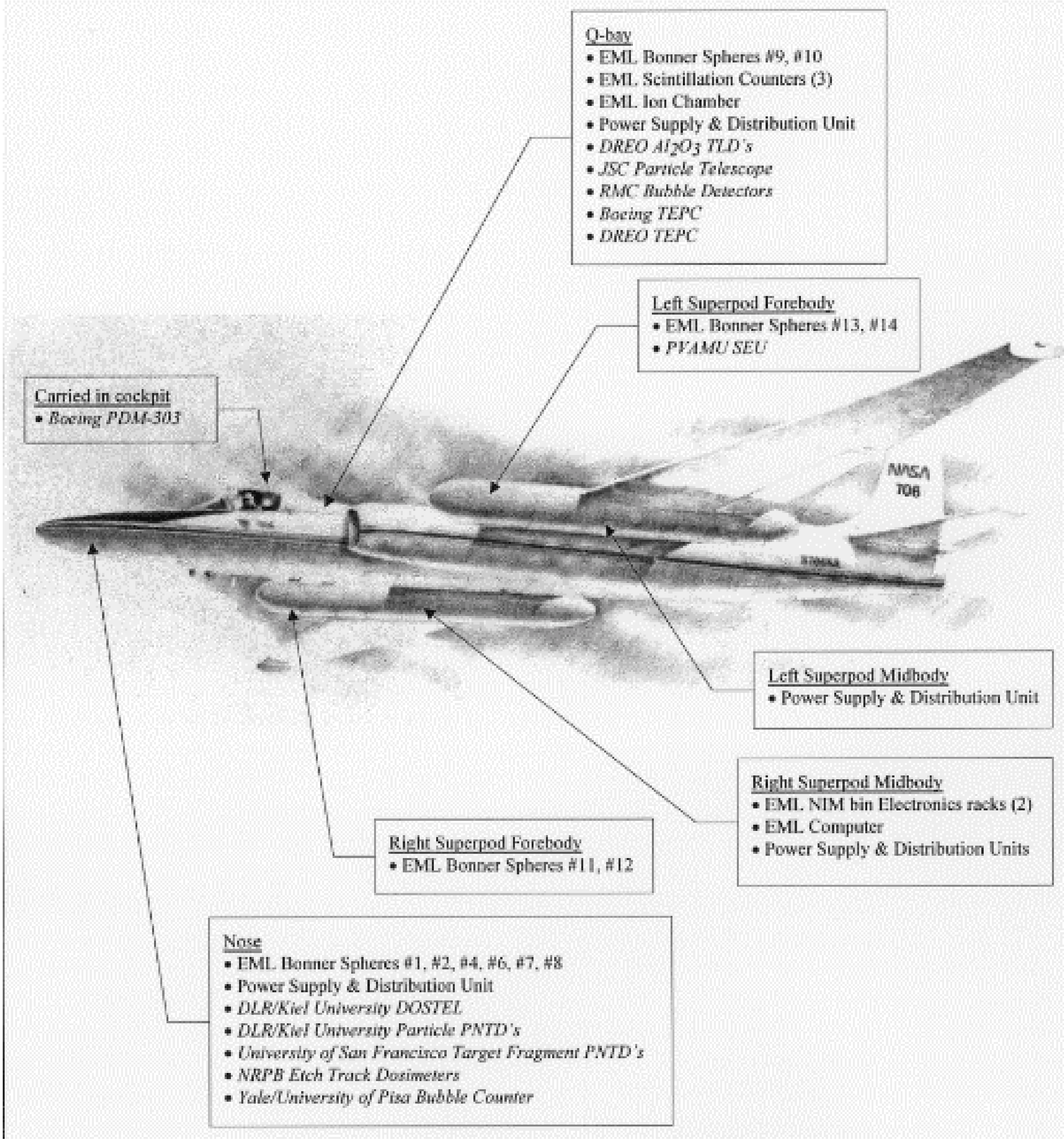

Figure 5.- Instrument Locations on the ER-2.

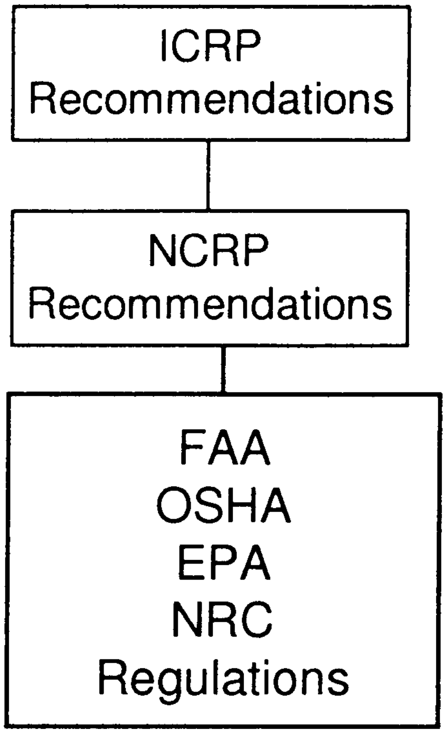

Figure 6. - US regulatory process

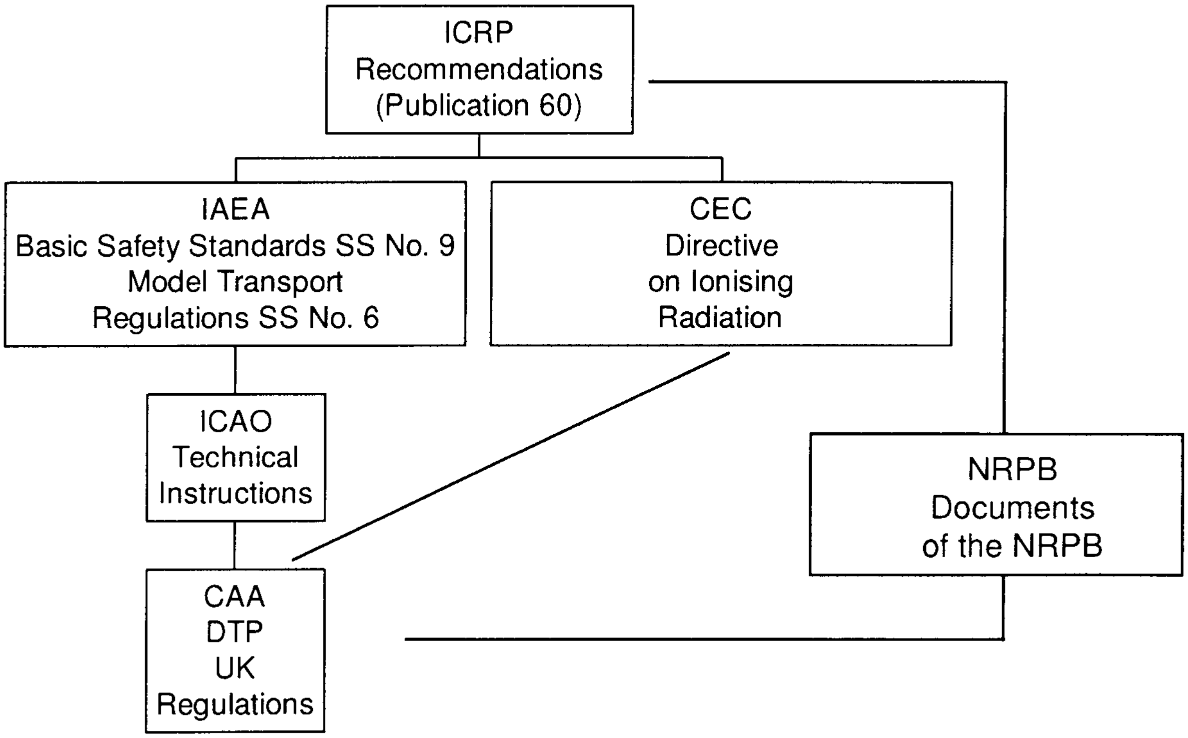

Figure 7. - Input to United Kingdom legislation

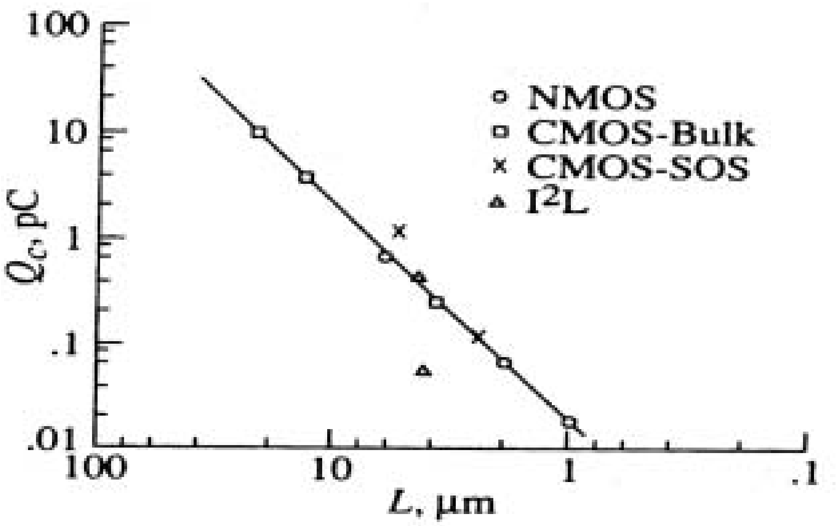

Figure 8.- Critical charge as a function of feature size in several device types.

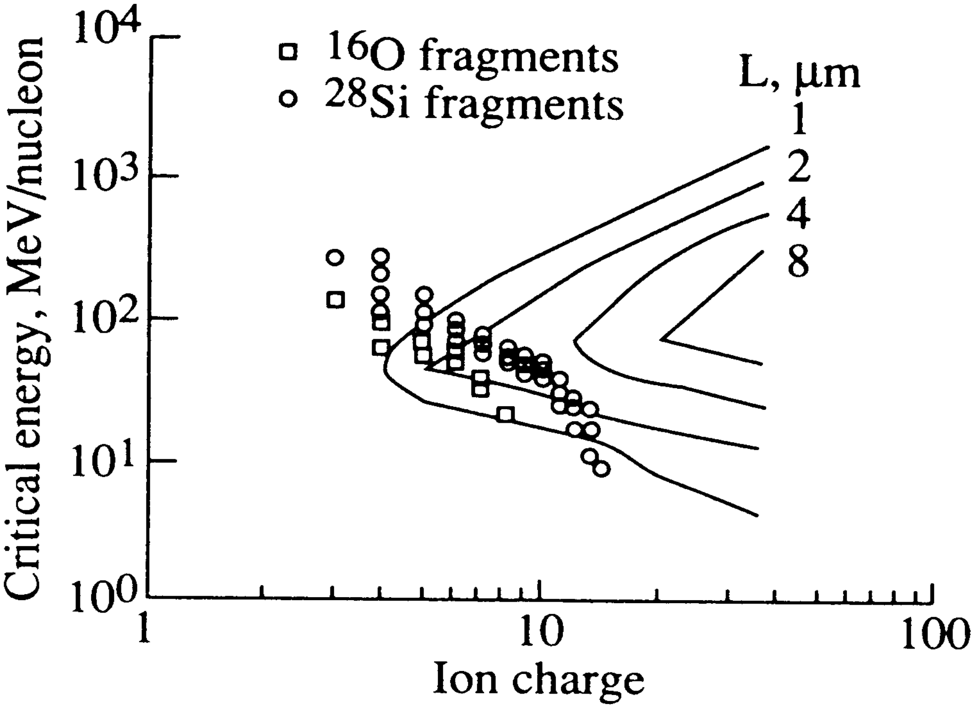

Figure 9.- Critical energy as a function of ion charge for several feature sizes. Average recoil energies of fragments of silicon and oxygen are superimposed.

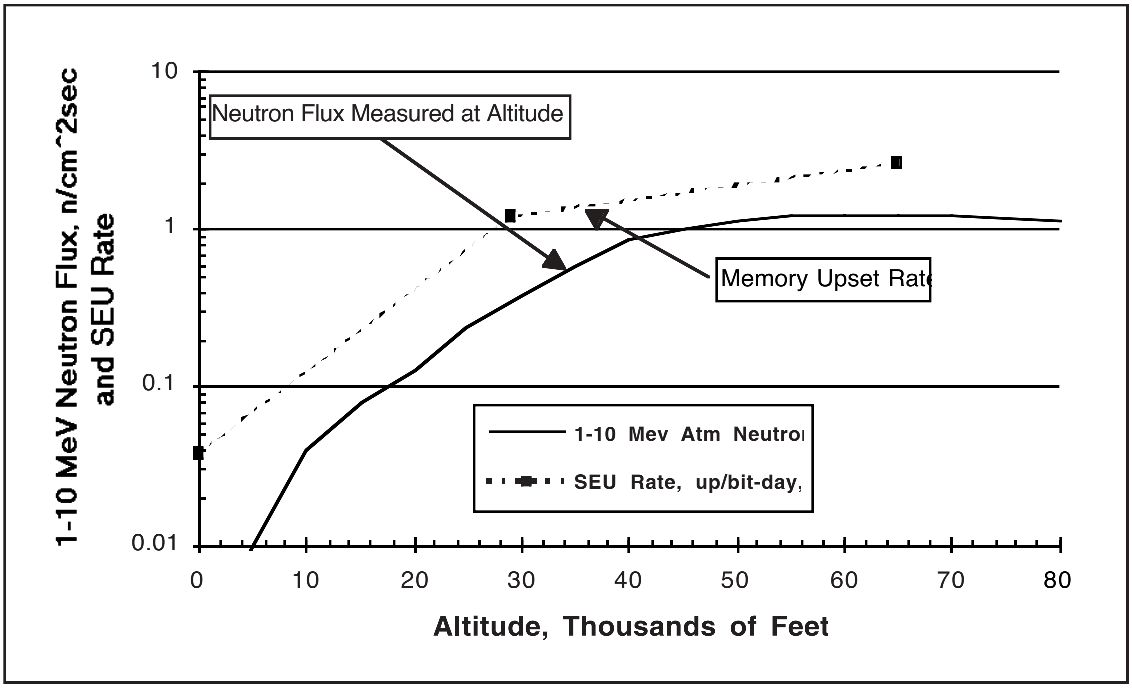

Figure 10.- Correlation of the inflight SEU rate in the IMS 1601 SRAM with atmospheric neutron flux as a function of altitude. The SRAM was operated at 2.5V (Normand 1994).