Chapter 8
Human Factors

"By the time Claggett and Linley reached their [lunar] rover and turned it around, they no longer bothered with their dosimeters, because once the reading passed the 1,000-Rem mark, any further data were irrelevant. They were in trouble and they new it..." [Space, James Michener]

On June 4, 1989 a powerful gas line explosion demolished a section of the 1,153-mile Trans-Siberian Railroad, engulfing two passenger trains in flames. Rescue workers worked frantically to aid the passengers, but only 723 could be saved. The rest perished. Many of the 500 victims were children bound for holiday camps by the Black Sea. *. "My sister and my aunt are somewhere here in these ashes"* said Natalya Khovanska as she stumbled among the remains of the trains which were still smoldering. Gas from a leak in the pipeline was ignited by the two passing trains. The gas settled into a valley near the towns of Ufa and Asha that the trains were passing through at the time. The explosion was estimated to have been equal to 10,000 tons of TNT, and it felled all the trees within 3 miles of the blast. By some accounts, a wall of flame nearly two miles wide engulfed the valley, hurling 28 railway cars off the tracks. The explosion cut the Soviet Union's gas supply by 20%. A commission was quickly set up to investigate the blast, but several days later they had still not determined why it happened, except that pipeline engineers had increased the pressure in the line rather than investigate the sudden pressure drop caused by the leak. Mikhail Gorbachev denounced the accident as an example of "irresponsibility, incompetence and mismanagement" in an address to the Congress. He even suspected sabotage. The cause of the explosion was later identified as the profound disrepair of the pipeline, which had become badly corroded over time and never properly maintained. In the Urals, the weakened walls had finally given-way to the pressure of the gas and begun to breach.

Just as geomagnetic storms can cause currents to flow in telegraph lines and trans-Atlantic cables, under certain circumstances, they can also flow in natural gas pipelines. The Ural pipeline disaster was, by all accounts, an extreme event. Because the pipeline is not oriented in a favorable direction to easily pick-up GICs, and because it is, in fact, very far away from the latitudes where GICs are most intense, it is unlikely that geomagnetic activity acting over time had much to do with this disaster. The Alaskan pipeline, on the other hand, extends over 800 miles a north-south direction, and its central 1/3 runs along the latitude of the auroral electrojet current. It was built during the 1970's and specifically designed to minimize these currents. Modern pipelines are protected from long-term current flows by a weak counter current of a few amperes which is applied so that the pipeline has a net, negative potential relative to ground. The problem is that auroral currents change polarity in minutes, rendering this 'cathodic protection' useless. During geomagnetic storms when the electrojet current flows erratically, currents as high as 1000 amperes have been detected. The lifetime of the Alaskan pipeline is now estimated to be many years shorter than originally planned. At that time, perhaps a decade from now, we will undoubtedly hear more about aggressive last-ditch countermeasures being employed to plug leaks, or replace whole sections of the pipeline. Some of these problems may arrive sooner than later. In 1990, plans to increase the pressure in the Alaskan pipeline had to await the results from a detailed federal investigation of the pipeline's corrosion. Although investigators turned up evidence of gross negligence on the part of the pipeline inspectors, they gave the project a clean bill of health and allowed the higher pressures to be used. Meanwhile, pipeline engineers in Finland have been monitoring GIC currents in their lines for over a decade and are far more concerned about what the future may bring. According to a report on space weather impacts by the French national space agency, CNES, the long-term impacts of these currents can be substantial. Pipelines designed to last 50 years can suffer wall erosion of 10% in only 15 years unless the pipeline is regularly monitored and upgraded. No one seriously expects another devastating explosion such as the one in the Urals from any, currently active, pipeline. At worst, GICs will enhance the rate of corrosion in certain pipelines in high-latitude countries which will require careful inspection. But there are other situations where human health can be more directly impacted by solar storms.

At 1:20 AM Eastern Daylight Time on August 4, 1972, the Sun let-loose one of the most powerful blasts of radiation ever recorded during the Space Age. The streams of X-rays and high-energy protons that flowed past the Earth within minutes, but not before triggering a major geomagnetic disturbance disrupting telephone service, and destroying a power transformer at the British Columbia Hydro and Power Authority. Although ground-based observers were kept on their toes by the unexpected power and communication outages, the event would have had a much more deadly outcome had it arrived four months later between December 7-19 while Apollo 17 astronauts were outside their spacecraft playing golf. Within a few hours, some estimates suggest that Harrison Schmidt and Eugene Cernan would have been hit by an incredible blast of radiation well over 1000 rem.

The astronauts would have suffered acute radiation sickness by the time they reached their Lunar Ascent Module, and probably even died some time later back on Earth. This is why James Michener, in his book 'Space' dwells on a similar event in his story of the fictional Apollo 18 mission. Some experts down play what a flare like the 'Apollo 17' flare might have actually done. Gordon Woodcock, for example, writes in his book 'Space Stations and Platforms' that

> *"Had an Apollo crew been on the lunar surface during the 1972 flare, they would very likely have received enough radiation to become ill. Radiation sickness effects at an exposure level of a few hundreds of rem take hours or days to become debilitating. James Michener's description in Space was not accurate"*

Others beg to differ. According to Alan Tribble's, The Space Environment:implications for spacecraft design,

"During August 1972 and again in October 1989, there were two extremely large solar proton [flares]. If an astronaut had been on the Moon, shielded by just a space suit, the radiation dose would probably have been lethal"

The orbiting Command Module would not have altered the outcome significantly according to shielding calculations by physicist Lawrence Townsend and his collaborators at NASA's Langley Research Center. Their 'worst case' analysis shows how the August 1972 flare radiation would have punched through bulkheads similar to those in the Apollo mission, and given the astronauts dosages as high as 250 rems,

"Such an acute exposure would likely have incapacitated the crew because of radiation sickness and could possibly be lethal"

Even this dosage is nothing to be sanguine about. Most radiation dosage tables say that 20% of the people exposed to even this level are sure to die within a month or two.

Radiation: most of us have an instinctive fear of it. Even the word, itself, is cloaked in mystery and a sense of foreboding. In reality, we are all more familiar with radiation than we suspect. No matter where you live, you receive 15-20 chest X-rays each year of environmental radiation - and there is almost nothing you can do about it. Even solar storms add their share to this cargo of potential damage. To see just how this happens, we are going to have to look a bit more quantitatively at what radiation is all about.

As you sit reading this book, you are being pummeled by various forms of electromagnetic energy from visible light to radio waves. You are also being struck by the daughters of particles that have streamed, literally, from the far corners of our universe. In casual conversation, these kinds of energy are simply called 'radiation' even though physicists have known for over a century that their various forms are quite different. Electromagnetic radiation includes the familiar rainbow of the visible spectrum, crammed between a vast range of other waves traveling at the speed of light. Some of these can be stopped by a sheet of ordinary paper. Other more energetic forms of light, like X-rays and gamma rays, require ever increasing thicknesses of matter to abate them.

In a separate category of radiation we have fast-moving particles which also come in several basic types such as electrons, protons, and the nuclei of the elements heavier than hydrogen. The amount of damage that these material forms of radiation can inflict depends on how much energy each particle is carrying. The bigger the energy, the more punch they can deliver, and the more collateral damage they produce as they penetrate the skin of a spacecraft, or the tissues in an organism. Electromagnetic radiation in the ultraviolet can give you a sunburn, but energetic particles can bore their way into your cells and explode like a small bomb, 'nuking' a gene.

Just as we can measure temperature in terms of 'degrees', it shouldn't surprise you that we can also measure the impact that radiation makes: Scientists call it a 'rad'. When a specific form of radiation delivers one watt of energy into 100 kilograms of tissue, this is one rad. Not all radiation affects tissue equally, so health physicists prefer to use another unit, the rem, to give an actual dosage equivalent for the different types or radiation as they impact biological tissue. For example, in one second, one watt of alpha particles (stripped helium atoms ejected by the decay of heavier radioactive atoms) causes 20 times more damage than absorbing the one watt of X-rays or gamma-rays. So, for one rad of absorbed dose, you get exactly one rem of equivalent dose if you are talking about X-rays, and 20 rems if you are talking about the more destructive alpha particles. You definitely want to stay away from alpha particles!

Now, how much radiation is too much? Unlike vitamins and money, more radiation is probably not better. Since the start of the Cold War and the first nuclear bomb tests, the general public has heard a lot about radiation effects; Hiroshima victims with their skin melting from their bones, genetic mutations, cancer. It all seems to be very ghastly stuff, and it is not hard to excuse the image that most people have, that radiation is always a bad thing. Like many things in nature, radiation is bad in degrees. But unlike the rather obvious summer monsoons that can kill thousands of people at a time, radiation is a very stealthy phenomenon that we have learned about only in the last 100 years of human history. Curiously, for the last few *billion* years, it is a phenomenon that is well known to evolution on this planet. Biologically, even at the cellular level, there are powerful mechanisms at work that can repair most radiation damage to an organism. Man-made forms of radiation, however, tend to be more powerful and concentrated than anything evolution has ever prepared us to deal with. Let's have a look at Table 2 prepared by Alan Tribble in his book 'The Space Environment: Implications for Spacecraft Design'. When you review these numbers, you might want to consider that a typical chest X-ray is worth a trifling 0.020 rads (for X-rays, remember that one rad is the same as one rem) on the same scale.

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The table is appropriate for what will happen during an acute, short-term (minutes to hours) radiation exposure. But, amazingly, if you took the 5000 rad dose and spread it over a 70-year lifetime, it may have little immediate effect, except to increase your cancer risk a bit. Depending on your lifestyle, or genetic heritage and predisposition, you may be more likely to die of some other factor rather than your cancer-induced radiation exposure. Astronauts, for example, are limited to 400 rads accumulated over their entire careers. If they absorbed this in one day, they would become deathly ill and have a good chance of dying from it.

To find actual instances of these kinds of high-level radiation dosages in humans, you have to look at what has happened to survivors of nuclear warfare or nuclear power plant accidents. In Hiroshima and Nagasaki, thousands of people were instantly vaporized as the radiation they absorbed raised their body temperatures to thousands of degrees in an instant. Many more people eventually died from the less-than-incandescent exposures they received. Even so, long-term studies of the survivors of the instantaneous, 10-50 rem Hiroshima and Nagasaki dosages show that they have LOWER rates for leukemia and genetic defects in their offspring than the unaffected Japanese populations in neighboring cities.

Still, Table 2 tells the average person very little about what they might expect from daily activities. To get this information, you have to look, for example, at the environmental dosages that have been tabulated by the International Atomic Energy Agency in Vienna Switzerland. As you can see in Table 3 the results are rather surprising. Compared to the biologically severe dosages in Table 2, typical annual dosages are thousands of times smaller, and we have to use a unit of 0.001 rem (one millirem) as a more convenient scale (A chest X-ray, on this scale, is about 20 millirems).

Table 3 about here.

Topping the list is radon gas, a natural by-product of certain radioactive elements found everywhere in the crust of the Earth, especially in granite-rich rocks, and clays. You probably never heard of radon gas until you bought, or sold, your first house. The radon gas hazard is the highest one we have to deal with, which is why basement radon gas monitors are a mandated part of home sales and purchases in the United States. This is a real and serious problem; not just another piece of legislation that the federal government wants to burden us with to make life complicated. The Environmental Protection Agency recommends that action be taken if radon levels exceed about 750 millirems per year. This usually means doing nothing more than installing a basement ventilation system to expel the stagnant, radiation-laced gases, which have seeped into the basement from the ground below the house foundation. And there we uncover yet another source of trouble.

The ground around your feet, the cement and brick in your homes, also emit radiation from their infinitesimal loads of trapped radioactive debris to the tune of about 60 millirem per year, but this changes quite a bit depending on where you live. For example, in states like Georgia, California, Florida and Maryland the terrestrial background radiation level is between 50-70 millirems per year, in Louisiana it is as low as 30, and in Colorado and South Dakota it can be as high as 115. The difference between living in Louisiana and Colorado is equal to an additional four chest X-rays per year added to your lifetime total.

If you really want to live on the edge, you have to visit places like Kerala, India, where the thorium-rich sands give you a dose of 380 millirem every year, and in Guarapari, Brazil where you get a sizzling 600 millirem per year. In comparison to the natural background sources and their variations, one wonders why so many people worry about one versus two extra chest X-rays per year. If you want a big savings in exposure, just move to a seacoast town, and forget about prolonged vacations in Denver, Brazil or India.

From Table 3 we can see some other surprising natural sources of radiation too. Just about every atom in nature has one or more radioactive variants called an isotope. When you add up the inhaled and ingested isotopes found in potassium and carbon this alone is equal to 23 millirems per year. Your own body is, itself, a low-grade source of nuclear radiation. If you are worried about your radiation risks, you should probably stop eating bananas (rich in radioactive potassium isotopes). You should also give up smoking (40 millirem per year, for a one pack a day habit)

If these were the only natural sources of radiation, you would already have a typical annual exposure of near 250 millirems or about ten chest X-rays per year. There is hardly anything you can do about this except perhaps to ventilate your basement and change your eating habits. But even so, there is another form of environmental radiation that you can do even less about.

One of the most unexpected sources of natural radiation doesn't come from the Earth at all. Instead, it rains down on our heads from the rest of the universe. Throughout the universe, massive stars grow old, die, and explode as supernova. These interstellar detonations fill space with particles that get accelerated to very high speeds and energies.

Dense cores of imploded stellar matter, pulsars, are powerful magnetic accelerators which push particles speeds to nearly that of light, hurling them deeply into the void. Even distant galaxies can have powerful magnetic fields that accelerate expelled stellar gases to very high energies. Over the course of billions of years, all of these sources suffuse space with a dilute, but energetic, gas of stripped atoms, electrons and protons, all rushing about at nearly the speed of light.

As these particles stream into our solar system, the solar wind and magnetic field serves as a weak umbrella to deflect the less energetic cosmic rays. As the remaining higher-energy cosmic rays penetrate deeper into the solar system, individual planetary magnetic fields deflect still more of them. Eventually, the most energetic cosmic rays make it all the way into the Earth's atmosphere where they collide with nitrogen and oxygen atoms to produce secondary 'showers' of energetic particles. These particles travel all the way to the ground and immerse the biosphere in a steady rain of particles, day-in and day-out. What this means for you and me is that a person living in Denver, the 'Mile High City', or in Laramie, Wyoming basks in an annual cosmic ray dosage of 120-130 millirems per year, while someone living in a seacoast town would only receive about 35 millirems. Travelers to remote mountaintops don't have to worry about bringing lead underwear to protect themselves. But it is true that prolonged stays on mountain peaks higher than 14,000 feet brings with it more than just the exhilaration of the experience. The cosmic ray drizzle bathes you with an invisible and relentless shower of radiation with each passing day.

We have all heard, since grade school, that radiation affects living systems by causing cell mutations. The particles strike particular locations in the DNA of a cell, causing the cell to malfunction, or survive and pass-on a mutation to its progeny. These accumulated 'defects' seem to happen at a steady rate over the course of millions of years, and paleobiologists use 'DNA differences' like a molecular clock to determine when species became separate. The DNA in chimpanzee and human blood hemoglobin tells a hidden story that about five million years have passed since these species shared about the same DNA. The steady rain of cosmic rays and other background radiation seems to be the very engine that drives evolution on this planet. In as much as we are all fearful of radiation, evolution on this planet requires it as the invisible agent of change. But sometimes the mutations are not beneficial to an organism, or to the evolution of its species. When this happens you can get cancer.

Cancer risks are generally related to the total amount of lifetime radiation exposure. The studies of Hiroshima survivors, however, still show that there is much we have to learn about just how radiation delivers its harmful impact. Very large dosages over a short period of time seem not to have quite the deleterious affect that, say, a small dosage delivered steadily over many years does. The National

Academy of Sciences has looked into this issue rather carefully over the years to find a relationship between lifetime cancer risks and low-level radiation exposure. What they concluded was that you get up to 100 cancers per 100,000 people for every 1000 millirems of additional dosage per year above the natural background rate. This has been translated, by the Occupation Safety and Health Agency (OSHA) into 'acceptable' risks and dosage levels for different categories of individuals and occupations.

OSHA assumes that the relationship between dosage and cancer death rates is a simple arithmetic proportion. If a dosage of 1000 millirems extra radiation per year, adds 100 extra deaths per 100,000, then as little as one extra millirem per annum could cause cancer in one person per million. Although it's just a statistical estimate, if you happen to be that 'one person' you will be understandably upset. No scientific study, by the way, has shown that radiation has such a 'linear' impact at all levels below 100 millirem, but that's what the blind application of arithmetic shows. It's just an educated guess, but it has caused lots of spirited debates and probably a fair measure of anxiety too, hence, the common worry about what that annual chest X-ray might do to you. I would be a lot more worried about that full-mouth dental X-ray that can deliver from 500 to 900 millirems, just so a dentist can fit you for braces. According to the linear model of dosages, that lead blanket they like to put on you in the doctor's office does little to protect you from tongue or throat cancer.

The OSHA has worked out dosages for many different professions by balancing future cancer risks against lifetime career exposures. For example, people who work with radiation, such as dentists, nuclear medicine technologists, or nuclear power plant operators, are given a maximum permissible dose limit of 500 millirems per year above the prevailing natural background rate. For you and me doing ordinary work in the office, factory or store, the acceptable maximum dose is 1000 milliRems/year. As a comparison, if you lived within 20 miles of the Chernobyl nuclear power plant at the time of its 1986 meltdown, your annual dose would have been about 1500 milliRem/year during the first year, declining slowly as the radioactive isotopes in the environment decay away. Some careers are worse than others for producing large incremental dosages compared to the environmental ones experienced at ground level. Surprisingly, one of those careers is that of the Airline Flight Attendant.

Jet airliners fly at altitudes above 35,000 feet which is certainly not enough to get them into space, but it is more than enough to subject the pilots and stewardesses to some respectable doses when looked at over the course of their careers, and thousands of flights. A trip on a jet plane is often taken in a party-like atmosphere with passengers confident that, barring any unexpected accidents and food problems, they will return to Earth safely and with no lasting physical affects. But depending on what the Sun is doing, a solar storm can produce enough radiation to equal a significant fraction of a chest X-ray's dosage even at typical passenger altitudes of 35,000 feet. Airline pilots and flight attendants can spend over 900 hours in the air every year, which makes them a very big target for cosmic rays and anything else our Sun feels like adding to this mix. According to a report by the Department of Transportation, the highest dosages occur on international flights passing close to the poles where the Earth's magnetic field concentrates the particles responsible for the dosages.

Although the dosage you receive on a single such flight per year is very small, about one milliRem per hour, frequent fliers that amass over 100,000 miles per year would accumulate nearly 500 millirems each year. Airline crews who spend 900 hours in the air would absorb even higher doses, especially on polar routes. For this population, their lifetime cancer rate would be 23 cancers per 100 people. By comparison, the typical cancer rate for ground dwellers is about 22 cancers per 100. But the impact does not end with the airline crew. The federally recommended limit for pregnant women is 500 millirems per year. Even at these levels, about four extra cases of mental retardation would appear on average per 100,000 women stewardesses if they are exposed between weeks 8 to 15 in the gestation cycle. This is a time when few women realize they are pregnant, and when critical stages in neural system formation are taking place in the fetus.

Matthew H. Finucane, air safety and health director of the Association of Flight Attendants in Washington DC, has claimed that these exposure rates are alarming, and demands that the FAA to do something about it. One solution is to monitor the cabin radiation exposure and establish OSHA guidelines for it. If possible, he also wants to set up a system to warn crews of unusually intense bursts of cosmic radiation, or solar storm activity during a flight. Meanwhile, the European Aviation Agency is contemplating going even further. They want to issue standard dosimetry badges to all airline personnel so that their annual exposures can be rigorously monitored. This is a very provocative step to take, because it could have a rather chilling effect on airline passengers. It might also raise questions at the ticket counter that have never been dealt with before*, 'Excuse me, can you give me a flight from Miami to Stockholm that will give me less than one chest X-ray extra dosage?'* How will the traveler process this new information, given our general nervousness over simple diagnostic X-rays?

Consider this: during September 29, 1989, for example, a powerful X-ray flare caused passengers on high-flying Concord airliners to receive dosages equal to two chest X-rays per hour. At the end of the flight, each passenger had silently received hundreds of additional millirems added to their regular background doses. Still, these occasional dosages the average person receives while flying, compared to the dosages we might accumulate once we land at another geographic location, are rather inconsequential over a lifetime. Compared to the quality of life that we gain in exchange for the minor radiation exposure we risk, most people will grudgingly admit the transaction is a bargain. Statisticians who work with insurance companies often think in terms of the number of days lost to your life expectancy from a variety of causes. On this scale, smoking 20 cigarettes a day costs you 2200 days; being overweight by 15% costs you 730 days; and an additional 300 millirem per year over the natural background dose reduces your life expectancy by 15 days. There is, however, one human activity that seems to walk a precariously thin line between hazard and benefit.

Airline travel is far less of a hazard than space travel. Astronauts currently make routine trips to low Earth orbit in the Space Shuttle. Eventually, they may even take a few trips to Mars in the next century. Since the dawn of the Space Age, we have known that this environment presents a severe hazard for human health. Battered satellites bare mute testimony to the ravages of the various forms of radiation that penetrate their skins and do internal damage. Astronauts are given full briefings about radiation health risks before they start their journeys...and yet they rise to the challenge. On the other hand, the general public hears quite a bit about the medical health risks of space travel, but curiously, these risks are couched almost exclusively in terms of loss of bone density, and peculiar cardiovascular changes. We never seem to hear much open discussion about astronaut radiation health effects. Compared to the tremendous intolerance we have on the ground for far less severe dosages, what astronauts are required to endure is positively horrific.

In space, radiation comes in three invisible packages delivered to the astronaut's doorstep at the start of each mission. The worst of these are solar flares. At the present time, solar flares are completely unpredictable. By the time telescopes spot their tell-tale signs on the solar surface millions of miles away, their deadly cargoes of X-rays have already reached Earth orbit. A half-hour later, a burst of energetic particles begins to arrive. Both of these components subject astronauts to high dosages of radiation, and depending on the amount of shielding, can pose a significant health hazard. During the Apollo program, there were several near misses between the astronauts on the surface of the Moon and deadly solar storm events. The Apollo 12 astronauts walked on the Moon only a few short weeks after a major solar flare would have bathed the astronauts in a 50-100 rem blast of radiation. This radiation level inside a spacesuit on the lunar surface would have been enough to make them feel ill several days later. But these are only the warm-up pitches in the celestial game of chance. Once every 10 years or so, the Sun lashes out with even more powerful pyrotechnics, and we never see them coming.

The instant death scenario that dramatically unfolded in

Michener's book was, perhaps, stretching the facts a bit too dramatically, but no space physicist finds fault with the basic idea that the most powerful solar flares can be capable of killing unshielded astronauts. At issue is how long it might take, not the inevitability of the outcome. How often do we have to be worried about these super flares? Historical data on solar flare intensities provides some good clues.

Robert Reedy, a physicist at the Los Alamos National Laboratory, has spent much of his professional life wondering about this very issue, and his conclusions are comforting. Satellites, such as those in the GEOS and IMP series, have kept a close watch on the high-energy protons emitted by solar flares for decades. You can also find fossil traces of 'solar proton flares' in the excess radioactive isotopes they produce in lunar rocks and terrestrial tree rings. What this far-flung data tells us is that flares in the same league as the August 1972 event happen only about once every 10 years; usually just after the peak of a solar cycle. The long-term also shows that solar flares 10 times stronger than the August 1972 event have not been recorded in at least the last 7000 years. James Michener's scenario of an instantly-fatal flare may be rare, but biologically significant ones do happen rather often during a solar cycle. Given enough opportunity, they are more than potent enough to cause severe radiation poisoning in an unshielded astronaut should their paths happen to cross in space and time.

Figure 5 about here

When you look at the recorded solar flares since the late 1950's, it is easy to see some interesting trends among the numbers, especially when the information is presented pictorially. The calmest times for flares are within two years of sunspot minimum. It is as though even the Sun needs to rest from its labors, to shore up energy for the next round of activity. Sunspot maximum, with its tangled magnetic fields concentrated in numerous sunspots, seems to be the best season to go hunting for flares. Within two years of sunspot maximum, you have the greatest likelihood of having a medically-significant flare within any given week. Near maximum, the typical time between significant (10 rem) flares can be about a month or so. The really major flares that deliver more than 100 rads to a space suited astronaut, happen once every year. But, like all flares, they happen randomly, and no one knows how to predict how powerful one will be before it happens. The really major flares that eventually kill you if you are unshielded happen every 10 years on average. Solar cycle 19 between 1955 and 1963 was a particularly nasty one, with no fewer than three flares that could have had some hazardous health effects. These happened during the years just past the sunspot maximum year. Cycles 20-22 were very similar in their flair statistics, but not as productive as Cycle 19 which had the highest sunspot number at its peak. Apparently, the more sunspots a cycle has, the more opportunities there are for spawning potentially lethal, or at the very least, medically hazardous flares.

In addition to solar flares, cosmic rays also pose a greater hazard in space than they do on the ground. The Earth's atmosphere is a natural shield against most of this radiation to the tune of a four-yard thick slab of aluminum. You would hardly think that something as insubstantial as air could shield you from cosmic rays, but there is simply so much of it over your heads that it literally 'all adds up'. A Space Shuttle aluminum bulkhead, meanwhile, provides about 200 times less shielding than this, but this is still enough to substantially reduce the health risk even from a flare that might be lethal outside the shuttle during a spacewalk.

Cosmic rays follow their own patterns of arrival here at the Earth, and as a population, they are far more predictable than solar flares. The number of cosmic ray particles entering the Earth's environment does not remain the same, but rises and falls exactly out of step with the solar activity cycle. When the Sun is very active near the peak of the sunspot cycle, its magnetic field is strong and penetrates farther out into the solar system, shielding the inner planets from some of the cosmic rays. When the Sun is less active during sunspot minimum, the solar magnetic field is drawn further in, and so cosmic rays can again penetrate into the Earth's environment.

Cosmic rays come and go with the solar cycle, and they also cause atmospheric carbon atoms to be converted into their radioactive form called carbon-14. This is ingested into trees and other elements of the biosphere, so that traces of the rise and fall of the solar cycle are literally imprinted into the biosphere at the atomic level. Each of us bares a signature in our bodies of the solar cycle, encoded in the levels of carbon-14 we have ingested over our lifetimes. When very old trees are studied, we can actually use the carbon-14 in tree rings to reconstruct the sunspot cycle, thousands of years before the advent of the telescope.

Cosmic rays are a constant source of trouble for astronauts and spacecraft electronics, but the particles that flow in and out of the geospace environment are an especially bothersome population. The Earth's magnetic field traps high-energy particles in temporary belts, or generates currents of particles like a magnetic dynamo. Closest to the Earth is a region called the plasmasphere, bounded by the most intense equatorial magnetic field lines. Within this moat of particles, high-energy electrons and protons in the van Allen radiation belts flow along the magnetic field lines. They actually bounce back and forth along their northern and southern loops. At the same time, the electrons in these belts flow eastward while the protons flow westward in two great intermingled 'ring currents'. This region is instantly lethal and would zap an astronaut with 1000 rems per hour if unshielded. Beyond the plasmasphere, the rest of geospace environment contains a shifting patina of particles and fields that adopt part of their populations from the impinging solar wind which constantly streams by just beyond the magnetopause boundary.

The flows of these particles is exquisitely complex, and far from random. Particles from Earth's own atmosphere are levitated out of the ionosphere on great polar currents, and are deposited in the plasmasphere. They buzz about like a superheated fog of matter held at temperatures of thousands of degrees. The main carriers of the ring current in the van Allen belts include oxygen atoms, which can only come from the atmosphere of the Earth itself. For many years it was thought that the solar wind supplies the van Allen belts with their particles, but satellite measurements soon showed that the chemistry was all wrong. The solar wind contains mostly hydrogen and helium nuclei, not oxygen. Instead, the ultimate source seems to be the Earth itself. Through a series of steps that are still not understood, these atmospheric particles are accelerated to very high energies. It is somewhere in these murky processes that they become transmuted into hazards for living organisms, but only if you venture into their lair.

So, with all these populations of particles ready to penetrate astronauts and cause them harm, you would think that very stringent health restrictions would be placed on astronauts as they leave the protective layers of the atmosphere. For a variety of technical reasons, OSHA pegs the career annual dosages at a far higher rate for astronauts than for the average person, or even the much-maligned nuclear plant worker. Their exposures to solar flares, cosmic rays and trapped particles are confined to only a few weeks at present. Besides, the risk is seen as going with the territory. Career dosage limits are set at an astonishing 100-600 rem depending on the astronaut's age and sex, but at no time can the doses exceed 50 rem per year.

As enormous as these limits may seem to us ground-dwellers, they are probably a rather generous lifetime limit for now; especially considering that typical mission-accumulated dosages have rarely exceed eight rem as Table 4 shows.

The total radiation dosage that an astronaut receives depends on a number of factors that are different from mission to mission. Being closer to the Earth (Gemini versus Space Shuttle) allows greater protection by the magnetic field and atmosphere of the Earth, and keeps you farther away from the inner edge of the van Allen radiation belts. A week-long junket to the Moon exposes you to far more cosmic ray and high-energy particle damage than LEO. Most of this is because you have to travel through the van Allen Belts themselves to get there, although the transit time through the belts takes less than an hour. Also, just staying in space a long time, no matter where you are, is also a major factor for increasing radiation dosage as we see in the data from the Skylab missions.

The MIR space station has been inhabited for over a decade, and according to Astronaut Shanon Lucid, the daily dosage of radiation is about equal to eight chest X-rays (160 millirem) per day. Typical MIR crew rotations are about 180 days, so a mission dosage can be up to 30 rads. This is about in the same ballpark as estimates by Tracy Yang at the Johnson Space Flight Center. The constant radiation dosage which human bodies absorb, causes chromosomal damage, and for MIR cosmonauts, Yang discovered that this wear and tear implied dosages up to 15 rads. This is about equal to a thousand chest X-rays over the course of the mission. Meanwhile, Ts. Dachev and his colleagues at the Space Research Institute in Bulgaria arrived at similar radiation exposure levels from actual dosage measurements on the MIR. Each transversal through the South Atlantic Anomaly provides 2 millirads behind the MIR bulkhead. Since there are about 18 orbits per day in a 180-day shift, this works out to a total mission dosage of about 55 rads. So the bottom line is that, prospective International Space Station astronauts will probably receive somewhere from 15 - 50 rads of radiation per shift, as they go about their work. Eventually, the laws of chance dictate that solar flares and human space activity must inevitably coincide with potentially hazardous consequences.

Figure 6 about here

During the April 12, 1981 Great Aurora, STS-1 commanded by Robert Crippen on its maiden flight, was launched while the storm was actually still in progress. Astronauts were told by NASA that the radiation levels inside the Shuttle might be high enough to trip the smoke alarms, although this never actually happened. The actual dose accumulated by STS-1 astronauts was rather small compared to other flights because they only spend 2 days in orbit. Eight years later, during the October 1989 storm, Space Shuttle Atlantis astronauts experienced light flashes in their eyes during the storm events, and they retreated to the interior of the Shuttle. This did little good, and the light flashes were still seen, accompanied by eye irritation as well especially during the episodes of high radiation fluxes. These light flashes are charged particles passing through the Shuttle bulkhead and through the eyes of the astronauts, causing comet-like flashes and streaks. At about the same time, solar storms towards the end of 1989 caused MIR cosmonauts to accumulate in a few hours, a full-years dosage limit (probably exceeding 25 rads) within a few days.

So far, we have been discussing astronauts working and living inside air-conditioned spacecraft in shirtsleeves. Normally, astronauts and cosmonauts do spend the vast majority of their time inside the shielded spacecraft with very few space walks. Space walks are still considered the most risky thing that an astronaut can be called upon to do. Little wonder, when you consider what kinds of hazards can be lurking outside the hatch. But soon these expectations will, at least temporarily, be a thing of the past as we reach the peak of Solar Cycle 23. The Space Station will be assembled in LEO orbit at an altitude of 220 miles, and its assembly will involve a projected 960 hours of space walks by 18 astronauts. There will be about 100 space walks planned during 39 assembly flights between 1999 and 2003.

The vulnerability of the astronauts to solar flares is a major concern by EVA planners because they can occur with little warning. Conceivably, the very tight assembly, and EVA, schedules for the ISS may slip by six months or more if the Sun decides to favor us with a potentially hazardous state during the missions. The actual probability that an astronaut will be affected by a solar flare large enough to be medically important is rather low, but it is not zero. The smaller, more frequent flares, which NOAA's Space Weather Center classifies as 'S3' happen about once a year. Astronauts would have to stay inside the Space Shuttle for several days while the radiations subside. For the more powerful flares in classes S4 and S5 that happen up to once every three years, the mission may be aborted altogether. Caught outside with a once-per-cycle S5 flare, an astronaut could find him or herself removed from further space duty.

Radiation exposure problems will, of course, not end with the assembly of the ISS. Once completed, the ISS will be occupied by up to eight astronauts in shifts lasting about five months each. A five-month stay, at a typical dose rate experienced by the MIR cosmonauts, leads to an accumulated dose of up to 25 rads per shift. This is comfortably below the 400-rad lifetime limit set by OSHA, and the 75 rad limit for annual dosages. But a single solar flare could, as we have seen, change this in a hurry. For the longer stays in space needed for interplanetary travel, measured in years, the exposure situation is much worse, and far harder, to anticipate.

Voyagers to Mars will find themselves utterly unprotected by the Earth's magnetic field, whose invisible cloak at least shielded them from some of the cosmic ray and solar particles. The shielding needed to reduce flare dosage levels below the OSHA astronaut health limits is substantial, and can easily exceed many tens of tons. When you consider that current launch vehicle technology allows for shipping rates to Earth orbit between $5,000 and $15,000 per pound, shielding weight is bought at a premium. In the end, the Mars crew will probably still receive between 100 - 300 rems of accumulated dosage during the 500-day Mars mission, depending on when the started their journey, and the level of solar storminess they experienced.