AN ABSTRACT OF THE THESIS OF

Kathryn M. Brock for the degree of Master of Science in Environmental Health Management presented on April 26, 1999. Title: A Dose Reconstruction of ^{60}Co Contaminated Window Frames in a Taiwanese School.

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Abstract Approved:__ ________

Catherine M. Neumann

In 1992, hundreds of buildings in Taiwan were discovered to have ^{60}Co contamination in the structural rebar. The contamination resulted from improper handling of ^{60}Co contaminated scrap metal in 1982 and 1983 that was subsequently recycled and used throughout Taiwan. One example was the Hsin-hsin Kindergarten (HHK) school which had three ^{60}Co contaminated steel window frames from which dose rates up to 150 microSieverts (15 millirem) per hour were measured. HHK enrolled about 600 students over the ten year period before the contamination was discovered. A dose reconstruction of the HHK school was performed using ISOSHLD dose modeling software. Results of this experiment were used in conjunction with Crystal Ball® software, which employs a Monte Carlo simulation, to estimate a potential range of doses received by the HHK students. These dose ranges (0.08 μSv h^{-1} to 75.38 μSv h^{-1}) were then applied to the nominal detriment coefficients for stochastic effects as published in the National Council on Radiation Protection and Measurements (NCRP) Report No. 115, *Risk Estimates for Radiation Protection*, in order to perform a risk assessment of habitants of the school for

the first year after construction. Risk estimates ranged from 1.46×10^{-4} excess fatal cancers to 7.42×10^{-4} excess fatal cancers per lifetime.

A Dose Reconstruction of ^{60}Co Contaminated Window Frames in a Taiwanese School

by

Kathryn M. Brock

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APPROVED:

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Major Professor, representing Environmental Health Management

Redacted for Privacy

Chair of Department of Public Health

Redacted for Privacy

Dean of Graduate School

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Kathryn M. Brock, Author

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1. INTRODUCTION

A school located in Taipei, Taiwan was chosen as a site to perform a dose reconstruction. Hsin-hsin Kindergarten (HHK) school is a private institution that was one of the hundreds of buildings built in the early 1980's discovered in 1992 to contain steel contaminated with ^{60}Co. The contamination in HHK was limited to three steel window frames within three classrooms (Room A, Room B, and Room C). No contamination was found in the structural rebar, as was common in other buildings in Taiwan. When the contamination was discovered, the window frames were replaced and retained for future research purposes (Chang et al., 1997).

A team of researchers in Taiwan performed measurements on the stored window frames using Geiger Mueller survey instruments to determine the content of radiation in each frame. Each of the window frames consisted of twenty-six interior bars and two external rims. The rims were not contaminated, but the bars, 0.95 centimeters (cm) deep and 0.95 cm wide, were. Two different estimates of the activities were made by researchers (and decayed to 1984 values) for the individual bars. This study only takes into consideration the 1984 activity levels. Decay was never considered. The aim was to produce a worst case scenario for the students attending HHK in the first year after construction when the dose rates would be at maximum values. The first was 1.62×10^{-4} micro Curies per gram (μCi g^{-1}) and the second was 3.24×10^{-4} μCi g^{-1}. The dimensions of the window in Room A were 268 cm in width and 62 cm in height. The frame was located 215 cm above the ground. Eleven bars were identified with 1.62×10^{-4} μCi g^{-1}

radioactivity and two bars were characterized with 3.24×10^{-4} μCi g^{-1} radioactivity. The dimensions of the frames in Rooms B and C were 268 cm in width by 133 cm in height. These windows were located 135 cm above the ground. In Room B, nine bars had 1.62×10^{-4} μCi g^{-1} of radioactivity and one bar contained 3.24×10^{-4} μCi g^{-1} of radioactivity. In Room C, ten bars were identified with 1.62×10^{-4} μCi g^{-1}of radioactivity and zero bars of 3.24×10^{-4} μCi g^{-1} of radioactivity (Personal correspondence, Chang 1998).

This study tests one method of dose reconstruction followed by a human health risk assessment. The ISOSHLD dose modeling code, developed by Westinghouse Hanford Company (Hanford, Washington), was the program chosen to perform the dose reconstruction based on the measurements taken by Taiwanese researchers. ISOSHLD allows the user to perform shielding calculations by incorporating radioisotope data, nuclide inventories, and source/shield combinations. ISOSHLD utilizes the point kernel technique of calculation. This method involves dividing the source area into many points, or kernels, and integrating the source strength over all the kernels in the entire source area. The detector responds to the entire integrated source area (Chilton, 1984).

Results from the ISOSHLD simulation were used in a Monte Carlo simulation program called Crystal Ball® which is made by Decisioneering, Inc.(Boulder, Colorado) to determine a range of possible exposures children at HHK may have received due to the contaminated window frames. The Monte Carlo method is a numerical stochastic process that correlates sequences of random events in order to produce various possible outcomes of the same question (Kalos, 1986). It measures the effects of uncertainty on the model predictions. Crystal Ball works within a spreadsheet model, such as Microsoft Excel®. The mean exposure rate produced by Crystal Ball for each of the classrooms at HHK was then correlated with a risk estimate published in National Council on Radiation Protection and Measurements (NCRP) Report No. 115 (NCRP 1993, Bethesda, MD). An estimate of excess fatal cancers due to exposure to the window frames ranged from 1.46×10^{-43} to 7.42×10^{-43} numbers of increased cancers for the children attending HHK in the first year after HHK was constructed. Given the small population size of HHK students in the first year, a measurable number of increased cancers would not be evident. When these risk values are extrapolated to a larger population, however, the increased number of cancer would be observed.

2. LITERATURE REVIEW

2.1 Background Radiation

2.1.1 Dose Limits

Generally, doses of radiation to the public are controlled by managing the source of radiation, not the environment they are affecting. The responsibility of ensuring public protection from unacceptable dose rates of radiation is with the owner of the radioactive material, who must ensure the public does not receive a dose of radiation above the limits prescribed by the International Commission on Radiological Protection (ICRP). The ICRP is a committee, originally formed in 1928 by the Second International Congress of Radiology, that provides general guidance on the widespread use of radiation sources caused by developments in the field of nuclear energy. The committee aims to help regulatory, advisory agencies, and management bodies deal with radiation safety and ultimately, protect humans. The ICRP chose limits that would be below unacceptable levels for continued exposure to radioactive materials. This dose limit to the public is 1 mSv y^{-1} effective dose equivalent (ICRP 60 1991). Under special circumstances, such as a nuclear plant emergency, the dose limit could be higher, providing the total dose equivalent received does not average greater than 1 mSv y^{-1} for five years. This limit comes from data suggesting the average background radiation, without considering radon, is about 1 mSv y^{-1}, and the risk of an increased mortality rate from receiving a dose in the range of 1-5 mSv y^{-1} is very small (NCRP, 1993). This dose limit does not consider doses received from radon in dwellings, which are managed by the U.S. Envrionmental Protection Agency

(EPA) action levels, or from doses received from major accidents (ICRP 60, 1991).

2.1.2 Acute Radiation Effects

Data on the acute effects of radiation comes from animal experiments, survivors of the Japanese atomic bombs, Marshallese residents exposed to weapons fallout in 1954, and victims of accidents at nuclear facilities (ICRP 60, 1991). For example, Los Alamos Laboratory had two accidental nuclear reactions in 1945 and 1946 that injured ten people, two of whom died. One individual who died was exposed up to 40,000 rem (roentgen equivalent man) on one hand and up to 480 roentgen of gamma rays to his whole body (Hemplemann, 1952).

Acute radiation syndrome is the name applied to the group of signs and symptoms that characterize the illness produced by exposure to ionizing radiation over a large part of the body (Karas, 1965). Prodromal radiation syndrome describes the symptoms that occur in an individual who has been irradiated typically above a dose of 2.5 Gray (Gy). These symptoms appear soon after irradiation and last for a limited period of time. Depending on the dose received, the prodromal symptoms might reach a maximum within 30 minutes and last for a few days. The symptoms, which can be separated into two groups (neuromuscular and gastrointestinal), vary with the level of the dose received, the time of onset, and the duration of the irradiation. Neuromuscular symptoms include fatigue, apathy, sweating, fever, headache, and hypotension. Gastrointestinal symptoms include anorexia, nausea, vomiting, diarrhea, cramps, dehydration, and weight loss. These symptoms are not seen until the dose is at a level that would be lethal to fifty % of the population (LD_{50}) of 4 Gy. Prodromal syndrome ends when it merges with one of the three modes of death for acute radiation exposure, cerebrovascular syndrome, gastrointestinal syndrome, and hematopoietic syndrome (Hall, 1988). Postmortem analysis of the Los Alamos worker revealed that there was widespread destruction of tissues throughout the body, which was the basis for his clinical responses to exposure to radiation (Hemplemann, 1952).

Hematopoeitic syndrome is documented at doses ranging from 3 to 8 Gy. The symptoms are similar to those of prodromal syndrome with nausea and vomiting as the chief symptoms. The latent period is about three weeks because it is the precusor cells in the hematopoeitic system that are sterilized with the irradiation. As a result, the precursor cells are not allowed to mature and the subsequent population of red blood cells, white blood cells, and platelets is diminished. Death is a result of damage to the hematopoeitic system. Regeneration of the bone marrow through transplants can save an individual from death. Gastrointestinal syndrome occurs at a dose of about 10 Gy. Symptoms include nausea, vomiting, diarrhea, and lethargy. Death ensues three to ten days later due to depopulation of the epithelial lining of the gastrointestinal tract. Cerebrovascular syndrome occurs at a dose of approximately 100 Gy. Only two known cases of this syndrome have been documented. Symptoms include severe nausea and vomiting within minutes of exposure followed by disorientation, loss of coordination of muscle movement, respiratory distress, diarrhea, convulsive seizures, and death. The cause of death is an increase of fluid content in the brain due to leakage from small vessels, resulting in an increase in stress within the confines of the skull (Hall, 1988).

2.1.3 Chronic Radiation Effects

Ionizing radiation can cause deterministic and stochastic effects in irradiated tissue.

The dose limits are set to ensure that deterministic effects do not occur. Deterministic is defined as "causally determined by preceding events" and the effects occur when radiation damage kills somatic cells, resulting in irreparable damage to the cell and impaired function of the tissue. The probability of deterministic effects is zero at low doses, and above a threshold of a few Gray, the severity of tissue damage increases with the dose. Stochastic effects are caused when an irradiated cell is modified rather than killed. There is no threshold associated with stochastic effects, although this is the source of significant scientific controversy as explained in Section 2.1.4, and the probability of cell alteration increases with an increasing dose, but the severity of the alteration does not increase with an increasing dose (ICRP 60, 1991).

Stochastic effects, which are regarded as the principal risks to health from exposure to radiation at low levels, can be divided into two types. First, modification to cells in the germinal tissue can result in hereditary disorders in the progeny of those irradiated, and secondly, cancer may occur when damage is done to somatic cells. Heredity disorders involving radiation are not well documented. Radiation exposures do not induce unique mutations in a species, instead they increase the frequencies of mutations that occur naturally (Hall, 1988). The induction of cancer after irradiation averages about a ten-year latency period. In addition to animal data, there are several examples of human experiences with radiation-induced cancers. Skin cancer among early x-ray workers, lung cancer in pitchblende miners, bone tumors in radium dial painters, and Japanese atomic bomb survivors (Hall, 1988).

2.1.4 The Low Dose Controversy

There has been a great amount of controversy regarding low doses and low dose rates of radiation and the induction of cancer and other adverse health effects. The subject of controversy is the Linear No-Threshold Model (LNT). LNT assumes that radiation risks are related to radiation dose by a linear model. Linear means that as there is an increase in the dose, a proportional increase in risk will follow. No threshold means that any dose above zero produces some risk. Exposure to radiation does not guarantee harm to a living organism, but there is no dose of radiation considered too small to have some adverse effect (Nuclear Regulatory Commission, 1998).

Most regulatory and advisory agencies such as the Nuclear Regulatory Commission (NRC) and the ICRP endorse the LNT model because it offers a conservative approach to estimating risk of radiation harm at low levels. They, however, are quick to acknowledge shortcomings in research involving low doses of radiation. Confounding factors for low dose studies include small sample sizes, social factors, extraneous effects other that radiation, and lack of adequate controls. Additionally, some low dose studies give risk estimates with wide confidence limits (ICRP 60, 1991).

Those who challenge the LNT model believe that there is not enough human evidence to prove a linear relationship between cancer risk and low doses of radiation. The data from Japanese atomic bomb survivors was from high dose rates and the information at low levels is not well developed. Much of the current data on low dose effects relies on animal experiments (Doll, 1998). Opponents to the LNT model believe the probability of induced carcinogenesis is low at small doses while the natural rate of cancer is high in human populations. They cite this as a problem in answering the question of whether or not low levels of radiation cause cancer (Trosko, 1996). The normal background rate of oxidative DNA damage is about 240,000 damage events per cell per day and 0.3 cGy adds only six DNA damage events to each cell per day. This supports the current belief that cancer development is a multistage iterative biological process, and precludes the possibility of a linear cancer response to a linear damage effect. In addition, some suspect DNA and cellular damage from radiation is insignificant in the normal rate of metabolic cellular and DNA damage, and stimulates both DNA repair mechanisms and immune function producing biopositive effects (Muckerheide, 1997). The belief that radiation at low levels can be helpful to organisms is called hormesis. One of the most common complaints for using a no threshold approach when considering the low doses of radiation, is the cost involved in clean-up or preventing exposures. Billions of dollars are spent on radiation protection and remediation of waste sites to approach the unattainable zero exposure level. It is not economical to implement radiation protection policies that provide no significant associated health benefit (Muckerheide, 1997). Supporters of the LNT model contend that there is enough epidemiological evidence of risks at low doses in Japanese atomic bomb survivors that show statistically significant excess risks down to 50mGy. There is also the conviction that a finite risk must be accepted at any level of radiation exposure (Clarke, 1996). Others believe in a dose and dose rate effectiveness factor (DDREF) used in conjunction with the LNT model. A DDREF is a ratio of the slope of the high dose rate line to the low dose rate line using LNT data. A DDREF that is not equal to one is a way of 'unlinearizing' the linear effect of the LNT model to take into account the differences from linear extrapolation from high doses to low doses. Some researchers believe that the scientists proposing a threshold level for low level doses of radiation will never be able to convince a court of law that any amount of radiation above a background level will be acceptable. Additionally, if a threshold is established and exposures to the general public exceed the level, lawsuits may ensue in order to fix the blame or be compensated for future potential damages (Strom, 1995).

2.1.5 Background Radiation

According to the EPA, exposures to doses of natural radiation can be estimated at 3.6 mSv y^{-1}. Natural ionizing radiation is about 80% of the collective dose received by the public and is the largest contributor of dose to people (Lin, 1996). The breakdown of natural radiation is as follows:

- 55% Radon (1.98 mSv y^{-1})
- 26% Natural sources excluding radon (0.94 mSv y^{-1})
- 11% Medical x-rays (0.40 mSv y^{-1})
- 4% Nuclear medicine (0.14 mSv y^{-1})
- 3% Consumer products (0.11 mSv y^{-1})
- 1% Other (0.04 mSv y^{-1})

The Taiwan Radiation Monitoring Center (TRMC) carried out natural background measurements in Taiwan and made some related dose assessments. The TRMC found the average annual effective dose from cosmic rays is 0.25 mSv y^{-1}. This took into consideration that most Taiwanese live in reinforced concrete buildings with two layers of twelve centimeters thick concrete that may absorb up to 20% of cosmic rays. The terrestrial effective dose was estimated at 41 nSv hr^{-1} and the indoor gamma effective dose rate was 72 nSv hr^{-1} (Lin, 1996).

2.2 History of the ^{60}Co Contamination in Taiwan

2.2.1 Scrap Metal

Scrap metal is routinely recycled and used in many forms and industries throughout the world. Over the last couple of decades industries have become increasingly aware of radioactive contamination in recycled metals. The origin of this problem may be traced back to early research using radium sources. Gold jewelry contaminated with radium was discovered as early as 1910. Recycled gold/radon brachytherapy pellets were recycled into rings which caused dermatological changes to the skin, including skin cancer (Lubenau, 1995). Since 1983 there have been 35 known incidents of radioactive sources being unintentionally smelted during the scrap metal recycling process (Lubenau, 1995). Twenty-four of the incidents were involved in the smelting of ferrous scrap. Cobalt-60 (^{60}Co) and Cesium-137 (^{137}Cs) were the most common nuclides found in the ferrous scrap. Fifty-one % of the incidents involved ^{137}Cs. When ^{137}Cs is smelted, the cesium volatilizes, condenses, and is collected in the furnace dust. It is a common practice to collect these dusts in order to reduce atmospheric pollution and recover some metals. Not only is the furnace dust a human health hazard, but it is classified as mixed waste. Mixed waste is very expensive to dispose of not only because of landfill costs, but because it must be assayed, treated, and segregated before going to disposal. Twenty-three % of ferrous scrap consists of ^{60}Co. ^{60}Co is primarily incorporated into the ferrous products (Lubenau, 1995).

Nuclear measuring devices are often the source of these radioactive contaminants.

These devices are used to measure thicknesses, fluid levels, and densities in industrial manufacturing processes. Owners of the sources must posses a license to store and use the source. These radioactive sources are regulated in the United States by the Nuclear Regulatory Commission (NRC) or by individual states holding agreements with the NRC and are safe if used properly. Often, the sources are no longer useful to the owner and in order to avoid staggering disposal costs, licensees often store the source. Over years of storage, the labels often become dirty and illegible. Eventually, the source can be mistaken for ordinary scrap metal and later slotted for recycling. If used improperly or not marked appropriately, the finished products may be distributed and have the potential to cause risks to humans and the environment (Lubenau, 1995).

2.2.2 Scrap Metal Contaminations Incidents

Perhaps the most famous incident of contaminated metals took place in Ciudad Juarez, Mexico. In late 1993 a ^{60}Co teletherapy source was taken out of a storage facility, disassembled, and sold as scrap. During the scrapping process the ^{60}Co source cladding was breached and 6,000 small pellets each containing 2.6 GBq (70 mCi) of activity were incorporated in the metal. The scrap metal, including the radioactive pellets, was sent to several steel mills and iron foundries in Mexico where smelted caused contamination of the steel, the steel mill and the foundries coming into contact with the radioactive material. Consequently, about 2,500 pounds of contaminated cast iron tables were produced, and later had to be tracked down, and returned to Mexico for disposal. A study by Oak Ridge Laboratories estimated that external doses to those involved were between 0.13 Gray (Gy) and 5.5 Gy. No internal doses were recorded (Lubenau, 1995).

Another case where radioactive material was smelted occurred in Kentucky in 1992. Newport Steel shut down operations for 23 days and incurred costs of $2,500,000 for the decontamination and disposal of a 12 Gbq ^{137}Cs source that was breached during smelting operations. This incident illustrates the extreme costs incurred by cleanup and production loss (American Metals, 1997).

2.2.3 Taipei, Taiwan

Since late 1992 more than 100 buildings ranging from apartment buildings to schools have been identified in Taiwan as containing elevated levels of gamma radiation. Levels of radiation reached up to 1000 μSv hr^{-1} compared with 0.1 μSv hr^{-1} of general background radiation in most Taiwanese buildings. The radiation stems from ^{60}Co contaminated rebar in building materials. Unlike the Juarez case, the contamination was not discovered in a timely manner. Most of the buildings in question were built as early as 1983. As many as 4,000 people have been identified as receiving doses in excess of recommended annual doses. These exposures have been continuing for almost fifteen years (Chang et al., 1997).

The problem in Taiwan is widespread and complicated because the exact source of the ^{60}Co is unknown. Taiwan lacks domestic iron ores and traditionally steel factories depend on recycled steel. In the early 1980's there were no regulations for recycled metals or monitoring programs in the steel factories. Possibilities of the source of contamination range from ^{60}Co gauges which produce a relatively smaller amount of radiation that was found in the steel, to a single radiotherapy source that would have produced much higher radiation levels than were found. It is also possible that several sources of ^{60}Co were mixed at different times or a large source was mixed with different batches of steel over many months. This may explain why over the seven months of production of the contaminated steel, concentrations of radiation varied by several orders of magnitude. Due to the complexity of the distribution of recycled steel and the lack of specific regulations for steel companies to monitor for radiation, the contaminated steel was spread among several steel factories and schools throughout Taiwan (Chang et al., 1997).

There are several key incidents that led to the investigation of the contaminated steel. On January 14, 1983 newly purchased steel entering the first Nuclear Power Plant in Chinshan, Taiwan set off alarms upon entering the plant. Radiation levels were measured at 70 μSv hr^{-1}. In August 1984 a pipe fitting was purchased for use by an employee of GA Technologies in La Jolla, California. When the fitting proved to be useless for the job, it was prepared for returned to the store. Upon leaving the facility a radiation survey detected a surface dose rate of 0.8 μSv hr^{-1}. In December 1988 United States Navy submarines reported eleven shower kits contained fittings with elevated dose rates. In March of 1984 the contaminated steel was found in a business/residential complex, named Ming Shan Village, when a regulator performed a preliminary survey before installing an x-ray machine in a dentist's office. The radiation dose rate detected by inspectors was 130-280 μSv hr^{-1}. The elevated levels of radiation were not reported to the dentist or residents of the building. In July 1992 a man using a radiation monitor borrowed from a nuclear plant detected elevated levels in a building built in 1983. Before the 1992 incident, all other contamination cases were handled quietly by the Atomic Energy Commission (AEC), the radiation regulation body in Taiwan. It was the 1992 information along with a tip from an AEC employee to a local reporter that helped bring the case into the mainstream (Chang et al., 1997).

Two groups of scrap collectors are suspect for acquiring the contaminated metal in Northern Taiwan. The first company sold metal to the Shin-long Steel Factory (SLSF) and the second company sold to the Han-hwa Steel Factory (HHSF). SLSF sold steel to the Wen-pu Company, who used the steel in the support frames for the Ming Shan Village. Both steel factories sold standard steel billets to the Chia-san Steel Factory (CSSF). CSSF reprocessed the recycled steel into specifically ordered steel compartments in late 1983 and early 1984. The Kin-shan Steel Factory (KSF) purchased this recycled steel from CSSF and sold two tons to Swan-chan Construction Company (SCC) who had a contract to build a nuclear power plant, where contamination was eventually discovered. KSF also sold 29.92 tons of the metal to Chian-Kan Construction Company (CKCC) who was involved in building new office buildings in Taipei. When the AEC visited the yard storing the metal in March 1983, only 12.66 tons of the original 29.92 tons remained. The leftover steel, and that already used in construction, was restricted from use and put in a storage facility. Ten years later the storage facility was excavated and yielded only 14.34 tons of steel. Sixteen tons were not located and assumed sold to the Tai-yang Company who supplied plumbing materials to the United States (Chang, 1997).

Since the AEC acknowledged the radioactive building problem in 1992, several actions have been taken to ensure this type of accident does not happen again and that residents of the contaminated buildings are cared for. The Ministry of Health in Taiwan organized an epidemiological study to evaluate the potential health effects of residents of the Ming Shan Village and other affected buildings. This study includes an assay of the buildings using thermoluminescent dosimeters to help characterize the dose. All occupants of buildings with a dose of 1-5 mSv y^{-1} are eligible for a government sponsored medical examination. In addition, access will be prohibited to buildings with greater than 1 mSv y^{-1} and residents who received greater than 1.5 mSv y^{-1} at their current residence could be relocated. Changes were also made in the construction and steel industries. The AEC established an appropriate standard for radioactivity in building materials. All construction projects must provide certification that radioactive steel was not used in the construction, and monitoring stations will be installed at all construction sites. All buildings in Taipei must have a 'no radiation pollutants' certificate and contaminated buildings will be posted and registered by the AEC. Mobile monitoring units containing a 203.2 mm sodium iodide (NaI) detector will be utilized in Northern Taiwan to ensure contaminated sited do not go unregistered (Chen, 1996).

There has been great concern among some residents of the contaminated buildings as well as the Radiation Safety Association of Taiwan. A large humanitarian concern campaign has been launched in order to assure the concerns and fears of the residents are being met. The Radiation Safety Association of Taiwan and the residents are far from pleased by the attention and progress of the AEC. Some individuals have turned to Japanese physicians who have experience with atomic bomb and Chernobyl survivors because they felt Taiwanese officials were not taking care of them. Occupants believe the evacuation of occupants in buildings detecting 1 mSv y^{-1} is too high (compared to 0.1 mSv y^{-1}), because at this rate IAEA standards for lifetime exposure will be exceeded. Residents also believe the AEC fears legal action from the public and is therefore trying to understate the potential harm to the community (Nuclear Report from Taiwan, 1994). At least 65 residents of the Ming Shan Village have filed lawsuits in the Taipei district court and up to

8,000 more claims are expected over the next thirteen years (Kau, 1997).

2.2.4 Research

A medical study was conducted with the purpose of studying the biological effects of chronic low dose exposure to ionizing radiation using residents of the Ming Shen Village as a study group (Chang, 1997). Micronucleus formation in Ming Shen Village residents was compared with a group of controls. Micronucleus formation is a reliable biomarker of exposure to clastogenic or aneuploidogenic hazards because they consist of acentric chromosomes that are not found in the main nuclei during anaphase. This assay has been valuable in evaluation cytogenic damage from low and high dose exposure to ionizing radiation in Chernobyl studies. The cohort consisted of seventy-three residents of a contaminated building and seventy-seven controls who were matched for age and sex. Of the controls, thirty-one were close relatives of the residents and thirty-eight lived in a non-contaminated building next door to the cohort group. The cohort group had significantly higher micronucleus formation than the controls. Radiation exposure was more strongly related to the micronuclei formation than were age, sex, and cigarette smoking. Results suggest that DNA damage may be carried in the genomes of lymphocytes and if unrepaired, DNA damage could persist. This study provided preliminary evidence that the biological damage in humans is not negligable for low-dose continuous radiation exposure (Chang, 1997).

In addition to medical examinations and medical studies, a dose reconstruction program was initiated by scientists and medical professionals in Taiwan as part of an epidemiological study by the National Yang Ming University Medical School. The model is set up to predict the time weighted exposures to gamma radiation in buildings containing structural steel contaminated with ^{60}Co. The dose reconstruction is complicated because the contamination is not uniformly distributed in the building, thereby causing radiation levels to vary widely. Thermoluminescent Dosimeters (TLD's) were placed in an apartment considered representative of the standard contaminated dwelling, and measurements were taken with radiation equipment in order to accurately characterize the potential exposure levels. Occupancy patterns were characterized by interviewing residents of the building to assess the amount of time spent in each area of the dwelling. The model is a mathematical algorithim that provides estimates of chronic radiation exposure by taking into account differences in the survey data including differences between adults and children, variable occupancy patterns, background radiation, and radioactive decay. The combination of time dependent variables and occupancy factors introduced the highest degree of uncertainty in the equation. Eventually, this model will be used to characterize chronic exposures to residents in all contaminated buildings throughout Taiwan (Cardarelli, 1997).

3. MATERIALS AND METHODS

3.1 ISOSHLD

ISOSHLD is a program designed to allow the user to perform shielding calculations by incorporating radioisotope data, nuclide inventories, and source/shield combinations. ISOSHLD was written by Oak Ridge National Laboratories in the 1960's, originally in FORTRAN format, and adapted for use with personal computers in 1987 by the Westinghouse Hanford Company and renamed ISO-PC. There have been several upgrades of the ISOSHLD code, and the most current version added five photon energy groups and twenty-five new shielding materials to the program. ISOSHLD has been adapted to a more user friendly program, MICROSHIELD[1], which allows a more convenient method to input information. However, ISOSHLD was chosen for this project because of the availability of the program to Oregon State University at no cost.

ISOSHLD utilizes the point kernel technique of calculation. This method involves dividing the source area into many points, or kernels, and integrating the source strength over all the kernels in the entire source area. The detector responds to the entire integrated source area (Chilton,1984).

3.1.1 ISOSHLD Input Information

Several parameters must be chosen by the ISOSHLD operator to prepare the program for computation. The variables are separated into five categories: (1) program

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[1]MICROSHIELD is a trademark of Grove Engineering, Inc.

control, (2) source definition, (3) geometry, (4) shielding, and (5) integration.

Program Control

The program control variables are NEXT, IPRNT, OPTION, ISPEC, and DUNIT.

6. NEXT: This controls the type of input expected by the computer. Values range from one to six, and it alerts the computer whether a new shielding material or isotope will be used, or if the ISO-PC run will be terminated.

7. IPRNT: This command specifies whether a full ISOSHLD printout will be generated or a partial printout that omits printing information on each energy group.

8. OPTION: One can choose if a table showing the photon source strength by radionuclide will be produced.

9. ISPEC: This instructs the computer to do calculations based on only gamma rays, only bremsstrahlung, or both gamma rays and bremsstrahlung.

10. DUNIT: The output of the calculation can be in either exposure rate or dose equivalent rate and several units are possible.

Source Definition

The source definition variables are WEIGHT, SOURCE, ICONC, and SFACT.

1. WEIGHT: This variable identifies the specific isotope and amount of radiation to be used in the calculation. The user may choose from 550 isotopes.

2. SOURCE: Describes the source strength in untis of μCi.

3. ICONC: This parameter describes the source as a total activity in μCi or as a concentration in μCi cm^{-1}, μCi cm^{-2}, or μCi cm^{-3} .

4. SFACT: This is a scaling factor that is used to change the source strength when the value of ICONC is in units other that μCi or μCi per volume or area.

Geometry

The variables for geometry include IGEOM, ANG1, ANG2, T, X, Y, SLTH, and TRUNC.

1. IGEOM: This variable identifies one of twelve geometry choices. Among the choices include a line source, point source, spherical source, and rectangular source.
2. ANG1 and ANG2: Adjust the angle of the source from normal.
3. T: The thickness of the shield.
4. X: The distance from the source to the point of calculation.
5. Y: The perpendicular offset distance.
6. SLTH: The length of the source.
7. TRUNC: This variable controls how the change in distance affects the source dimensions and volumes.

Shielding

The variables for shielding include NSHLD and JBUF.

1. NSHLD: This variable tells the program how many shields will be used in the calculation.
2. JBUF: This instructs the program which of the shields will be applied in the calculation. The shield closest to the point of calculation is the most common choice.

Integration

The variables for integration determine how many intervals into which to slice the source and they include NTHETA, NPSI, and DELR. These values depend on the distance from the source and the geometry chosen. DELR is a thickness and should be smaller than a relaxation length. The relaxation length is the additional distance, in centimers, away from the source required to reduce the detector response by a factor of e (e=2.72). The relaxation length is the inverse of the mean free path (Chilton,1984). The mean free path is defined as the average distance a photon of a given energy travels before an interaction in a given medium occurs. For example, NTHETA and NPSI should be no longer than the distance from the face of the source.

3.1.2 HHK Scenario

Computations were run using ISOSHLD for the three window frames in the three rooms of the HHK school. A rectangle geometry was chosen because it most closely resembled the shape of the window frames. Even though the frames were not made of a solid, rectangular plane, the calculation assumed a solid shape. The inventory of the activity in each window frame was estimated using the dimensions of each bar and the density of steel (7.8 g cm^3). This method adjusted for the voids in the rectangle caused by the bars and thereby best estimating the total activity or inventory of the frame. The dimension of each of the bars was 62 cm x 0.95 cm x 0.95 cm. In Room A, eleven of the bars contained 0.162 μCi g^{-1} and two bars contained 0.324 μCi g^{-1}. This is the calculation for Room A:

(7.8 g cm^{-3}) x (0.162 μCi g^{-1}) x (62 cm) x (0.95 cm) x (0.95 cm) = 70.7 μCi per bar

(70.7 μCi) x (11 bars) = 777.8 μCi

(7.8 g cm^{-3}) x (0.324 μCi g^{-1}) x (62 cm) x (0.95 cm) x (0.95 cm) = 141.4 μCi per bar

(141.4 μCi) x (2 bars) = 282.8 μCi

The total inventory for Room A was:

(778.8 μCi) + (282.8 μCi) = 1060.2 μCi

Using the same method, the inventory for Room B was 1668.4 μCi and the inventory for Room C was 1517.0 μCi.

Source receptor points were located at 10 cm, 50 cm, 100 cm, 200 cm, 300 cm, and 400 cm on the horizontal axis away from the frame. This was done to illustrate how the radiation dose decreased at increasing distances from the window frames. Because the only receptor point from a rectangle is from the center of the identified rectangle, adjustments had to be made to ISOSHLD to create receptor points on each corner of the rectangle, each edge of the rectangle, and at different heights along the vertical axis. The dimensions of the original rectangle had to be adjusted to put the desired receptor point at the center of the rectangle (Binney, 1998). For example, to determine the dose at the corner of the original rectangle, the original rectangle was doubled in both height and width. This adjustment put the corner in the center of the new dimension. In addition to changing the dimensions of the rectangle, the activity inventory had to be adjusted to match the changes in the dimension. The activity must be halved for each doubling of a dimension. In the scenario where the corner of the rectangle was the dose receptor point, the activity was quartered. To find the dose at the top, middle edge of the rectangle, the activity was halved, the original rectangle was doubled in height, and the dimension of the width stayed the same.

```
     0      2 RECTANGLE GEOMETRY: FILENAME: ROOMA1
CO-60 CONTAMINATED WINDOW FRAME ROOM A AT THE MIDDLE OF
WINDOW
&INPUT NEXT=1, ICONC=0, NSHLD=1, SFACT=1,
 IGEOM=10, SLTH=268, X=10, T(1)=1, Y=62,
 NTHETA=10, NPSI=10, DELR=2,
 WEIGHT(472)=0.00106062,
 JBUF=1 &
1Fe    9 7.86
MEASUREMENT AT 50 CM FROM MIDDLE OF FRAME
&INPUT NEXT=4, X=50 &
MEASUREMENT AT 100 CM FROM MIDDLE OF FRAME
&INPUT NEXT=4, X=100 &
MEASUREMENT AT 200 CM FROM MIDDLE OF FRAME
&INPUT NEXT=4, X=200 &
MEASUREMENT AT 300 CM FROM MIDDLE OF FRAME
&INPUT NEXT=4, X=300 &
MEASUREMENT AT 400 CM FROM MIDDLE OF FRAME
&INPUT NEXT=4, X=400 &
End of input file
&INPUT NEXT=6 &
```

Figure 1. An Example of an ISOSHLD Input

Room A

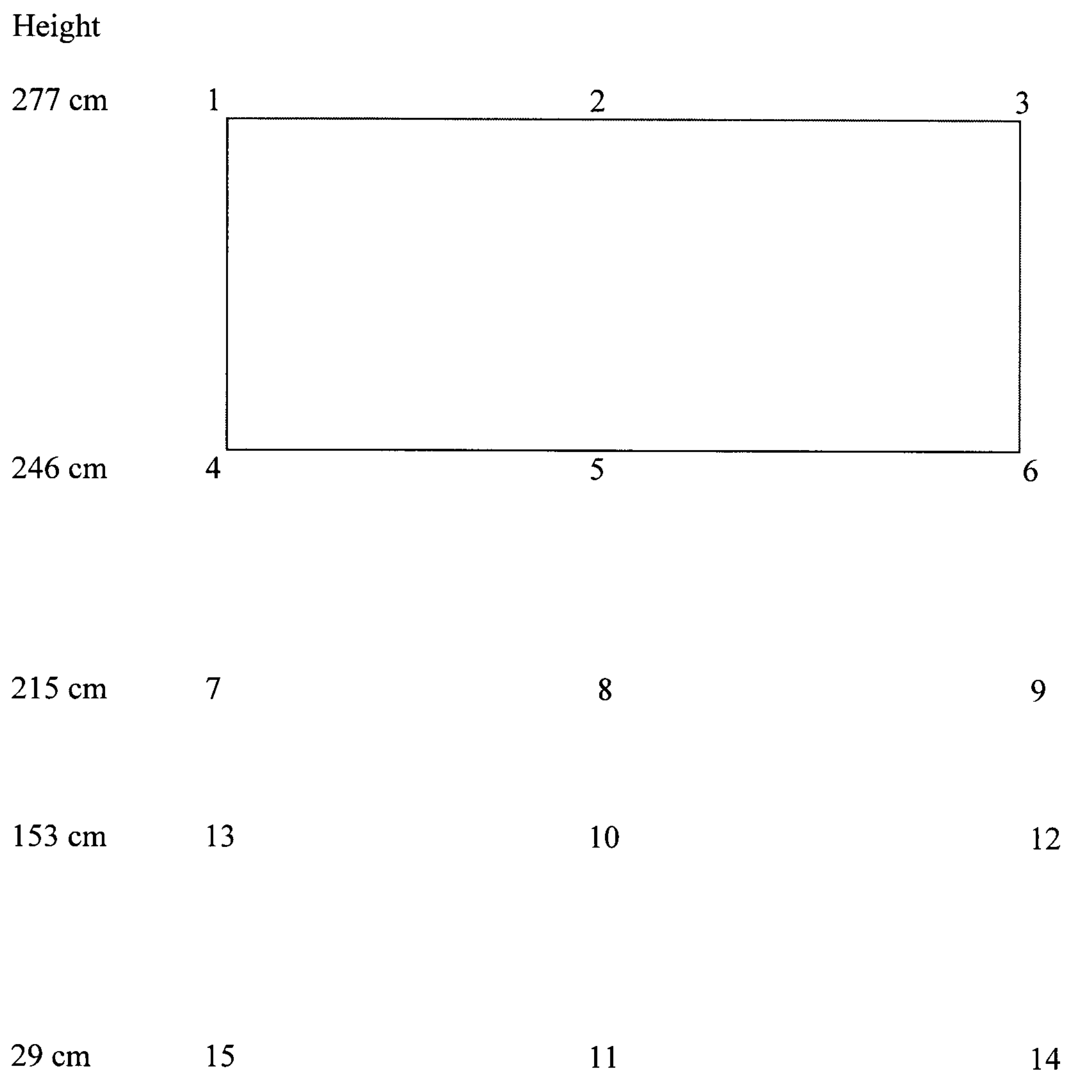

Figure 2. Locations of Measurements Taken in Room A

Rooms B&C

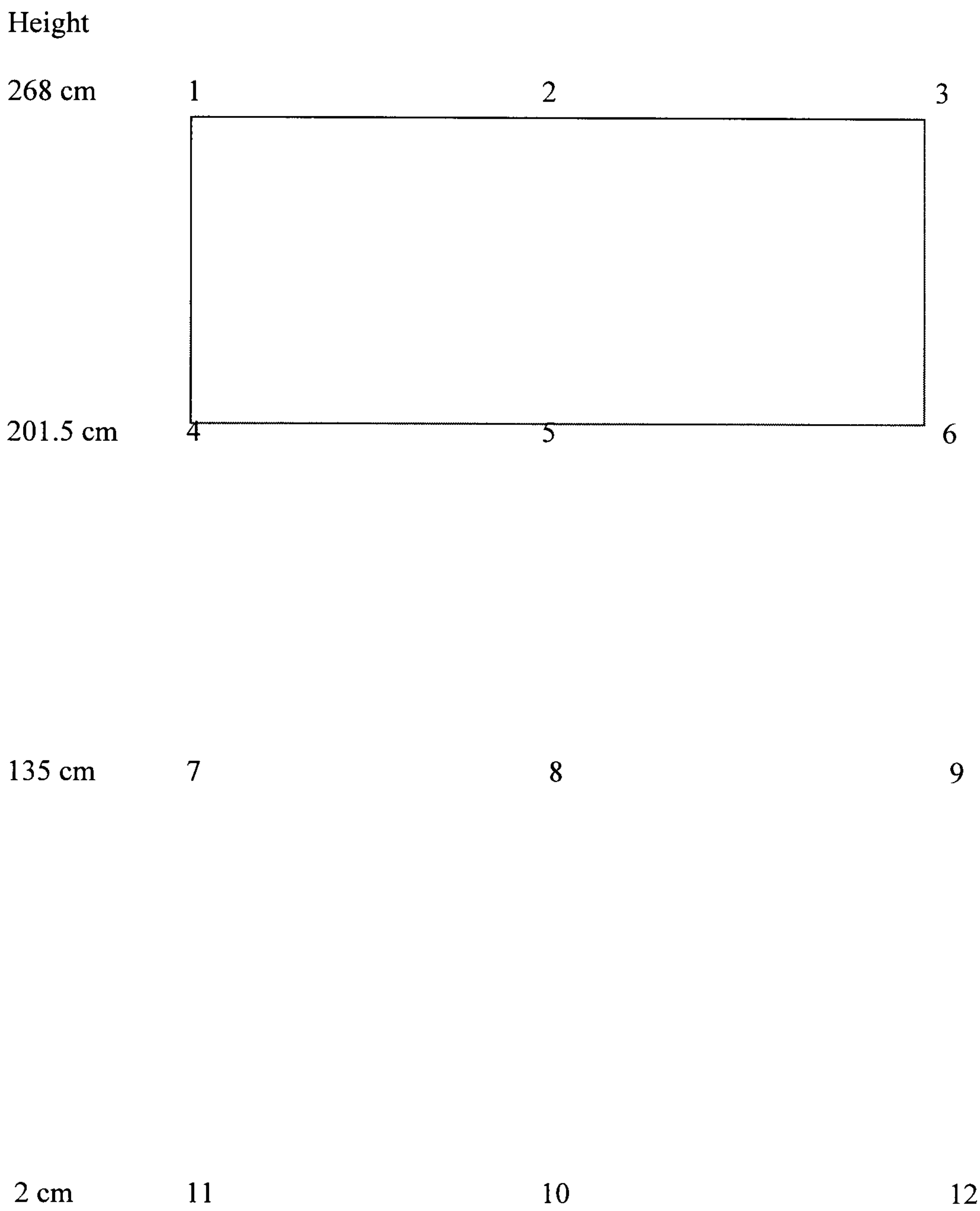

Figure 3. Locations of Measurements Taken in Rooms B and C

3.2 Crystal Ball

Crystal Ball is a program created by Decisioneering, Inc. (Boulder, Colorado) that acts as an addition to spreadsheet programs such as Microsoft Excel and utilizes the Monte Carlo method of data analysis. The Monte Carlo method is a numerical stochastic process that correlates sequences of random events in order to produce various possible outcomes of the same question. (Kalos, 1986). Monte Carlo measures the effects of uncertainty in a spreadsheet model. Crystal Ball allows the user to input variables that are distributions of data. For each analysis, Crystal Ball draws random values from each distribution and produces a single result. The user specifies how many analyses will be run by Crystal Ball. When all the runs have been completed, Crystal Ball produces a complete distribution of results that are then compiled into a statistical report (Decisioneering, 1993).

Three variables were used in the Crystal Ball computation. The first variable was the dose received at any of the receptor points (in μSv hr^{-1}), as computed by ISOSHLD. Dose receptor points were chosen from the ISOSHLD output that encompassed the living area of a small child. Because only three to five year old children were educated in HHK , all points were from 153 cm and below, as small children would not normally stand taller than 153 cm. In Room A, dose receptor points at locations 10, 11, 12, 13, 14, and 15 and at distances of 10 cm, 50, cm, 100 cm, 200, cm, 300 cm, and 400 cm from the window frames were incorporated into the Crystal Ball spreadsheet. In Rooms B and C, dose receptor points at locations 7, 8, 9, 10, 11, and 12 were used at the same distances as Room A. An equal probability of being in any of the locations was assumed and data was incorporated into a log-normal distribution. The log-normal distribution was chosen by using the 'fit' capability of Crystal Ball. This function uses a chi squared goodness of fit test to compare the distribution of data to known distributions. Crystal Ball determined the best fit for the data in the spreadsheet, figured a mean and standard deviation for the data, and chose the log-normal distribution.

The second and third variables consisted of residency times for students in the classrooms. Triangular distributions were identified by the user for these variables instead of using the 'fit' capability of Crystal Ball because not many data points were known. The triangular distribution allows the user to input a minimum, maximum, and most likely value. The first residency variable was the number of hours spent in the school per day. Based on personal correspondence with researchers in Taiwan, the minimum time spent at school was zero hours per day, the maximum was eight hours per day, and the most likely was four hours per day (Personal correspondence, Chang, 1999). The second residency variable was the number of days spent in school per year. The minimum number of days per year spent at school was 180, based on a nine month school year. The maximum number of days spent at school was 250 days, based on only two weeks of vacation per year. The most likely number of days spent at school was 210 days, based on a six week vacation from school. For all scenarios it was assumed the children were in the same class all day.

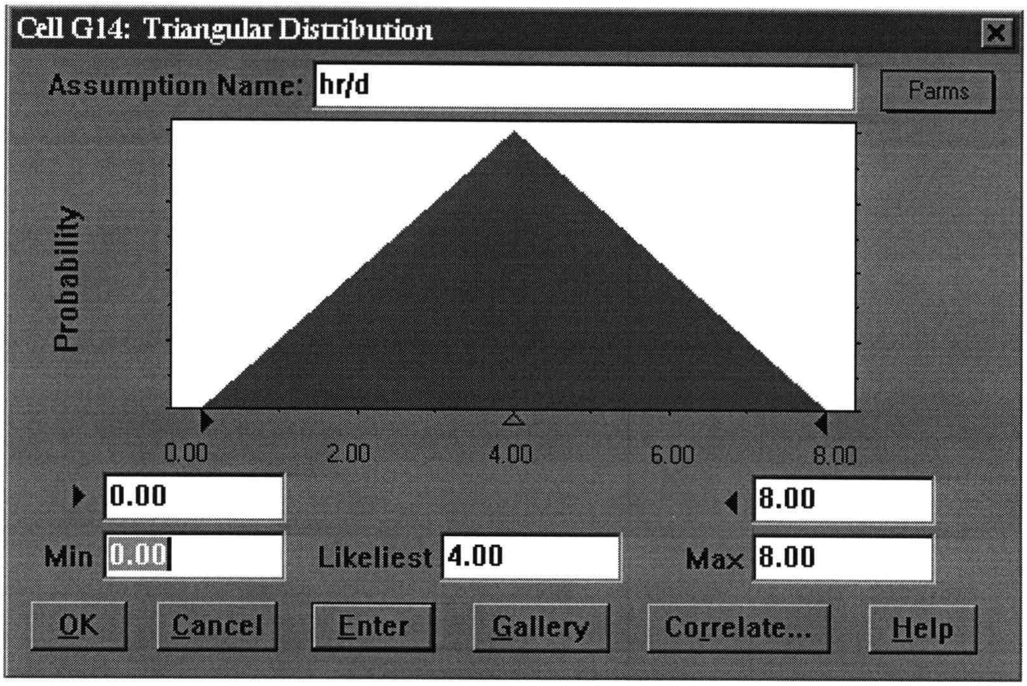

Figure 4. Example of a Crystal Ball Assumption Chart for Residency

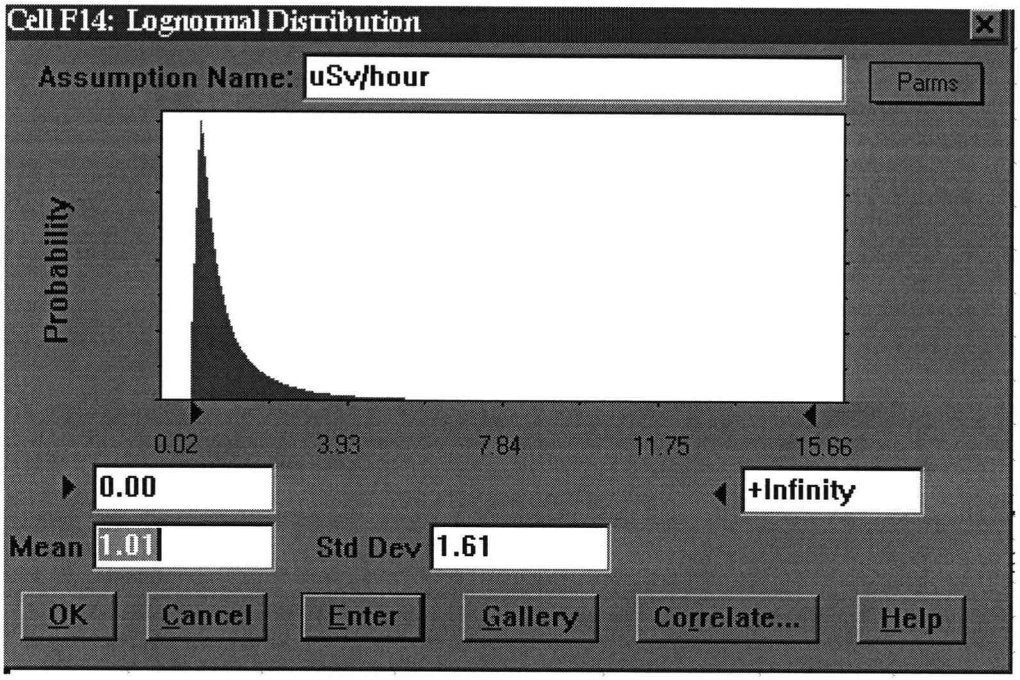

Figure 5. Example of a Crystal Ball Assumption Chart for Dose Rate

4. RESULTS AND DISCUSSION

4.1 ISOSHLD

The results for the ISOSHLD simulation are presented in the following tables.

Table 1. Dose Rates in μSv/h at Each Position and Distance from the Window Frame for Room A

	Dose Rate at Each Position (μSv/h)					
Position	10 cm	50 cm	100 cm	200 cm	300 cm	400 cm
1,3,7,9	23.24	10.92	5.60	2.29	1.21	0.74
2,8	23.13	9.59	4.31	1.46	0.70	0.41
4,6	18.82	6.33	2.96	1.16	0.61	0.37
5	75.38	22.58	9.92	2.98	1.42	0.82
10	6.29	3.42	1.79	0.68	0.34	0.20
11	1.59	1.03	0.61	0.27	0.15	0.09
12,13	3.18	2.01	1.19	0.54	0.29	0.18
14,15	0.83	0.63	0.43	0.29	0.13	0.0

Table 2. Dose Rates in μSv/h at Each Position and Distance from the Window Frame for Room B

	Dose Rate at Each Position (μSv/h)					
Position	10 cm	50 cm	100 cm	200 cm	300 cm	400 cm
1,3,7,9	18.72	12.15	7.31	3.33	1.83	1.14
2,8	18.46	10.29	5.45	2.10	1.05	0.62
4,6	17.28	8.40	4.36	1.79	0.95	0.58
5	68.74	29.41	13.39	4.57	2.20	1.28
10	4.68	3.04	1.83	0.83	0.46	0.28
11,12	1.34	0.80	0.52	0.52	0.17	0.11

Table 3. Dose Rates in μSv/h at Each Position and Distance from the Window Frame for Room C

	Dose Rate at Each Position (μSv/h)					
Position	10 cm	50 cm	100 cm	200 cm	300 cm	400 cm
1,3,7,9	17.03	11.05	6.64	3.03	1.66	1.03
2,8	16.79	9.36	4.96	1.10	0.96	0.56
4,6	15.71	7.63	3.97	1.63	0.87	0.52
5	62.52	22.67	12.18	4.15	2.00	1.16
10	4.26	2.77	1.67	0.76	0.42	0.26
11,12	1.22	0.72	0.48	0.25	0.15	0.10

4.2 Crystal Ball

Results from the Monte Carlo simulation are presented in tabular and graphical form. Crystal Ball uses a frequency chart to illustrate that most of the dose rates calculated are in the lower portion of the positively skewed log-normal graph. Summary tables of the Crystal Ball results are shown below. Crystal Ball performed 10,000 repetitions of the calculations of the three variables, dose rate and residency times. A 95th percentile value representing the dose in μSv d^{-1} is the desired value to be used in the human health risk assessment.

Percentile	Value
0.0%	1.69
2.5%	33.17
5.0%	51.88
50.0%	419.98
95.0%	2,927.63
97.5%	4,177.24
100.0%	28,221.40

Figure 6. Crystal Ball Summary of Room A Percentiles

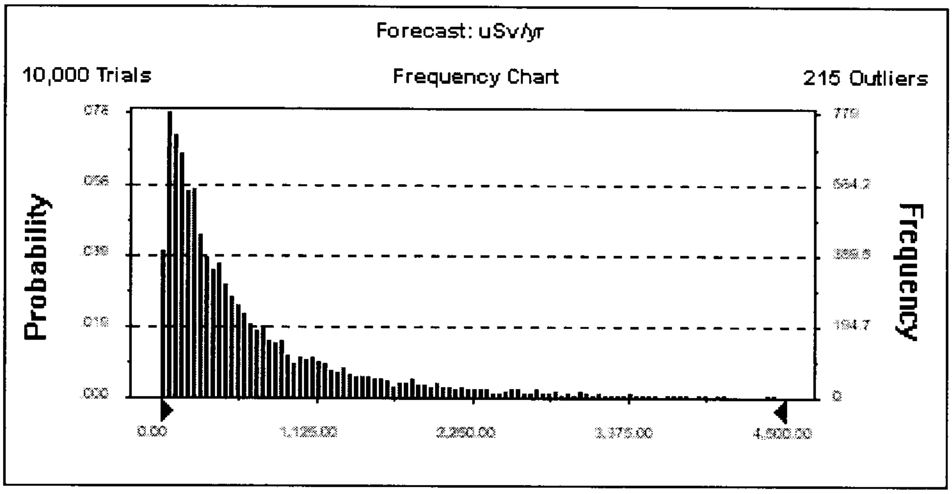

Figure 7. Crystal Ball Frequency Chart for Room A

Percentile	Value
0.0%	4.71
2.5%	58.31
5.0%	94.17
50.0%	1,211.36
95.0%	14,844.62
97.5%	23,855.84
100.0%	285,518.58

Figure 8. Crystal Ball Summary for Room B Percentiles

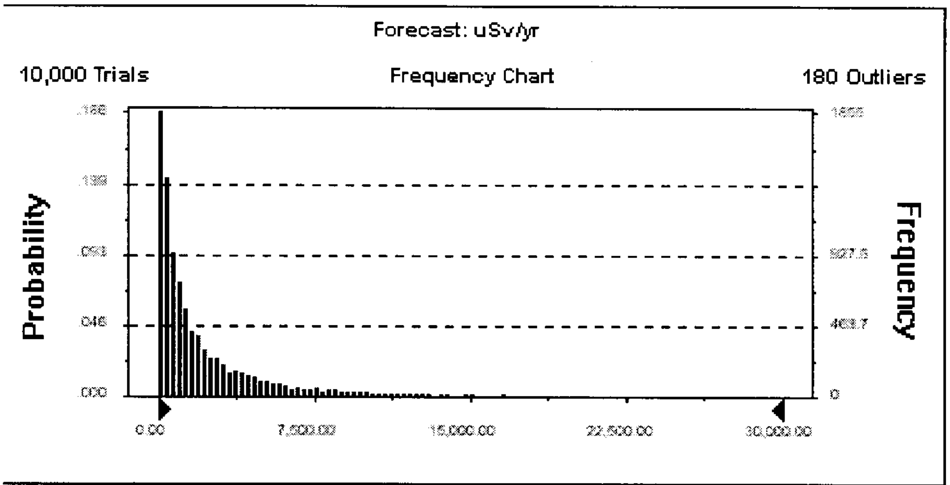

Figure 9. Crystal Ball Frequency Chart for Room B

Percentile	Value
0.0%	1.77
2.5%	47.46
5.0%	76.43
50.0%	1,020.61
95.0%	12,863.65
97.5%	20,766.18
100.0%	189,573.02

Figure 10. Crystal Ball Summary for Room C Percentiles

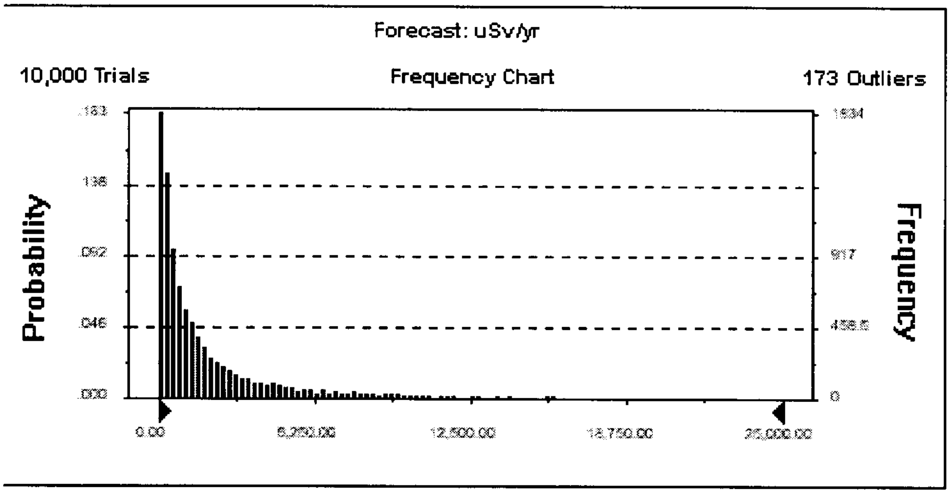

Figure 11. Crystal Ball Frequency Chart for Room C

4.3 Human Health Risk Assessment

A human health risk assessment was performed using the 95th percentile dose rate values calculated by Crystal Ball in conjunction with nominal detriment coefficients for stochastic effects as published in NCRP Report No. 115 (NCRP, 1998). The National Council on Radiation Protection and measurements is an organization that makes recommendations to the radiation protection community for protection of human health from the effects of ionizing radiation. NCRP No. 115, Risk Estimates for Radiation Protection, presents and compares research conducted by The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1988), International Council on Radiation Protection (ICRP), and the National Academy of Sciences/National Research Council's BIER V (Biological Effects of Ionizing Radiation) Report. The UNSCEAR and BIER V reports use data mainly from Japanese atomic bomb survivors to calculate risk estimates for lifetime excess cancer mortality and life shortening as a result of exposure to ionizing radiation.

The value of detriment chosen for this risk assessment came from the ICRP report that analyzes detriment due to radiation exposure at low doses. ICRP estimates the fatal cancer effect to the entire population (0 to 90 years of age) is 5.0×10^{-2} Sv^{-1}. For every Sievert of exposure there will be an excess of 5.0×10^{-2} fatal cancers. This value is higher than the value for the working population (20 to 64 years of age) that is usually comprised of generally healthier individuals, and is appropriate for estimating detriment to a child. UNSCEAR reported detriment values associated with many age groups, but this information was only for acute, high dose exposures and would therefore be inappropriate for this study.

The 95th percentile dose rates for Rooms A, B, and C are 2,927.63 μSv year^{-1}, 14,844.62 μSv year^{-1}, and 12,863.65 μSv year^{-1}, respectively. These numbers were put in an equation with the ICRP cancer risk estimates to determine the risk of increased cancers after exposure to the HHK classrooms during the first year after construction. Here is an example equation for Room A:

$$(0.05 \text{ cancers Sv}^{-1}) \text{ x } (2{,}927.63\ \mu\text{Sv y}^{-1}) \text{ x } (1 \text{ x } 10^{6}\ \mu\text{Sv Sv}^{-1}) = 1.46 \text{ x } 10^{-4}$$

The answer reveals that the risk of increased lifetime fatal cancers after one year of exposure to the dose rates seen in Room A is 1.46 x 10^{-4}. If this number were translated to a population of one million, the number of increased cancers would be 146. Complete calculated values are shown in Table 4.

Table 4. Number of Excess Lifetime Fatal Cancers per Year for Each Classroom

	Room A	Room B	Room C
Number of Excess Cancers per Year for the Class	1.46x 10^{-4}	7.42 x 10^{-4}	6.43 x 10^{-4}
Number of Excess Cancers per Million People	146	742	643

5. CONCLUSION

This study presents a risk estimate of the increased number of fatal cancers per classroom in the first year at HHK. Risk estimates ranged from 1.46 x 10^{-4} excess fatal cancers to 7.42 X 10^{-4} excess fatal cancers over a lifetime due to exposure to ^{60}Co contaminated steel window frames. Due to the small population size at HHK, these cancers will most likely not be measurable, however, when extrapolated to a large population these risk values are of concern.

The results of this study show that the dose rates at HHK school are of public health concern. Dose rates that ranged from 0.08 μSv h^{-1} to 75.38 μSv h^{-1} were clearly greater than the background levels of 0.1 μSv h^{-1} and exceeded recommended doses to the public of 1 mSv yr^{-1}. Additional research may be necessary because this study was rudimentary in nature and there were several limitations to the methodology. For example, dose rates were not integrated over the year to account for decay of ^{60}Co (half life = 5.27 years), residency time could be more accurately described, risk analysis could have included adults, and a computer modeling code that did not require as many assumptions could have been used. Further research on the children attending HHK from 1984 to 1992 using sharper exposure and risk assessment tools is warrented, given the results of this study.

Based on the estimates of excess cancer risk per year for students in the three HHK classrooms, it is clear that more attention should be paid to the many buildings in Taiwan contaminated with the contaminated scrap metal as well as to the health of the residents of these buildings. There is a potential for an increase in cancers in the Taiwanese people due to exposure to the contaminated scrap metal in residential, educational, and other buildings. Governmental involvement including public health education, policy making, epidemiological studies, and ongoing medical examinations would benefit the people of Taiwan who were exposed to the elevated levels of radiation for more than ten years.

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